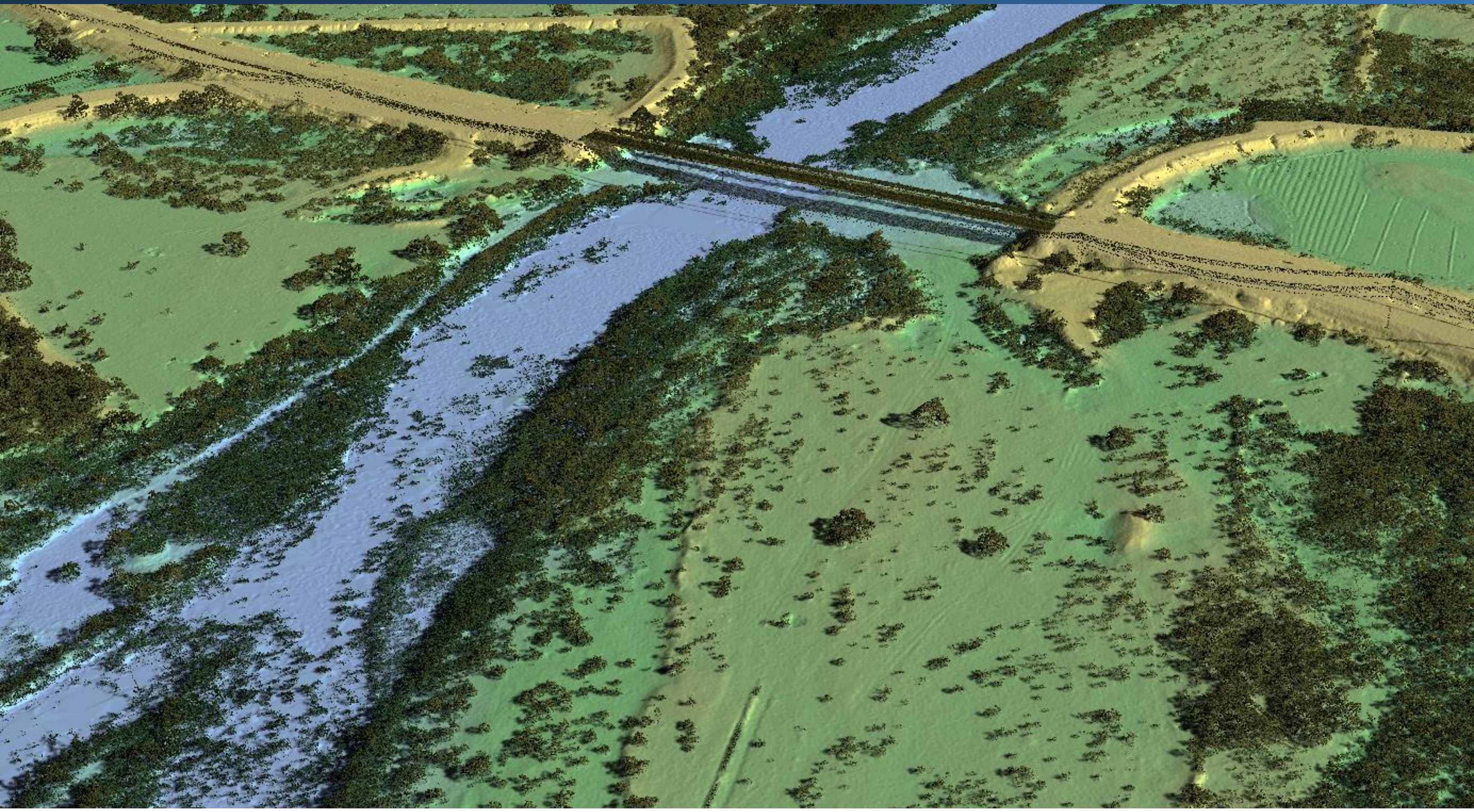
August 13, 2014



Colorado River Basin Pre-Pulse LiDAR

USGS Contract G10PC00026, Task Order G14PD00258

Project Report

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Cover Photo: A view looking north-northwest at a bridge near General Francisco Murguia on the Colorado River. The image was created from the LiDAR bare earth model colored by elevation and overlain with the above-ground LiDAR point cloud.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the canal system that connects to the Colorado River in the project area.

In February 2014, GMR Aerial Surveys Inc. d/b/as Photo Science, a Quantum Spatial Company (QSI), was contracted by the United States Geological Survey (USGS) (contract no. G10PC00026, task order no. G14PD00258) to collect Light Detection and Ranging (LiDAR) data of the Colorado River Basin from the US/Mexico Border near Morelos Dam to just north of the Sea of Cortez. Data collection was contracted to aid USGS in assessing the impact of water released to Mexico and the Colorado River Delta per the Minute 319 Agreement. Data collection was therefore scheduled for both pre and post water release. The first acquisition (pre-pulse) occurred on March 7th-20th, 2014. Water was subsequently released on March 23rd, 2014. The second acquisition (post-pulse) then occurred from July 31st to August 6th, 2014[1].

This report accompanies the delivered LiDAR data of the pre-pulse acquisition 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 USGS is shown in Table 2, and the project extent is shown in Figure 1. Post pulse data and information will be covered in a forthcoming delivery upon completion of data processing.

[1] Project limits were modified under USGS Mod-1, to better meet USGS needs for post-pulse data acquisition.

Table 1: Acquisition dates, acreage, and data types collected on the Colorado River Basin Pre-Pulse site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Colorado River Basin Pre-Pulse	168,320	175,606	03/07/2014 – 03/08/2014, 03/12/2014 & 03/14/2014 – 03/20/2014	LiDAR

Deliverable Products

Table 2: Products delivered to USGS for the Colorado River Basin Pre-Pulse site

Colorado River Basin Pre-Pulse Products Projection: UTM Zone 11 Horizontal Datum: WGS 84 Vertical Datum: NAVD88 (GEOID12a) Units: Meters	
Points	LAS v 1.3 • Classified Point Cloud • Flightline Swaths (unclassified)
Rasters	1.0 Meter ERDAS .img • Hydroflattened Bare Earth Model 0.5 Meter GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Site Boundary • LiDAR Tile Index • Base Station Control • Supplemental Ground Control Points • Ground Control Quality Check Points (QCP)* • Contours (0.3 m interval)

**Due to ground access limitation during the Pre-Pulse acquisition, updated Ground Control Quality Check Points were collected during the Post-Pulse acquisition and used for accuracy assessment of the Pre-Pulse dataset.*

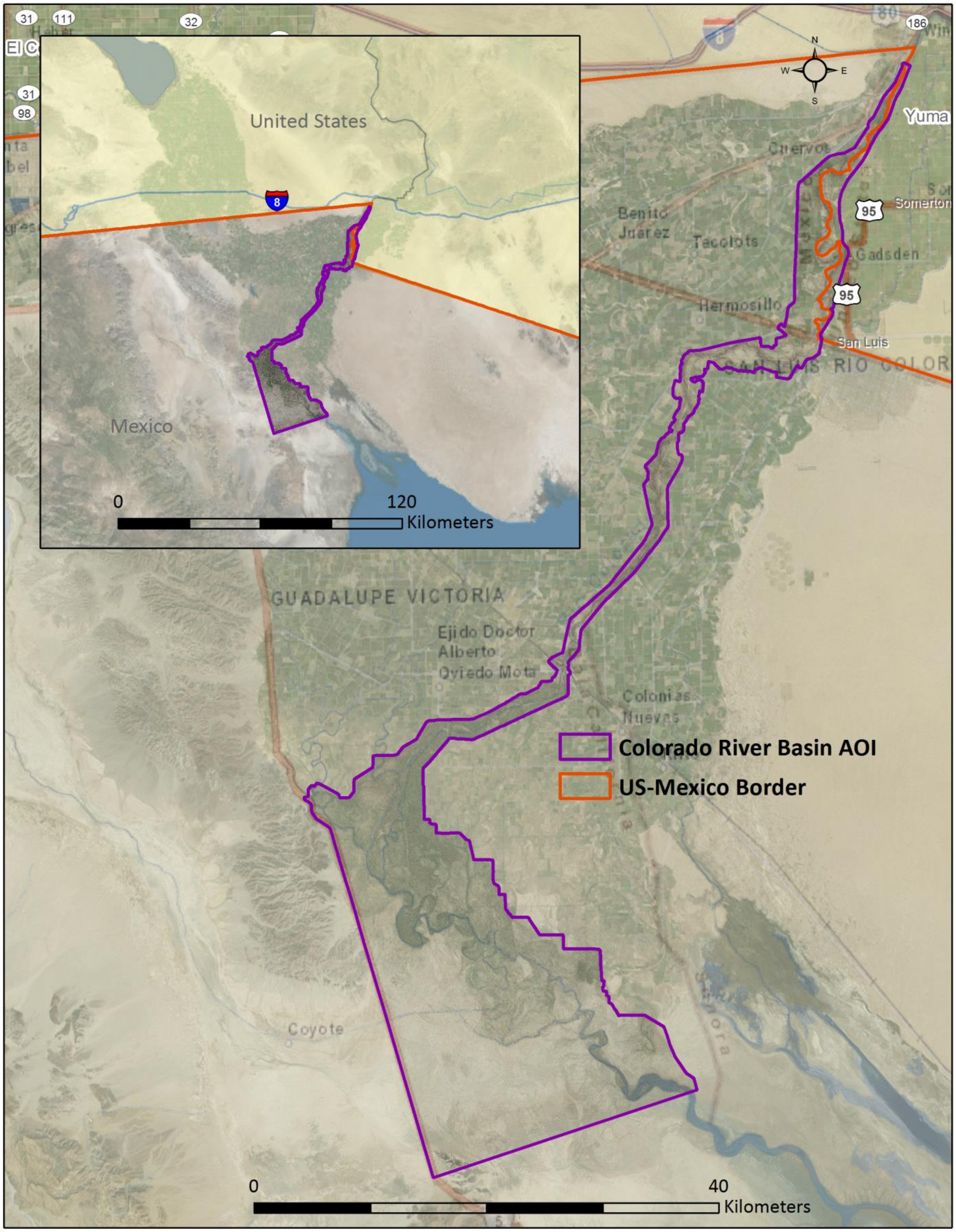


Figure 1: Location map of the Colorado River Basin Pre-Pulse site spanning the US/Mexico Border

QSI's ground acquisition equipment set up in the Colorado River Basin Pre-Pulse LiDAR study area.

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Colorado River Basin Pre-Pulse LiDAR study area at the target point density of ≥8.0 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 and road access were reviewed.

