Appendix C

LiDAR Survey Data Reports

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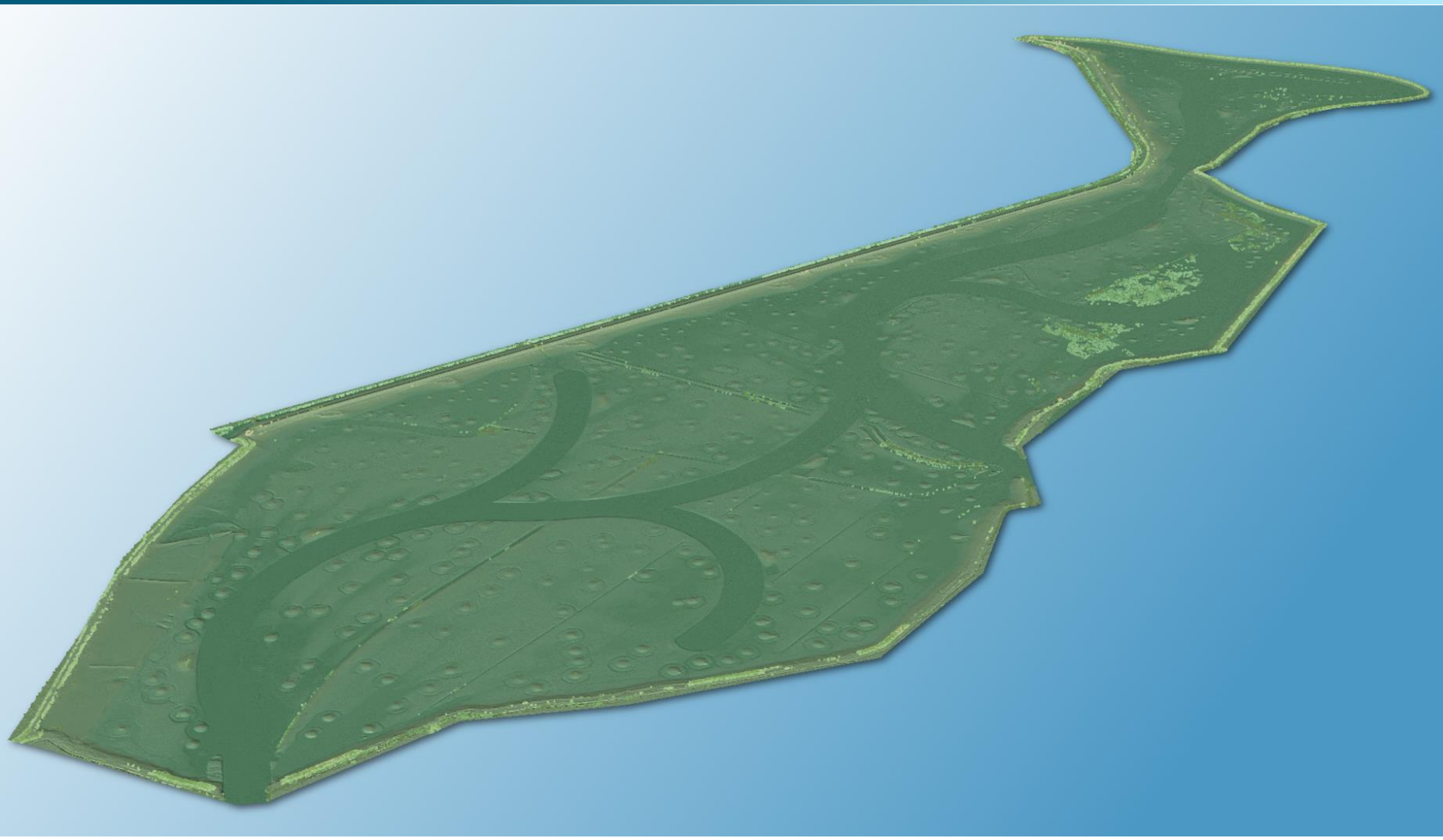
August 30, 2017



Sears Point, California LiDAR

Technical Data Report

Julian Meisler
Sonoma Land Trust
822 Fifth Street
Santa Rosa, CA 95404
PH: 707-526-6930

QSI Corvallis
517 SW 2nd St., Suite 400
Corvallis, OR 97333
PH: 541-752-1204

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Cover Photo: A view looking north over the entire Sears Point project area. The image was created from the LiDAR bare earth model colored by elevation and overlaid with the above-ground point cloud.

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INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the Sears Point site north of San Francisco in California

In June 2017, Quantum Spatial (QSI) was contracted by the Sonoma Land Trust (SLT) to collect Light Detection and Ranging (LiDAR) data in the summer of 2017 for the Sears Point site in San Pablo Bay in California. Data were collected to aid the SLT in assessing the topographic and geophysical properties of the study area to support the Sears Point Restoration Project; a collaborative effort between the Sonoma Land Trust and Ducks Unlimited to restore 960 acres of tidal wetland marsh in the San Pablo Bay, along the central coast of California[1].

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 the SLT is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected for the Sears Point, California site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Sears Point	1,024	1,325	06/26/2017	High Resolution LiDAR

[1] *https://www.sonomalandtrust.org/news_room/press_releases/1406-sears-point.html*

Deliverable Products

Table 2: Products delivered to SLT for the Sears Point site

Sears Point LiDAR Products Projection: California State Plane Zone II Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID 12B) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	1.5 Foot ESRI Grids • Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) 1.5 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Data Extent • Area of Interest • Tile Index

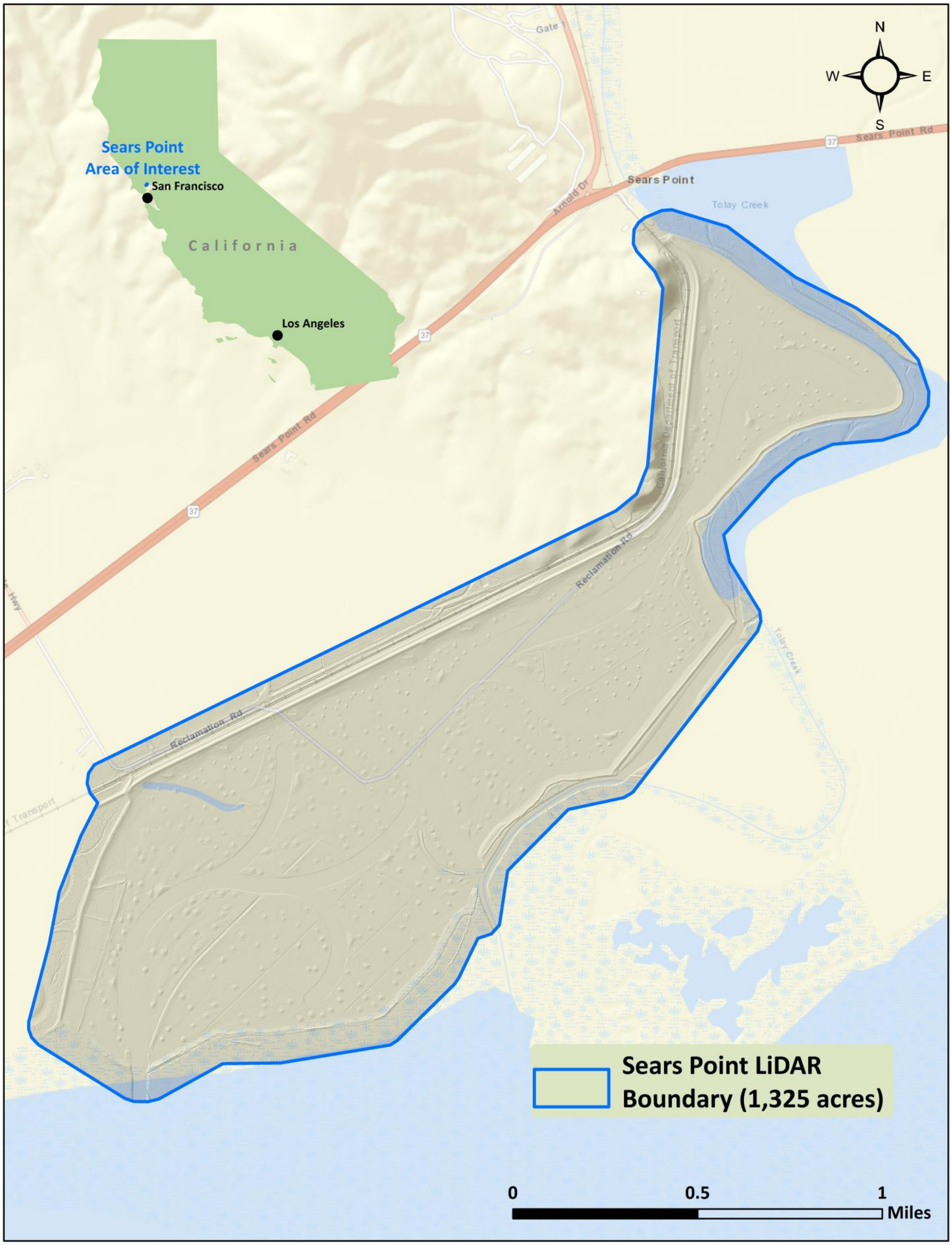


Figure 1: Location map of the Sears Point site in California

ACQUISITION

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 Sears Point LiDAR study area at the target point density of ≥10.0 points/m^2 (0.93 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed. QSI acquisition staff coordinated with the San Francisco Bay National Estuarine Research Reserve (SF NERR) to ensure data collection occurred during optimal tidal windows (Figure 2).

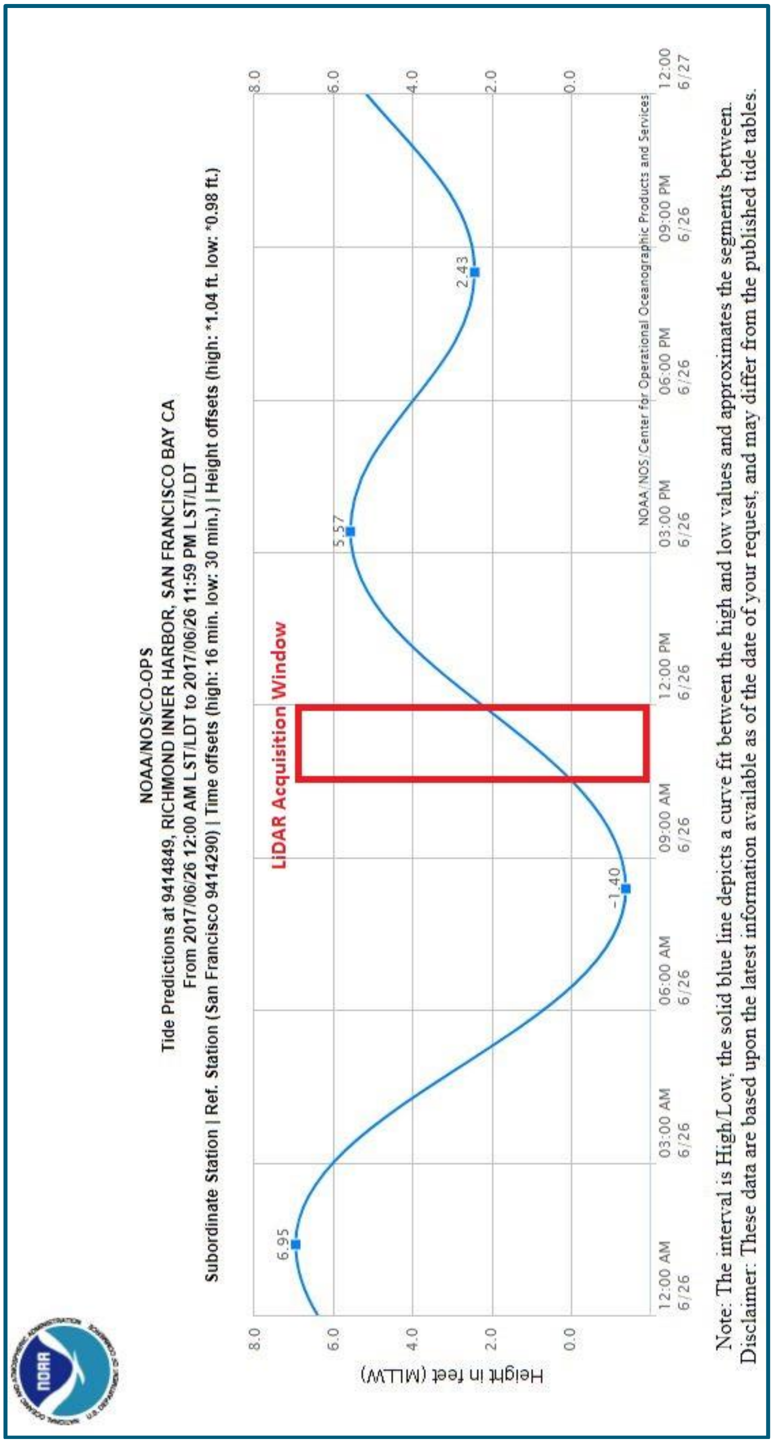


Figure 2: NOAA tidal chart on day of acquisition

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥10 pulses/m^2 over the Sears Point project area. The Leica ALS80 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: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	June 26, 2017
Aircraft Used	Cessna Caravan
Sensor	Leica
Laser	ALS80
Maximum Returns	Unlimited, but typically no more than 7
Resolution/Density	Average 10 pulses/m^2
Nominal Pulse Spacing	0.32 m
Survey Altitude (AGL)	700 m
Survey speed	130 knots
Field of View	40º
Mirror Scan Rate	52 Hz
Target Pulse Rate	377.2 kHz
Pulse Length	2.5 ns
Laser Pulse Footprint Diameter	15.4 cm
Central Wavelength	1064 nm
Pulse Mode	Single Pulse in Air (SPiA)
Beam Divergence	22 mrad
Swath Width	510 m
Swath Overlap	59%
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Intensity	8-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 9 cm

Leica ALS80 LiDAR sensor

All areas were surveyed with an opposing flightline 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 Control

Ground control surveys were conducted to support the airborne acquisition. Ground control data were used to geospatially correct and perform quality assurance checks on final LiDAR data products. In addition, permanent base stations from two different networks were utilized to geospatially correct the aircraft positional coordinate data and as base stations for Ground Survey Point (GSP) collection.

Base Stations

One base station from the UNAVCO Plate Boundary Observatory (PBO) was utilized as a static base station for the Sears Point airborne acquisition. The spatial configuration of the base stations provided redundant control within 13 nautical miles of the mission areas for LiDAR flights.

In addition, one base station from the California Surveying and Drafting Supply (CSDS) Real Time Network (RTN) was used for GSP collection. Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage.

In total, QSI utilized two permanent base stations for the Sears Point LiDAR project (Table 4, Figure 3).

Table 4: Base stations utilized for the Sears Point acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00.

CORS ID	Owner	Latitude	Longitude	Ellipsoid (meters)
NO1I	CSDS RTN	38° 06’ 43.13238”	-122° 34’ 10.62197”	-19.848
P199	UNAVCO PBO	38° 15’ 49.27872”	-122° 30’ 12.32660”	56.169

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 each 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) survey techniques. CSDS RTN stations broadcasted kinematic corrections to a roving Trimble R8 GNSS receiver. 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. When collecting RTK, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. 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 may not be equitably distributed throughout the study area (Figure 3).

Table 5: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble NetR9 GNSS	Zephyr GNSS Geodetic Model 2	TRM55971.00	CSDS RTN Station
Trimble NetR9 GNSS	Dorne Margolin GNSS with Chokerings and SCIT Radome	TRM 59800.00 SCIT	UNAVCO PBO Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	Rover

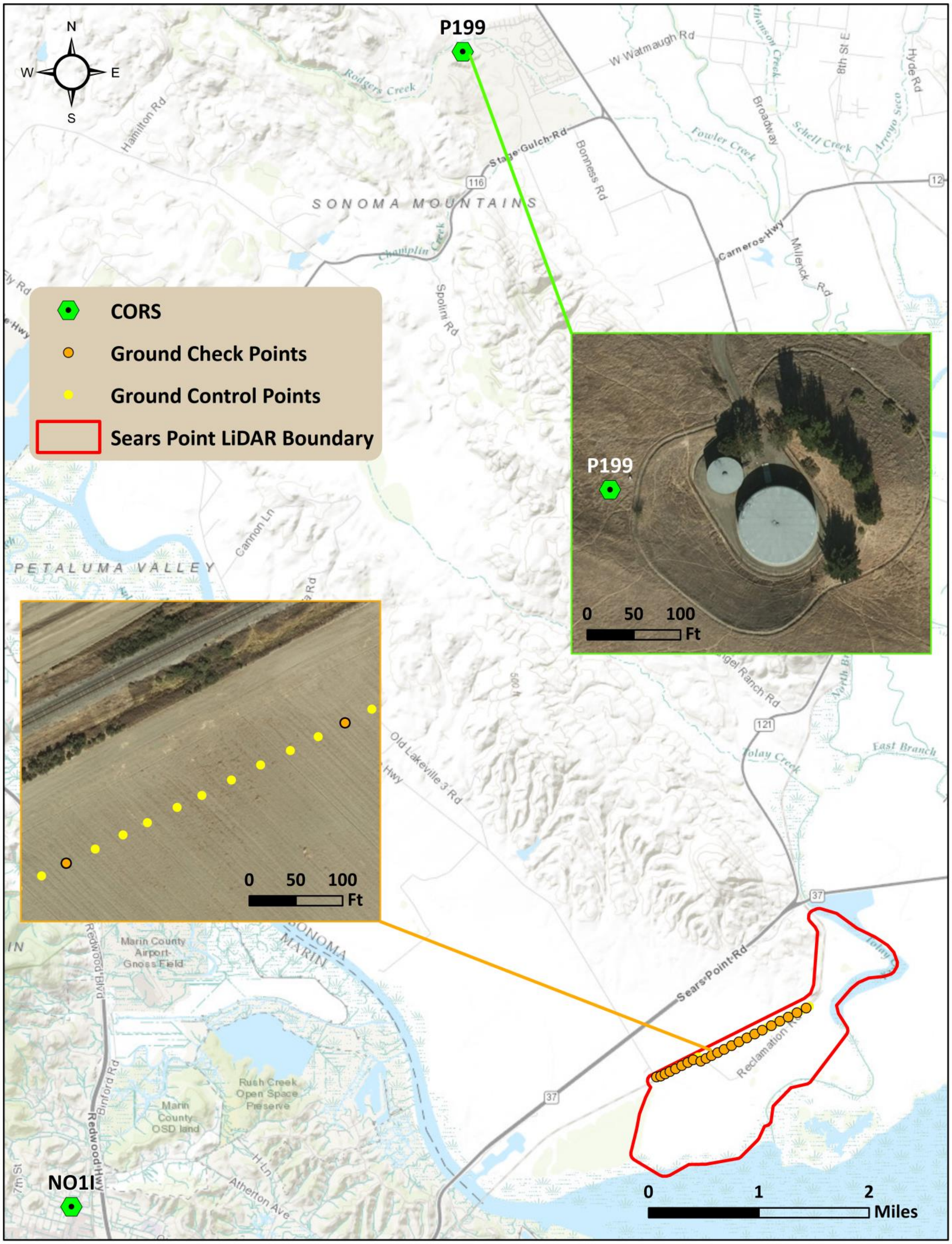
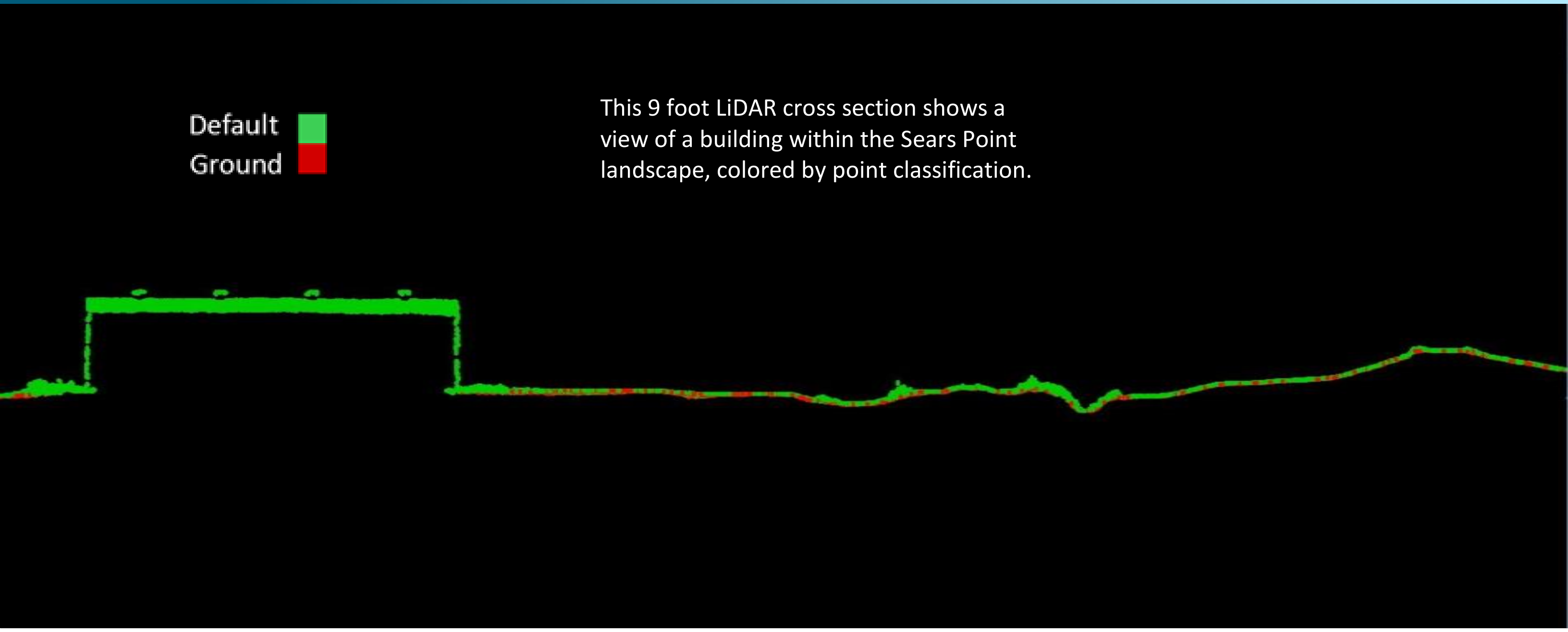


Figure 3: Ground survey location map

PROCESSING



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 6). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 7.

