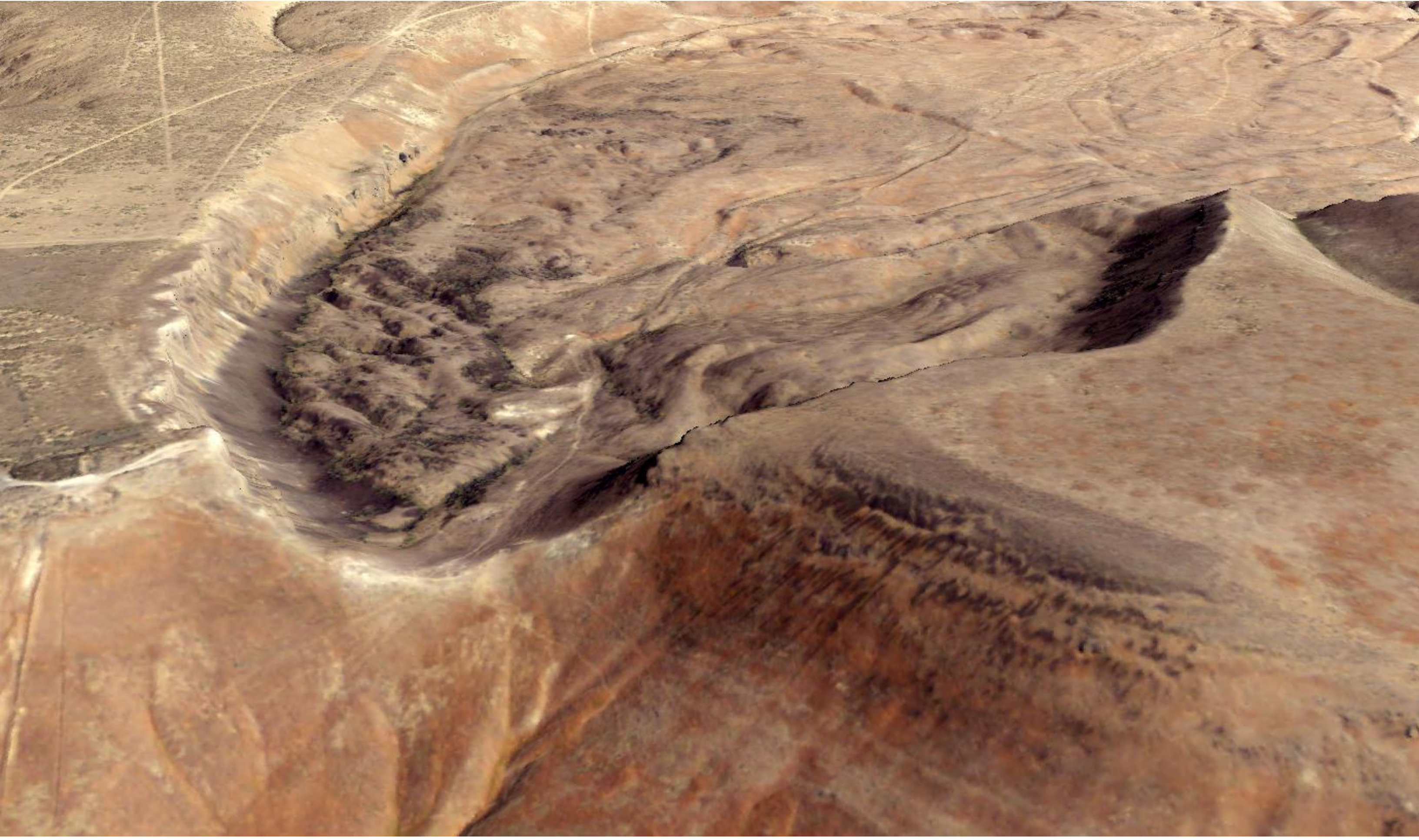
March 25, 2014



Saddle Mountain LiDAR

Technical Data Report

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Cover Photo: The view looking north at a historic landslide in the Saddle Mountain study area. This image was created from the LiDAR point cloud colored with RGB values assigned from 2009 NAIP imagery.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the Wanapum Dam just north of the Saddle Mountain site in Washington.

In October 2013, WSI, a Quantum Spatial Company (QSI), was contracted by the Puget Sound LiDAR Consortium (PSLC) to collect Light Detection and Ranging (LiDAR) data in the fall of 2013 for the Saddle Mountain site in south-central Washington. Data were collected to aid the PSLC in providing complete coverage of the Saddle Mountain fault system for earthquake hazard assessment and mapping. The Saddle Mountain study area is a continuation of data collection within the greater Hanford area, and is of key importance due to its proximity to critical infrastructure and development.

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 assessment. Acquisition dates and acreage are shown in Table 1, the project extent can be seen in Figure 1, and a complete list of contracted deliverables provided to PSLC can be found in Table 2.

