

LIDAR REMOTE SENSING: SALMON RIVER DATA REPORT

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LIDAR REMOTE SENSING: SALMON RIVER STUDY AREA

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1. Overview

1.1 Salmon River Study Area

Watershed Sciences, Inc. collected Light Detection and Ranging (LiDAR) data for Oregon Trout on 1,573 acres along the Salmon River in Oregon on May 18th and 19th, 2007. The map below shows the extent of the LiDAR total flight area (TAF) collected. The TAF acreage of the study area is greater than the original area of interest (AOI) due to buffering and optimization for flight planning. The data delivered conforms to the AOI requested and the statistics in this report reflect only the AOI. Data for the existing flight area along the Salmon River will be available through the Puget Sound LiDAR Consortium (PSLC) after it has passed their quality assurance protocol.

Figure 1.1. Extent of area of interest (AOI) and total flight area (TAF) acquired for Oregon Trout.

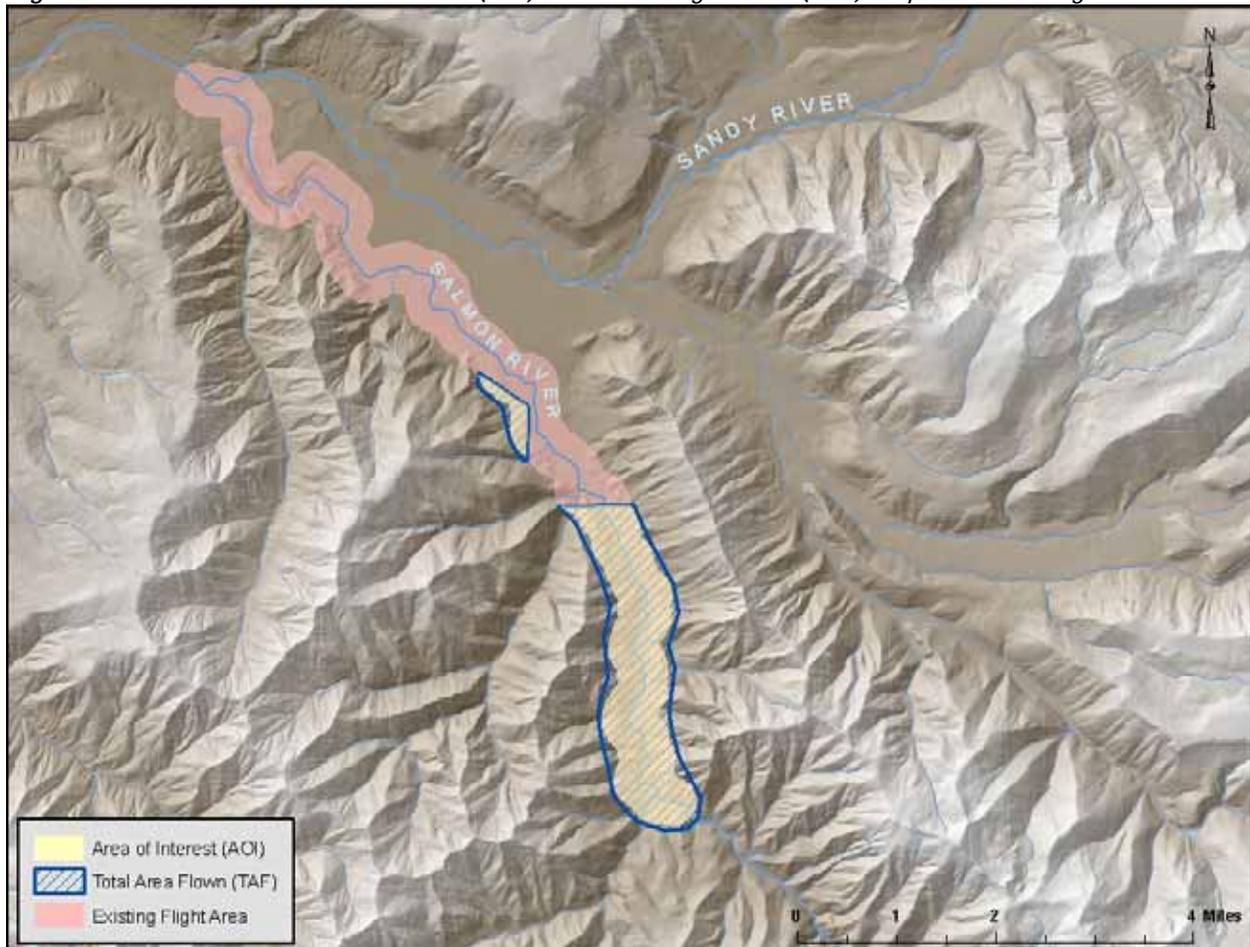
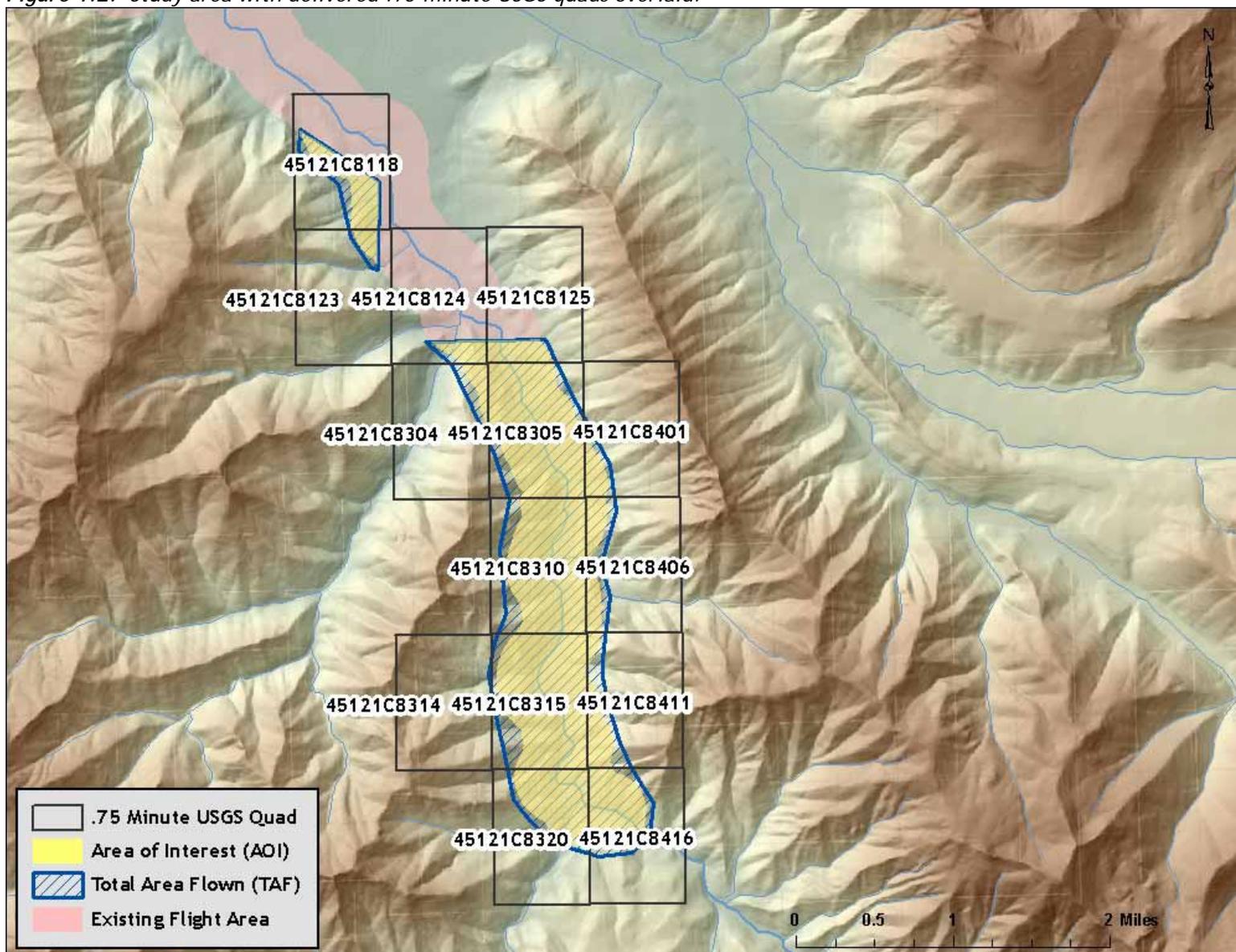