Due to the project area spanning an international border, additional considerations for air space restrictions and ground access were made. Due to security and other constraints, Quantum Spatial's task order scoping did not provide for the deployment of its own personnel to support ground based activities on the Mexican side of the border (where the majority of the Task Order AOI resides). Although QSI aircraft did fly and acquire LiDAR data of that entire AOI (US & MX), the aircraft and crew never based or landed in Mexico. In order to establish control within Mexico, project partner , the Sonoran Desert Institute (SDI) working with USGS and BOR separately contracted and coordinated all ground survey work for the project area (including Base Station Control and Supplemental Ground Control) falling within Mexican territory. This work was completed by independent Mexican survey contractor Geo Castellini (See Appendix B). QSI flight and survey operation staff coordinated and utilized base station data and supplemental control survey data provided by Geo Castellini to support the post processing of the LiDAR data. All ground survey work for the project area falling within the United States was completed by survey crews associated with GMR Aerial Surveys Inc., d/b/a Photo Science, a Quantum Spatial Company.

Ground Survey Work

Ground surveys, including base station control, and supplemental ground control (SGC) were conducted to support the airborne acquisition process. Supplemental ground control data were used to geospatially correct the aircraft positional coordinate data and ground control quality check points were used to perform quality assurance checks on final LiDAR data.

Base Station Control

The spatial configuration of base station control provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Base stations were also used for collection of supplemental ground control points using real time kinematic (RTK) survey techniques.

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for SGC coverage. QSI established four new base stations in the United States for the Colorado River Basin Pre-Pulse LiDAR project (Table 3, Figure 3). In addition, Mexican surveying firm Geo Castellini established three new base stations in Mexican territory.

Table 3: Base Stations established for the Colorado River Basin Pre-Pulse acquisition. Coordinates are on the WGS84 datum, epoch 2014.20.

Base Station ID	Agency	Latitude	Longitude	Ellipsoid (meters)
CRB_01	Geo Castellini	31° 58' 15.68057"	-115° 13' 04.76887"	-27.074
CRB_02	Geo Castellini	32° 12' 01.53005"	-115° 09' 31.88033"	-23.519
CRB_03	Geo Castellini	32° 23' 00.16894"	-114° 58' 31.83067"	-12.765
CRD_01	QSI	32° 30' 03.20128"	-114° 47' 39.60133"	-4.548
CRD_02	QSI	32° 30' 10.27714"	-114° 47' 43.68409"	-5.044
CRD_03	QSI	32° 36' 41.51145"	-114° 47' 17.77803"	-0.115
CRD_04	QSI	32° 42' 25.56057"	-114° 43' 27.86648"	2.584

To correct the continuously recorded onboard measurements of the aircraft position, QSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each base station established within the United States. During post-processing, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[2]) for precise positioning. Multiple independent sessions over the same base station were processed to confirm antenna height measurements and to refine position accuracy.

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

QSI Control Points

Control points (both supplemental ground control and quality check points) within the United States were collected by QSI using real time kinematic survey techniques. A Trimble R7 base unit was positioned at a nearby base station to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All 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 the position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 4 for Trimble unit specifications.

Table 4: 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	Rover

Supplemental Ground Control

Supplemental Ground Control points were collected within the United States (by QSI) and within Mexico (by Geo Castellini) in order to refine Airborne GPS positional accuracy during the calibration process. Supplemental ground control were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. Ground control 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 within as many flightlines as possible, however the distribution of ground control points depended on ground access constraints and base station locations and may not be equitably distributed throughout the study area (Figure 2).

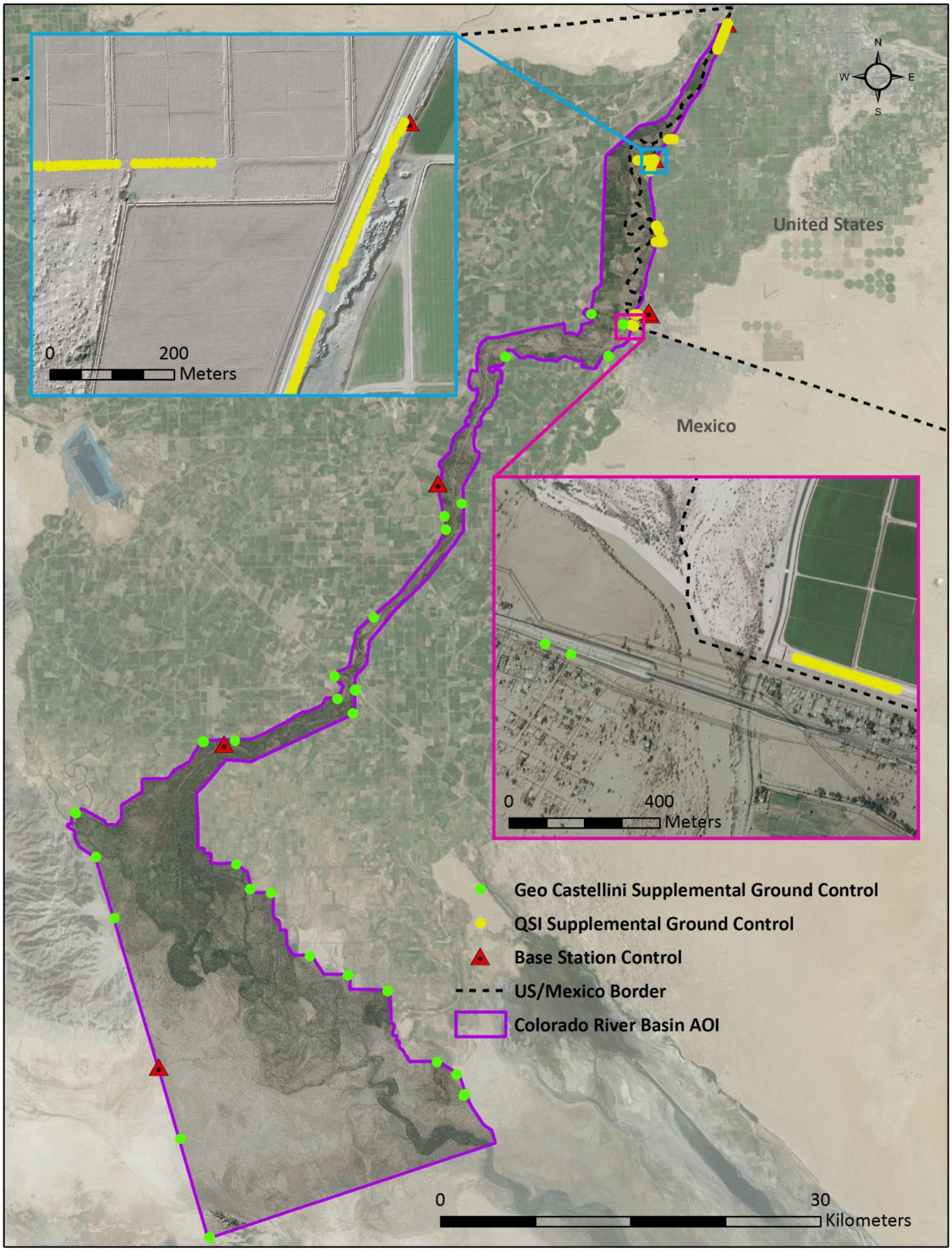


Figure 2: Supplemental Ground Control point location map

Ground Control Quality Check Points (QCP)

Ground Control Quality Check Points (QCPs) were collected by QSI personnel within *only* the United States portion of the Project AOI to support accuracy assessment and reporting within the Colorado River Basin study area. Budget constraints prohibited the collection of any QCPs within the Mexican portion of the AOI by SDI's survey contractor. Ground control QCPs were collected exclusively for accuracy assessment, and were not used in data calibration. Due to ground access limitations during the pre-pulse LiDAR acquisition, it was necessary to reacquire these ground control QCPs during the contracted post-pulse acquisition (Figure 3). Individual accuracies were calculated for each QCP land cover type to assess confidence in the LiDAR derived ground models across land cover classes, and reported statistics were updated. Land cover types and descriptions are shown in Table 5.

Table 5: Land cover descriptions of check points taken for the Colorado River Basin Pre-Pulse site

Land cover type	Number of Points	Land cover code	Example	Description
Bare Earth/Gravel	131	BARE GVL		Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material
Tall Grass	59	TALL_GRASS TALL_WEEDS		Areas characterized by grasses, legumes, or natural and semi-natural grasslands
Brush/Shrubland	76	SHRUB BRUSH		Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material
Urban	34	URBAN URBAN(PAVED) PARK/URBAN/REC		Urban and developed areas

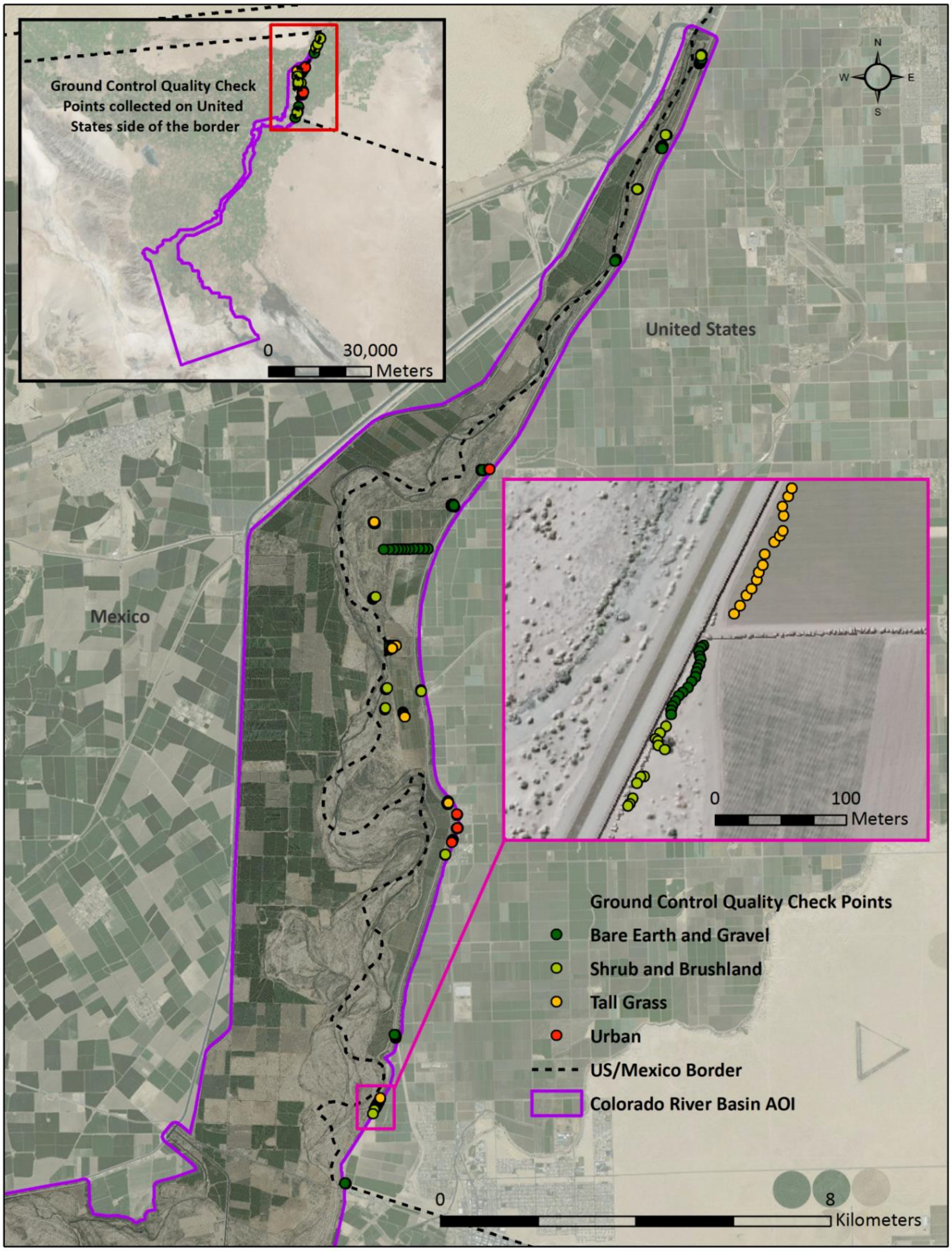


Figure 3: Location Map of Ground Control Quality Assurance Points (QAPs)

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Leica ALS70 system mounted in a Partenavia. Table 6 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Colorado River Basin Pre-Pulse project area. The Leica ALS70 laser system can record unlimited range measurements (returns) per pulse, but typically does not record more than 5 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.

