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River Design Group
Montana, Summer 2008

LiDAR Remote Sensing Data Collection:
Montana

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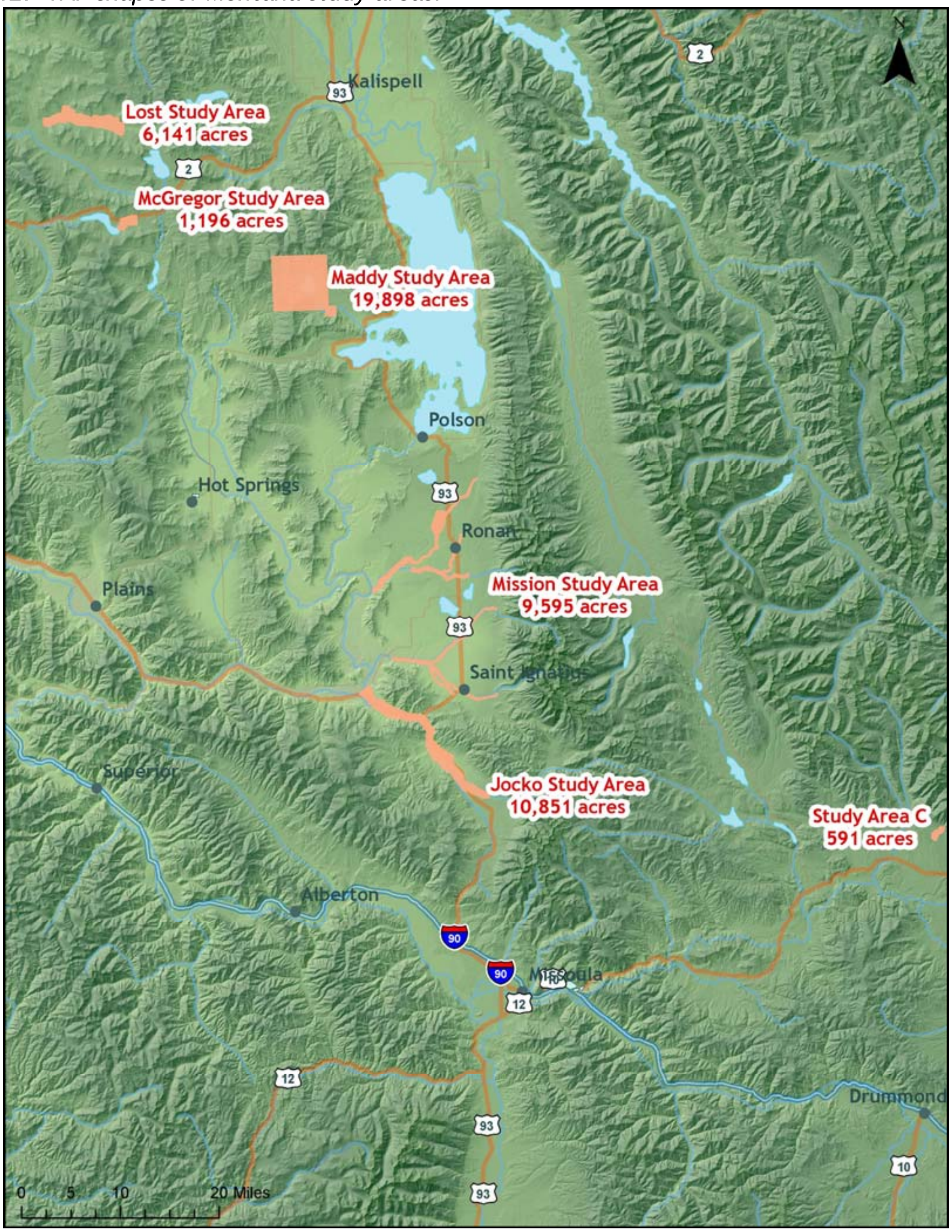
1. Overview

1.1 Study Area

Watershed Sciences, Inc. collected Light Detection and Ranging (LiDAR) data in Montana for this delivery to River Design Group. The area of interest (AOI) requested by River Design Group totals 48,272 acres. For optimal flight planning, this area has been buffered into a total area flown (TAF) shape of 56,260 acres. Table 2.2 breaks down these AOI and TAF acres by study area.

Figure 1.1. TAF shapes of Montana study areas.



1.2. Data Format, Projection, and Units

Projection: Montana State Plane (FIPS 2500)
Vertical datum: NAVD88
Horizontal datum: NAD83
Units: US Survey Feet
Delineation: processing bins

Deliverables include:

- Report of data collection methods and summary statistics
- 3-foot resolution bare earth digital elevation model in ESRI grid format
- 3-foot resolution highest hit digital elevation model in ESRI grid format
- All return and ground classified points in ASCII format with fields: GPS week, GPS second, easting, northing, elevation in .las v1.1 format

1.3. Overview of Statistics

The absolute accuracy range for all study areas delivered is 3 – 6 centimeters (.15 to .28 feet), and the expected was <13 centimeters. The pulse density range was 7.68 – 10.3 points per square meter; the contracted density was >8 points per square meter.

2. Acquisition

2.1. Airborne Survey Overview – Instrumentation and Methods

The LiDAR survey utilized a Leica ALS50 Phase II sensor mounted in a Cessna Caravan. The Leica ALS50 Phase II system was set to acquire ≥105,000 laser pulses per second (i.e. 105 kHz pulse rate) and flown at 900 meters above ground level (AGL), capturing a scan angle of ±14° from nadir[1]. These settings are developed to yield points with an average native density of ≥8 points per square meter over terrestrial surfaces. The native pulse density is the number of pulses emitted by the LiDAR system. Some types of surfaces (i.e., dense vegetation or water) may return fewer pulses than the laser originally emitted. Therefore, the delivered density can be less than the native density and vary according to distributions of terrain, land cover, and water bodies.

The completed areas were surveyed with opposing flight line side-lap of ≥60% (≥100% overlap) to reduce laser shadowing and increase surface laser painting. The system allows up to four range measurements per pulse; all discernable laser returns were processed for the output dataset.

To solve for laser point position, an accurate description of aircraft position and attitude is vital. Aircraft position is described as x, y, and z and measured twice per second (2 Hz) by an onboard differential GPS unit. Aircraft attitude is measured 200 times per second (200 Hz) as pitch, roll, and yaw (heading) from an onboard inertial measurement unit (IMU).

Table 2.1. LiDAR Survey Specifications

Sensor	Leica ALS50 Phase II
Survey Altitude (AGL)	900 m
Pulse Rate	>105 kHz
Pulse Mode	Single
Mirror Scan Rate	52.2 Hz
Field of View	28° (±14° from nadir)
Roll Compensated	Up to 20°
Overlap	≥100% (60% Side-lap)

2.1.1. Acquisition Specifics of Delivery

LiDAR data was collected on June 8, 9, 12, 13, and 14, 2008, as permitted by weather conditions.

Table 2.2. Delivery areas by TAF and AOI Acres with dates flown.

Delivery Areas	*AOI Acres*	*TAF Acres*	*Dates flown*
Jocko River	*10,851*	*12,436*	*June 8, 2008*
Maddy River	*19,898*	*20,996*	*June 13, 2008* *June 14, 2008*
Mission	*9,595*	*14,447*	*June 9, 2008* *June 12, 2008*
Lost Trail	*6,141*	*6,975*	*June 14, 2008*
Area C	*591*	*765*	*June 13, 2008*
McGregor	*1,196*	*1,441*	*June 14, 2008*

[1] Nadir refers to a vector perpendicular to the ground directly below the aircraft. Nadir is commonly used to measure the angle from the vector and is referred to as "degrees from nadir".

Figure 2.1. Jocko River study area flightlines.

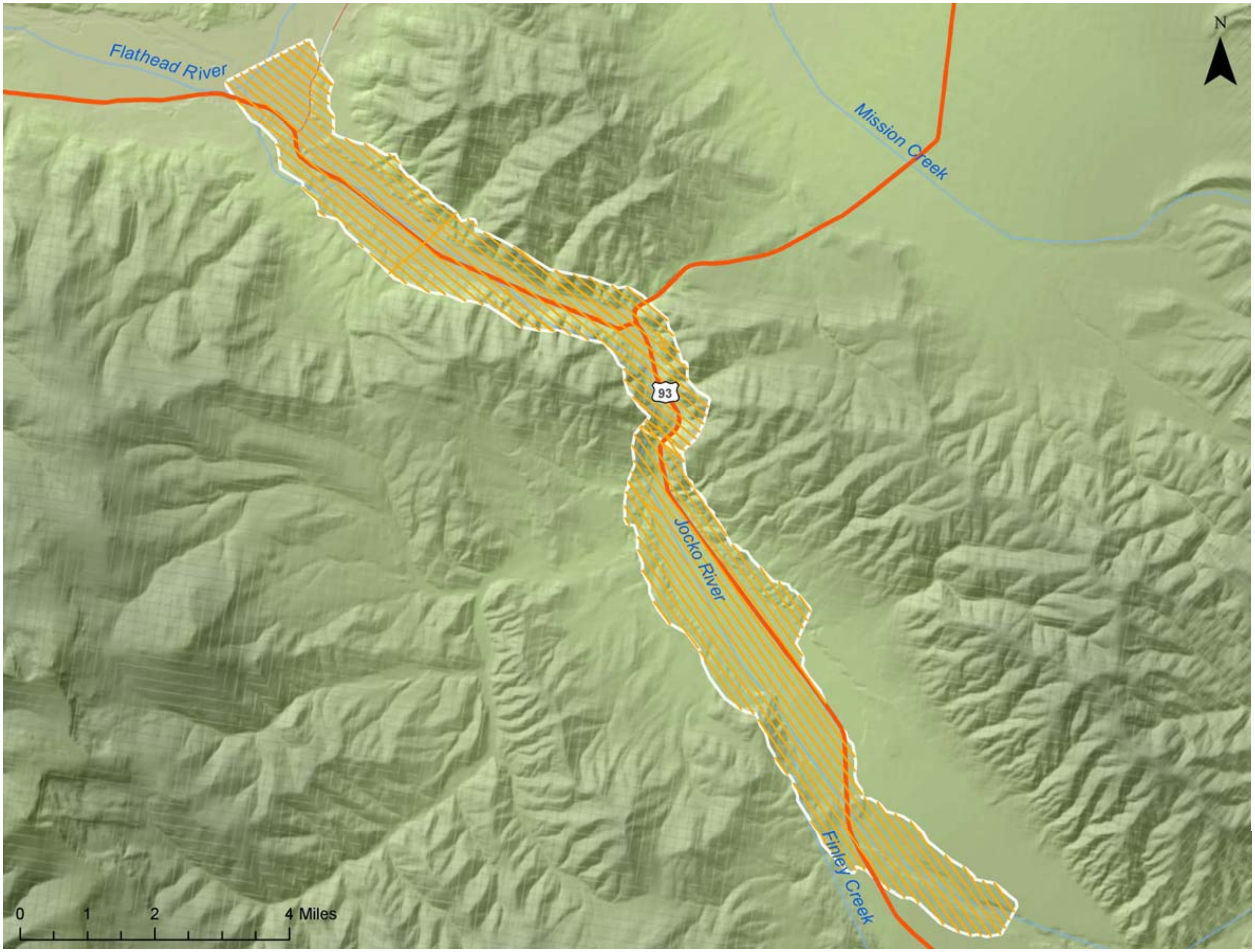


Figure 2.2. Maddy River study area flightlines.

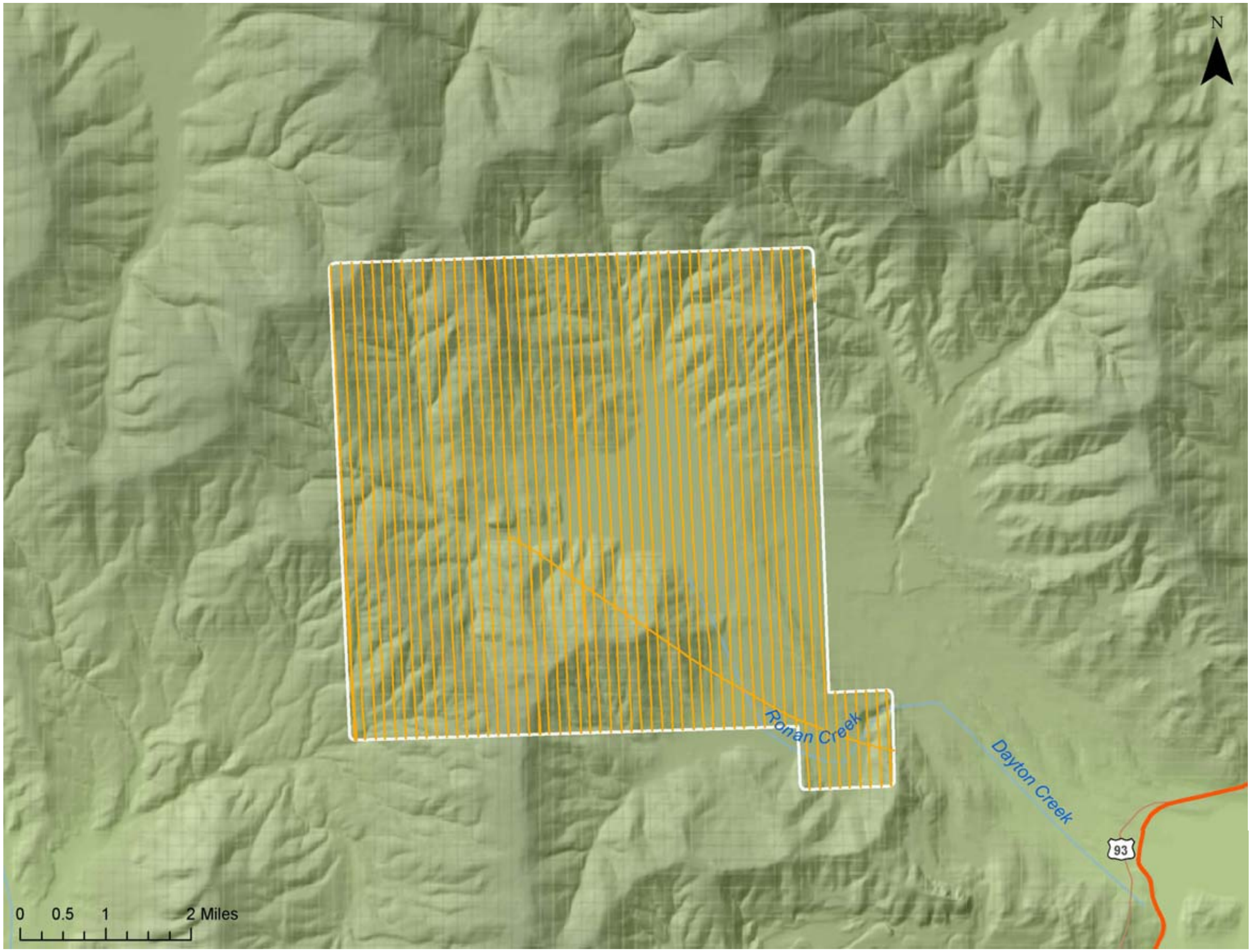


Figure 2.3. Lost and McGregor study area flightlines.

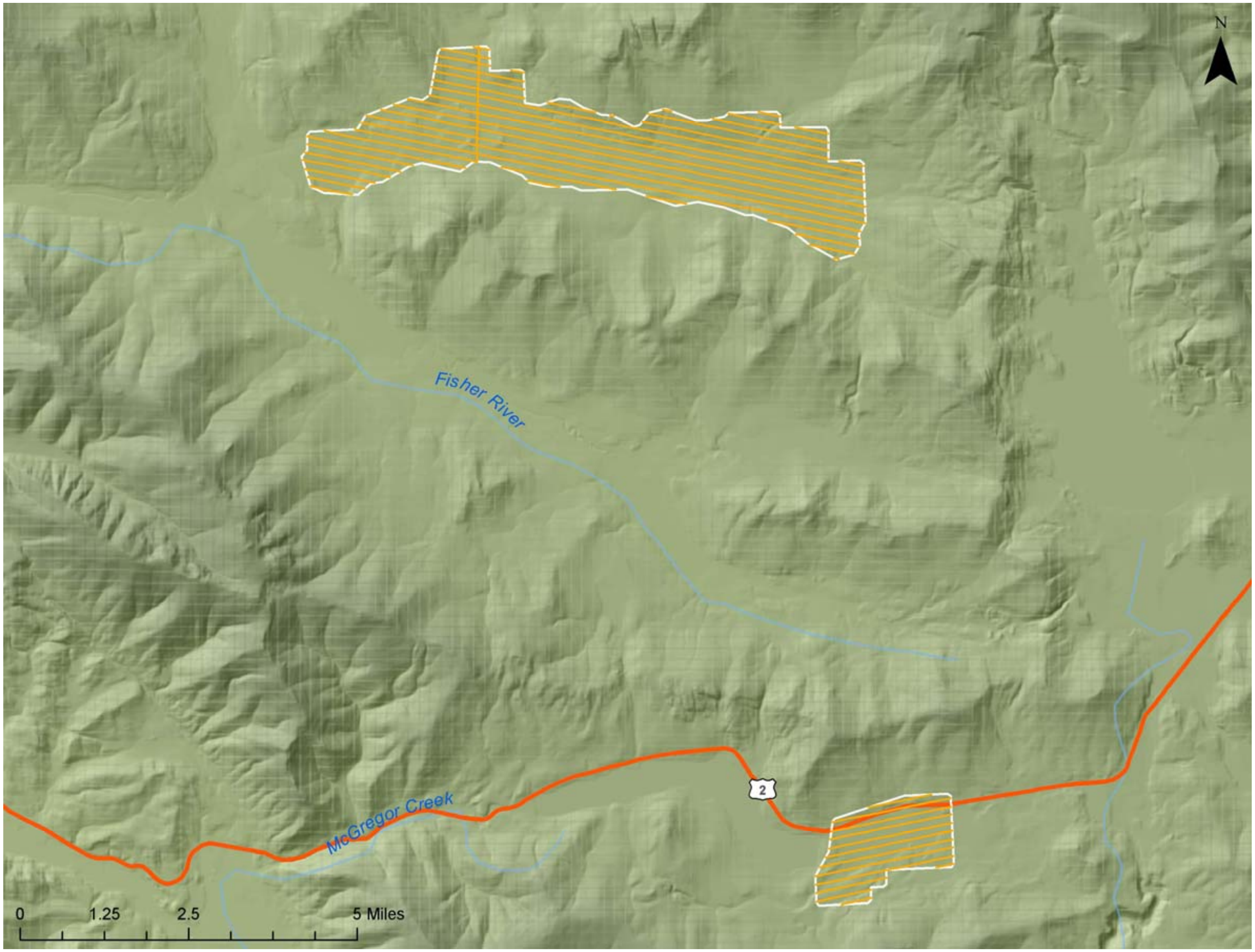


Figure 2.4. Mission study area flightlines.