Figure 1.2. Study area with delivered .75-minute USGS quads overlaid.



1.2 Accuracy and Resolution

Real-time kinematic (RTK) surveys were conducted in multiple locations throughout the study area for quality assurance purposes. The accuracy of the LiDAR data is described as standard deviations of divergence (σ) from RTK ground survey points and root mean square error (RMSE) which considers bias (upward or downward). For the Salmon River study area, the data have the following accuracy statistics:

- RMSE of 0.09 feet
- 1-sigma absolute deviation of 0.08 feet
- 2-sigma absolute deviation of 0.18 feet

Data resolution specifications are for ≥ 8 points per m^2 . Section 4.2 demonstrates the total pulse density for the AOI delivered is 8 points per m^2 (0.7 points per square foot).

1.3 Data Format, Projection, and Units

Deliverables include: point data in .las v 1.1 and ascii formats, 3-foot resolution bare earth ESRI GRID, 3-foot resolution above ground surface ESRI GRID, 1.5-foot resolution intensity images in GeoTIFF format, smoothed best estimate of trajectory (5Hz frequency) information in ascii text format, and the data report. Data are delivered in Oregon State Plane North with horizontal units in International Feet and vertical units in US Survey Feet using the NAD83 HARN/NAVD88 datum (Geoid 03).

2. Acquisition

2.1 Airborne Survey - Instrumentation and Methods

The LiDAR survey utilized a Leica ALS50 Phase II sensor mounted in a Cessna Caravan 208B. The Leica ALS50 Phase II system was set to acquire $\geq 105,000$ laser pulses per second (i.e. 105 kHz pulse rate) and flown at 900 meters above ground level (AGL), capturing a scan angle of $\pm 14^\circ$ from nadir¹. These settings were 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 distribution of terrain, land cover and water bodies.



The Cessna Caravan is a powerful, stable platform, ideal for the remote and mountainous terrain of the Pacific Northwest. The Leica ALS50 sensor head installed in the Caravan is shown on the right.

The completed areas were surveyed with opposing flight line side-lap of $\geq 50\%$ ($\geq 100\%$ overlap) to reduce laser shadowing and increase surface laser painting. The system allows up to four range measurements per pulse, and 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

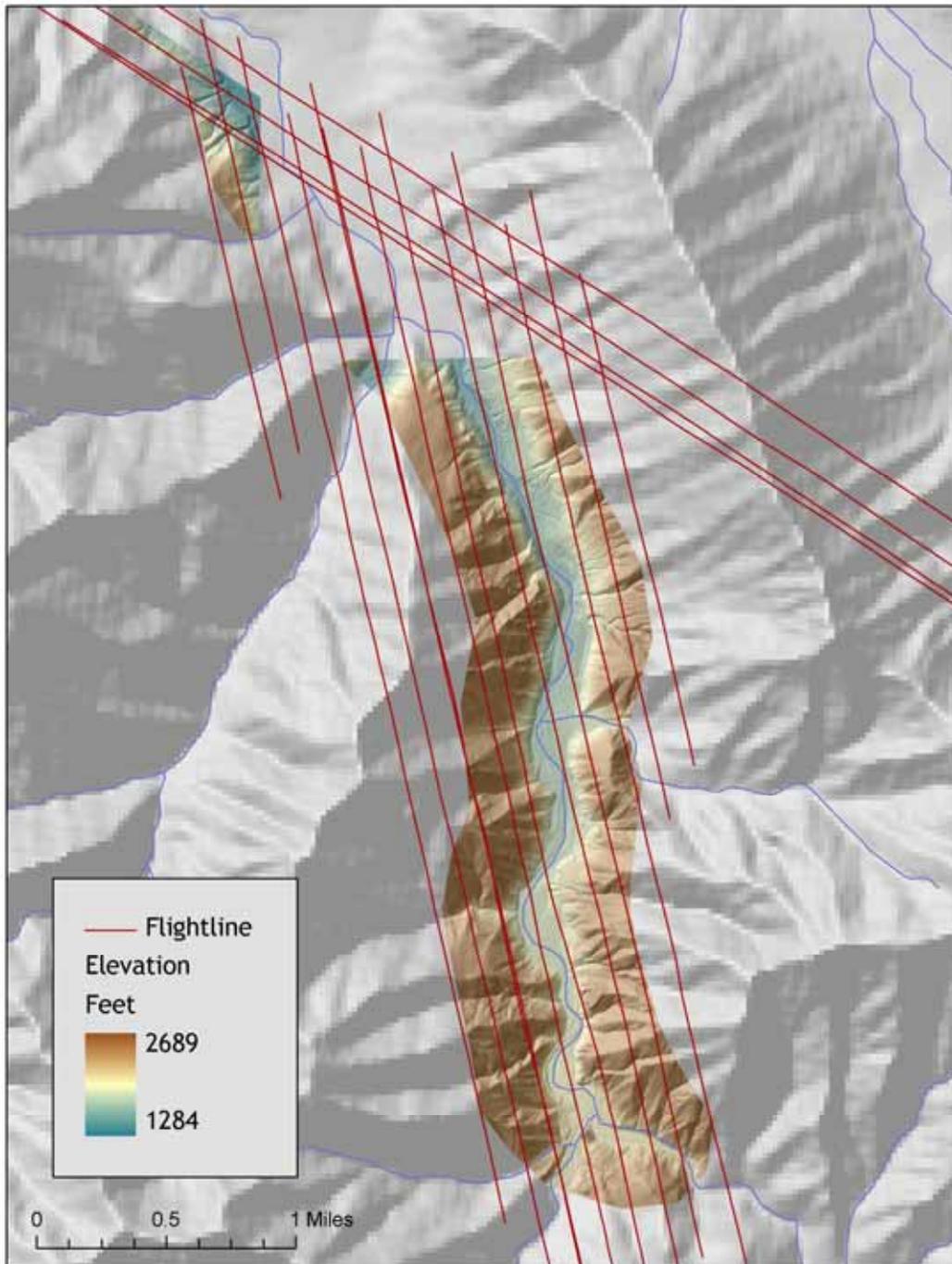
Sensor	Leica ALS50 Phase II
Survey Altitude (AGL)	900 m
Pulse Rate	>105 kHz
Pulse Mode	Single
Mirror Scan Rate	52 Hz
Field of View	28° ($\pm 14^\circ$ from nadir)
Roll Compensated	Up to 15°
Overlap	100% (50% Side-lap)