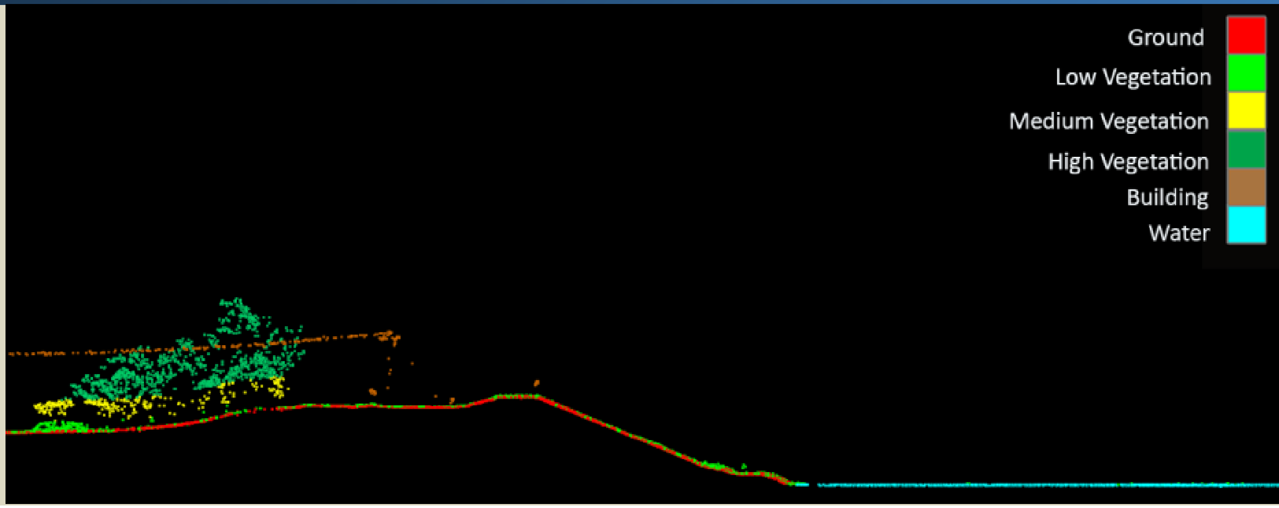
Table 6: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	March 7 – 8, 2014, March 12, 2014 and March 14 – 20, 2014
Aircraft Used	Partenavia
Sensor	Leica ALS70
Survey Altitude (AGL)	1400 m
Target Pulse Rate	180 – 199 kHz
Sensor Configuration	Single Pulse in Air (SPiA)
Laser Pulse Diameter	32 cm
Field of View	30º
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	5
Intensity	8-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS70 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.

This 3D LiDAR cross section colored by classification shows water, vegetation, and a power line in the Colorado River Basin project area.



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 Colorado River Basin Pre-Pulse dataset

Classification Number	Classification Name	Classification Description
2	Ground	Bare earth ground, determined by a number of automated and manual cleaning algorithms
3	Low Vegetation	Any vegetation within 1.5 m of the ground surface
4	Medium Vegetation	Any vegetation between 1.5 and 4.6 m above ground
5	High Vegetation	Any vegetation greater than 4.6 m above ground
6	Building	All man-made structures such as buildings, bridges, fences and utilities.
7	Noise	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
11	Withheld	Laser returns that have intensity values of 0 or 255

Table 8: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	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. 1.3) format. Convert data to orthometric elevations by applying a geoid12a correction.	ALS Post Processing Software v.2.75
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.14
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.14
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 supplemental ground control points.	TerraScan v.14 TerraModeler v.14
Generate bare earth models as triangulated surfaces with hydro-flattening breaklines enforced. Export surface models in EDRAS Imagine (.img) format at a 1 meter pixel resolution.	TerraScan v.14 TerraModeler v.14 ArcMap v. 10.1
Export intensity images as GeoTIFFs at a 0.5 meter pixel resolution.	TerraScan v.14 TerraModeler v.14 ArcMap v. 10.1

Feature Extraction

Water's edge breaklines

The Colorado River and other water bodies within the project area were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 30 meters, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. The hydro-flattening 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.

Hydro-flattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify lake boundaries and water levels. Water boundary polygons were developed using an algorithm which weights LiDAR-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary. Specific care was taken to not hydro-flatten wetland and marsh habitat found throughout the study site.

Once polygons were developed, water elevations were obtained from the filtered LiDAR returns. Lakes were assigned a consistent elevation for an entire polygon while the river was assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel. The initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model and replaced with the flat water surface of the water's edge breaklines.

Water boundary breaklines were then incorporated into the hydro-flattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3D water edge breaklines resulting in the final hydroflattened model (Figure 4).

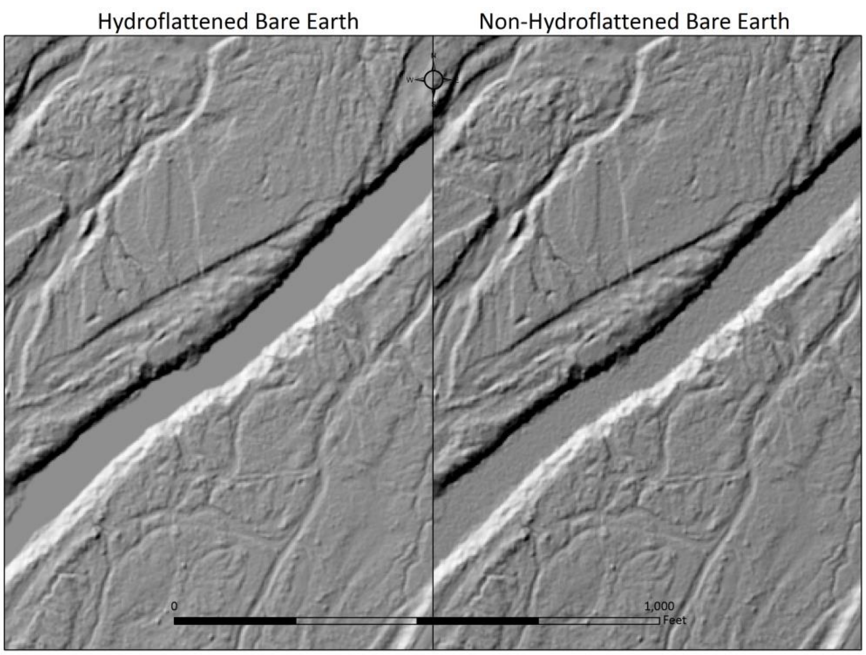


Figure 4: Example of hydro-flattening in the Colorado River Basin Pre-Pulse LiDAR dataset

Contours

Contour generation from LiDAR point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. These model key points were selected from the ground model every 6.09 m with the spacing decreased in regions with high surface curvature (Z tolerance of 0.07 m). Generation of model key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the model key points at even elevation increments.

Elevation contour lines were then intersected with ground point density rasters and a confidence field was added to each contour line. Contours which crossed areas of high point density have high confidence levels, while contours which crossed areas of low point density have low confidence levels. These areas with low ground point density were commonly beneath buildings and bridges, in locations with dense vegetation, over water, and in other areas where laser penetration to the ground surface was impeded (Figure 5).