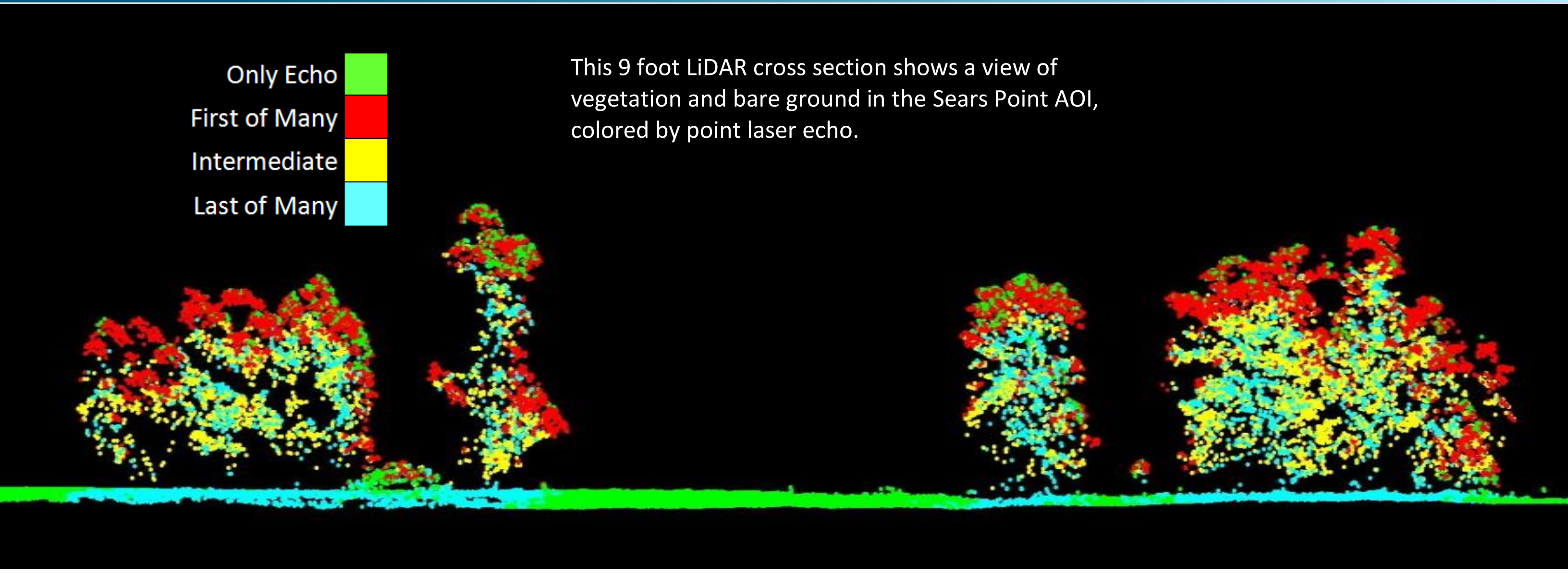
Table 6: ASPRS LAS classification standards applied to the Sears Point dataset

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

Table 7: 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.	Waypoint Inertial Explorer v.8.6
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.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.2
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flightlines.	TerraScan v.17
Using ground classified points per each flightline, 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 flightlines and apply results to all points in a flightline. Use every flightline for relative accuracy calibration.	TerraMatch v.17
Classify resulting data to ground and other client designated ASPRS classifications (Table 6). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.17 TerraModeler v.17
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 1.5 foot pixel resolution.	TerraScan v.17 TerraModeler v.17 ArcMap v. 10.2.2
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	Las Monkey 2.2.7 SP1 (QSI proprietary) LAS Product Creator 1.5 (QSI proprietary) ArcMap v. 10.2.2

RESULTS & DISCUSSION



LiDAR Density

The acquisition parameters were designed to acquire an average first-return density of 10 points/m^2 (0.93 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 Sears Point project was 2.15 points/ft^2 (23.16 points/m^2) while the average ground classified density was 0.46 points/ft^2 (4.93 points/m^2) (Table 8). 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 6.

Table 8: Average LiDAR point densities

Classification	Point Density
First-Return	2.15 points/ft^2 23.16 points/m^2
Ground Classified	0.46 points/ft^2 4.93 points/m^2

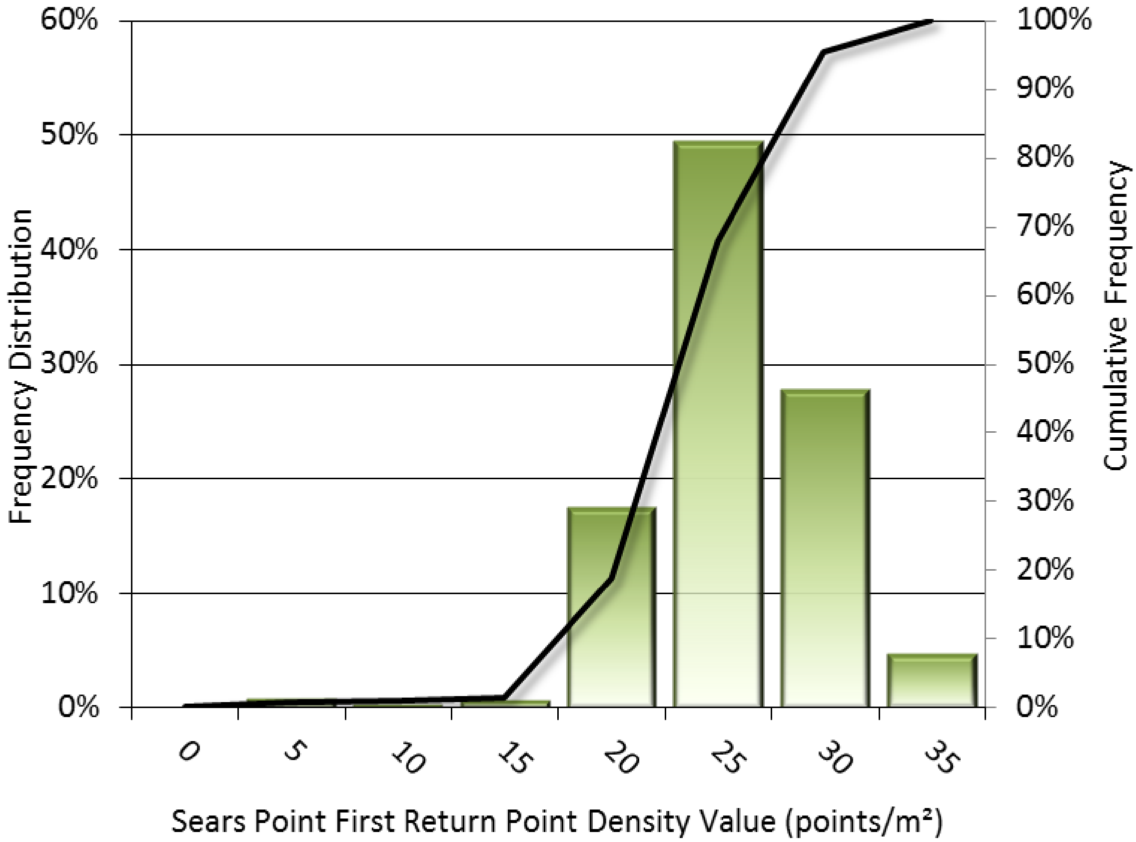


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

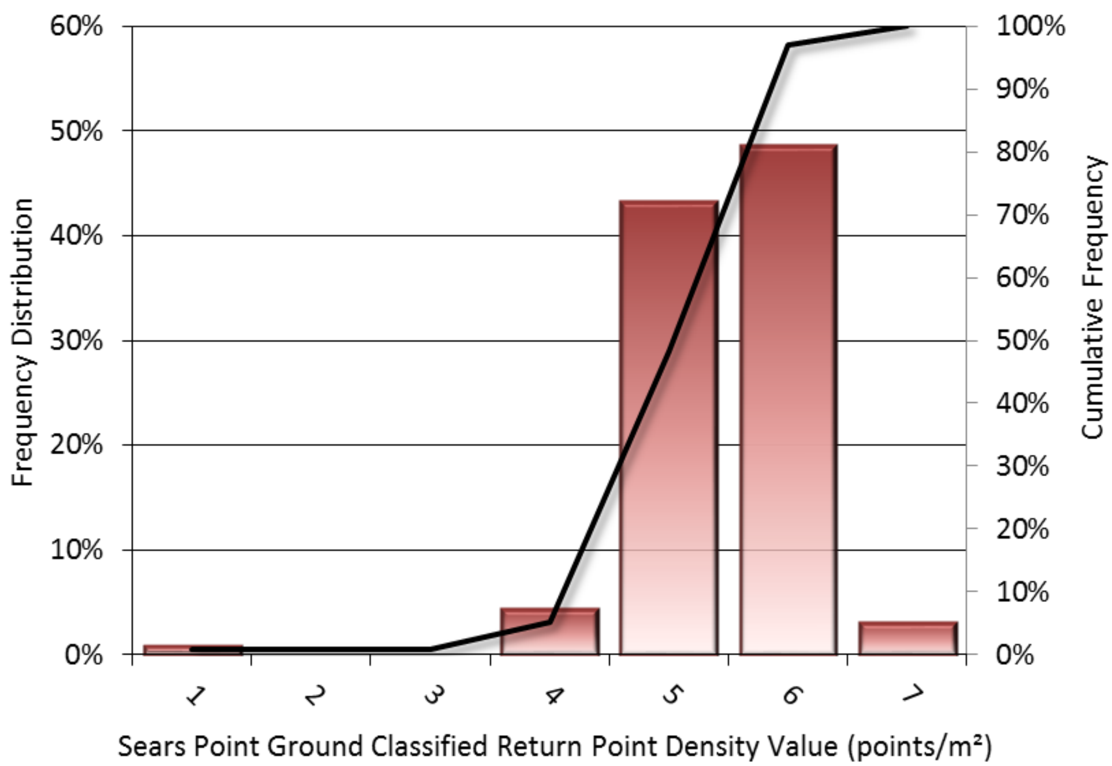


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

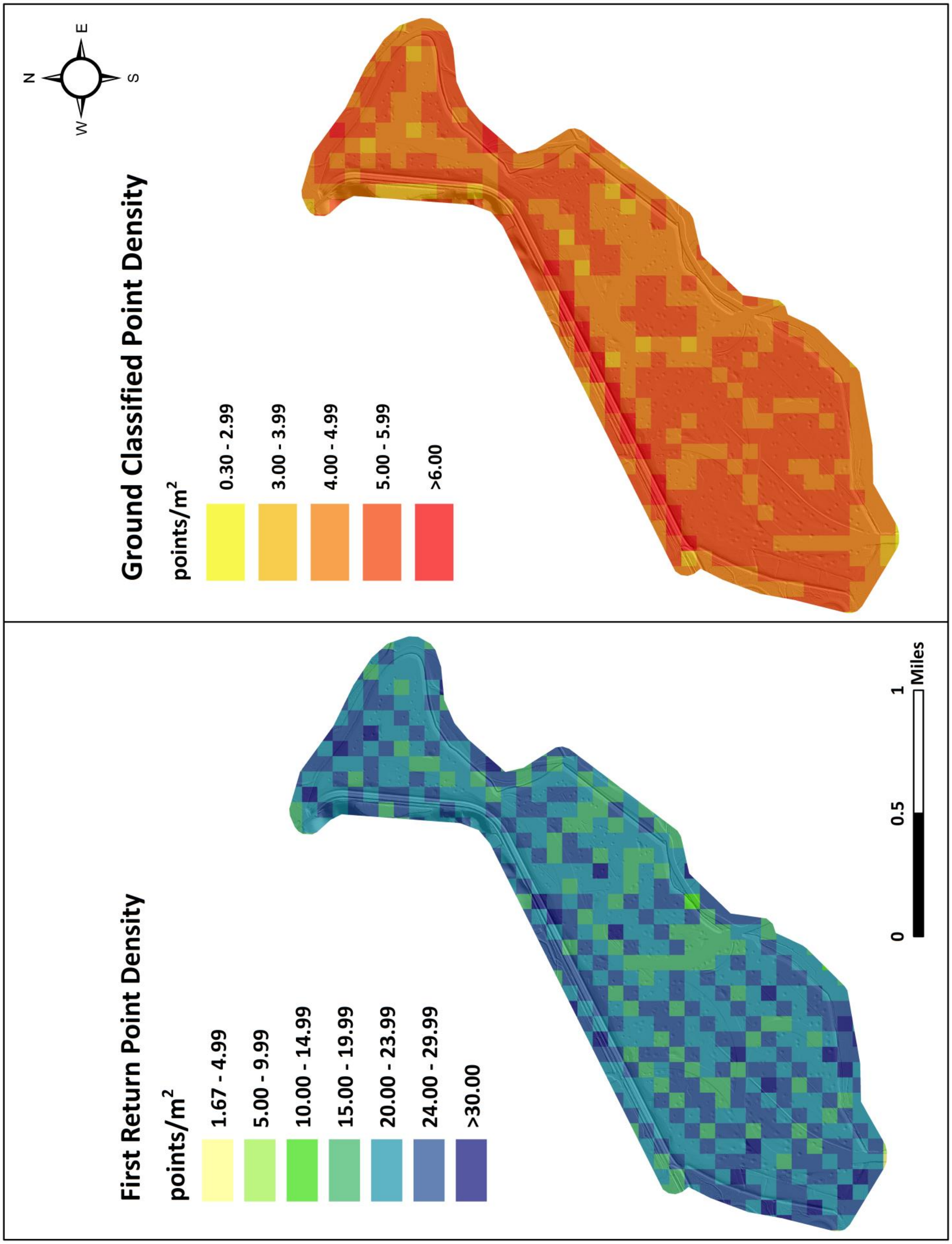


Figure 6: First return and ground-classified point density map for the Sears Point site (100 m x 100 m cells)

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 collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. 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 9.

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 Sears Point survey, 23 ground check points were withheld from the calibration and post processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.092 feet (0.028 meters), with 95% confidence (Table 9, Figure 7).

QSI also assessed absolute accuracy using 202 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 9 and Figure 10.

Table 9: Absolute accuracy results

Non-Vegetated Vertical Accuracy		
	Ground Check Points (NVA)	**Ground Control Points**
Sample	23 points	202 points
NVA (1.96*RMSE)	0.092 ft 0.028 m	0.078 ft 0.024 m
Average	-0.018 ft -0.006 m	-0.014 ft -0.004 m
Median	-0.010 ft -0.003 m	-0.016 ft -0.005 m
RMSE	0.047 ft 0.014 m	0.040 ft 0.012 m
Standard Deviation (1σ)	0.044 ft 0.013 m	0.037 ft 0.011 m

[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.