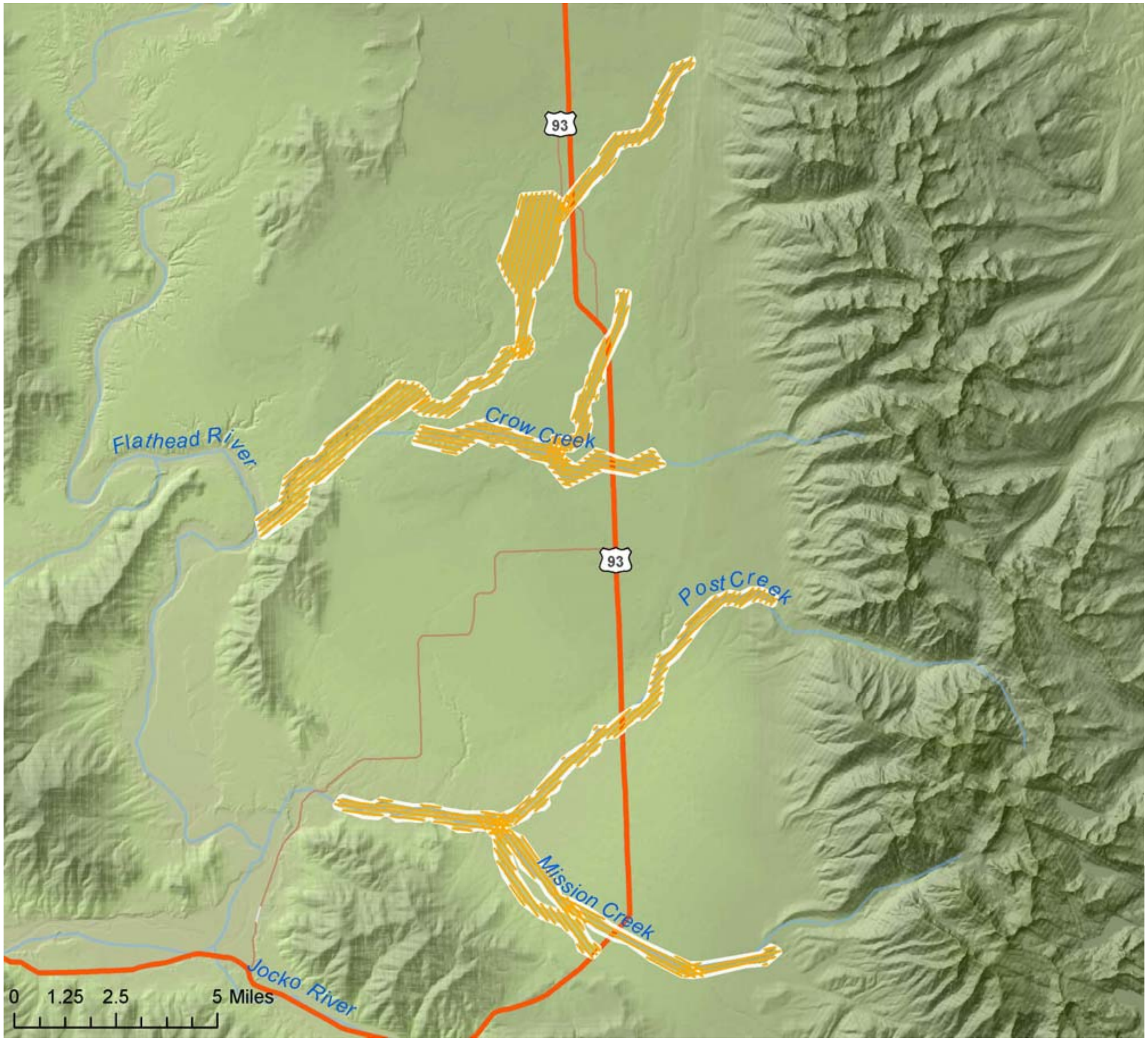
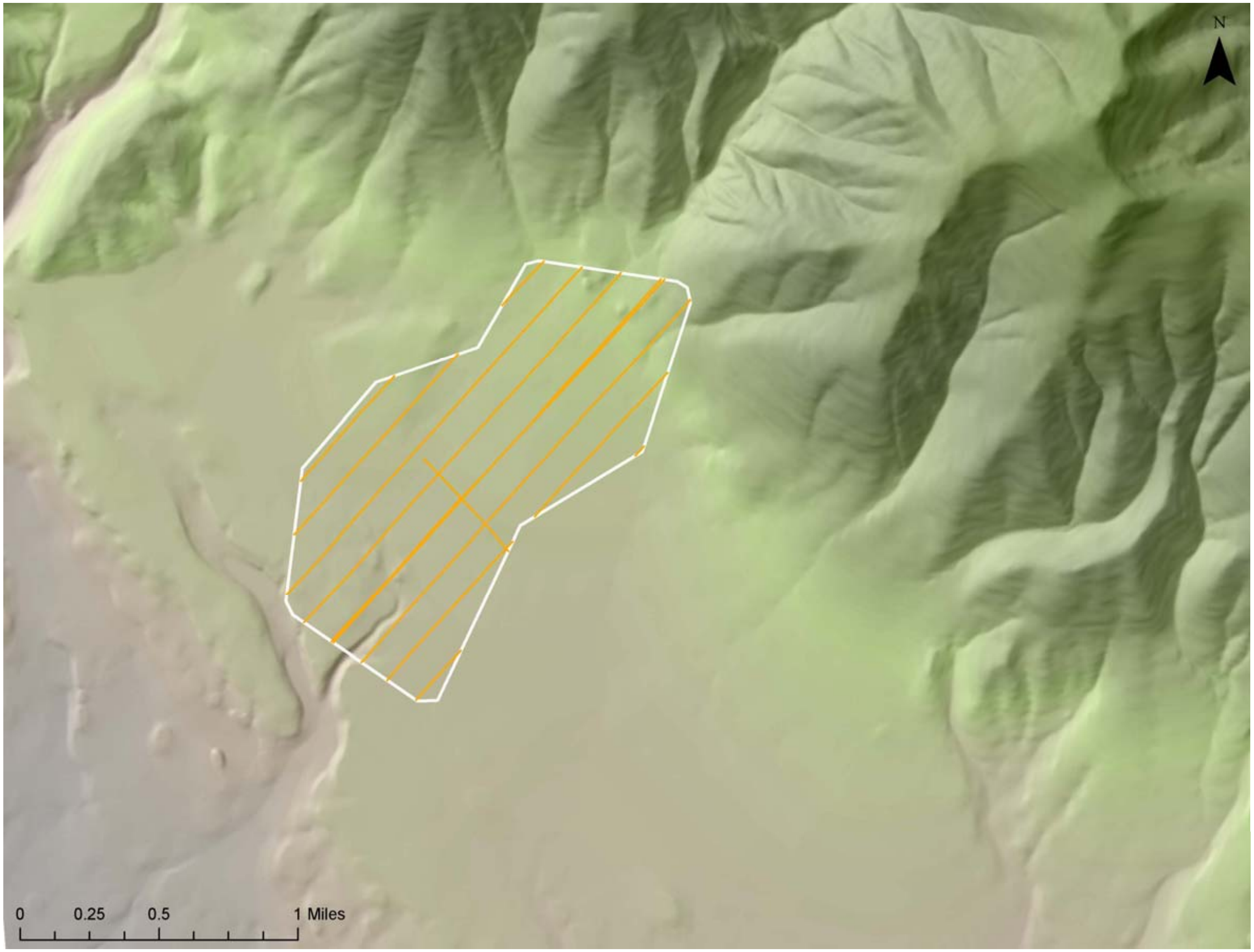


Figure 2.5. Area C flightlines.



2.2. Ground Survey – Instrumentation and Methods

During the LiDAR survey, static (1 Hz recording frequency) ground surveys were conducted over monuments with known coordinates. Monument coordinates are provided in Table 2.3 and shown in Figures 2.6– 2.12. After the airborne survey, the static GPS data are processed using triangulation with CORS stations and checked against the Online Positioning User Service (OPUS[2]) to quantify daily variance. Multiple sessions are processed over the same monument to confirm antenna height measurements and reported position accuracy.

River Design Group, Inc. conducted the ground survey for this data acquisition. RTK ground points were collected for each study area and compared by area to LiDAR data for accuracy assessment using a total of 2732 points. Figures 2.6 – 2.9 show base station locations and Figures 2.10 – 2.12 detail selected RTK point locations.

Table 2.3. Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data for River Design Group's Montana study areas.

Base Station ID	Datum: NAD83 (CORS96)		GRS80
	Latitude	Longitude	Ellipsoid Z (meters)
Asfalof	47 19 01.519	114 18 56.711	753.222
JD56	47 08 33.375	114 02 57.988	970.029
Gloin	47 14 41.493	114 10 56.925	876.009
Squigley	47 23 04.995	114 04 30.593	848.059
1002Field	47 30 41.550	114 09 57.653	898.383
1008Mission	47 22 36.801	114 16 03.406	778.734
MIS_AIR	46 55 19.401	114 05 02.608	961.268
1000Airport	47 34 36.668	114 05 30.955	931.359
MADDY_3	47 56 12.269	120 24 38.672	1083.154
MADDY_5	47 55 49.823	123 28 26.971	1254.604
MADDY_7	47 56 12.269	120 24 38.067	1196.486
MADDY_9	47 56 02.598	114 25 55.336	1172.034
GLIN1	48 18 20.735	114 15 01.944	886.960
D101	47 01 09.587	113 07 52.696	1237.113
Dick1	47 04 35.756	113 05 22.398	1386.714
McGregor	48 01 43.499	114 47 27.194	1184.309
Lost Trail 2	48 10 36.354	114 51 40.157	1095.839

[2] Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

Figure 2.6. Base station locations for the Jocko River study area displayed on a 30 meter DEM.

Figure 2.7. Base station locations for the Maddy River study area displayed on a 30 meter DEM.

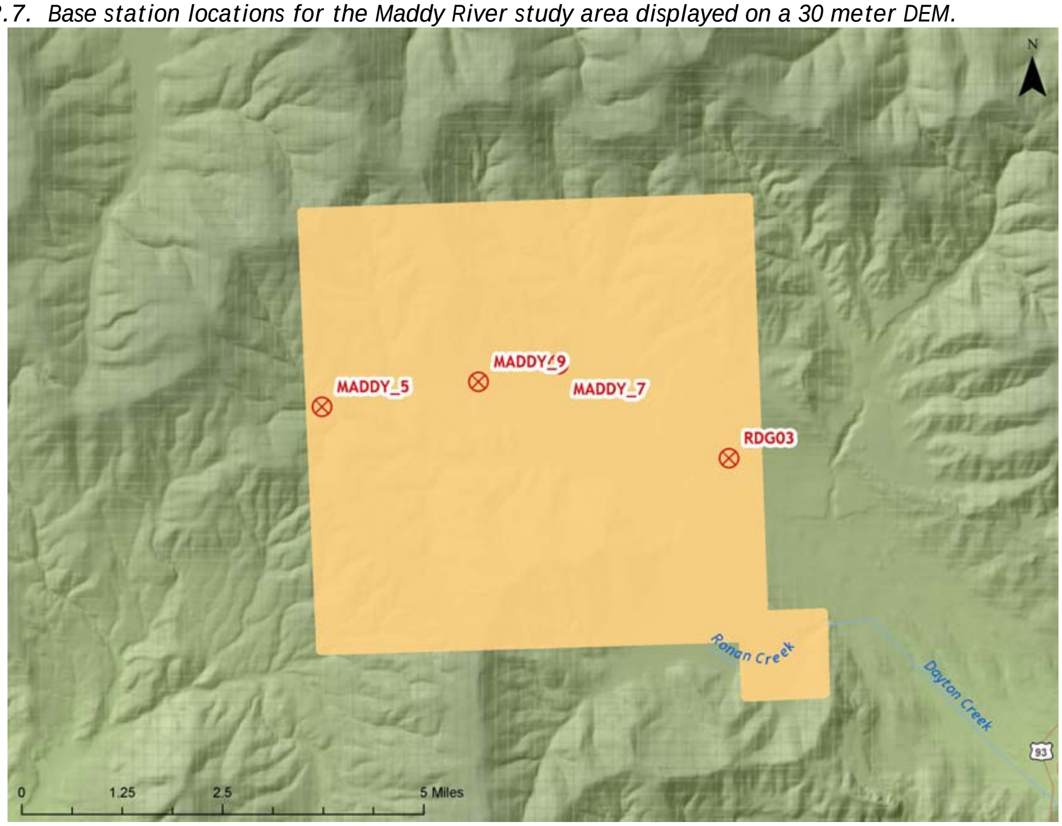


Figure 2.8. Base station locations for the McGregor and Lost study areas displayed on a 30 meter DEM.

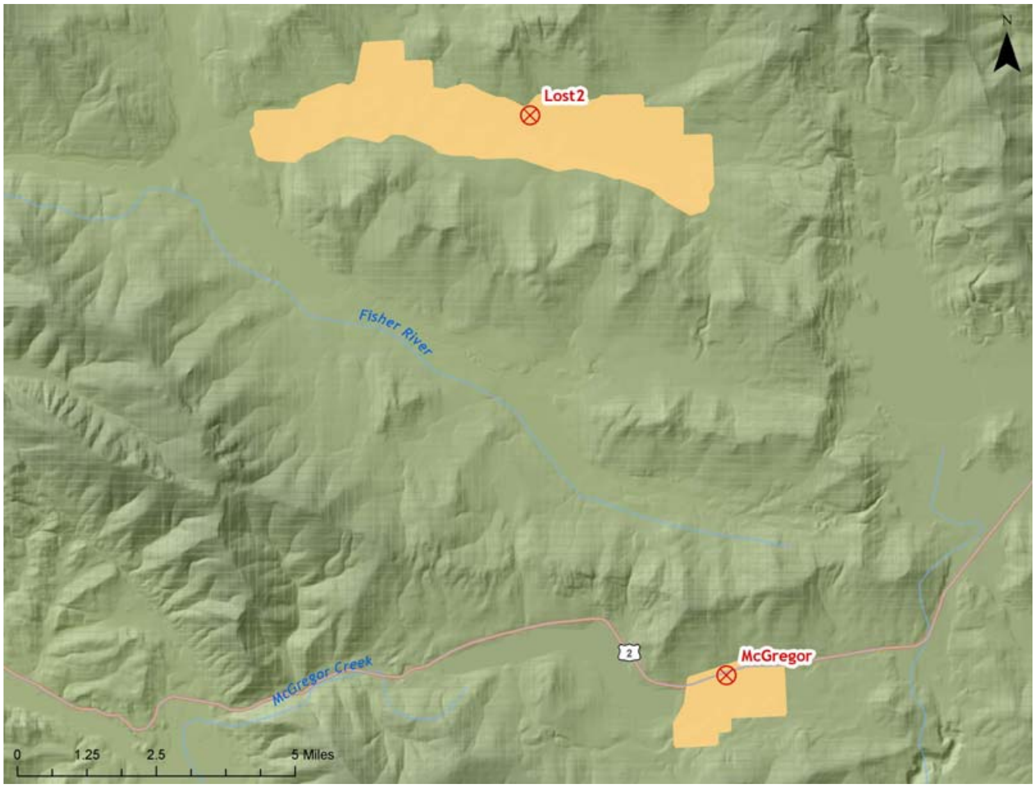


Figure 2.9. Base station locations for the Mission study areas displayed on a 30 meter DEM.

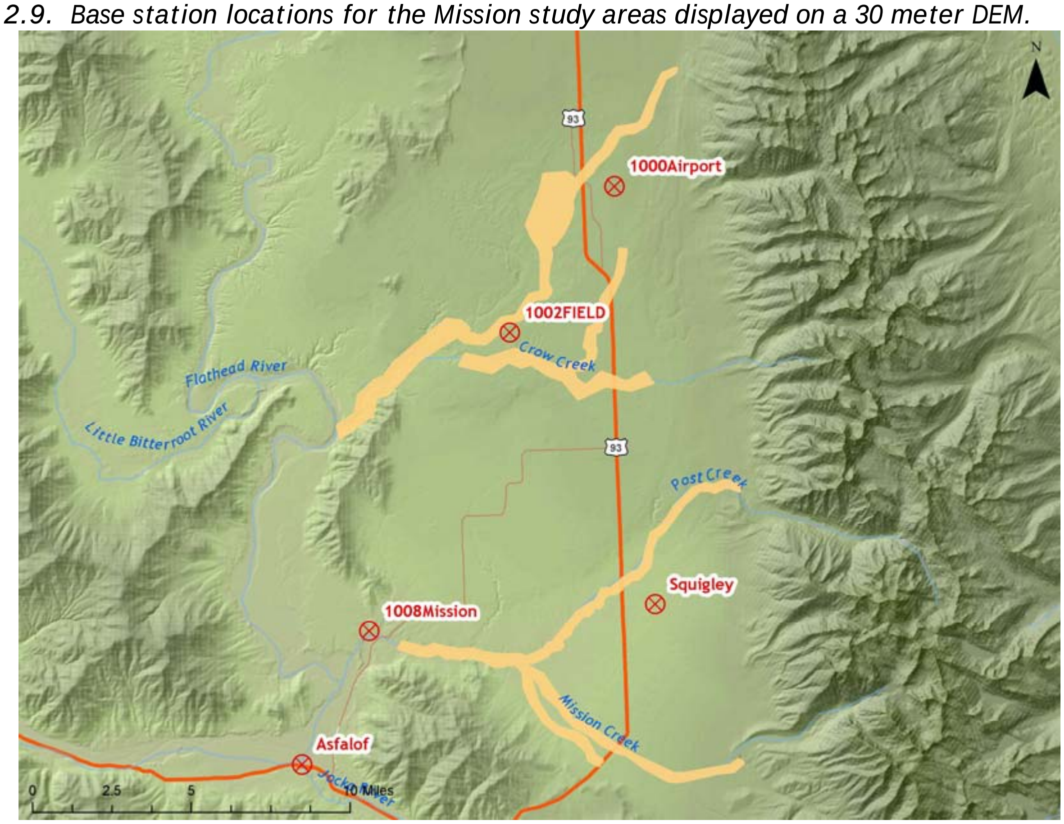


Figure 2.10. Selected RTK point locations from Jocko River study area displayed on a NAIP orthophoto.

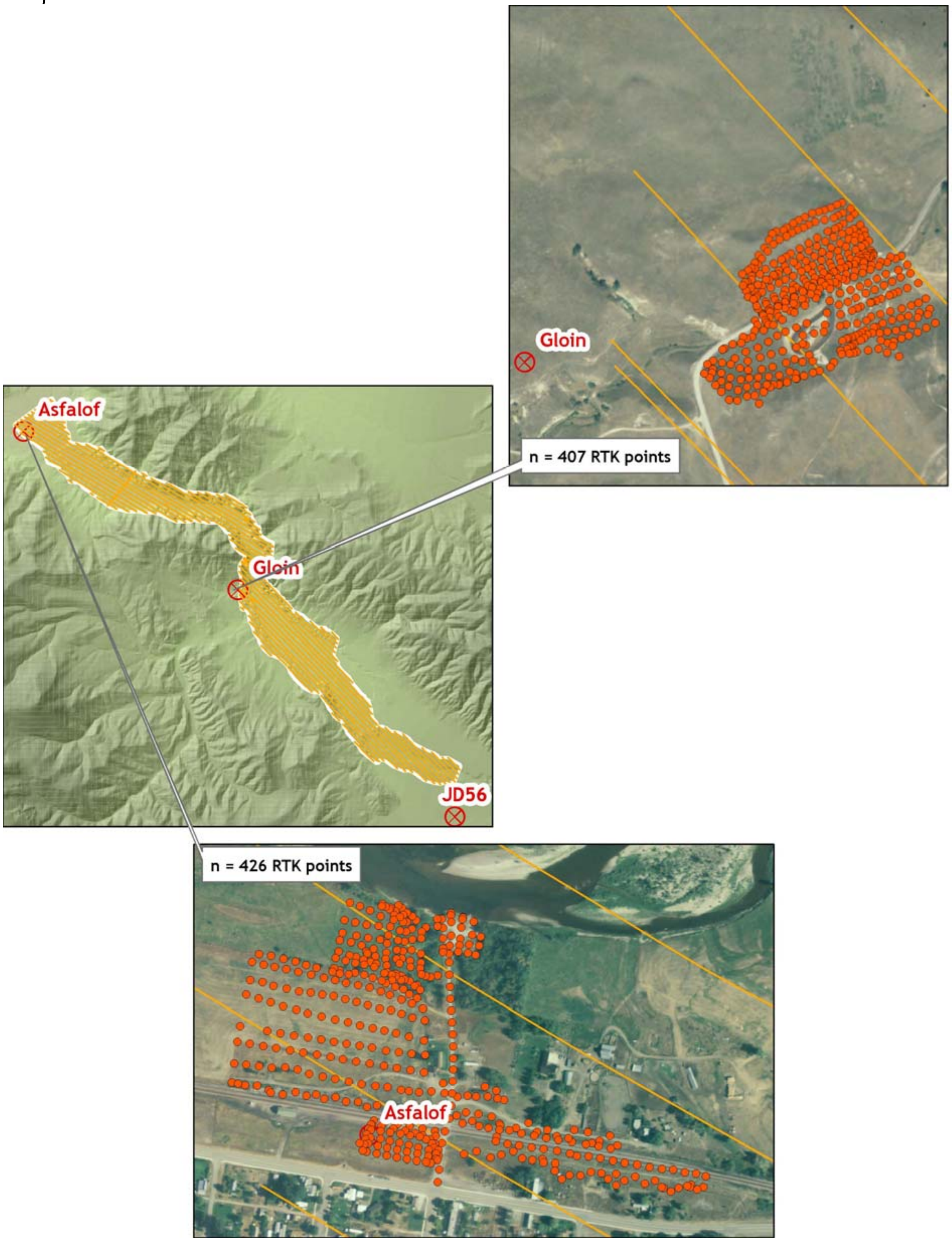


Figure 2.11. Selected RTK point locations from Maddy River study area displayed on a NAIP orthophoto.