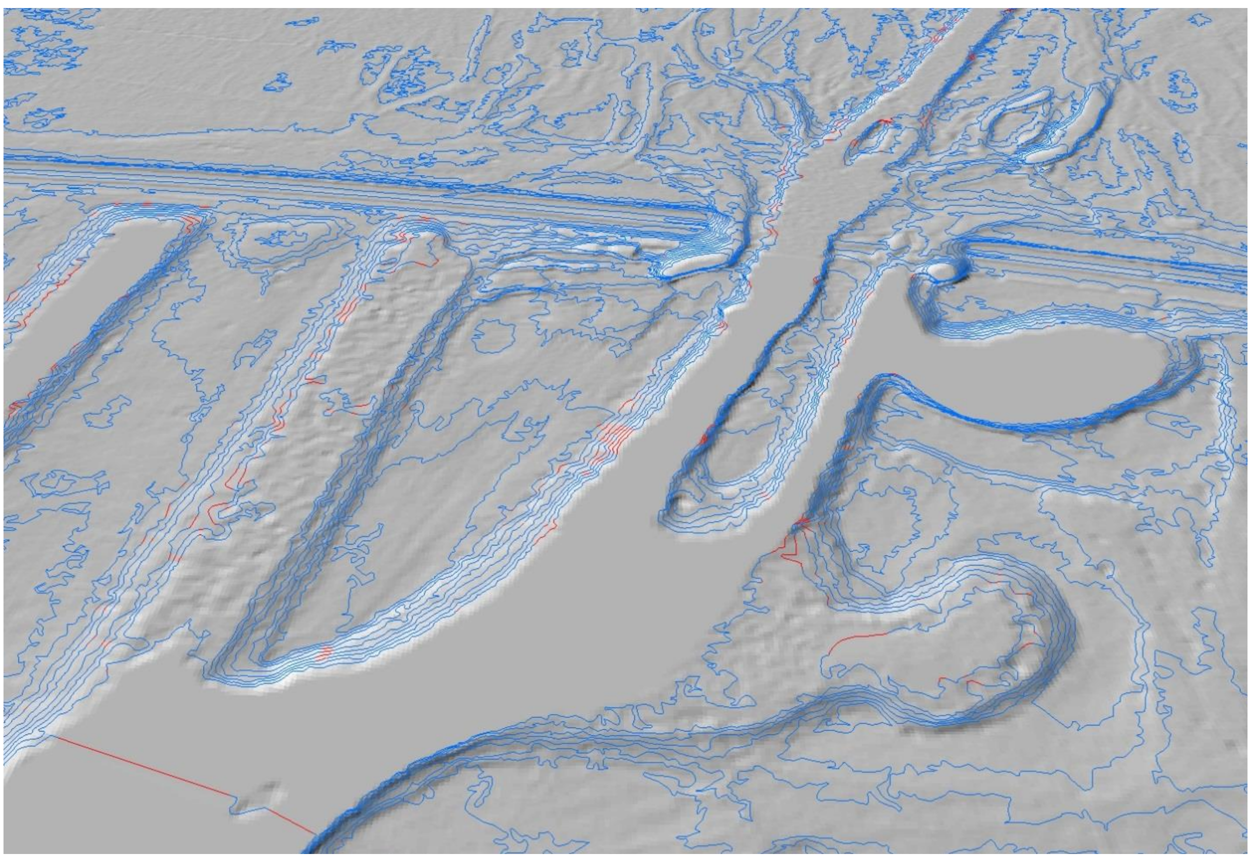
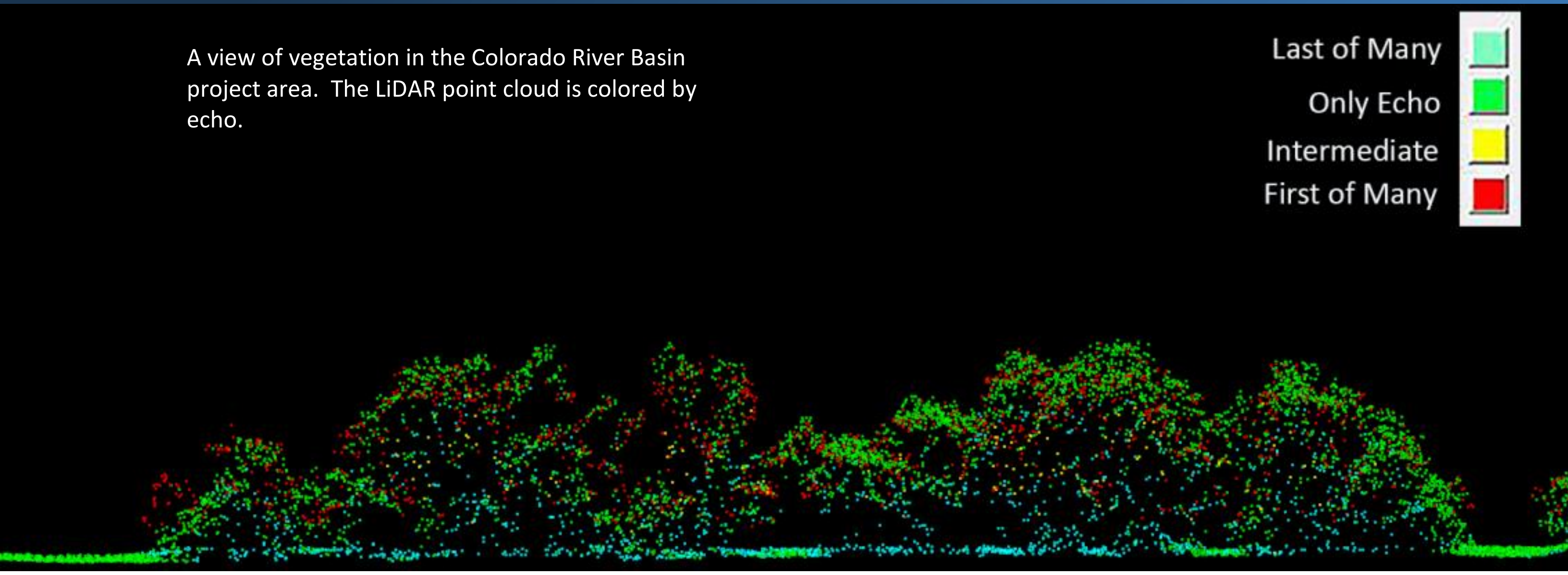


Figure 5: Contours draped over the Colorado River Basin Pre-Pulse bare earth elevation model. Blue contours represent high confidence while the red contours represent low confidence.



A view of vegetation in the Colorado River Basin project area. The LiDAR point cloud is colored by 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. Pulse density distribution varied within the study area due to laser scan pattern and flight conditions. Additionally, 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 Colorado River Basin Pre-Pulse project was 10.67 points/m^2 while the average ground classified density was 5.77 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 6 through Figure 9.

Table 9: Average LiDAR point densities

Classification	Point Density
First-Return	10.67 points/m^2
Ground Classified	5.77 points/m^2

