Marin County, California QL1 LiDAR
Technical Data Report

Prepared For:

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Cover Photo: A view looking over the Marin County project area, created from the bare earth digital elevation model colored by elevation, overlaid with the above-ground LiDAR point cloud colored using digital imagery.

This photo taken by QSI acquisition staff shows a scenic view of the San Francisco Bay and Golden Gate Bridge in the Marin County site in California.

In August 2018, Quantum Spatial (QSI) was contracted by the Golden Gate National Parks Conservancy (GGNPC) to collect and process QL1 Light Detection and Ranging (LiDAR) data over the entirety of Marin County in California, with the purpose of upgrading existing LiDAR coverage from QL2 to QL1 resolution data. Data were collected to aid GGNPC in assessing the topographic and geophysical properties of the study area to support County-wide mapping interests.

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 GGNPC 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 Marin County site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Marin County, California	336,142	358,512	12/22/2018 – 03/15/2019	High Resolution QL1 LiDAR

Deliverable Products

Table 2: Products delivered to GGNPC for the Marin County site

Marin County LiDAR Products Projection: California State Plane Zone 3 (FIPS 0403) Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12A) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	1.5 Foot GeoTiffs • Hydroflattened Bare Earth Model (DEM) • Highest Hit Digital Surface Model (DSM) • Normalized Intensity Images
Vectors	Shapefiles (*.shp) • Area of Interest • LiDAR Tile Index • Water's Edge Breaklines • Ground Survey Data ESRI Geodatabase (*.gdb) • 1.0 Foot Contours at Medium Smoothing (50 setting) • 1.0 Foot Contours at Medium Smoothing (1 setting)

Figure 1: Location map of the Marin County site in California

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Marin County LiDAR study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^2). During contracting it was specified that acquisition would take place +/- 1 hour of low tide, though after discussion with the stakeholders this constraint was changed to acquire data during negative tide only. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

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

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Reigl VQ-1560i sensor system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Marin County project area. The Riegl laser system records unlimited range measurements (returns) per pulse; however, 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	12/22/2018 – 03/15/2019
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-1560i
Maximum Returns	Unlimited
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2000 m
Survey speed	160 knots
Field of View	29⁰
Mirror Scan Rate	46 Hz
Target Pulse Rate	100 kHz
Pulse Length	3 ns
Laser Pulse Footprint Diameter	36 cm
Central Wavelength	1064 nm
Pulse Mode	Single Pulse in Air (1PiA)
Beam Divergence	0.18 mrad
Swath Width	2,217 m
Swath Overlap	55%
Intensity	16-bit
Accuracy	RMSE$_z$ (Non-Vegetated) ≤ 15 cm
	NVA (95% Confidence Level) ≤ 29.4 cm
	VVA (95th Percentile) ≤ 45 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.

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 collection of ground survey points using real time kinematic (RTK) 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 one existing continuously operating reference station (CORS) base station, and established one new monument for the Marin County LiDAR project (Table 4, Figure 2). New monumentation was set using 5/8" x 30" rebar topped with stamped 2 ½ " aluminum caps. QSI's professional land surveyor, Evon Silvia (CAPLS#9401) oversaw and certified the utilization of all bases.

Table 4: Monument positions for the Marin County acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
NO1J	38° 06' 43.13878"	-122° 34' 10.62783"	-19.837
TNC_MARIN_01	38° 10' 33.88396"	-122° 43' 33.10359"	194.388

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.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) 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. FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK 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 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 R6	Integrated Antenna	TRM_R6	Rover
Trimble R8	Integrated Antenna	TRM_R8_GNSS	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).