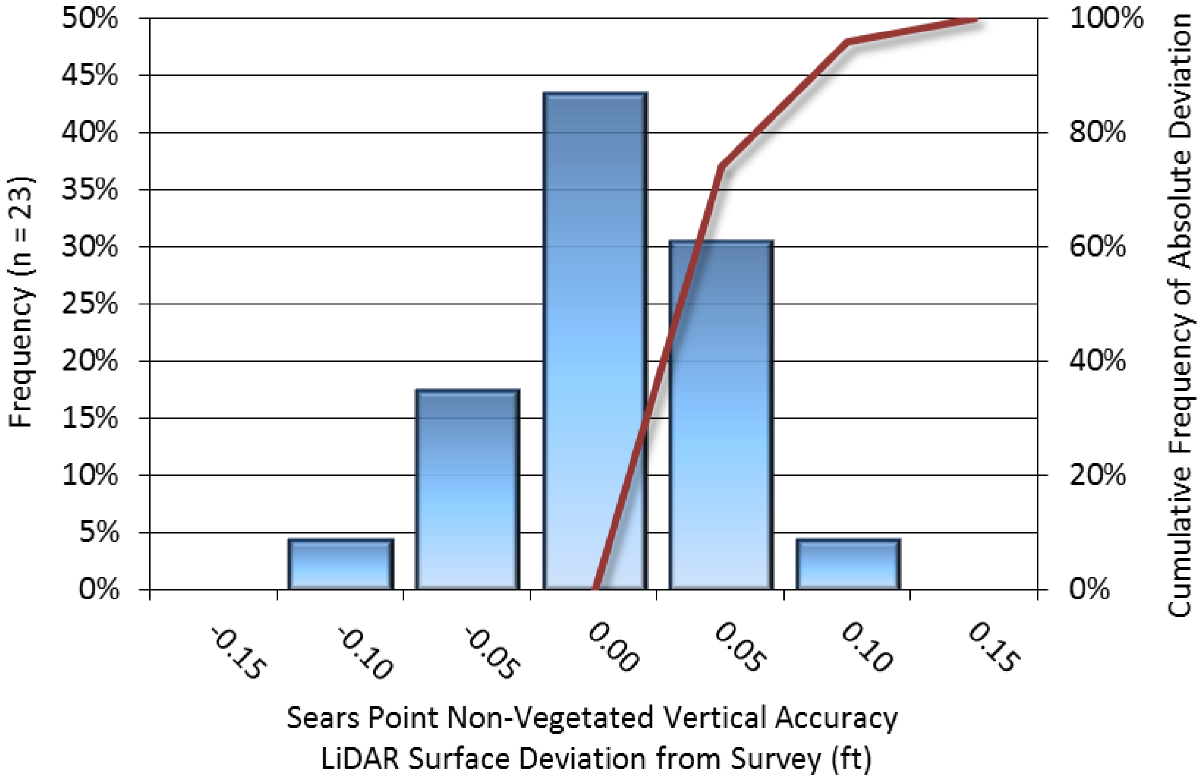


Figure 7: Frequency histogram for LiDAR surface deviation from ground check point values

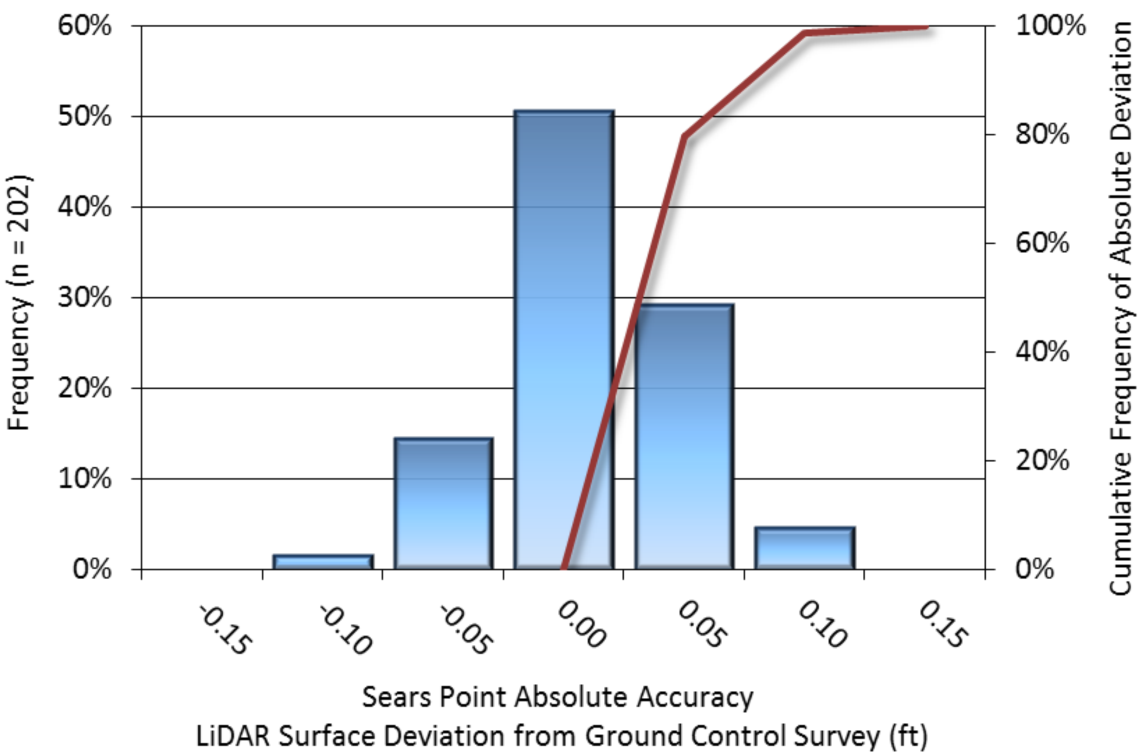


Figure 8: Frequency histogram for LiDAR surface deviation ground control point values

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flightlines, 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 flightline with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Sears Point LiDAR project was 0.080 feet (0.024 meters) (Table 10, Figure 9).

Table 10: Relative accuracy results

Relative Accuracy	
Sample	10 surfaces
Average	0.080 ft 0.024 m
Median	0.080 ft 0.024 m
RMSE	0.080 ft 0.024 m
Standard Deviation (1σ)	0.003 ft 0.001 m
1.96σ	0.006 ft 0.002 m

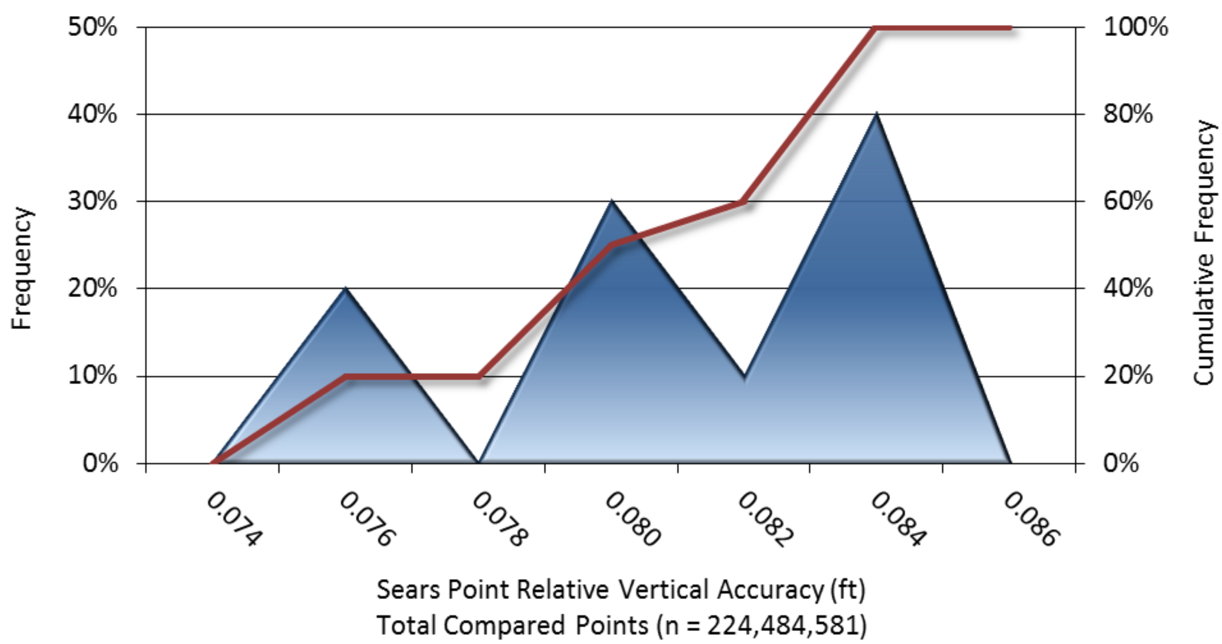


Figure 9: Frequency plot for relative vertical accuracy between flightlines

CERTIFICATIONS

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

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

Sep 1, 2017

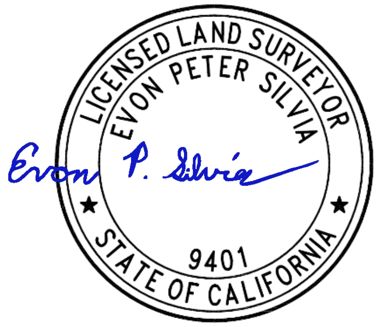
Eric Morris
Project Manager
Quantum Spatial, Inc.

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 June 25, 2017.

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".

Sep 1, 2017

Evon P. Silvia, PLS
Quantum Spatial, Inc.
Corvallis, OR 97333



Signed: Sep 1, 2017

SELECTED IMAGES

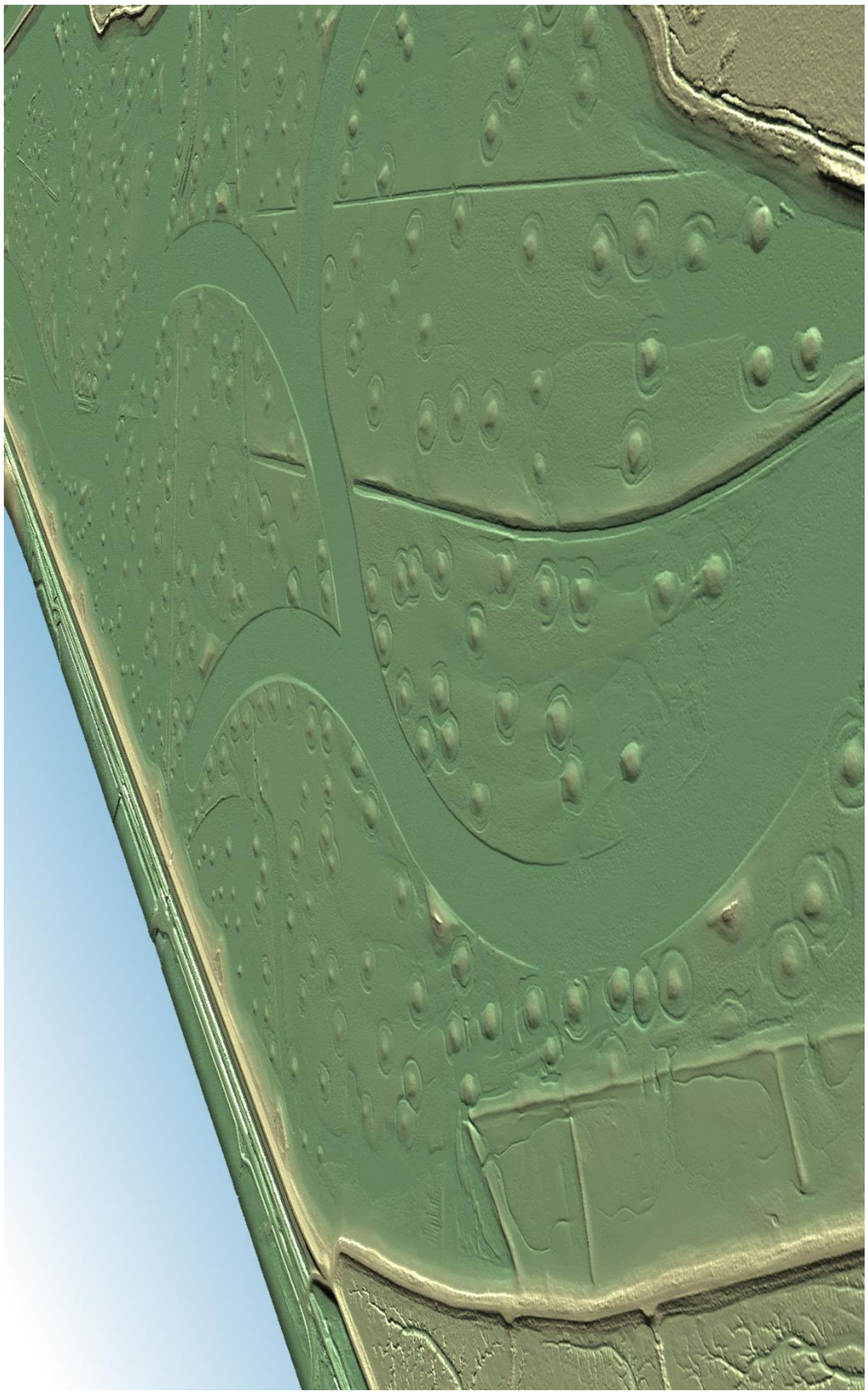


Figure 10: View looking northeast over the southern portion of Sears Point. The image was created from the LiDAR bare earth model.

Appendix C-1

Figure 11: View looking southeast over the northern portion of Sears Point. The image was created from the LiDAR bare earth model.

GLOSSARY

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

1.96 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95^{th} 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 flightlines, 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 flightlines within an overlapping area. Divergence is most apparent when flightlines 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 flightline.

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

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

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

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

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

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

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

Appendix A - Accuracy Controls

Relative Accuracy Calibration Methodology:

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

Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flightline 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 $\pm 20^{o}$ 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.

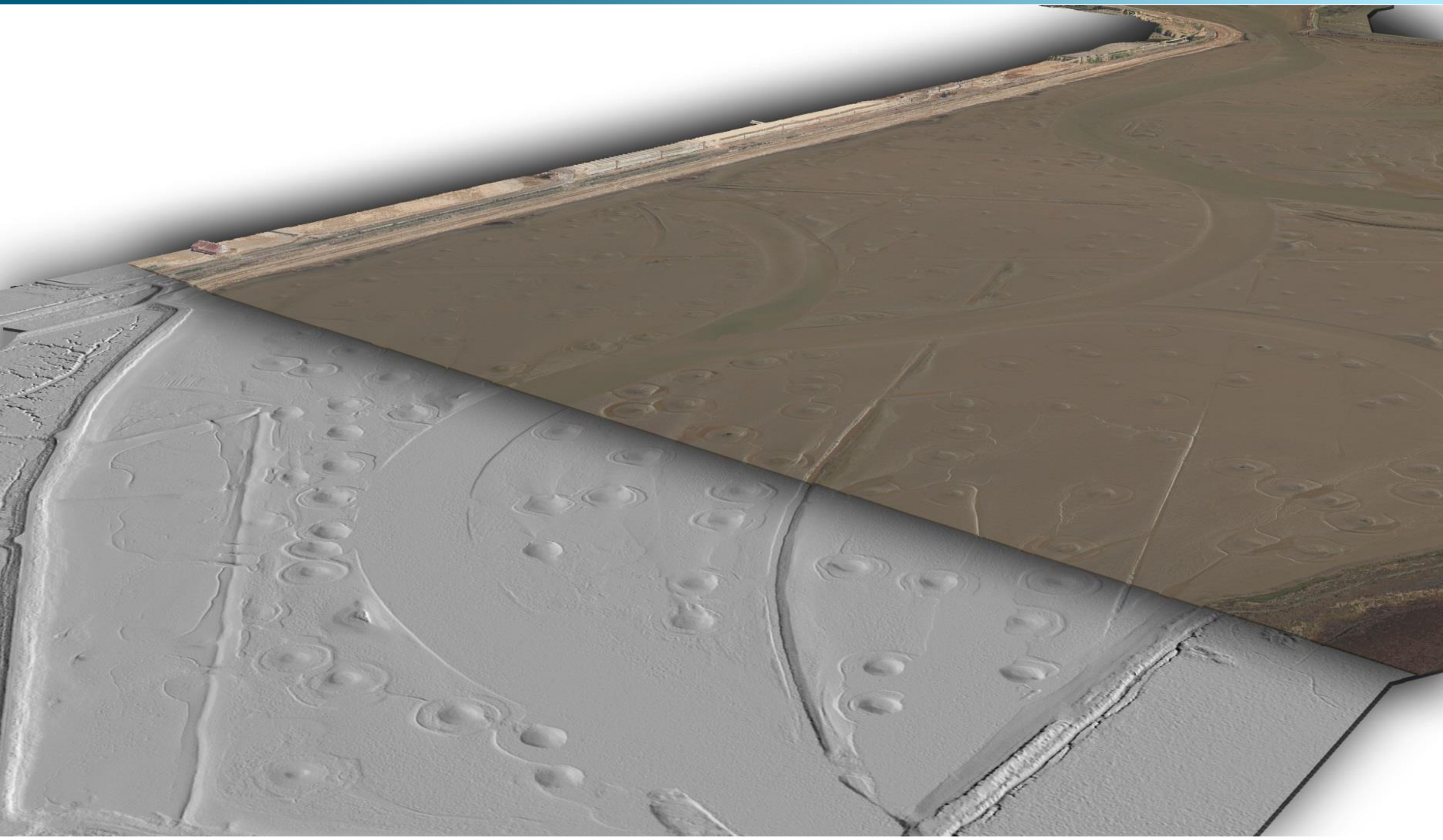
Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent possible throughout multiple flightlines 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 flightline coincides with the swath edge portion of overlapping flightlines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

Opposing Flightlines: All overlapping flightlines have opposing directions. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flightline(s), making misalignments easier to detect and resolve.

Appendix C-2

August 20, 2018



Sears Point 2018, California

DRAFT Topobathymetric LiDAR and Orthoimagery Technical Data Report

Prepared For:

SONOMA LAND TRUST

Dr. Stuart Siegel
SF Bay National Estuarine Preserve
3150 Paradise Drive
Tiburon, CA 94920
415.299.8746

Prepared By:

quantum SPATIAL

QSI Corvallis
1100 NE Circle Blvd, Ste. 126
Corvallis, OR 97330
PH: 541-752-1204

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Cover Photo: A View of Sears Points with high hit model colored by 0.5 ft imagery in the background with the bare earth model hillshaded in the foreground.

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INTRODUCTION

Channel intersections in the Sears Point study area surrounded by marsh mounds that will hasten the process of accruing sediment designed to boost the land. This image of the high hit model is colored by 0.5 ft imagery.

In June 2018, Quantum Spatial (QSI) was contracted by the Sonoma Land Trust (SLT) to collect Light Detection and Ranging (LiDAR) data and 4-band digital imagery in the summer of 2018 for the Sears Point 2018 site in San Pablo Bay, California. LiDAR data for the site were also previously collected in the summer of 2017. The information gathered from these datasets is being used to aid the SLT in assessing the topographic and geophysical properties of the study area to support the Sears Point Restoration Project; a collaborative effort between the Sonoma Land Trust and Ducks Unlimited to restore 960 acres of tidal wetland marsh in the San Pablo Bay, along the central coast of California[1].

This report accompanies the delivered LiDAR data and imagery, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to SLT 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 Sears Point 2018 site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Sears Point 2018, California	1,024	1,325	06/16/2018	LiDAR
			07/16/2018	4-band (RGB-NIR) Digital Imagery

[1] *https://www.sonomalandtrust.org/news_room/press_releases/1406-sears-point.html*

Deliverable Products

Table 2: Products delivered to SLT for the Sears Point 2018 site

Sears Point LiDAR and Imagery Products Projection: California State Plane Zone 2 Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12b) Units: US Survey Feet	
LiDAR	
Points	LAS v 1.4 • All Classified Returns
Rasters	3 Foot ESRI Grids • Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) 1.5 Foot GeoTiffs • Green Sensor Intensity Images • NIR Sensor Intensity Images
Vectors	Shapefiles (*.shp) • Data Extent • Area of Interest • Tile Index
4 Band (RGB-NIR) Digital Imagery	
Digital Imagery	0.5 ft Imagery • Tiled Mosaics (*.tif) • AOI Mosaic (*.sid)

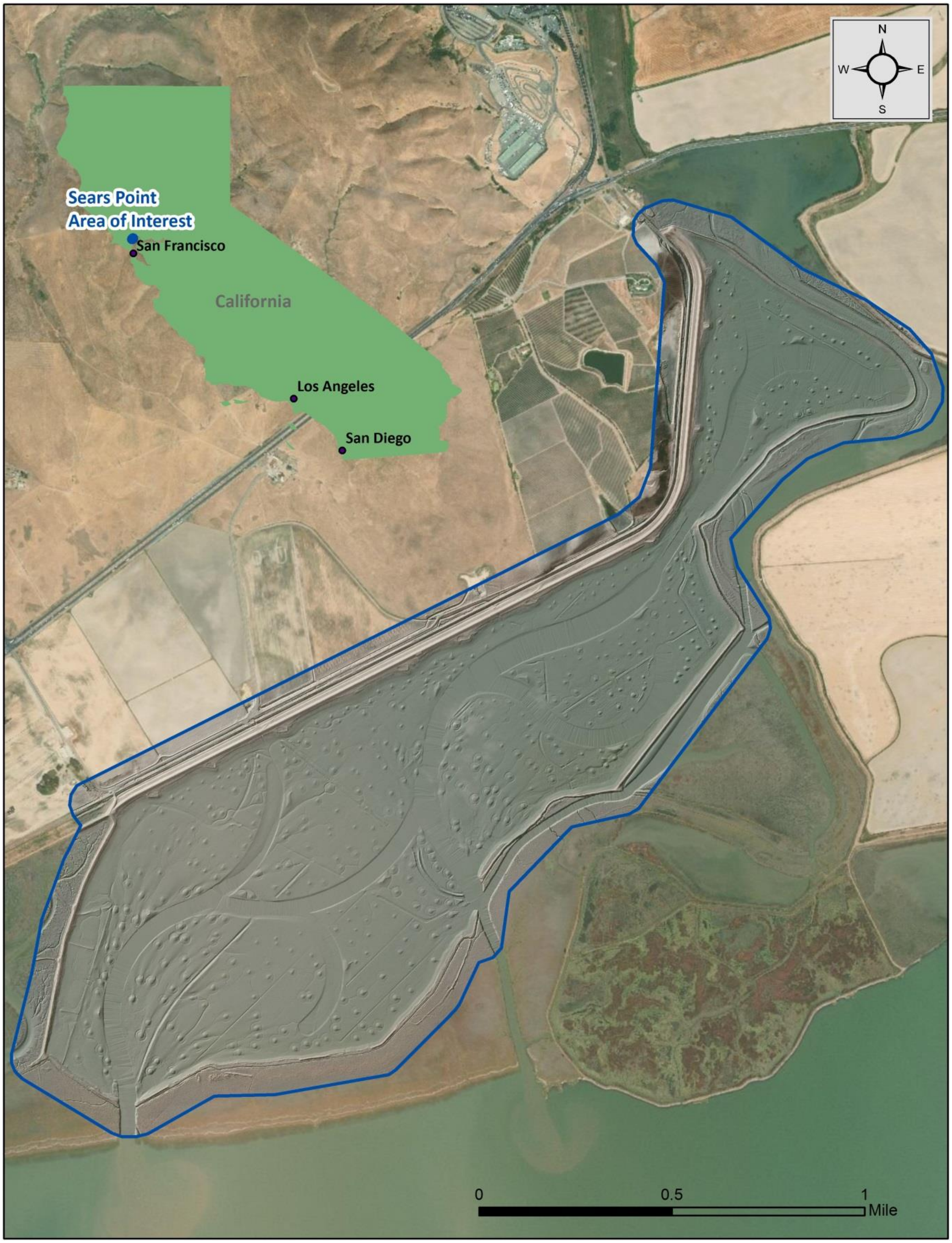

Figure 1: Location map of the Sears Point 2018 site in California

ACQUISITION

Bell 206L-3 Rotorcraft used in the acquisition of the Sears Point 2018 LiDAR and Orthoimagery Site

LiDAR Sensor Selection: the Riegl VQ-880-G

The Riegl VQ-880-G was selected as the airborne laser scanner for the Sears Point 2018 project based on fulfillment of several considerations deemed necessary for effective mapping of the project site. A high repetition pulse rate, high scanning speed, small laser footprint, wide field of view, and combined NIR and Green wavelength lasers allow for seamless collection of high resolution data of both topographic and bathymetric surfaces. A short laser pulse length allows for discrimination of underwater surface expression in shallow water, critical to shallow and dynamic environments such as the Sears Point 2018. The Riegl system has demonstrated hydrographic depth ranging capability up to 1.5 Secchi depths on bright reflective surfaces. While bathymetric collection derived from the green wavelength channel was not part of contract specifications, utilizing the Riegl VQ-880-G allowed for decreased project cost with the added benefit of some discernable bathymetric data for the site. Sensor specifications and settings for the Sears Point 2018 acquisition are displayed in Table 3.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Sears Point 2018 LiDAR study area at the target point density of ≥10.0 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

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, potential air space restrictions, and tide conditions (Figure 2) were reviewed.