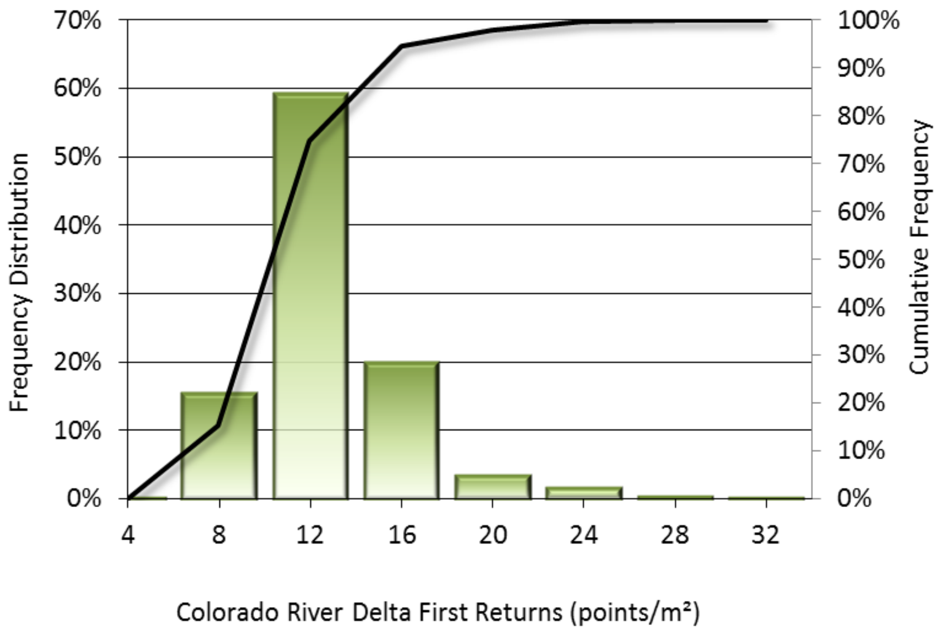


Figure 6: Frequency distribution of first return densities per 100 x 100 m cell

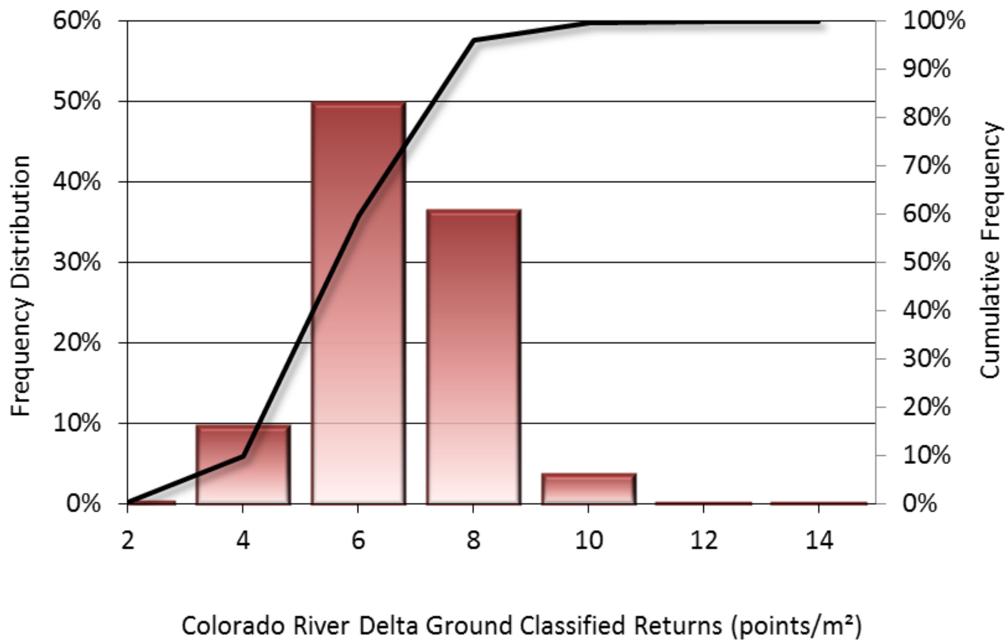


Figure 7: Frequency distribution of ground return densities per 100 x 100 m cell

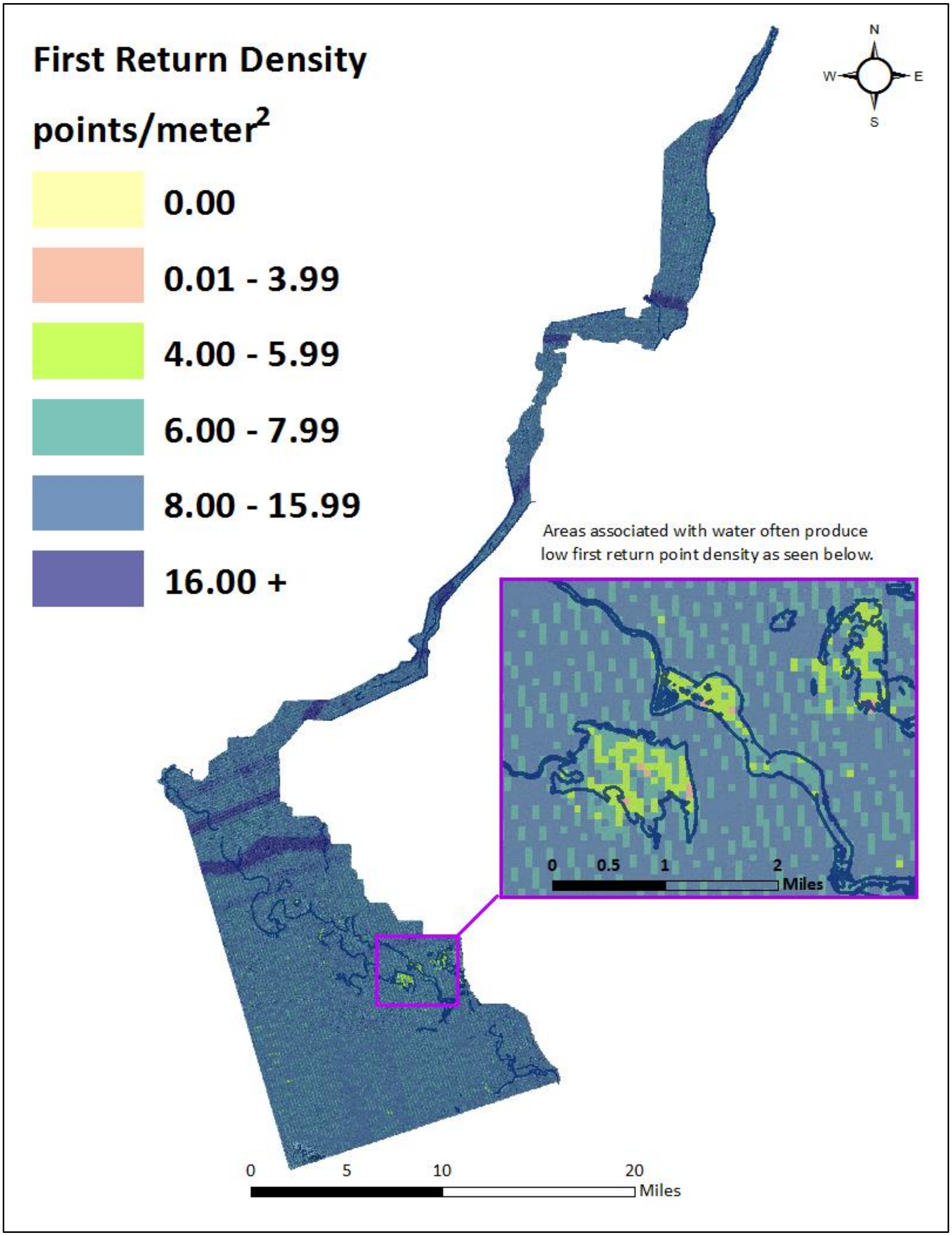


Figure 8: First return density map for the Colorado River Basin Pre-Pulse site (100 m x 100 m cells)

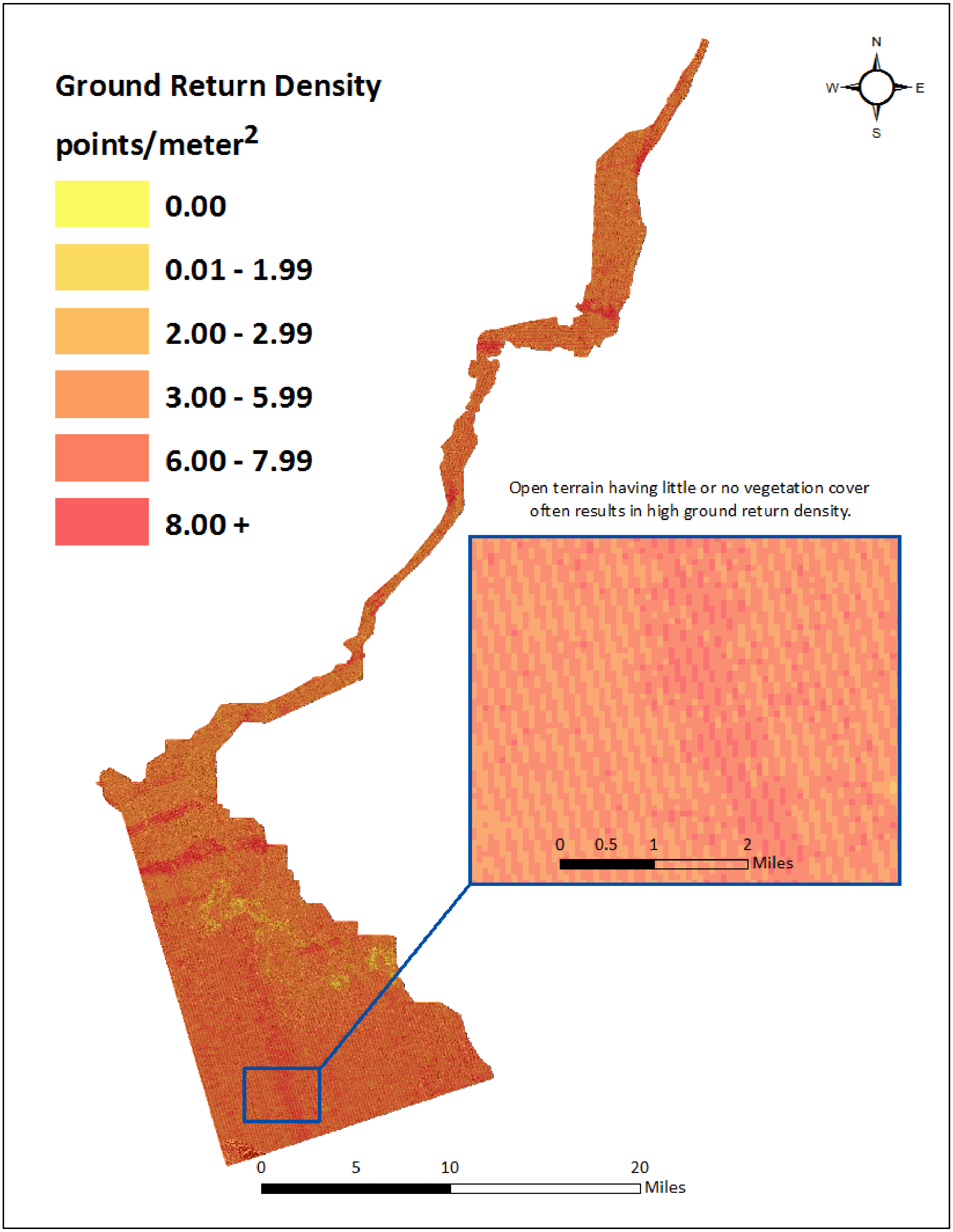


Figure 9: Ground density map for the Colorado River Basin Pre-Pulse site (100 m x 100 m cells)

LiDAR Accuracy Assessment

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). *Accuracy assessment could only be conducted for data within the United States as ground control quality check points were not collected in Mexico by Geo Castellini*. See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Fundamental Vertical Accuracy

Fundamental Vertical Accuracy (FVA) compares known real-time kinematic ground control quality check points 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 high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 10. The required FVA of 18.13 cm was exceeded for this project with a final FVA of 6.3 cm at the 95% confidence interval (Table 10, Figure 10).

Table 10: Absolute accuracy – FVA

Absolute FVA Accuracy	
Sample	131 Points
FVA (1.96*RMSE)	0.063 m
Average	0.002 m
Median	0.000 m
RMSE	0.032 m
Standard Deviation (1σ)	0.032 m

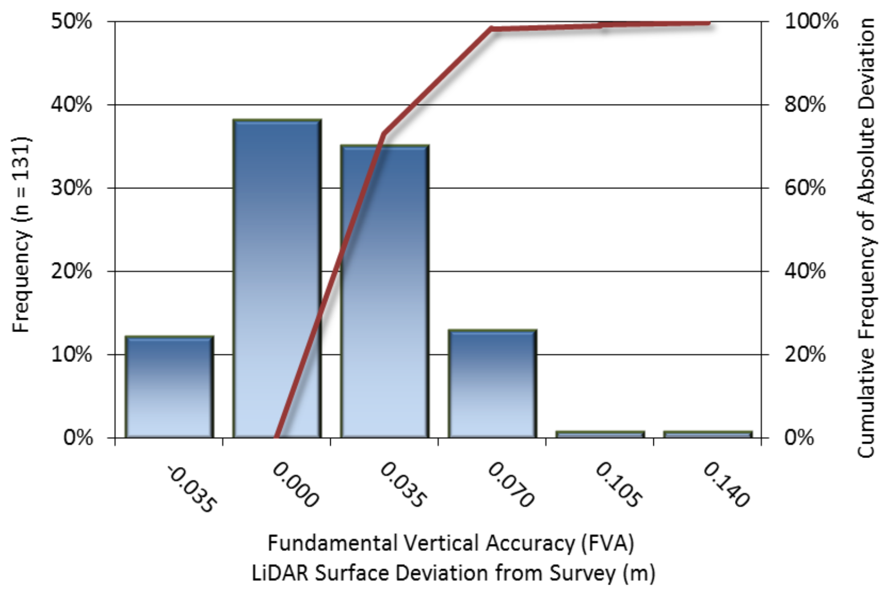


Figure 10: Frequency histogram for LiDAR surface deviation from ground check point values – FVA

LiDAR Supplemental and Consolidated Vertical Accuracies

QSI also assessed absolute vertical accuracy using Supplemental Vertical Accuracy (SVA) and Consolidated Vertical Accuracy (CVA) reporting. SVA compares known ground control quality check point data within individual land cover class categories to the triangulated ground surface generated by the LiDAR points. CVA represents the comparison of all QCPs across all land cover classes to the triangulated ground surface generated by LiDAR points. SVA and CVA are evaluated at the 95th percentile, as shown in Table 11. Frequency histograms for all SVA and CVA accuracies can be seen in Figure 11 through Figure 15.

Table 11: Supplemental Vertical Accuracy

	Bare Earth/Gravel	Tall Grass	Brush/ Shrubland	Urban	CVA
Sample	131 Points	59 Points	76 Points	34 Points	300 Points
Average	-0.020 m	0.004 m	0.010 m	-0.027 m	-0.008 m
Median	-0.018 m	0.001 m	0.004 m	-0.028 m	-0.013 m
RMSE	0.038 m	0.043 m	0.049 m	0.039 m	0.042 m
Standard Deviation (1σ)	0.032 m	0.043 m	0.049 m	0.029 m	0.041 m
95th Percentile	0.077 m	0.088 m	0.115 m	0.064 m	0.065 m

