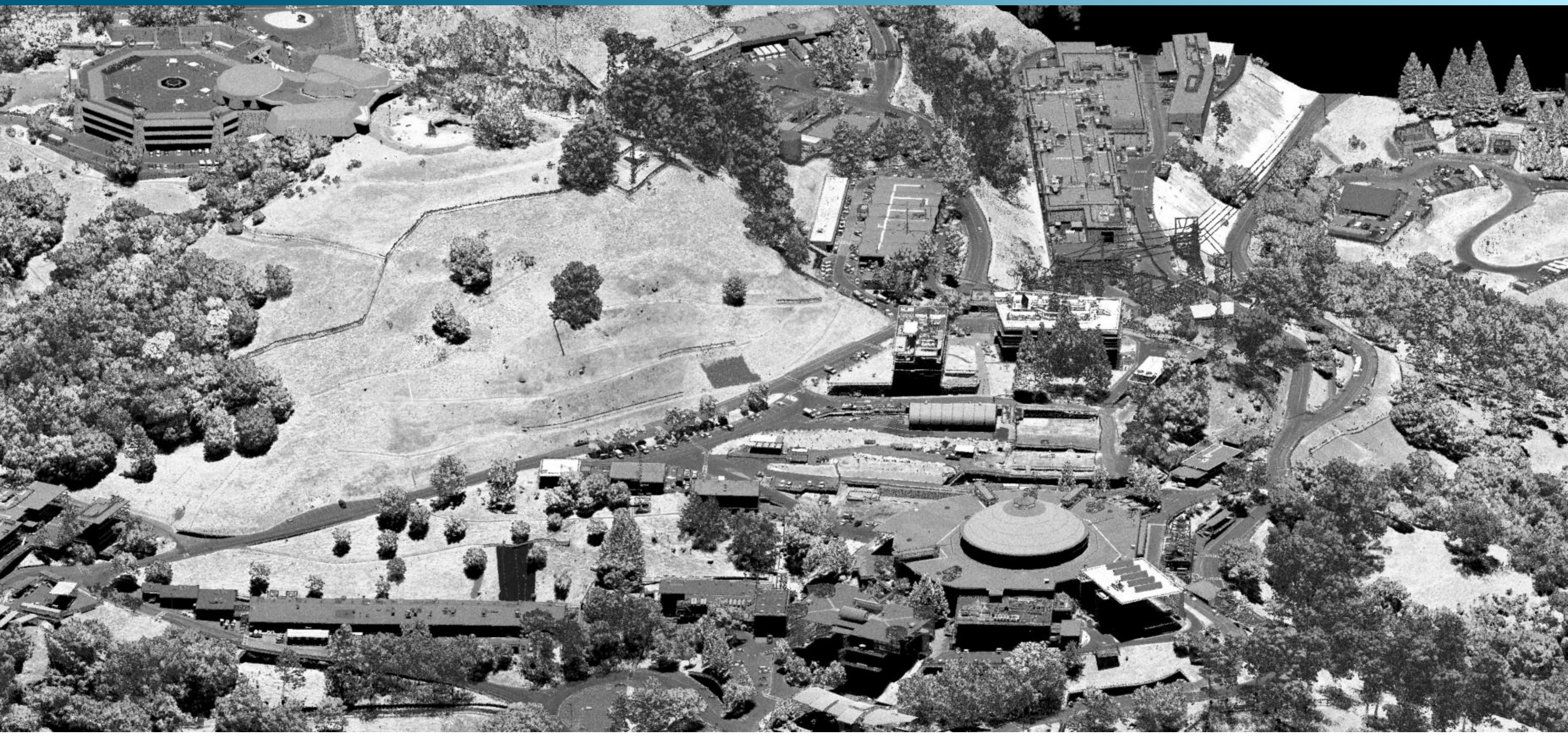
December 22, 2021



USGS 3DEP Alameda County, California Lidar Technical Data Report

Task Order: 140G00221F0140
Project ID: 221241

Contract: G16PC00016
Work Unit ID: 225024 / 225021 / 221238

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Cover Photo: A view looking southeast over the Lawrence Berkeley National Laboratory and Lawrence Hall of Science on the Berkeley Campus. The image was created from the lidar point cloud and colored by laser point intensity.

INTRODUCTION

This photo shows NV5 ground survey equipment set up for the collection of ground control in the USGS 3DEP Alameda County site in California.

In June 2021, NV5 Geospatial (NV5) was contracted by the United States Geological Survey (USGS) to collect Light Detection and Ranging (lidar) data in the summer of 2021 for the USGS 3DEP Alameda County site in California. In addition to the collection of new QL0 and QL1 level lidar, USGS contracted NV5 to upgrade previously collected 2019 Western Alameda County Lidar data on the borders of this new dataset to USGS 3DEP QL1 standards. Data were collected to further support the USGS 3D Elevation Program (3DEP) in assessing the topographic and geophysical properties of the study area to support disaster response planning, and wildfire mitigation and modeling.

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 for the 2021 QL0 and QL1 portions of the contract. The report relating to the 2019 Western Alameda County Lidar data collection can be found attached in Appendix B – 2019 Western Alameda County Report. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to USGS is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the USGS 3DEP Alameda County site

Project Site	Contracted Acres	Acquisition Dates	Data Type
USGS 3DEP Alameda County	119,073	06/21/2021, 06/22/2021, 06/30/2021, 07/02/2021, 07/03/2021	QL0 Lidar
	240,748	06/21/2021, 06/22/2021, 06/23/2021, 06/30/2121, 07/01/2021, 07/02/2021	QL1 Lidar
	138,113	07/02/2019, 07/03/2019, 07/05/2019, 07/06/2019, 08/14/2019, 08/15/2019, 09/05/2019	QL1+ Lidar

Deliverable Products

Table 2: Products delivered to USGS for the USGS 3DEP Alameda County project

USGS 3DEP Alameda County Lidar Products Projection: California State Plane Zone 3 Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID18) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	1.0 Foot Cloud Optimized GeoTiffs • Hydroflattened Bare Earth Model (DEM) • Maximum Surface Height Model (DSM) • Intensity Images • Swath Separation Images
Vectors	Shapefiles (*.shp) • Defined Project Area • Master Tile Index • Lidar Flightline Index • Lidar Swath Shapes • 3D Water's Edge Breaklines • 3D Bridge Breaklines • Ground Survey Data

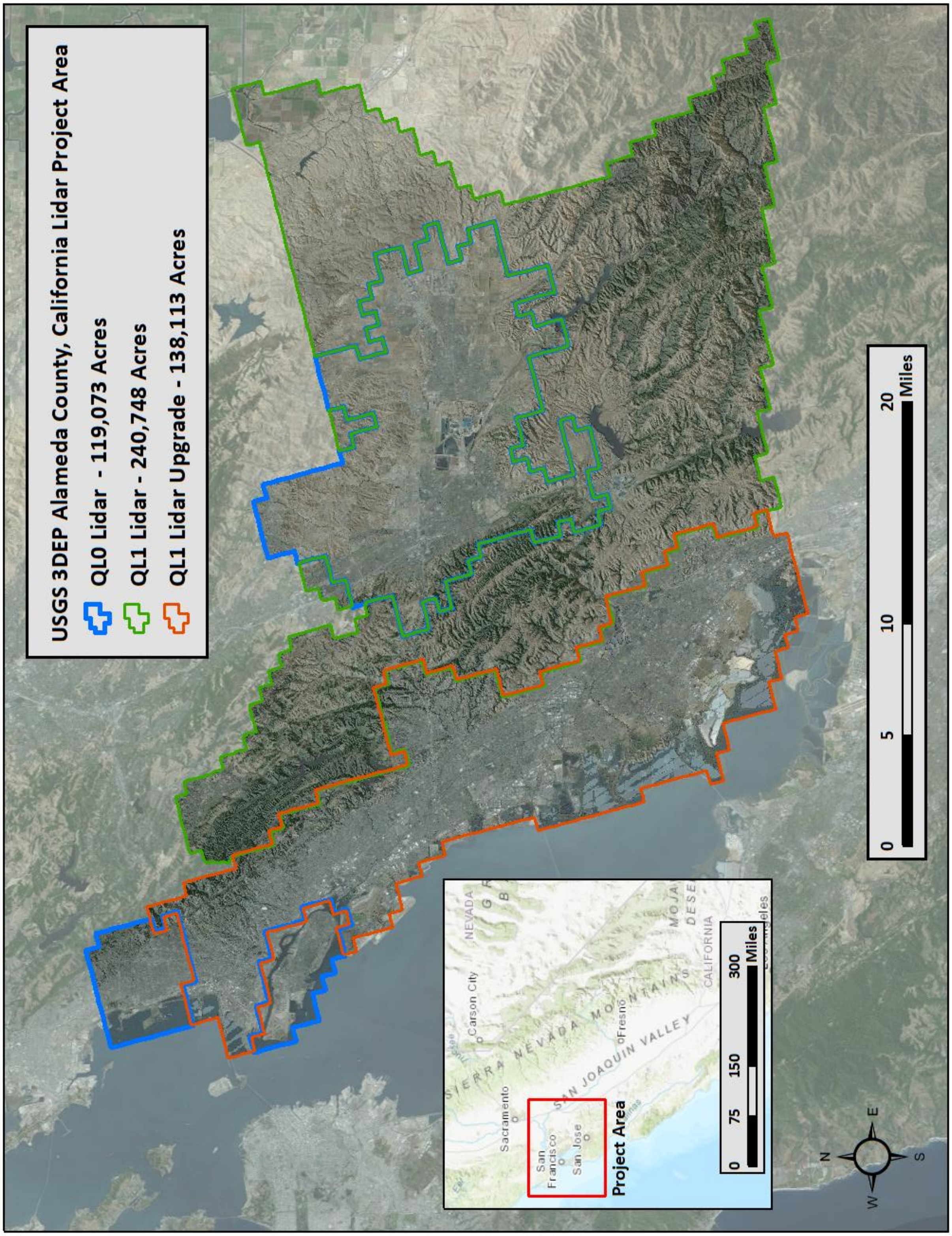


Figure 1: Location map of the USGS 3DEP Alameda County site in California

ACQUISITION

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 USGS 3DEP Alameda County lidar study area at the target point density of ≥20.0 points/m^2 for all QL0 lidar areas, and ≥8.0 points/m^2 for all QL1 lidar areas. 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 Lidar Survey

The lidar survey was accomplished using Riegl VQ-1560ii and Riegl VQ-1560ii-s systems mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥20 pulses/m^2 over the USGS 3DEP Alameda County QL0 project areas, while Table 4 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over all QL1 project areas. Both the Riegl VQ-1560ii and 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. 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 for the 2021 QL0 Lidar Collection

QL0 Lidar Survey Settings & Specifications	
Acquisition Dates	June 21 - July 03, 2021
Data Type	QL0 Lidar
Aircraft Used	Cessna
Sensor	Riegl
Laser	VQ-1560II & VQ-1560II-S
Maximum Returns	15
Resolution/Density	Average 20 pulses/m^2
Nominal Pulse Spacing	0.22 m
Survey Altitude (AGL)	1100 m
Survey speed	145 knots
Field of View	58.2°
Mirror Scan Rate	245 Hz
Target Pulse Rate	2000 kHz
Pulse Length	3.0 ns
Laser Pulse Footprint Diameter	9.0 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad
Swath Width	1,232 m
Swath Overlap	20%
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 6 cm
	NVA (95% Confidence Level) ≤ 9.8 cm
	VVA (95^{th} Percentile) ≤ 15 cm

Table 4: Lidar specifications and survey settings for the 2021 QL1 Lidar Collection

QL1 Lidar Survey Settings & Specifications	
Acquisition Dates	June 21 - July 02, 2021
Data Type	QL1 Lidar
Aircraft Used	Cessna
Sensor	Riegl
Laser	VQ-1560II-S
Maximum Returns	15
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2,196 m
Survey speed	145 knots
Field of View	58.2°
Mirror Scan Rate	131 Hz
Target Pulse Rate	1123 kHz
Pulse Length	3.0 ns
Laser Pulse Footprint Diameter	39.5 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad
Swath Width	2,460 m
Swath Overlap	20%
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
	NVA (95% Confidence Level) ≤ 19.6 cm
	VVA (95^{th} Percentile) ≤ 30 cm

All areas were surveyed with an opposing flight line side-lap of ≥20% 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 5: Flight Date Table

Date	Flight Line #	Start Time (Adjusted GPS)	End Time (Adjusted GPS)
07/02/2019	10202 - 10216	246118507	246122623
07/03/2019	10300 - 10319	246187324	246197814
07/05/2019	10001 - 10007	246359412	246362327
07/06/2019	10100 - 10107	246446011	246449467
08/14/2019	10400 - 10413	24979997	249807181
08/15/2019	10500 - 10511	249884872	249892200
09/05/2019	10600 - 10601	251745463	251745965
06/21/2021	100 - 125, 200 - 202	308305284	308318104
06/22/2021	300 - 313	308411075	308416353
06/23/2021	400 – 428	308477751	308491622
06/30/2021	500 – 510	309093800	309100792
07/01/2021	701 - 710	309184232	309192031
07/02/2021	800 - 847	309260577	309276257
07/03/2021	600 – 613	309356288	309359318

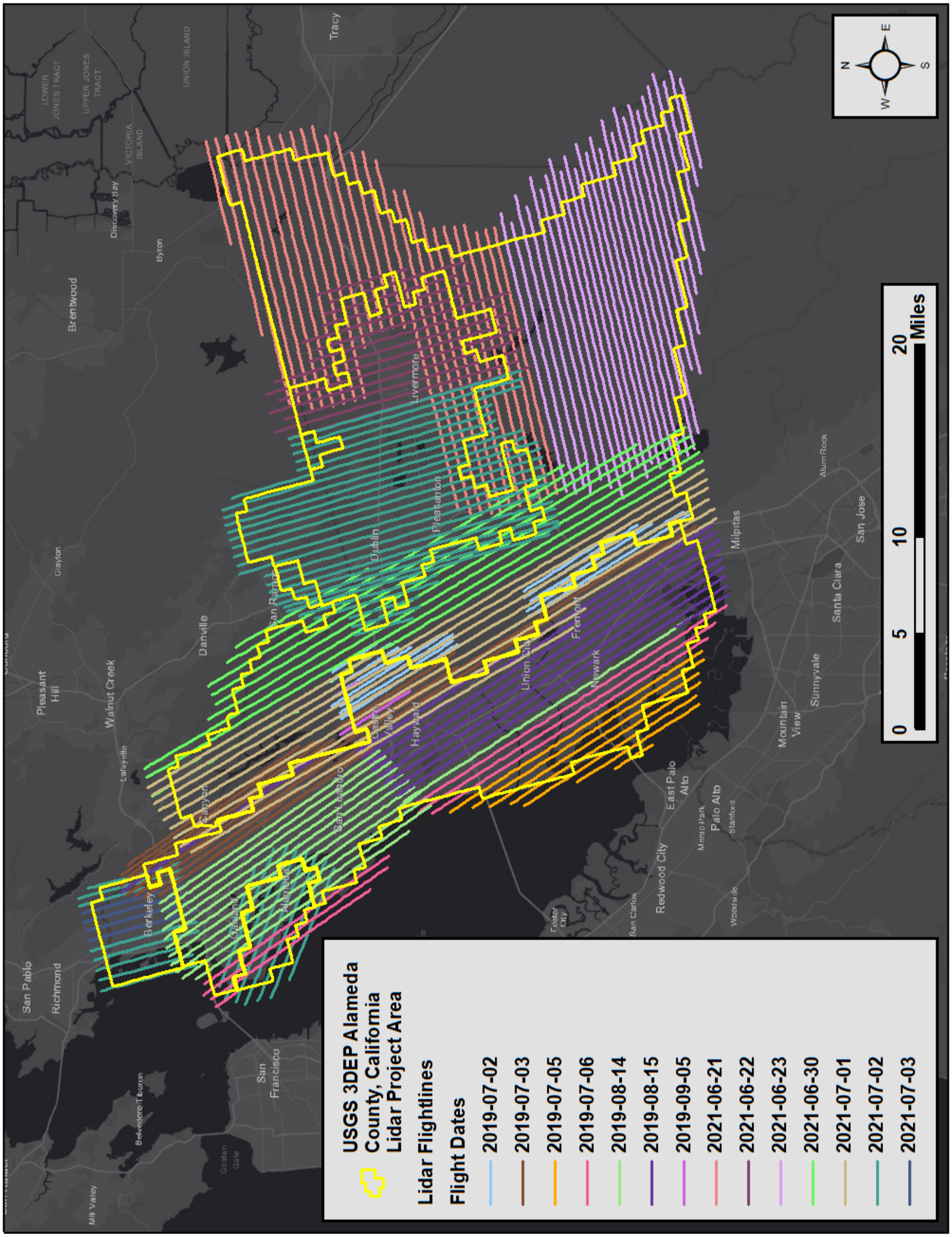


Figure 2: Flightline Survey Map

Ground Survey

NV5 Geospatial Established Monument

Ground control surveys, including monumentation, and ground survey points (GSPs) were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data. For additional information on the 2019 ground survey for the QL1 upgrade dataset please see the included Western Alameda County, California Lidar Technical Data Report (Appendix B – 2019 Western Alameda County Report.