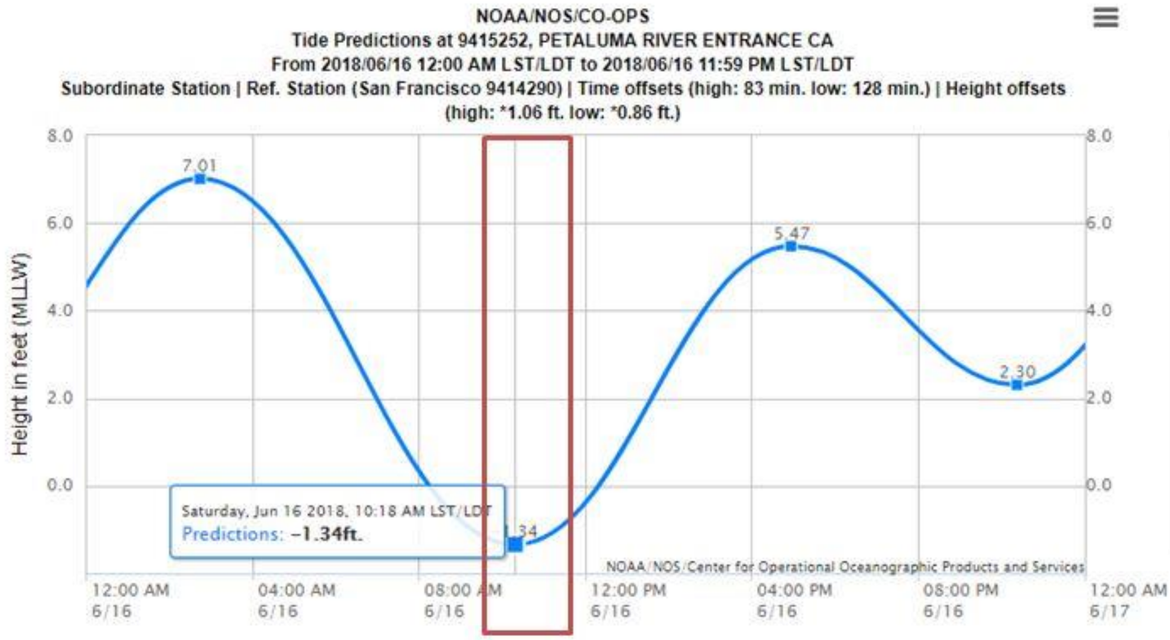

Figure 2: Station ID 9415252 – Petaluma River Entrance, CA gauge height along the Petaluma River at the time of LiDAR acquisition.

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Riegl VQ-880-G green laser system mounted in a Bell 206L-3 Rotorcraft. The Riegl VQ-880-G uses a green wavelength (Λ=532 nm) laser that is capable of collecting high resolution vegetation and topography data, as well as penetrating the water surface with minimal spectral absorption by water. The Riegl VQ-880-G contains an integrated NIR laser (Λ=1064 nm) that adds additional topography data and aids in water surface modeling. The recorded waveform enables range measurements for all discernible targets for a given pulse. The typical number of returns digitized from a single pulse range from 1 to 7 for the Sears Point 2018 project area. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset. Table 3 summarizes the settings used to yield an average pulse density of ≥10 pulses/m^2 over the Sears Point 2018 project area.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
Acquisition Dates	June 16th, 2018	
Aircraft Used	Bell 206L-3 Rotorcraft	
Sensor	Riegl	Riegl
Laser	VQ-880-G	VQ-880-G-IR
Maximum Returns	Unlimited	
Resolution/Density	Combined Average 10 pulses/m^2	
Nominal Pulse Spacing	0.32 m	
Survey Altitude (AGL)	400 m	
Survey speed	100 knots	
Field of View	40^o	
Mirror Scan Rate	80 Lines Per Second	Uniform Point Spacing
Target Pulse Rate	245 kHz	
Pulse Length	1.5 ns	3 ns
Laser Pulse Footprint Diameter	28 cm	8 cm
Central Wavelength	532 nm	1064 nm
Pulse Mode	Multiple Times Around	
Beam Divergence	0.7 mrad	0.2 mrad
Swath Width	290 m	
Swath Overlap	60%	
Intensity	16-bit	

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

Digital Imagery

Aerial imagery was collected using an UltraCam Eagle M3 digital mapping camera (Table 4). For the Sears Point 2018 site, nine images were collected in four spectral bands (red, green, blue, NIR) with 60% along track overlap. The acquisition flight parameters were designed to yield a native pixel resolution of ≤ 15 cm (6 in). Aerial photo acquisition specifications particular to the Sears Point 2018 survey are shown in Table 5.

Table 4: Camera manufacturer's specifications

UltraCam Eagle M3 Details	
Focal Length	100.5 mm
Spectral Bands	RGB-NIR
RCD Pixel Size	4.0 µm
Image Size	26,460 x 17,004 pixels
Frame Rate	GPS triggered
FOV	26,460 x 17,004 pixels

Table 5: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Spectral Bands	Red, Green, Blue, NIR
Ground Sampling Distance	≤15 cm pixel size (0.5 ft)
Along Track Overlap	≥60%
Flight Altitude (MSL)	12,000 ft
GPS Baselines	≤25 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Image	8-bit GeoTiff

Ground Control

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

Base Stations

The spatial configuration of Continuously Operating Reference Station (CORS) provided redundant control within 25 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground survey points using real time kinematic (RTK) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized 2 CORS for the Sears Point 2018 LiDAR project (Table 6). QSI's professional land surveyor, Mark Meade (CAPLS#9466) oversaw and certified the utilization of all base stations.

Table 6: Base Stations utilized for the Sears Point 2018 acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Base Station ID	Latitude	Longitude	Ellipsoid (meters)
VVA4	38° 21' 15.91037"	-121° 59' 24.49639"	33.599
NO1J	38° 06' 43.13215"	-122° 34' 10.62187"	-19.848

QSI triangulated static Global Navigation Satellite System (GNSS) data (1 Hz recording frequency) from each base station with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) to ensure alignment with the National Spatial Reference System (NSRS), updating record positions as necessary. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic survey techniques. A roving Trimble R8 GNSS receiver was used. 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. When collecting RTK data, the rover records data while stationary for five seconds, then calculates the pseudorange position using at least three one-second epochs. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 7 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 3).

Table 7: Trimble equipment identification

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

Aerial Targets

QSI collected and processed all ground survey data in support of aerial photo triangulation and accuracy assessment. Air target points (ATP) typically consisted of high visibility road markings such as stop bars or turn arrows (Figure 3). A total of 16 points were surveyed over 4 features; two air target points were withheld from the aerial triangulation adjustment as check points.

Each ATP was surveyed using RTK techniques. Relative errors for air target positions should be less than 1.5 cm horizontal and 2.0 cm vertical to be accepted. For Real Time Kinematic (RTK) surveys, the survey crew used a roving GPS unit to receive radio-relayed, corrected coordinates for all ATPs from a GNSS base unit occupying an established monument. The relative errors for the RTK positions must be less than 3.0 cm horizontal and 4.0 cm vertical at a 95% confidence interval to be accepted. No points were collected with a PDOP higher than 3.0, and all points rover seeing a minimum of 6 common satellites.

Aerial Target survey in the Sears Point 2018 AOI

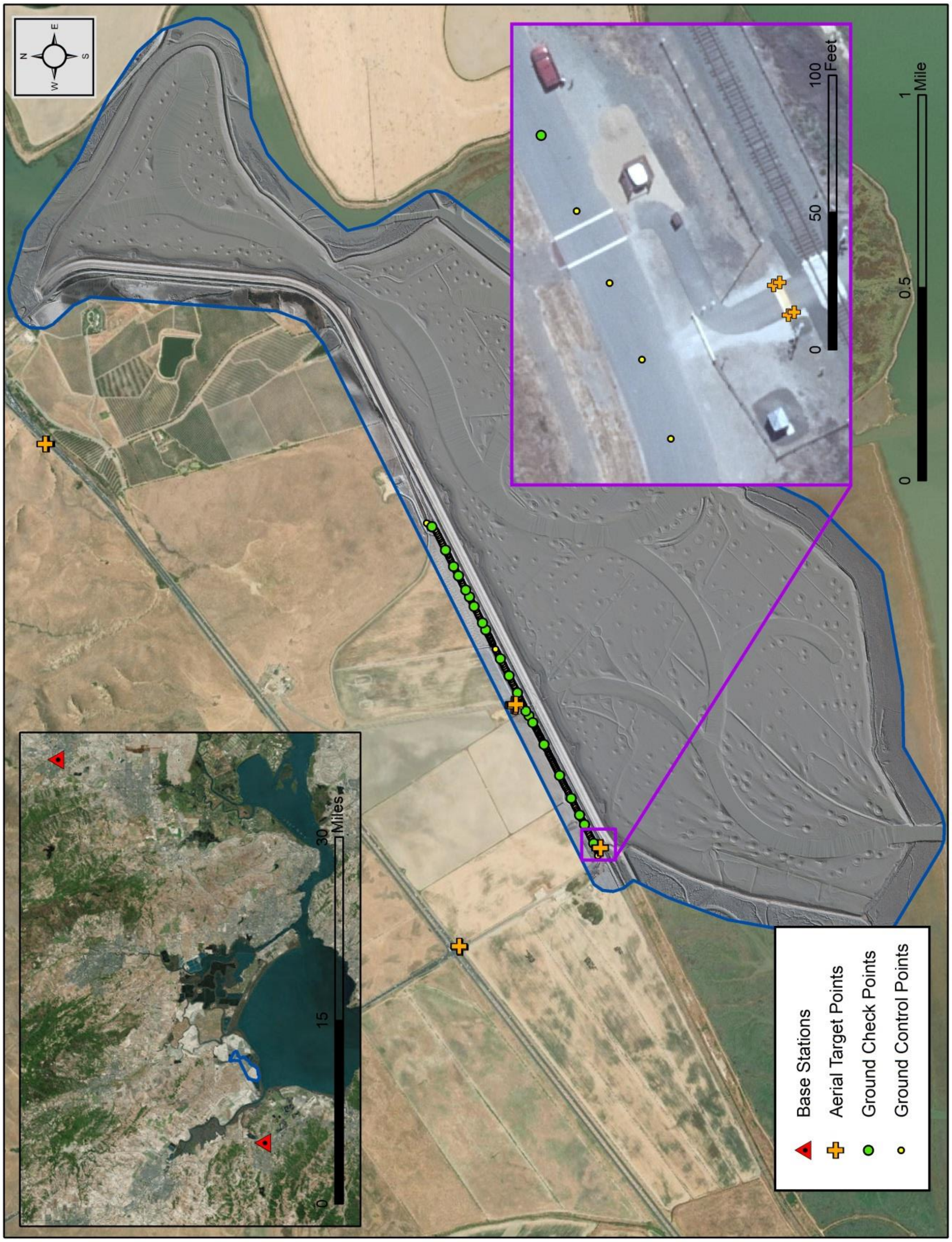

Figure 3: Ground survey location map

PROCESSING

Cross section showing the classification of the Sears Point 2018 LiDAR dataset

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 8).

Riegl's RiProcess software was used to facilitate bathymetric return processing. Once bathymetric points were differentiated, they were spatially corrected for refraction through the water column based on the angle of incidence of the laser. QSI refracted water column points using QSI's proprietary LAS processing software, LAS Monkey. The resulting point cloud data were classified using both manual and automated techniques. Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the Sears Point 2018 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
40	Bathymetric Bottom	Refracted Riegl sensor returns that fall within the water's edge breakline which characterize the submerged topography.
45	Water Column	Refracted Riegl sensor returns that are determined to be water using automated and manual cleaning algorithms.

Table 9: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.2
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. 1.2) format. Convert data to orthometric elevations by applying a geoid correction.	RiProcess v1.8.5 TerraMatch v.18
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.18
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.18
Apply refraction correction to all subsurface returns.	Las Monkey (QSI proprietary software)
Classify resulting data to ground and other client designated ASPRS classifications (Table 8). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.18 TerraModeler v.18
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 foot pixel resolution.	ArcMap v. 10.3.1 Las Product Creator (QSI proprietary software)
Export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	ArcMap v. 10.3.1 Las Product Creator (QSI proprietary software)

Bathymetric Refraction

Due to the project being collected with the Riegl VQ-880-G, it was necessary to apply a refraction correction to those points collected below the water's surface to ensure accurate ground modeling. Points are filtered and edited to obtain the most accurate representation of the water surface and are used to create a water surface model TIN. A tin model is preferable to a raster based water surface model to obtain the most accurate angle of incidence during refraction. The refraction processing is done using Las Monkey; QSI's proprietary LiDAR processing tool.

Digital Imagery

As with the LiDAR, the digital imagery went through multiple processing steps to create final orthophoto products. Initially, images were corrected for geometric distortion to yield level02 image files. Next, images were color balanced and levels were adjusted to exploit the full 14bit histogram and finally output as level03 pan-sharpened 8bit TIFF images. Camera position and orientation were calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET). Within Inpho's Match AT softcopy aerial triangulation software, analytical aerial triangulation was performed using ground control, automatically generated tie points, and camera calibration information.

Adjusted images were orthorectified using the LiDAR-derived ground model to remove displacement effects from topographic relief inherent in the imagery. During the mosaic process seamlines are found between adjacent orthos using the most nadir part of the frame while dodging above ground features such as buildings and other manmade features. Automated color balancing between frames is applied to normalize any remaining radiometric differences across the project. Final orthophoto mosaics are inspected for cutlines and tonality and further edits are made if needed. The processing workflow for orthophotos is summarized in Table 10.

Table 10: Orthophoto processing workflow

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 Hz), onboard IMU (collected at 200 Hz) and CORS static ground data. (performed by Keystone Aerial Surveys)	PosPac v8
Develop a smooth best estimate trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey. (performed by Keystone Aerial Surveys)	PosPac v8
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa. (performed by Keystone Aerial Surveys)	PosPac v8
Convert Level 00 raw imagery data into geometrically corrected Level 02 image files. (performed by Keystone Aerial Surveys)	UltraMap v4

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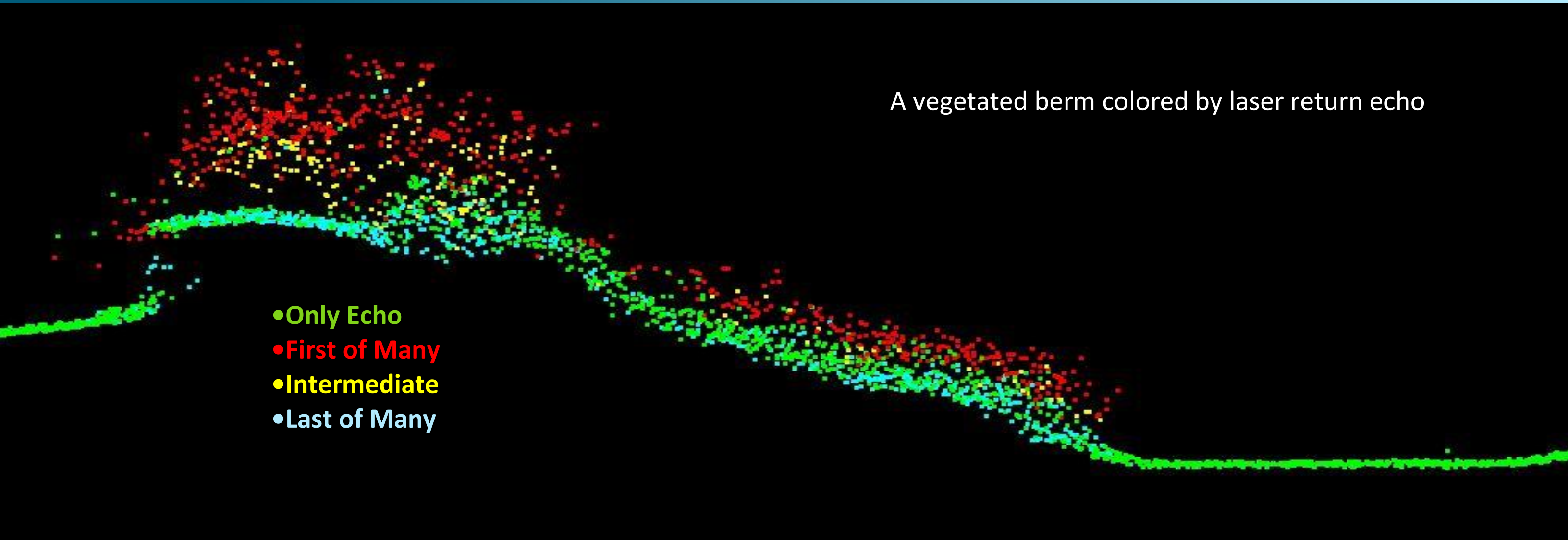
Apply radiometric adjustments to Level 02 image files to create Level 03 Pan-sharpened TIFFs. (performed by Keystone Aerial Surveys)	UltraMap v4
Apply EO to photos, measure ground control points and perform aerial triangulation.	Match AT v8.0
Import DEM, orthorectify and clip triangulated photos to the specified area of interest.	OrthoMaster v8.0
Mosaic orthorectified imagery, blending seams between individual photos and correcting for radiometric differences between photos.	OrthoVista/SeamEditor v8.0

RESULTS & DISCUSSION



LiDAR Point Density

First Return Point Density

The acquisition parameters were designed to acquire an average first-return density of 10 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser.