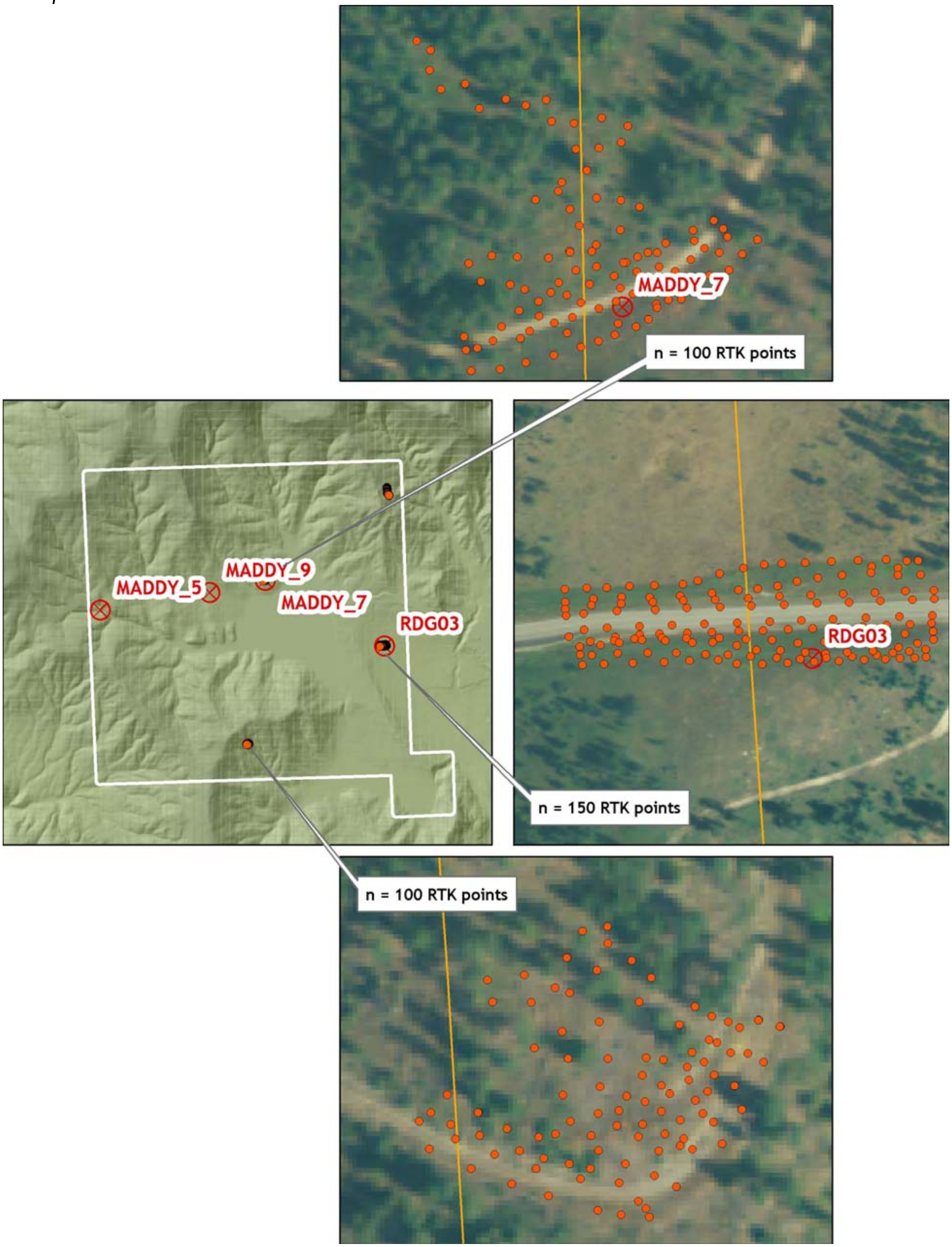
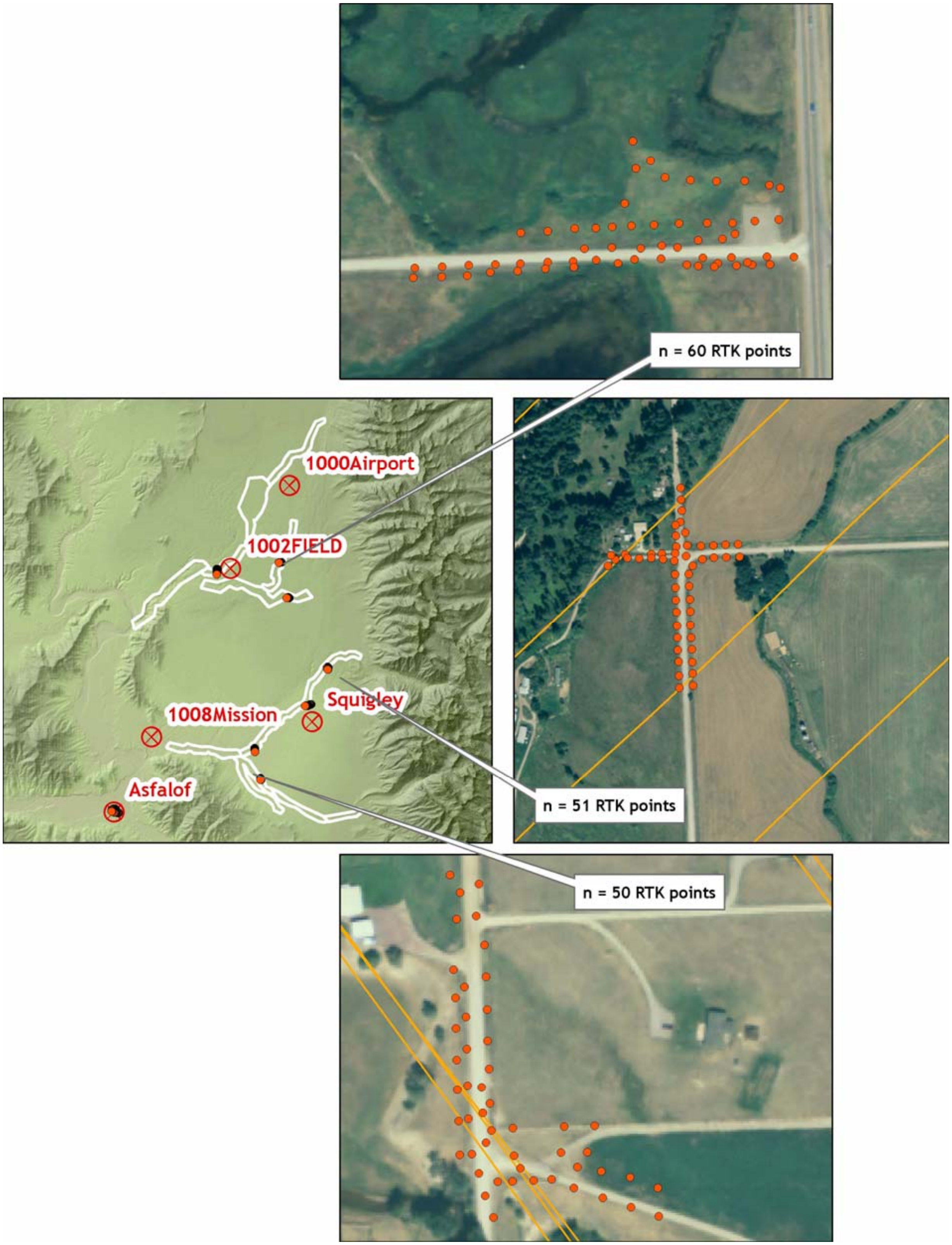


Figure 2.12. Selected RTK point locations from Mission study area displayed on a NAIP orthophoto.



3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolved kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.
   Software: Waypoint GPS v.7.80, Trimble Geomatics Office v.1.62
2. Developed a smoothed best estimate of trajectory (SBET) file blending post-processed aircraft position with attitude data. Sensor head position and attitude were calculated throughout the survey. The SBET data were used extensively for laser point processing.
   Software: IPAS v.1.4
3. Calculated laser point position by associating the SBET position to each laser point return time, scan angle, intensity, etc. Created raw laser point cloud data for the entire survey in .las (ASPRS v1.1) format.
   Software: ALS Post Processing Software
4. Imported raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filtered for pits/birds. Ground points were then classified for individual flight lines (to be used for relative accuracy testing and calibration).
   Software: TerraScan v.8.001
5. Using ground classified points for each flight line, the relative accuracy was tested. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations were performed on ground classified points from paired flight lines. Every flight line was used for relative accuracy calibration.
   Software: TerraMatch v.8.001
6. Position and attitude data were imported. Resulting data were classified as ground and non-ground points. Statistical absolute accuracy was assessed via direct comparisons of ground classified points to ground RTK survey data. Data were then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction.
   Software: TerraScan v.8.001, TerraModeler v.8.001

3.2 Aircraft Kinematic GPS and IMU Data

LiDAR survey datasets were referenced to 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collected 2 Hz kinematic GPS data and the inertial measurement unit (IMU) collected 200 Hz attitude data. Waypoint GPS v.7.80 was used to process the kinematic corrections for the aircraft. The static and kinematic GPS data were then post-processed after the survey to obtain an accurate GPS solution and aircraft positions. IPAS v.1.4 was used to develop a trajectory file including corrected aircraft position and attitude information. The trajectory data for the entire flight survey session were incorporated into a final smoothed best estimated trajectory (SBET) file containing accurate and continuous aircraft positions and attitudes.

3.3. Laser Point Processing

Laser point coordinates were computed using the IPAS and ALS Post Processor software suites based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point returns (first through fourth) were assigned an associated (x, y, and z) coordinate along with unique intensity values (0-255). The data were output into large LAS v. 1.1 files; each point maintaining the corresponding scan angle, return number (echo), intensity, and x, y, and z (easting, northing, and elevation) information.

These initial laser point files were too large to process. To facilitate laser point processing, bins (polygons) were created to divide the dataset into manageable sizes (< 500 MB). Flightlines and LiDAR data were then reviewed to ensure complete coverage of the study area and positional accuracy of the laser points.

Once the laser point data were imported into bins in TerraScan, a manual calibration was performed to assess the system offsets for pitch, roll, heading and mirror scale. Using a geometric relationship developed by Watershed Sciences, each of these offsets was resolved and corrected if necessary.

The LiDAR points were then filtered for noise, pits and birds by screening for absolute elevation limits, isolated points and height above ground. Each bin was then inspected for pits and birds manually, and spurious points were removed. For a bin containing approximately 7.5-9.0 million points, an average of 50-100 points were typically found to be artificially low or high. These spurious non-terrestrial laser points must be removed from the dataset. Common sources of non-terrestrial returns are clouds, birds, vapor, and haze.

Internal calibration was refined using TerraMatch. Points from overlapping lines were tested for internal consistency and final adjustments made for system misalignments (i.e., pitch, roll, heading offsets and mirror scale). Automated sensor attitude and scale corrections yielded 3-5 cm improvements in the relative accuracy. Once the system misalignments were corrected, vertical GPS drift was resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy. In summary, the data must complete a robust calibration designed to reduce inconsistencies from multiple sources (i.e. sensor attitude offsets, mirror scale, GPS drift).

The TerraScan software suite is designed specifically for classifying near-ground points (Soininen 2004). The processing sequence began with removal of all points not near the earth based on geometric constraints used to evaluate multi-return points. The resulting bare earth (ground) model was visually inspected and additional ground point modeling was performed in site-specific areas (over a 50-meter radius) to improve ground detail. This was only done in areas with known ground modeling deficiencies, such as bedrock outcrops, cliffs, deeply incised stream banks, and dense vegetation. In some cases, ground point classification included known vegetation (i.e., understory, low/dense shrubs, etc.) and these points were manually reclassified as non-grounds.

4. LiDAR Accuracy and Resolution

4.1. Laser Point Accuracy

Laser point absolute accuracy is largely a function of internal consistency (measured as relative accuracy) and laser noise:

- **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. The laser noise range for this mission is approximately 0.02 meters.

- **Relative Accuracy**: Internal consistency refers to the ability to place a laser point in the same location over multiple flight lines, GPS conditions, and aircraft attitudes.

- **Absolute Accuracy**: RTK GPS measurements taken in the study areas compared to LiDAR point data.

Statements of statistical accuracy apply to fixed terrestrial surfaces only, not to free-flowing or standing water surfaces, moving automobiles, et cetera.

Table 4.1. LiDAR accuracy is a combination of several sources of error. These sources of error are cumulative. Some error sources that are biased and act in a patterned displacement can be resolved in post processing.

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

4.1.1. Relative Accuracy

Relative accuracy refers to the internal consistency of the data set and 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). Internal consistency is affected by system attitude offsets (pitch, roll and heading), mirror flex (scale), and GPS/IMU drift.

Operational measures taken to improve relative accuracy:

1. Low Flight Altitude: Terrain following was targeted at a flight altitude of 900 meters above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground. Lower flight altitudes decrease laser noise on surfaces with even the slightest relief.
2. 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 maintained.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 16^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. 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 11 km (6.3 miles) at all times.
5. 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.
6. 50% Side-Lap (100% Overlap): Overlapping areas were optimized for relative accuracy testing. Laser shadowing was 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.
7. 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.

Relative Accuracy Calibration Methodology

1. Manual System Calibration: Calibration procedures for each mission require solving geometric relationships relating 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 completing the manual calibration and reported for each study area.
2. 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. The resulting overlapping ground points were used to compute and refine relative accuracy for each study area. System misalignment offsets (pitch, roll and heading) and mirror scale were solved for each individual mission. Attitude misalignment offsets (and mirror scale) occurs for each individual mission. The data from each mission were then blended when imported together to form the entire area of interest.
3. Automated Z Calibration: Ground points per line were utilized to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Relative Accuracy Calibration Results by Study Area

Jocko River

Relative accuracy statistics for Jocko River are based on the comparison of 39 flightlines and 265,336,783 points. For flightline coverage, see Figure 2.1 in Section 2.1.

- Project average = 0.11 feet
- Median relative accuracy = 0.11 feet
- 1σ relative accuracy = 0.12 feet
- 2σ relative accuracy = 0.13 feet

Figure 4.1. Distribution of relative accuracies per flight line, non slope-adjusted.

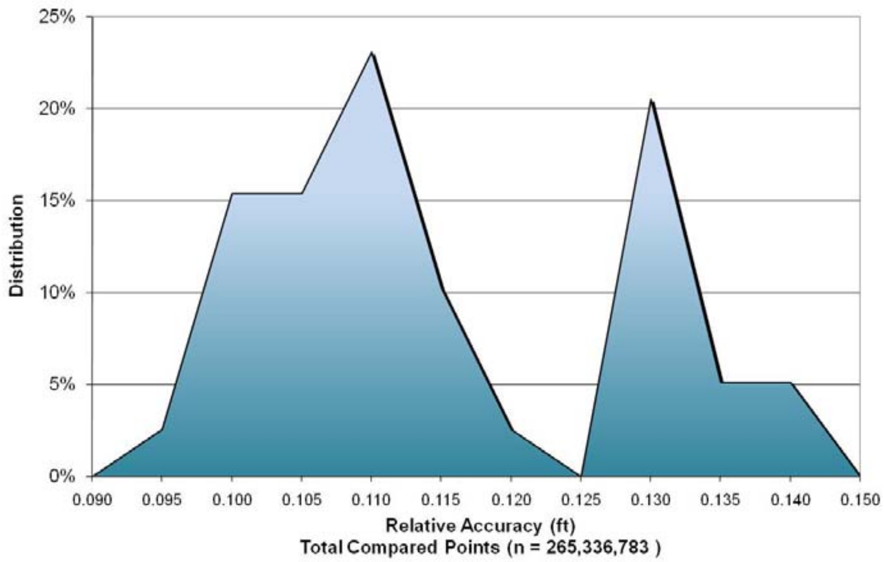
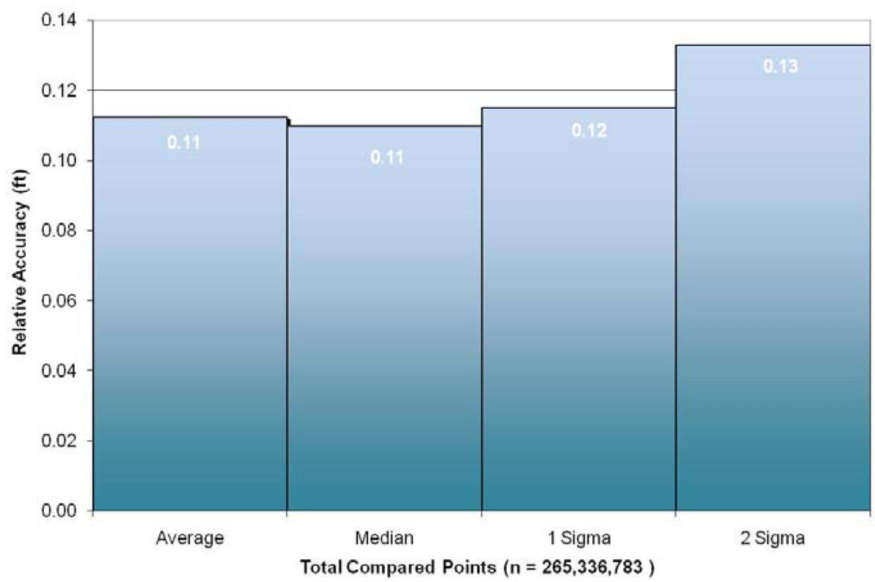


Figure 4.2. Statistical relative accuracies, non slope-adjusted.



Maddy River

Relative accuracy statistics for Maddy River are based on the comparison of 59 flightlines and 311,038,110 points. For flightline coverage, see Figure 2.2 in Section 2.1.

- Project average = 0.20 feet
- Median relative accuracy = 0.20 feet
- 1σ relative accuracy = 0.21 feet
- 2σ relative accuracy = 0.26 feet

Figure 4.3. Distribution of relative accuracies per flight line, non slope-adjusted.