Base Stations

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

Base stations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 Geospatial utilized three permanent real-time network (RTN) base stations from the California Surveying & Drafting Supply (CSDS) network and two existing NV5 owned monuments for the USGS 3DEP Alameda County Lidar project (Table 6, Figure 3). NV5 Geospatial's professional land surveyor, Evon Silvia (CAPLS#9401) oversaw and certified the ground survey and establishment of all monuments.

Table 6: Base station positions for the USGS 3DEP Alameda County acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Base Station ID	Owner	Latitude	Longitude	Ellipsoid (meters)
ALAMEDA_01	NV5	37° 30' 46.45120"	-121° 49' 44.52723"	97.109
ALAMEDA_02	NV5	37° 30' 49.63592"	-121° 32' 29.43138"	664.493
BR1I	CSDS	37° 52' 26.22678"	-122° 15' 34.71518"	91.555
LI1K	CSDS	37° 41' 15.35493"	-121° 46' 18.71197"	120.006
TC1C	CSDS	37° 43' 42.05933"	-121° 32' 04.00385"	49.361

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) and total station (TS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. All GSP measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. See Table 7 for Trimble unit specifications.

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

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

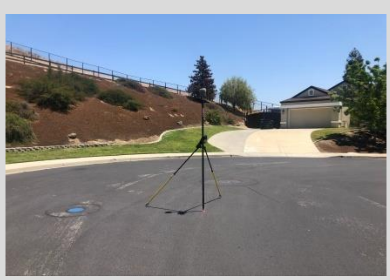
Table 7: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8 Model 2	Integrated Antenna	TRMR8_GNSS	Rover
Trimble R8 Model 3	Integrated Antenna	TRMR8_GNSS3	Rover
Trimble R10	Integrated Antenna	TRMR10	Rover
Nikon NPL-322+ 5” P Total Station		n/a	VVA
Trimble M3 Total Station		n/a	VVA

Land Cover Class

In addition to ground survey points, land cover class check points were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 8, see Lidar Accuracy Assessments, page 26).

Table 8: Land Cover Types and Descriptions

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

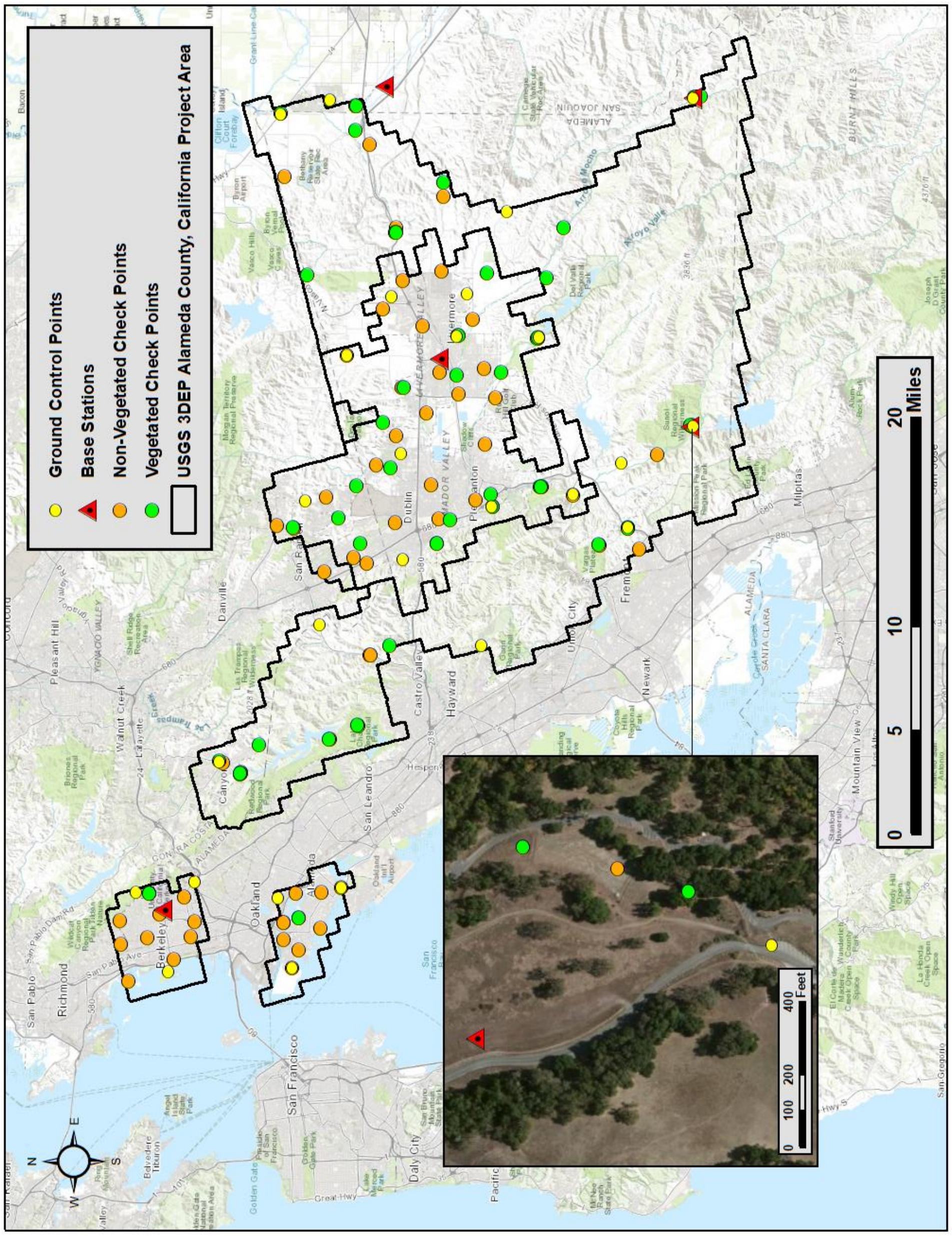
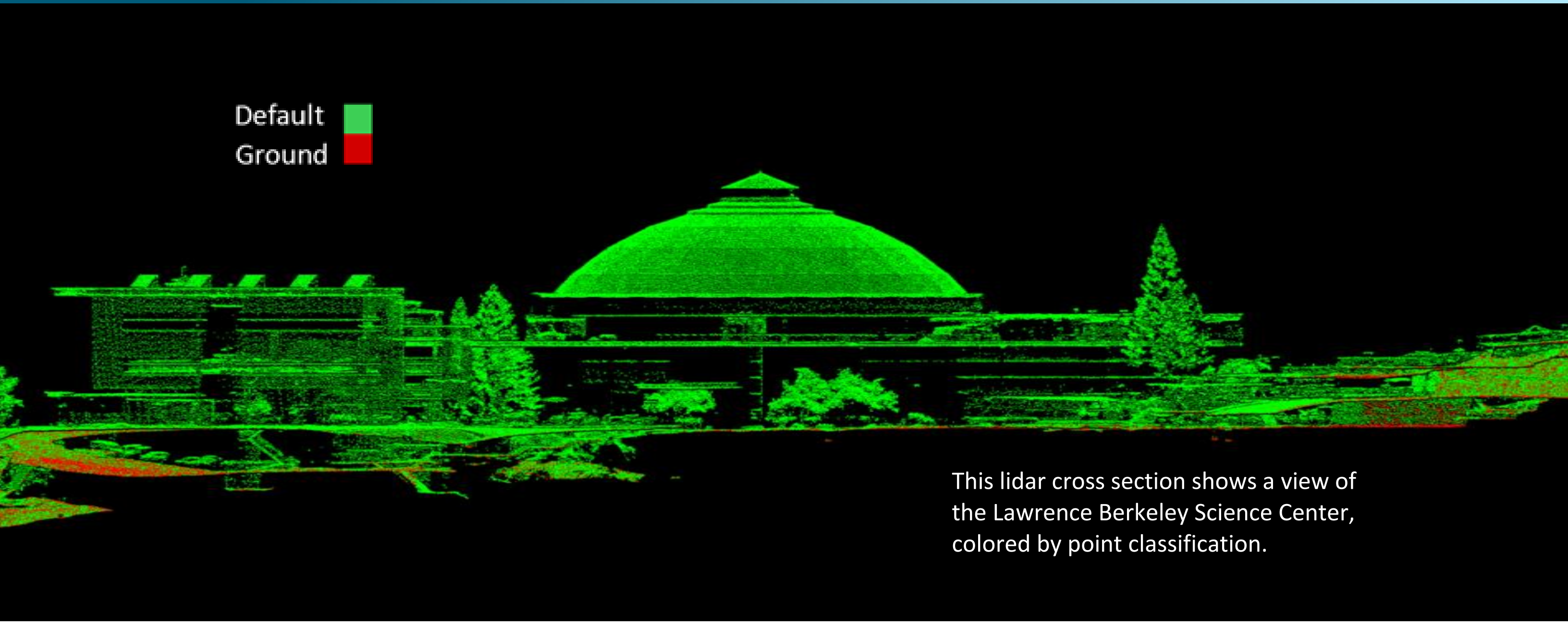


Figure 3: Ground survey location map



This lidar cross section shows a view of the Lawrence Berkeley Science Center, colored by point classification.

Lidar Data

Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and lidar point classification (Table 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 USGS 3DEP Alameda County dataset

Classification Number	Classification Name	Point Count QL0 Lidar	Point Count QL1 Lidar	Classification Description
1	Default/Unclassified	30,889,567,273	32,278,052,224	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1-W	Edge Clip/Withheld	252,868,589	343,247,905	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	4,217,453,896	6,764,257,067	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7-W	Noise/Withheld	16,186,138	75,066,317	Laser returns that are often associated with artificial points below the ground surface
9	Water	99,517,349	39,559,851	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	29,462,673	2,081,288	Bridge decks
18-W	High Noise/Withheld	303,857,621	75,872,070	Laser returns that are often associated with birds or scattering from reflective surfaces
20	Ignored Ground	2,092,095	1,211,369	Ground points proximate to water's edge breaklines; ignored for correct model creation

Table 10: lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS, Applanix PPRTX data and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.5
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiProcess v1.8.5
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	BayesMap StripAlign v2.19
Import calibrated points into manageable blocks for editing.	TerraScan v.21
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.21 TerraModeler v.21
Generate hydroflattened bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as Cloud Optimized GeoTiffs at a 1.0-foot pixel resolution.	Las Product Creator 3.5 (NV5 proprietary software) TerraModeler v.21 ArcMap v. 10.3.1
Export intensity images and swath separation images as Cloud Optimized GeoTIFFs at a 1.0-foot pixel resolution.	Las Product Creator 3.5 (NV5 proprietary software) ArcMap v. 10.7

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The San Francisco Bay surrounding the USGS 3DEP Alameda County 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, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. Additionally, NV5 hydroflattened a small subset of streams down to 5 meters based on a provided 2012 stream shapefile. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges and 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. Specific care was taken to not hydroflatten wetland and marsh habitat found throughout the study site.

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 3D water edge breaklines resulting in the final hydroflattened model (Figure 4).

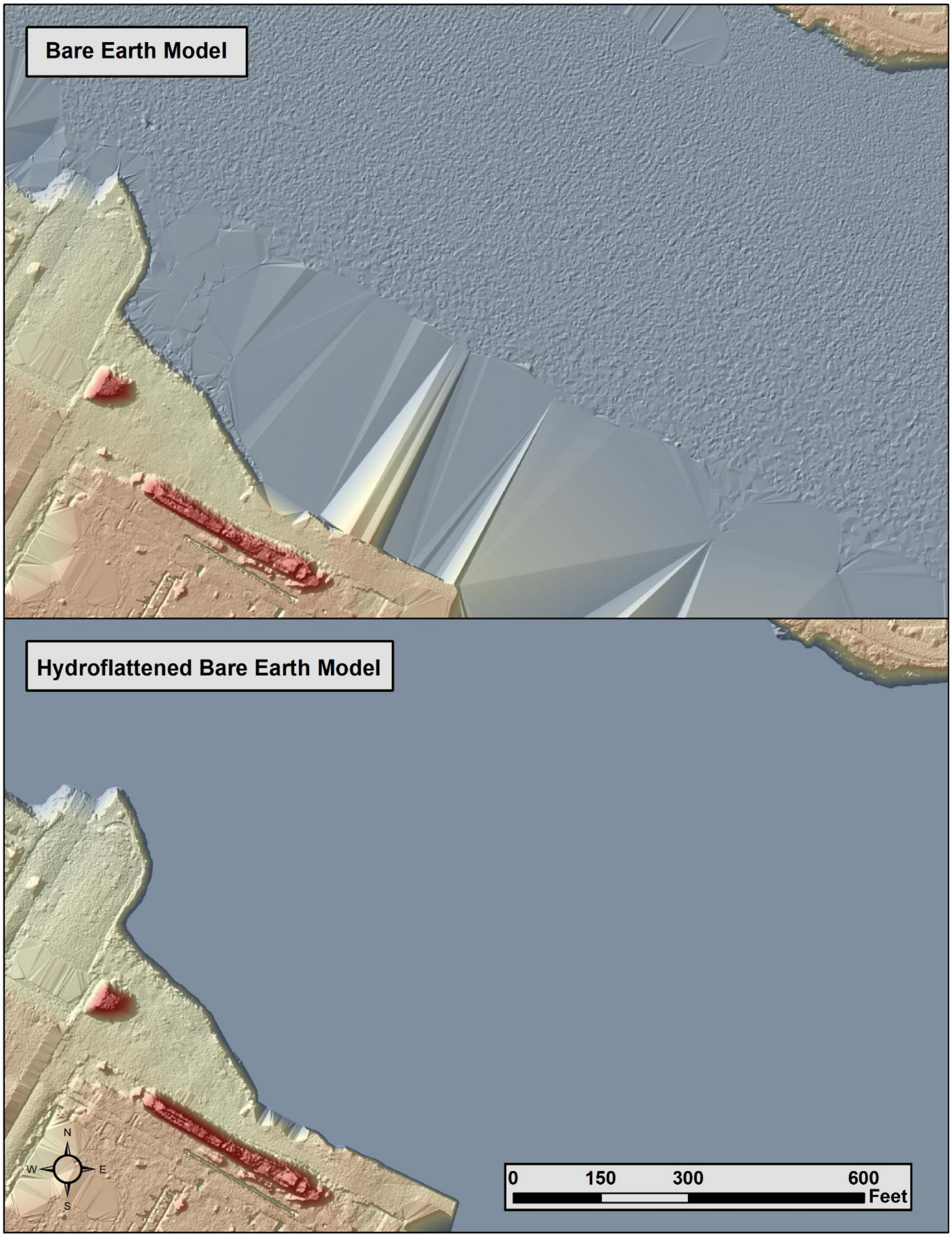
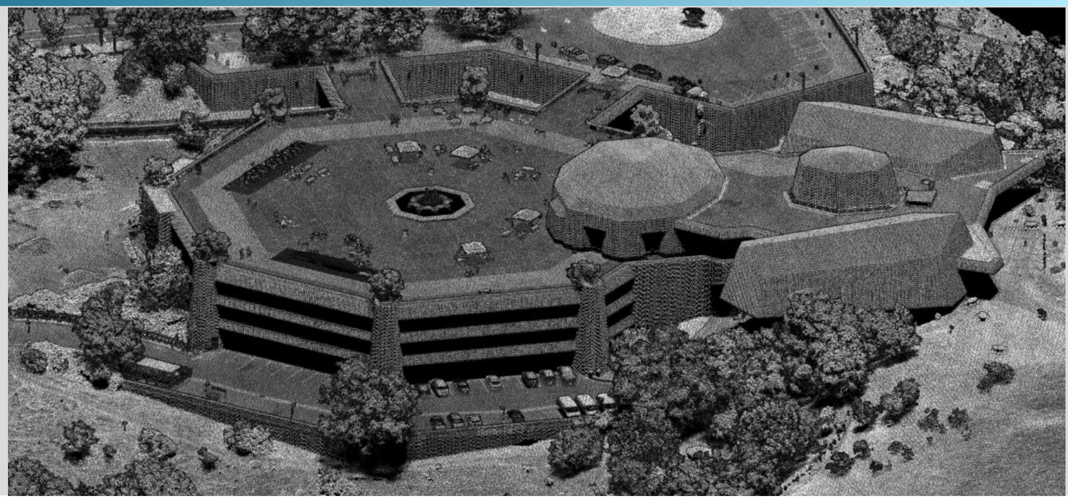


Figure 4: Example of hydroflattening in the USGS 3DEP Alameda County Lidar dataset

This image of the Lawrence Science Center was created from the lidar point cloud and colored by laser point intensity values.