First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The average first-return density of the Sears Point 2018 LiDAR project was 4.46 points/ft^2 (47.97 points/m^2) (Table 11). The statistical and spatial distributions of all first return densities per 100 m x 100 m cell are portrayed in Figure 4 and Figure 6.

Bathymetric and Ground Classified Point Densities

The density of ground classified LiDAR returns and bathymetric bottom returns were 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 have penetrated the canopy, resulting in lower ground density. Similarly, the density of bathymetric bottom returns was influenced by turbidity, depth, and bottom surface reflectivity. In turbid areas, fewer pulses may have penetrated the water surface, resulting in lower bathymetric density.

The ground and bathymetric bottom classified density of LiDAR data for the Sears Point 2018 project was 0.71 points/ft^2 (7.59 points/m^2) (Table 11). The statistical and spatial distributions ground classified and bathymetric bottom return densities per 100 m x 100 m cell are portrayed in Figure 5 and Figure 6.

Table 11: Average LiDAR point densities

Density Type	Point Density
First Returns	47.97 points/m²
Ground and Bathymetric Bottom Classified Returns	7.59 points/m²

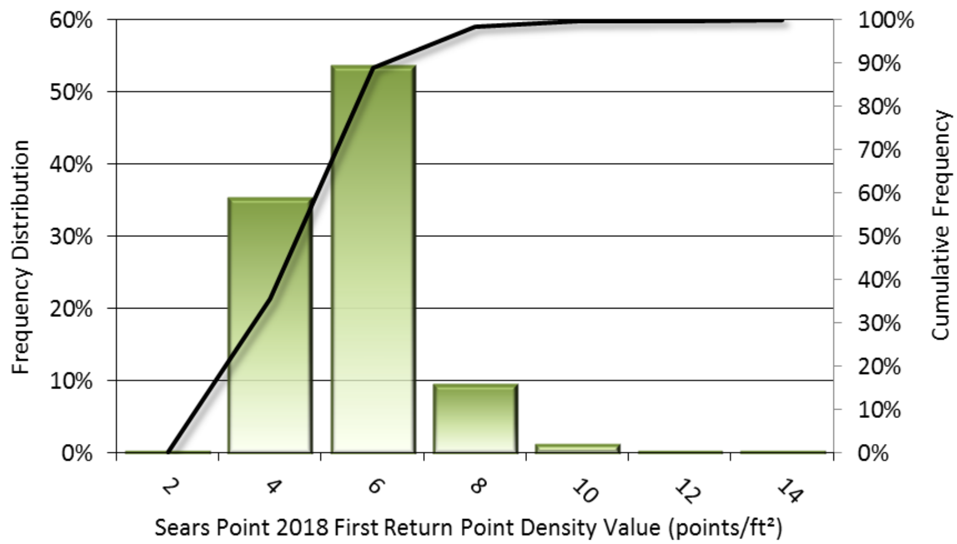


Figure 4: Frequency distribution of first return densities per 100 x 100 m cell

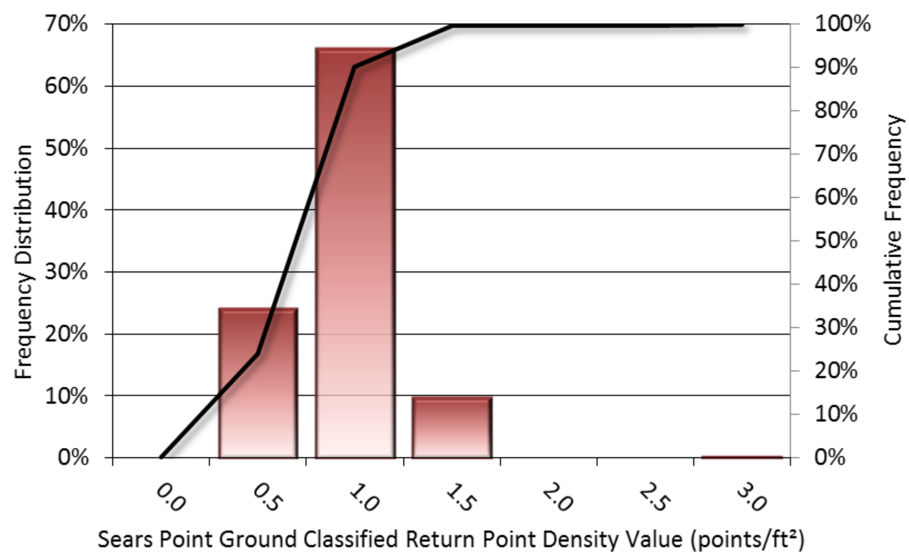


Figure 5: Frequency distribution of ground and bathymetric bottom classified return densities per 100 x 100 m cell

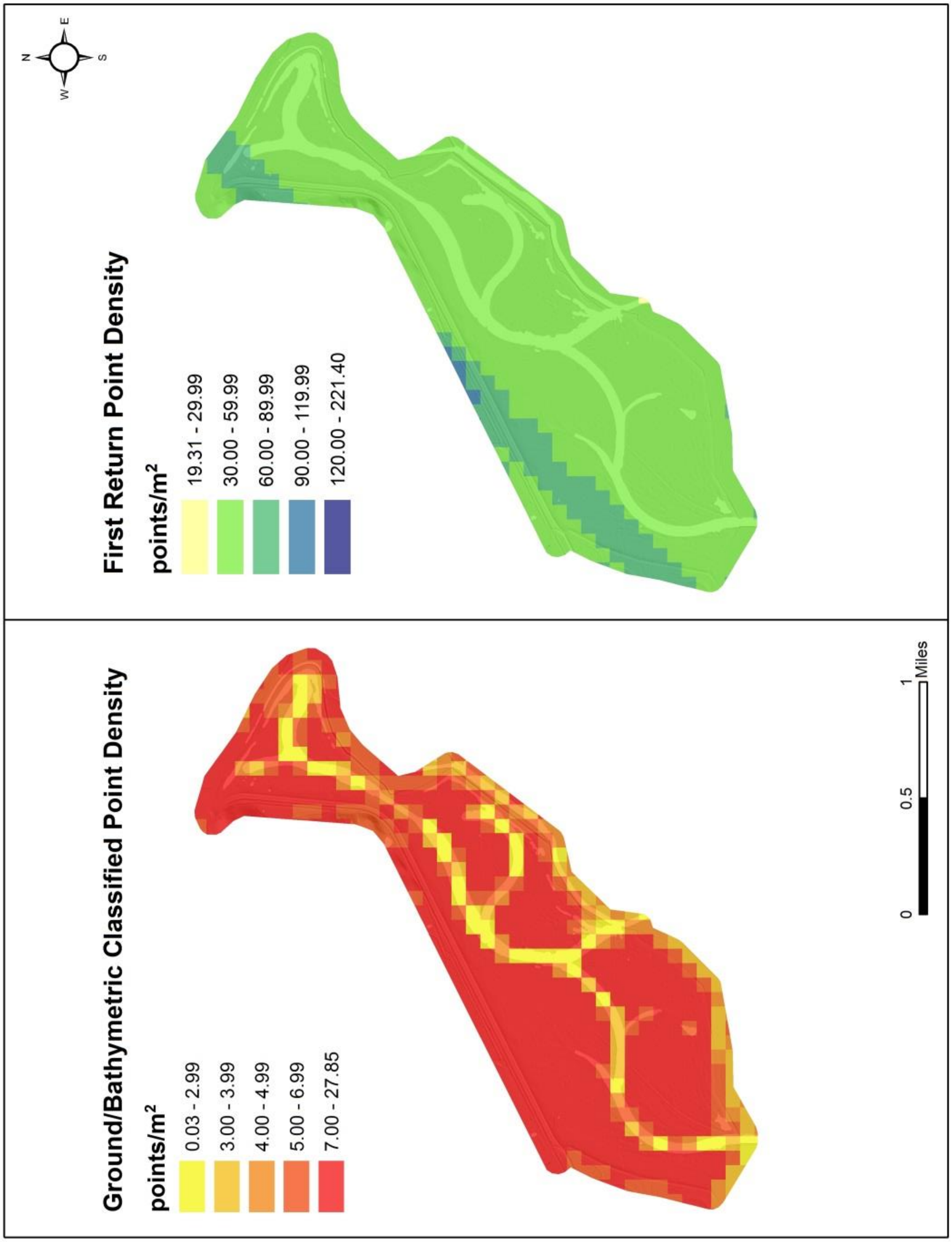


Figure 6: First return and ground and bathymetric bottom density map for the Sears Point 2018 site (100 m x 100 m cells)

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 quality assurance point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated surface generated by the LiDAR points. NVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 12.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check 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 Sears Point 2018 survey, 21 ground check points were withheld from the calibration and post-processing of the LiDAR point cloud, with resulting non-vegetated vertical accuracy of 0.243 feet (0.074 meters), with 95% confidence.

QSI also assessed absolute accuracy using 165 ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 12 and Figure 9.

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

Table 12: Absolute accuracy (NVA) results

	Ground Check Points (compared to unclassified LAS point cloud)	Ground Check Points (compared to bare earth DEM)	Ground Control Points (compared to classified LAS point cloud)
Sample	21 points	21 points	165 points
95% Confidence (1.96*RMSE)	0.243 ft 0.074 m	0.200 ft 0.061 m	0.193 ft 0.059 m
Average	0.070 ft 0.020 m	-0.006 ft -0.002 m	-0.013 ft -0.004 m
Median	0.072 ft 0.022 m	-0.007 ft -0.002 m	-0.033 ft -0.010 m
RMSE	0.124 ft 0.038 m	0.102 ft 0.031 m	0.099 ft 0.030 m
Standard Deviation (1σ)	0.105 ft 0.032 m	0.104 ft 0.032 m	0.098 ft 0.030 m

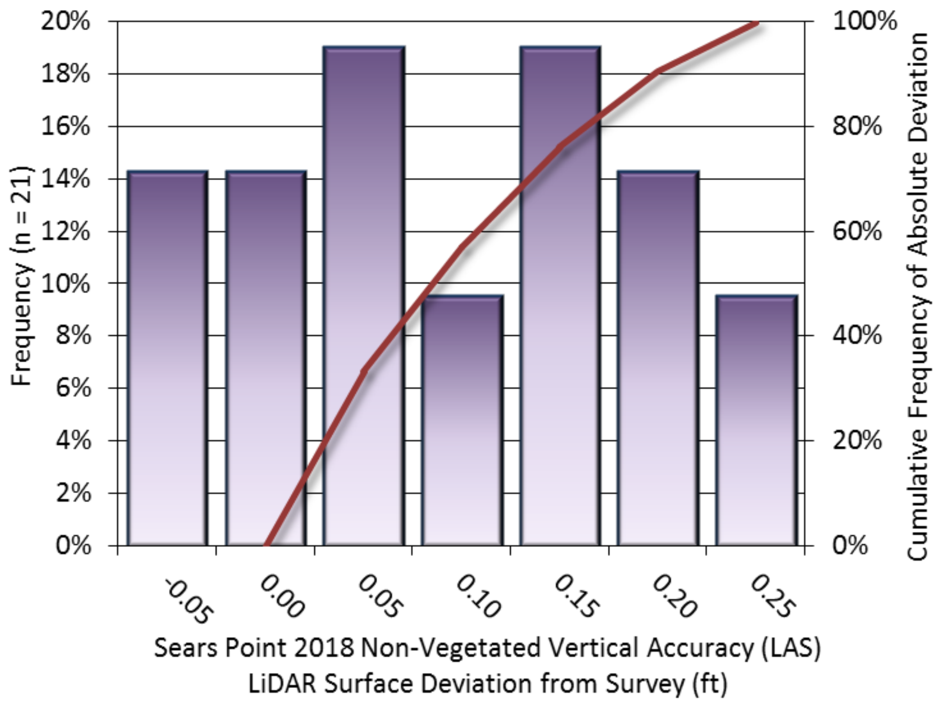


Figure 7: Frequency histogram for LiDAR surface deviation from ground check point values as compared to the unclassified point cloud

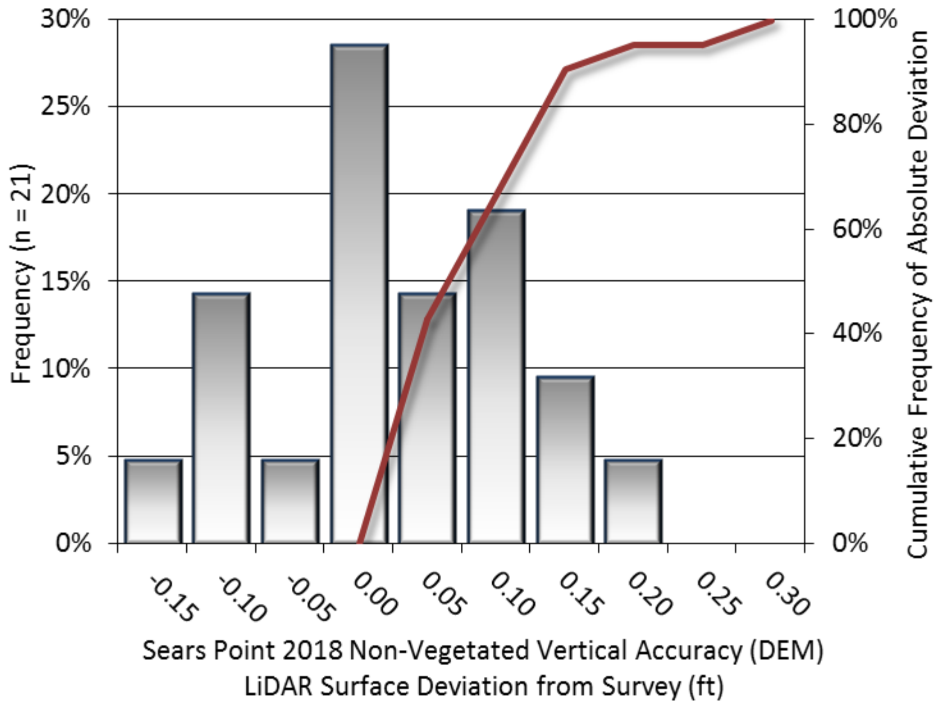


Figure 8: Frequency histogram for LiDAR surface deviation from ground check point values as compared to the derived bare earth DEM

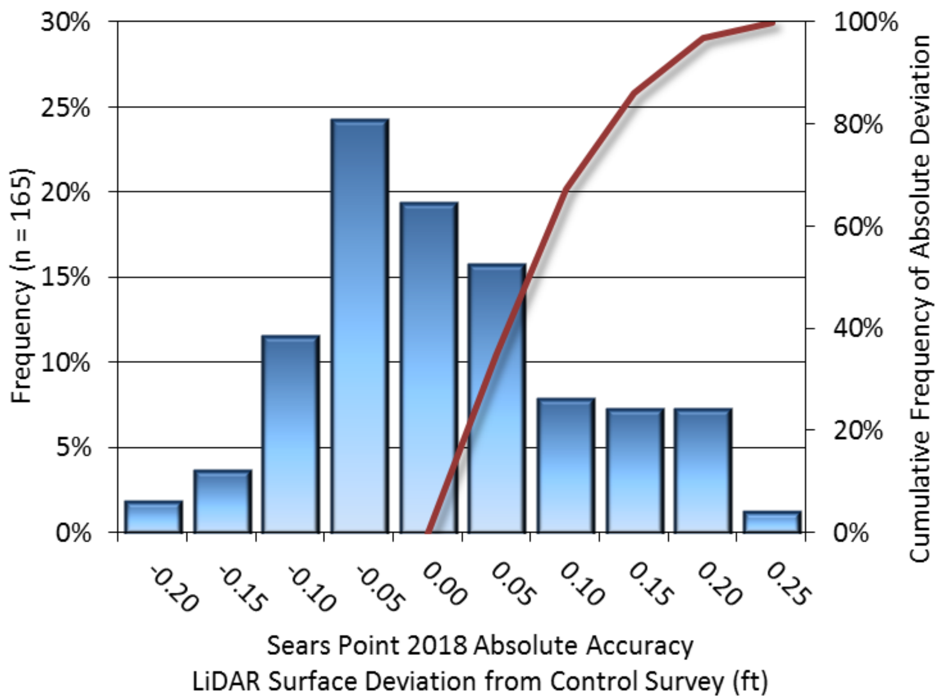


Figure 9: Frequency histogram for LiDAR surface deviation from ground control point values as compared to the classified point cloud

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 Sears Point 2018 LiDAR project was 0.090 feet (0.028 meters) (Table 13, Figure 10).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	42 surfaces
Average	0.090 ft 0.028 m
Median	0.088 ft 0.027 m
RMSE	0.091 ft 0.028 m
Standard Deviation (1σ)	0.012 ft 0.004 m
1.96σ	0.024 ft 0.007 m

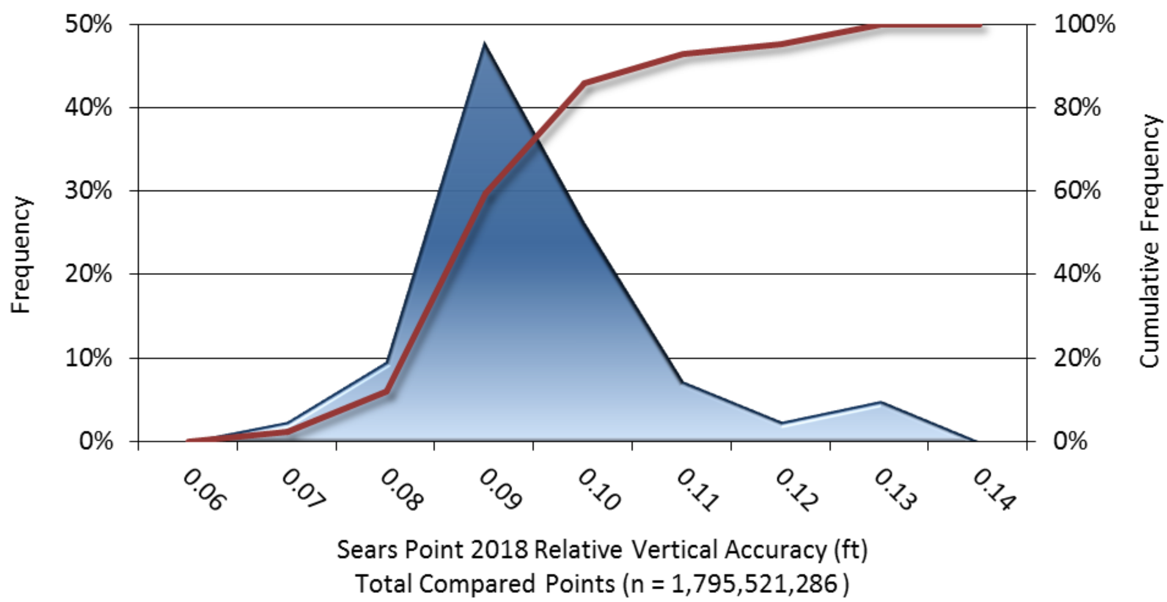


Figure 10: Frequency plot for relative vertical accuracy between flight lines

Sears Point Analytical Aerial Triangulation Report

Aerial triangulation was performed in one block to support photogrammetric mapping of the Sears Point study area. The block consisted of one flight line with 9 images flown with 60% forward overlap at a scale of 1:1,200 on July 16th, 2018. Adjustments were made to ground control established by QSI referencing CA State Plane Zone 2, NAD 83(2011) horizontal datum and NAVD 1988 vertical datum (Geoid12b), US survey feet. Digital imagery along with ground control and camera calibration data were used as inputs to Inpho's Match AT softcopy triangulation program. The digital camera utilized was an UltraCam Eagle M3.

Control Points

Air target points used in the aerial triangulation adjustment are listed with their location in Table 14, their residuals are listed in Table 15 and RMSE values can be found in Table 16.