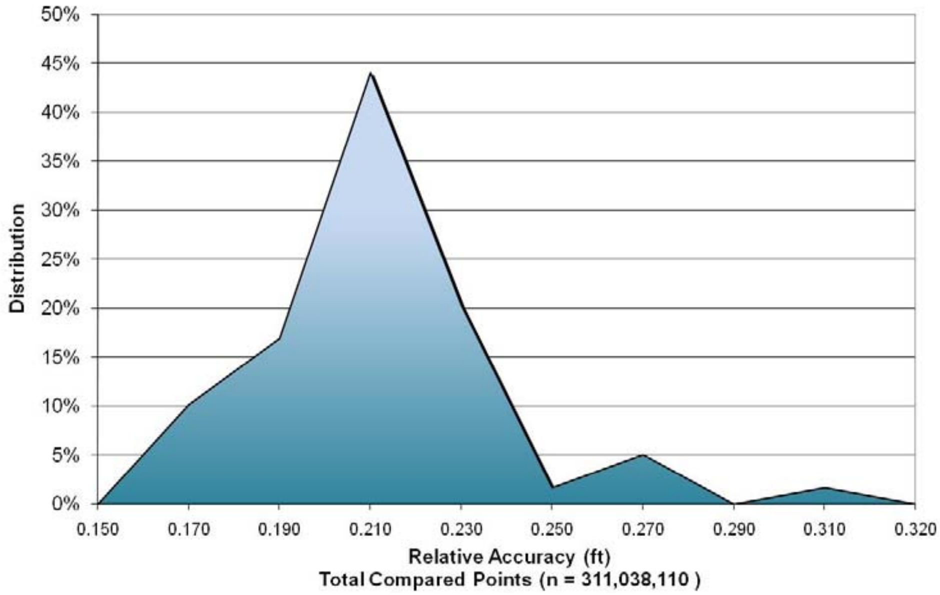
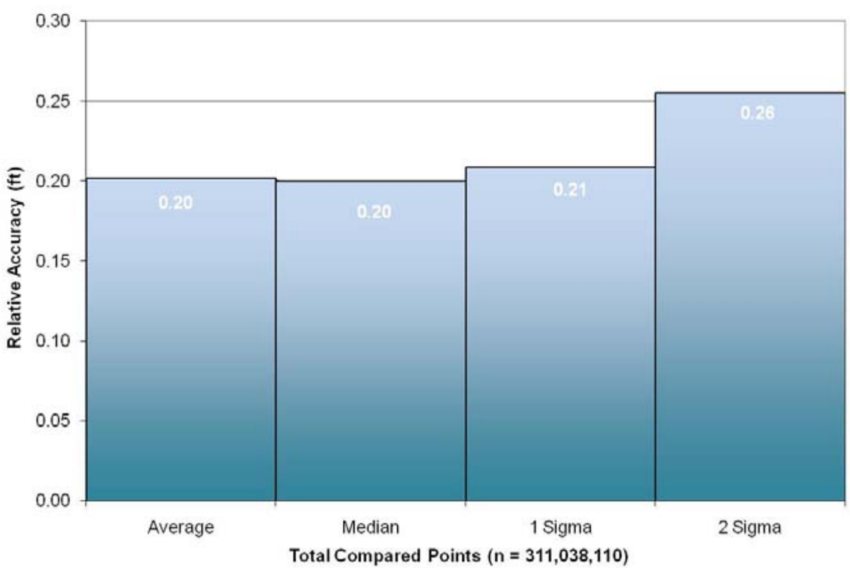


Figure 4.4. Statistical relative accuracies, non slope-adjusted.



Area C

Relative accuracy statistics for Area C are based on the comparison of 10 flightlines and 14,071,278 points. For flightline coverage, see Figure 2.5 in Section 2.1.

- Project average = 0.15 feet
- Median relative accuracy = 0.15 feet
- 1σ relative accuracy = 0.17 feet
- 2σ relative accuracy = 0.18 feet

Figure 4.5. Distribution of relative accuracies per flight line, non slope-adjusted.

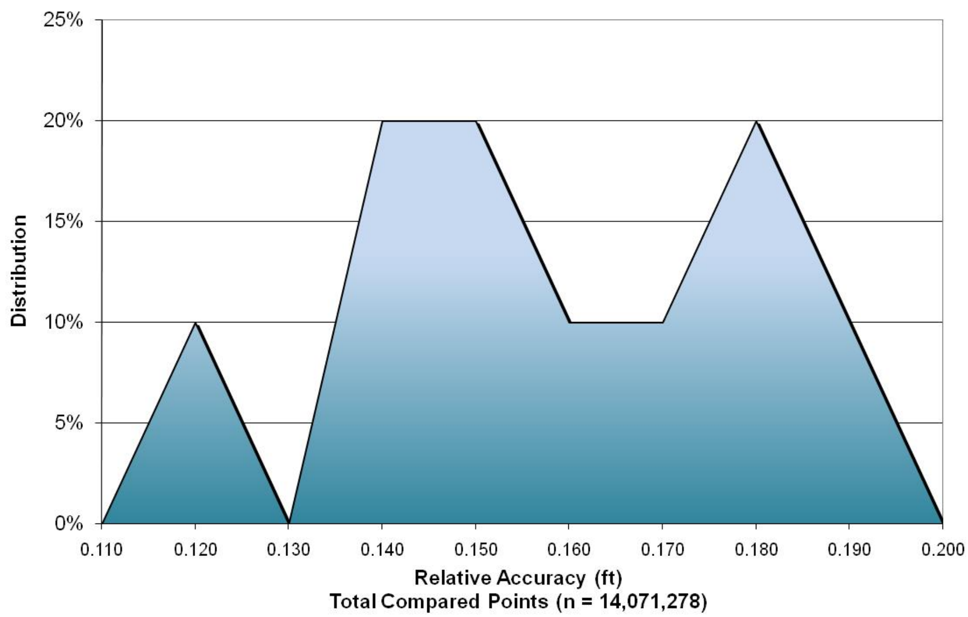
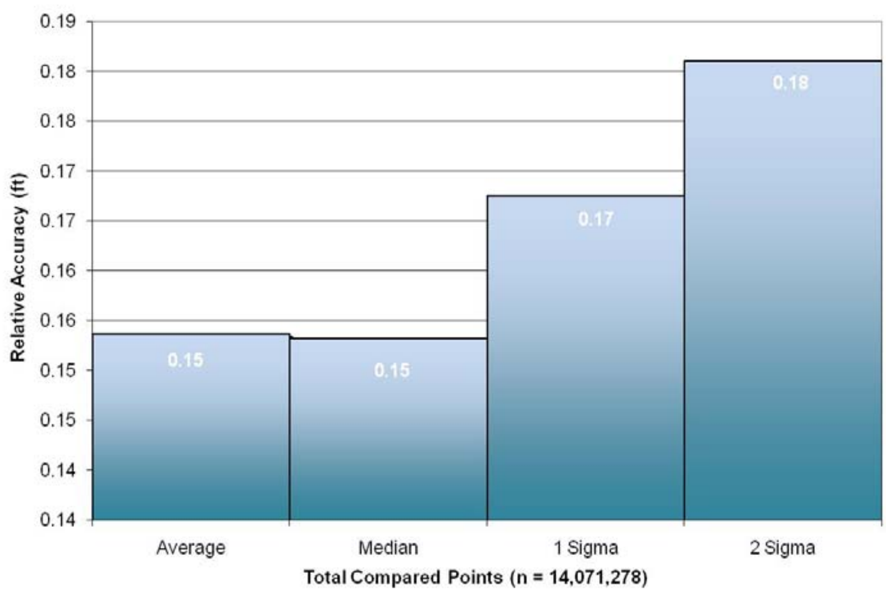


Figure 4.6. Statistical relative accuracies, non slope-adjusted.



McGregor

Relative accuracy statistics for McGregor are based on the comparison of 12 flightlines and 23,912,125 points. For flightline coverage, see Figure 2.3 in Section 2.1.

- Project average = 0.13 feet
- Median relative accuracy = 0.12 feet
- 1σ relative accuracy = 0.14 feet
- 2σ relative accuracy = 0.19 feet

Figure 4.7. Distribution of relative accuracies per flight line, non slope-adjusted.

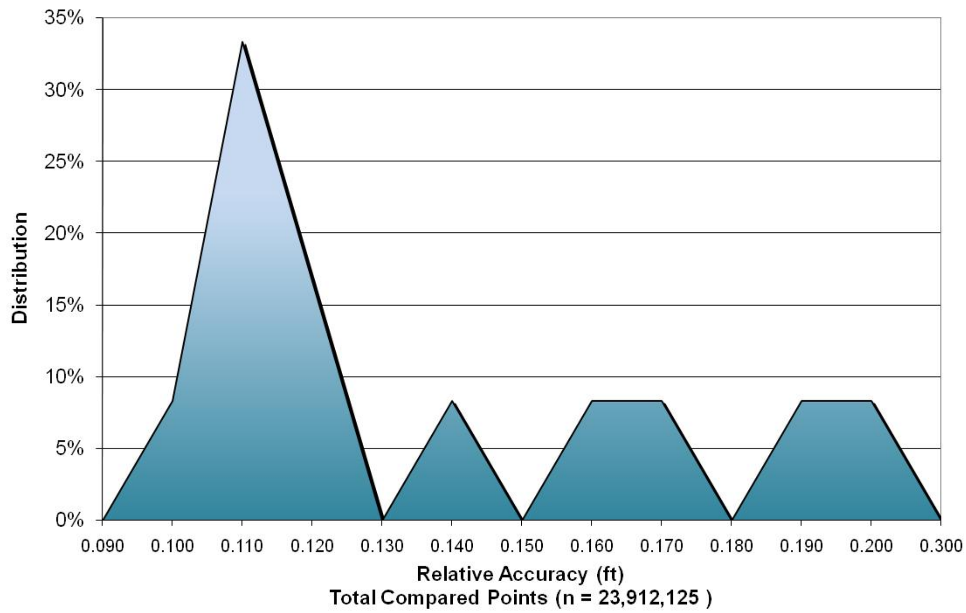
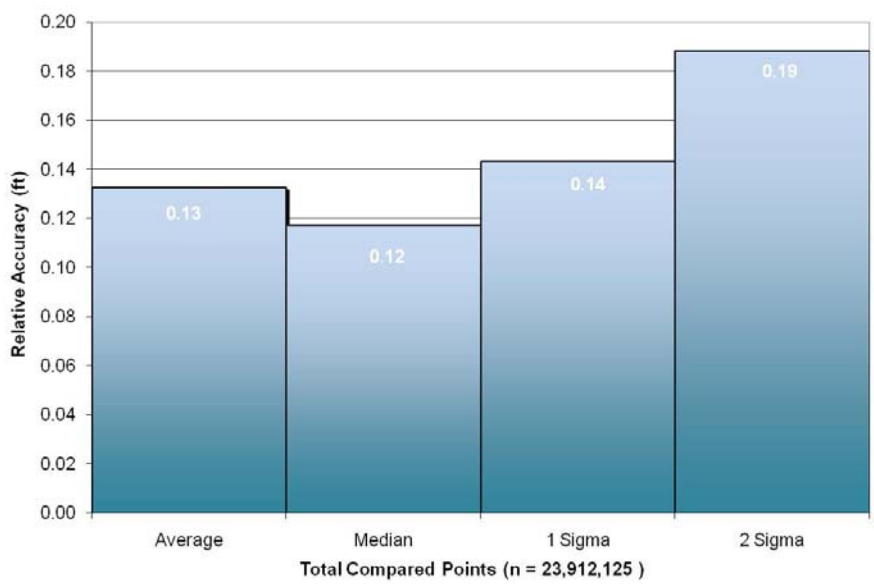


Figure 4.8. Statistical relative accuracies, non slope-adjusted.



Lost

Relative accuracy statistics for the Lost study area are based on the comparison of 24 flightlines and 125,641,880,points. For flightline coverage, see Figure 2.3 in Section 2.1.

- Project average = 0.12 feet
- Median relative accuracy = 0.12 feet
- 1σ relative accuracy = 0.12 feet
- 2σ relative accuracy = 0.14 feet

Figure 4.9. Distribution of relative accuracies per flight line, non slope-adjusted.

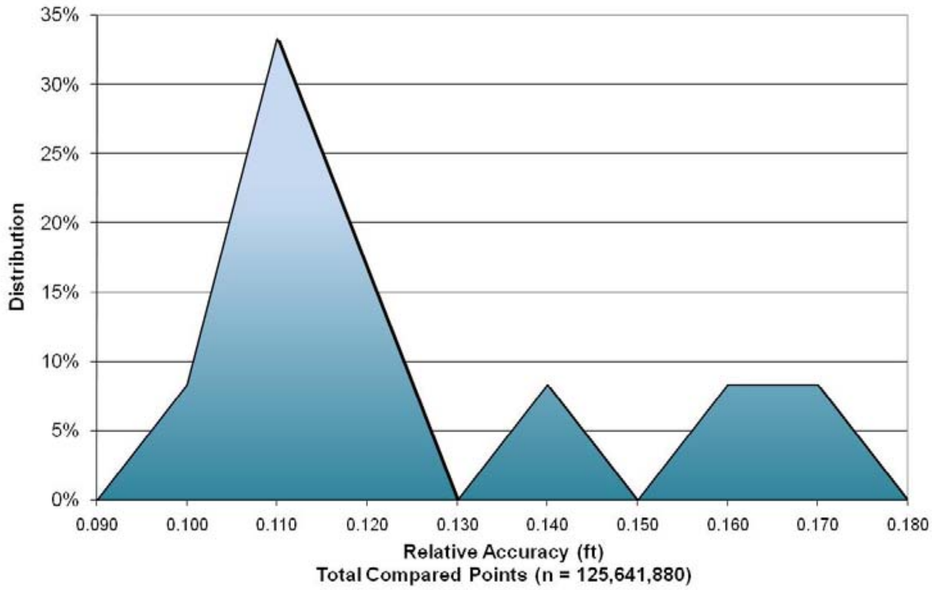
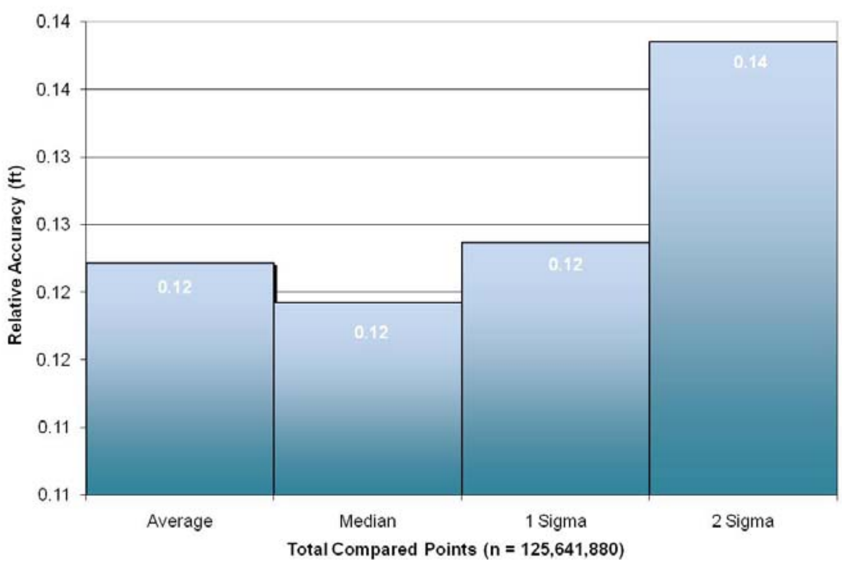


Figure 4.10. Statistical relative accuracies, non slope-adjusted.



Mission

Relative accuracy statistics for Mission are based on the comparison of 87 flightlines and 355,879,777 points. For flightline coverage, see Figure 2.4 in Section 2.1.

- o Project average = 0.13 feet
- o Median relative accuracy = 0.12 feet
- o 1σ relative accuracy = 0.12 feet
- o 2σ relative accuracy = 0.19 feet

Figure 4.11. Distribution of relative accuracies per flight line, non slope-adjusted.

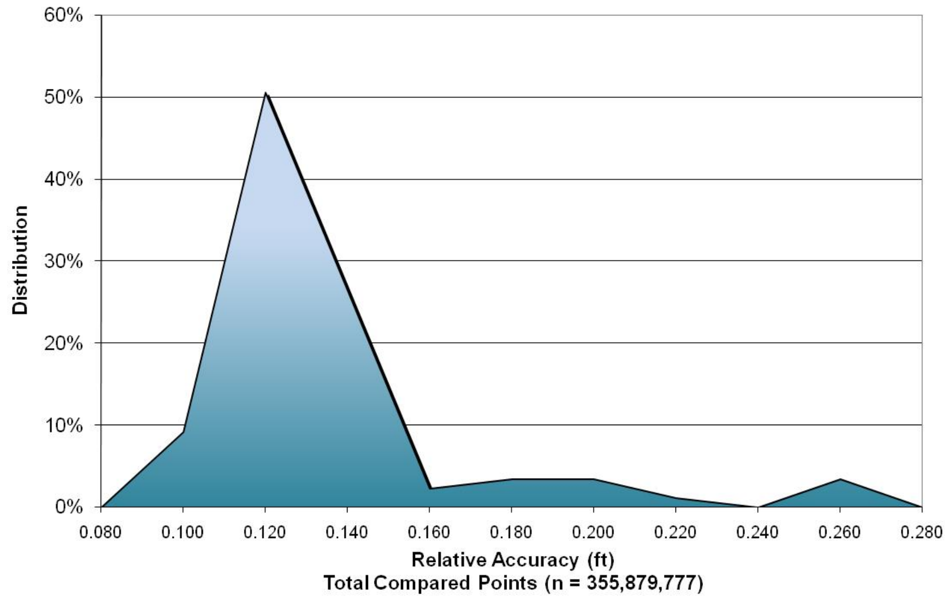
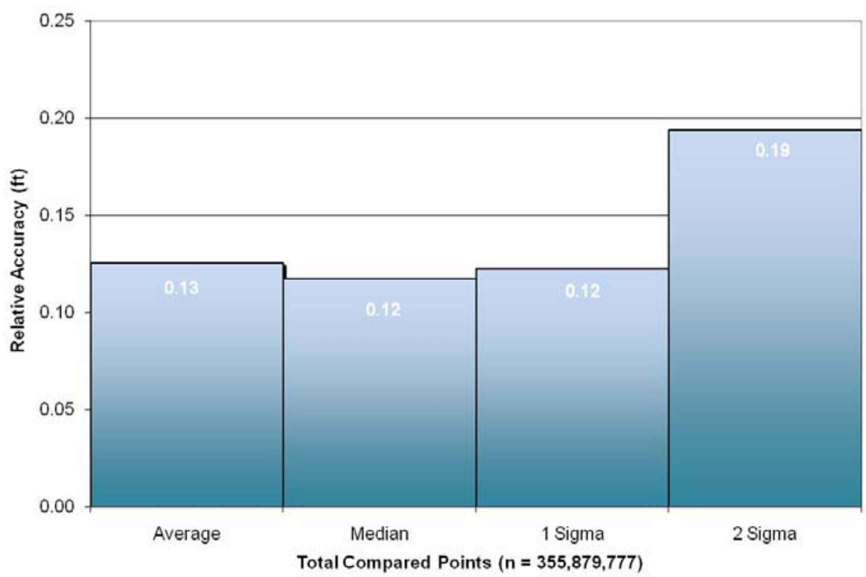


Figure 4.12. Statistical relative accuracies, non slope-adjusted.



4.1.2. Absolute Accuracy by Study Area

The final quality control measure is a statistical accuracy assessment comparing known RTK ground survey points to the closest laser points. Accuracy statistics for each study area are reported below.

Jocko River

Table 4.2. Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 1203	
Root Mean Square Error (RMSE): 0.22 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.18 feet	**Minimum Δz:** -0.82 feet
2 sigma (σ): 0.46 feet	**Maximum Δz:** 0.96 feet
	Average Δz: 0.01 feet

Figure 4.13. Absolute deviation histogram statistics.