Table 1: Acquisition dates, acreages, and data types collected on the Saddle Mountain site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Saddle Mountain	168,553	172,093	11/19-20/2013 11/23-27/2013 12/01-03/2013	LiDAR

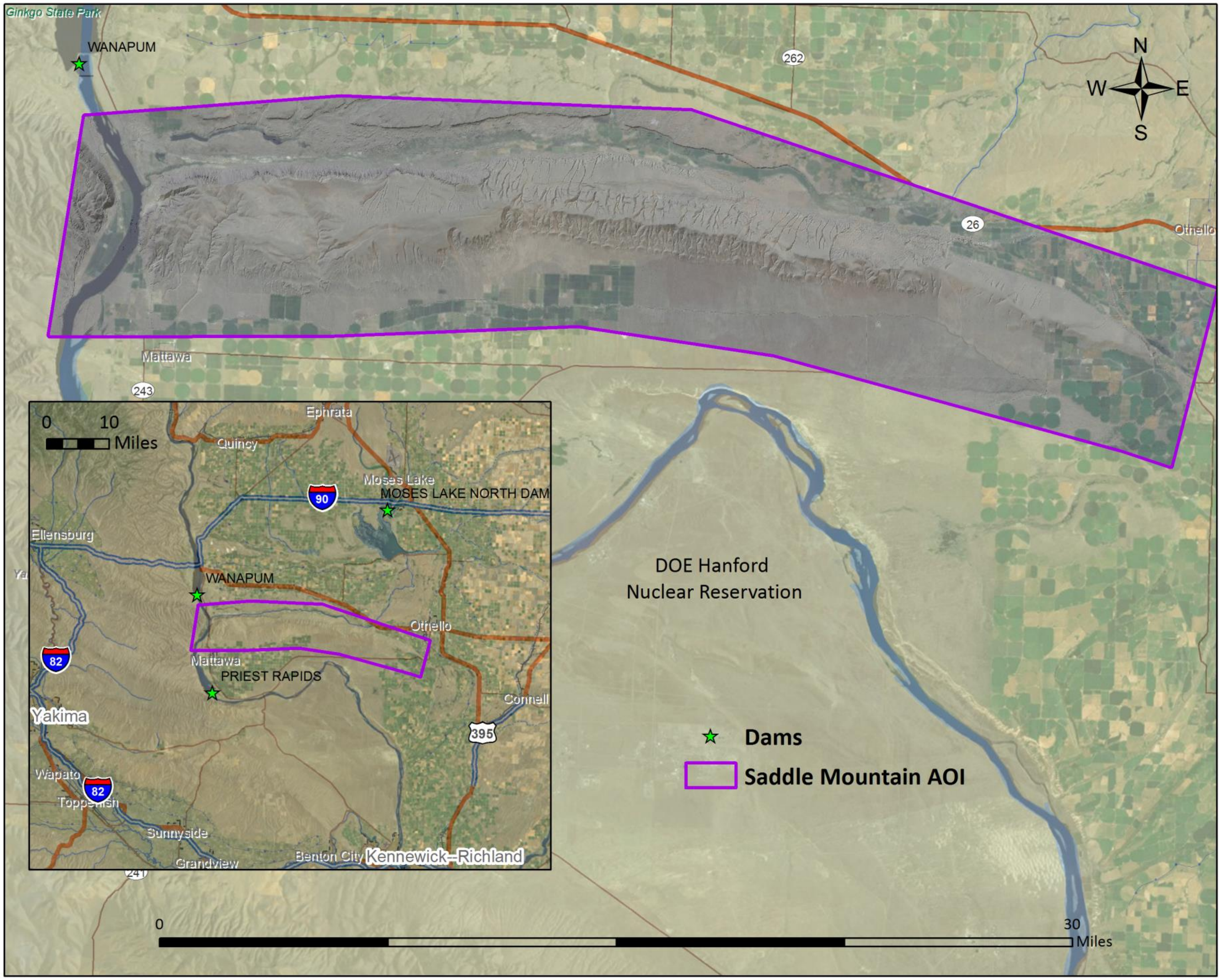

Figure 1: Location map of the Saddle Mountain site in Washington

Deliverable Products

Table 2: Products delivered to PSLC for the Saddle Mountain site

Saddle Mountain Products **Projection: Washington State Plane South** **Horizontal Datum: NAD83 (CORS96)** **Vertical Datum: NAVD88 (GEOID03)** **Units: US Survey Feet**	
LIDAR Point Files	LAS v 1.2 • All Returns Comma Delimited ASCII Text Files • All Returns (*.asc) • Ground Points (*.gnd)
Rasters	3.0 Foot ESRI Grids and GeoTiffs • Bare Earth Model • Highest Hit Model 1.5 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • DEM/DSM Tile Index • Real-time Kinematic Ground Control Points (RTK) • Control Monuments Comma Delimited Text Files (*csv) • Smooth Best Estimate Trajectory (SBETs)

**The data were created in NAD83 (CORS96), but for GIS purposes are defined as NAD83 (HARN) as per PSLC specifications.*

Oblique aerial photo of the Saddle Mountain site taken by QSI flight acquisition staff

ACQUISITION

QSI's ground acquisition equipment set up in the Saddle Mountain study area.

Planning

In preparation for data collection, QSI reviewed the project area using Google Earth and developed a specialized flight plan using a combination of planning software. Acquisition parameters specified in the planning process include orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed to ensure complete coverage of the Saddle Mountain LiDAR study area at the target point density of ≥8 pulses per square meter (0.74 pulses/square foot). Effort is taken to optimize flight paths by minimizing 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 such as property access and potential air space restrictions were reviewed.

Ground Survey

Existing NGS Monument

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

Monumentation

QSI-Established Monument

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground control points using RTK survey techniques (see **RTK** below).

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for RTK coverage. QSI established eight new monuments and utilized one existing National Geodetic Survey (NGS) monument for the Saddle Mountain project (Table 3, Figure 2). New monumentation was set using 5/8”x30” rebar topped with stamped 2" aluminum caps. QSI’s professional land surveyor, Chris Brown (WAPLS#46328LS) oversaw and certified the establishment of all monuments.