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 20 points/m^2 (1.86 points/ft^2) for all QL0 areas and 8 points/m^2 (0.74 points/ft^2) for all QL1 areas. 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 all QL0 areas of the USGS 3DEP Alameda County project was 5.75 points/ft^2 (61.29 points/m^2) while the average ground classified density was 0.83 points/ft^2 (8.97 points/m^2) (Table 11). QL1 lidar areas yielded an average first-return density of 2.82 points/ft^2 (30.31 points/m^2) while the average ground classified density was 0.65 points/ft^2 (7.00 points/m^2) (Table 12). 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 12.

Table 11: Average QL0 lidar point densities

Classification	Point Density
First-Return	5.75 points/ft^2 61.92 points/m^2
Ground Classified	0.83 points/ft^2 8.97 points/m^2

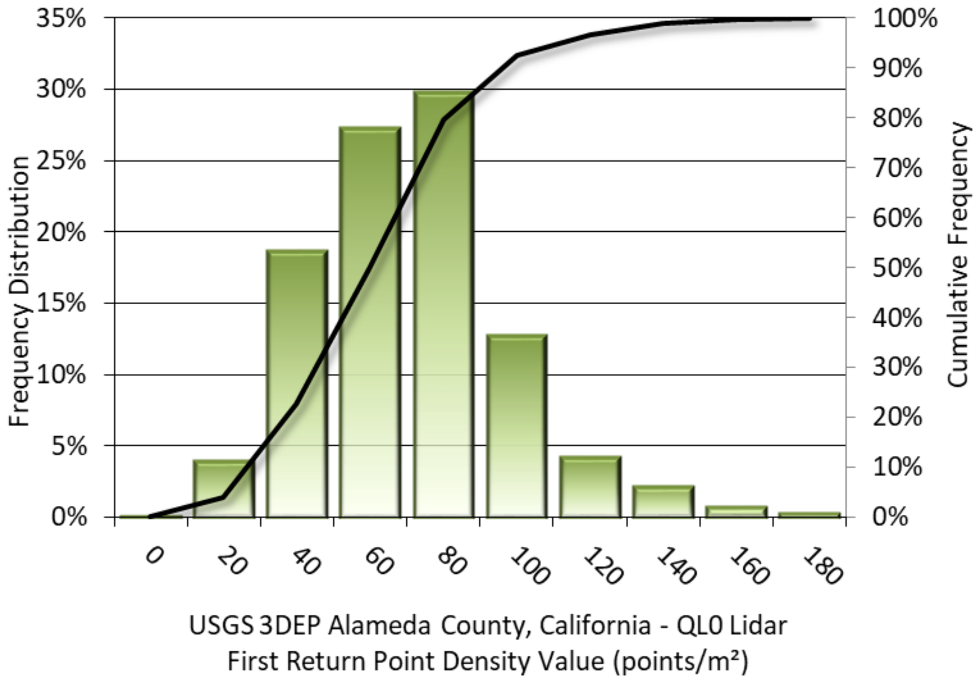


Figure 5: Frequency distribution of QL0 first return point density values per 100 x 100 m cell

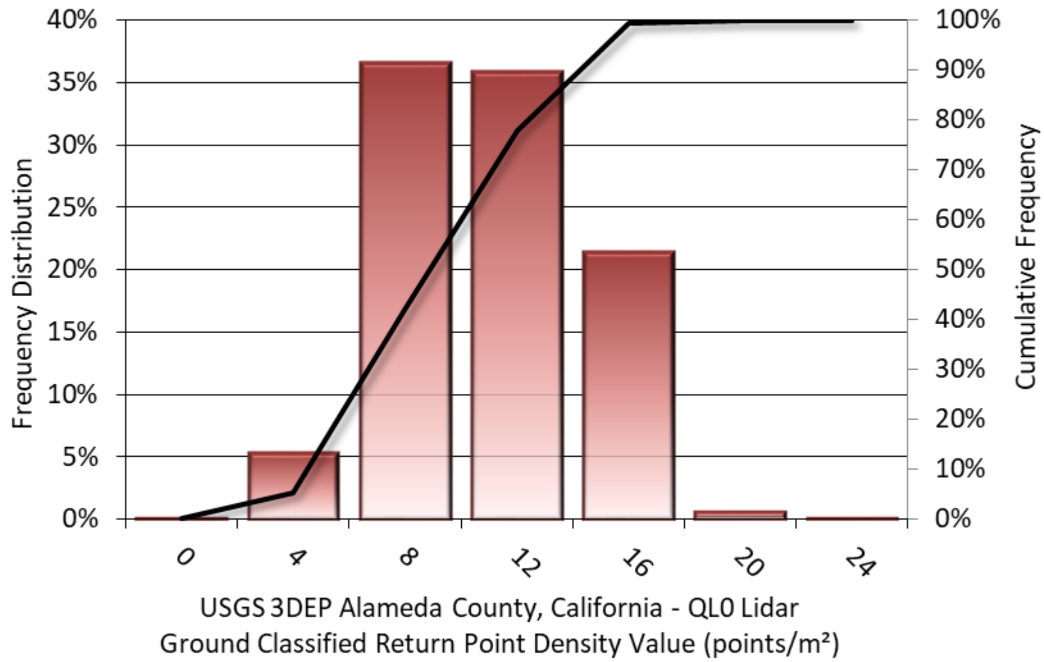


Figure 6: Frequency distribution of QL0 ground-classified return point density values per 100 x 100 m cell

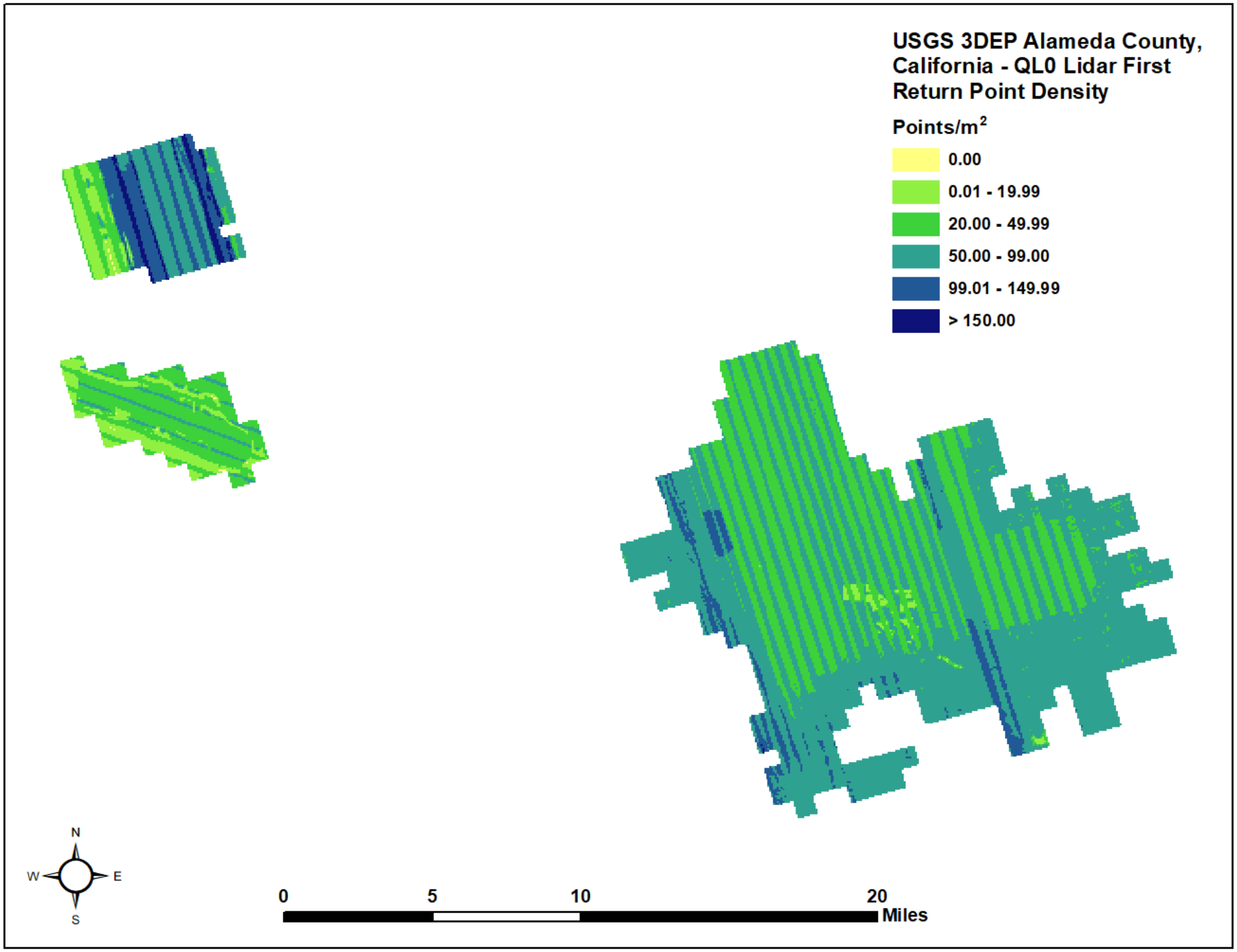


Figure 7: First return point density map for the USGS 3DEP Alameda County QL0 Lidar site (100 m x 100 m cells)

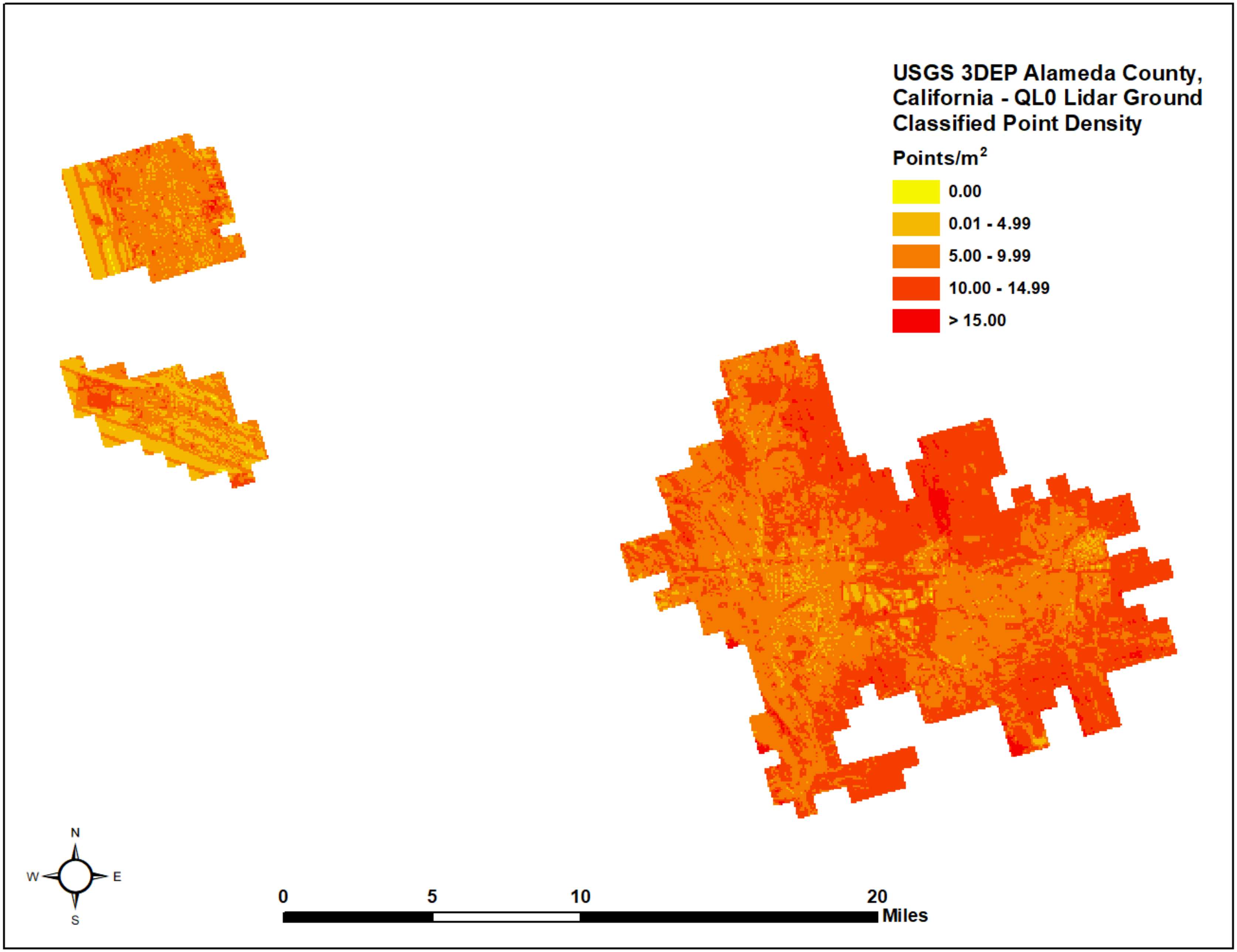


Figure 8: Ground point density map for the USGS 3DEP Alameda County QL0 Lidar Site (100 m x 100 m cells)

Table 12: Average QL1 lidar point densities

Classification	Point Density
First-Return	2.82 points/ft^2 30.31 points/m^2
Ground Classified	0.65 points/ft^2 7.00 points/m^2

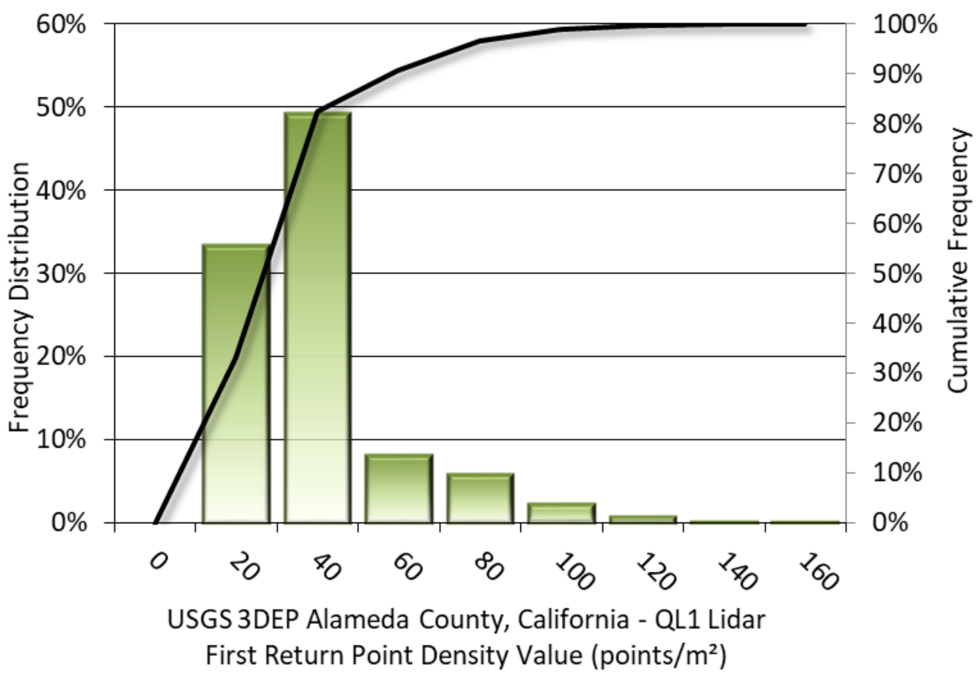


Figure 9: Frequency distribution of QL1 first return point density values per 100 x 100 m cell