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 a “degrees from nadir”.

2.1.1 Acquisition Specifics of Delivery Area

The Salmon River study area was flown on May 18th and 19th, 2007 in conjunction with data collection on the Upper Salmon for the Oregon Department of Geology and Mineral Industries (DOGAMI). The AOI flown for Oregon Trout has been acquired and processed using the same methodology as the DOGAMI data set for the purpose of compatibility. **Figure 2.1** illustrates the location, swath width and overlap of the flight lines, as executed in the Salmon River AOI.

Figure 2.1. Flightlines in Salmon River study area.



2.2 Ground Survey - Instrumentation and Methods

During the LiDAR survey of the study area, a static (1 Hz recording frequency) ground survey was conducted over monuments with known coordinates. Coordinates are provided in **Table 2.2** and shown in **Figure 2.2**. After the airborne survey, the static GPS data are processed using triangulation with CORS stations and checked against the Online Positioning User Service (OPUS²) to quantify daily variance. Multiple sessions are processed over the same monument to confirm antenna height measurements and position accuracy.

Table 2.2. Base station surveyed coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data.

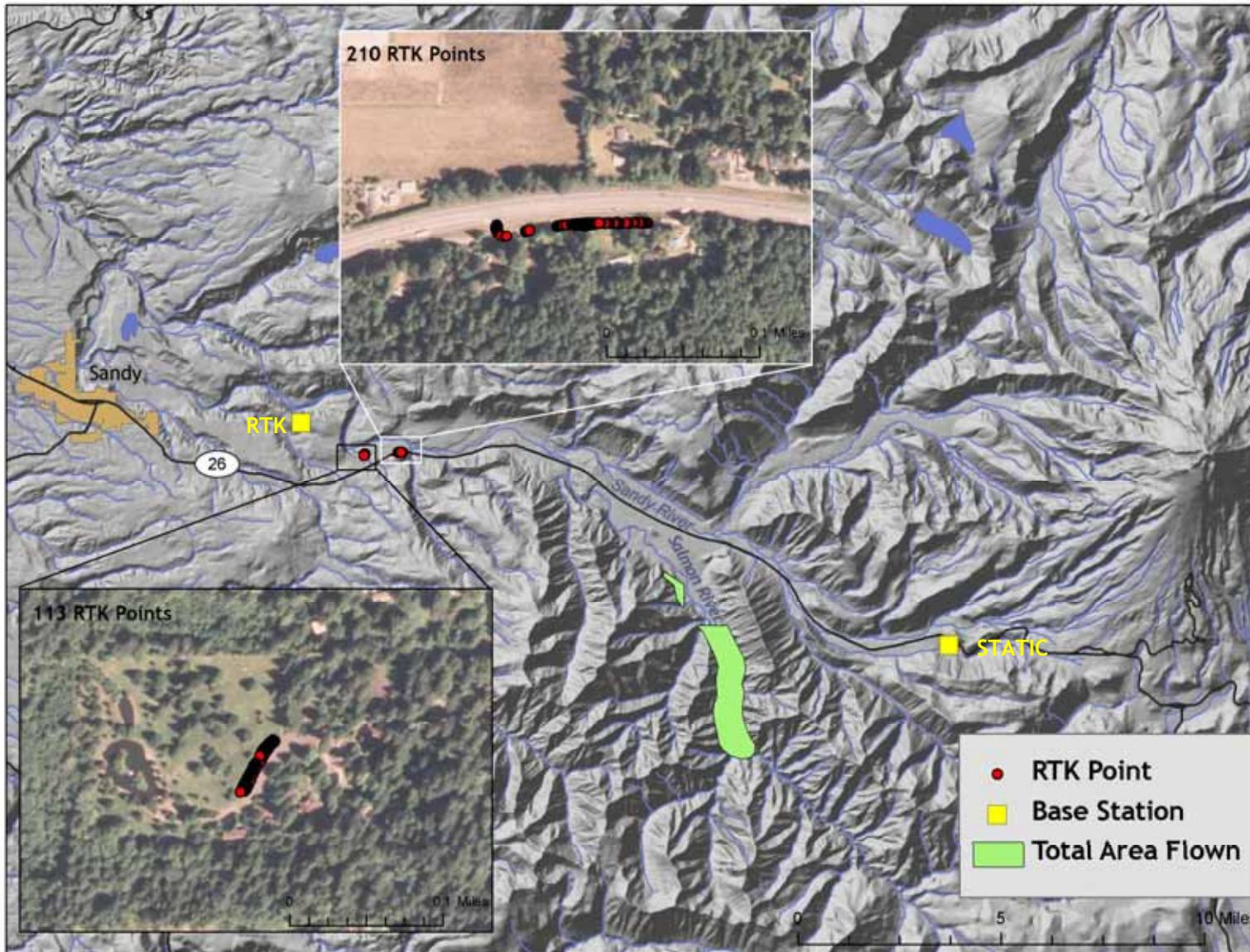
Study Area	Base Station ID	Datum NAD83(HARN)		GRS80
		Latitude (North)	Longitude (West)	Ellipsoid Height (m)
Upper Salmon River	ORJR21	45 18 23.10077	121 49 49.67527	808.484
Upper Salmon River	ORSP20	45 23 19.99348	122 09 23.35649	359.167

Multiple DGPS units are used for the ground real-time kinematic (RTK) portion of the survey. To collect accurate ground surveyed points, a GPS base unit is set up over monuments to broadcast a kinematic correction to a roving GPS unit. The ground crew uses a roving unit to receive radio-relayed kinematic corrected positions from the base unit. This method is referred to as real-time kinematic (RTK) surveying and allows precise location measurement ($\sigma \leq 1.5 \text{ cm} \sim 0.6 \text{ in}$). For the Salmon River study area, 323 RTK points were collected in the vicinity and compared to LiDAR data for accuracy assessment. **Figure 2.2** shows base station locations and a detailed view of RTK point locations.