Table 3: Monuments established for the Saddle Mountain acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
SA2392	46° 48' 48.90785"	-119° 40' 16.38022"	779.754
SADDLE_MTN_01	46° 45' 15.80590"	-119° 53' 34.61906"	262.818
SADDLE_MTN_02	46° 45' 15.44491"	-119° 48' 37.57894"	267.021
SADDLE_03	46° 48' 36.08045"	-119° 37' 41.14660"	759.102
SADDLE_06	46° 50' 02.47483"	-119° 36' 44.21404"	309.628
SADDLE_07	46° 50' 25.85118"	-119° 39' 40.22189"	147.021
SADDLE_05	46° 48' 41.49153"	-119° 11' 52.77608"	271.765
SADDLE_08	46° 46' 02.36286"	-119° 14' 09.60500"	236.470
SADDLE_09	46° 44' 15.31077"	-119° 16' 55.62383"	312.511

To correct the continuous onboard measurements of the aircraft position recorded throughout the missions, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

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

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project can be seen in Table 4.

Table 4: Federal Geographic Data Committee monument rating

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

For the Saddle Mountain LiDAR project, the monument coordinates contributed no more than 5.4 cm of positional error to the geolocation of the final RTK and LiDAR, with 95% confidence.

RTK Surveys

For the real time kinematic (RTK) ground control point data collection, a Trimble R7 or R8 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All RTK 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 would record data while stationary for five seconds, then calculate the pseudorange position using at least three one-second epochs. Relative errors for the 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.

RTK ground control point positions were collected on paved roads when available and other hard surfaces such as gravel or packed dirt roads with good satellite visibility. RTK 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. Ground control points were collected over as many flightlines as possible. The distribution of ground control points depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area. See Figure 2 for the distribution of ground control points in this project.

Table 5: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	Static, RTK

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[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

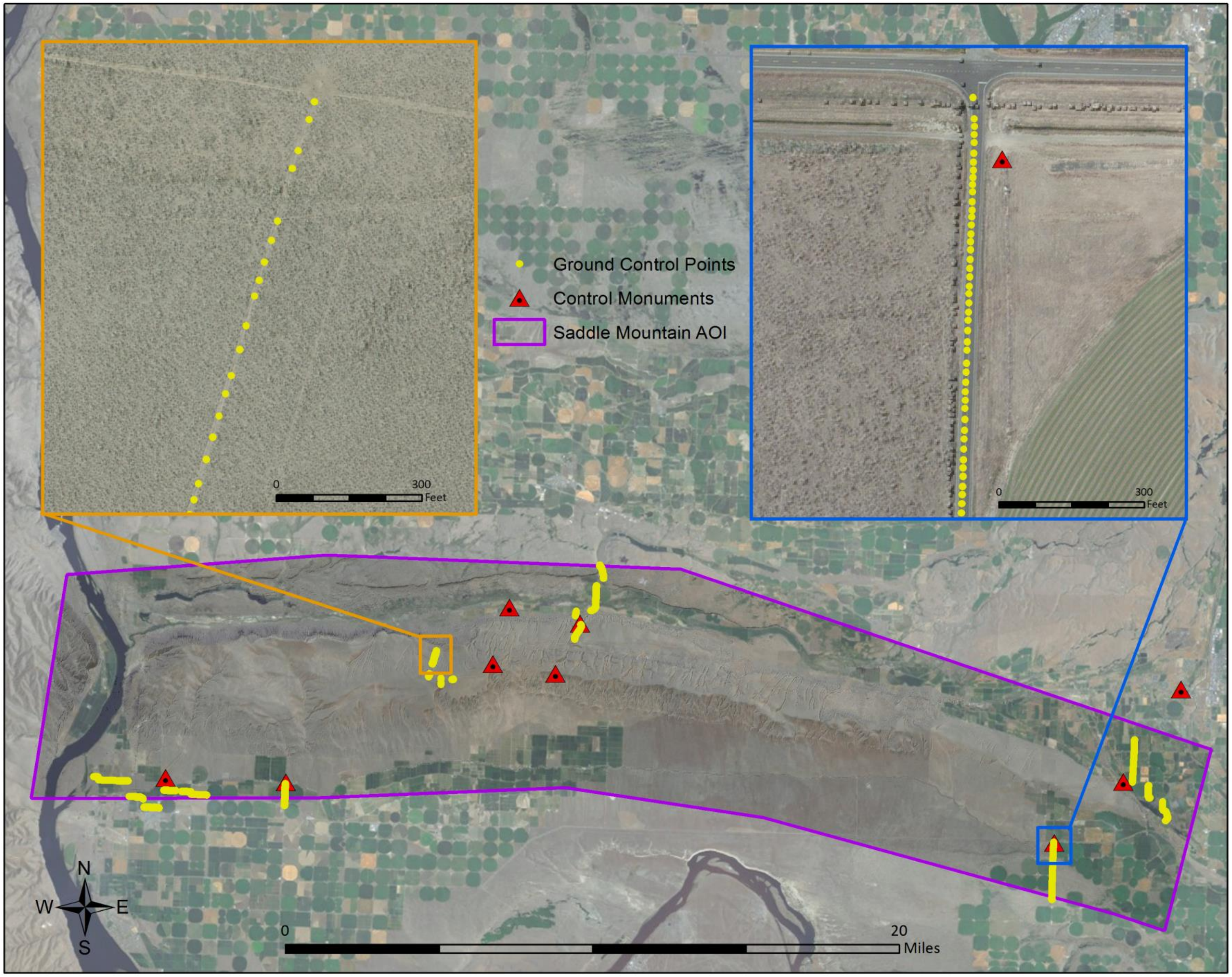


Figure 2: Monument and Ground Control Point location map

Airborne Survey

The LiDAR survey was accomplished with a Leica ALS60 system mounted in a Cessna Caravan, and a Leica ALS70 system mounted in a Partenavia aircraft. Table 6 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Saddle Mountain terrain. 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 native and delivered density will vary depending on terrain, land cover, and the prevalence of water bodies.

