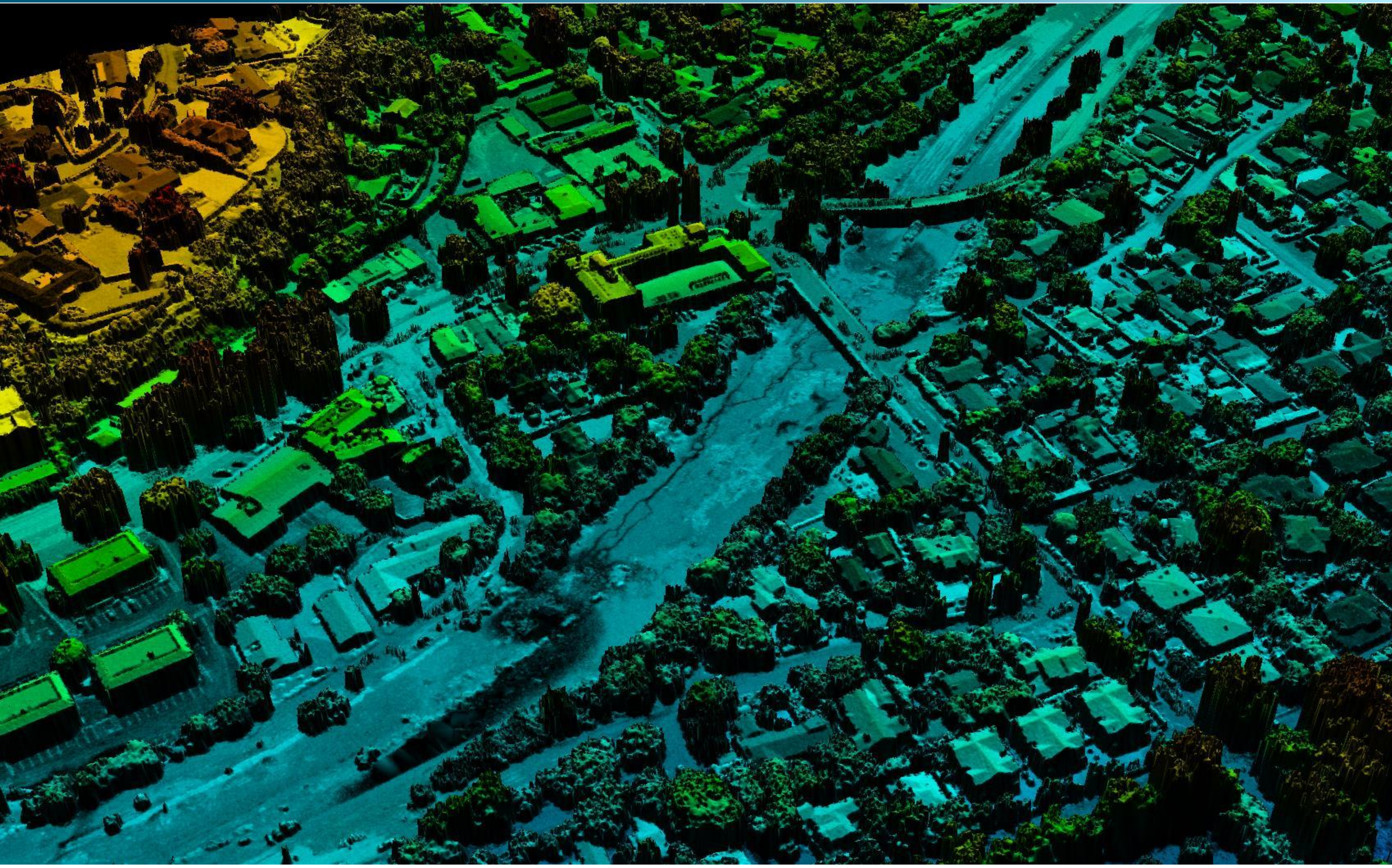
April 27, 2018



Santa Barbara County Mudslide, California LiDAR Technical Data Report

Prepared For:

USGS
science for a changing world

Dan Vincent
1400 Independence Road, MS 664
Rolla, MO 65401
PH: 573-308-3689

Prepared By:

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

TABLE OF CONTENTS

INTRODUCTION 1
Deliverable Products 2
ACQUISITION 4
Planning 4
Airborne LiDAR Survey 5
Ground Control 6
Ground Survey Points (GSPs) 6
Quality Assurance Points 7
PROCESSING 10
LiDAR Data 10
Hydroflattening and Water's Edge Breaklines 12
RESULTS & DISCUSSION 13
LiDAR Density 13
LiDAR Accuracy Assessments 16
LiDAR Non-Vegetated Vertical Accuracy 16
LiDAR Vegetated Vertical Accuracies 19
LiDAR Relative Vertical Accuracy 20
CERTIFICATIONS 21
SELECTED IMAGES 22
GLOSSARY 24
APPENDIX A - ACCURACY CONTROLS 25

Cover Photo: This image shows a view of mudslide debris on US Highway 101 along the Pacific Ocean, created from the LiDAR highest hit model colored using elevation and intensity values.

Introduction

These comparison images show a view of the change along Randall Road in Montecito, California. The left image shows pre-slide imagery from Google Earth, while the right image shows the post-slide LiDAR highest hit hillshade.

On January 9th, 2018, heavy rains scoured the destabilized, post-wildfire hillsides above the community of Montecito, California, causing large debris and devastating mudslides to rush through the densely populated community, resulting in extensive loss of life and property. In order to assist with emergency response efforts and post-landslide analysis, Quantum Spatial (QSI) utilized assets and crews in the area to rapidly collect Light Detection and Ranging (LiDAR) data on January 11th, 2018, for the Santa Barbara County Mudslide site in California. Data were collected as quickly as possible to aid data users in mapping the topographic and geophysical properties of the study area to support emergency response efforts, as well as future analysis of post-slide assessment.

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

Table 1: Acquisition dates, acreage, and data types collected over the Santa Barbara County Mudslide site

Project Site	Total Acres	Acquisition Dates	Data Type
Santa Barbara County Mudslide, California	48,766	01/11/2018	High Resolution QL1 LiDAR

Deliverable Products

Table 2: Products created for the Santa Barbara County Mudslide site

<table>
<tr><th colspan="2">Santa Barbara County Mudslide, California LiDAR Products
Projection: UTM Zone 11 North
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12B)
Units: Meters</th></tr>
<tr><td>Points</td><td>LAS v 1.4
• All Classified Returns
• Ground Classified Returns</td></tr>
<tr><td>Rasters</td><td>1 Meter ESRI Grids, Tiled & Mosaicked
• Hydroflattened Bare Earth Digital Elevation Model (DEM)
• Highest Hit Digital Surface Model (DSM)
0.5 Meter GeoTiffs, Tiled & Mosaicked
• Intensity Images</td></tr>
<tr><td>Vectors</td><td>Index Shapefiles (*.shp)
• Site Boundary
• LiDAR Tile Index
• 3D Water’s Edge and Bridge Breaklines
Ground Survey Shapefiles (*.shp)
• Non-Vegetated & Vegetated Ground Check Points
• Ground Control Points
• CASN CORS Location</td></tr>
</table>