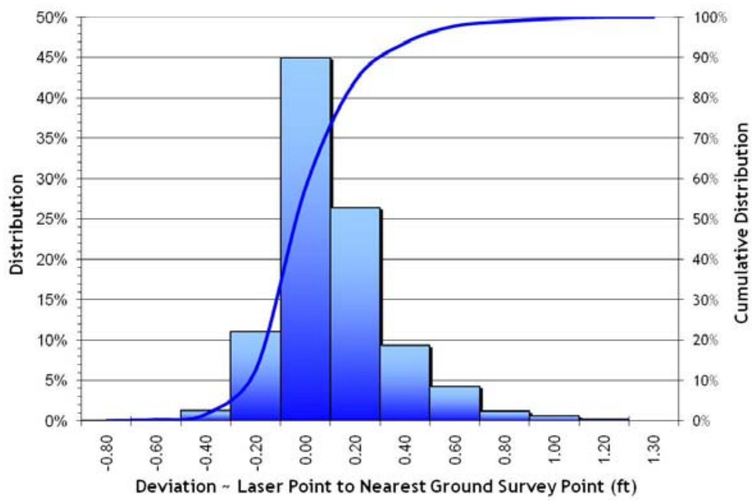
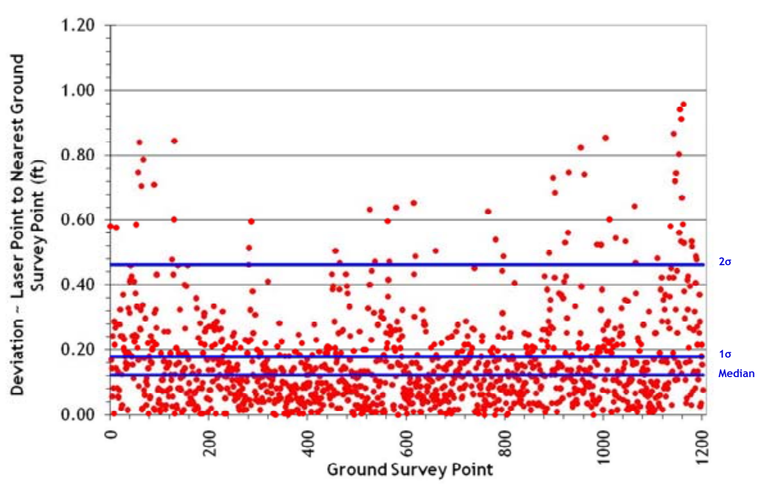


Figure 4.14. Point absolute deviation statistics.



Maddy

Table 4.3. Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 450	
Root Mean Square Error (RMSE): 0.21 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.19 feet	**Minimum Δz:** -0.75 feet
2 sigma (σ): 0.42 feet	**Maximum Δz:** 1.15 feet
	Average Δz: -0.01 feet

Figure 4.15. Absolute deviation histogram statistics.

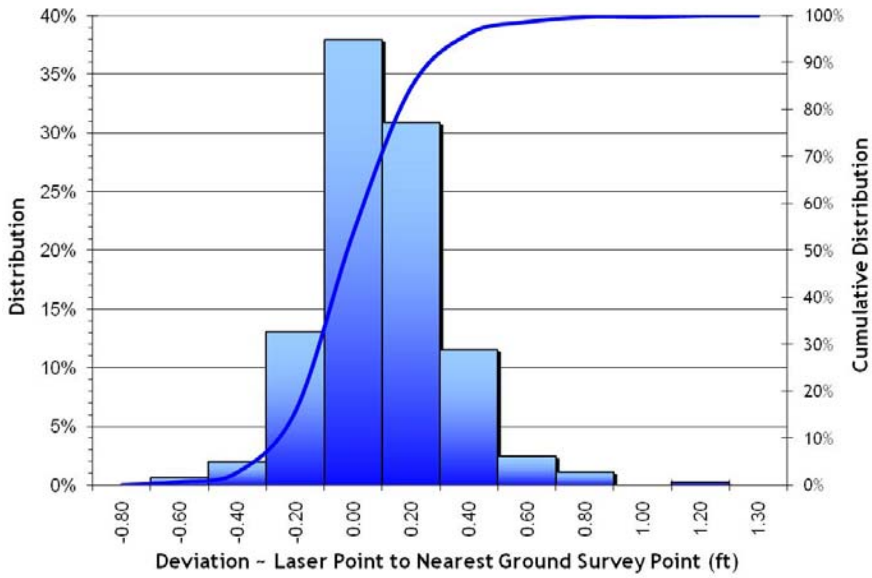
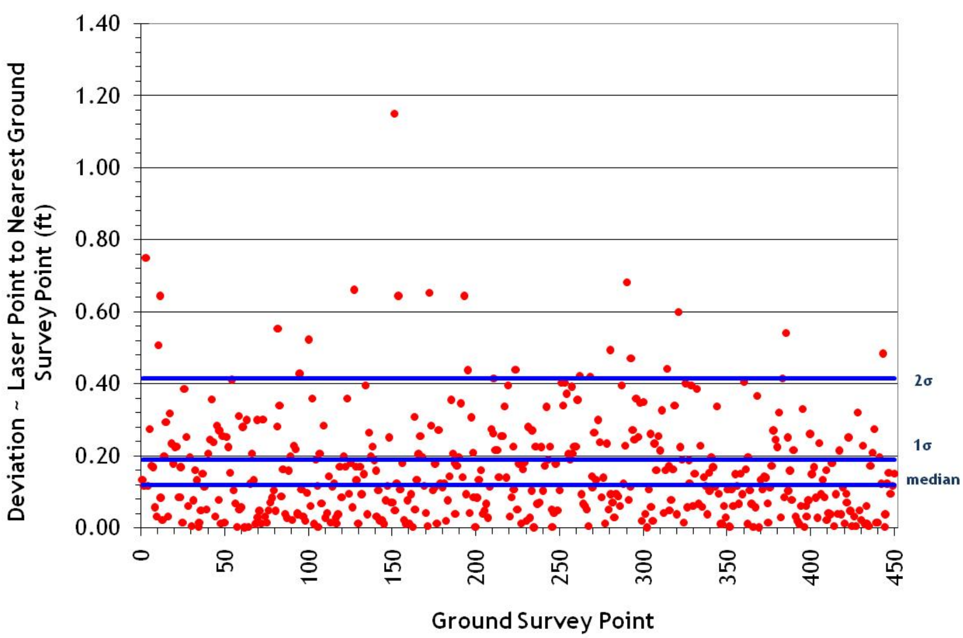


Figure 4.16. Point absolute deviation statistics.



Area C

Table 4.4. Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 286	
Root Mean Square Error (RMSE): 0.15 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.14 feet	**Minimum Δz:** -0.61 feet
2 sigma (σ): 0.29 feet	**Maximum Δz:** 0.47 feet
	Average Δz: 0.01 feet

Figure 4.17. Absolute deviation histogram statistics.

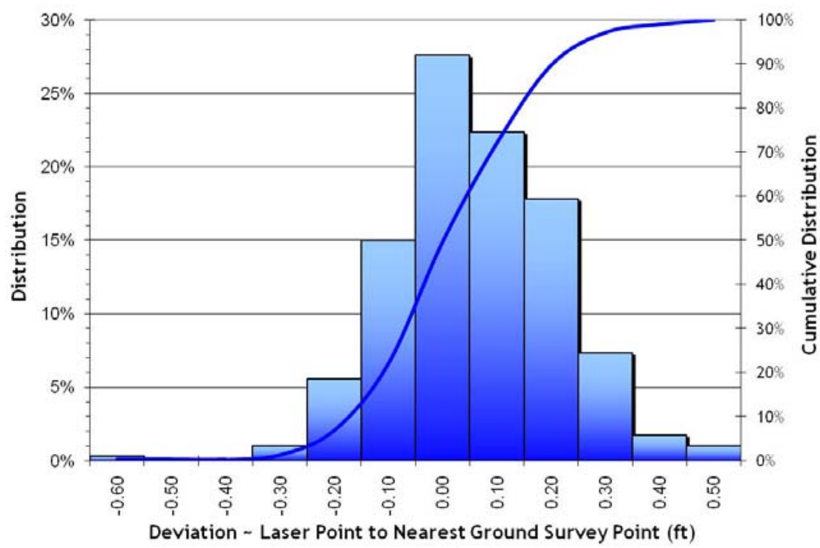
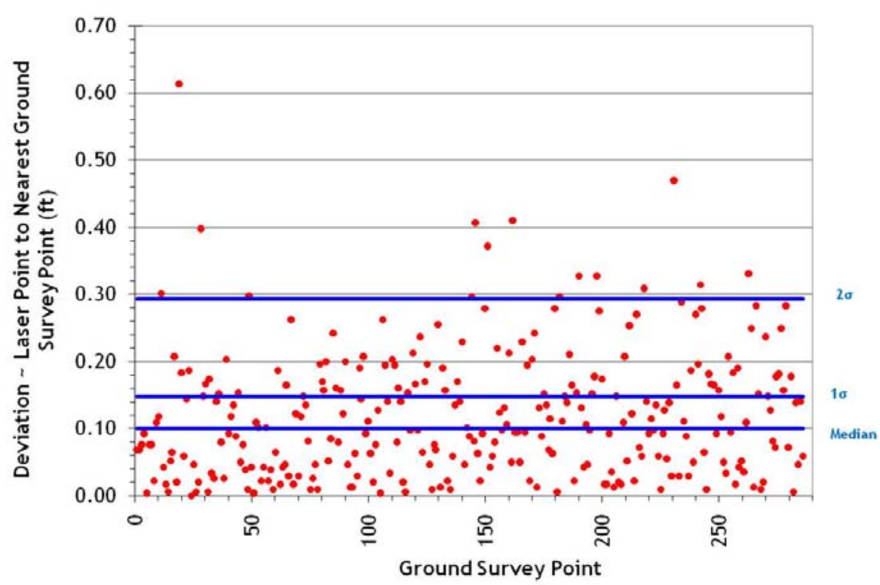


Figure 4.18. Point absolute deviation statistics.



McGregor

Table 4.5. Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 209	
Root Mean Square Error (RMSE): 0.19 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.17 feet	**Minimum Δz:** -0.31 feet
2 sigma (σ): 0.31 feet	**Maximum Δz:** 0.74 feet
	Average Δz: 0.00 feet

Figure 4.19. Absolute deviation histogram statistics.

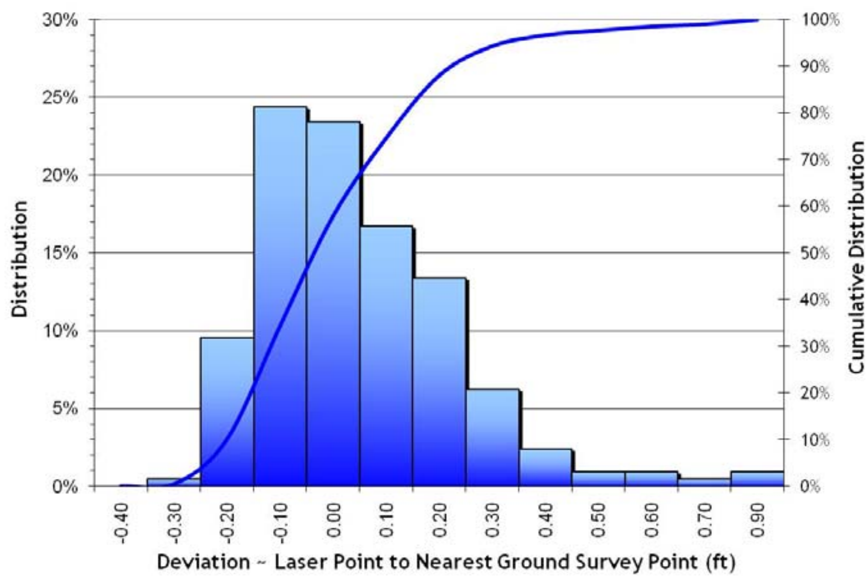
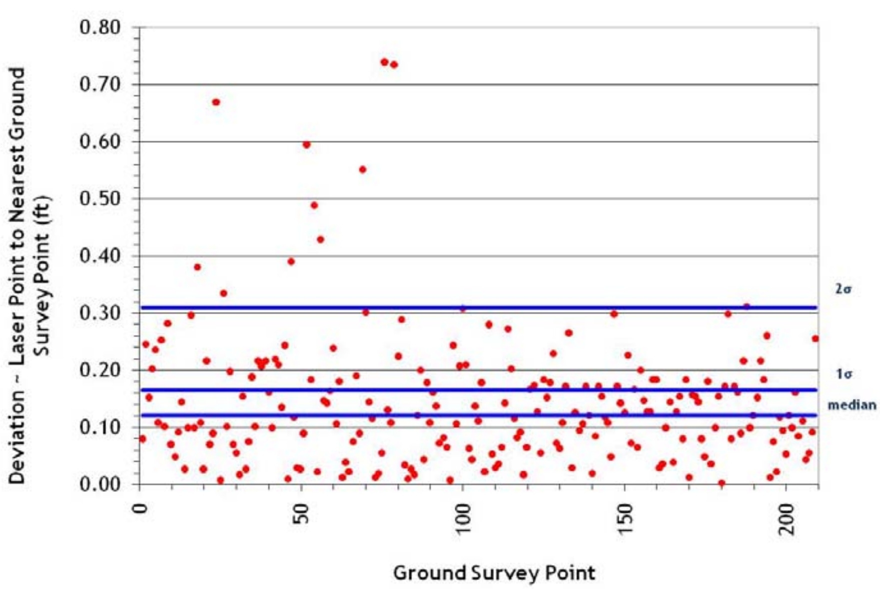


Figure 4.20. Point absolute deviation statistics.



Lost

Table 4.6. Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 292	
Root Mean Square Error (RMSE): 0.18 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.17 feet	**Minimum Δz:** -0.33 feet
2 sigma (σ): 0.33 feet	**Maximum Δz:** 0.75 feet
	Average Δz: 0.01 feet

Figure 4.21. Absolute deviation histogram statistics.

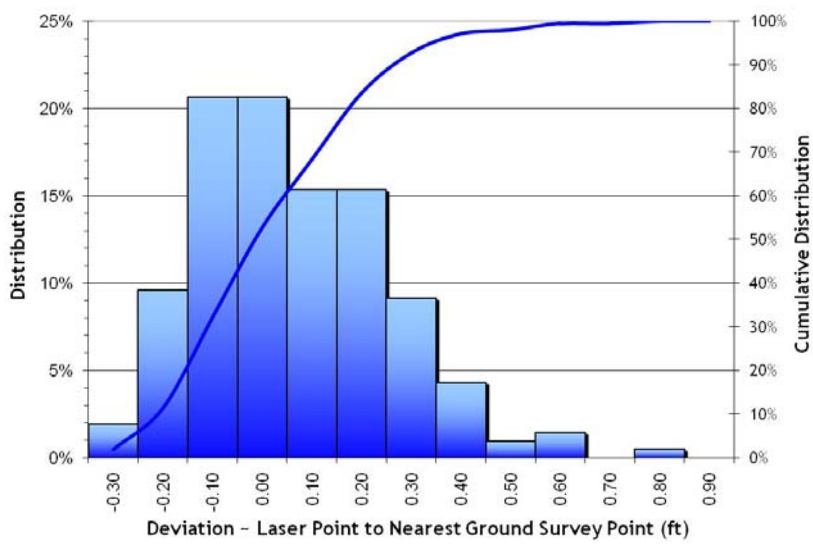
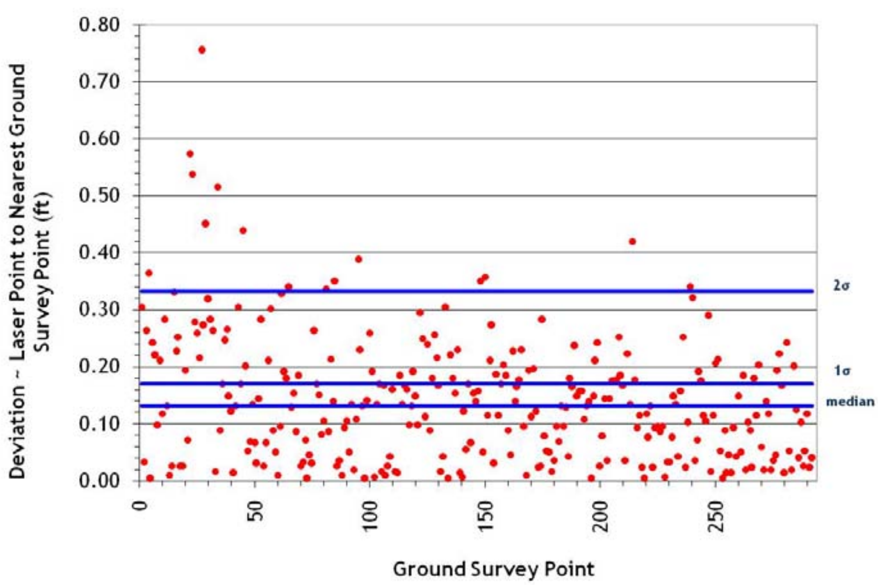


Figure 4.22. Point absolute deviation statistics.



Mission

Table 4.7. Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 292	
Root Mean Square Error (RMSE): 0.28 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.28 feet	**Minimum Δz:** -0.55 feet
2 sigma (σ): 0.52 feet	**Maximum Δz:** 0.75 feet
	Average Δz: 0.00 feet

Figure 4.23. Absolute deviation histogram statistics.

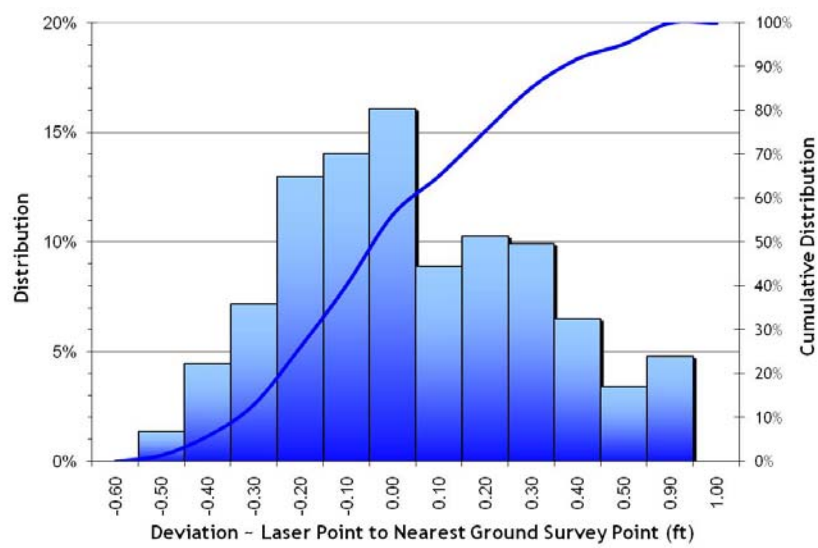
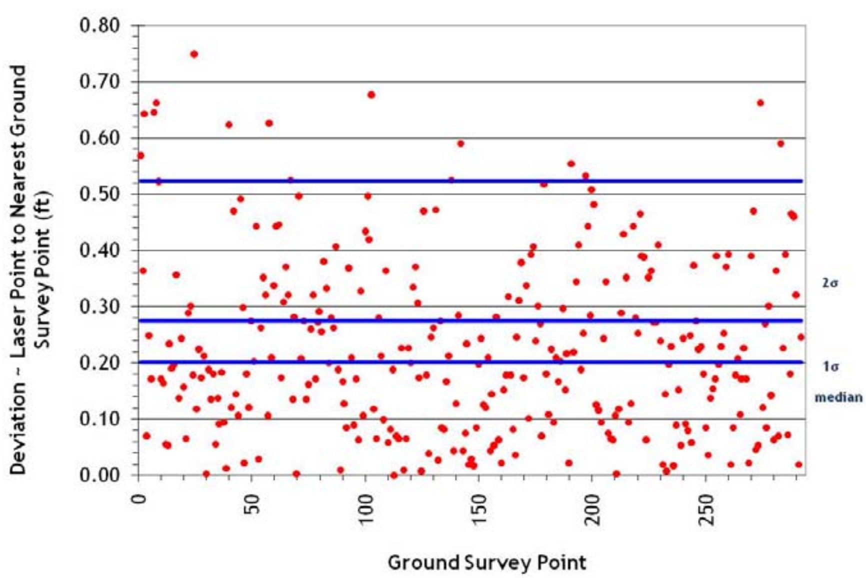


Figure 4.24. Point absolute deviation statistics.