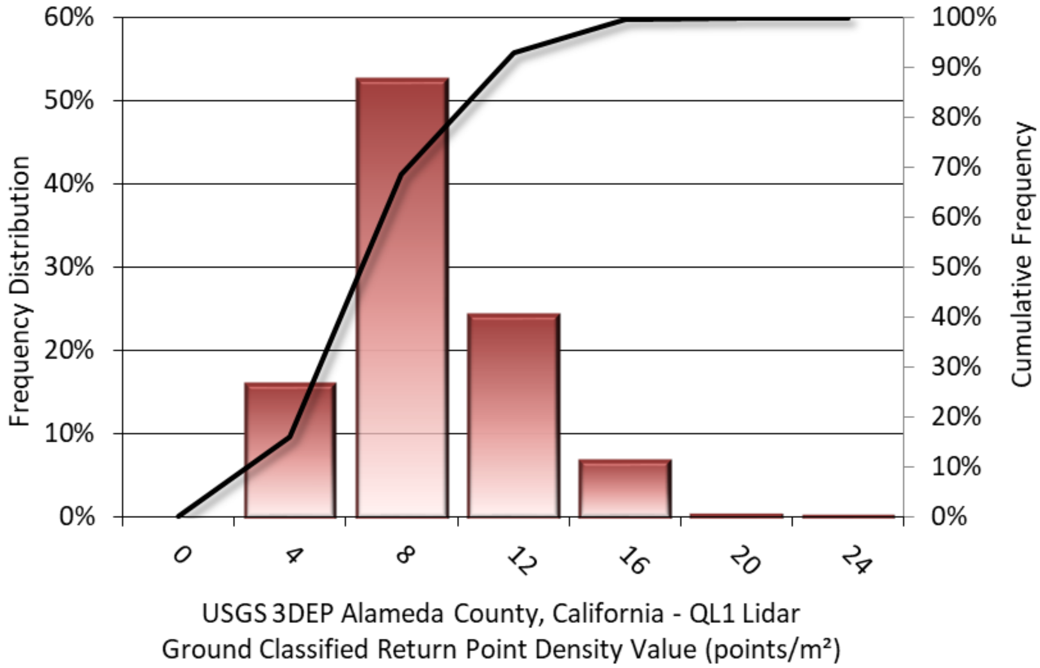


Figure 10: Frequency distribution of QL1 ground-classified return point density values per 100 x 100 m cell

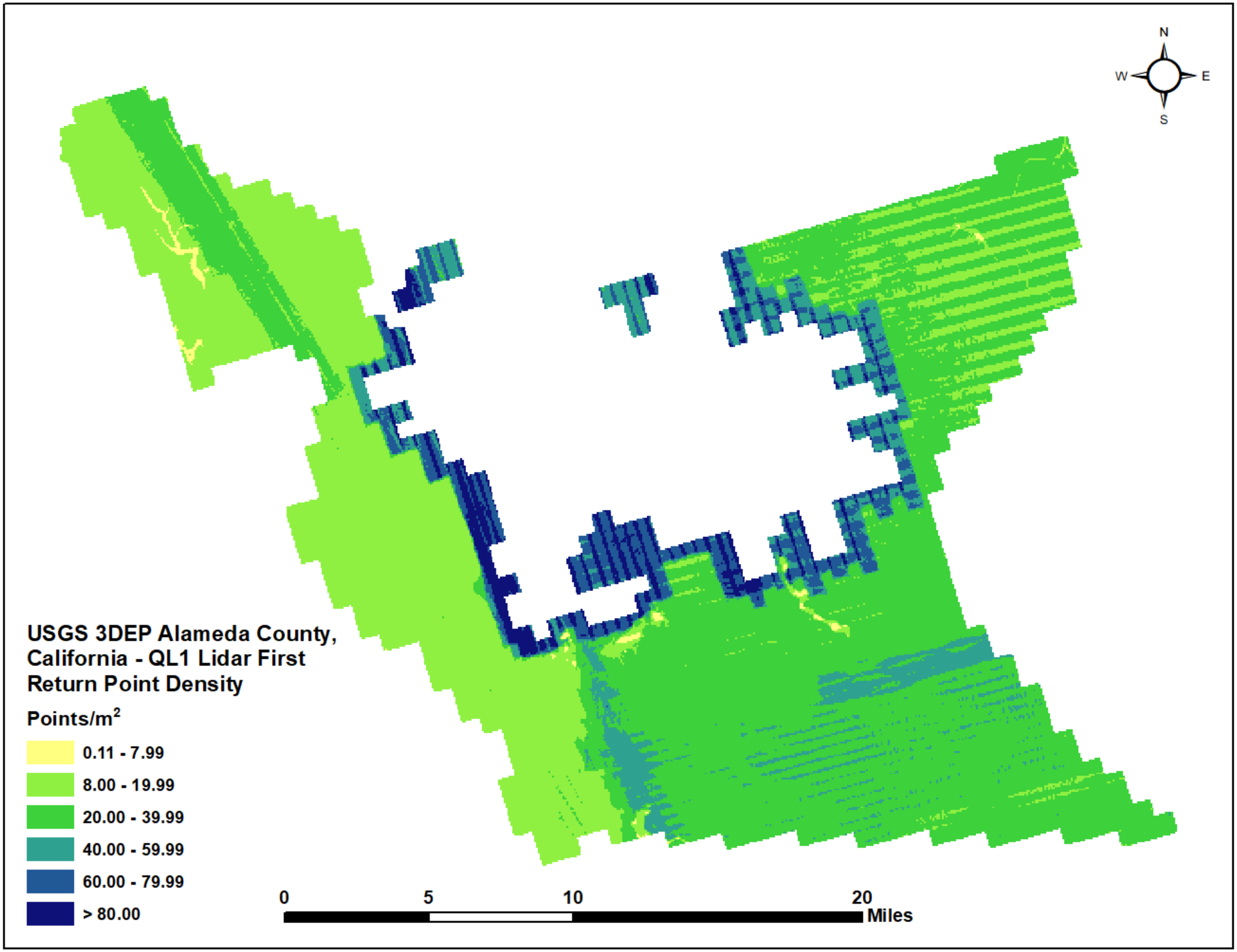


Figure 11: First return point density map for the USGS 3DEP Alameda County QL1 Lidar site (100 m x 100 m cells)

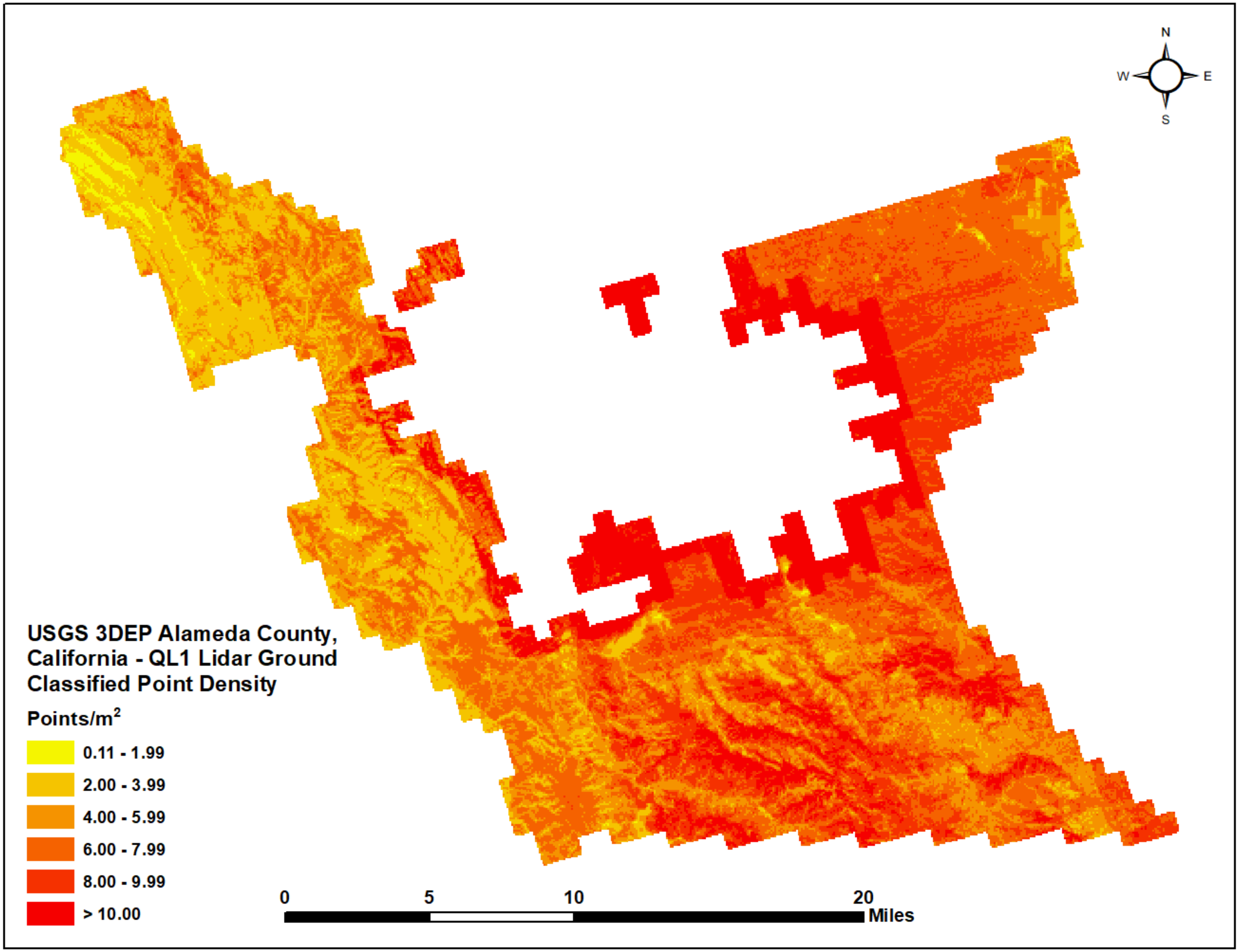


Figure 12: Ground point density map for the USGS 3DEP Alameda County QL1 Lidar site (100 m x 100 m cells)

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 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 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 USGS 3DEP Alameda County survey, 66 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.133 feet (0.041 meters) as compared to classified LAS, and 0.131 feet (0.040 meters) as compared to the bare earth DEM, with 95% confidence (Figure 13, Figure 14).

NV5 Geospatial also assessed absolute accuracy using 26 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 15.

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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 13: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	66 points	66 points	26 points
95% Confidence (1.96*RMSE)	0.133 ft 0.041 m	0.131 ft 0.040 m	0.106 ft 0.032 m
Average	0.002 ft 0.000 m	0.000 ft 0.000 m	0.015 ft 0.005 m
Median	-0.007 ft -0.002 m	0.005 ft 0.002 m	0.007 ft 0.002 m
RMSE	0.068 ft 0.021 m	0.067 ft 0.020 m	0.054 ft 0.016 m
Standard Deviation (1σ)	0.068 ft 0.021 m	0.067 ft 0.021 m	0.053 ft 0.016 m