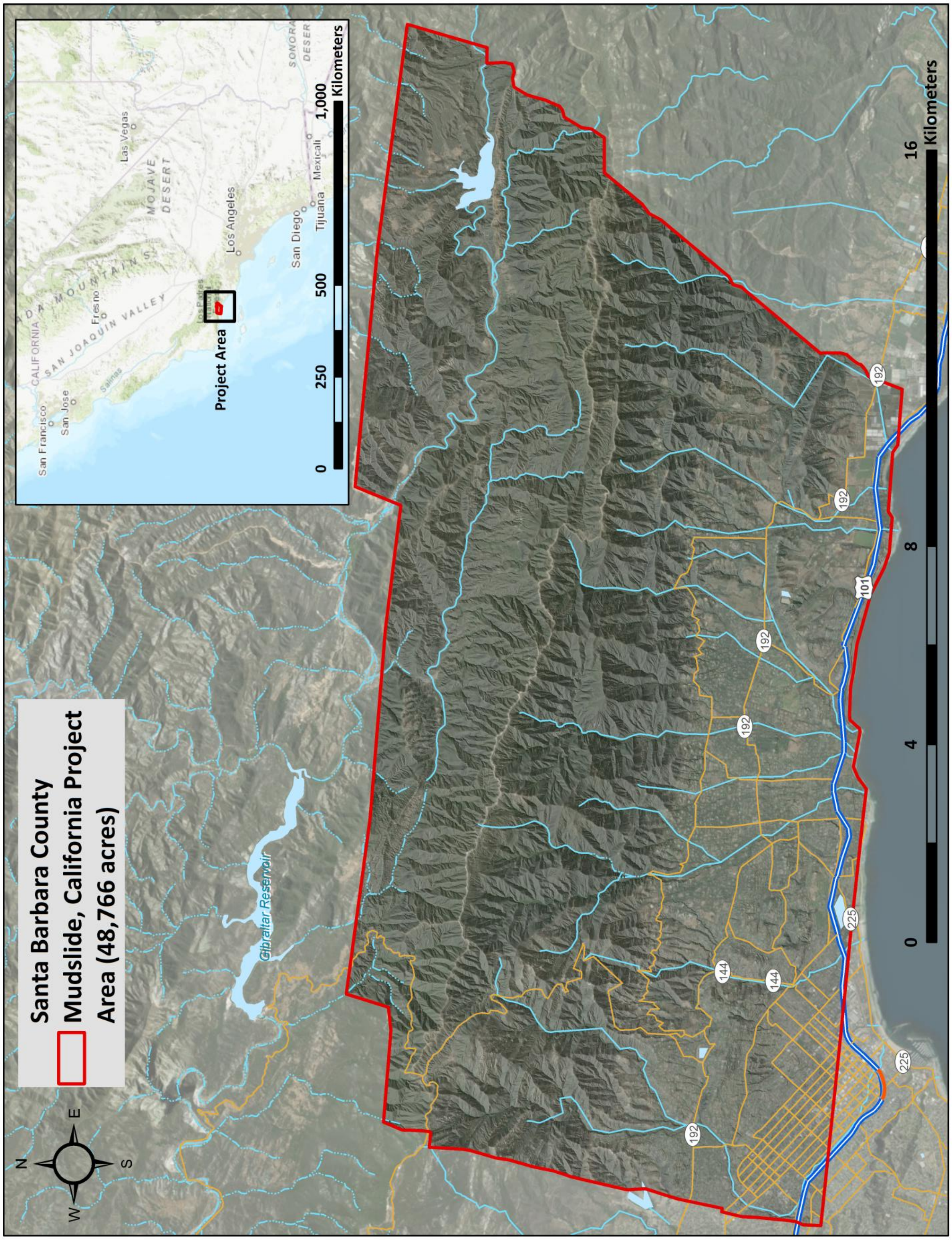


Figure 1: Location map of the Santa Barbara County Mudslide site in California

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI acquisition teams mobilized and worked to immediately review the project area and develop a specialized flight plan to ensure complete coverage of the Santa Barbara County Mudslide LiDAR study area at the target point density of ≥8.0 points/m^2. Due to the emergency needs within the project area, QSI crews initiated, planned, and executed all flights on January 11th, 2018. All flightlines were flown twice in order to ensure the LiDAR acquisition met the required standards to produce a highly accurate dataset which could be used to assist in emergency response and planning efforts. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

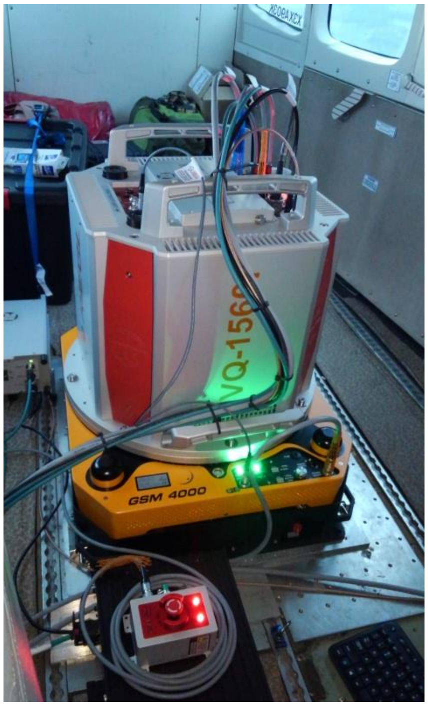
Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flights were continuously monitored due to their potential impact on the daily success of airborne and ground operations. Due to the need for rescue flights in the area at the time of LiDAR acquisition, QSI conducted all flights at an above ground level of 2100 meters, in accordance with FAA airspace restrictions. In addition, logistical considerations affecting ground survey access, including property access and any necessary coordination with emergency personnel were carefully reviewed.

Airborne LiDAR Survey

The LiDAR survey was accomplished using a Riegl VQ-1560i sensor system mounted in a Cessna Caravan 208. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Santa Barbara County Mudslide project area. The Riegl VQ-1560i laser system can record unlimited range measurements (returns) per pulse. It is not uncommon for some types of surfaces (e.g., dense vegetation or water) to return fewer pulses to the LiDAR sensor than the laser originally emitted. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	January 11th, 2018
Aircraft Used	Cessna Caravan 208
Sensor	Riegl
Laser	VQ-1560i
Maximum Returns	Unlimited
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2100 m
Survey speed	100 knots
Field of View	58.5°
Mirror Scan Rate	154 LPS (lines per second)
Target Pulse Rate	500 kHz per channel
Pulse Length	3 ns
Laser Pulse Footprint Diameter	30-35 cm
Central Wavelength	1064 nm
Pulse Mode	MTA (Multiple-Time-Around)
Beam Divergence	0.18 – 0.25 mrad
Swath Width	600 m
Swath Overlap	60 %
Intensity	16-bit
Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
	NVA (95% Confidence Level) ≤ 19.6 cm



Riegl VQ-1560i LiDAR sensor

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

Ground Control

Ground control surveys were conducted to support the airborne acquisition. PP-RTX technology was used to geospatially correct the aircraft positional coordinate data, while ground survey points were collected to perform final positional corrections to the LiDAR point cloud, and to perform quality assurance checks on final LiDAR data.

One Leica SmartNet Real-Time Network (RTN) base station was utilized for the collection of ground survey points using real time kinematic (RTK) survey techniques. QSI's professional land surveyor, Evon Silvia (CAPLS#9401) oversaw and certified the ground survey work.

Table 4: CORS utilized for ground survey point collection for the Santa Barbara County Mudslide acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

CORS ID	Latitude	Longitude	Ellipsoid (meters)
CASN	34° 24' 56.46406"	-119° 50' 42.98101"	4.138

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) survey techniques. The Leica GRX1200 GNSS station broadcasted kinematic corrections to a roving Trimble R8 receiver. 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 monument locations and may not be equitably distributed throughout the study area (Figure 2).

Table 5: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
LEICA GRX1200GGPRO	External Geodetic Antenna L1/L2	LEIAS10	Leica SmartNet
Trimble R6	Integrated GNSS Antenna R6	TRM_R6	Rover
Trimble R8	Integrated Antenna R8	TRMR8_GNSS	Rover

Quality Assurance Points

In addition to ground survey points, QSI returned to the project area in April 2018 to collect non-vegetated and vegetated quality assurance points across land cover classes to be used in accuracy assessment. Land cover class quality assurance points were collected throughout the study area as feasible, although some ground access constraints such as locked gates in the area may have prevented an even distribution within the project site (Figure 2). In total, 22 non-vegetated and 8 vegetated quality assurance points were collected to meet USGS requirements for NVA and VVA assessment. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the LiDAR derived ground models across land cover classes (Table 6, see LiDAR Accuracy Assessments, page 16).