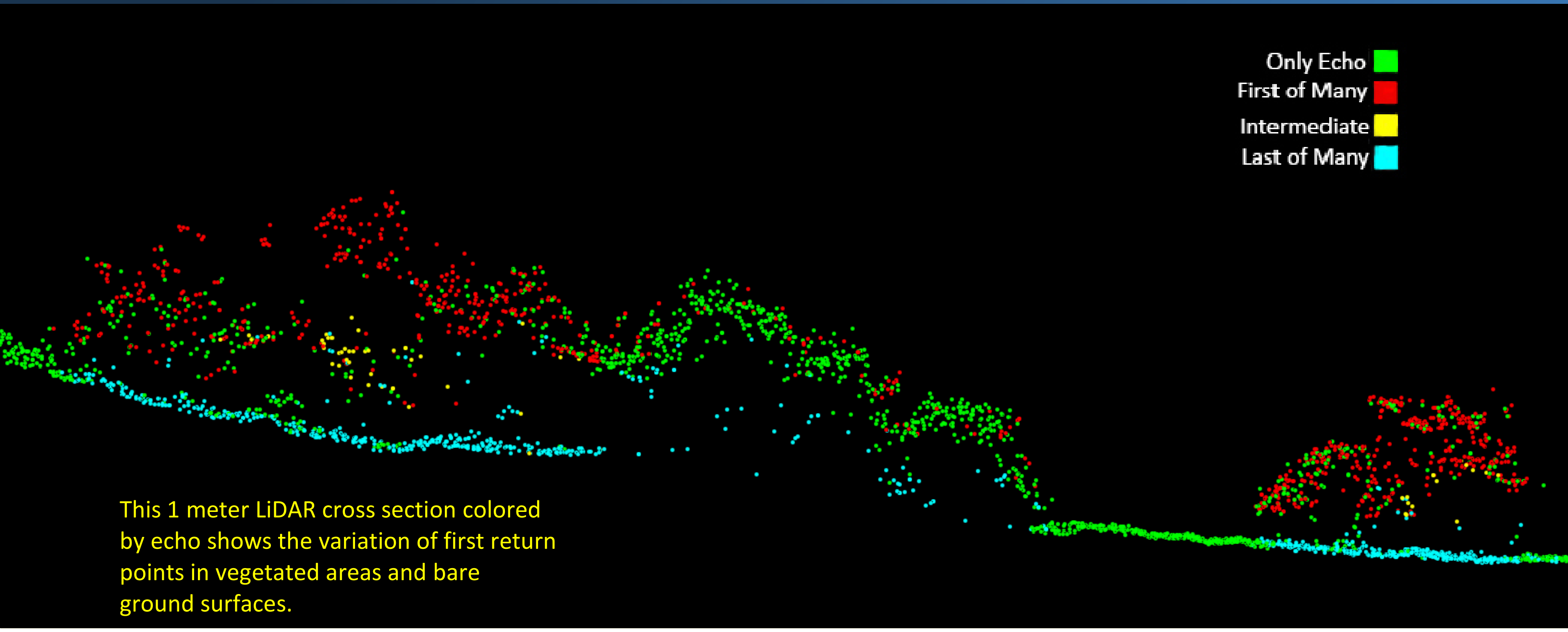
Table 6: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications		
Acquisition Dates	November 19-27, 2013	December 1-3, 2013
Aircraft Used	Cessna Caravan	Partenavia
Sensor	Leica ALS60	Leica ALS70
Survey Altitude (AGL)	900-1,100 m	1,300 m
Target Pulse Rate	86-106 kHz	160-209.4 kHz
Sensor Configuration	Single Pulse in Air (SPiA)	Single Pulse in Air (SPiA)
Laser Pulse Diameter	21-26 cm	30 cm
Mirror Scan Rate	58.3-64 Hz	42.7 Hz
Field of View	28°	30°
GPS Baselines	≤13 nm	≤13 nm
GPS PDOP	≤3.0	≤3.0
GPS Satellite Constellation	≥6	≥6
Maximum Returns	4	Unlimited
Intensity	8-bit	8-bit
Resolution/Density	Average 8 pulses/m^2	Average 8 pulses/m^2
Accuracy	$RMSE_Z \leq 15$ cm	$RMSE_Z \leq 15$ cm

To reduce laser shadowing and increase surface laser painting, all areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap). The Leica ALS60 laser system records up to four range measurements (returns) per pulse. While the Leica ALS70 laser system can record unlimited range measurements, it typically does not return more than five. All discernible laser returns were processed for the output dataset.

To accurately solve for laser point position (geographic coordinates x, y, 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. 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/sensor position and attitude data are indexed by GPS time.