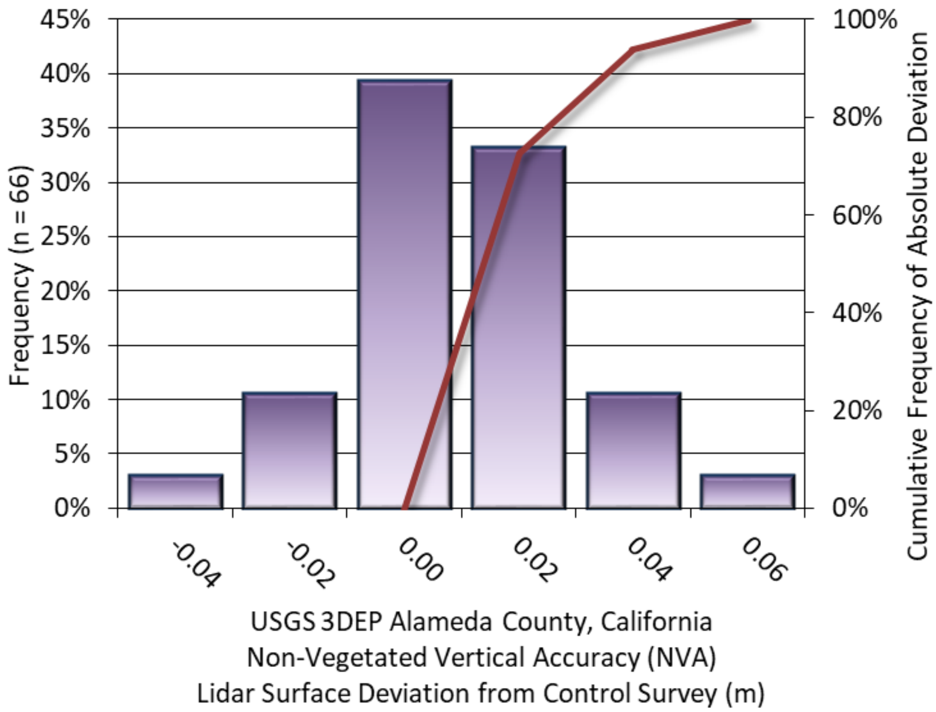

Figure 13: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

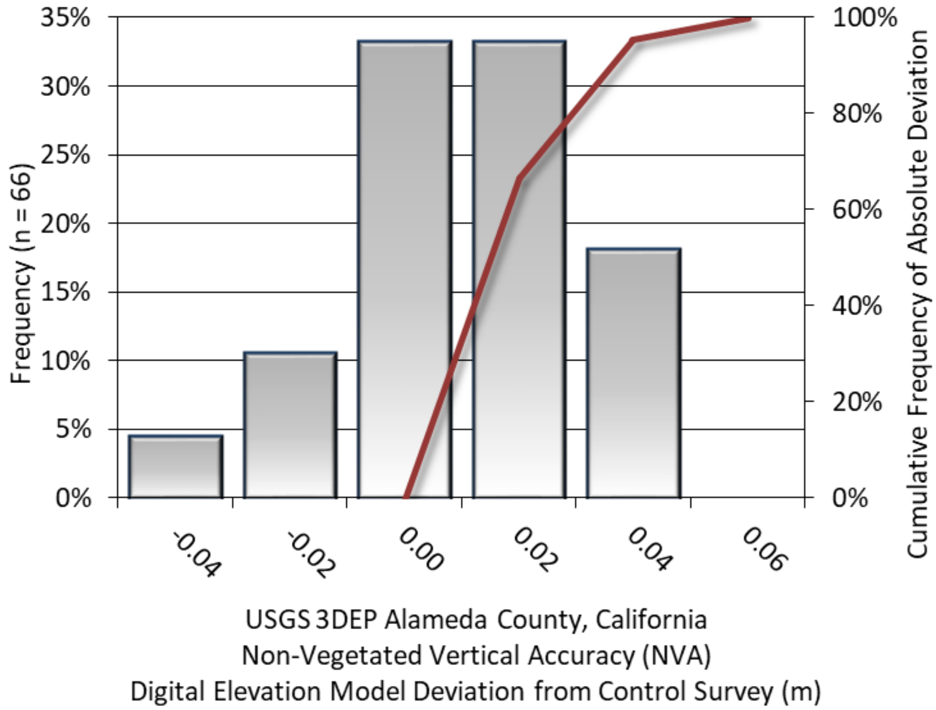

Figure 14: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

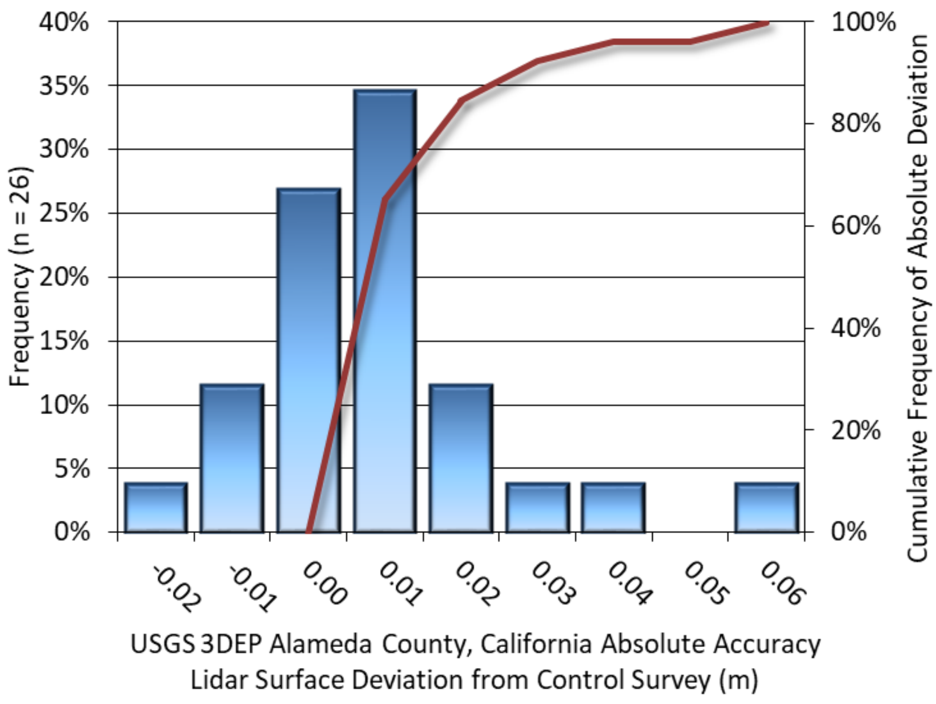

Figure 15: Frequency histogram for lidar surface deviation from ground control point values

Lidar Vegetated Vertical Accuracies

NV5 also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points. For the USGS 3DEP Alameda County survey, 48 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.349 feet (0.106 meters) as compared to the classified LAS, and 0.333 feet (0.102 meters) as compared to the bare earth DEM evaluated at the 95th percentile (Table 14, Figure 16).

Table 14: Vegetated vertical accuracy results

Vegetated Vertical Accuracy		
	VVA, as compared to classified LAS	**VVA, as compared to bare earth DEM**
Sample	48 points	48 points
95th Percentile	0.349 ft 0.106 m	0.333 ft 0.102 m
Average	0.113 ft 0.035m	0.080 ft 0.025 m
Median	0.097 ft 0.030 m	0.069 ft 0.021 m
RMSE	0.194 ft 0.059 m	0.170 ft 0.052 m
Standard Deviation (1σ)	0.159 ft 0.049 m	0.151 ft 0.046 m

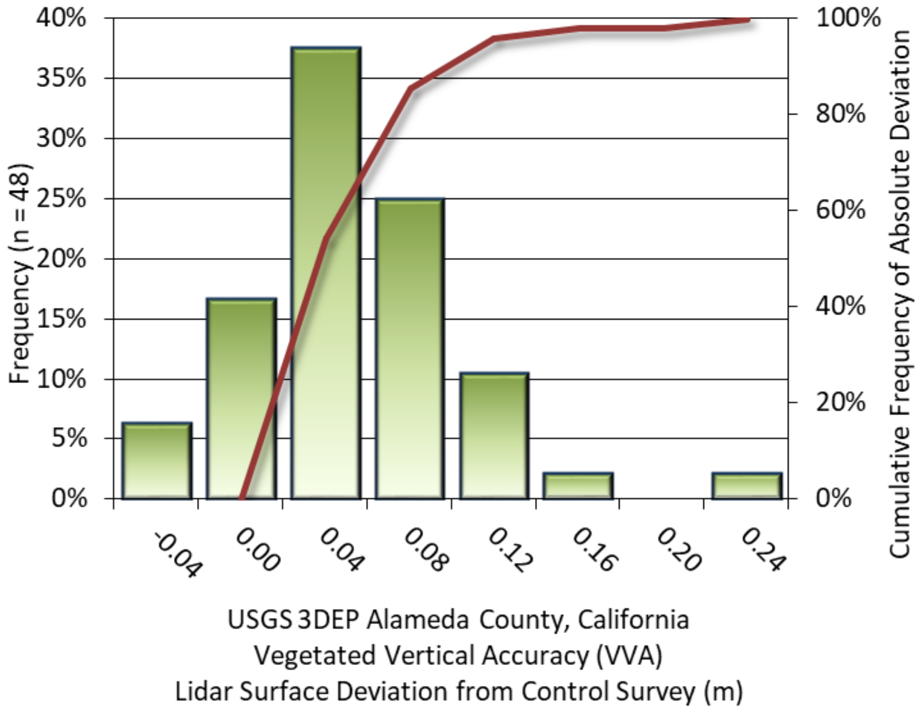

Figure 16: Frequency histogram for the lidar surface deviation from vegetated check point values (VVA)

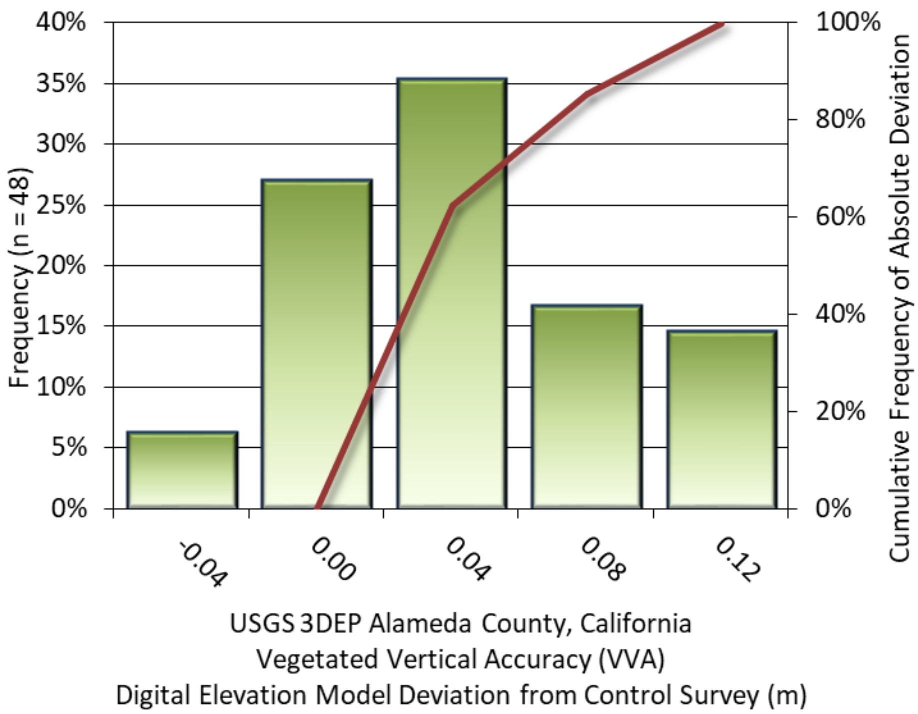

Figure 17: Frequency histogram for the lidar bare earth DEM deviation from vegetated check point values (VVA)

Lidar Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the USGS 3DEP Alameda County project QL0 areas was 0.061 feet (0.018 meters) and 0.074 feet (0.022 meters) for all QL1 areas (Table 15, Table 16, Figure 18, and Figure 19).

Table 15: QL0 Lidar relative accuracy results

QL0 Lidar - Relative Accuracy	
Sample	103 surfaces
Average	0.061 ft 0.018 m
Median	0.059 ft 0.018 m
RMSE	0.067 ft 0.020 m
Standard Deviation (1σ)	0.016 ft 0.005 m
1.96σ	0.031 ft 0.009 m

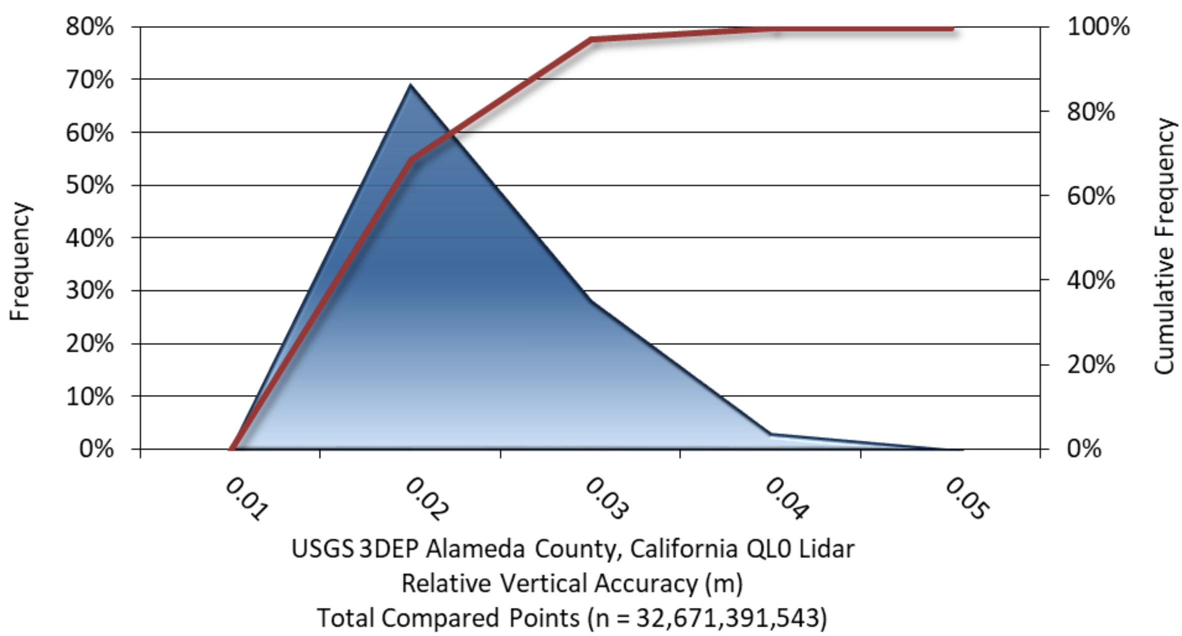

Figure 18: Frequency plot for relative vertical accuracy between flight lines

Table 16: QL1 Lidar relative accuracy results

QL1 Lidar - Relative Accuracy	
Sample	117 surfaces
Average	0.074 ft 0.022 m
Median	0.072 ft 0.022 m
RMSE	0.074 ft 0.023 m
Standard Deviation (1σ)	0.016 ft 0.005 m
1.96σ	0.032 ft 0.010 m

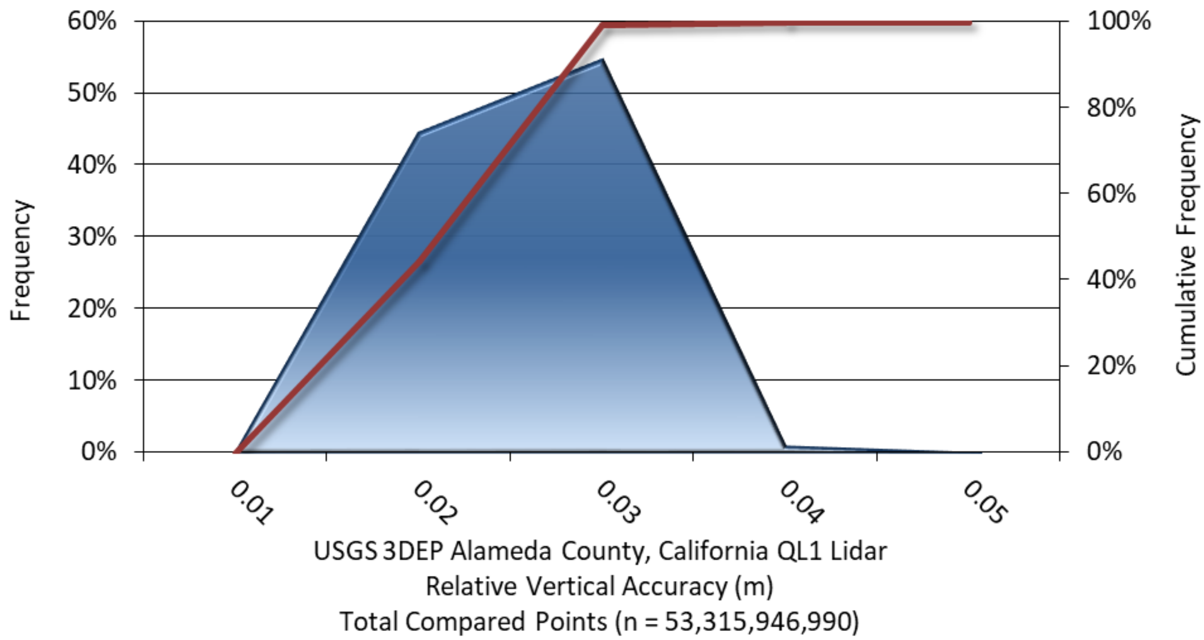

Figure 19: Frequency plot for relative vertical accuracy between flight lines

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. All QL0 areas surveyed at a flying altitude of 1,100 meters, with an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.019 meters, were produced to meet 0.40 ft (0.12 m) horizontal accuracy at the 95% confidence level. All QL1 areas surveyed at a flying altitude of 2,196 meters, with an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.019 meters, were produced to meet 0.79 ft (0.24 m) horizontal accuracy at the 95% confidence level.

Table 17: QL0 Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.23 ft 0.07 m
ACC_r	0.40 ft 0.12 m

Table 18: QL1 Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.45 ft 0.14 m
ACC_r	0.79 ft 0.24 m

NV5 Geospatial provided lidar services for the USGS 3DEP Alameda County 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 Dec 23, 2021

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 California, 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 21, 2021 and July 20, 2021. Field work for the 2019 survey reflects conditions at the time of survey and may not reflect present conditions.

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 23, 2021

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

Signed: Dec 23, 2021

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.

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 ±29.1° 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.