Table 6: Land Cover Types and Descriptions

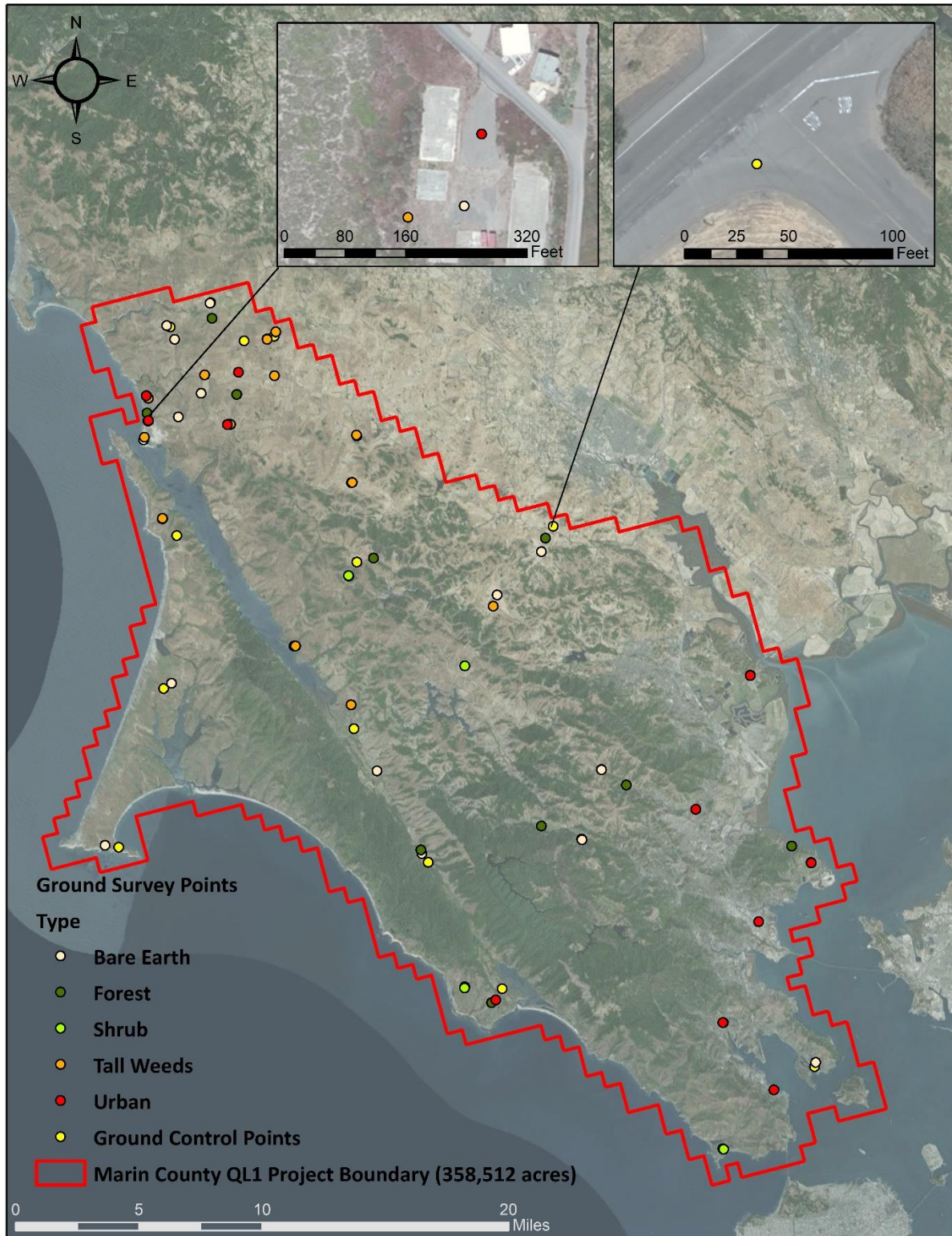| Land cover type	Land cover code	Description	Accuracy Assessment Type
Shrub	SHRUB	Areas dominated by herbaceous shrubland growth	VVA
Tall Weed	TALL_WEED	Herbaceous grasslands in advanced stages of growth	VVA
Forest	FOR	Forested areas of mixed species	VVA
Bare Earth	BARE, BE	Areas of bare earth surface	NVA
Urban	URBAN	Areas dominated by urban development, including parks	NVA