Table 6: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Tall Grass/Weeds	TALL_GRASS		Herbaceous grasslands in advanced stages of growth	VVA
Shrubland	SHRUB		Areas dominated by shrubs	VVA
Forest	FOREST		Forested areas dominated by deciduous species	VVA

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Bare Earth	BARE		Areas of bare earth surface	NVA
Urban	URBAN		Areas of urban development	NVA

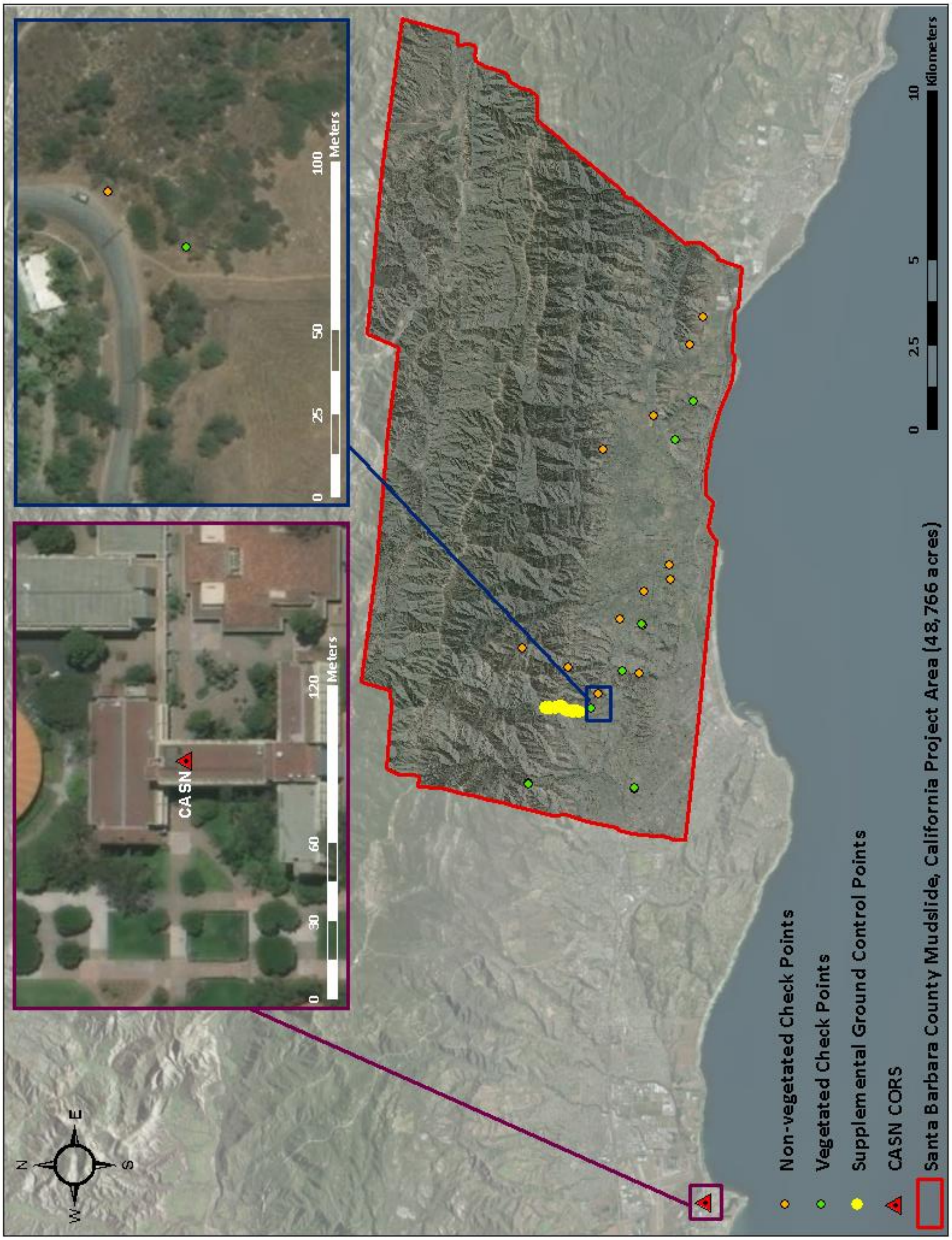
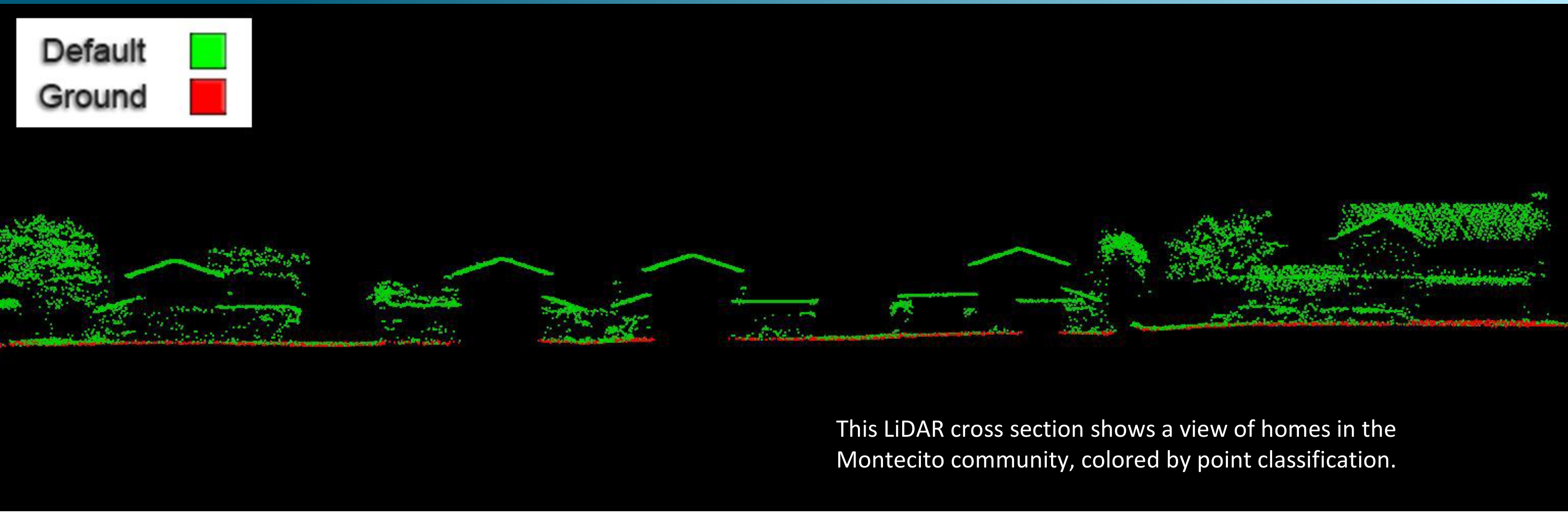


Figure 2: Ground survey location map



This LiDAR cross section shows a view of homes in the Montecito community, colored by point classification.

LiDAR Data

Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

Table 7: ASPRS LAS classification standards applied to the Santa Barbara County Mudslide 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
1OW	Default/Unclassified - Overlap	Laser returns that are deemed not necessary to form a complete single, non-overlapped, gap-free coverage with respect to adjacent swaths
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7W	Noise - Withheld	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
10	Ignored Ground	Ground points proximate to water’s edge breaklines; ignored for correct model creation
17	Bridge	Bridge decks

Table 8: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position using aircraft GNSS and IMU data and Trimble CenterPoint PP-RTX methodologies. 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.8.0 MoveOUT v.1.3 (QSI proprietary)
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 v.1.8.4 TerraMatch v.17
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.17
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.17
Classify resulting data to ground and other client designated ASPRS classifications (Table 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.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 meter pixel resolution.	TerraScan v.17 TerraModeler v.17 ArcMap v. 10.2.2
Export intensity images as GeoTIFFs at a 0.5 meter pixel resolution.	Las Monkey 2.2.2 (QSI proprietary) LAS Product Creator 1.5 (QSI proprietary) ArcMap v. 10.2.2

Hydroflattening and Water's Edge Breaklines

The Pacific Ocean along the Santa Barbara County Mudslide project boundary, and other water bodies with a surface area greater than 2 acres within the project area were flattened to a consistent water level. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary.