4.2. Data Density/Resolution

Some types of surfaces (i.e. dense vegetation or water) may return fewer pulses than originally emitted by the laser. Delivered density may therefore be less than the native density and vary according to distributions of terrain, land cover, and water bodies. The density histograms and maps in figures 4.25 – 4.36 have been calculated based on first return laser point density and ground-classified laser point density.

4.2.1 First Return Laser Pulses per Square Meter by Study area

Jocko River

Average Pulse Density: 8.18 points/square meter

Figure 4.25. Histogram of first return laser point density per processing bin.

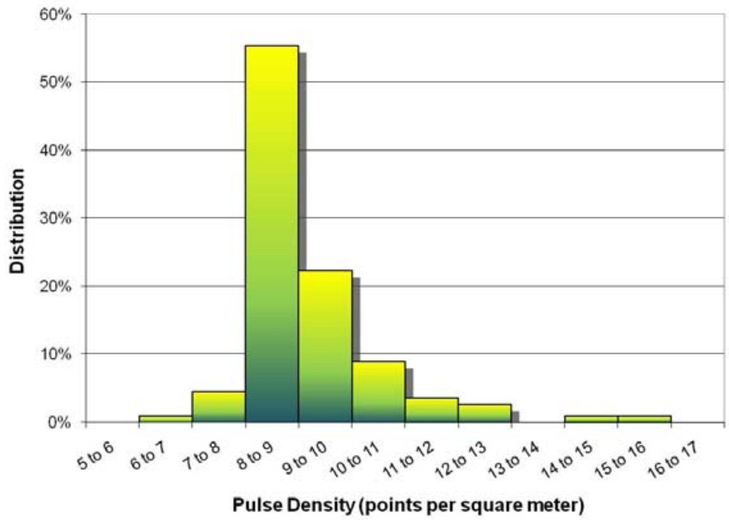
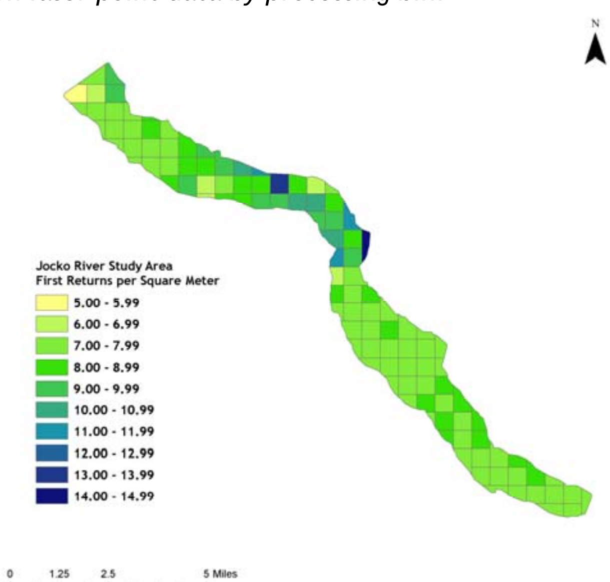


Figure 4.26. First return laser point data by processing bin.



Maddy River

Average Pulse Density: 8.45 points/square meter

Figure 4.27. Histogram of first return laser point density per processing bin.

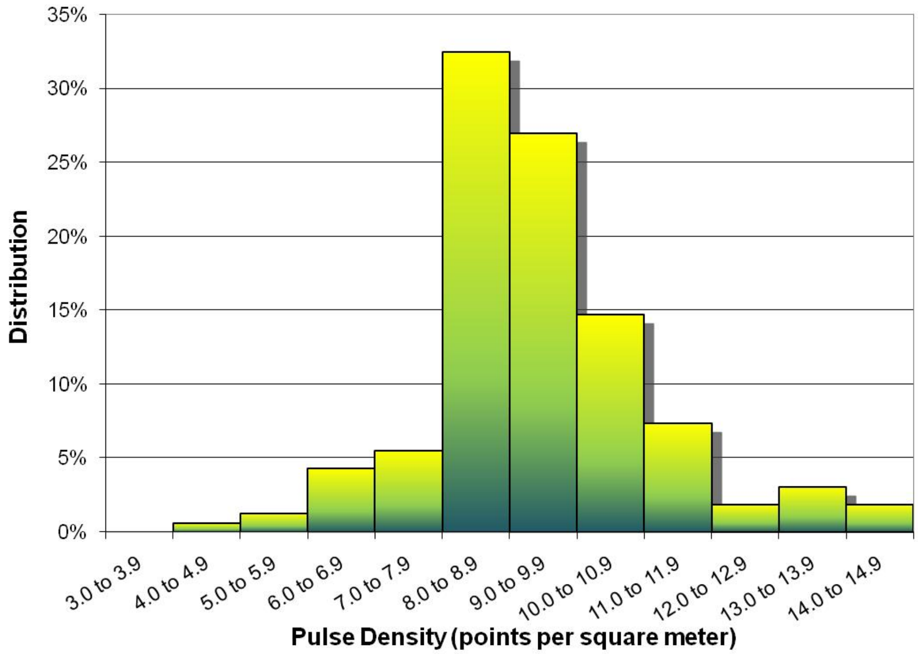
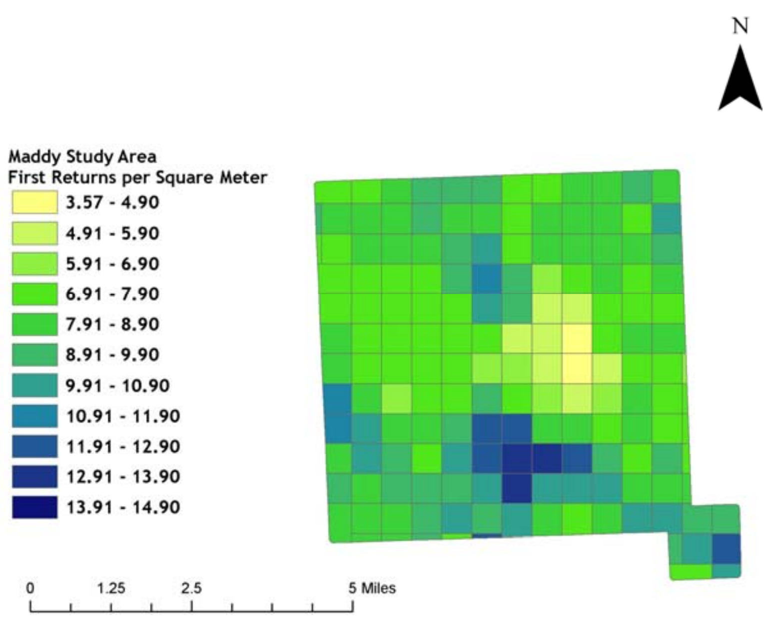


Figure 4.28. First return laser point data by processing bin.



Study Area C

Average Pulse Density: 10.30 points/square meter

Figure 4.29. Histogram of first return laser point density per processing bin.

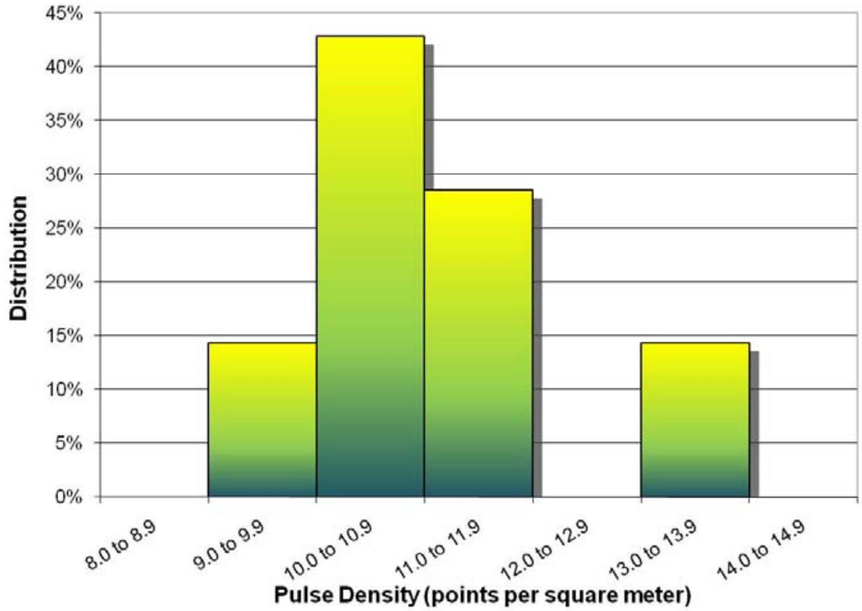
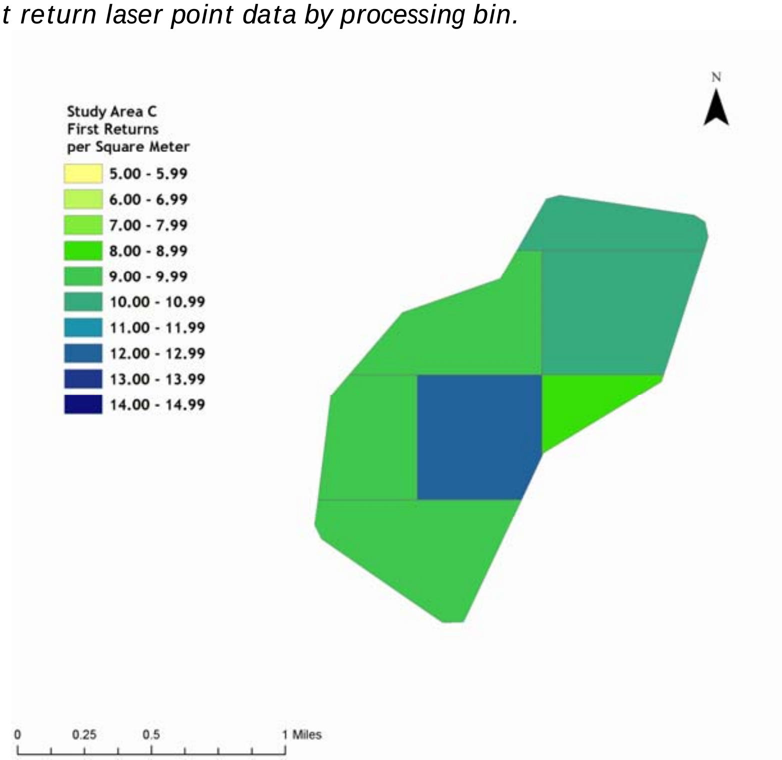


Figure 4.30. First return laser point data by processing bin.



McGregor

Average Pulse Density: 7.68 points/square meter

Figure 4.31. Histogram of first return laser point density per processing bin.

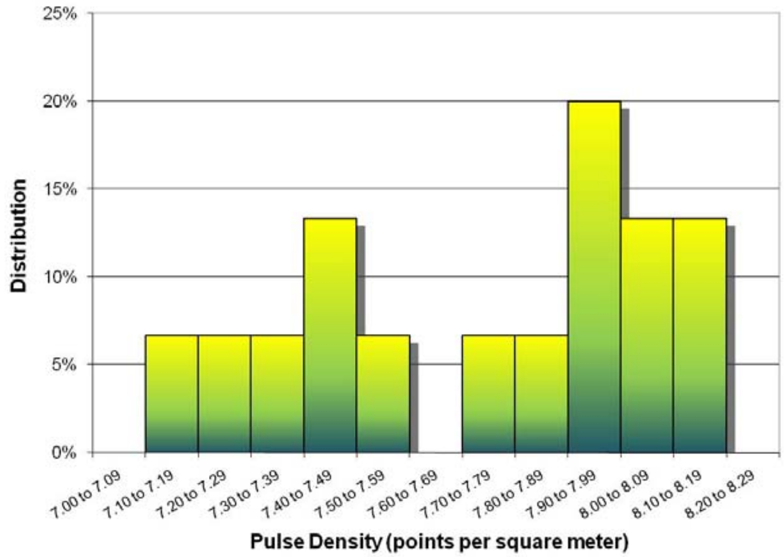
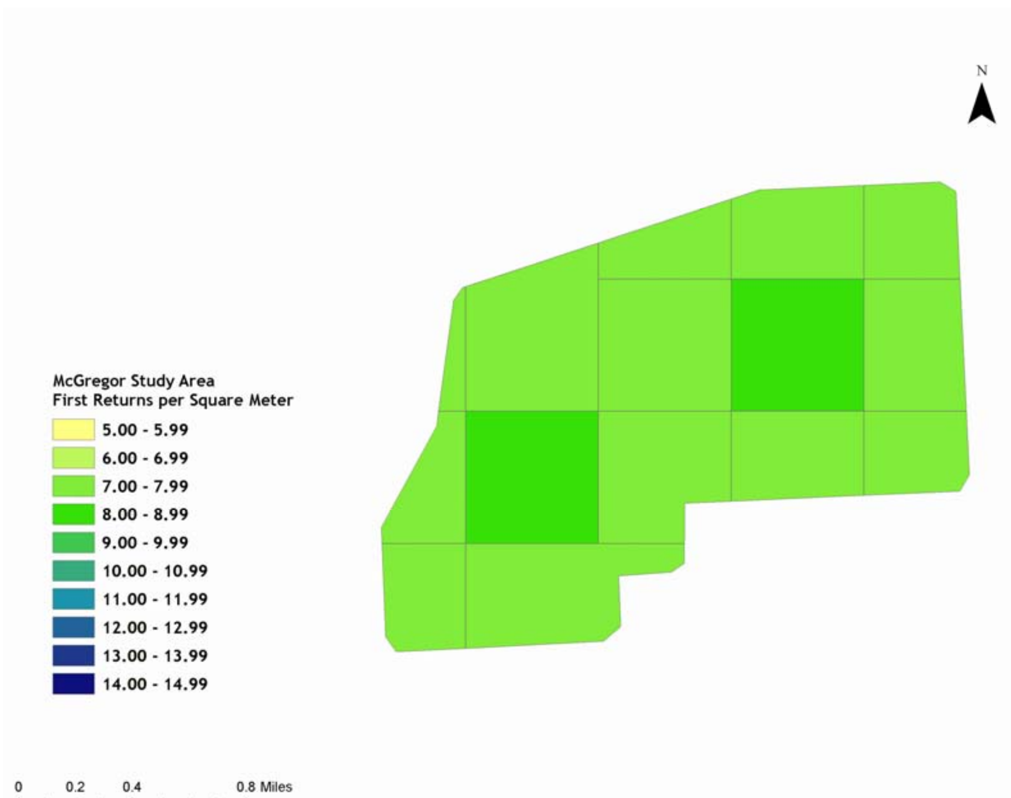


Figure 4.32. First return laser point data by processing bin.



Lost

Average Pulse Density: 7.79 points/square meter

Figure 4.33. Histogram of first return laser point density per processing bin.

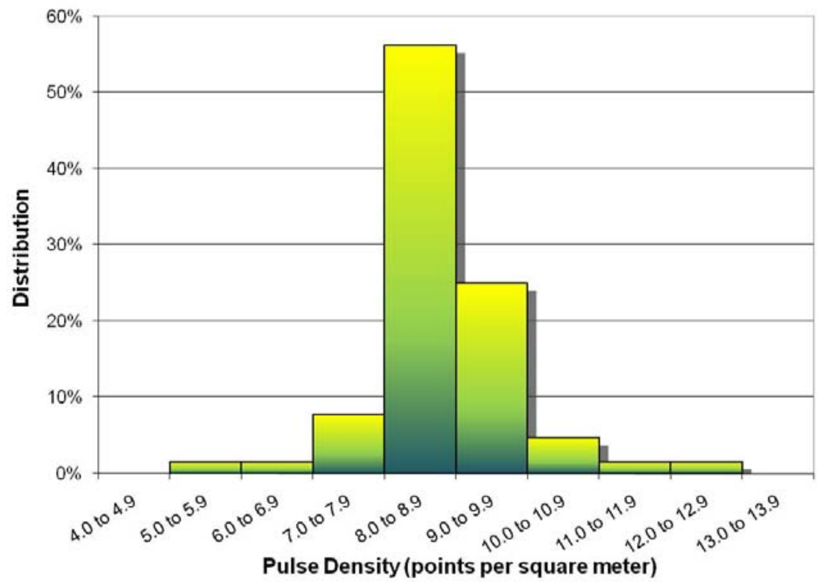
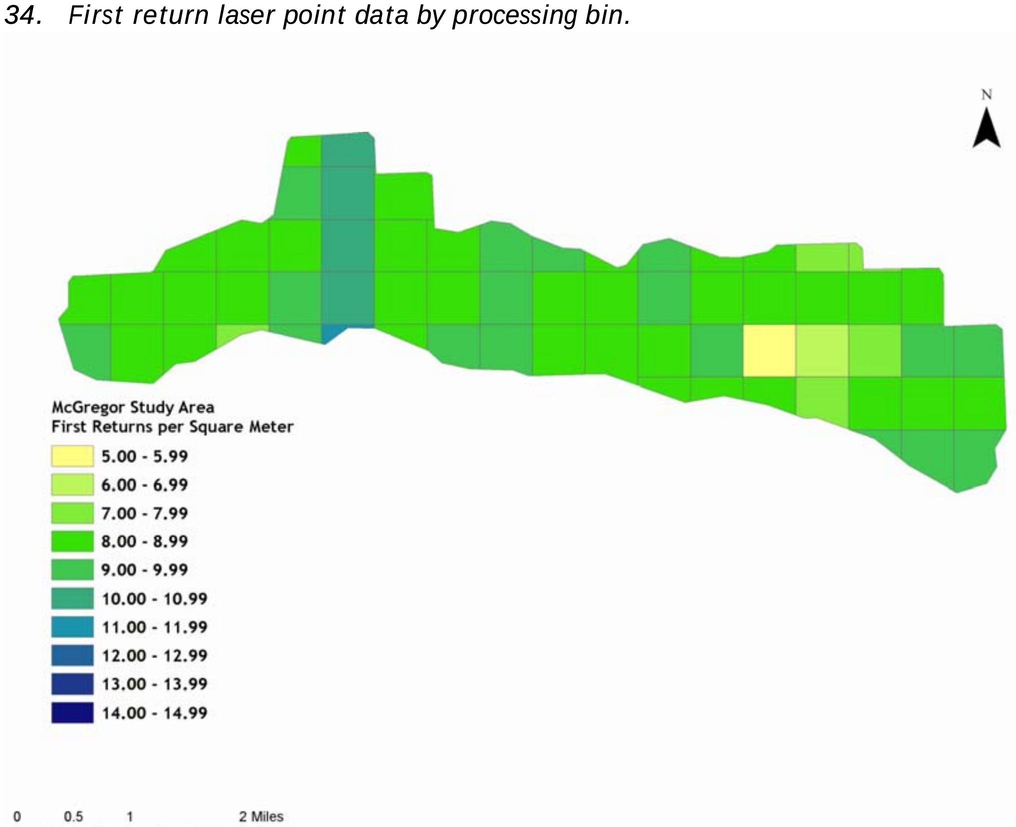


Figure 4.34. First return laser point data by processing bin.



Mission

Average Pulse Density: 8.26 points/square meter

Figure 4.35. Histogram of first return laser point density per processing bin.