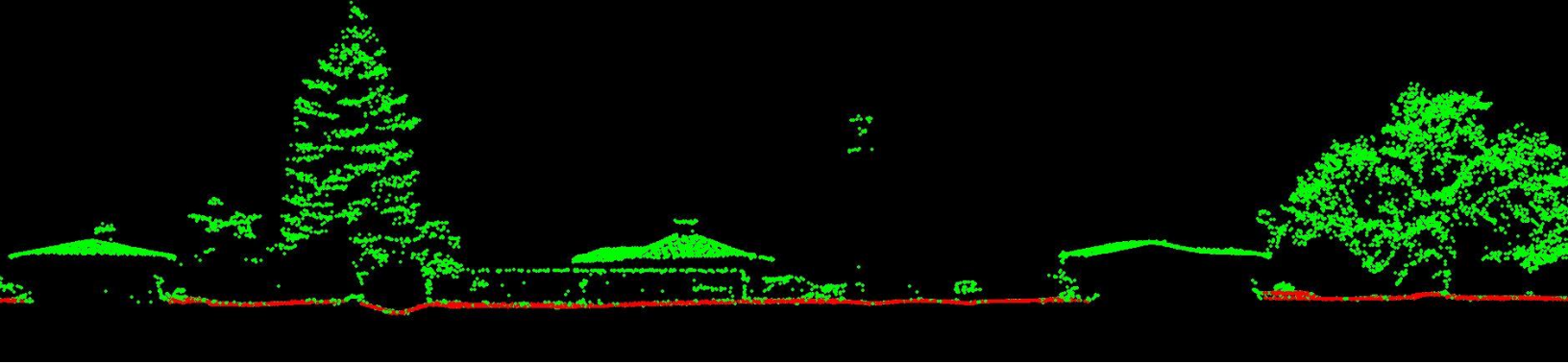**Figure 2: Ground survey location map**

This LiDAR cross section shows a view of the Marin County point cloud, 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 Marin 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	Low laser returns that are often associated with 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.
17	Bridge	Bridge decks
18	High Noise	High laser returns that are often associated with birds or scattering from reflective surfaces
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation

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 v.8.2
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 POSPac MMS v.8.2
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 GeoTIFFs at a 1.5 foot pixel resolution.	LAS Product Creator 3.0 (QSI proprietary)
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	Las Monkey 2.4.0 (QSI proprietary) LAS Product Creator 3.0 (QSI proprietary) ArcMap v. 10.3.1

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The ocean surrounding Marin 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. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. 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.

Contours

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. Model key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature. Generation of model 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 model 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.

Only Echo
First of Many
Intermediate
Last of Many

This LiDAR cross section shows the same view of the Marin County point cloud, colored by point classification.

LiDAR Density

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

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

The average first-return density of LiDAR data for the Marin County project was 1.26 points/ft^2 (13.58 points/m^2), while the average ground classified density was 0.63 points/ft^2 (6.81 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 3 through Figure 5.

Table 9: Average LiDAR First Return Point Density

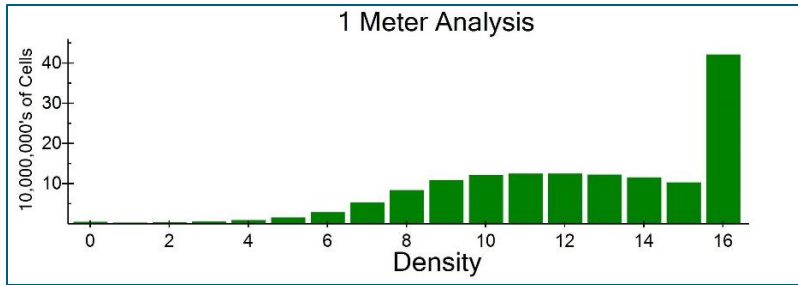| Classification	Point Density
First-Return	1.26 points/ft^2 13.58 points/m^2
Ground-Classified	0.63 points/ft^2 6.81 points/m^2