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

Figure 2.2. Base station and RTK points for Salmon River study area.



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.7.012
5. Using ground classified points per 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.7.004
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. Ground models were created as a triangulated surface and exported as ArcInfo ASCII grids at a 3-foot pixel resolution.
Software: TerraScan v.7.012, ArcMap v9.2, TerraModeler v.7.006

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. Ground surface rasters were developed from triangulated irregular networks (TINs) of ground points.

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 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 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 (i.e., $\sim 1/3000^{\text{th}}$ AGL flight altitude). 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 $\pm 14^\circ$ 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 19 km (11.5 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. The ground survey collected 323 RTK points that are distributed throughout multiple flight lines across the study areas.
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 (per line) total over 117 million points from which to compute and refine relative accuracy.* 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 are then blended when imported together to form the entire area of interest.
3. Automated Z Calibration: Ground points per line are utilized to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration is the final step employed for relative accuracy calibration.

Relative Accuracy Calibration Results

Relative accuracy statistics for the Salmon River study area are based on the comparison of 70 flightlines and over 117 million points. For flightline coverage, see **Figure 2.2** in Section 2.1.

- Project Average = 0.29 ft
- Median Relative Accuracy = 0.36 ft
- 1 σ Relative Accuracy = 0.42 ft
- 2 σ Relative Accuracy = 0.55 ft

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

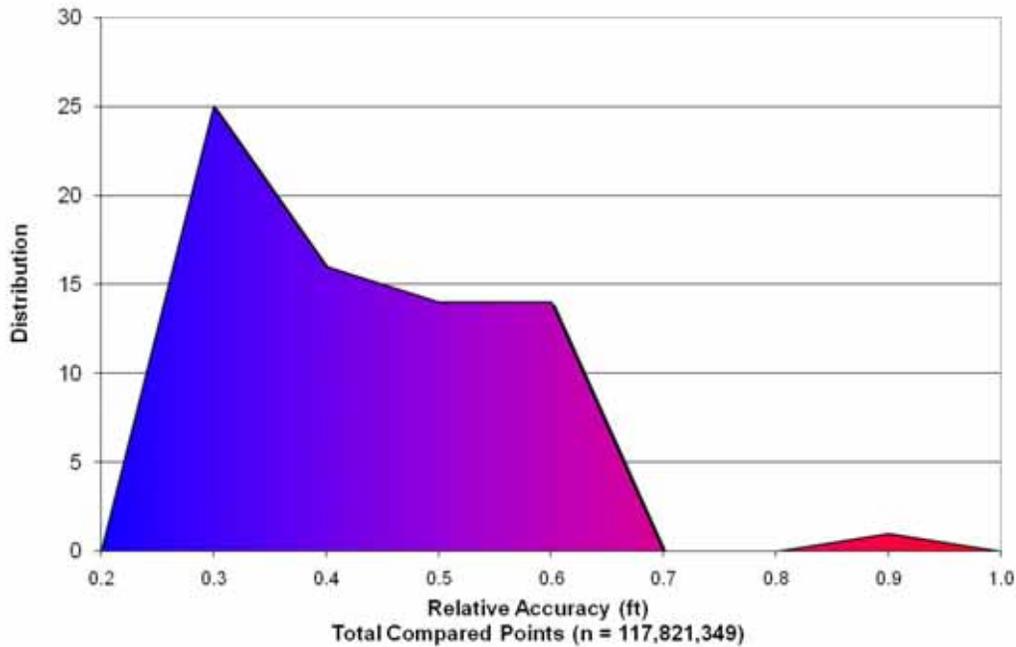
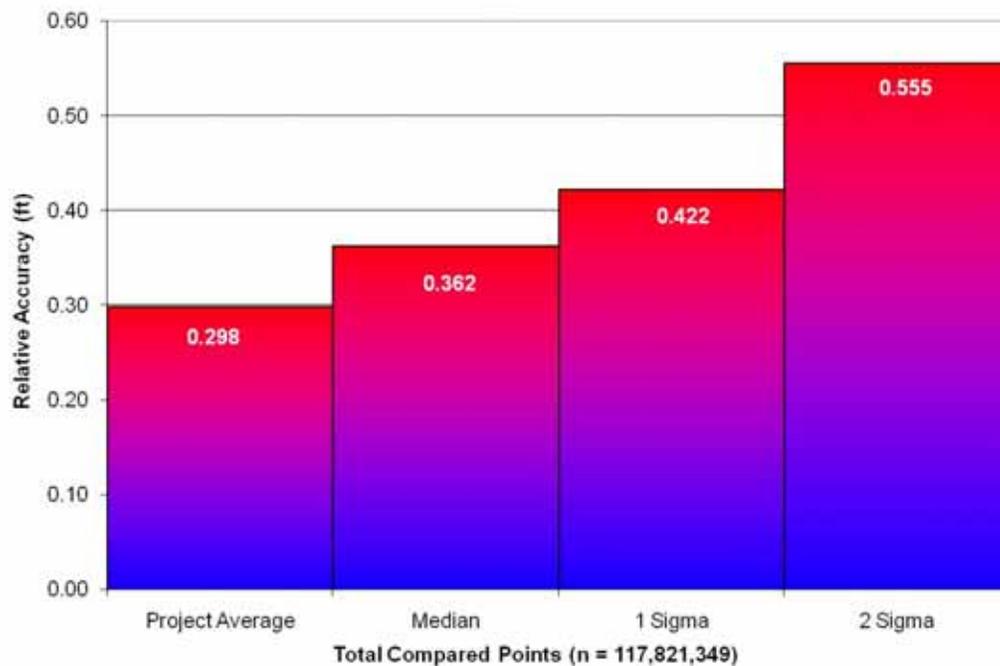


Figure 4.2. Statistical relative accuracies, non slope-adjusted.



4.1.2 Absolute Accuracy

The final quality control measure is a statistical accuracy assessment comparing RTK ground survey points to the closest laser points. 323 RTK points were collected near the Salmon River study area for absolute accuracy analysis. Accuracy statistics are reported in Table 4.2 and shown in Figures 4.3-4.4.

Table 4.2. Absolute Accuracy: deviation between laser points and RTK survey points.