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 Pacific Ocean and lakes within the project site were assigned a consistent elevation for an entire polygon. Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 3).

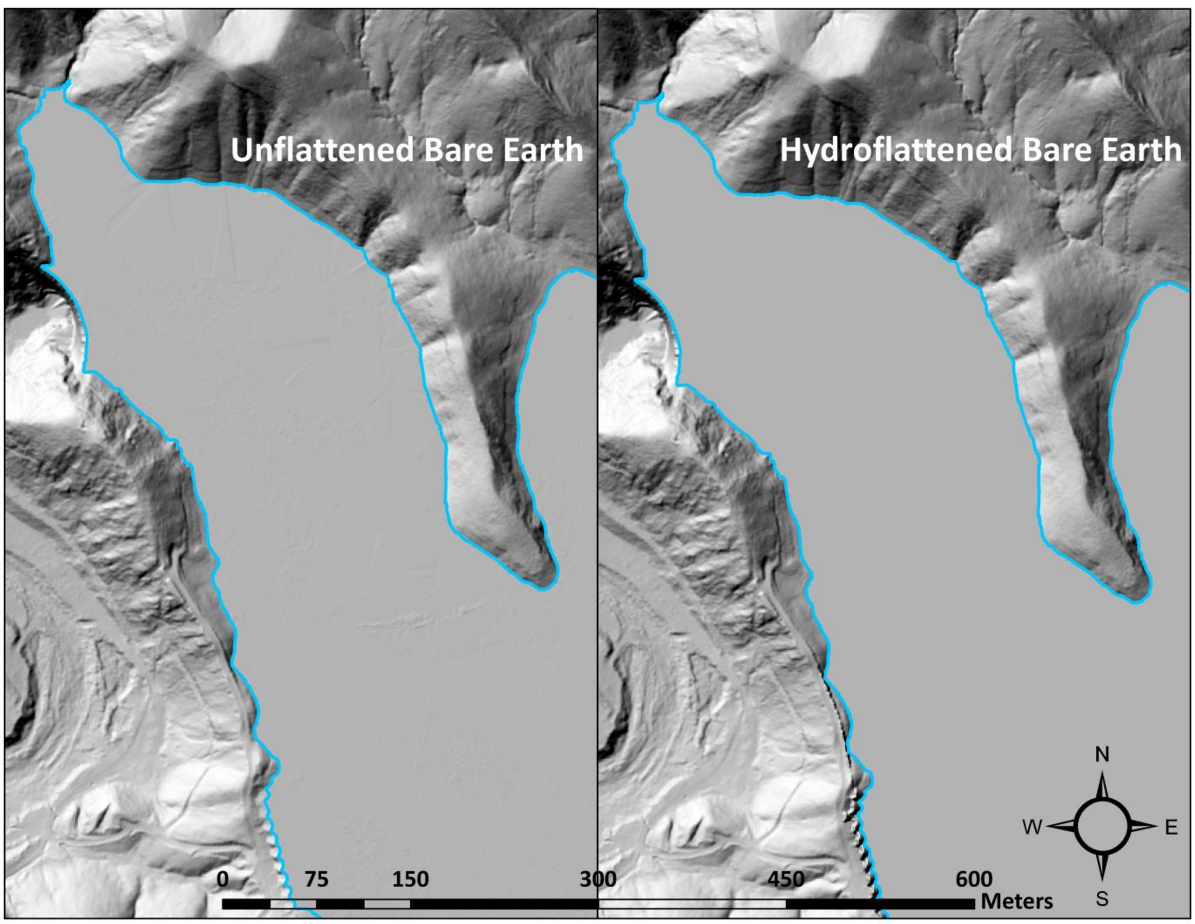
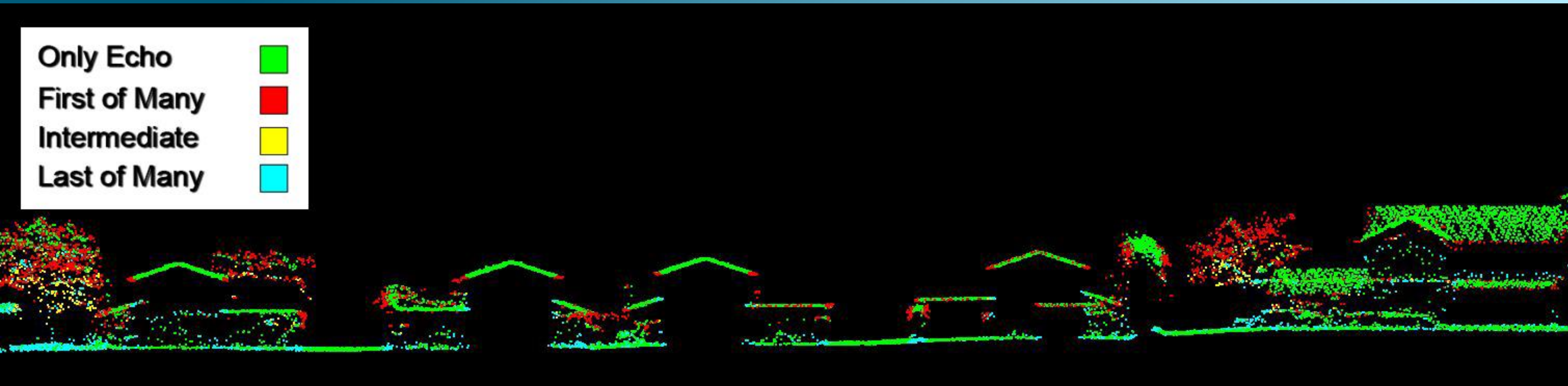


Figure 3: Example of hydroflattening in the Santa Barbara County Mudslide LiDAR dataset



This same LIDAR cross section shows a view of homes in the Montecito community, colored by laser point echo.

LiDAR Density

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

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

The average first-return density of LiDAR data for the Santa Barbara County Mudslide project was 23.80 points/m^2 while the average ground classified density was 5.64 points/m^2 (Table 9). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 4 through Figure 6.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	23.80 points/m^2
Ground Classified	5.64 points/m^2

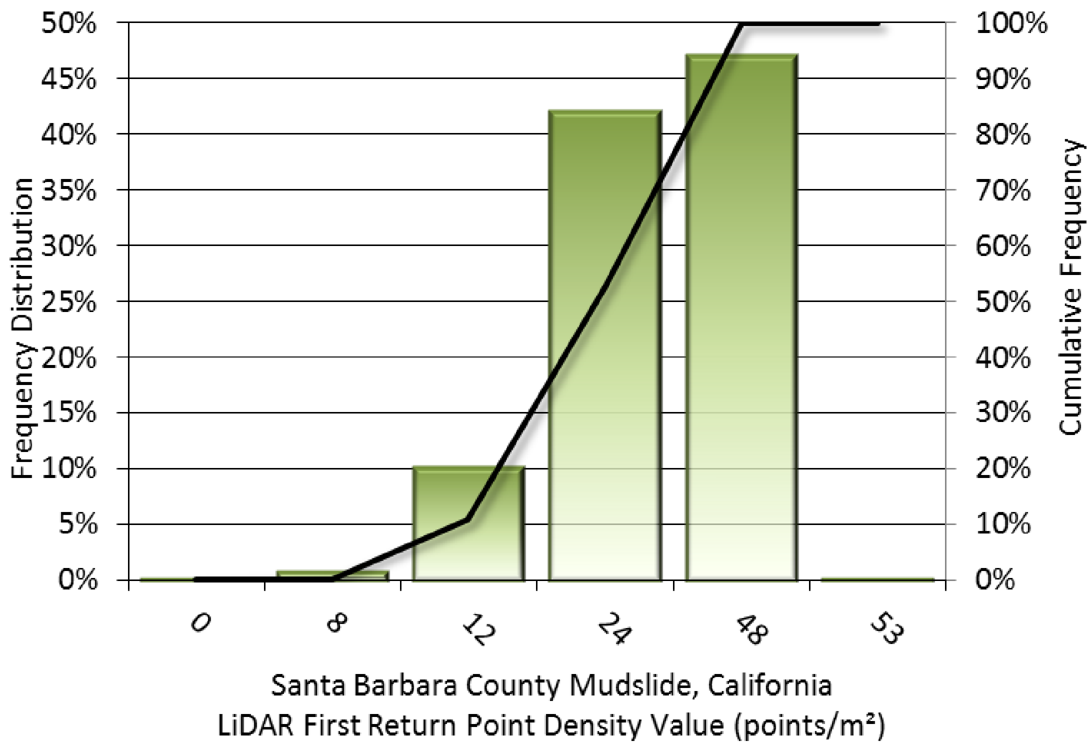


Figure 4: Frequency distribution of first return point density values per 100 x 100 m cell