Table 14: Location of air target points used as control for aerial triangulation adjustment

Control Point Coordinates (us ft) - 2 Total Points			
Point ID	X	Y	Z
AT001d	6431644.540	1816545.740	74.610
AT003d	6426023.450	1808993.200	3.320

Table 15: Residuals for air target points used as control for aerial triangulation adjustment

Control Point Residuals (us ft) -2 Total Points			
Point ID	X	Y	Z
AT001d	0.031	0	-0.073
AT003d	-0.031	0	0.073

Table 16: RMSE for air target points used as control for aerial triangulation adjustment

Control Point RMSE (us ft) - 2 Total Points		
X	Y	Z
0.031	0.000	0.073

Check Points

Air target points withheld from the aerial triangulation adjustment are listed with their location in Table 17, their residuals are listed in Table 18 and RMSE values can be found in Table 19.

Table 17: Location of air target points used as check points

Control Point Coordinates (us ft) - 2 Total Points			
Point ID	X	Y	Z
AT002c	6427981.280	1810141.530	2.060
AT004a	6424684.320	1810933.910	2.870

Table 18: Residuals for air target points used as check points

Control Point Residuals (us ft) -2 Total Points			
Point ID	X	Y	Z
AT002c	-0.099	-0.357	-0.326
AT004a	0.196	0.005	1.27

Table 19: RMSE for air target points used as check points

Control Point RMSE (us ft) - 2 Total Points		
X	Y	Z
0.155	0.252	0.927

CERTIFICATIONS

Quantum Spatial, Inc. provided LiDAR services for the Sears Point 2018 project as described in this report.

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

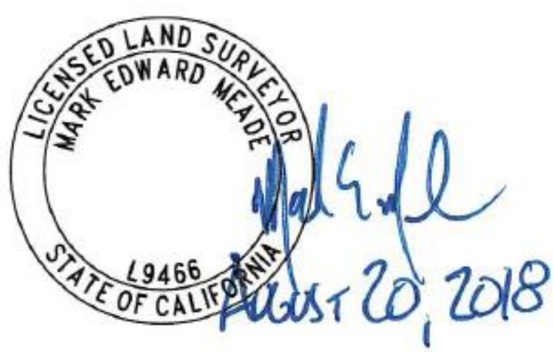
Tucker Selko (Aug 21, 2018) Aug 21, 2018

Tucker Selko
Project Manager
Quantum Spatial, Inc.

I, Mark Meade, 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 June 16th, 2018.

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".

Mark Meade, PLS
Quantum Spatial, Inc.



SELECTED IMAGES

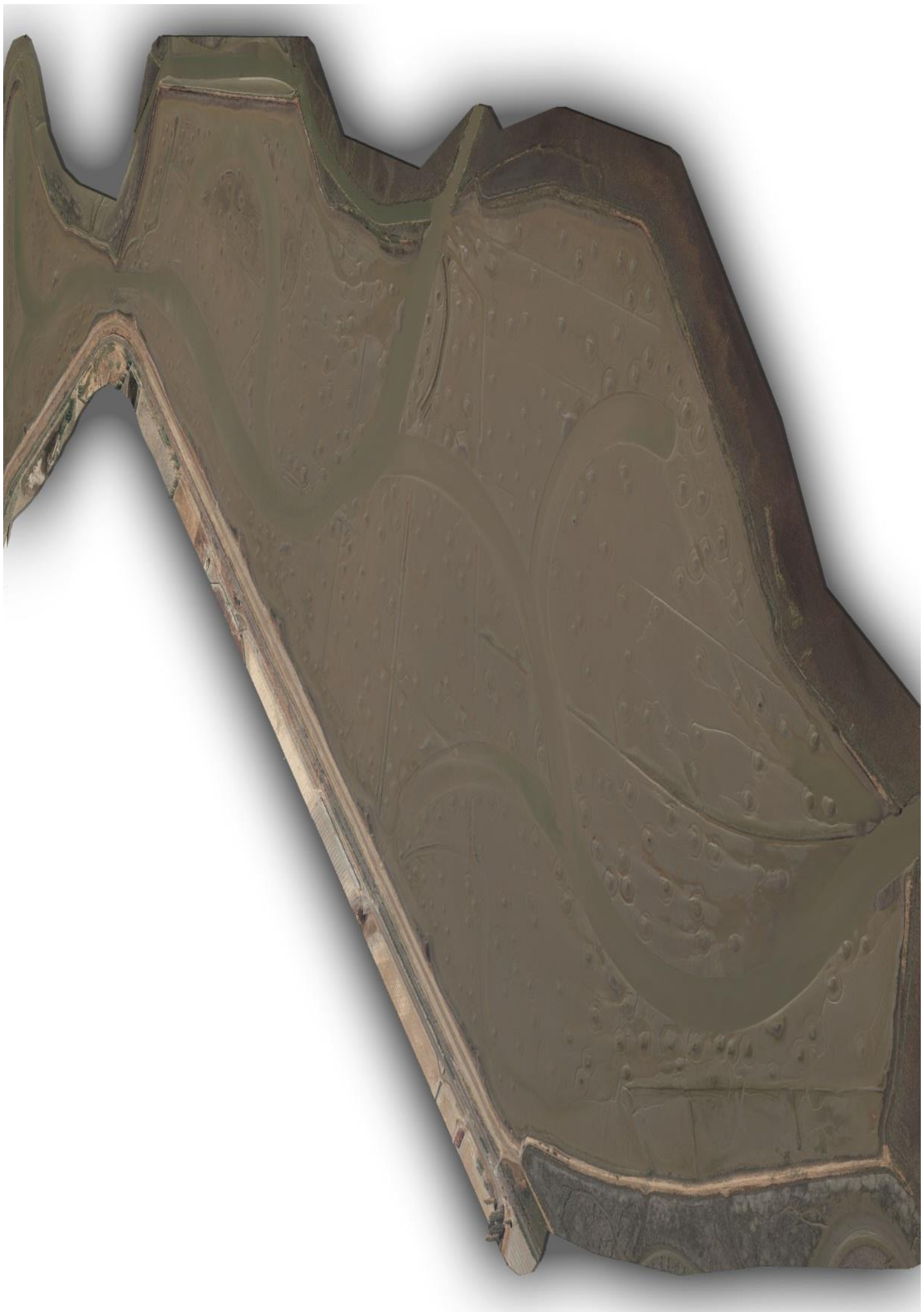


Figure 11: View looking east over Sears Point 2018. The image was created from the LiDAR the high hit model colored by 0.5 ft imagery.

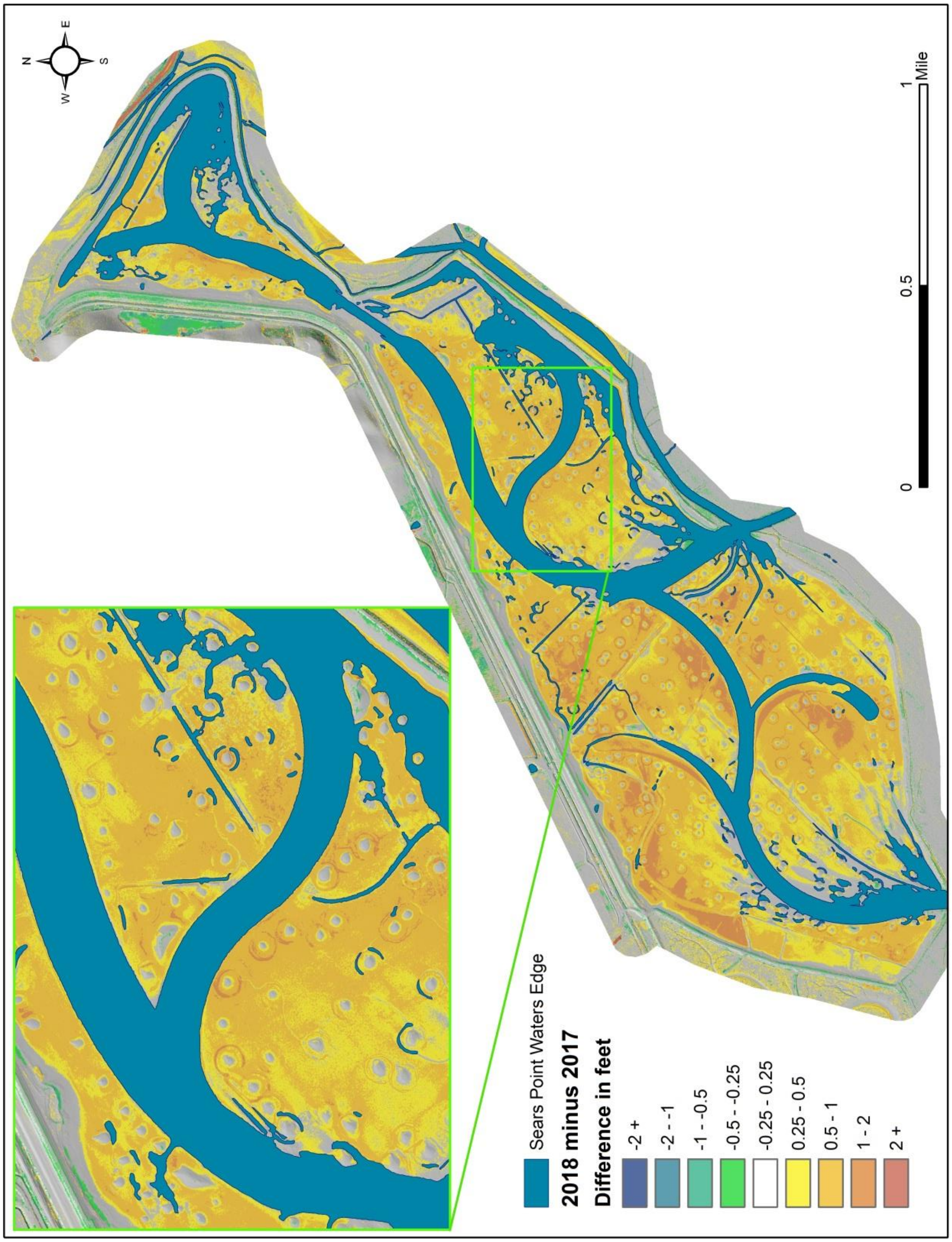


Figure 12: A map displaying the sediment accrual between the 2017 and 2018 LiDAR acquisitions

GLOSSARY

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

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

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

> **Absolute Accuracy:** The vertical accuracy of LiDAR data is described as the mean and standard deviation (sigma σ) of divergence of LiDAR point coordinates from ground survey point coordinates. To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y and z are normally distributed, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. Affected by system attitude offsets, scale and GPS/IMU drift, internal consistency is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<10 cm).
>
> **Root Mean Square Error (RMSE):** A statistic used to approximate the difference between real-world points and the LiDAR points. It is calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

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

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

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

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

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

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

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

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

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

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

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

APPENDIX A - ACCURACY CONTROLS

Relative Accuracy Calibration Methodology:

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

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

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

LiDAR accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

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

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 20^{o}$ 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 25 nm at all times.

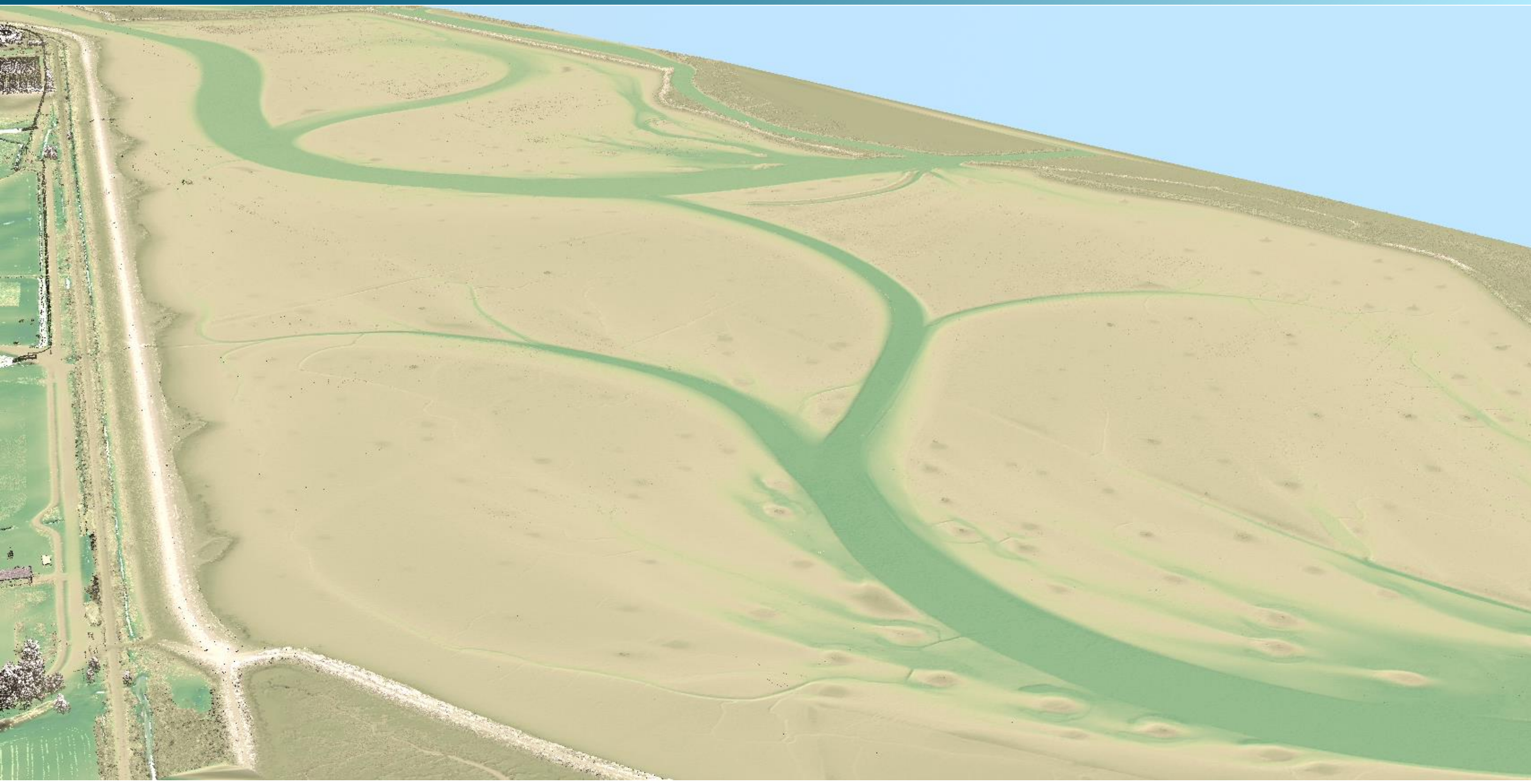
Ground Survey: Ground survey point accuracy (<1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. Ground survey points are distributed to the extent 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 C-3

August 6, 2020



Sears Point, California Lidar and Imagery

Technical Data Report

Prepared For:

Dr. Stuart Siegel
Siegel Environmental, LLC
2 Belle Avenue
San Rafael, California 94901
PH: 415-823-3746

Prepared By:

QSI Corvallis
1100 NE Circle Blvd, Ste. 126
Corvallis, OR 97330
PH: 541-752-1204

Appendix C-3

Table of Contents

Cover Photo: A view looking east over the mud flats of Sears Point. The image was created from the lidar bare earth model colored by elevation.

Appendix C-3

INTRODUCTION

This photo taken by ground survey staff shows a view of the Sears Point surrounding area in Southern California.

In April 2020, Quantum Spatial (QSI) was contracted by Siegel Environmental, LLC to collect Light Detection and Ranging (lidar) data and digital imagery in the summer of 2020 for the Sears Point site in California. Data were collected to aid Siegel in assessing the topographic and geophysical properties of the study area to support environmental restoration efforts.

This report accompanies the delivered lidar data and imagery, and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including lidar accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to Siegel Environmental, LLC (Siegel) 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 Sears Point site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Sears Point, California	1,142	1,489	06/07/2020	lidar
			06/07/2020	4 band (RGB-NIR) Digital Imagery

Deliverable Products

Table 2: Products delivered to Siegel Environmental, LLC for the Sears Point site

Sears Point Lidar and Imagery Products Projection: California State Plane Zone II Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID12B) Units: US Survey Feet	
Points	LAS v 1.4 • All Classified Returns
Rasters	1.5 Foot ESRI Grids • Unclipped Bare Earth Digital Elevation Model (DEM) • Clipped Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) 1.0 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Data Extent • Area of Interest • Tile Index • Water's Edge Breaklines
Imagery	GeoTiffs • Orthophotos (6-inch Ground Sampling Distance) Vectors (*.shp) • Orthophoto Index • Area of Interest

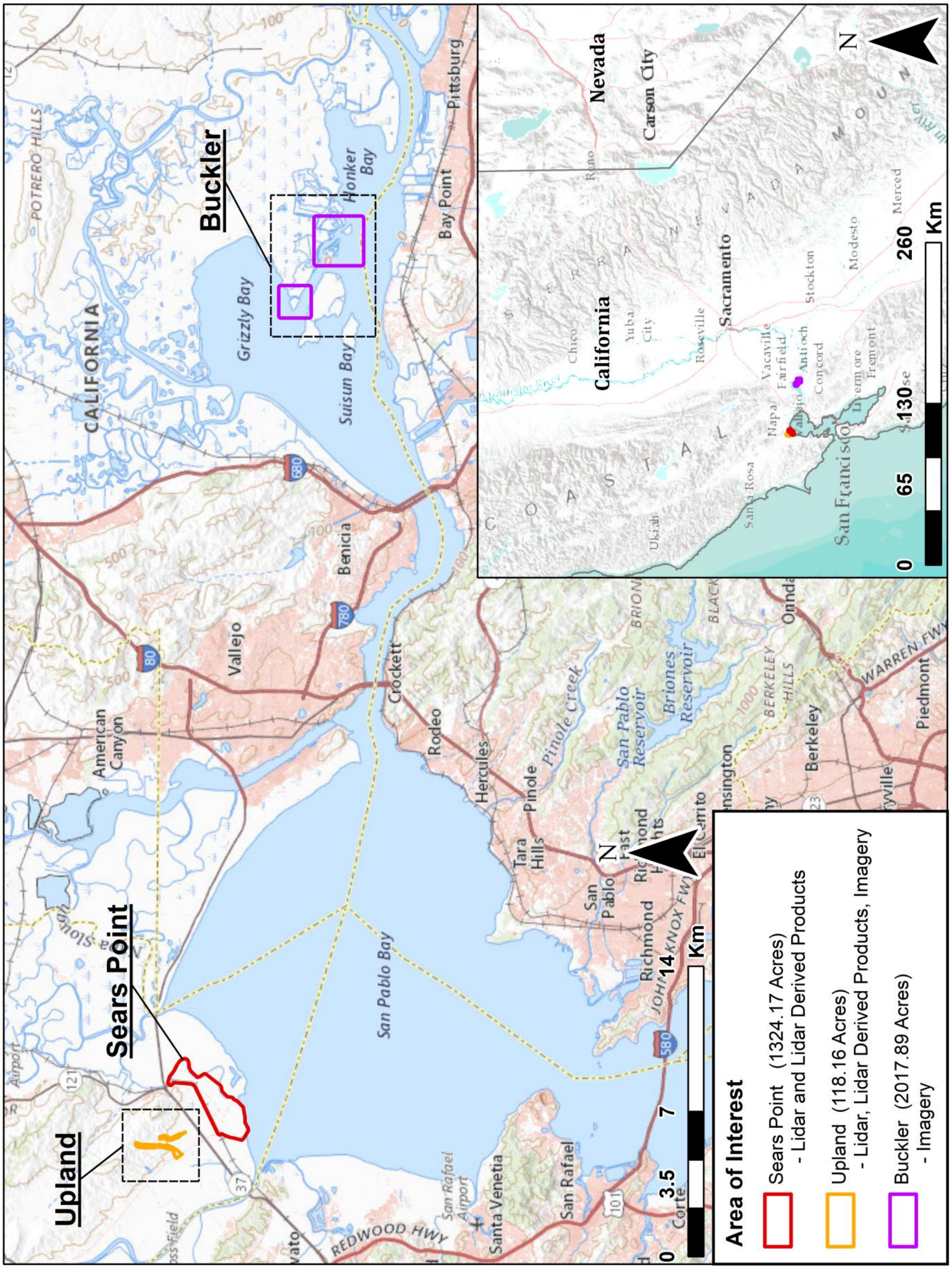


Figure 1: Location map of the Sears Point site in California

Acquisition

QSI's ground acquisition equipment set up in the Sears Point study area in Southern California.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Sears Point lidar study area at the target point density of ≥10.0 points/m^2 (0.93 points/ft^2). Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability, tidal water level, 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. Acquisition was to correspond with the mid-day low tide window to allow for maximum mud flat exposure. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne Survey

Lidar

The lidar survey was accomplished using a Riegl system mounted in a Cessna Stationair. Table 3 summarizes the settings used to yield an average pulse density of ≥10 pulses/m^2 over the Sears Point project area. The Riegl laser system can record up to 15 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: Lidar specifications and survey settings

Lidar Survey Settings & Specifications	
Acquisition Dates	June 7, 2020
Aircraft Used	Cessna Stationair
Sensor	Riegl
Laser	VQ-1560i
Maximum Returns	15
Resolution/Density	Average 10 pulses/m^2
Nominal Pulse Spacing	0.32 m
Survey Altitude (AGL)	1621 m
Survey speed	150 knots
Field of View	58.5^o
Mirror Scan Rate	139 Hz
Target Pulse Rate	700 kHz
Pulse Length	3 ns
Laser Pulse Footprint Diameter	29 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.18 mrad
Swath Width	1816 m
Swath Overlap	60%
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 9 cm

Riegl VQ-1560i lidar sensor

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the lidar data collection mission. Position of the aircraft was measured twice per second (2 Hz) by an onboard differential GPS unit, and aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). To allow for post-processing correction and calibration, aircraft and sensor position and attitude data are indexed by GPS time.