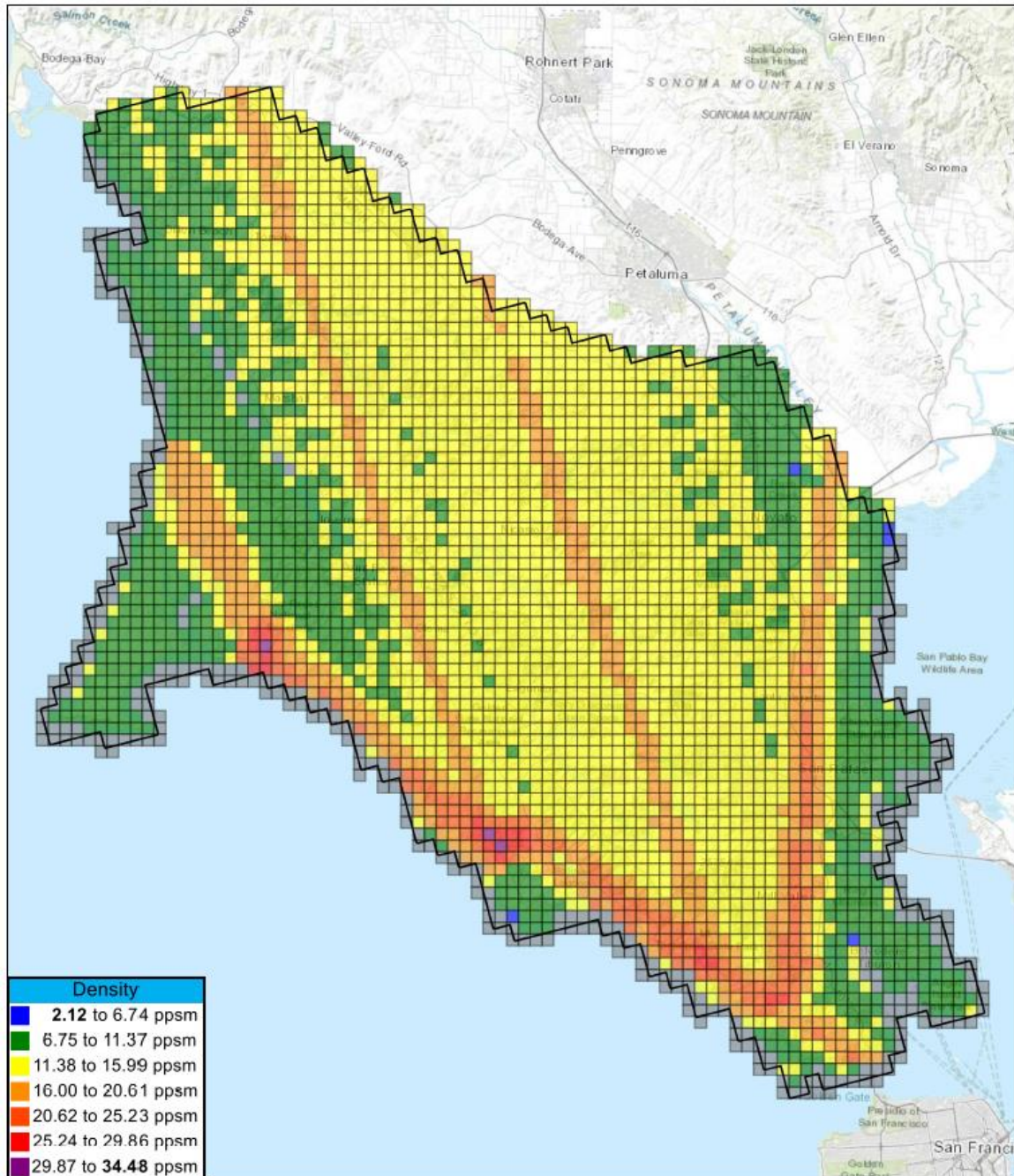**Figure 3: Frequency distribution of first return point density values per 1 m cell**