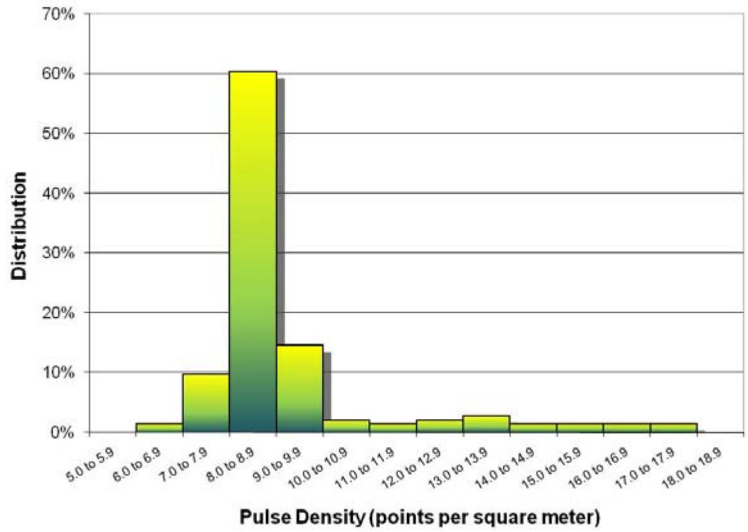
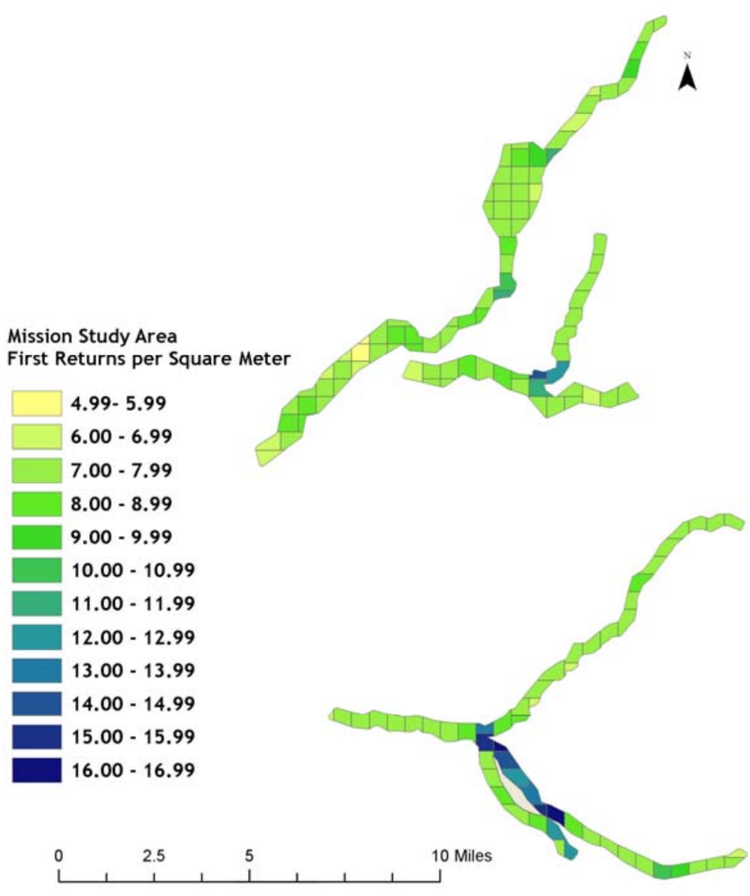


Figure 4.36. First return laser point data by processing bin.



4.2.2 Ground Classified Points per Square Meter

Ground classifications are derived from ground surface modeling. Supervised classifications were performed by reseeding where it is determined that the ground model has failed, usually under dense vegetation, at breaks in terrain, or at bin boundaries. Ground point density information is summarized below by study area.

Jocko River

Average Ground Classified Point Density: 2.32 points/square meter

Figure 4.37. Histogram of ground classified data density per processing bin.

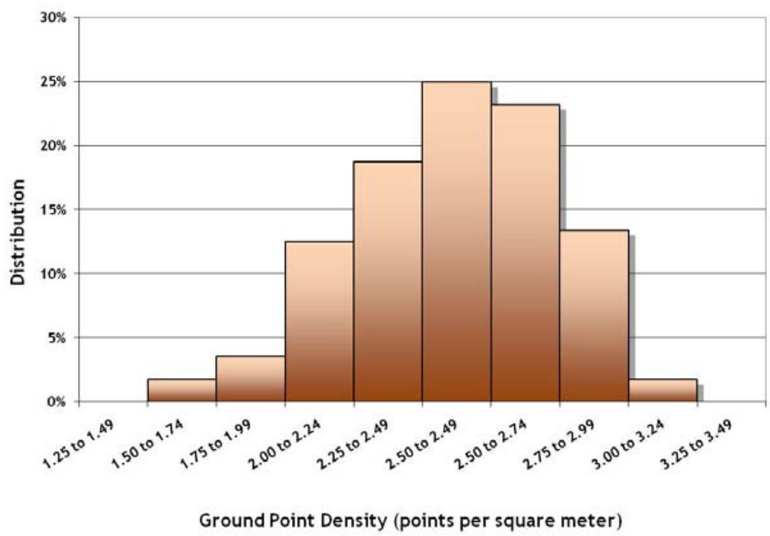
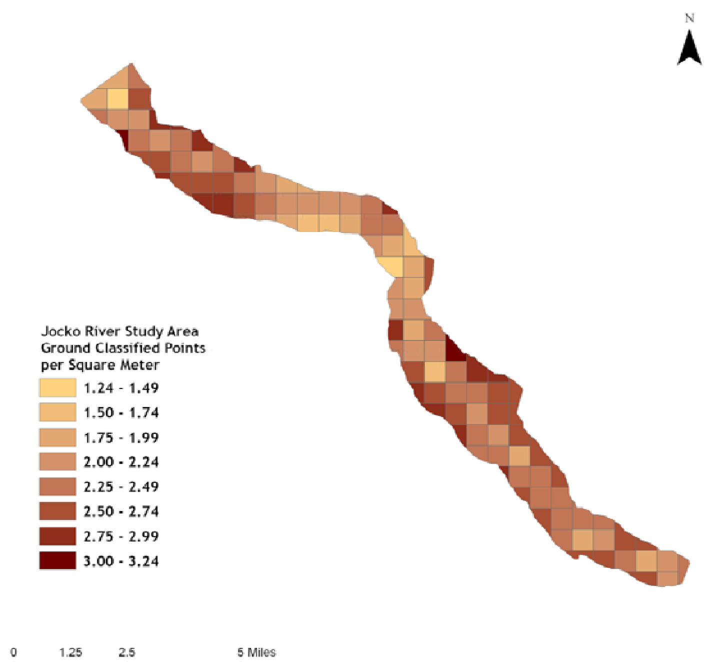


Figure 4.38. Ground classified point data density by processing bin for Jocko River.



Maddy River

Average Ground Classified Point Density: 1.73 points/square meter

Figure 4.39. Histogram of ground classified data density per processing bin.

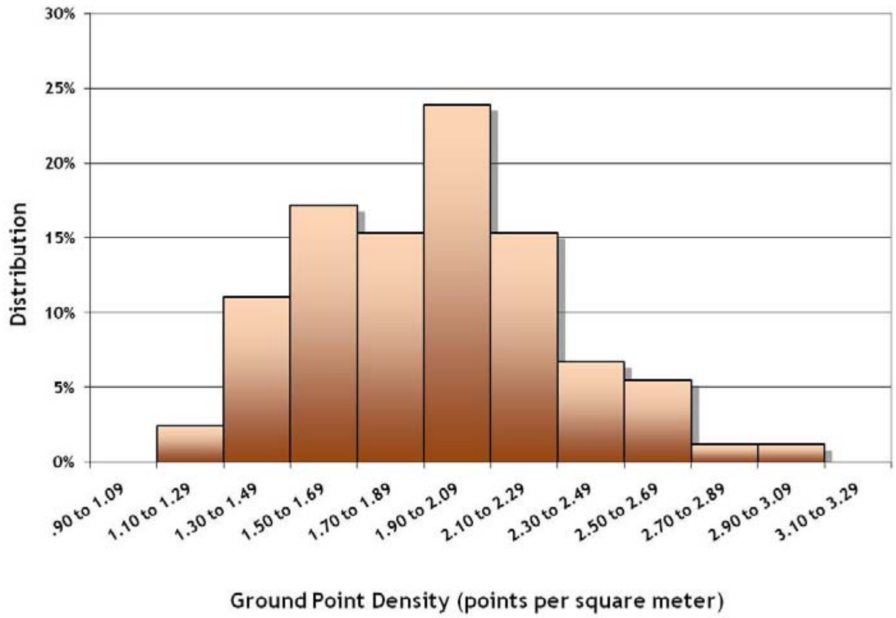
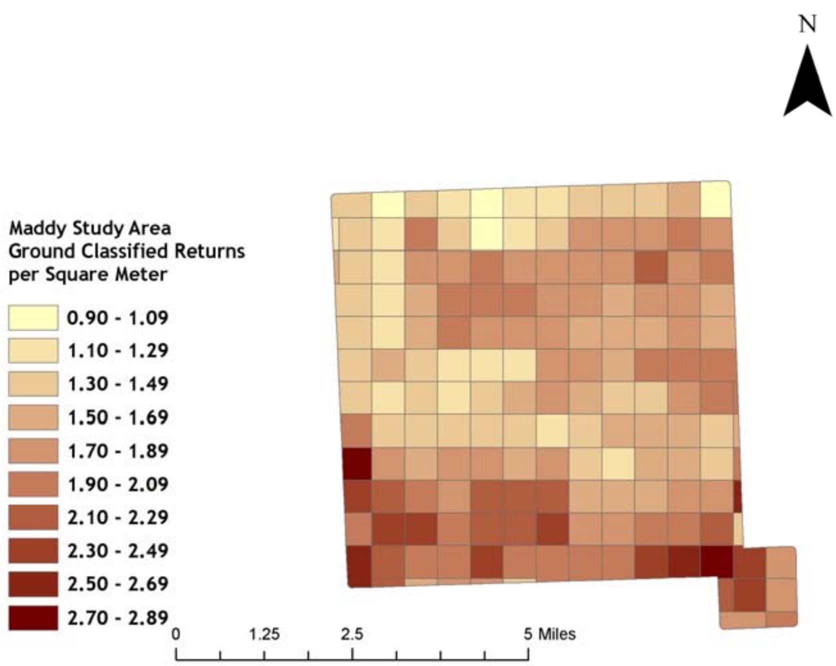


Figure 4.40. Ground classified point data density by processing bin for Maddy River.



Area C

Average Ground Classified Point Density: 1.68 points/square meter

Figure 4.41. Histogram of ground classified data density per processing bin.

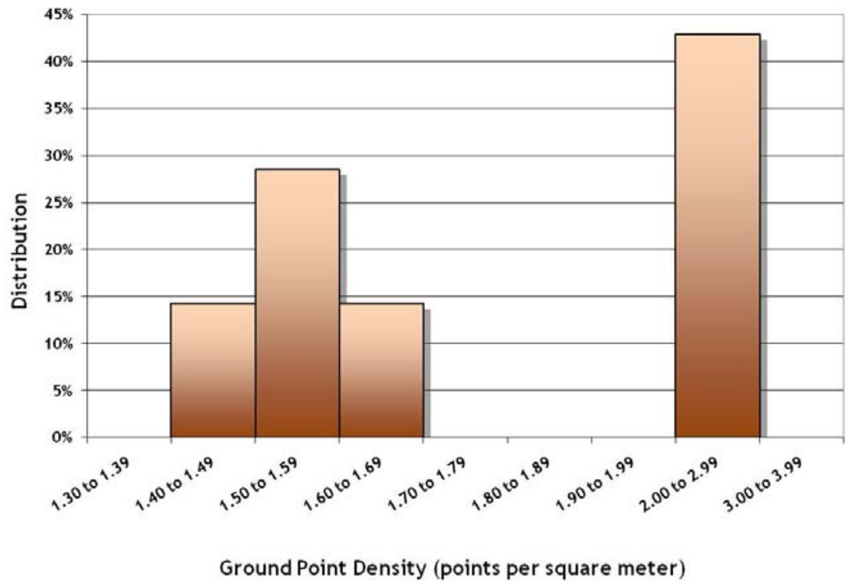
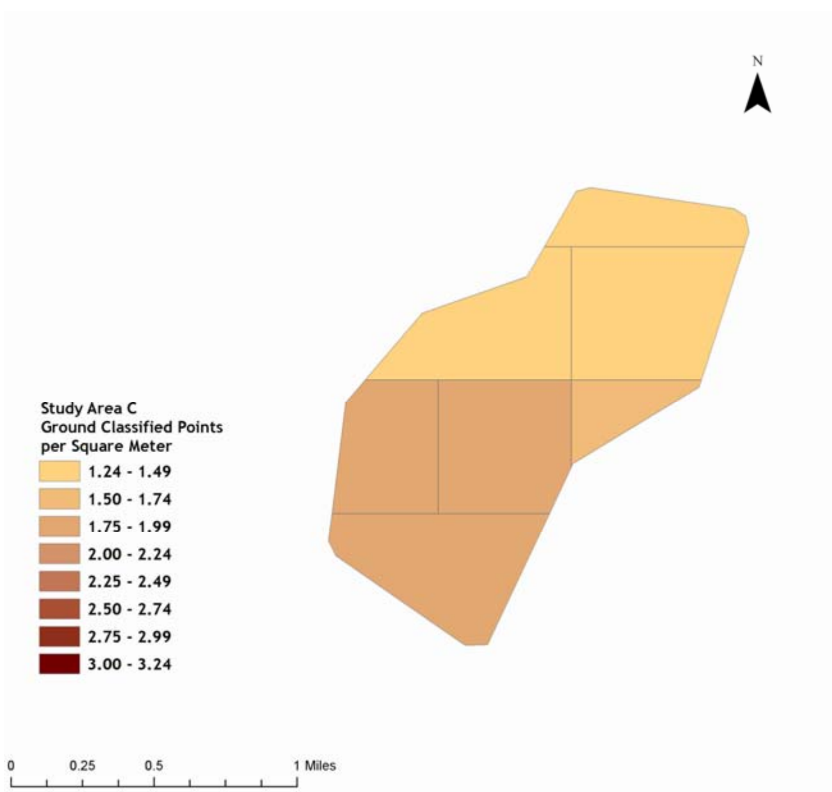


Figure 4.42. Ground classified point data density by processing bin for study area C.



McGregor

Average Ground Classified Point Density: 2.00 points/square meter

Figure 4.43. Histogram of ground classified data density per processing bin.

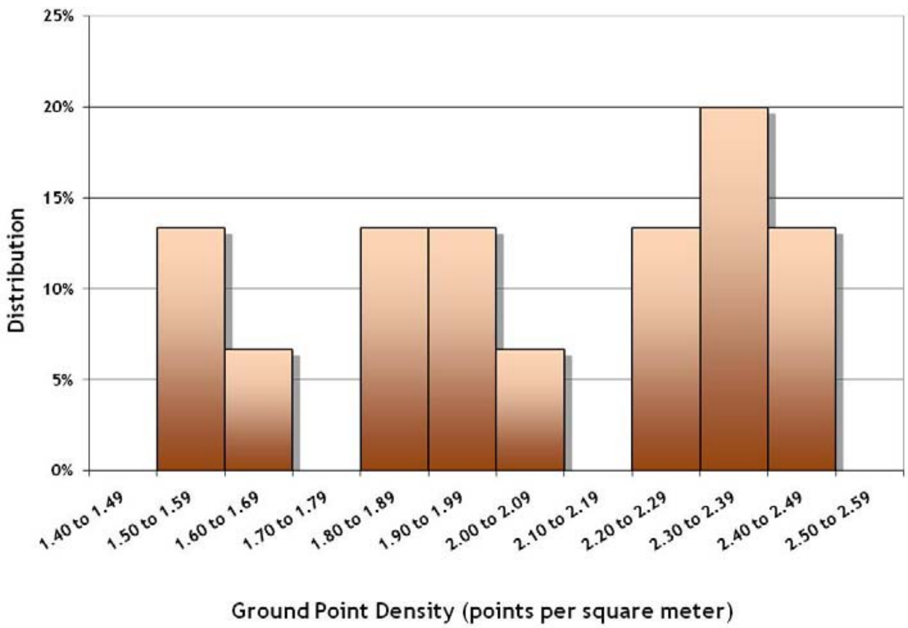
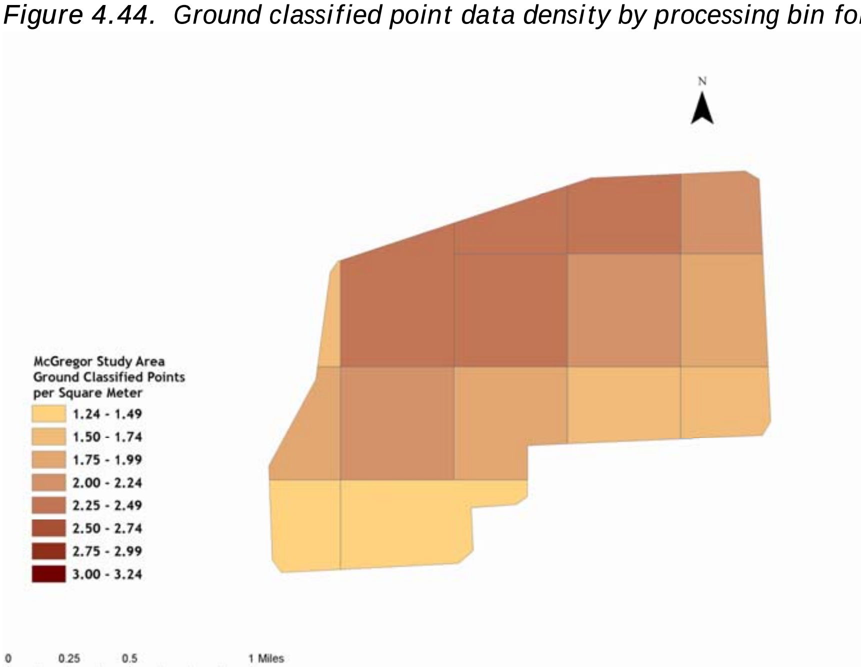


Figure 4.44. Ground classified point data density by processing bin for McGregor study area.



Lost

Average Ground Classified Point Density: 2.36 points/square meter

Figure 4.45. Histogram of ground classified data density per processing bin.