Digital Imagery

The aerial imagery was collected using an UltraCam Eagle M3 camera. The UltraCam Eagle is a large format digital mapping camera manufactured by Vexcel; camera specifications can be found in Table 4. The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery.

Table 4: Camera manufacturer's specifications

UltraCam Eagle M3	
Focal Length	100.5 mm
Data Format	RGB NIR
Pixel Size	4.0 μm
Image Size	26,460 x 17,004 pixels
Frame Rate	1.5 seconds
FOV	55° x 37°

For the Sears Point site, 8 images were collected in four spectral bands (red, green, blue, NIR) with 60% along track overlap between frames. The acquisition flight parameters were designed to yield a native pixel resolution of ≤ 15 cm. Orthophoto specifications particular to the Sears Point project are in Table 5.

Table 5: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Sensor	UltraCam Eagle M3
Spectral Bands	Red, Green, Blue, NIR
Ground Sampling Distance	≤ 15 cm pixel size
Along Track Overlap	≥60%
Cross Track Overlap	NA
Flight Altitude (MSL)	3,100 meters
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Image	8-bit Tiff

Ground Survey


Air Target Point

Ground control surveys, including air target points and ground survey points (GSPs), were conducted to support the airborne acquisition. Ground control data were used to perform quality assurance checks on final lidar data.

Base Stations

One monument from the California Surveying and Drafting Supply (CSDS) Real Time Network (RTN) was used for GSP collection for the Sears Point Lidar project (Table 6, Figure 2). This base station was utilized for collection of ground survey points using real time kinematic (RTK) survey techniques. QSI's professional land surveyor, Evon Silvia (CAPLS#9401) oversaw the ground survey work.

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

Base Station ID	Owner	Latitude	Longitude	Ellipsoid (meters)
NO1L	CSDS RTN	38° 06' 43.13202"	-122° 34' 10.62181"	-19.838

Ground Survey Points (GSPs)

Ground survey points were collected using RTK survey techniques where a roving receiver received corrections from the CSDS 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.

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 7: QSI ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R10 Model 2	Integrated Antenna	TRMR10-2	Rover

Aerial Targets

QSI collected hard surface air targets typically on high visibility road markings, cement corners or temporary vinyl chevrons. Ten air target points were surveyed throughout the Sears Point study area using RTK survey techniques. Hard surface points consisted of high contrast, road markings such as stop bars or turn arrows. Typically, each corner of the road marking was surveyed, in this way only one point was used for aerial triangulation while the remaining points were used for quality assurance purposes.

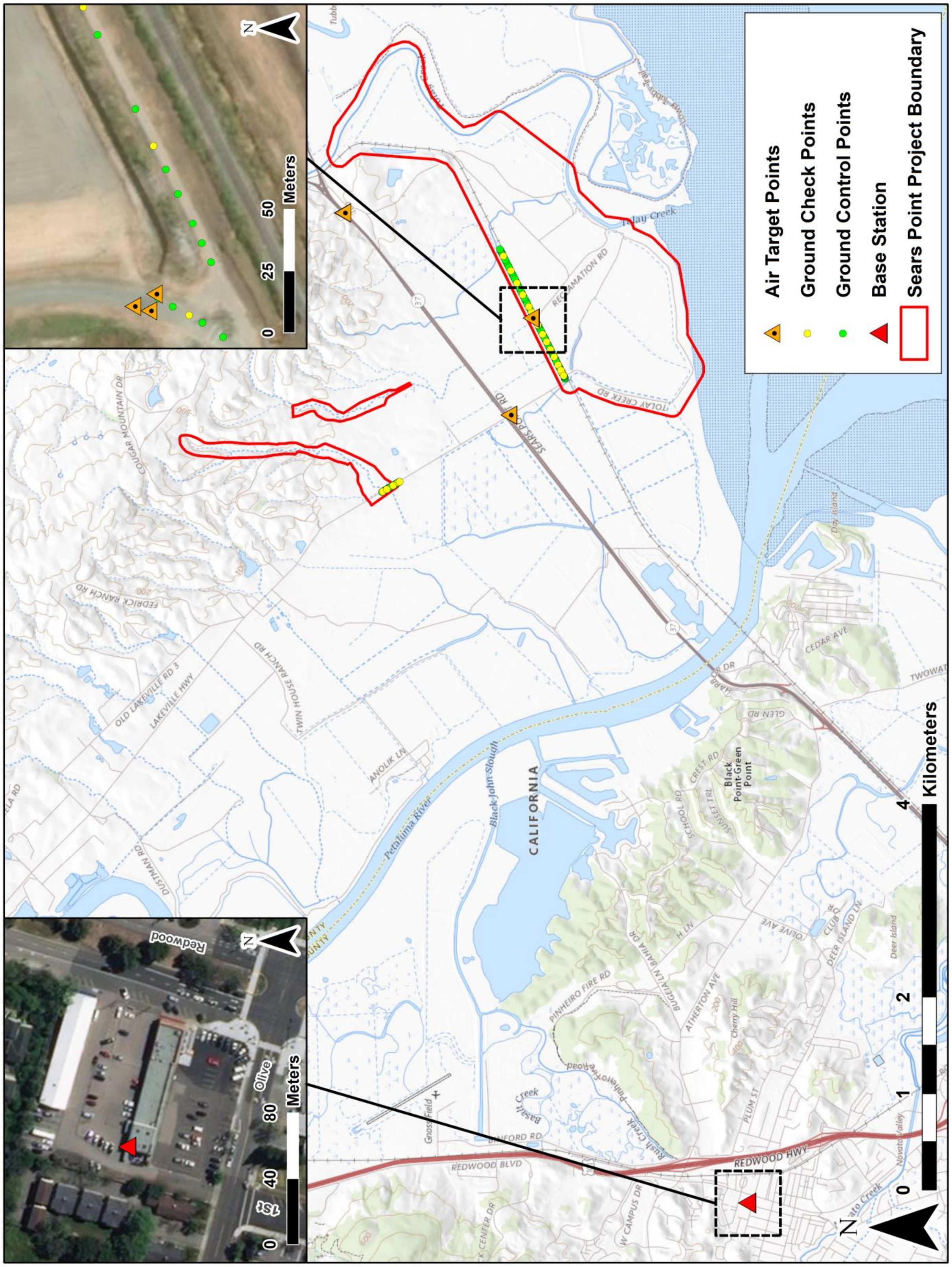
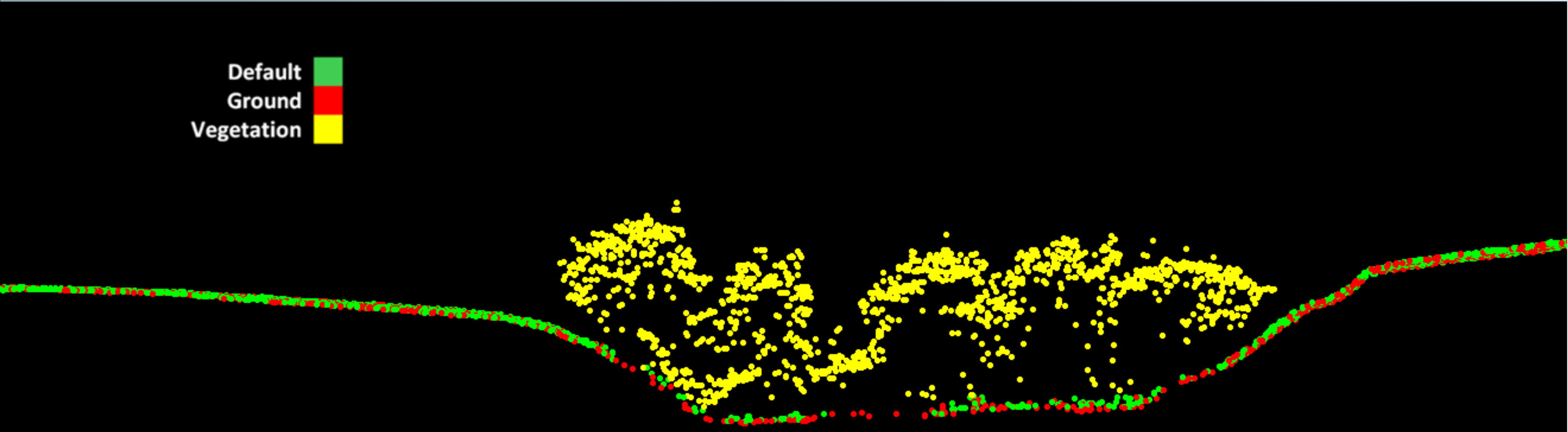


Figure 2: Ground survey location map

PROCESSING



This 3 foot lidar cross section shows a view of the Sears Point Upland 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 8). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 9.

Table 8: ASPRS LAS classification standards applied to the Sears Point dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation below 1.5 feet and anthropogenic features
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
3	Vegetation	Any vegetation greater than 1.5 feet above the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms

Table 9: lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.3
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiProcess v1.8.5 POSPac MMS v.8.3
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19
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 8). 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 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 1.0 foot pixel resolution.	LAS Product Creator 3.0 (QSI proprietary)

Feature Extraction

Water's Edge Breaklines

The delineation of all bodies of water within the Sears Point area of interest was performed through a combination of automated and manual detection and adjustment techniques. Boundary polygons were manually digitized to define the water's edge. The water edges were then manually reviewed and edited as necessary.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered lidar returns to create the final breaklines. The final water boundary breaklines were used to clip water out of the final bare earth digital elevation models.

Digital Imagery

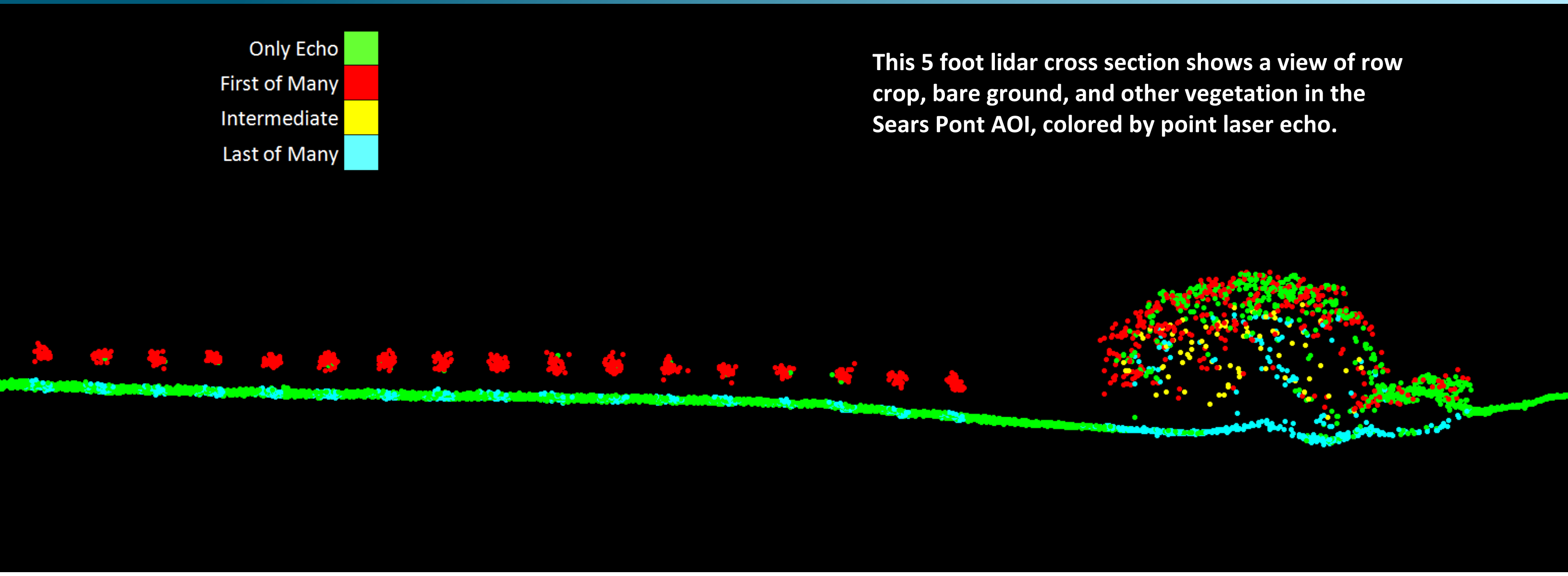
The collected digital photographs went through multiple processing steps to create final orthophoto products. Initially, images were corrected for geometric distortion to yield level02 image files. Next, images were color balanced and levels were adjusted to exploit the full 14bit histogram and finally output as level03 pan-sharpened 8bit TIFF images. Photo position and orientation were calculated by linking the time of image capture to the smoothed best estimate of trajectory (SBET). Within Inpho's Match AT softcopy photogrammetric software, analytical aerial triangulation was performed using ground control, automatically generated tie points, and camera calibration information.

Adjusted images were orthorectified using the LiDAR-derived ground model to remove displacement effects from topographic relief inherent in the imagery. The resulting images were mosaicked within Inpho's Ortho Vista blending seams and applying automated global color-balancing. The final mosaics were inspected and edited for seam cutlines across above ground features such as buildings and other man-made features. The processing workflow for orthophotos is summarized in Table 10.

Table 10: Orthophoto processing workflow

Orthophoto Processing Step	Software Used
Resolve GPS kinematic corrections for the aircraft position data using kinematic aircraft GPS (collected at 2 Hz), onboard IMU (collected at 200 Hz) and Applanix PPRTX data.	PosPac MMS v8.20
Develop a smooth best estimate trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey.	PosPac MMS v8.20
Create an exterior orientation file (EO) for each photo image with omega, phi, and kappa.	PosPac MMS v8.20
Convert Level 00 raw imagery data into geometrically corrected Level 02 image files.	UltraMap 4
Apply radiometric adjustments to Level 02 image files to create Level 03 Pan-sharpened TIFFs.	UltraMap 4
Apply EO and camera calibration parameters to photos; perform aerial triangulation using automatically generated tie points and ground control processed on project datum.	Inpho Match AT v10.0
Import LiDAR derived DEM and generate individual ortho frames.	Inpho OrthoMaster v10.0
Mosaic orthorectified imagery, blending seams between individual photos and correcting for radiometric differences between them.	OrthoVista/SeamEditor v. 10.0

Results & Discussion



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 10 points/m^2 (0.93 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 Sears Point project was 1.50 points/ft^2 (16.18 points/m^2) while the average ground classified density was 0.46 points/ft^2 (4.90 points/m^2) (Table 11). 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 11: Average lidar point densities

Classification	Point Density
First-Return	1.50 points/ft^2 16.18 points/m^2
Ground Classified	0.46 points/ft^2 4.90 points/m^2

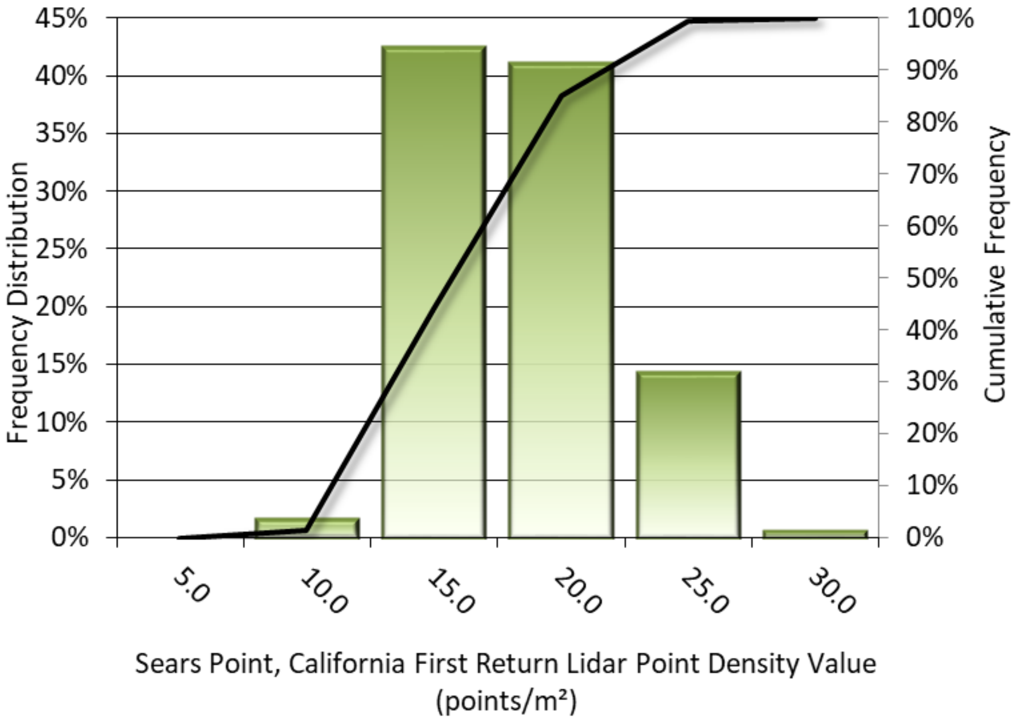


Figure 3: Frequency distribution of first return lidar point density values per 100 x 100 m cell

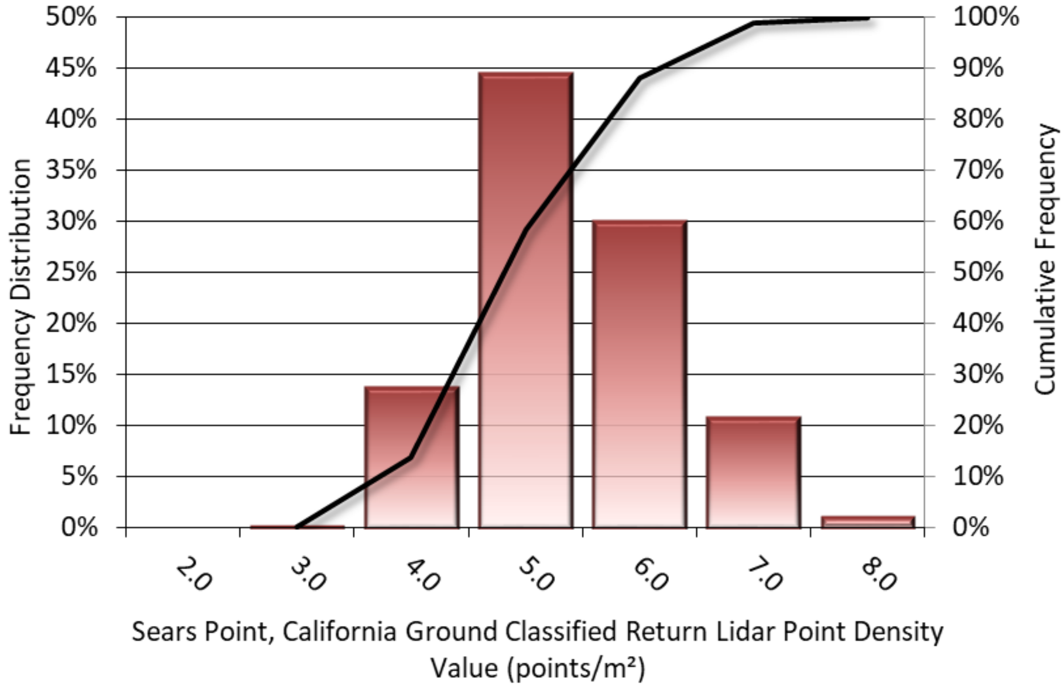


Figure 4: Frequency distribution of ground-classified return lidar point density values per 100 x 100 m cell