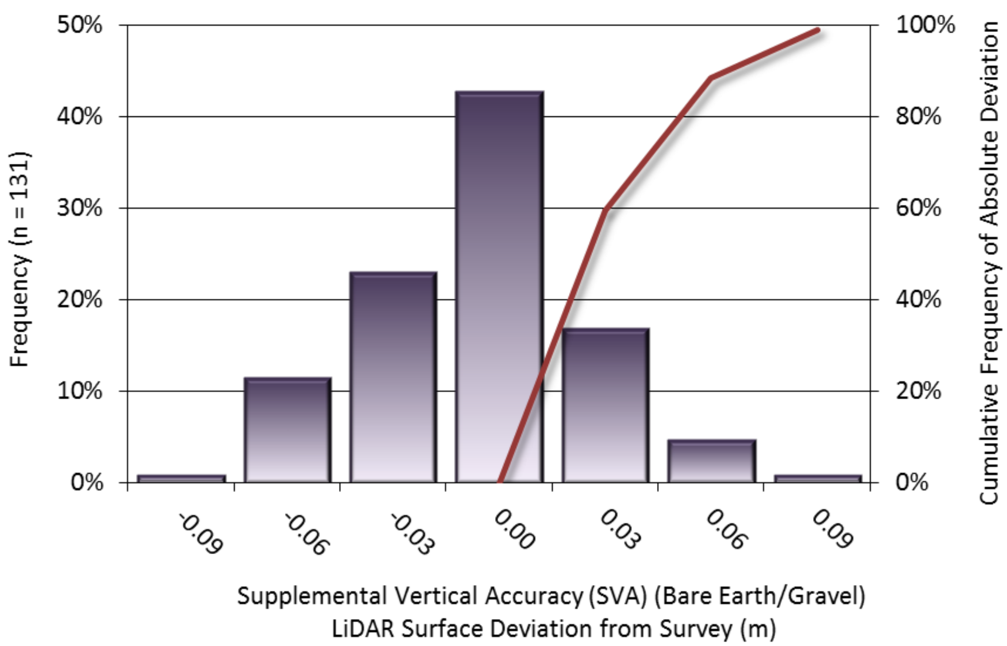


Figure 11: Frequency histogram of LiDAR surface deviation from Bare Earth/Gravel QCP values - SVA

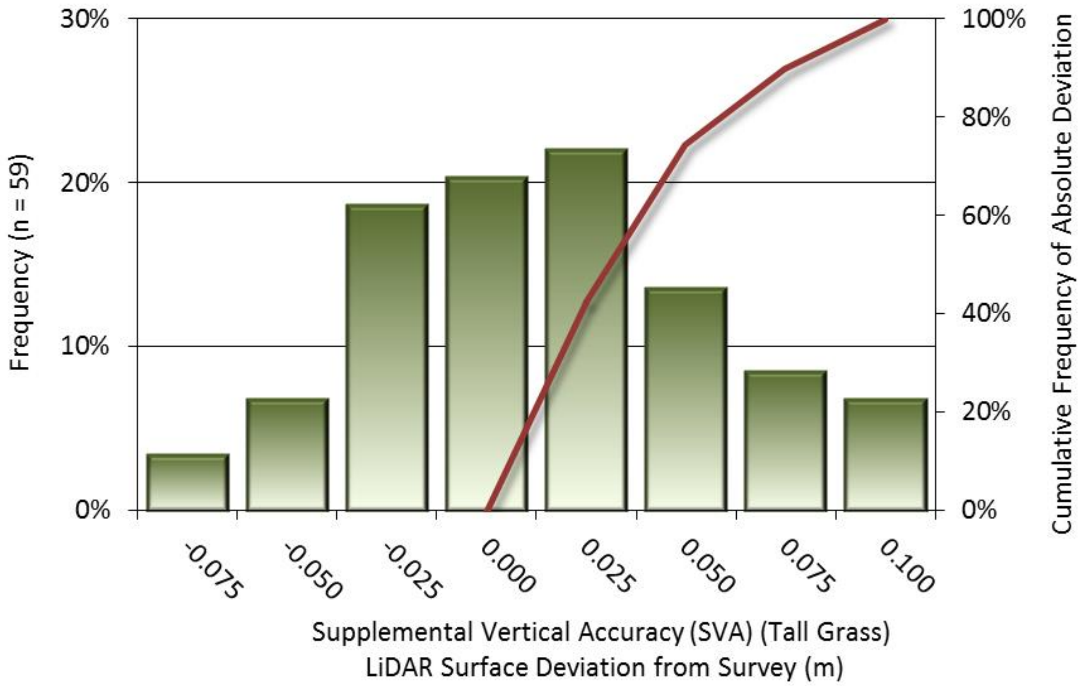


Figure 12: Frequency histogram of LiDAR surface deviation from Tall Grass QCP values - SVA

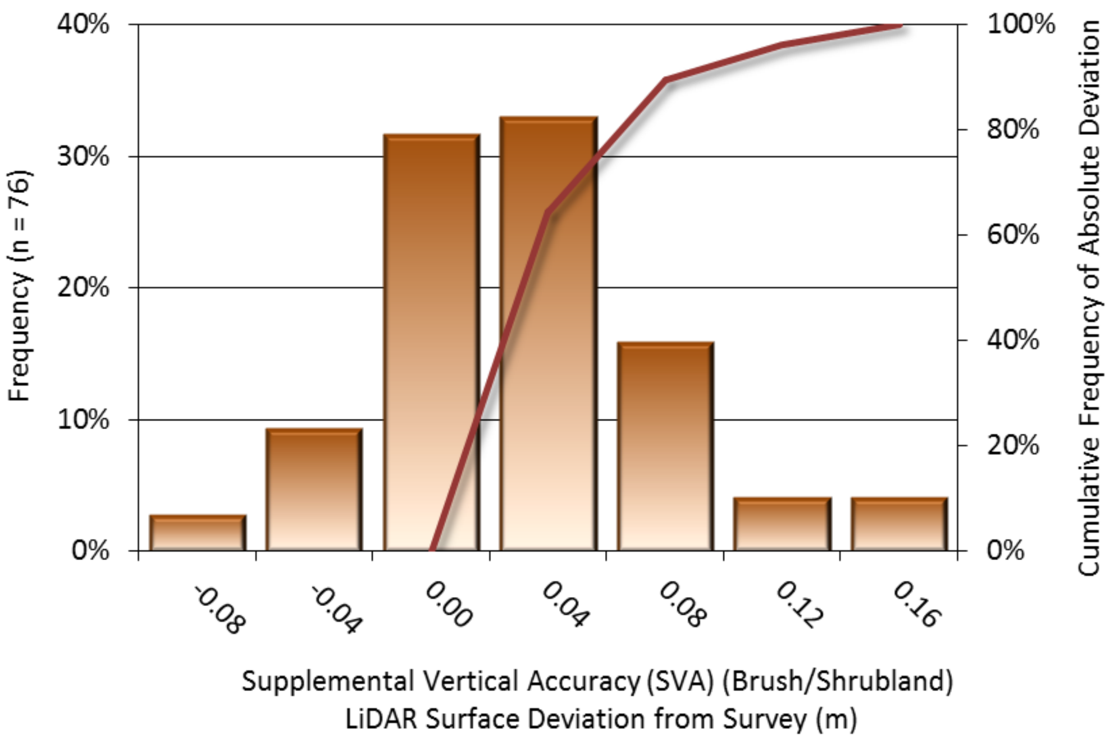


Figure 13: Frequency histogram of LiDAR surface deviation from Brush/Shrubland QCP values - SVA

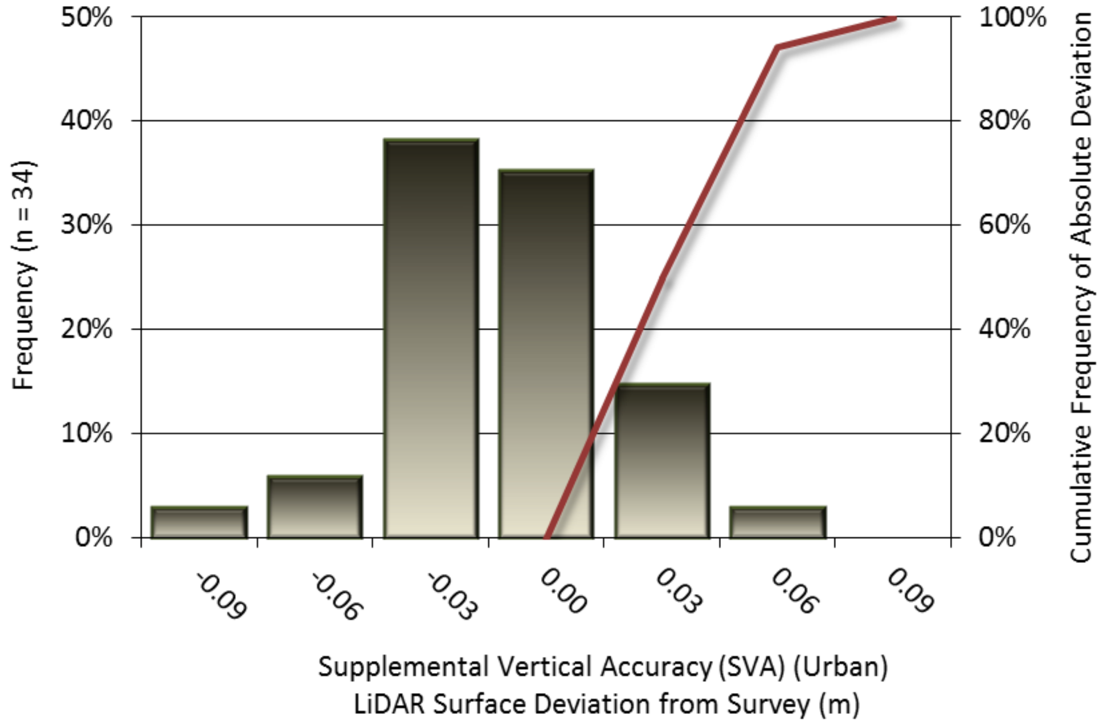


Figure 14: Frequency histograms for LiDAR surface deviation from Urban QCP values – SVA

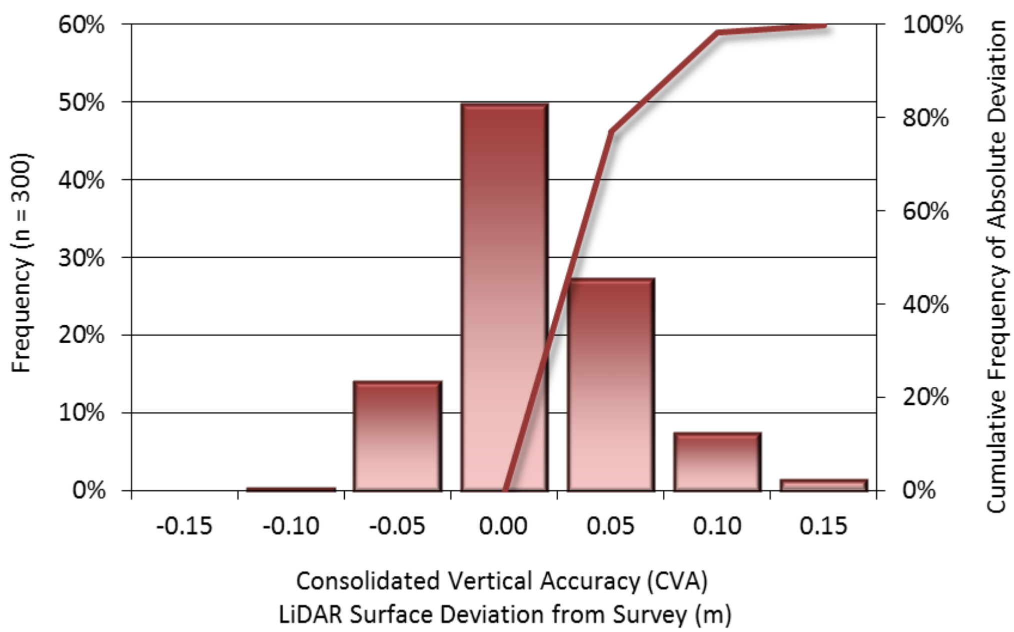


Figure 15: Frequency histogram of LiDAR surface deviation from Land Cover Class QCP values - CVA

LiDAR Vertical Relative 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. Relative accuracy was set to comply with ≤5 cm $RMSE_z$ within individual swaths and ≤8 cm $RMSE_z$ between adjacent swaths. 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 Colorado River Basin Pre-Pulse LiDAR project was 0.032 meters (Table 12, Figure 16).