Appendix B – 2019 Western Alameda County Report

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November 1, 2019

Western Alameda County, California LiDAR

Technical Data Report

Prepared For:

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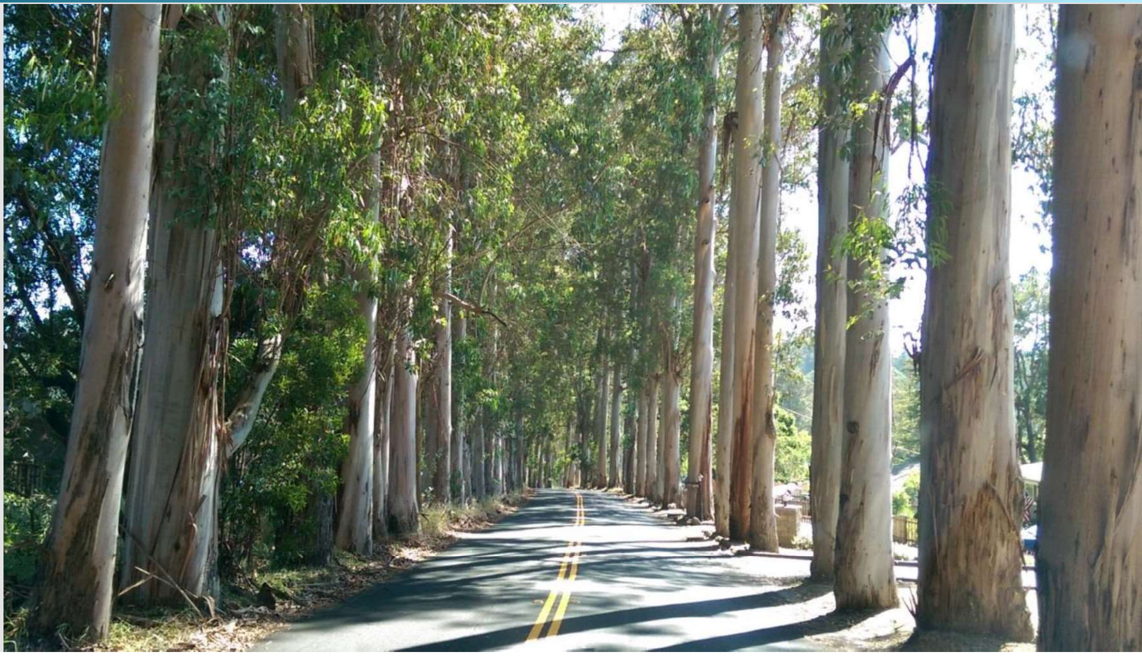
TABLE OF CONTENTS

Cover Photo: A view looking southwest over the city of Hayward, in Alameda County, California. The image was created by layering the LiDAR point cloud over the LiDAR-derived bare earth model and coloring by satellite imagery.

INTRODUCTION

This photo taken by QSI acquisition staff shows a scenic roadway in the Western Alameda AOI.



In May 2019, Quantum Spatial (QSI) was contracted by Wreco to collect high resolution, high accuracy Light Detection and Ranging (LiDAR) data in the summer of 2019 for the Western Alameda County site in California. Data were collected and provided to the Alameda County Flood Control and Water Conservation District, to aid Wreco and Alameda County in mapping fluvial and tidal system interactions in the San Francisco Bay Area.

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 Wreco 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 Western Alameda County site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Western Alameda County, California	156,286	160,522	07/02/2019-08/15/2019	High Resolution LiDAR

Deliverable Products

Table 2: Products delivered to Wreco for the Western Alameda County site

<table>
<tr><th colspan="2">Western Alameda County LiDAR Products
Projection: California State Plane Zone 3
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Units: US Survey Feet</th></tr>
<tr><td>Points</td><td>LAS v 1.4
• All Classified Returns</td></tr>
<tr><td>Rasters</td><td>3.0 Foot ESRI Grids
• Bare Earth Digital Elevation Model (DEM)
• Highest Hit Digital Surface Model (DSM)
1.5 Foot GeoTiffs
• Intensity Images</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Project Boundary
• LiDAR Tile Index
• 0.5 Foot Contours
Drawing Exchange Files (*.dxf)
• Contours (0.5 Foot)</td></tr>
</table>

Figure 1: Location map of the Western Alameda County site in California

This image taken by QSI acquisition staff shows a view of field survey equipment set up in the Alameda County project area.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Western Alameda County LiDAR 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.

Prior to acquisition, factors such as satellite constellation availability and weather windows must be considered. For this project, collection of data was coordinated to coincide with lowest tide conditions (< 1ft). 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.

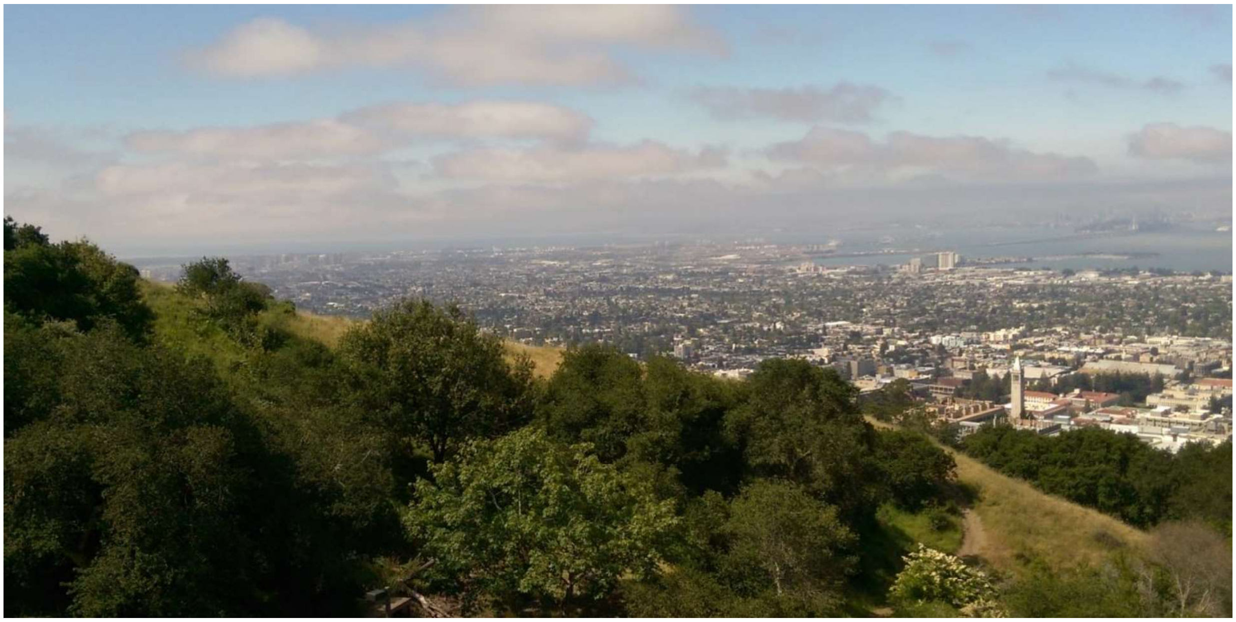
Airborne LiDAR Survey

The LiDAR survey was accomplished using a Riegl VQ-1560i system mounted in a Cessna Caravan. The Reigl VQ-1560i laser system can record unlimited range measurements (returns) per pulse. 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 summarizes the settings used to yield an average pulse density of ≥ 20 pulses/m^2 (1.85 pulses/ ft^2) over the Western Alameda County project area.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
Acquisition Dates	July 2-6, 2019	August 14-15, 2019
Aircraft Used	Cessna Caravan 704MD	Cessna Caravan 840JA
Sensor	Riegl	Riegl
Laser	VQ-1560i	1560i
Maximum Returns	Unlimited	Unlimited
Resolution/Density	Average 20 pulses/m^2	Average 20 pulses/m^2
Nominal Pulse Spacing	0.22 m	0.22 m
Survey Altitude (AGL)	830 m	830 m
Survey speed	105 knots	105 knots
Field of View	58.5º	58.5º
Mirror Scan Rate	Uniform Point Spacing	Uniform Point Spacing
Target Pulse Rate	1000 kHz	1000 kHz
Pulse Length	3 ns	3 ns
Laser Pulse Footprint Diameter	149.40 cm	149.40 cm
Central Wavelength	1,064 nm	1,064 nm
Pulse Mode	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)
Beam Divergence	0.18 mrad	0.18 mrad
Swath Width	431.2 m	930 m
Swath Overlap	20%	20%
Intensity	16-bit	16-bit
Accuracy	Vertical Accuracy (RMSE) ≤5cm	Vertical Accuracy (RMSE) ≤5cm
	Horizontal Accuracy (RMSE) ≤30cm	Horizontal Accuracy (RMSE) ≤30cm
	Relative Accuracy ≤10 cm	Relative Accuracy ≤10 cm

All areas were surveyed with an opposing flight line side-lap of ≥20% in order to help 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.



Scenic photos taken in the Western Alameda County survey area by the QSI acquisition team.

Ground Survey

Ground control surveys, including monumentation, and ground survey points (GSPs) were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data.

Base Stations

Base stations were utilized for the 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. QSI utilized six existing base stations from the California Surveying and Drafting Supply (CSDS) Real-Time Network, for the Western Alameda County LiDAR project (Table 4, Figure 2). QSI's professional land surveyor, Evon Silvia (CAPLS#9401) oversaw and certified the utilization of all base stations.

Table 4: Base Station positions for the Western Alameda County acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Network
BR1G	37° 52' 26.22673"	-122° 15' 34.71511"	91.556	CSDS
CAPO	37° 42' 51.02030"	-122° 13' 19.44534"	-20.340	CSDS
LI1I	37° 41' 15.35504"	-121° 46' 18.71215"	120.991	CSDS
SW1E	37° 18' 07.47743"	-121° 55' 56.57007"	30.588	CSDS
TC1A	37° 43' 42.05952"	-121° 32' 04.00365"	49.358	CSDS
VV1G	38° 21' 15.91034"	-121° 59' 24.49664"	33.591	CSDS

To correct the continuously recorded onboard measurements of the aircraft position, QSI utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency by the base station. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS) to verify and update record positions as needed to align with the National Spatial Reference System (NSRS).

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK). For RTK surveys, a roving receiver receives corrections from a 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 5 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 5: QSI ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble M3 Total Station	n/a	n/a	VVA
Trimble R8	Integrated Antenna	TRM_R8_GNSS	Rover
Trimble R10	Integrated Antenna	TRMR10	Static, Rover

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 6, see LiDAR Accuracy Assessments, page 17).

Table 6: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Short Grass	SH_GRASS		Maintained or low growth herbaceous grasslands	VVA
Tall Grass	TALL_GRASS		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FOR		Areas dominated by forest	VVA
Bare Earth	BARE, BE		Areas of bare earth surface	NVA
Urban	URBAN		Areas dominated by urban development, including parks	NVA

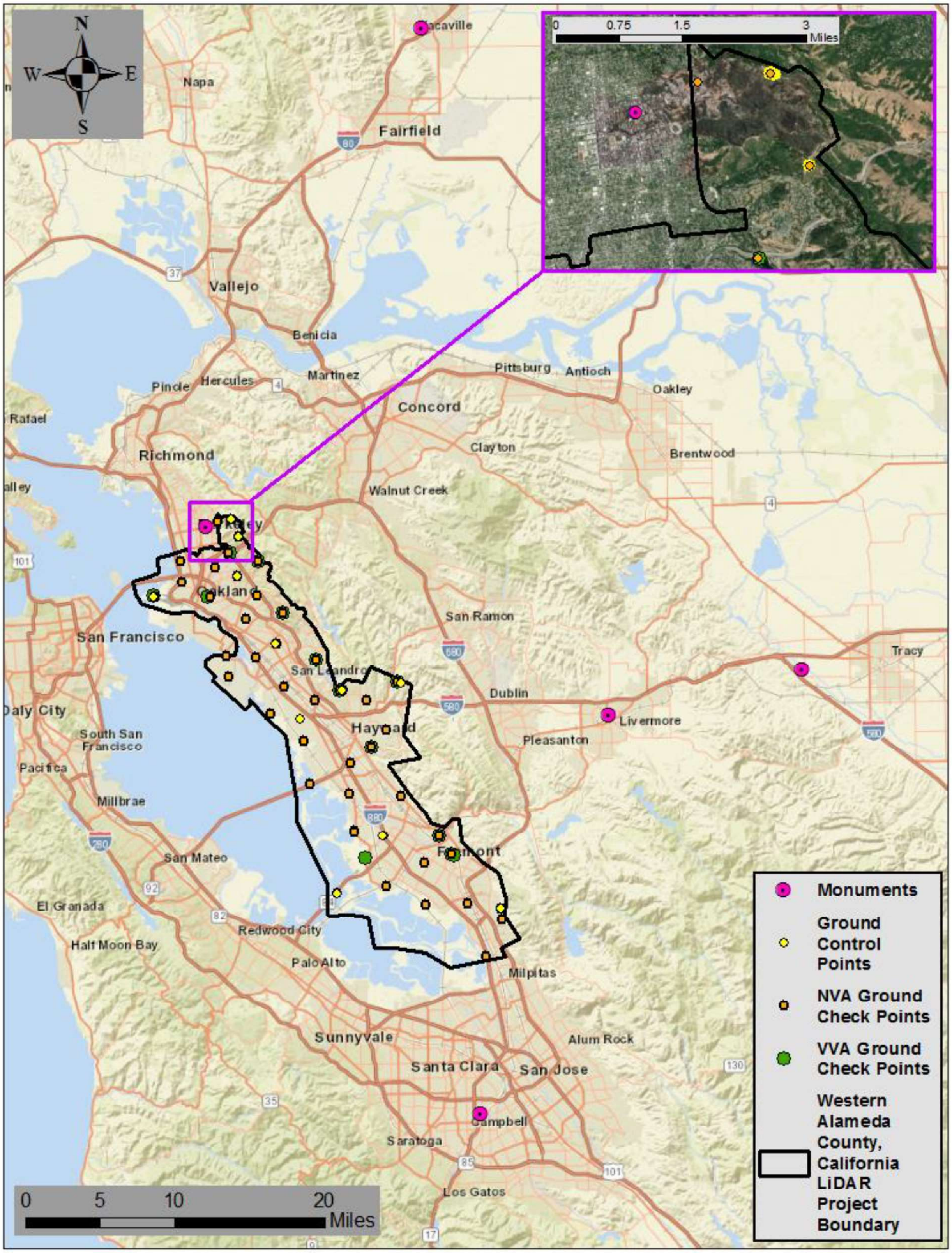
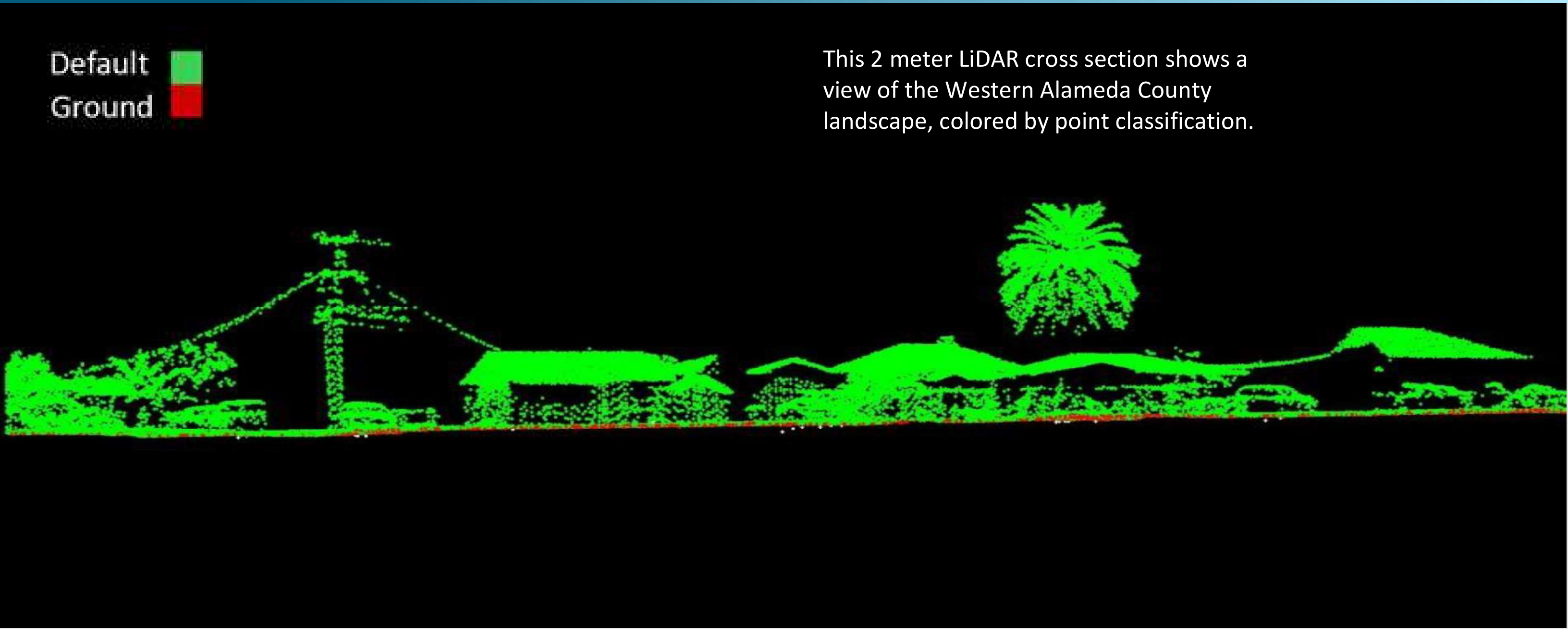


Figure 2: Ground survey location map



This 2 meter LiDAR cross section shows a view of the Western Alameda County 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 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

Table 7: ASPRS LAS classification standards applied to the Western Alameda County 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, scattering from reflective surfaces, or artificial points below the ground surface

Table 8: 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 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 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.	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 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19 TerraModeler v.19
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 3.0-foot pixel resolution.	LAS Product Creator 3.0 (QSI proprietary)
Export intensity images as GeoTIFFs at a 1.5-foot pixel resolution.	LAS Product Creator 3.0 (QSI proprietary) ArcMap v. 10.3.1

Contour Generation

Contour generation from LiDAR point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. Contour key points were selected from the ground model every 0.5 feet with the spacing decreased in regions with high surface curvature. Generation of contour key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the contour key points at even elevation increments.