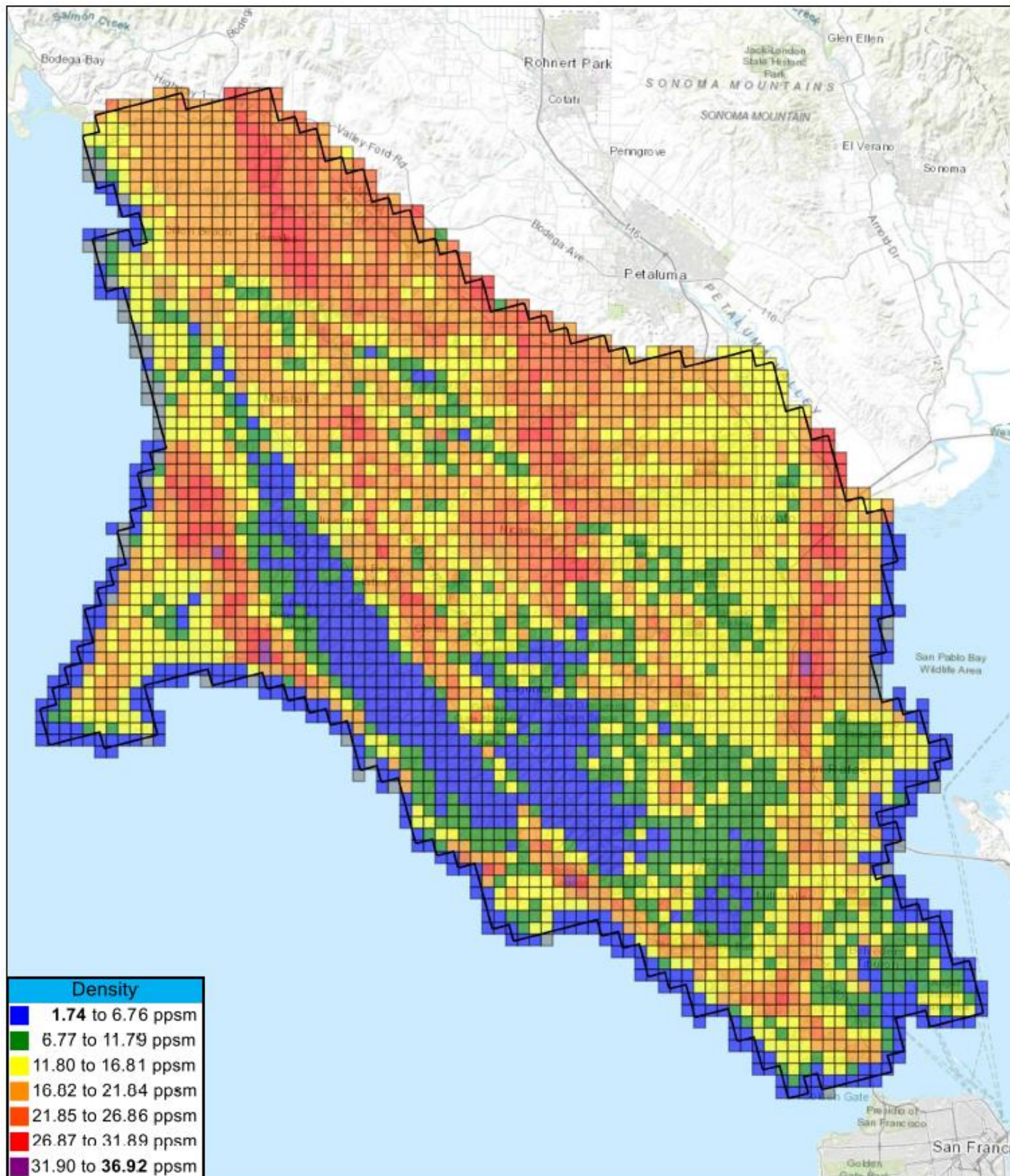**Figure 4: LiDAR First Return Density Map**