Table 12: Relative accuracy

Relative Accuracy	
Sample	228 surfaces
Average	0.032 m
Median	0.033 m
RMSE	0.033 m
Standard Deviation (1σ)	0.004 m
1.96σ	0.009 m

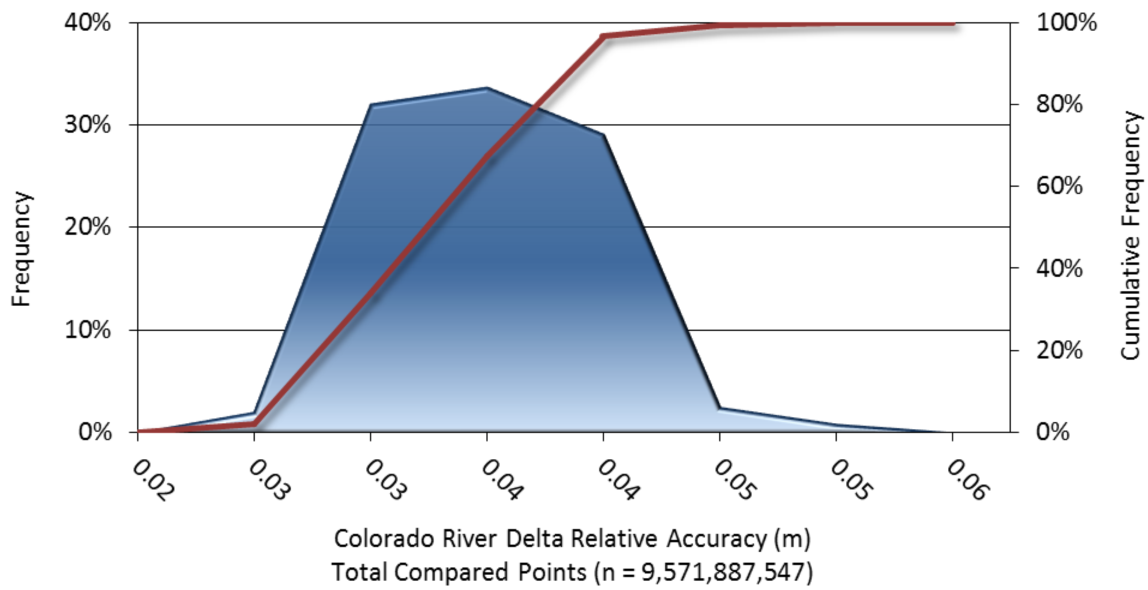


Figure 16: Frequency plot for relative vertical accuracy between flight lines

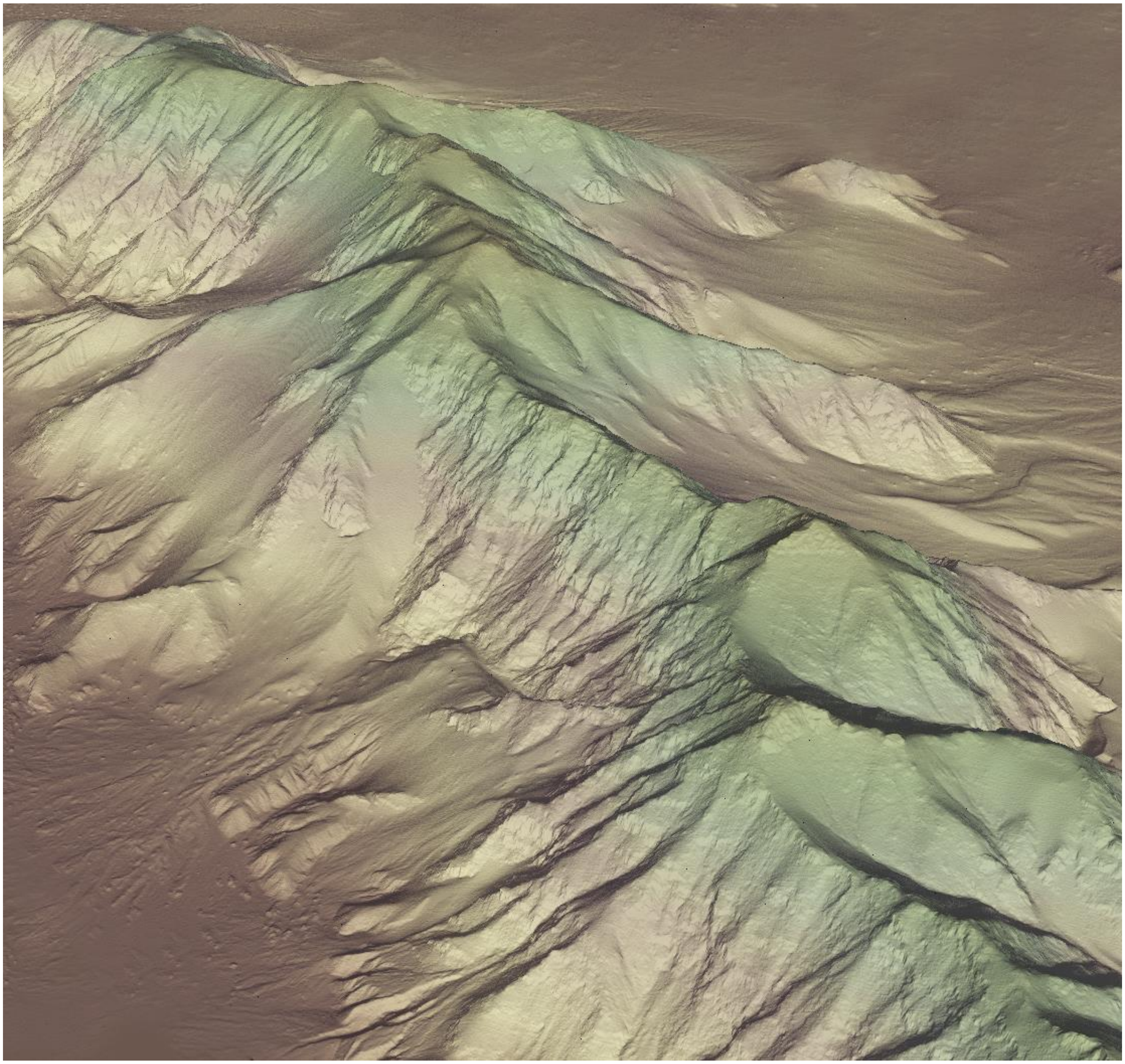


Figure 17: Image looking north-northeast of a mountain range in the Colorado River Basin study area. The image was created from the LiDAR bare earth model colored by elevation.

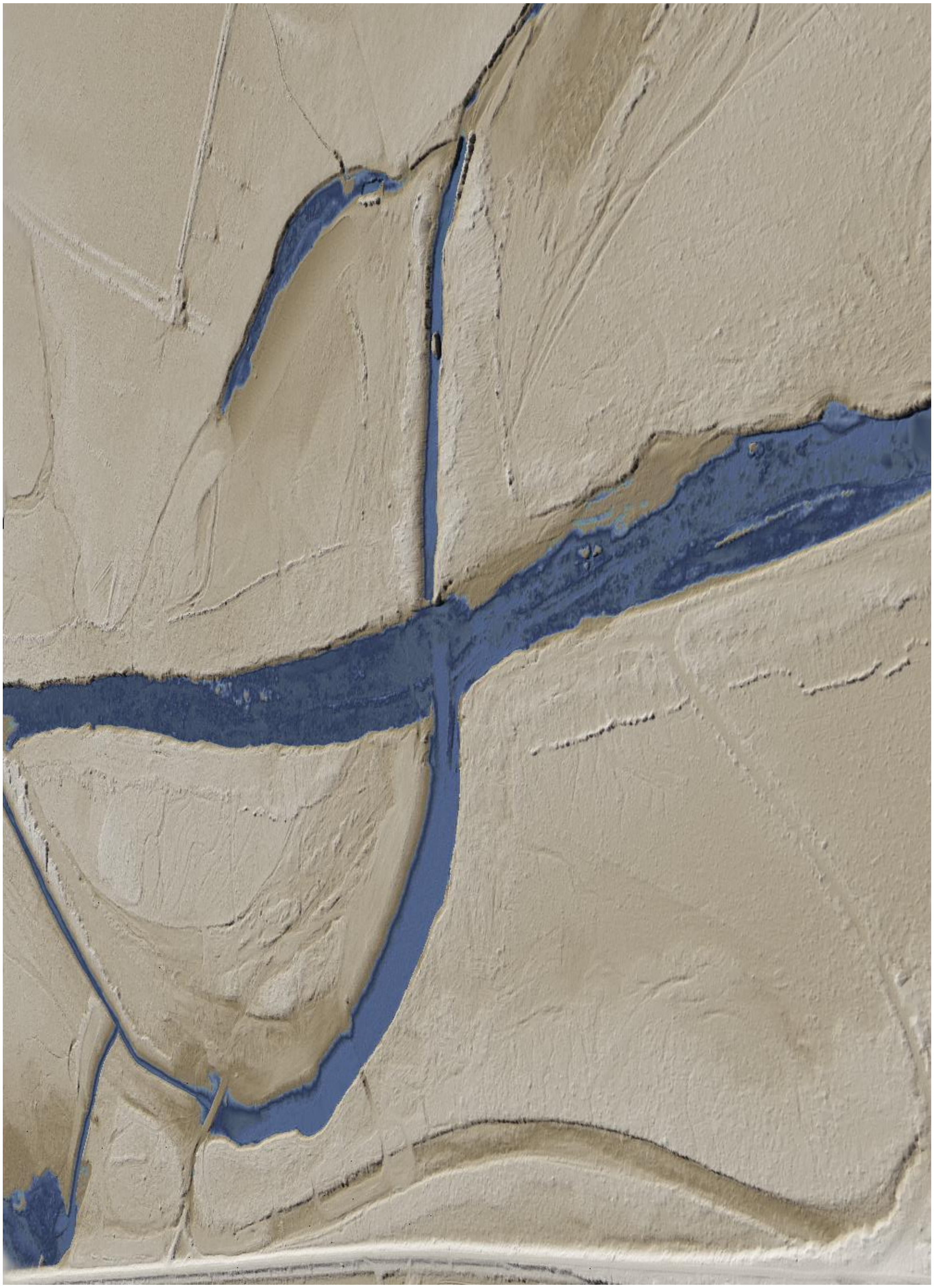


Figure 18: View looking east at the Colorado River, south-southeast of El Vergel. The image was created from the LiDAR bare earth model colored by elevation.