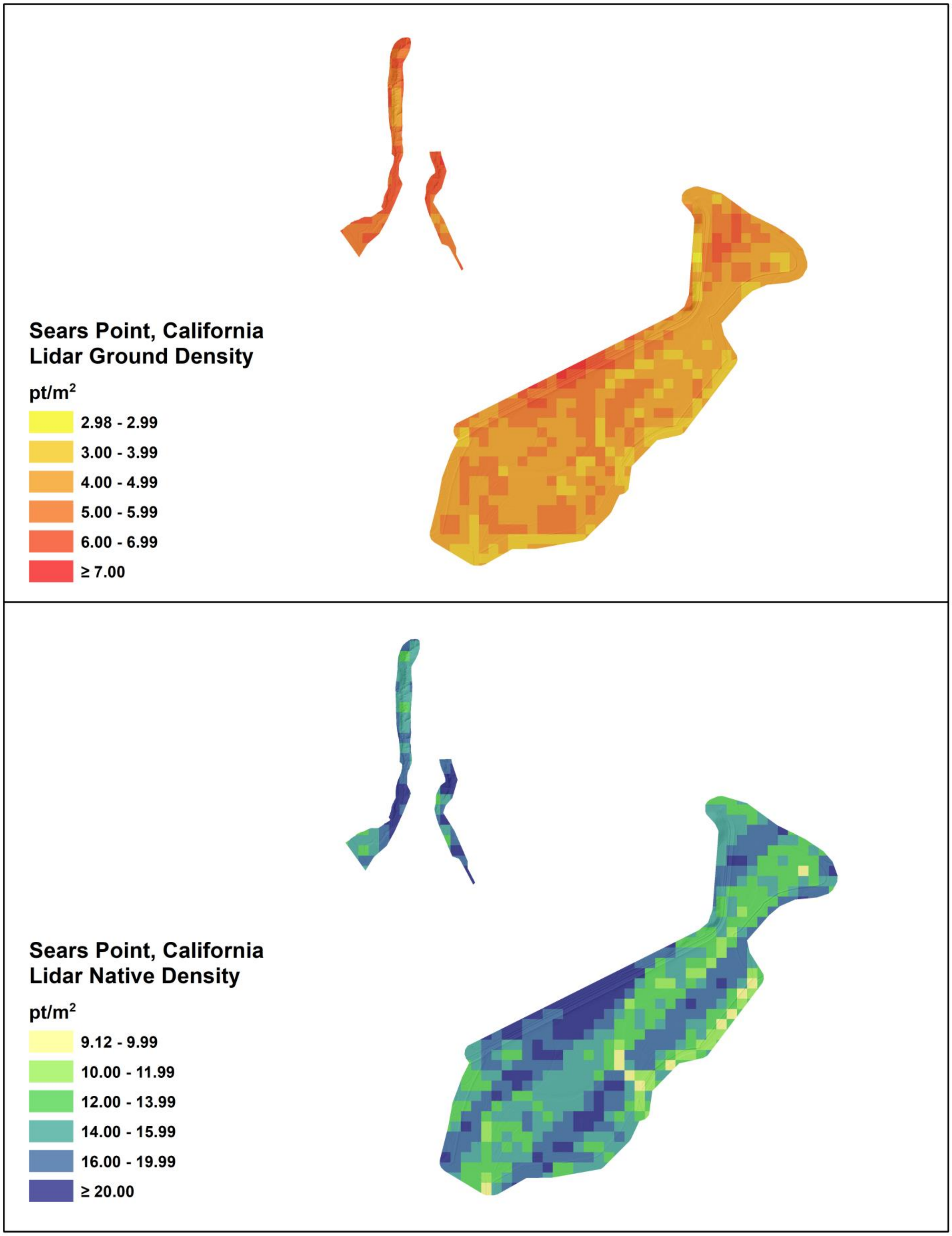


Figure 5: First return and ground-classified lidar point density map for the Sears Point, CA site (100 m x 100 m cells)

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 12.

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 Sears Point survey, 21 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0. 188 feet (0.057 meters) as compared to unclassified LAS, and 0.119 feet (0.036 meters) as compared to the bare earth DEM, with 95% confidence (Figure 6, Figure 7).

QSI also assessed absolute accuracy using 141 ground control points. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset, and therefore have been provided in Table 12 and Figure 8.

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[1] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 12: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to unclassified LAS	NVA, as compared to bare earth DEM	Ground Control Points
Sample	21 points	21 points	141 points
95% Confidence (1.96*RMSE)	0.188 ft 0.057 m	0.119 ft 0.036 m	0.143 ft 0.044 m
Average	0.069 ft 0.021 m	-0.003 ft -0.001 m	-0.013 ft -0.004 m
Median	0.056 ft 0.017 m	0.003 ft 0.001 m	-0.016 ft -0.005 m
RMSE	0.096 ft 0.029 m	0.061 ft 0.018 m	0.073 ft 0.022 m
Standard Deviation (1σ)	0.069 ft 0.021 m	0.062 ft 0.019 m	0.072 ft 0.022 m

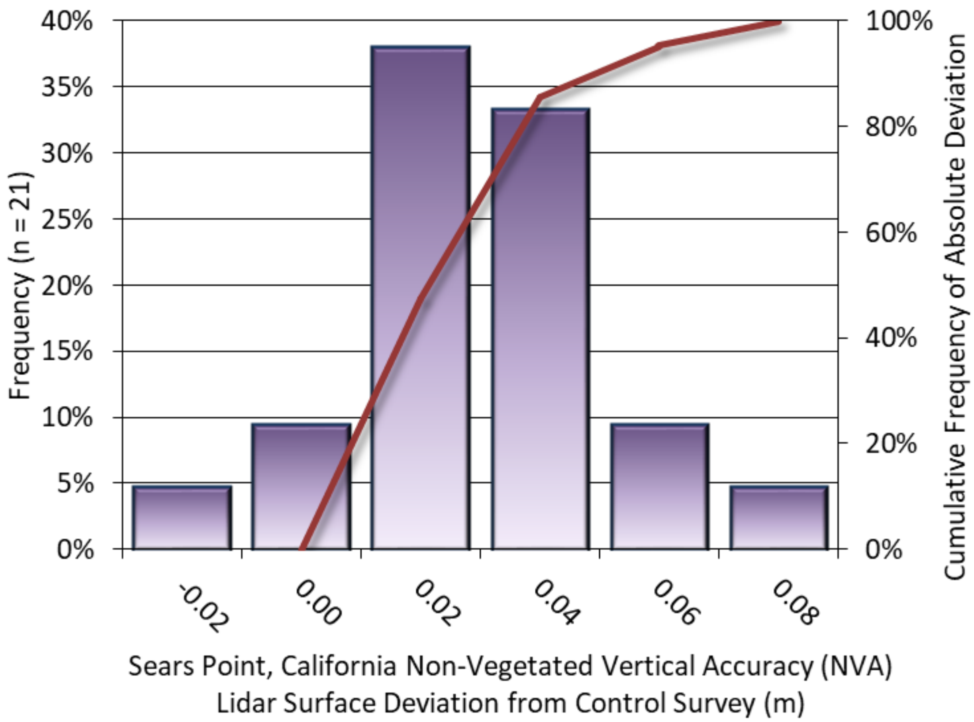

Figure 6: Frequency histogram for lidar unclassified LAS deviation from ground check point values (NVA)

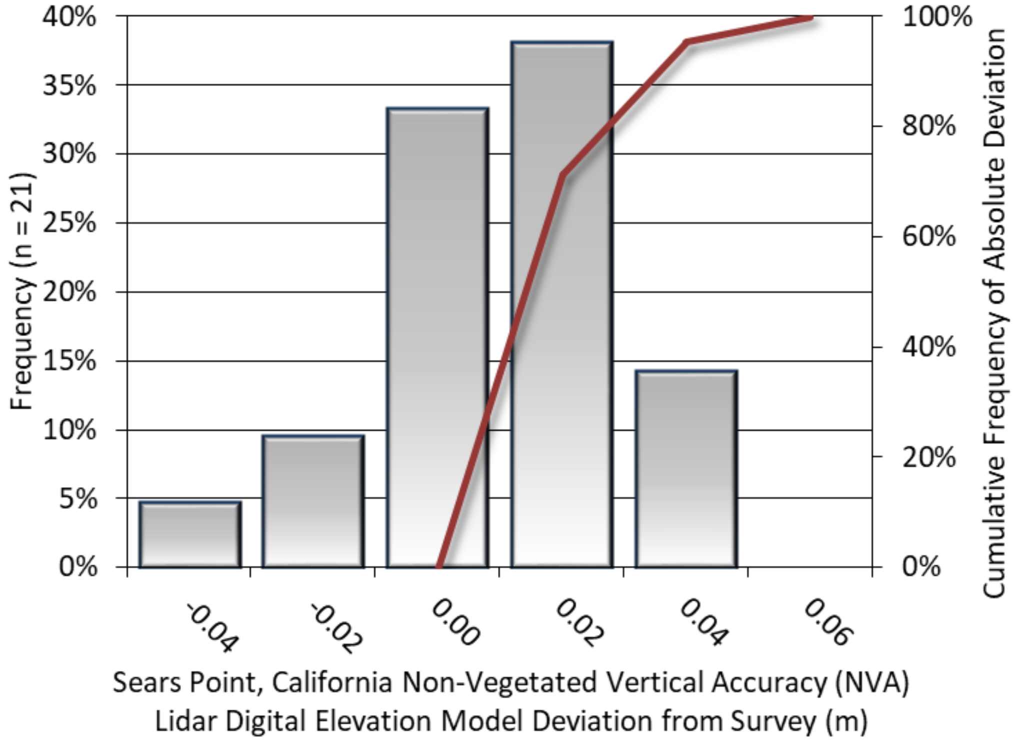

Figure 7: Frequency histogram for lidar bare earth DEM surface deviation from ground check point values (NVA)

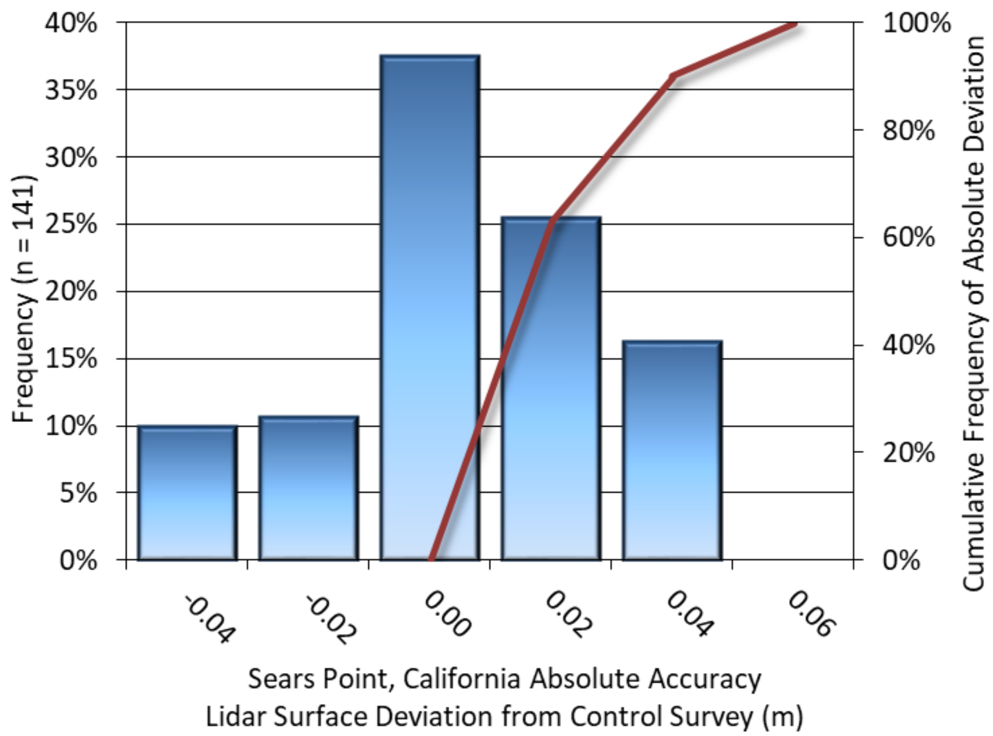

Figure 8: Frequency histogram for lidar surface deviation from ground control point values

Lidar 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 Sears Point Lidar project was 0.085 feet (0.026 meters) (Table 13, Figure 9).

Table 13: Relative accuracy results

Relative Accuracy	
Sample	8 flight line surfaces
Average	0.085 ft 0.026 m
Median	0.084 ft 0.026 m
RMSE	0.086 ft 0.026 m
Standard Deviation (1σ)	0.005 ft 0.001 m
1.96σ	0.010 ft 0.003 m

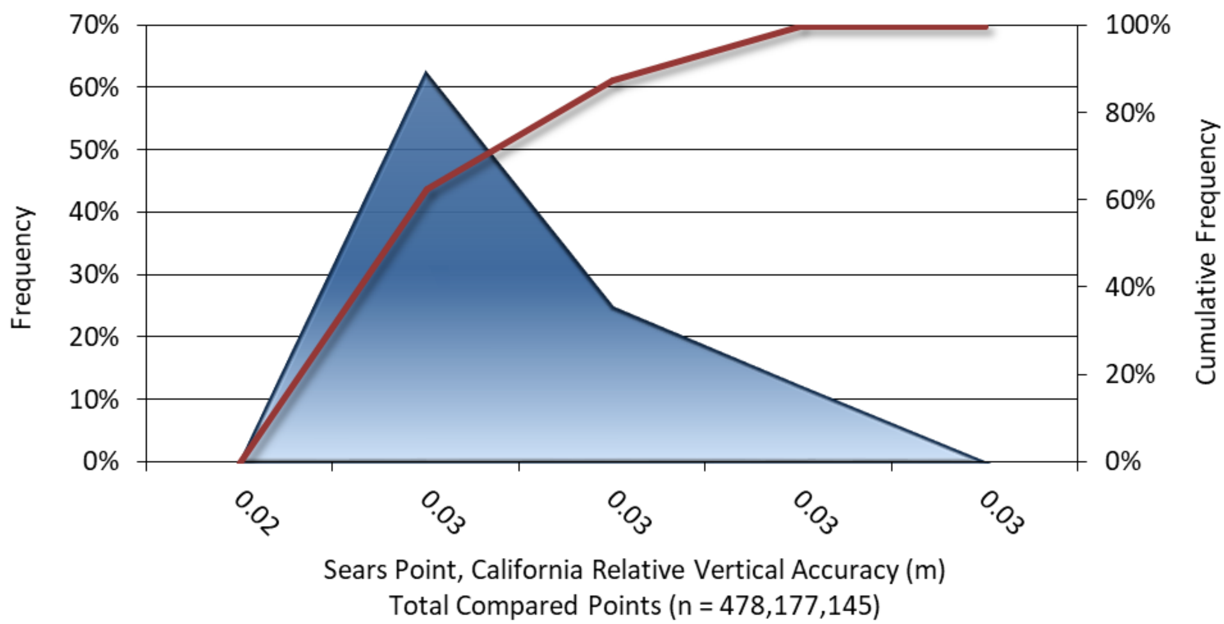

Figure 9: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Based on a flying altitude of 1,621 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was compiled to meet 0.984 feet (0.300 m) horizontal accuracy at the 95% confidence level.

Table 14: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.34 ft 0.10 m
ACC_r	0.58 ft 0.18 m

Analytical Aerial Triangulation Report

Overview

Aerial triangulation was performed in one Block to support photogrammetric mapping of the Sears Point study area. The Block consisted of one flight line with 8 images flown at a scale of approximately 1:1,200 on June 8th, 2020. Adjustments were made to ground control established by QSI referencing California State Plane Zone II, NAD83(2011) horizontal datum and NAVD 1988 vertical datum (Geoid12b). Digital imagery along with ground control and camera calibration data were used as input to Inpho's Match AT softcopy photogrammetry program. The digital camera utilized was an UltraCam Eagle M3. Of the 10 total surveyed air target points, 6 were used for aerial triangulation and 4 were withheld from the block adjustment as check points for accuracy assessment.

Control Points

Air target points used in the aerial triangulation adjustment are listed with their location and residuals in Table 15. Control point RMSE values can be found in Table 16.

Table 15: Location and residual of air target points used as control for aerial triangulation adjustment

Control Point Coordinates (us ft) – 6 Total Points				Control Point Residuals (us ft) - 6 Total Points		
Point ID	X	Y	Z	X	Y	Z
AT001b	6424684.558	1810933.483	3.304	-0.297	-0.089	0.546
AT002a	6431643.65	1816545.298	74.685	0.012	0.137	0.584
AT002b	6431644.762	1816545.263	74.721	0.221	0.141	0.345
AT002c	6431643.363	1816525.921	75.879	0.079	0.079	0.029
AT003a	6428004.837	1810133.715	2.421	-0.146	-0.118	0.477
AT003b	6427982.54	1810141.235	2.152	0.023	-0.272	0.125

Table 16: RMSE for air target points used as control for aerial triangulation adjustment

Control Point RMSE - 6 Total Points		
US survey feet		
X	Y	Z
0.166	0.153	0.409

Check Points

Air target check points withheld from the aerial triangulation adjustment are listed with their location and residuals in Table 17. Check point RMSE values can be found in Table 18.

Table 17: Location of air target check points withheld from aerial triangulation adjustment

Check Point Coordinates (us ft) - 4 Total Points				Check Point Residuals (us ft) -4 Total Points		
Point ID	X	Y	Z	X	Y	Z
AT001a	6424685.091	1810932.677	3.255	-0.674	-0.016	0.332
AT001c	6424699.038	1810944.151	2.930	-0.441	-0.224	0.425
AT002d	6431644.23	1816526.798	75.827	0.073	-0.134	0.297
AT003c	6427988.803	1810162.686	2.129	0.007	0.010	0.271

Table 18: RMSE for air target points withheld from aerial triangulation adjustment

Check Point RMSE - 4 Total Points		
US survey feet		
X	Y	Z
0.404	0.131	0.336

CERTIFICATIONS

Quantum Spatial, Inc. provided lidar services for the Sears Point project as described in this report.

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

Aug 7, 2020

Tucker Selko
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 June 5-7, 2020.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

Aug 7, 2020

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

Signed: Aug 7, 2020

Glossary

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

<u>1.96 * RMSE Absolute Deviation</u>: 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.

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

> **<u>Absolute Accuracy</u>:** 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.
>
> **<u>Relative Accuracy</u>:** 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).
>
> **<u>Root Mean Square Error (RMSE)</u>:** 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.

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

<u>Digital Elevation Model (DEM)</u>: 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.

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

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

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

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

<u>Pulse Returns</u>: 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.

<u>Real-Time Kinematic (RTK) Survey</u>: 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.

<u>Post-Processed Kinematic (PPK) Survey</u>: 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.

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

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

Appendix A - Accuracy Controls

Relative Accuracy Calibration Methodology:

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

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

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

Lidar accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

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

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±29.25^{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.

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.