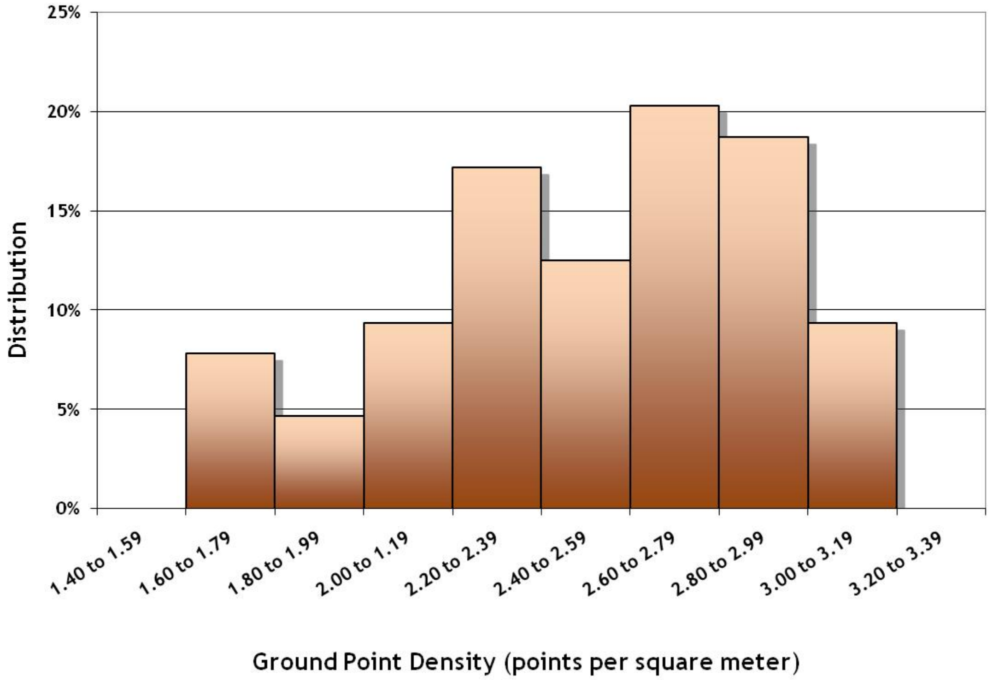
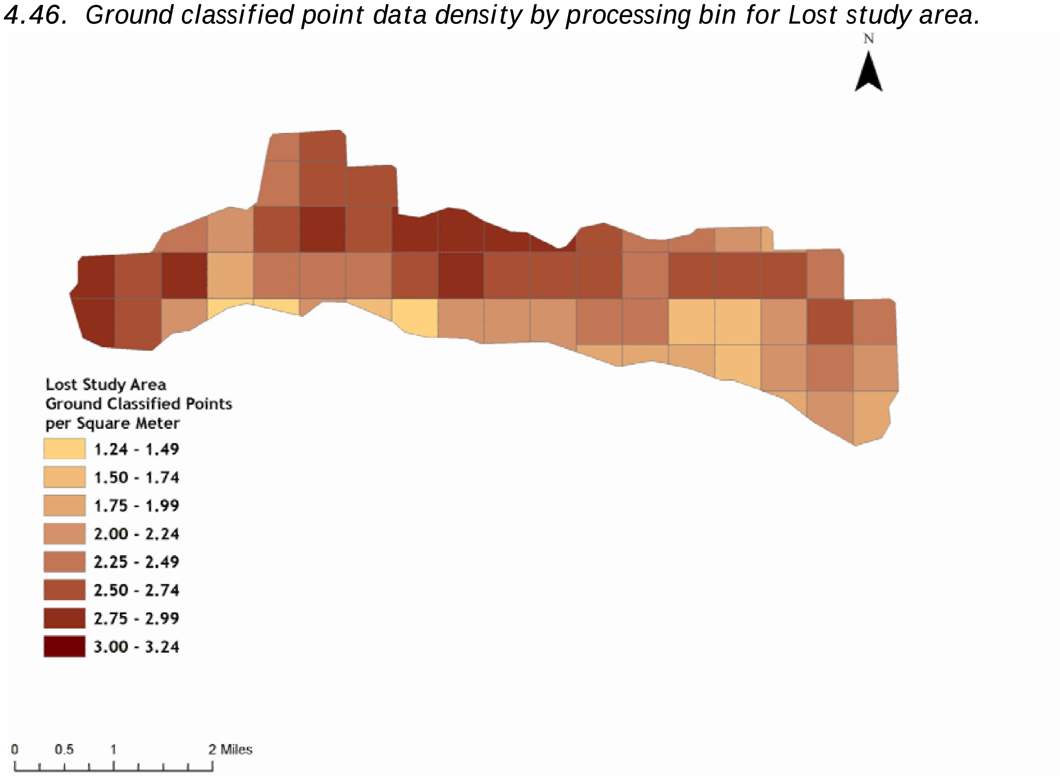


Figure 4.46. Ground classified point data density by processing bin for Lost study area.



Mission

Average Ground Classified Point Density: 2.36 points/square meter

Figure 4.47. Histogram of ground classified data density per processing bin.

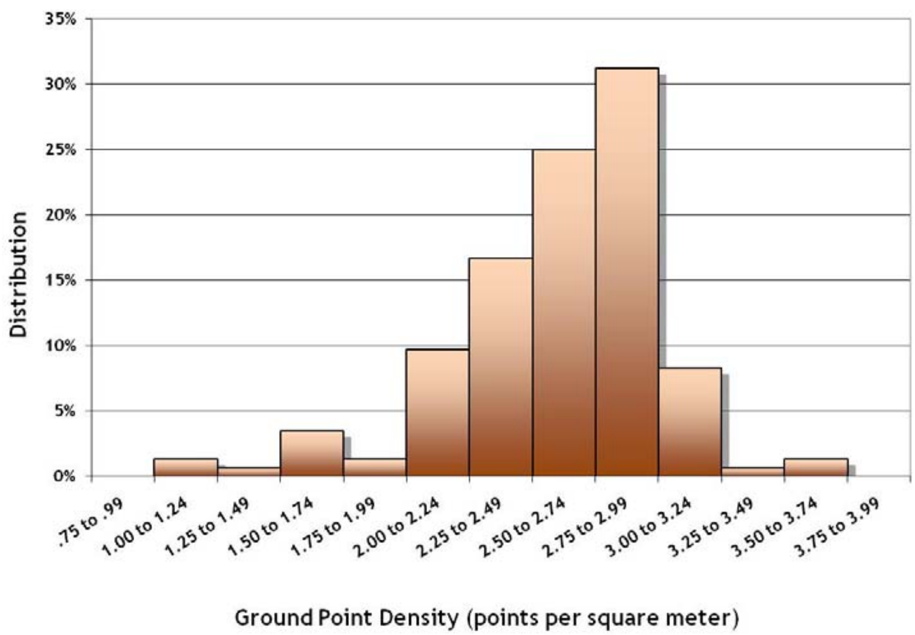
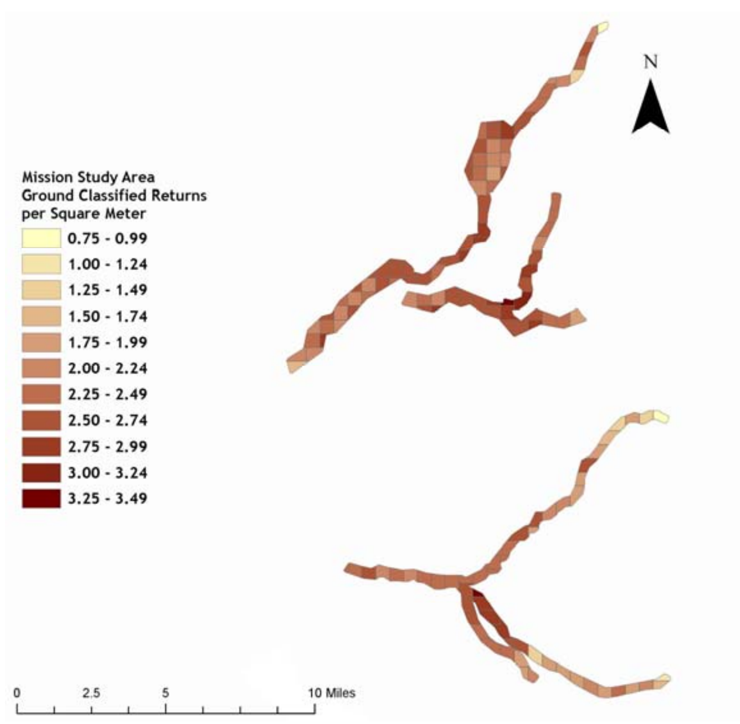


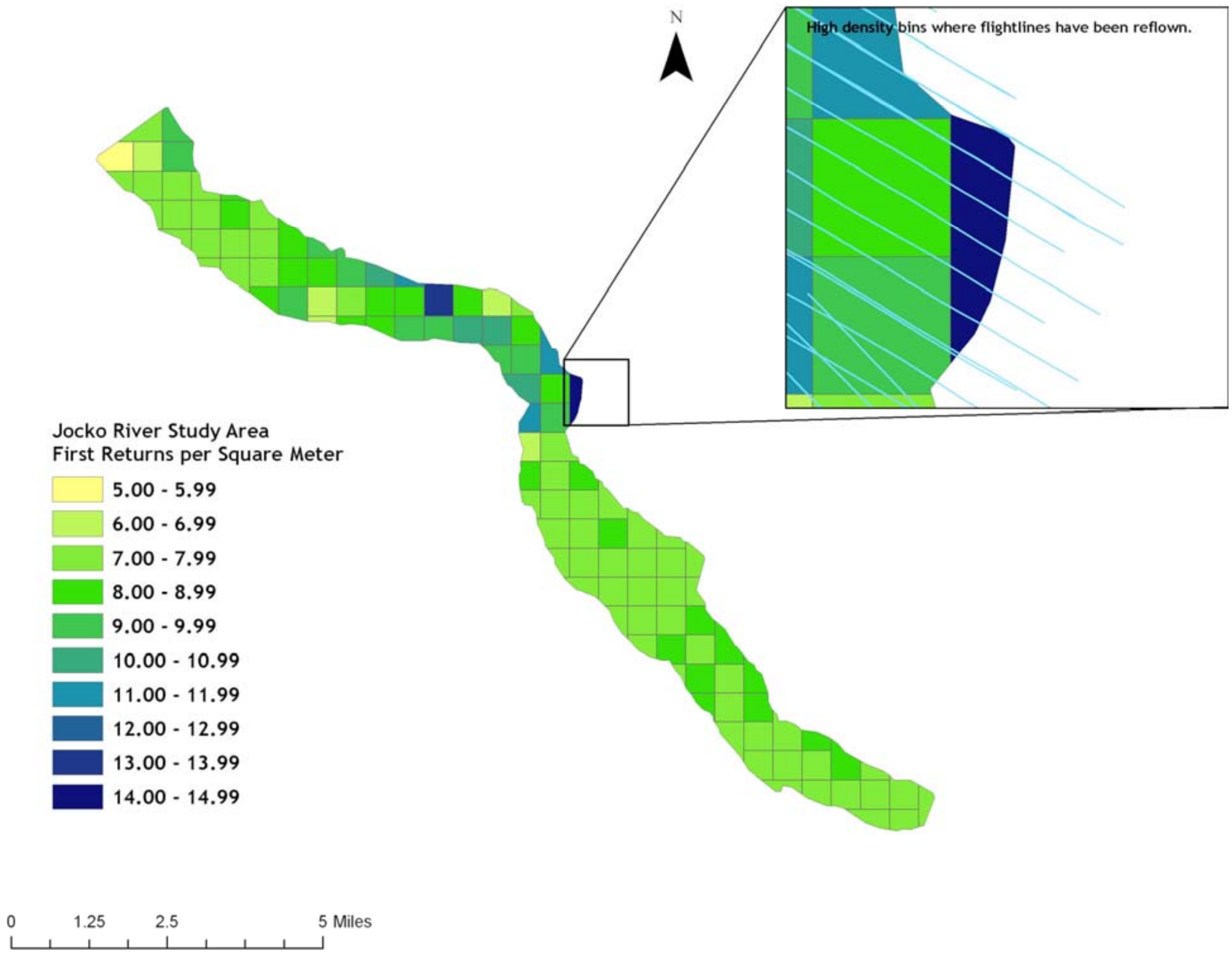
Figure 4.48. *Ground classified point data density by processing bin for Mission study area.*



4.2.3 Data Density/Resolution per Delivery Block

At the edges of the delivery area, the borders of the LiDAR data scan may overlap bins repeatedly, causing processing bins with higher than average data density.

Figure 4.49. Processing bins with high point density at the edges of the study area where flightlines overlap.



5. Data Specifications

	Targeted	Achieved
Resolution:	>8 points/m^2	7.7 - 10.3 points/m^2
Vertical Accuracy (1 σ):	<13 cm	3 - 6 cm

6. Projection/Datum and Units

The data were processed as ellipsoidal elevations and required a Geoid transformation to be converted into orthometric elevations (NAVD88). In TerraScan, the NGS published Geiod03 model is applied to each point. The data were processed in Universal Transverse Mercator (UTM) Zone 11; NAD83 (CORS96); NAVD88.

	Projection:	Montana State Plane, FIPS 2500
Datum	**Vertical:**	NAVD88 Geoid03
	Horizontal:	NAD83
	Units:	US Survey Feet

7. Selected Images

Figure 7.1. Oblique view along Jocko River valley and Highway 93. Top image derived from highest hit LiDAR, bottom image derived from bare earth LiDAR.

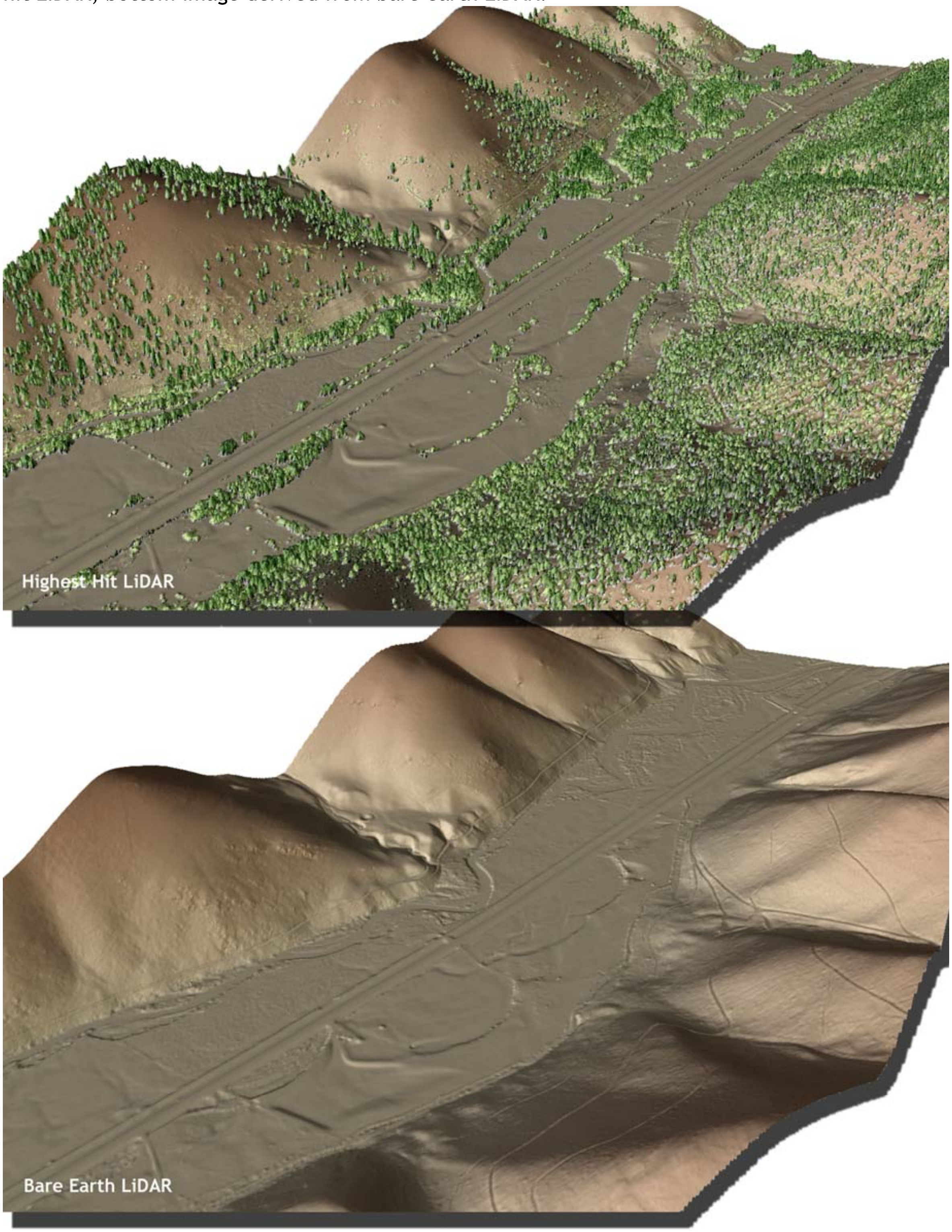
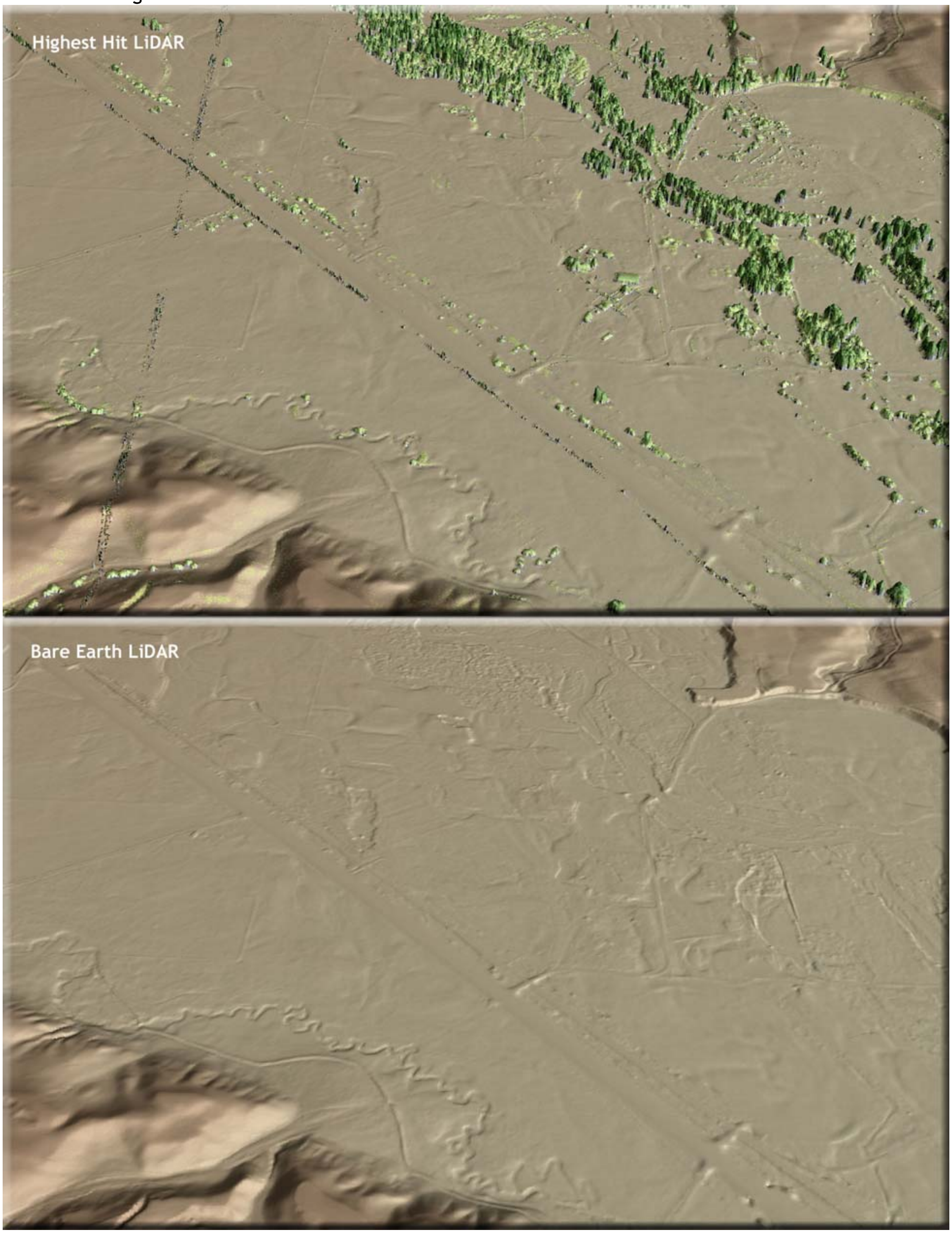


Figure 7.2. Oblique view along Jocko River and Highway 9, top image derived from highest hit LiDAR and lower image derived from bare earth LiDAR.



8. 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.

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

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.

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 Leica ALS 50 Phase II system can record *up to four* wave forms 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.

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).

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

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

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

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.

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

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

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.

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.

10. Citations

Soininen, A. 2004. TerraScan User's Guide. TerraSolid.