Elevation contour lines were then intersected with ground point density rasters and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which crossed areas of low point density have low confidence levels. Areas with low ground point density are commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded (Figure 3).

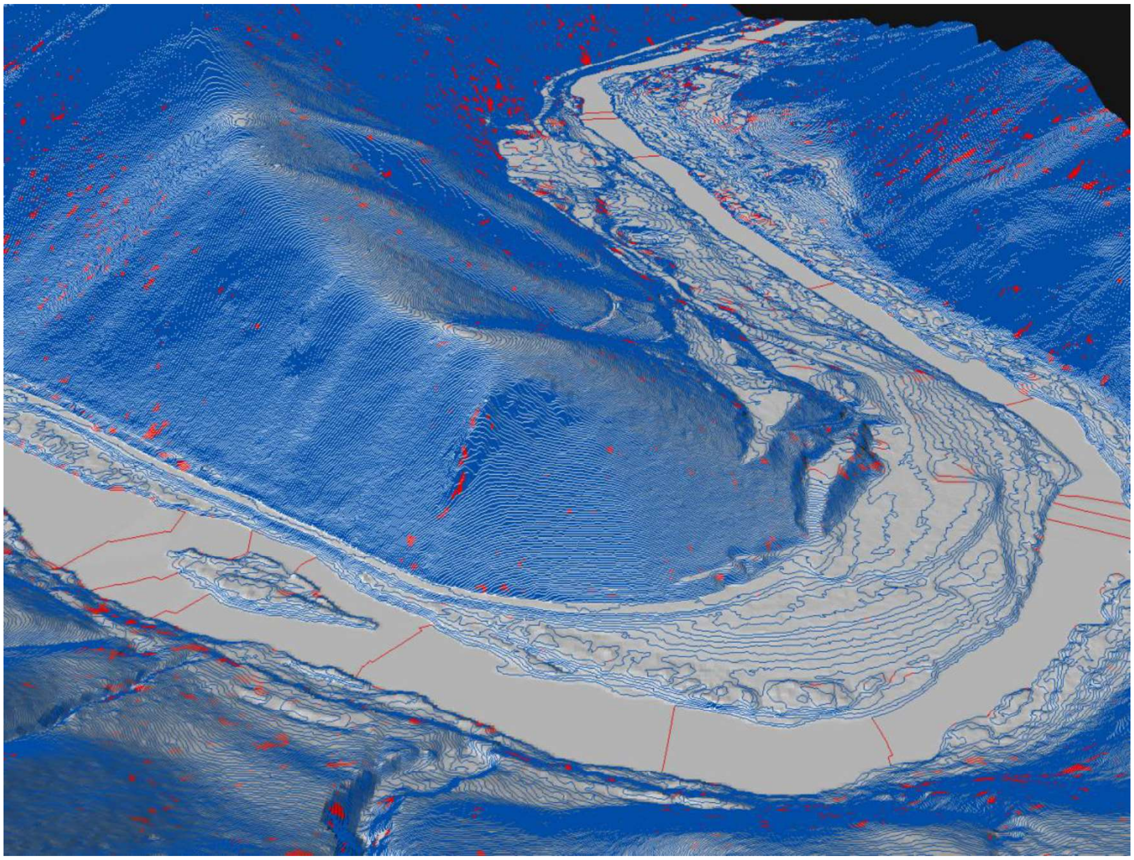
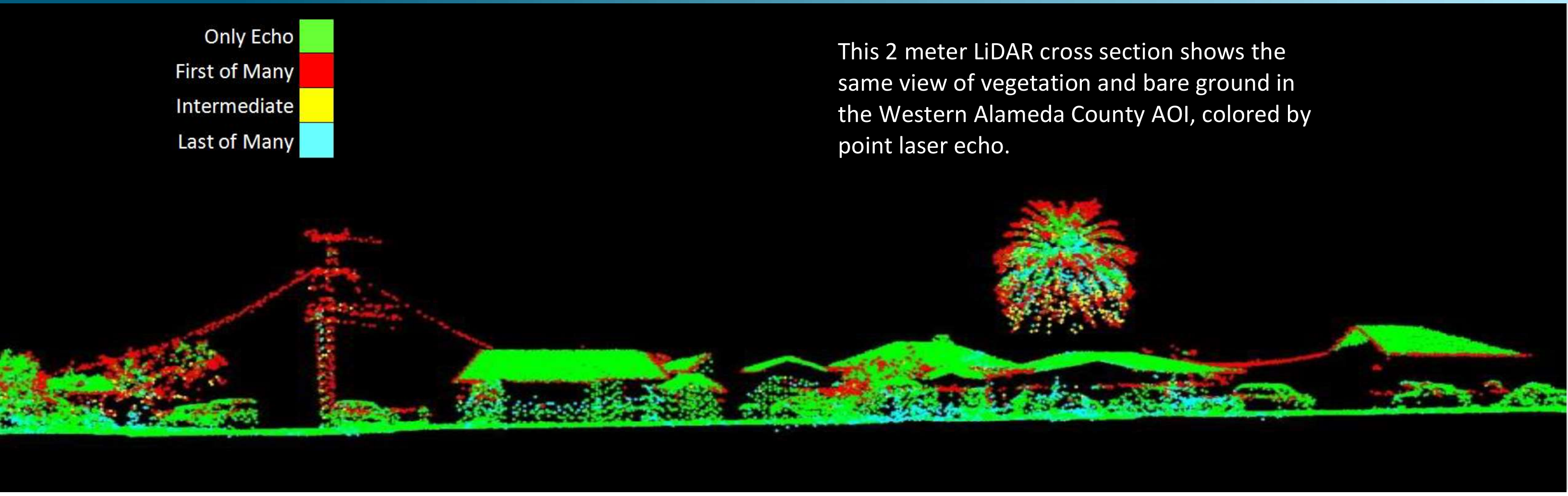


Figure 3: An example of contours draped over a bare earth elevation model. Blue contours represent high confidence while the red contours represent low confidence.



This 2 meter LiDAR cross section shows the same view of vegetation and bare ground in the Western Alameda County 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 Western Alameda County project was 4.32 points/ft^2 (46.48 points/m^2) while the average ground classified density was 0.64 points/ft^2 (6.88 points/m^2) (Table 9). 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 4 through Figure 7.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	4.32 points/ft^2 46.48 points/m^2
Ground Classified	0.64 points/ft^2 6.88 points/m^2

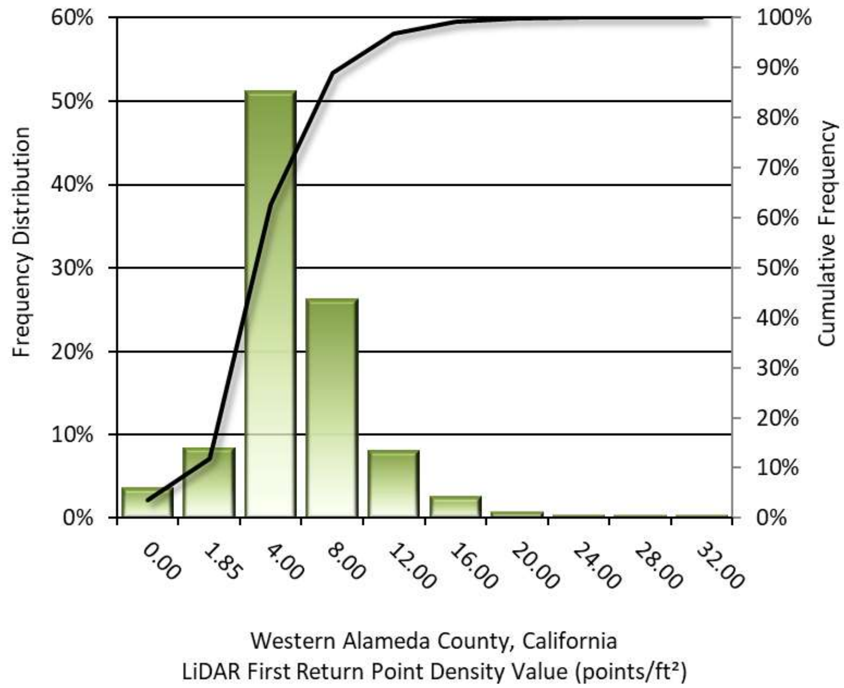


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

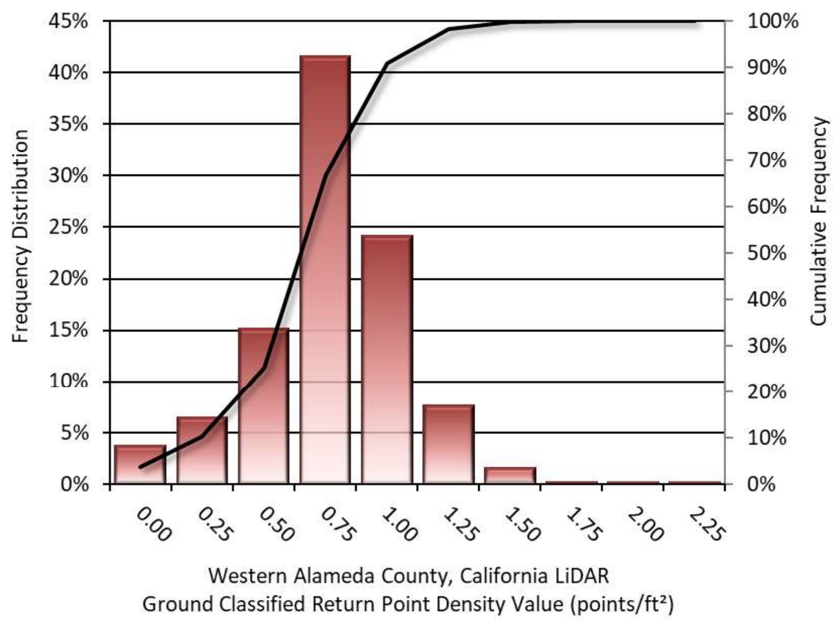


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

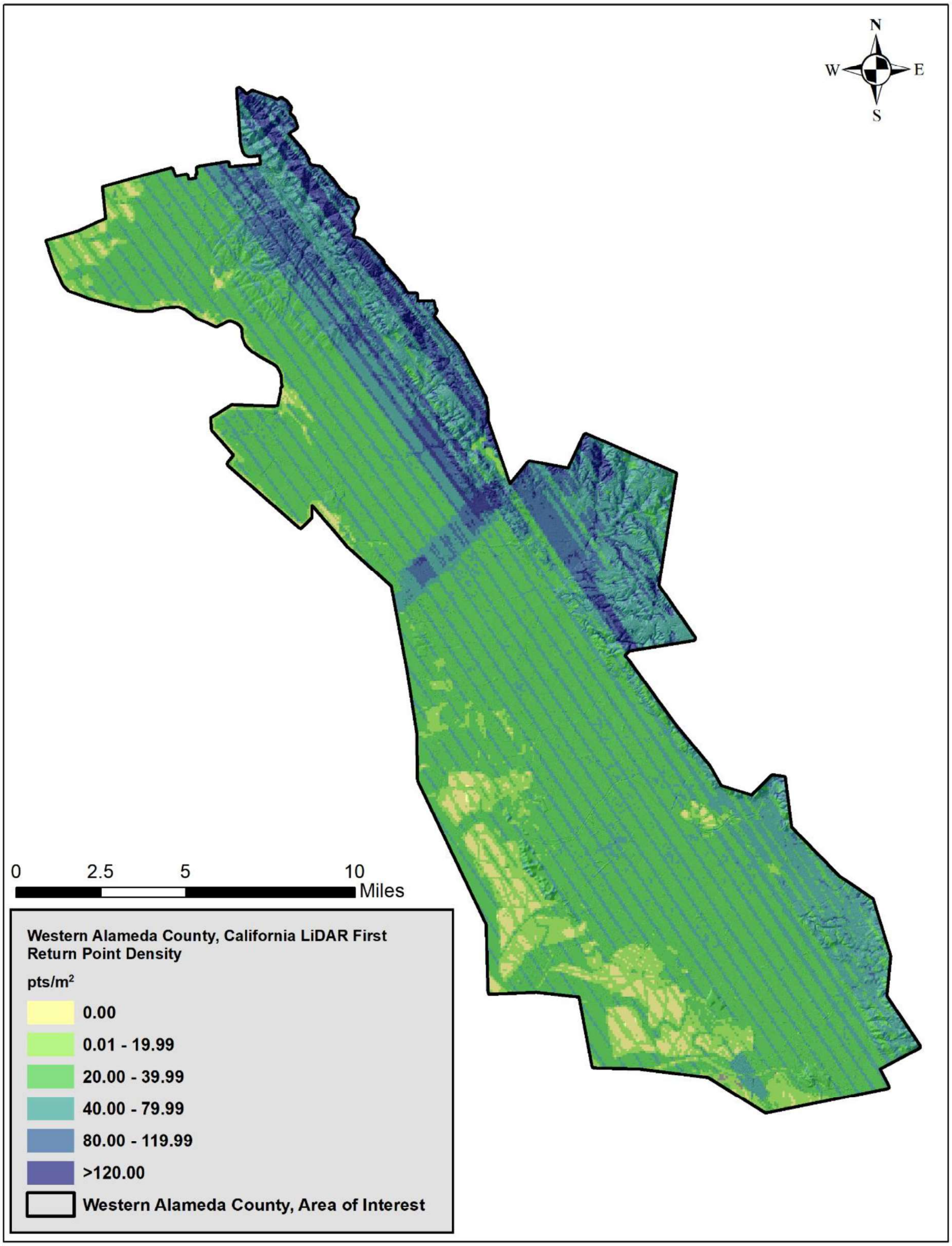


Figure 6: First return point density map for the Western Alameda County site (100 m x 100 m cells)