Figure 5: Ground Classified Point Density Map

Legend — Density:
- 1.74 to 6.76 ppsm
- 6.77 to 11.79 ppsm
- 11.80 to 16.81 ppsm
- 16.82 to 21.84 ppsm
- 21.85 to 26.86 ppsm
- 26.87 to 31.89 ppsm
- 31.90 to 36.92 ppsm

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). LiDAR relative accuracy was tested during LiDAR processing and results were found to meet all project requirements. Non-Vegetated Vertical Accuracy results are presented below. 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 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 Marin County survey, 45 ground check points were withheld from the calibration and post processing of the LiDAR point cloud for accuracy assessment, with resulting non-vegetated vertical accuracy of 0.287 feet (0.088 meters) as compared to unclassified LAS, and 0.273 feet (0.083 meters) as compared to the bare earth DEM, with 95% confidence (Figure 6, Figure 7).

QSI also assessed absolute accuracy using 34 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 8.

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[2] 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	45 points	45 points	34 points
95% Confidence (1.96*RMSE)	0.287 ft 0.088 m	0.273 ft 0.083 m	0.209 ft 0.064 m
Average	0.057 ft 0.017 m	0.048 ft 0.015 m	-0.026 ft -0.008 m
Median	0.020 ft 0.006 m	0.014 ft 0.004 m	-0.054 ft -0.016 m
RMSE	0.147 ft 0.045 m	0.139 ft 0.043 m	0.107 ft 0.033 m
Standard Deviation (1σ)	0.136 ft 0.042 m	0.132 ft 0.040 m	0.105 ft 0.032 m

Marin County, CA LiDAR Non-Vegetated Vertical Accuracy (NVA)
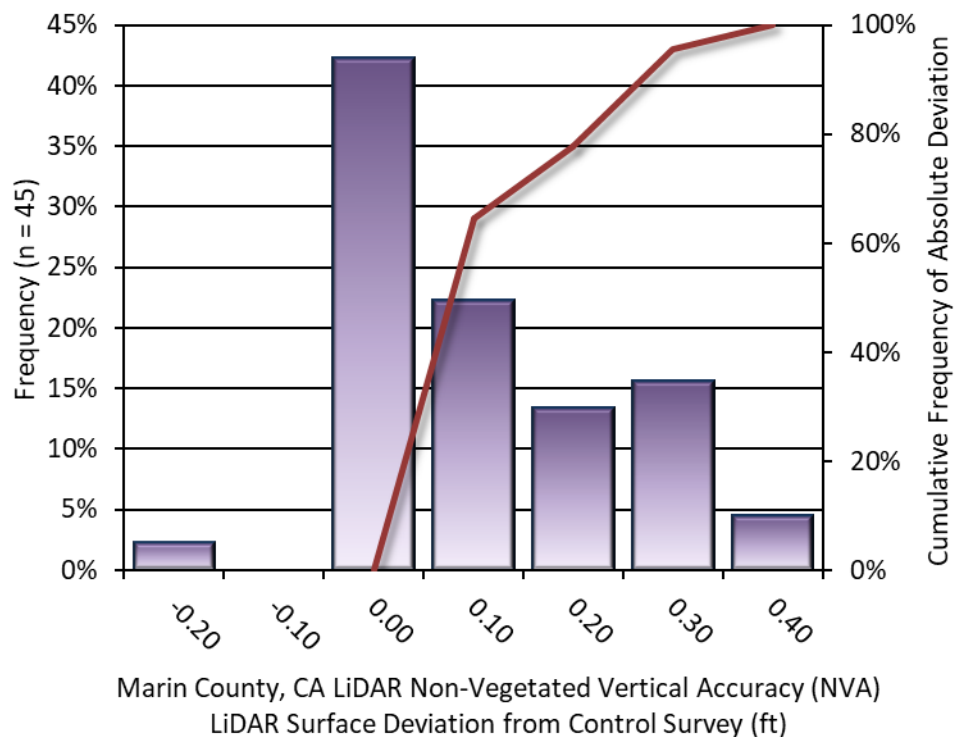LiDAR Surface Deviation from Control Survey (ft)