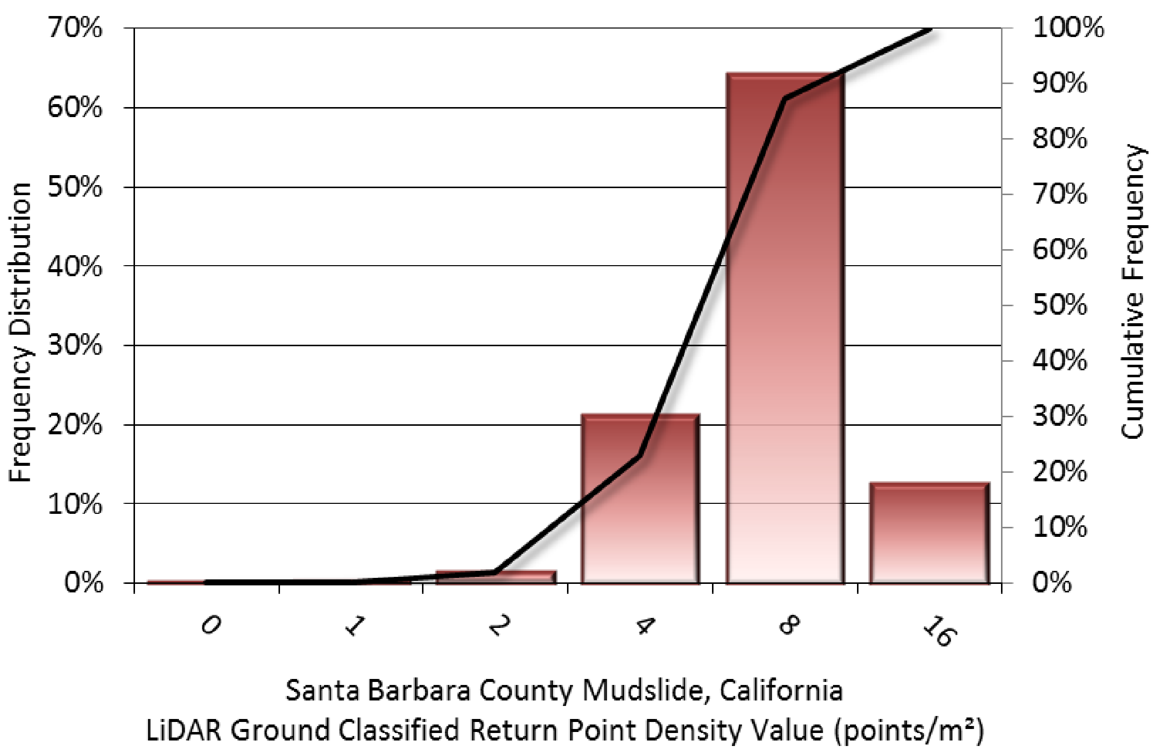


Figure 5: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

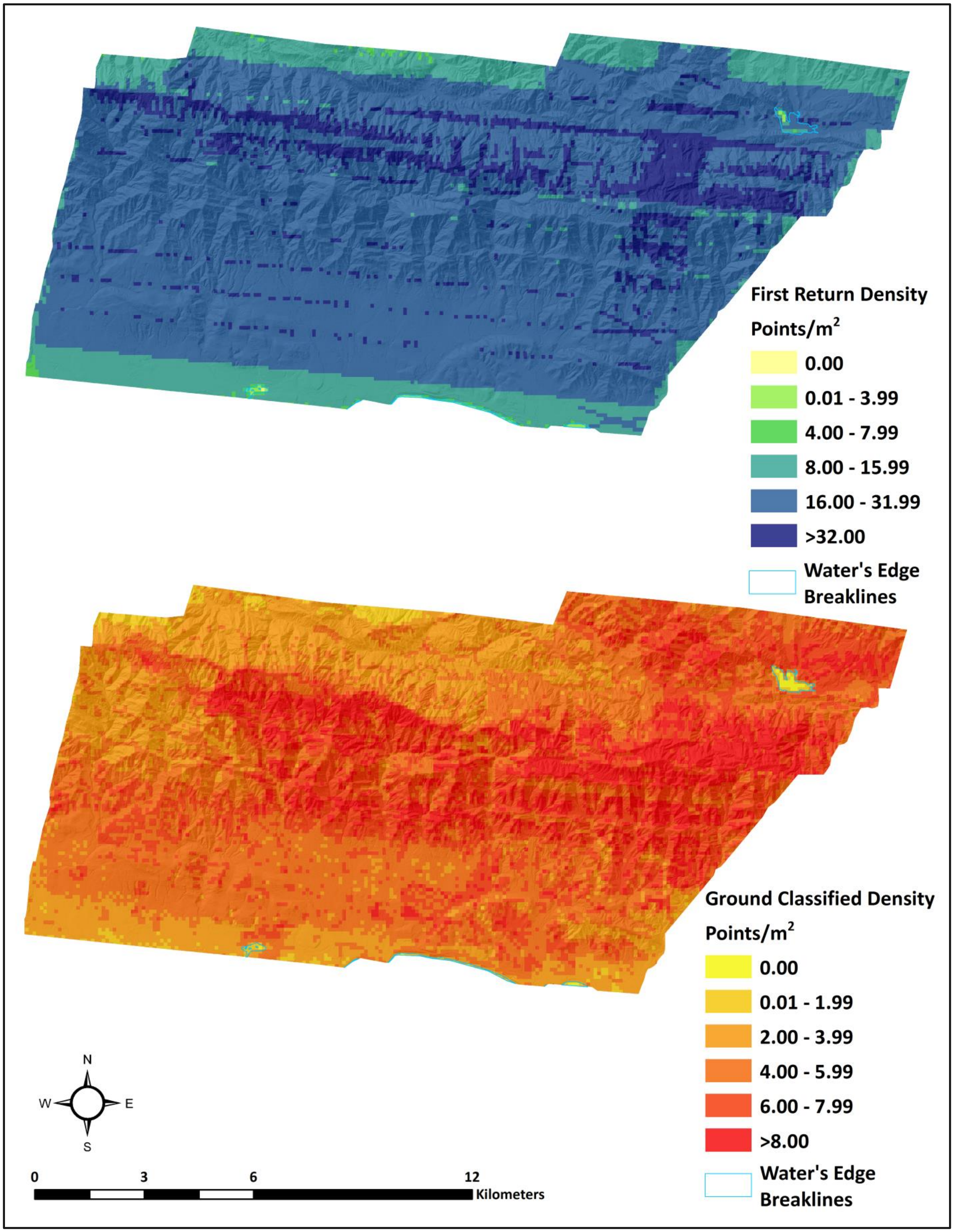


Figure 6: First return and ground classified density map for the Santa Barbara County Mudslide site (100 m x 100 m cells)

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 quality assurance point (QAP) 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 10.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. These statistics assume the error for x, y and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Santa Barbara County Mudslide survey, 22 quality assurance points tested 0.087 meters vertical accuracy at 95% confidence level as compared to the bare earth DEM (Figure 7). As compared to the unclassified point cloud, 22 quality assurance points tested 0.051 meters vertical accuracy at 95% confidence level (Figure 8).