Sample Size (n): 323	
Root Mean Square Error (RMSE): 0.09 feet	
Standard Deviations	Deviations
1 sigma (σ): 0.08 feet	Minimum Δz : -0.28 feet
2 sigma (σ): 0.18 feet	Maximum Δz : 0.20 feet
	Average Δz : 0.00 feet

Figure 4.3. Absolute deviation histogram statistics

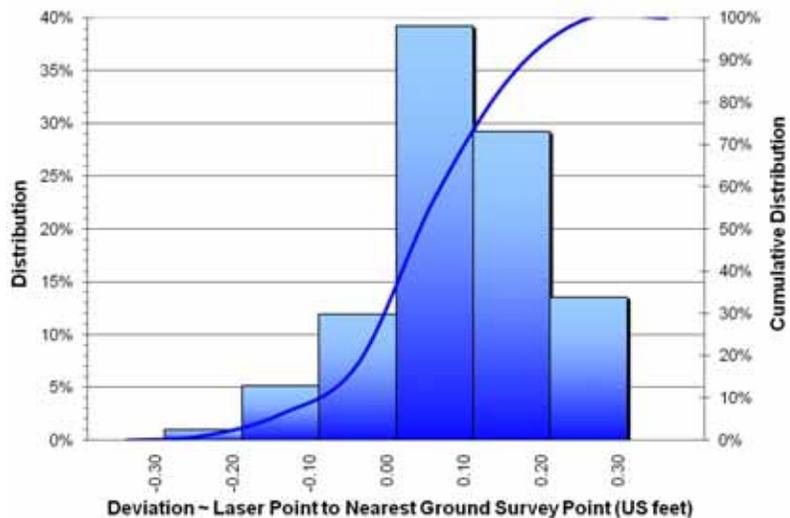
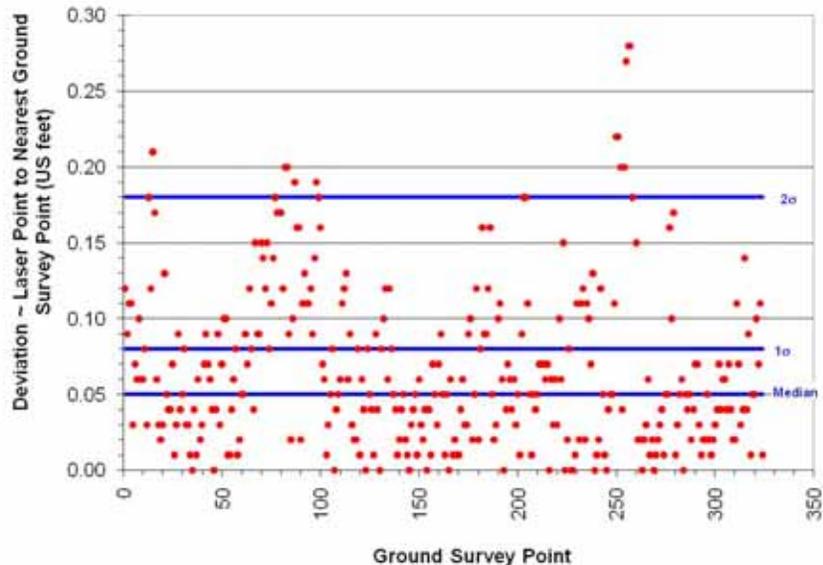


Figure 4.4 Absolute deviation statistics



4.2 Data Density/Resolution

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. Density histograms and maps (Figures 4.5-4.8) are based on calculations of first return laser point density and ground-classified laser point density.

- The total average delivered density for the Salmon River AOI is 0.7 points per square foot (8 points per square meter, based on first return pulses only).

4.2.1 First Return Laser Pulses per Square Foot

Figure 4.5. Histogram of first return laser point data density per 0.75' USGS Quad.

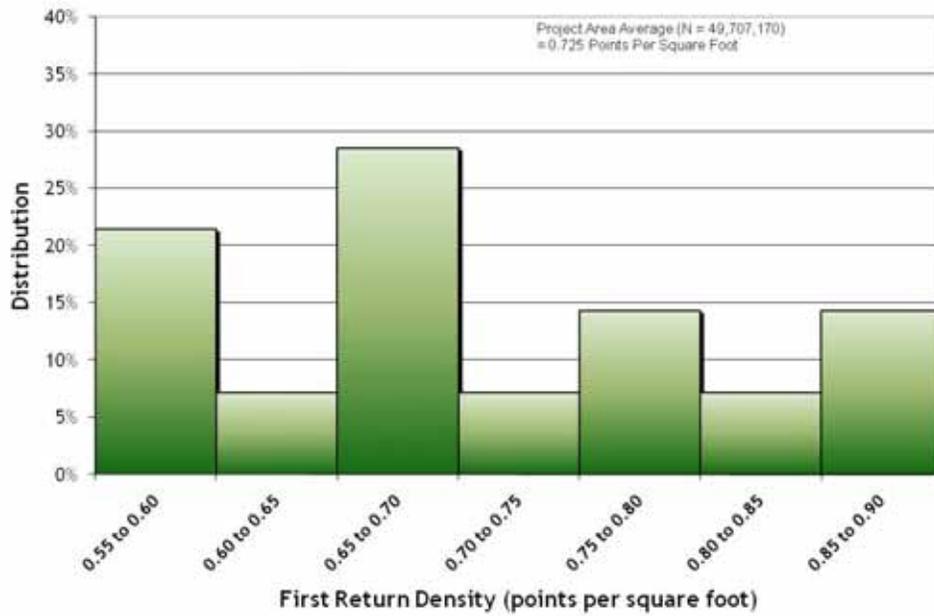
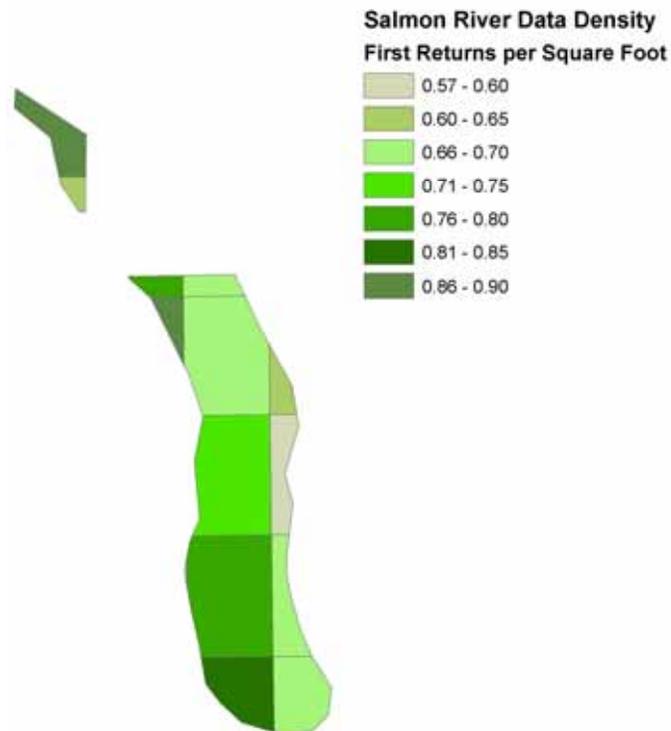


Figure 4.6. First return laser point data density per 0.75' USGS Quad.



4.2.2 Classified Ground Points per Square Foot

Ground classifications are derived from ground surface modeling. Supervised classifications were performed by reseeding the ground model where it is determined that the ground model has failed, usually under dense vegetation and/or at breaks in terrain, steep slopes, and at bin boundaries.