PROCESSING



This 1 meter LiDAR cross section colored by echo shows the variation of first return points in vegetated areas and bare ground surfaces.

LiDAR Data

Upon the LiDAR data's arrival to the office, QSI processing staff initiates a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks include 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 are tailored for the landscape and intended application of the data. Brief descriptions of these tasks can be found in Table 8.

Table 7: ASPRS LAS classification standards applied to the Saddle Mountain dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class and not dismissed as Noise or Withheld points
2	Ground	Laser returns that are classified as ground using a number of automated and manual cleaning algorithms.

Table 8: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.	Waypoint GPS v.8.3 Trimble Business Center v.3.10 Geographic Calculator 2013
Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data. Sensor head position and attitude are calculated throughout the survey. The SBET data are used extensively for laser point processing.	IPAS TC v.3.1
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. Data are converted to orthometric elevations (NAVD88) by applying a Geoid03 correction.	ALS Post Processing Software v.2.74
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).	TerraScan v.13.008
Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are calculated on ground classified points from paired flight lines and results are applied to all points in a flight line. Every flight line is used for relative accuracy calibration.	TerraMatch v.13.002
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 RTK survey data.	TerraScan v.13.008 TerraModeler v.13.002
Generate bare earth models as triangulated surfaces. Highest hit models were created as a surface expression of all classified points (excluding the noise and withheld classes). All surface models were exported as ESRI Grids at a 3 foot pixel resolution.	TerraScan v.13.008 ArcMap v. 10.1 TerraModeler v.13.002
Export intensity images as GeoTIFFs at a 1.5 foot pixel resolution.	TerraScan v.13.008 ArcMap v. 10.1 TerraModeler v.13.002

This image shows a view looking north at drainage from the Saddle Mountains. The gridded ground-classified LiDAR points are colored by elevation.

LiDAR Density

The LiDAR sensor was set to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^2). First return density describes the density or pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse are not considered in first return density analysis. Pulse density distribution will vary within the study area due to laser scan pattern and flight conditions. Additionally, some types of surfaces (e.g., breaks in terrain, water, steep slopes) may return 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 represents the bare-earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Ground-classified return density is dictated by a combination of variables; terrain character, land cover, and ground surface reflectivity all influence the density of echoes returning to the sensor. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return LiDAR density for the Saddle Mountain study area was 1.00 points/ft^2 (10.74 points/m^2) while the average ground classified density was 0.57 points/ft^2 (6.14 points/m^2) (Table 9). The statistical distribution of first returns (Figure 3) and classified ground points (Figure 4) are portrayed. Also presented are the spatial distributions of average first return and ground point densities for each 100mx100m cell (Figure 5).

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	1.00 points/ft^2 10.74 points/m^2
Ground Classified	0.57 points/ft^2 6.14 points/m^2

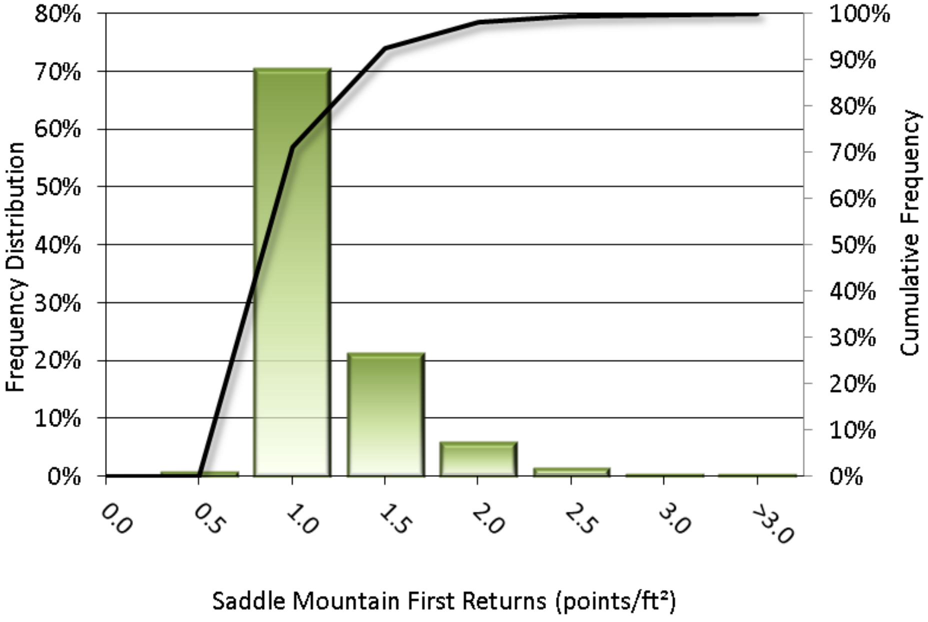


Figure 3: Frequency distribution of first return densities of the gridded study area