QSI also assessed absolute accuracy using 190 supplemental ground control points. Although these points were used in the calibration and post-processing of the LiDAR point cloud, they still provide a good indication of the overall accuracy of the LiDAR dataset, and therefore have been provided in Table 10 and Figure 9.

Table 10: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA as compared to Bare Earth DEM	NVA as compared to Unclassified LAS	Supplemental Ground Control Points
Sample	22 points	22 points	190 points
95% Confidence (1.96*RMSE)	0.087 m	0.051 m	0.053 m
Average	0.012 m	0.015 m	0.001 m
Median	0.007 m	0.013 m	-0.001 m
RMSE	0.045 m	0.026 m	0.027 m
Standard Deviation (1σ)	0.044 m	0.022 m	0.027 m

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

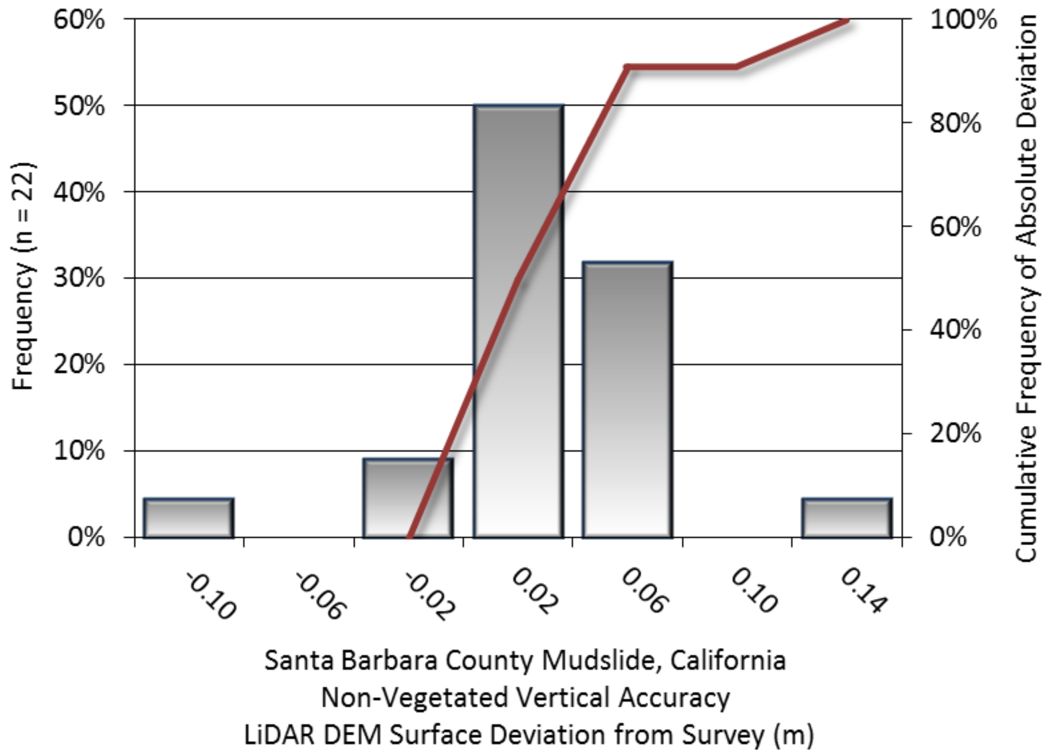


Figure 7: Frequency histogram for LiDAR surface deviation from quality assurance point values (NVA)

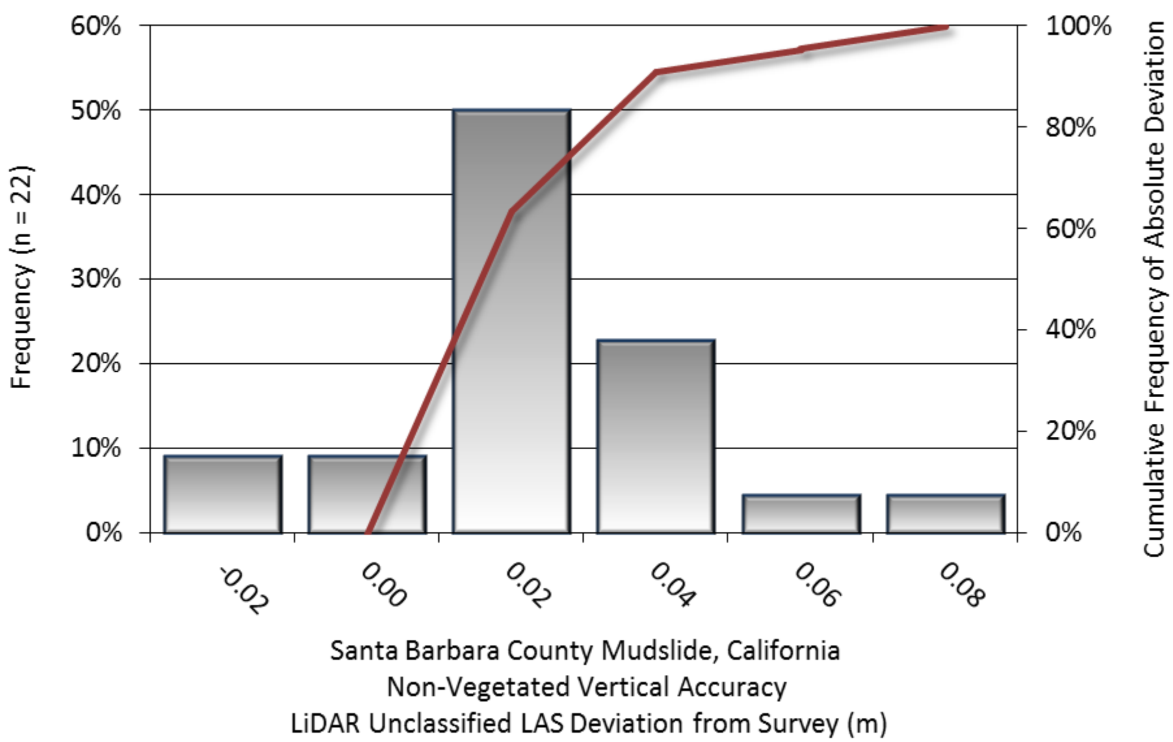


Figure 8: Frequency histogram for LiDAR unclassified LAS deviation from quality assurance point values (NVA)

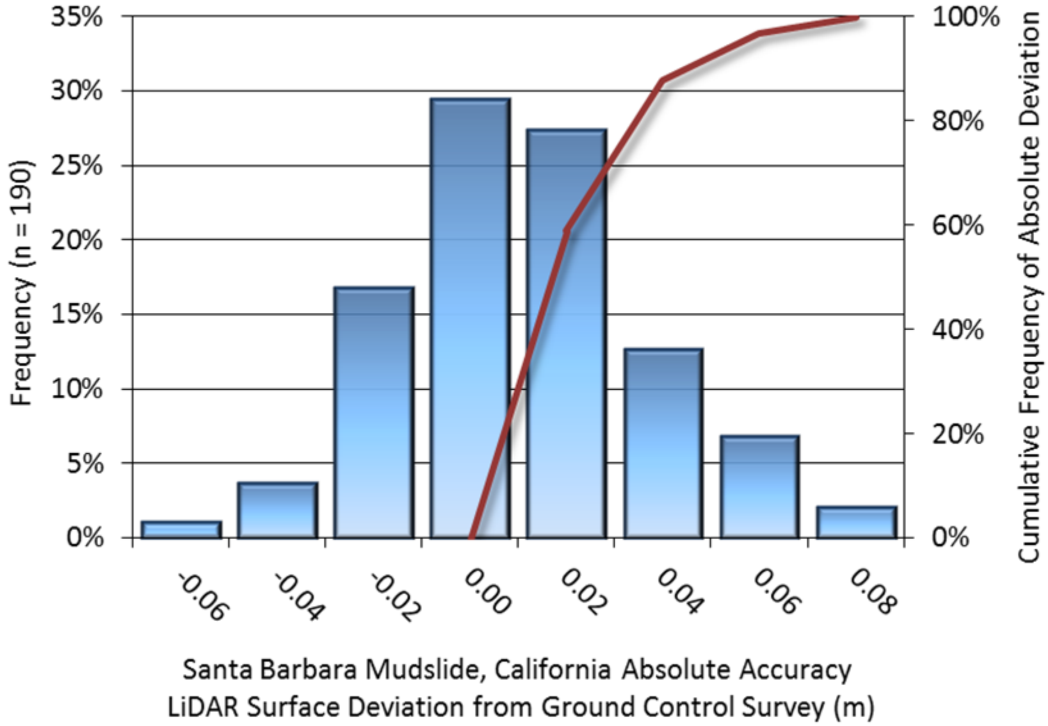


Figure 9: Frequency histogram for LiDAR surface deviation from ground control point values

LiDAR Vegetated Vertical Accuracies

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known quality assurance point data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified LiDAR points. Evaluation of 8 vegetated check points resulted in a vegetated vertical accuracy of 0.145 meters, evaluated at the 95th percentile (Table 11, Figure 9).