Figure 19: Image shows the Morelos Dam, looking north-northeast. The image was created from the bare earth model colored by elevation, and is overlain with the above-ground LiDAR point cloud.

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 Fundamental 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 laser 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., echos) 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 ±15^{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 nautical miles at all times.

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

50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the nadir portion of one flight line coincides with the swath edge portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

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

APPENDIX B - GEO CASTELLINI GROUND SURVEY REPORT

GEO CASTELLINI

ING. YALEXY GUERRA CASTELLINI

ING. FOTO-TOPÓGRAFO

TECHNICAL REPORT

MEXICALI, BC. MEXICO
MARCH 2014

PROJECT

COLORADO RIVER BASIN
TERRESTRIAL CONTROL
GPS

Calle Baralla #169 Fracc Villa Lomas Altas 3ra secc cp 21355, Mexicali, B. C., Cell: (686) 1575830
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Summary

The measurement of Geodetic Control Points was primarily carried out in the Mexicali Municipal, B.C. specifically in the agricultural zone Mexicali Valley at the edge of the Colorado River Delta with dual frequency GPS equipment, brand Topcon model GR3, measuring four vertices "**CRB**" of control, designated **CRB1, CRB2, CRB3, ARE1**.

The static measurements were recorded at intervals of 1", with various sessions taking place on different days at various hours. Additionally, the measurement of diverse control points as real time kinematic (RTK) designated as "GCP" were taken. Serving as an initial reference, the absolute coordinates of these points were used to later recalculate the final GCP coordinates from the four points mentioned above.
The work consisted in the localization, Monumentation and field measurement of each control point, based on the approximate coordinates that were provided by the Sonora Institute.

The general procedure was as follows:

a.) Obtain information (approximate coordinates) of the points of interest.
b.) Localization of the points of interest to Monument.
c.) Monumentation of each one of the points according to the requested method (concrete monument with aluminum plate).
d.) In field measurement of all of the points to be used.
e.) Daily delivery of the raw data by internet for analysis and/or revision.
f.) Receipt of the definitive coordinates of the four monuments "**CRB**".
g.) Using the four monuments, recalculate the "**GCP**" coordinates.
h.) Prepare a report.

GENERAL OBJECTIVE:

Provide terrestrial support based on satellite measurements from dual frequency GPS, utilizing both Glonass and Navstar constellations, and recording at 1 Hertz intervals over four concrete monuments for the support of LiDAR acquisition in the zone known as Mexicali Valley and/or the Colorado River Delta.

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STUDY AREA LOCATION:

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WORK CARRIED OUT

MONUMENTATION:

Before carrying out the measurements, four control landmarks were created from 40 cm length rods with an aluminum plate 2 inches in diameter and 2 inches thick (pyramid form); the majority of the monuments sat 5 cm above the ground surface. The location of these were as close as possible to those provided by the Sonora Institute, the criteria for the location of each landmark was to ensure their permanence and included: highest place with least obstruction at an angle of 15 degrees above the horizon.

Photos of the plate:

Photos of the locations during the process of monumentation:

CRB1

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CRB2

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CRB3

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ARENITAS

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MEASUREMENT:

Control Points (CRB)

To carry out the control point measurements a dual frequency GPS receiver was used (Topcon brand, model GR3 with dual constellation capability) with wooden tripod for centering and leveling. The procedure was to measure receiver height from the center of the aluminum plate to three different corners of the receiver as slant height, recording the measurements on paper and/or field document, with differences not exceeding one millimeter, the final height is considered their average.

To guarantee stability during measurement periods the tripod feet were reinforced with sand filled bags or heavy rocks, placed to minimize the influence of winds in this area. To supply power to the equipment an external battery was used that would be sufficient during the period of measurement.

Ground control points (GCP)

To carry out the ground control point measurements a dual frequency GPS receiver was used (Topcon brand, model GR3 with dual constellation capability) with a bipod containing a marker at 2 m plus an adapter (Quik adapter) with a height of 0.04 m which resulted in a total vertical height of 2.04 m.

For point measurements the techniques for measuring RTK were used. The closest Control Point (CRB) was used as a point of reference while measuring each of the GCPs; in some of the requested areas for GCP measurement more than one CRB was used as reference, where existing landmarks were present; these points were marked with a nail and tag.

It is worth mentioning that the only point that was not possible to measure among those provided was point No. 12, the reason being that the roads leading to it had been destroyed, alternatively two points were taken as close to the requested area as possible, these points are GCP 12 P and GCP 12 PB.

Documents of each survey are attached containing each point measured in static mode.

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Photos of the locations during the process of monumentation:

CRB1

CRB2

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CRB3

ARENITAS

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CALCULATIONS:

In order to recalculate the coordinates of the GCP points collected during the survey the software Magnet Field was used. Final coordinates for each monument were received from the Sonora Institute. These points were entered into the program in order to modify the initial GCP coordinates taken in the field.

RESULTS

SURVEY SUMMARY

Gregorian Day	Julian Day	Pto Base	Period of Measurement (Real)	Hrs of Measurement	RTK SURVEY	BASE HEIGHT
March 7	66	CRB 3	8:27 - 5:06	8:38		1.4466
8	67	CRB 3	8:05 - 5:02	8:56	*	1.585
11	70	CRB 3	8:20 - 5:00	8:40		1.602
12	71	CRB 3	8:37 - 13:40	5:09		1.5233
13	72	CRB 2	8:27 - 17:04	8:36	*	1.547
14	73	CRB 2	8:08 - 16:03	7:54		1.5366
15	74	CRB 1	8:25 - 18:52	10:26	*	1.5836
16	75	CRB 1	8:13 - 17:10	8:57		1.5383
17	76	CRB 1	7:54 - 16:42	8:47	*	1.5563
18	77	CRB 1	8:07 -15:14	7:06		1.498
19	78	CRB 1	8:10 - 16:04	7:55		1.545
20	79	ARE 1	8:10 - 15:04	6:53	*	1.7133
21	80	ARE 1	8:00 -12:00	4:00		1.758
			TOTAL HOURS OF MEASUREMENT	**101:57:00**		

*.- Days in which RTK measurements were taken

GCP COORDINATES REFERENCED TO THE FINAL CRB COORDINATES

ID	X	Y	Z
ARE1	657353.717	3578977.909	-18.87
CRB1	668385.175	3538610.523	-27.074
CRB2	673539.568	3564137.776	-23.519
CRB3	690441.106	3584734.23	-12.765
GCPARE4	655206.2	3588196.868	-23.626
GCPARE5	656171.792	3588438.692	-13.751
GCPARE6	660096.692	3588916.902	-22.124
GCP017A	670074.375	3532962.206	-31.052
GCP11	672373.971	3525180.484	-23.5
GCP017	670062.925	3532958.467	-27.985
GCP5	664868.78	3550395.621	-26.367
GCP5A	664856.078	3550404.978	-29.542
GCP1	661788.94	3558721.913	-28.198
GCP1A	661794.713	3558714.172	-25.957
GCP1A1	661804.375	3558709.59	-28.946
NO19	661439.551	3558573.879	-29.007
GCP8	680305.399	3547413.368	-29.195
GCP10	686468.761	3544652.198	-29.369
GCP10A	686463.625	3544643.811	-31.806
GCP14	690342.527	3539018.522	-29.818
GCP13	691905.088	3538043.931	-29.595
GCP13A	691904.518	3538034.41	-31.567
GCP12P	692478.522	3536350.214	-31.363
GCP12PB	692514.956	3536466.806	-31.299
GCP9	683314.748	3545877.248	-31.291
GCP9A	683324.368	3545893.886	-29.475
GCP19	682492.243	3567717.951	-20.521
GCP18	674404.857	3564443.91	-21.724
GCP7A	677246.624	3552380.206	-28.743
GCP18A	674404.071	3564450.601	-23.642
GCP20A	682497.744	3567734.152	-19.163
GCP21	682267.909	3569515.651	-20.809
GCP21A	682275.241	3569539.615	-19.035
GCP030	685343.005	3574147.563	-18.944
GCP030A	685343.423	3574176.956	-14.976
GCP031	683704.662	3566569.938	-20.555
GCP031A	683692.717	3566577.749	-19.612

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GCP16	674476.764	3554648.168	-30.206
GCP6	675584.075	3552675.164	-30.204
GCP16A	674483.432	3554656.208	-27.37
GCP6A	675592.499	3552677.973	-27.96
GCP7	677241.071	3552375.713	-30.548
GCP 026	702549.021	3598140.496	-4.301
GCP 027	705011.701	3597323.045	-7.746
GCP 027B	705082.21	3597296.033	-8.089
GCP 028	703891.26	3594843.204	-6.236
GCP 029	695765.234	3594759.368	-10.322
GCP 029B	695764.373	3594775.543	-9.266
GCP 024	692321.683	3583157.934	-13.586
GCP 022	691061.241	3581117.09	-15.636
GCP 023	690946.683	3582188.837	-15.559
GCP 23B	690965.908	3582157.912	-14.475
GCP2	663406.088	3555224.559	-25.908
GCP2B	663422.937	3555235.106	-30.05
GCP20	683922.417	3568420.907	-18.859
GCP020A	683903.591	3568403.28	-20.743
GCP020B	683910.678	3568454.742	-18.609
GCP021A	682275.304	3569539.857	-19.349
GCP4	671860.501	3564345.113	-26.386
GCP4A	671836.843	3564361.815	-26.002
GCP4A1	671888.127	3564362.418	-25.936
GCP4A2	671902.277	3564337.391	-22.568
GCP25	694214.462	3596155.827	-8.062
GCP25A	694215.299	3596152.406	-8.314
GCP25B	694213.601	3596159.277	-8.125
GCP25C	694203.794	3596186.619	-9.282
GCP25D	694217.146	3596144.155	-9.06
MOJR	690422.793	3584762.406	-15.185
GCPARE1A	657775.723	3579267.389	-23.106
GCPARE1	657771.588	3579337.448	-23.181
GCPARE2A	659306.655	3579791.183	-24.37
GCPARE2B	659261.01	3580011.205	-22.418
GCPARE2C	659267.942	3580007.977	-24.408
GCPARE2	659265.48	3579968.313	-24.352
GCPARE3	660895.306	3580804.95	-24.462

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With thanks:

Ing. Yalexy Guerra Castellini

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