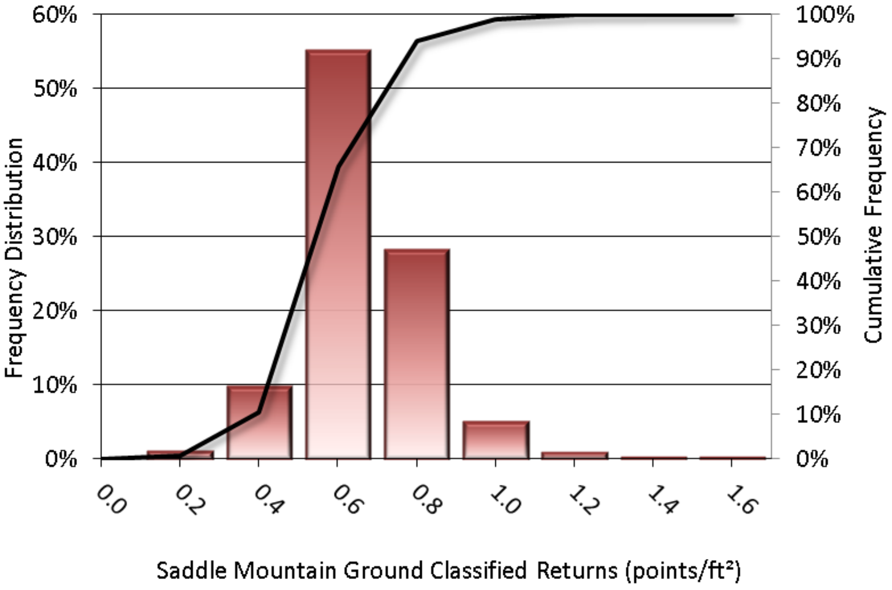


Figure 4: Frequency distribution of ground return densities of the gridded study area

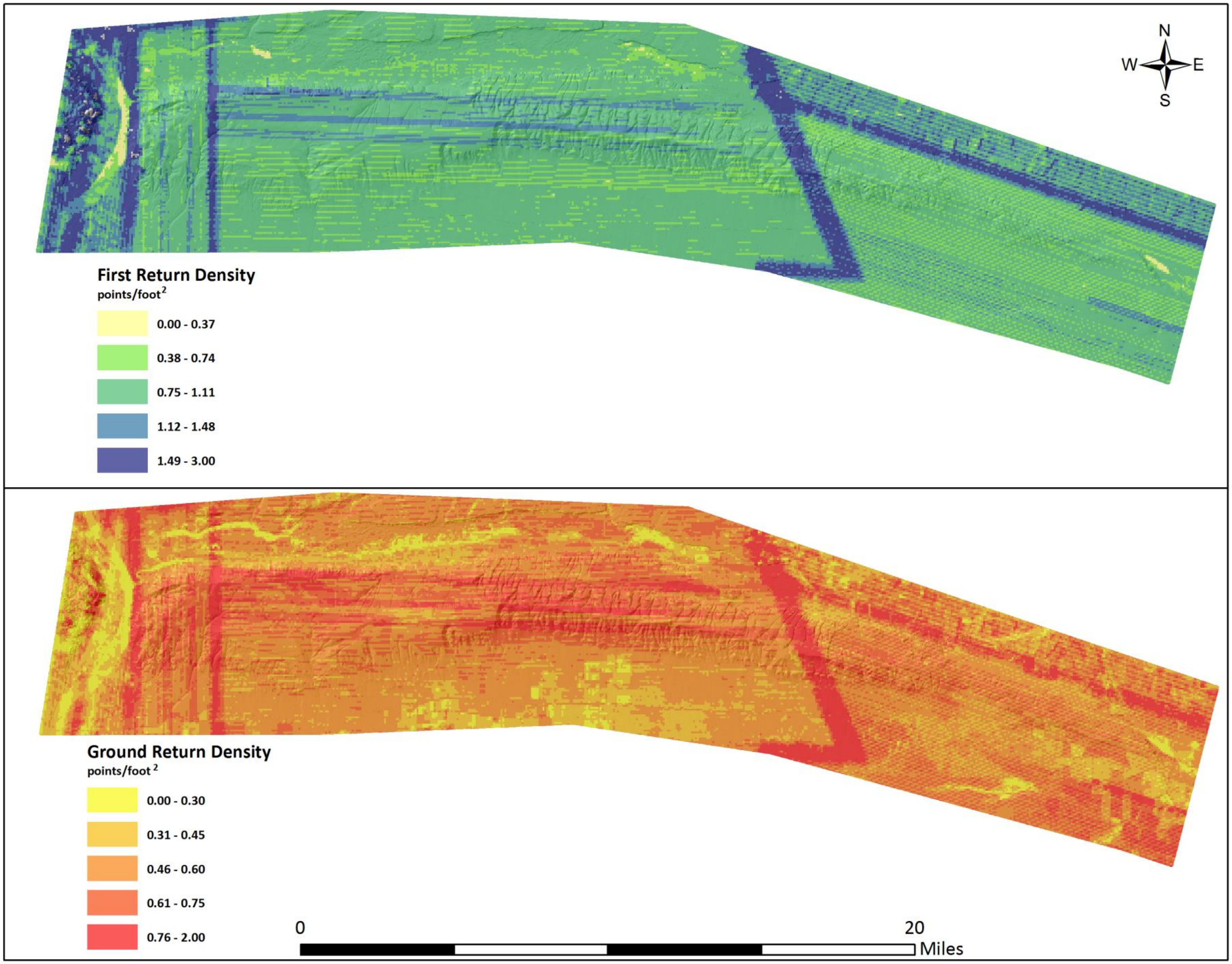


Figure 5: First return and ground density maps for the Saddle Mountain site (100mx100m cells)

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 Absolute Vertical Accuracy

Absolute accuracy was assessed using Fundamental Vertical Accuracy (FVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. FVA compares known RTK ground control point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated ground surface generated by the LiDAR points. FVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a "very high probability" of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 σ).