Figure 6: Frequency histogram for LiDAR unclassified LAS deviation from ground check point values (NVA)
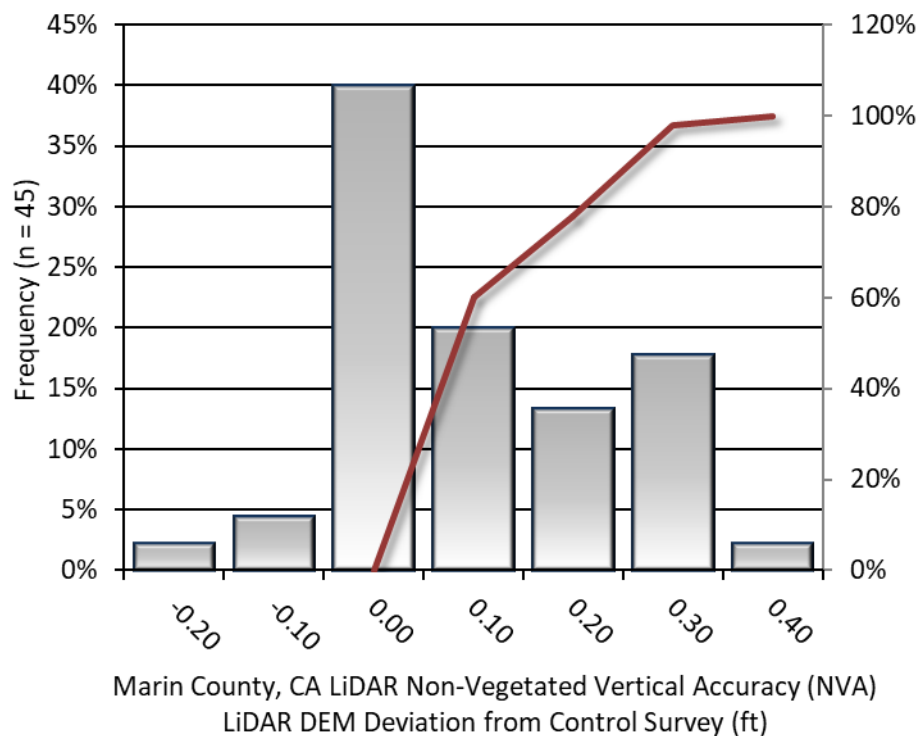
Figure 7: Frequency histogram for LiDAR bare earth DEM surface deviation from ground check point values (NVA)
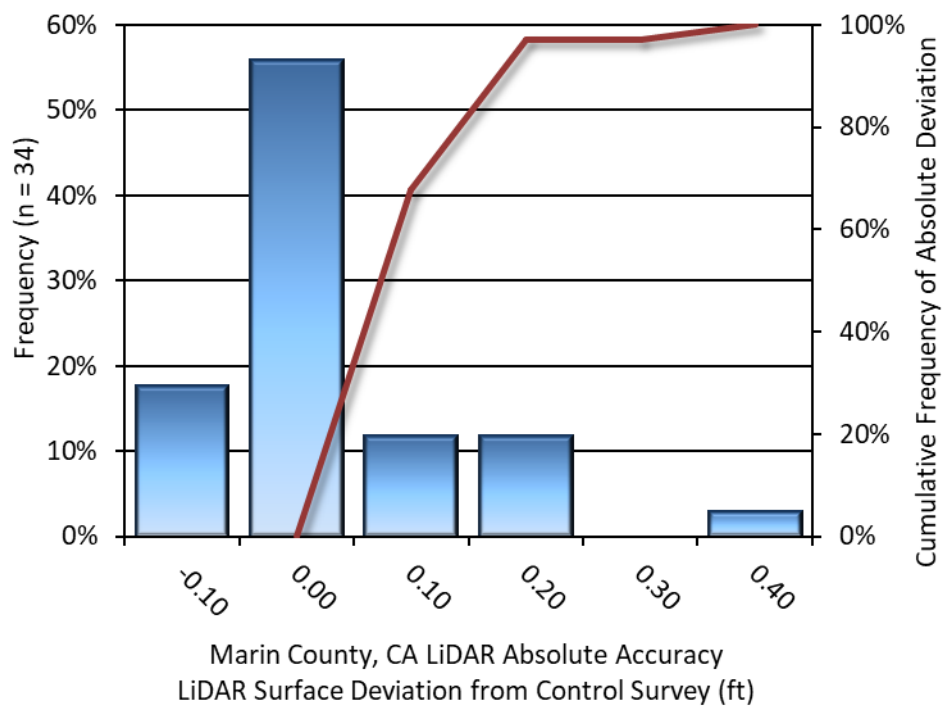