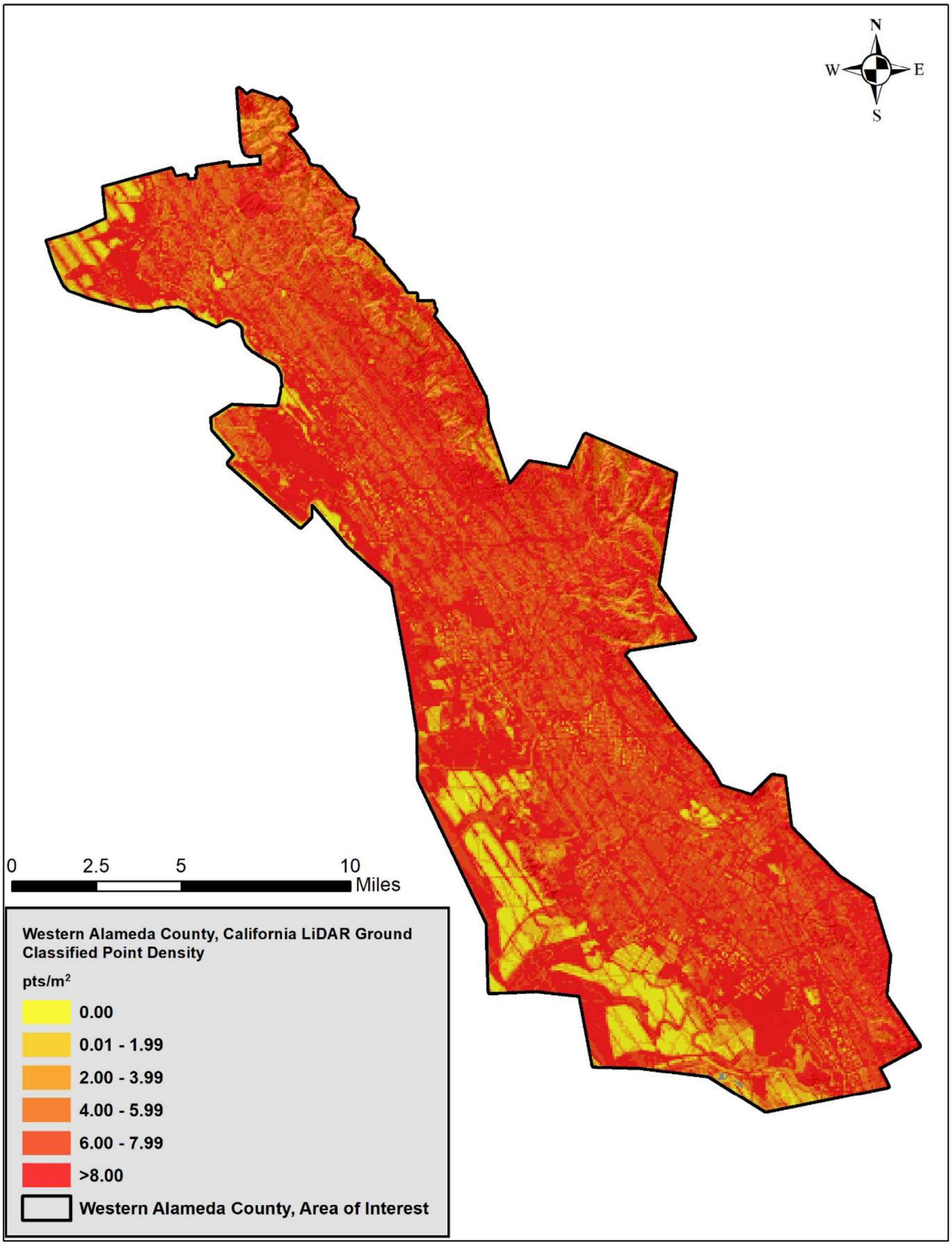


Figure 7: Ground point density map for the Western Alameda County site (100 m x 100 m cells)

LiDAR Accuracy Assessments

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

LiDAR Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[1]. 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 10.

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 Western Alameda County survey, 44 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.195 feet (0.059 meters) as compared to unclassified LAS, and 0.238 feet (0.073 meters) as compared to the bare earth DEM, with 95% confidence (Figure 8, Figure 9).

QSI also assessed absolute accuracy using 280 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 10 and Figure 10.

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[1] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. http://www.asprs.org/PAD-Division/ASPRS-POSITIONAL-ACCURACY-STANDARDS-FOR-DIGITAL-GEOSPATIAL-DATA.html.

Table 10: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	44 points	44 points	280 points
95% Confidence (1.96*RMSE)	0.195 ft 0.059m	0.238 ft 0.073 m	0.192 ft 0.059 m
Average	0.073 ft 0.022 m	-0.009 ft -0.003 m	-0.021 ft -0.007 m
Median	0.079 ft 0.024 m	-0.007 ft -0.002 m	-0.021 ft -0.007 m
RMSE	0.099 ft 0.030 m	0.122 ft 0.037 m	0.098 ft 0.030 m
Standard Deviation (1σ)	0.069 ft 0.021 m	0.123 ft 0.037 m	0.096 ft 0.029 m

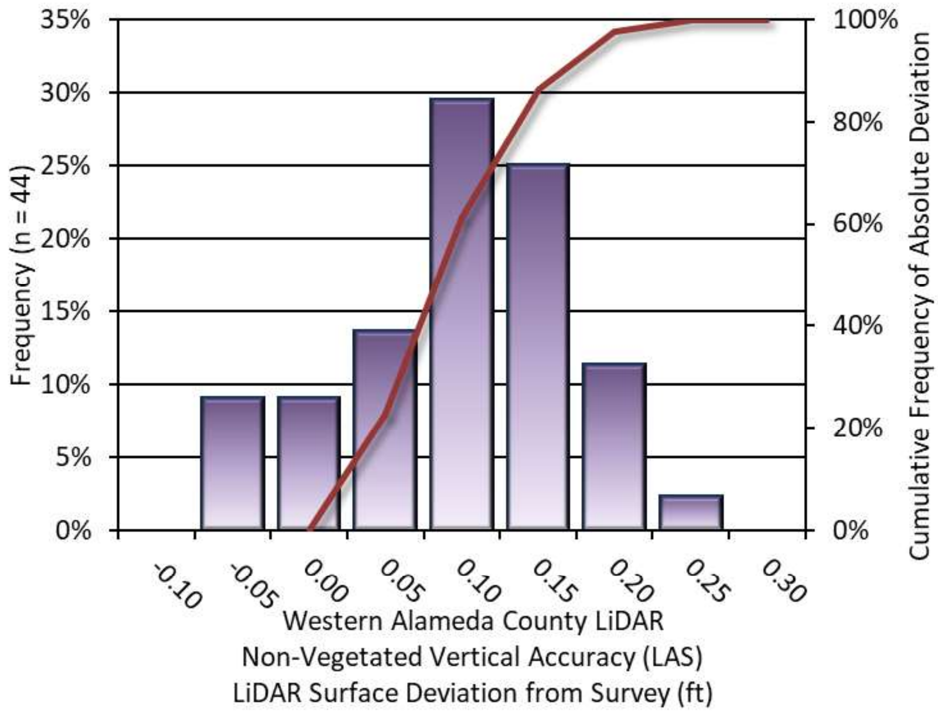

Figure 8: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)

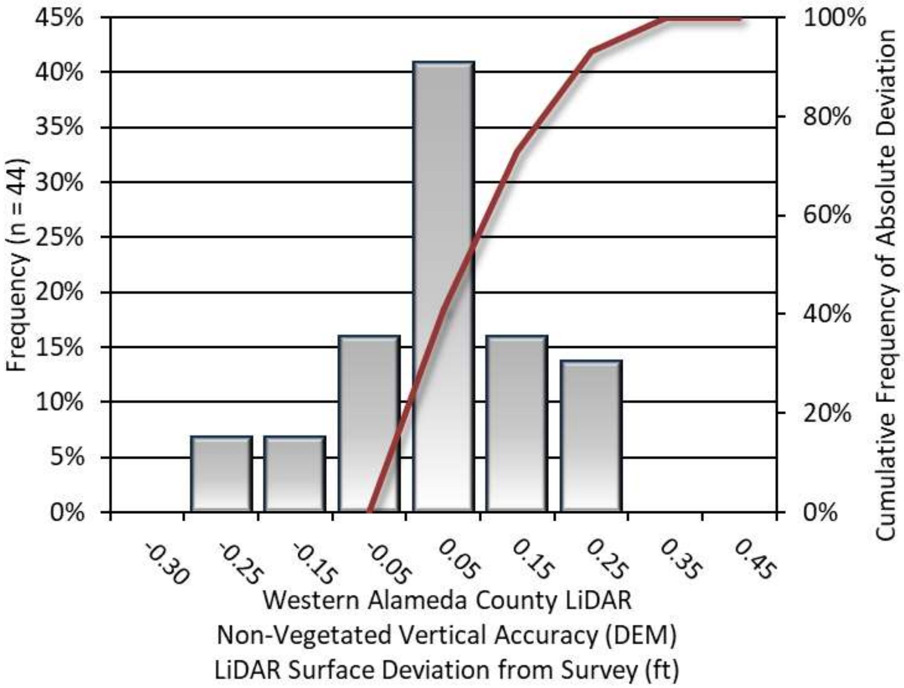

Figure 9: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)

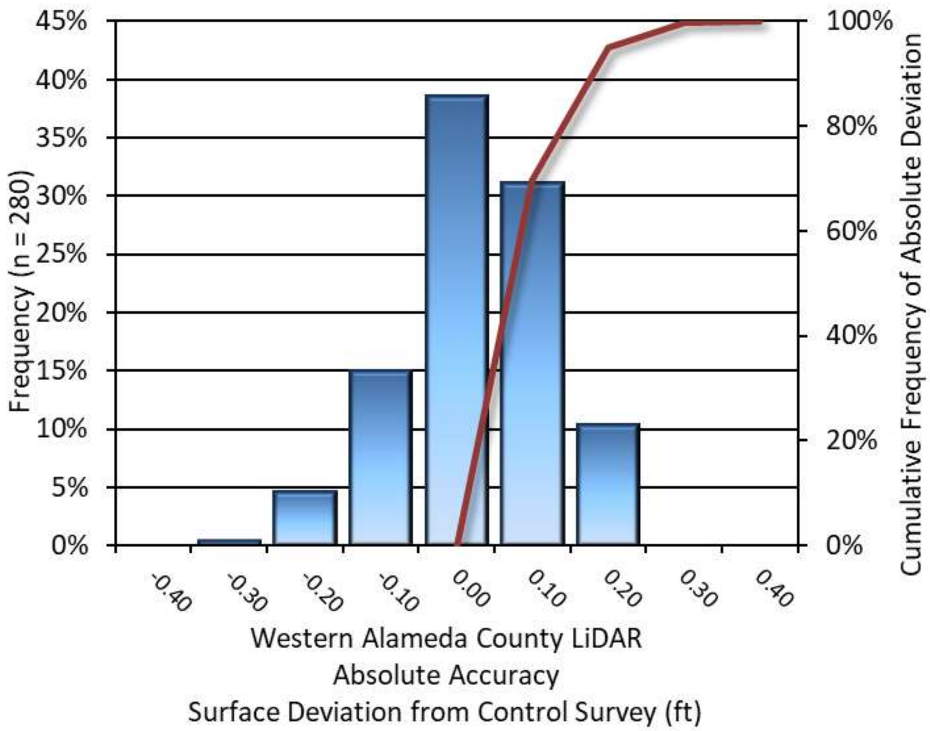

Figure 10: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI 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 Western Alameda County survey, 13 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.712 feet (0.217 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 11, Figure 11).

Table 11: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	13 points
95th Percentile	0.712 ft 0.217 m
Average	-0.061 ft -0.018 m
Median	-0.092 ft -0.028 m
RMSE	0.380 ft 0.116 m
Standard Deviation (1σ)	0.390 ft 0.119 m

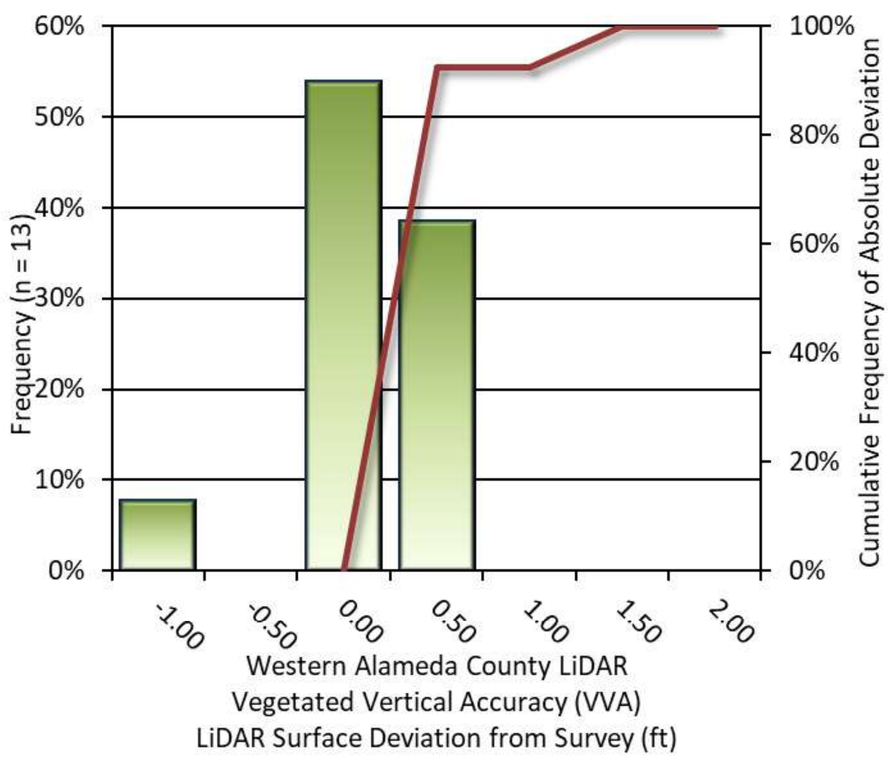

Figure 11: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)

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 Western Alameda County LiDAR project was 0.073 feet (0.022 meters) (Table 12, Figure 12)

Table 12: Relative accuracy results

Relative Accuracy	
Sample	83 surfaces
Average	0.073 ft 0.022m
Median	0.072 ft 0.022 m
RMSE	0.087 ft 0.027 m
Standard Deviation (1σ)	0.032 ft 0.010 m
1.96σ	0.063 ft 0.019 m

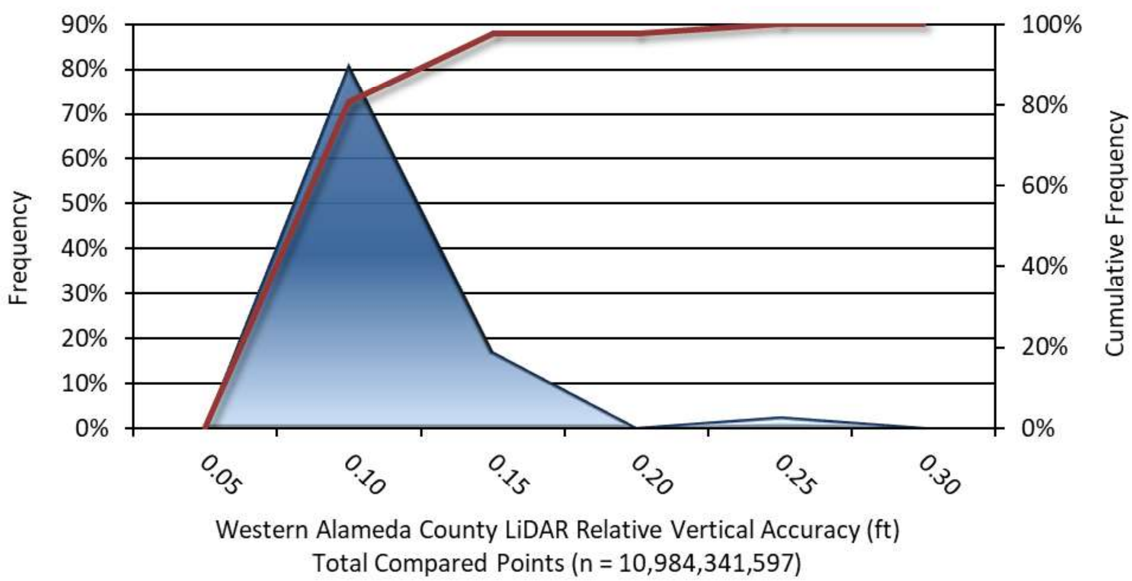

Figure 12: Frequency plot for relative vertical accuracy between flight lines

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. Using a flying altitude of 830 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was compiled to meet 0.31 feet (0.09 meters) horizontal accuracy at the 95% confidence level.

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the Western Alameda County project as described in this report.

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

Nov 1, 2019

Kristen Mattison
Project Manager
Quantum Spatial, Inc.

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of California, 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 May 28-31, 2019, and between July 2 and August 15, 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”.

Nov 1, 2019

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

Signed: Nov 1, 2019

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.

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^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). Before each flight, the PDOP was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1 second epochs was utilized and a maximum baseline length between the aircraft and the control points was less than 13 nm at all times.

Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flight lines and across the survey area.

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.