Absolute vertical accuracy is described as the mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates. 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 Saddle Mountain survey 2,345 RTK points were collected in total resulting in an average accuracy of -0.012 feet (-0.004 meters) (Table 10, Figure 6).

Table 10: Absolute Accuracy

Absolute Accuracy	
Sample	2,345 points
Average	-0.012 ft -0.004 m
Median	-0.007 ft -0.002 m
RMSE	0.085 ft 0.026 m
Standard Deviation (1σ)	0.084 ft 0.026 m
1.96σ	0.165 ft 0.050 m

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[3] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

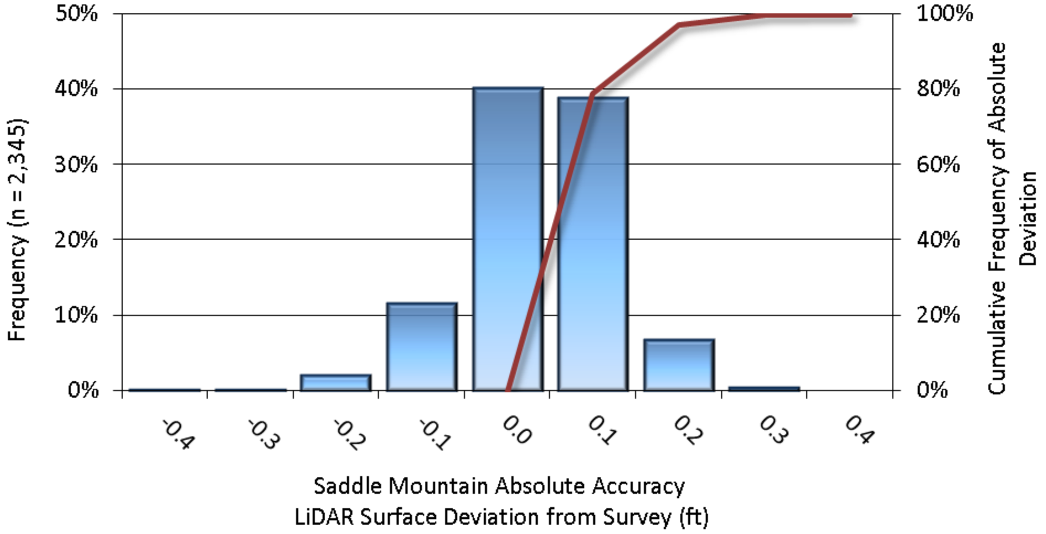

Figure 6: Frequency histogram for LiDAR surface deviation from RTK Ground Control Point values

LiDAR Vertical Relative Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole, i.e., 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 is 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 Saddle Mountain study area was 0.101 feet (0.031 meters) (Table 11, Figure 7).

Table 11: Relative Accuracy

Relative Accuracy	
Sample	232 surfaces
Average	0.101 ft 0.031 m
Median	0.097 ft 0.030 m
RMSE	0.102 ft 0.031 m
Standard Deviation (1σ)	0.017 ft 0.005 m
1.96σ	0.034 ft 0.010 m

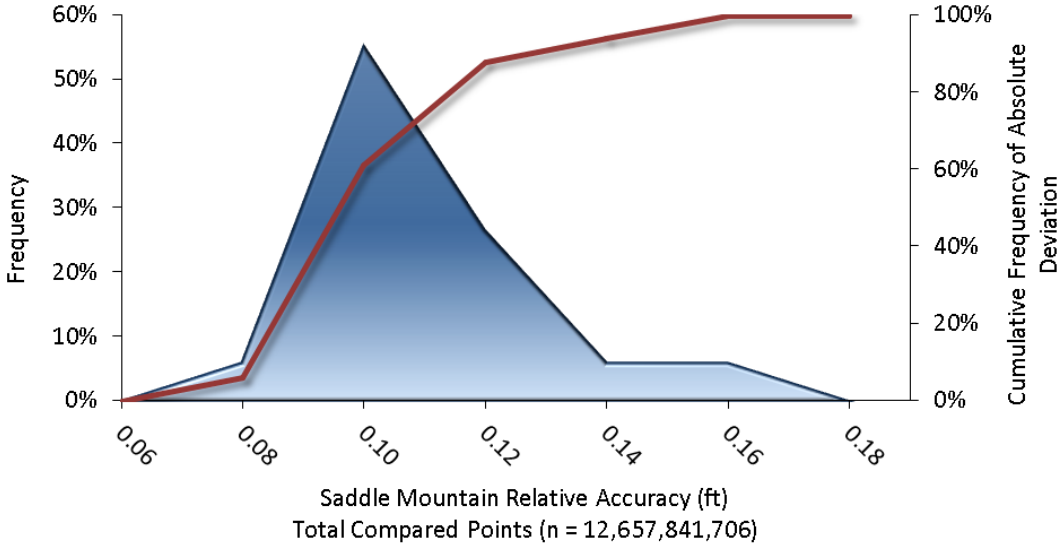

Figure 7: Frequency plot for relative vertical accuracy between flight lines

CERTIFICATIONS

Quantum Spatial provided LiDAR services for the Saddle Mountain project as described in this report.

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

Kris Fausti, PMP
Operations Manager
QSI

I, Christopher W. Brown, being duly registered as a Professional Land Surveyor in the state of Washington, say that I hereby certify the methodologies and results of the attached LiDAR project, and that Static GNSS occupations on the Base Stations listed during airborne flights and RTK survey on hard-surface, was performed by me or under my direct supervision using commonly accepted Standard Practices. Field work for this report was conducted between November 19, 2013 and December 3, 2013.