Figure 4.7. Histogram of ground-classified laser point data density per 0.75' USGS Quad.

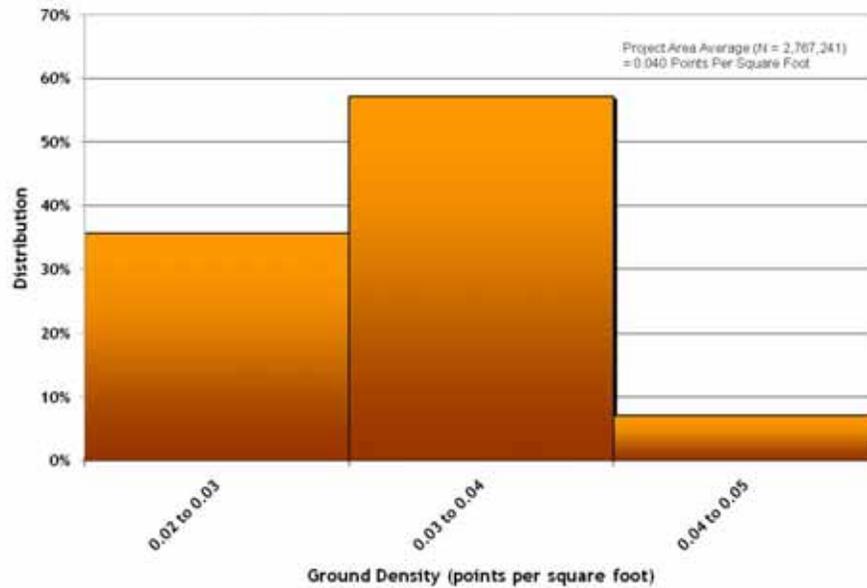
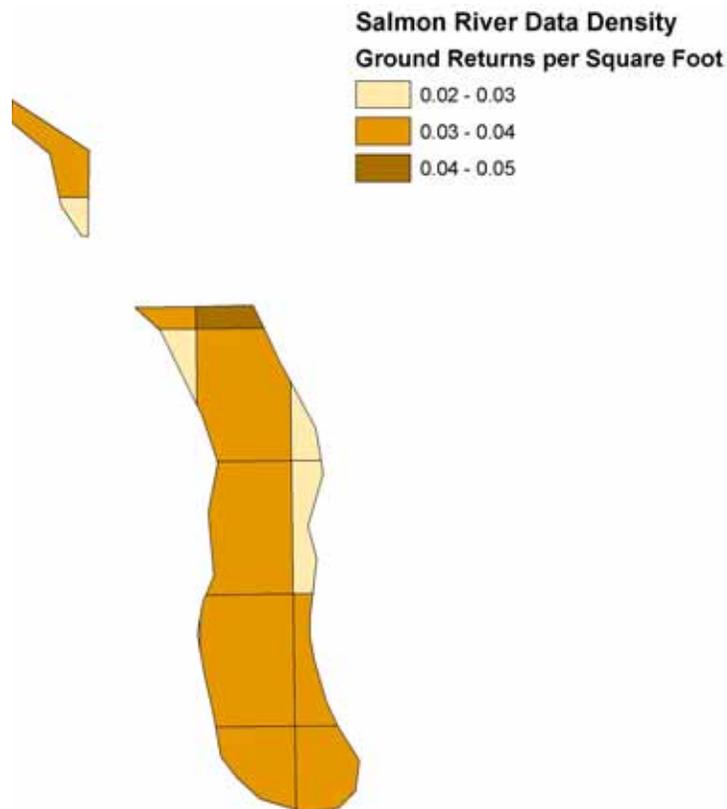


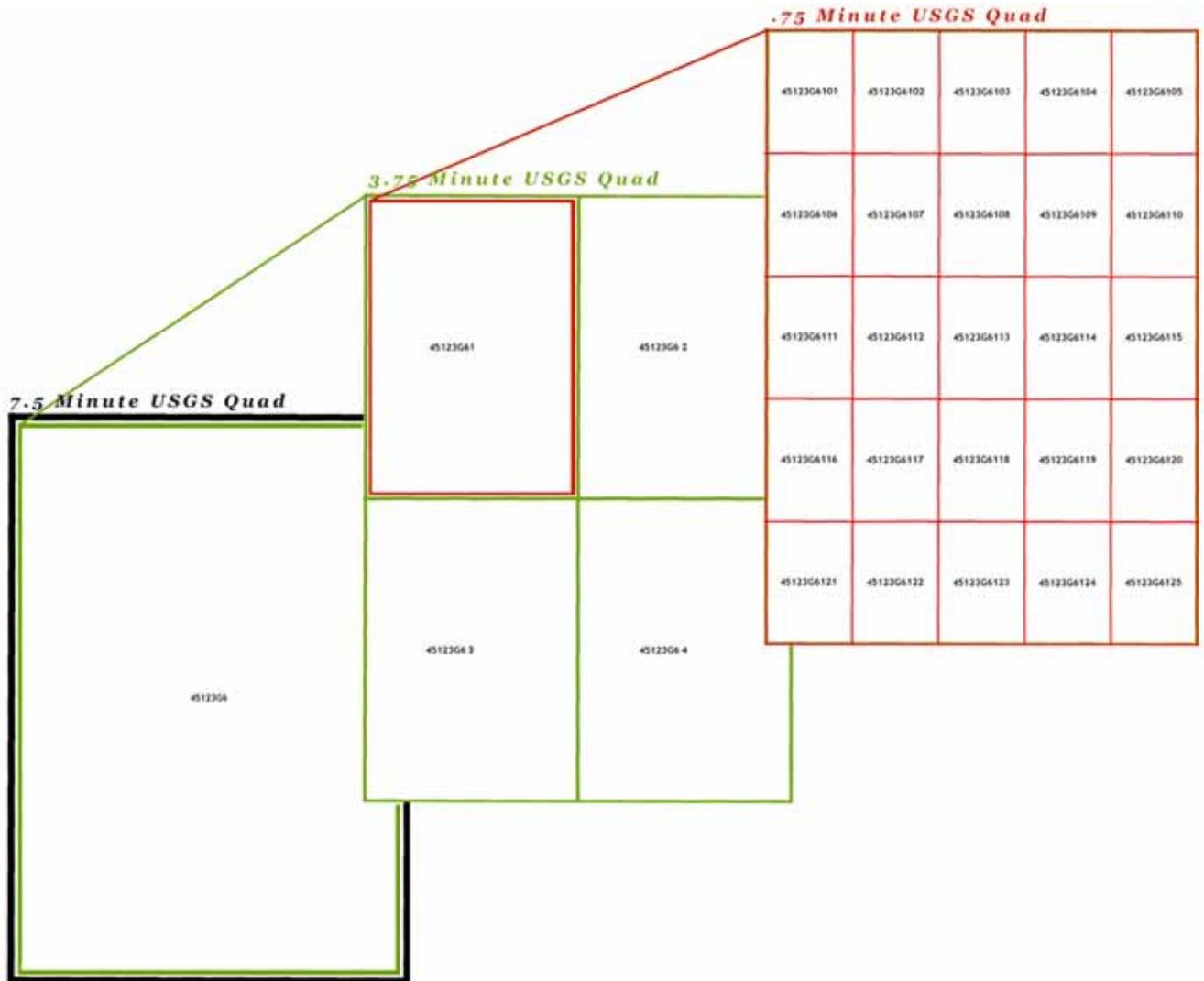
Figure 4.8. Ground-classified laser point data density per 0.75' USGS Quad.