Figure 8: Frequency histogram for LiDAR surface deviation from ground control point values

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 Marin County survey, 45 vegetated check points were collected, with resulting vegetated vertical accuracy of 0.657 feet (0.200 meters) as compared to the bare earth DEM, evaluated at the 95th percentile (Table 11, Figure 9).

Table 11: Vegetated vertical accuracy results

Vegetated Vertical Accuracy	
Sample	45 points
95th Percentile	0.657 ft 0.200 m
Average	0.293 ft 0.089 m
Median	0.256 ft 0.078 m
RMSE	0.385 ft 0.117 m
Standard Deviation (1σ)	0.252 ft 0.077 m

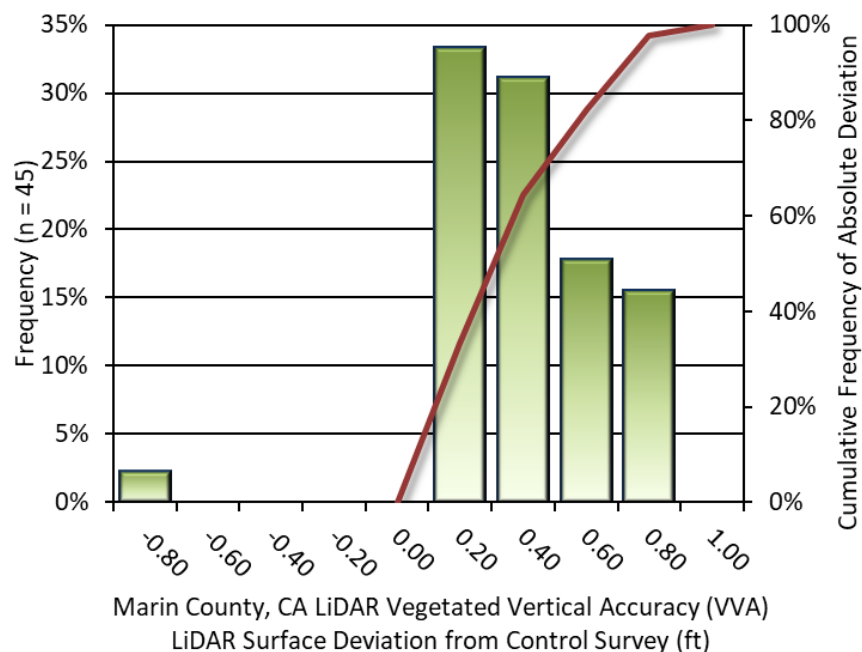**Figure 9: Frequency histogram for LiDAR surface deviation from vegetated check point values (VVA)**

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

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

Ashley Daigle   Nov 8, 2019

Ashley Daigle
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 between December 22, 2018 and March 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".

Evon P. Silvia Nov 8, 2019

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

Signed:Nov 8, 2019

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 ±18° 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.