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”.

2/21/2014

Christopher W. Brown, PLS Oregon & Washington
QSI
Portland, OR 97204

CHRISTOPHER W. BROWN
46328

Renews: 12/21/2014

Figure 8: A view looking south at a historic landslide in the Saddle Mountain study area. The image was created from the LiDAR point cloud with RGB values assigned from 2009 NAIP imagery.

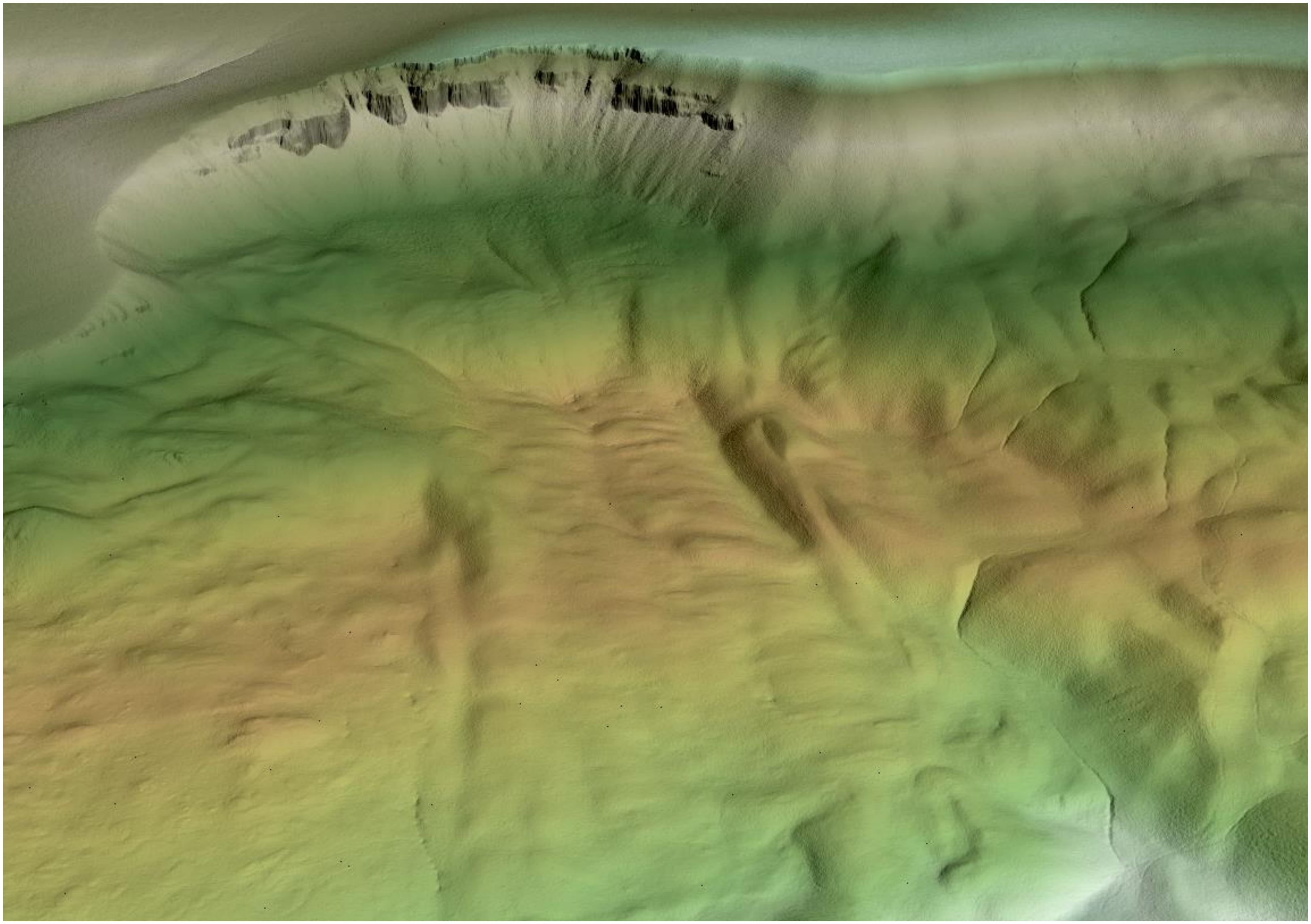

Figure 9: A view looking southeast at a scarp in the Saddle Mountains. Image created from the gridded ground-classified LiDAR points colored by elevation.

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-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set.

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 RTK 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, 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 - 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.

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Intensity Values: The peak power ratio of the laser return to the emitted laser. It is a function of surface reflectivity.

Laser Noise: For any given target, laser noise is the breadth of the data cloud per laser return (i.e., last, first, etc.). Lower intensity surfaces (roads, rooftops, still/calm water) experience higher laser noise.

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 as thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of waveforms reflected back to the sensor. Portions of the wave form that return earliest 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: GPS surveying is 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.

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

Spot Spacing: Also a measure of LiDAR resolution, measured as the average distance between laser points.

Native Density: The number of pulses emitted by the LiDAR system, commonly expressed as Pulses per Square Meter (ppsm).

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 is employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 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 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 ±15° 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 nautical miles at all times.

Ground Survey: Ground survey point accuracy (i.e. <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 RTK 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 most nadir portion of one flight line coincides with the edge (least nadir) 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 are opposing. 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.