Table 11: Vegetated Vertical Accuracy for the Santa Barbara County Mudslide Project

Vegetated Vertical Accuracy (VVA)	
Sample	8 points
Average Dz	0.033 m
Median	0.050 m
RMSE	0.091 m
Standard Deviation (1σ)	0.178 m
95th Percentile	0.145 m

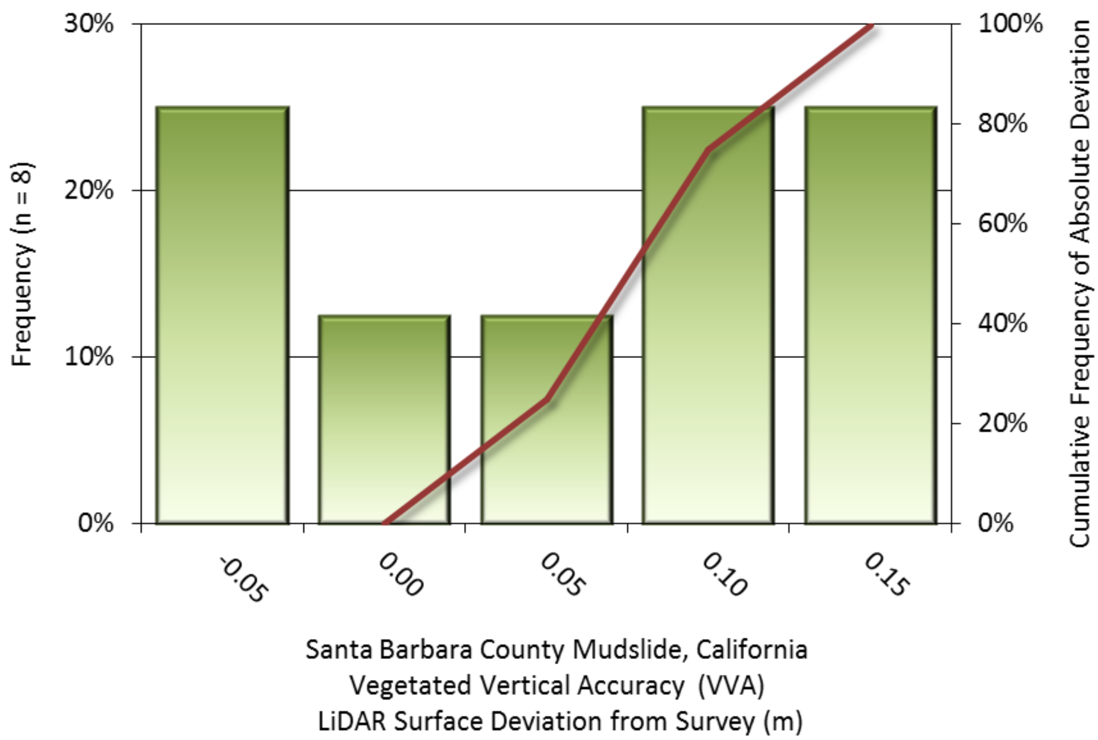


Figure 10: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

LiDAR Relative Vertical Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The root mean square error (RMSE) of line to line relative vertical accuracy for the Santa Barbara County Mudslide LiDAR project was 0.045 meters (Table 12, Figure 11).

Table 12: Relative accuracy results

Relative Accuracy	
Sample	24 surfaces
Average	0.045 m
Median	0.047 m
RMSE	0.045 m
Standard Deviation (1σ)	0.010 m
1.96σ	0.019 m

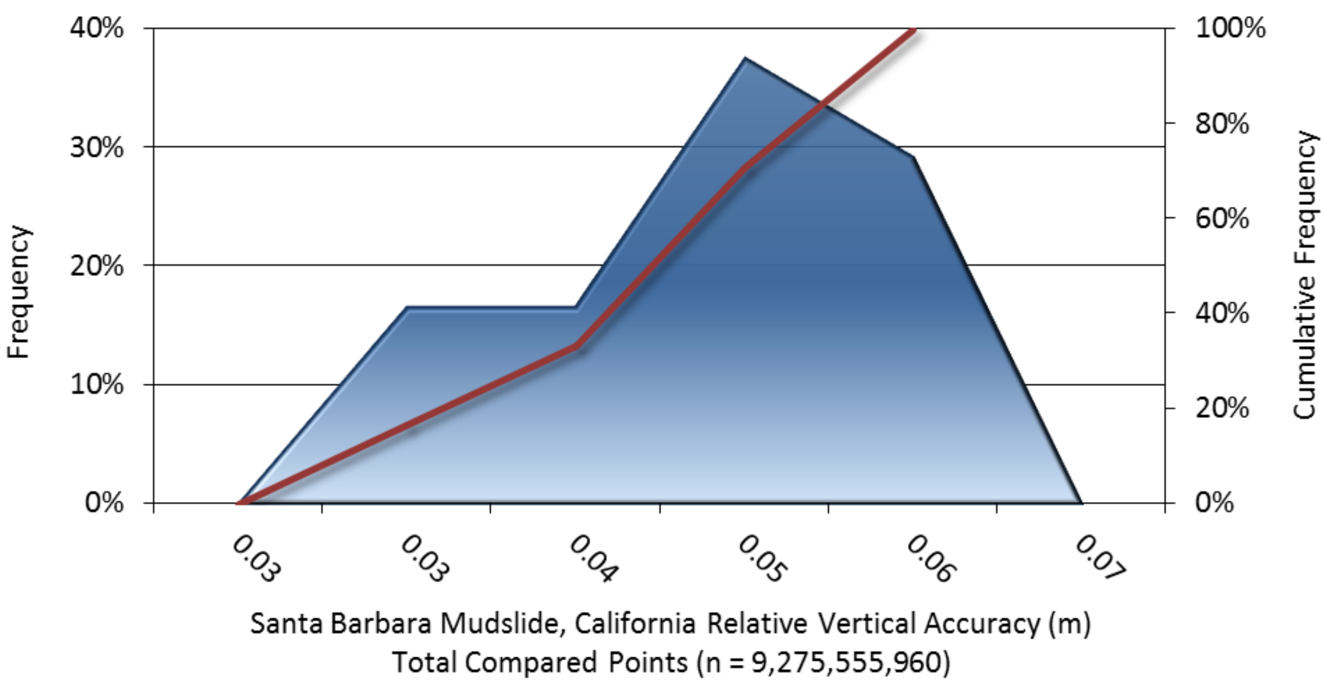


Figure 11: Frequency plot for relative vertical accuracy between flight lines

Certifications

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

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

Apr 30, 2018

Chris Holder
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 the lidar collection was conducted between January 7 and 9, 2018. Field work for absolute accuracy assessment was conducted April 20 and 21, 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".