5. Deliverables

The data delivered conform to the following tiling scheme:

Figure 5.1. 0.75' USGS Quad Delineation Naming Convention.



5.1 Point Data (per 0.75' USGS Quad)

Data Fields: Number, X, Y, Z, Intensity, ReturnNumber, NumReturns, ScanDirection, EdgeOfFlightLine, Class, ScanAngleRank, FileMarker, UserBitField, GPSTime

- LAS v 1.1 Format and ASCII Format
 - All points
 - Ground classified points
 - Above ground points
 - Model keypoints
- Smoothed Best Estimate of Trajectory point files in ASCII format

5.2 Vector Data

- Total Area Flown
 - 0.75-minute quadrangle delineation in shapefile format (See **Figure 5.1** for illustration)
- Contours in 2-foot resolution, .dxf format

5.3 Raster Data

- ESRI GRID of Bare Earth Modeled LiDAR data points (3-foot resolution) delivered in 7.5' USGS Quad delineation
- ESRI GRID of above ground modeled LiDAR data points (3-foot resolution) delivered in 7.5' USGS Quad delineation
- Intensity images in GeoTIFF format (1.5-foot resolution) delivered per 0.75' Quad

5.4 Data Report

- Full report containing introduction, methodology, and accuracy.
 - Word format (*.doc)
 - PDF format (*.pdf)

5.5 Datum and Projection

The data were processed as ellipsoidal elevations and required a Geoid transformation to be converted into orthometric elevations (NAVD88). In TerraScan, the NGS published Geoid03 model is applied to each point. The data were processed using meters in the Universal Transverse Mercator (UTM) Zone 10 and NAD83 (CORS96)/NAVD88 datum and converted to the delivery projection. This AOI is delivered in Oregon State Plane North, with horizontal units in International Feet and vertical units in US Survey Feet in the NAD83 HARN/NAVD88 datum (Geoid 03).

6. Selected Images

Figure 6.1. Plan view of confluence of South Fork Salmon River and Salmon Main Fork. Top image derived from bare earth LiDAR points; bottom image contains highest hits LiDAR points.

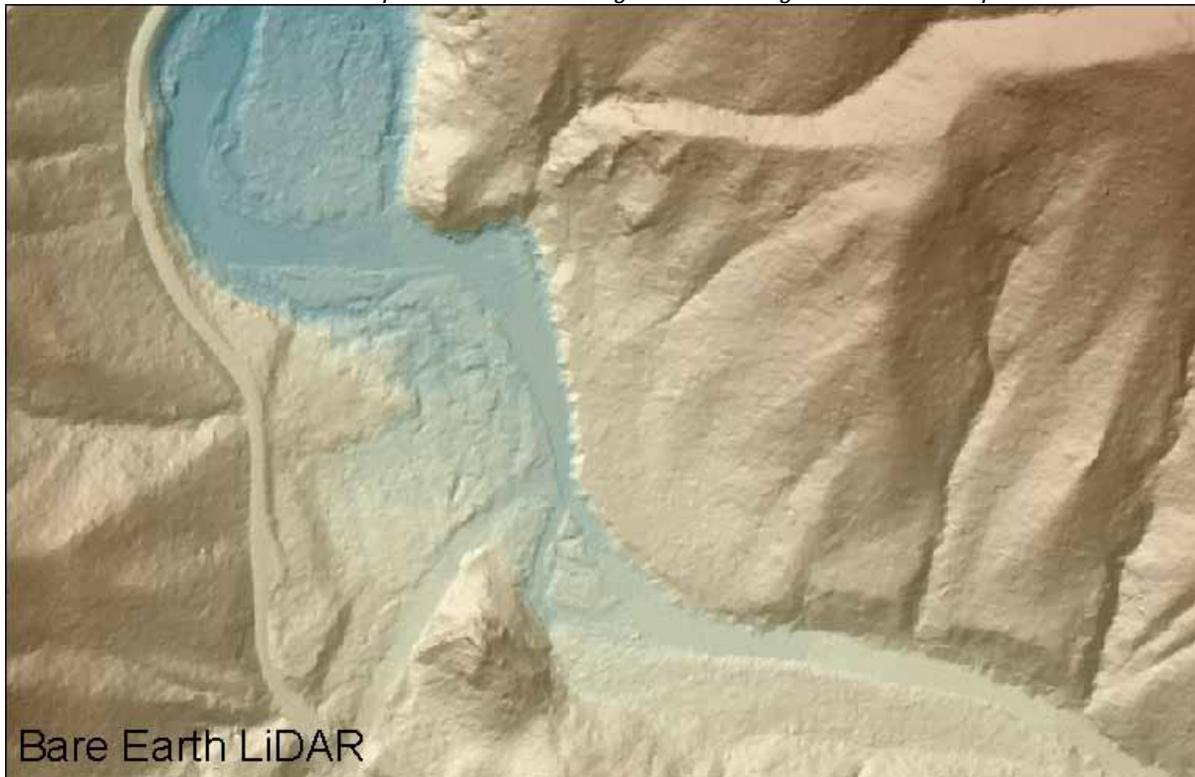


Figure 6.2. 3-d oblique view from the northern end of study area (top image derived from ground-classified LiDAR points, and bottom image from highest hit LiDAR points).

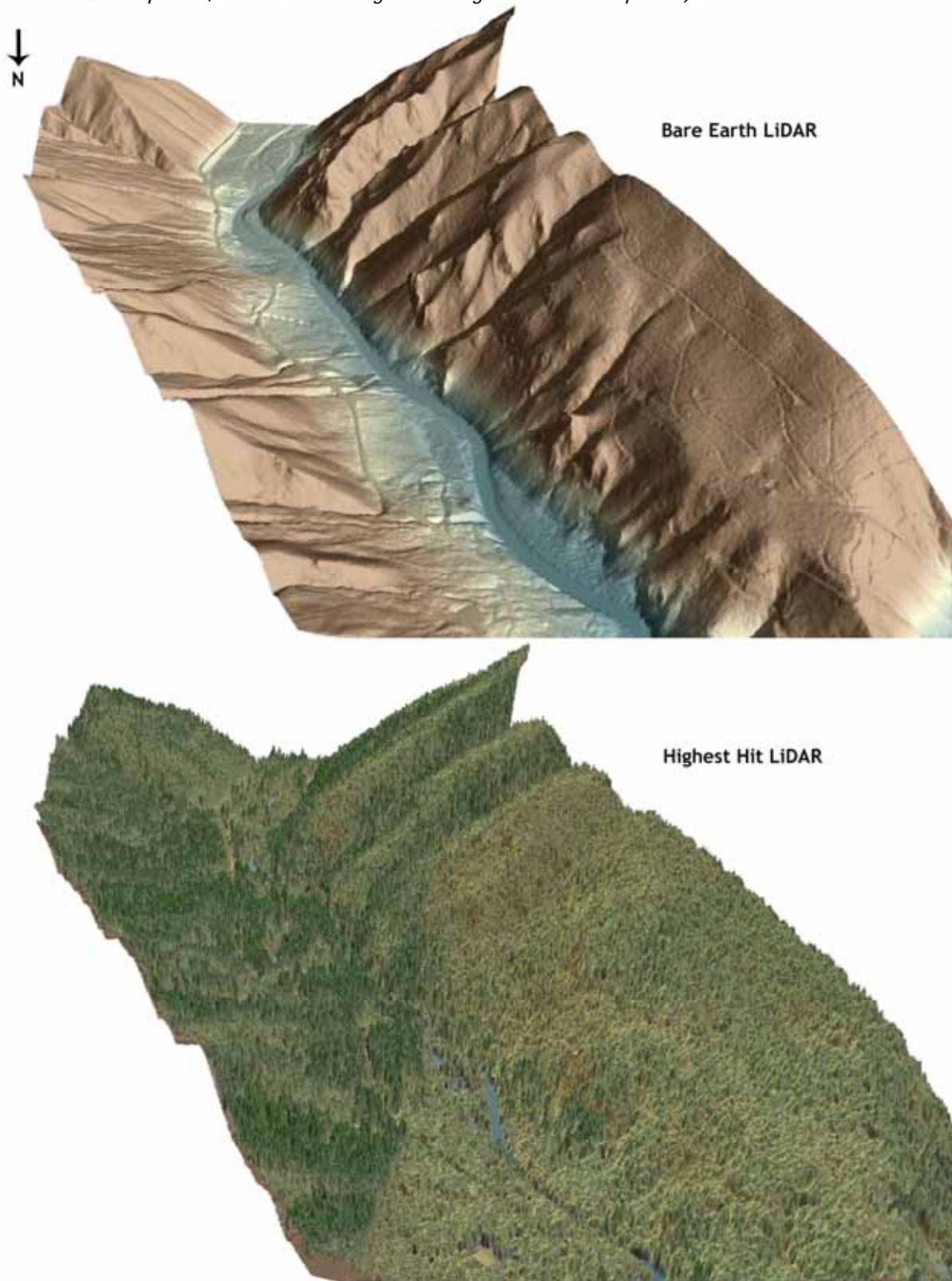
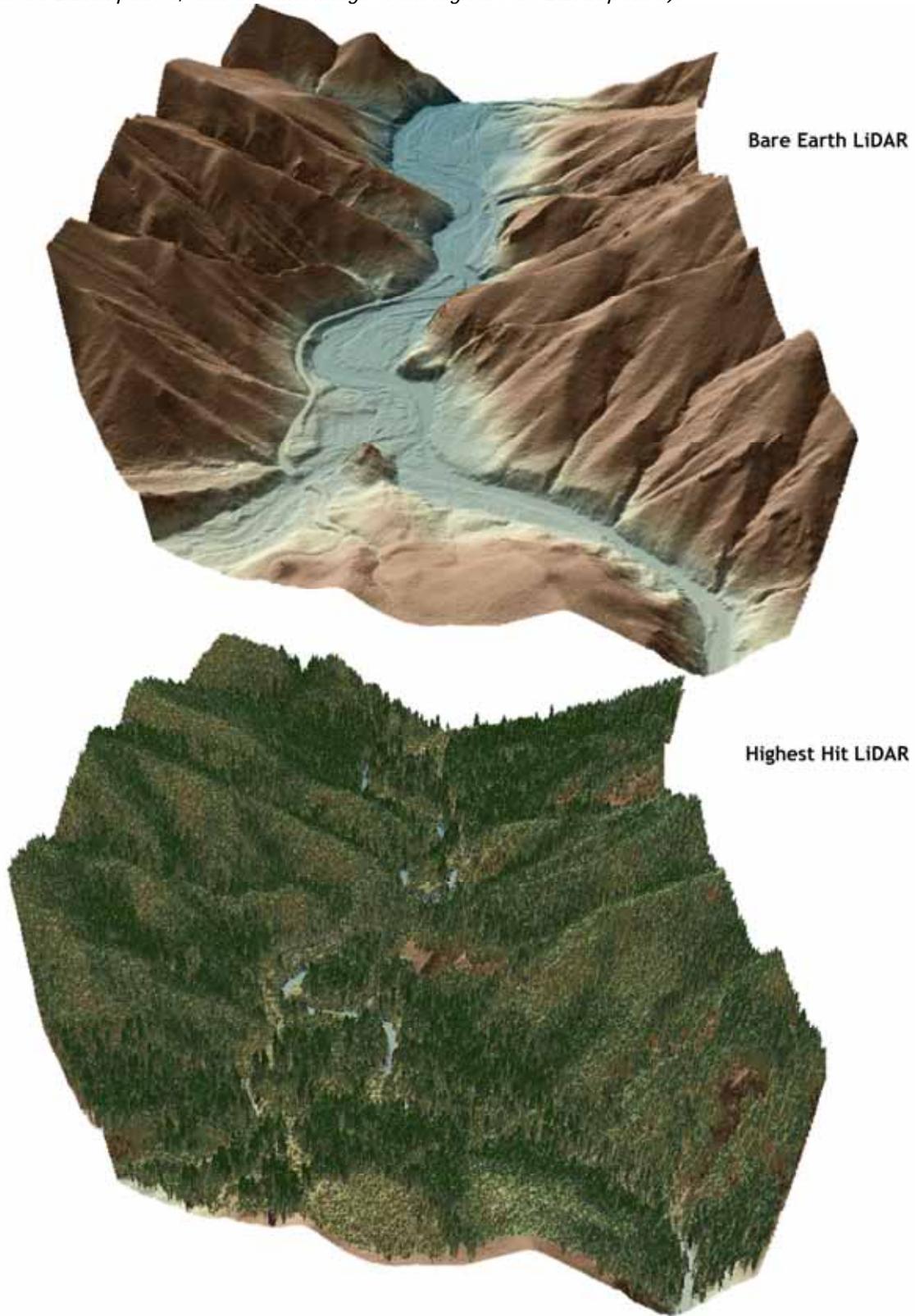


Figure 6.3. 3-d oblique view from southern end of study area (top image derived from ground-classified LiDAR points, and bottom image from highest hit LiDAR points).



7. 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 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 (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.

8. Citations

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