Apr 27, 2018

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

Signed: Apr 27, 2018

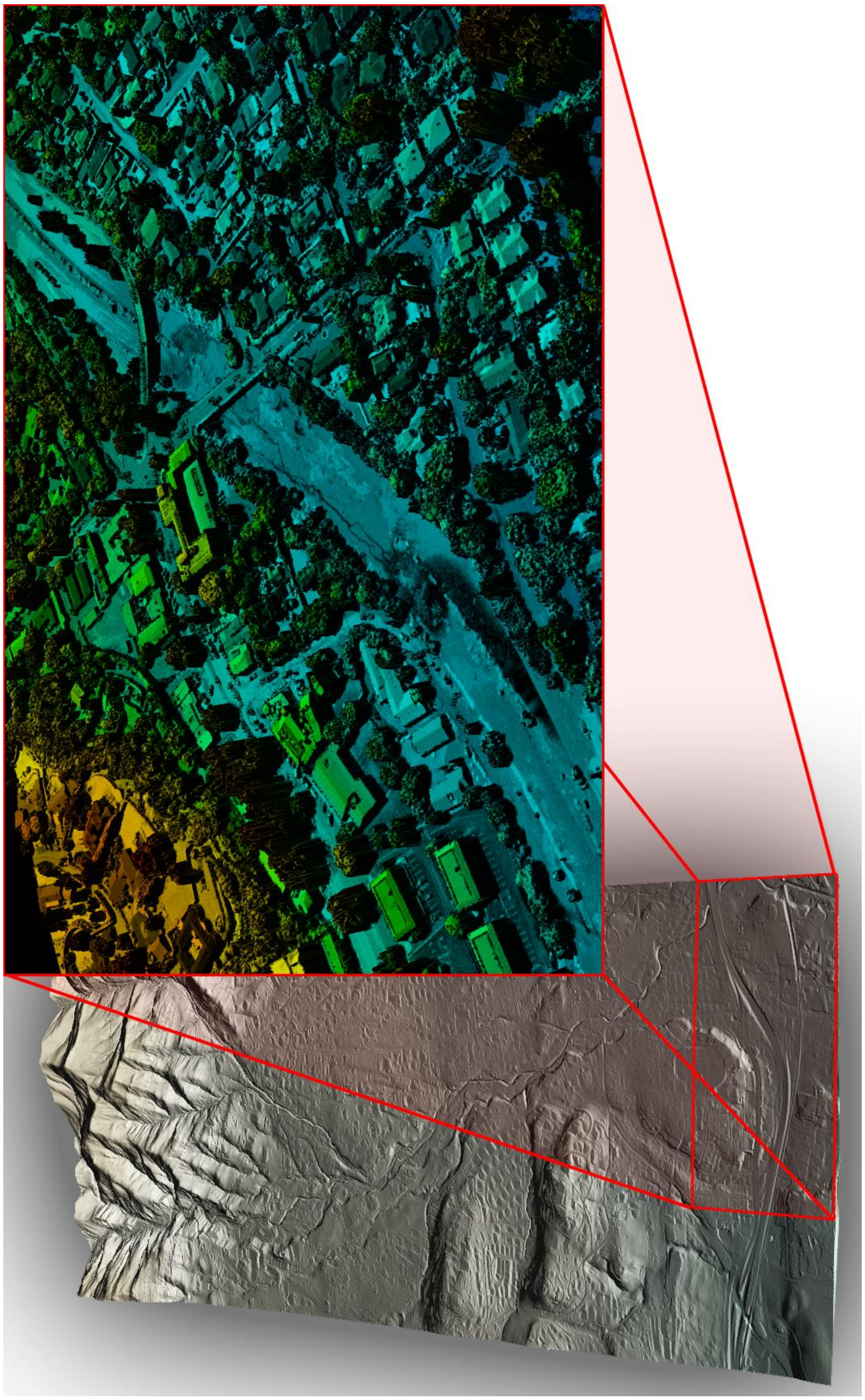


Figure 12: This image shows a zoomed view of the mudslide debris blocking US Highway 101, created from the highest hit LiDAR returns colored using elevation and intensity value. In the background, a wider view of the site can be seen, created by the bare earth digital elevation model colored by elevation.

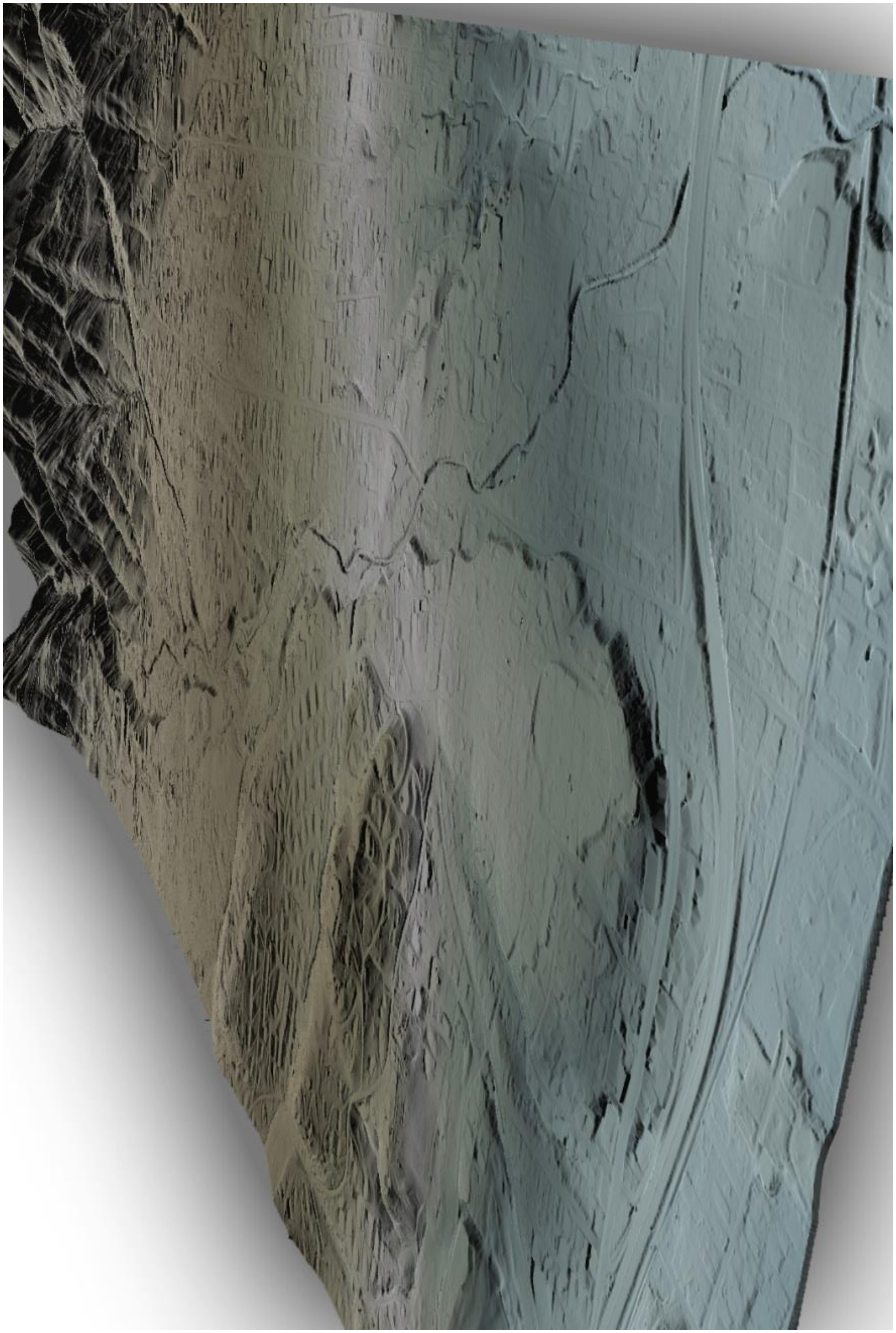


Figure 13: This image shows a view of the Santa Barbara Mudslide area, created from the gridded bare earth model colored by elevation.

GLOSSARY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Relative Accuracy Calibration Methodology:

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

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

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

LiDAR accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

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

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

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 29^{o}$ 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.