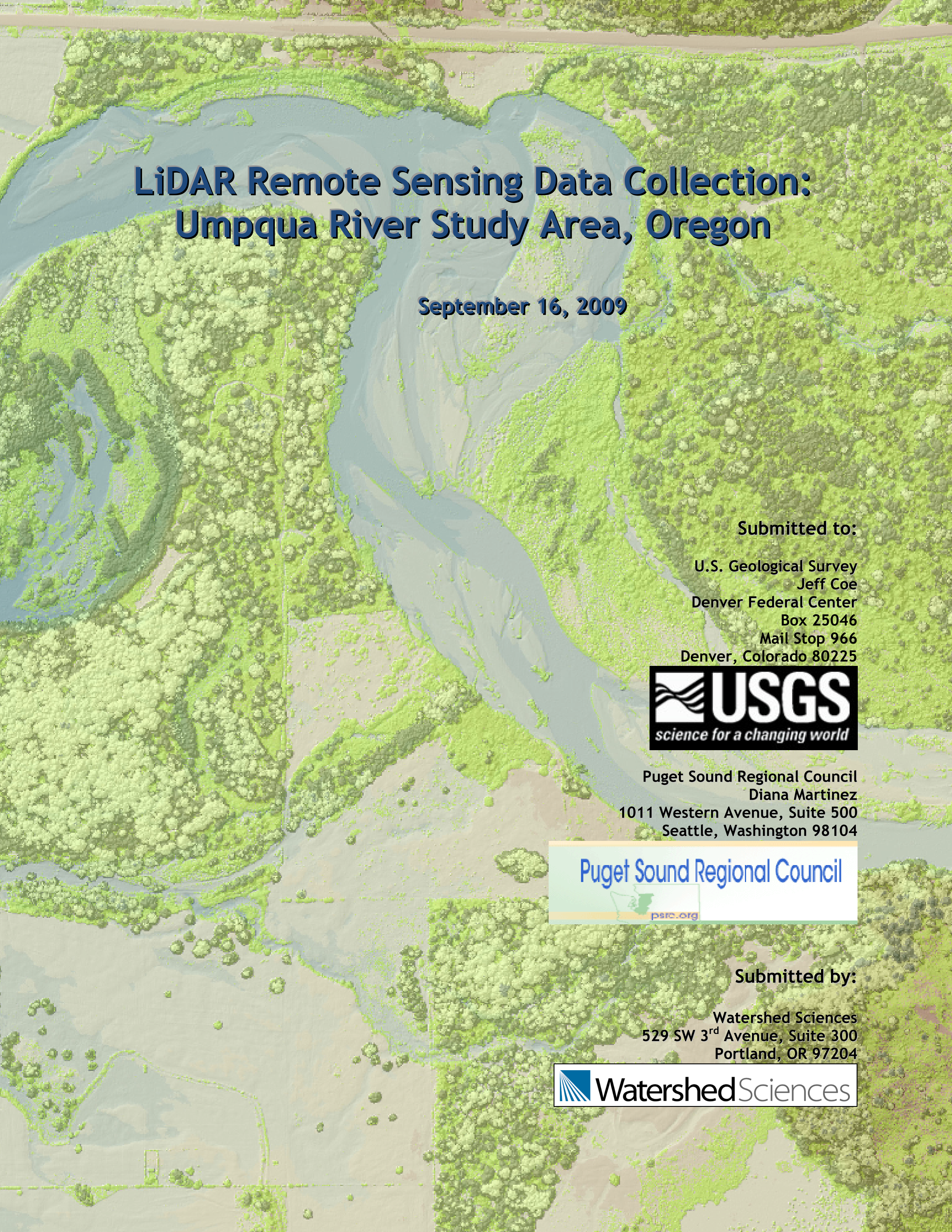

LiDAR Remote Sensing Data Collection: Umpqua River Study Area, Oregon

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LiDAR Remote Sensing Data Collection:
Umpqua River, Oregon

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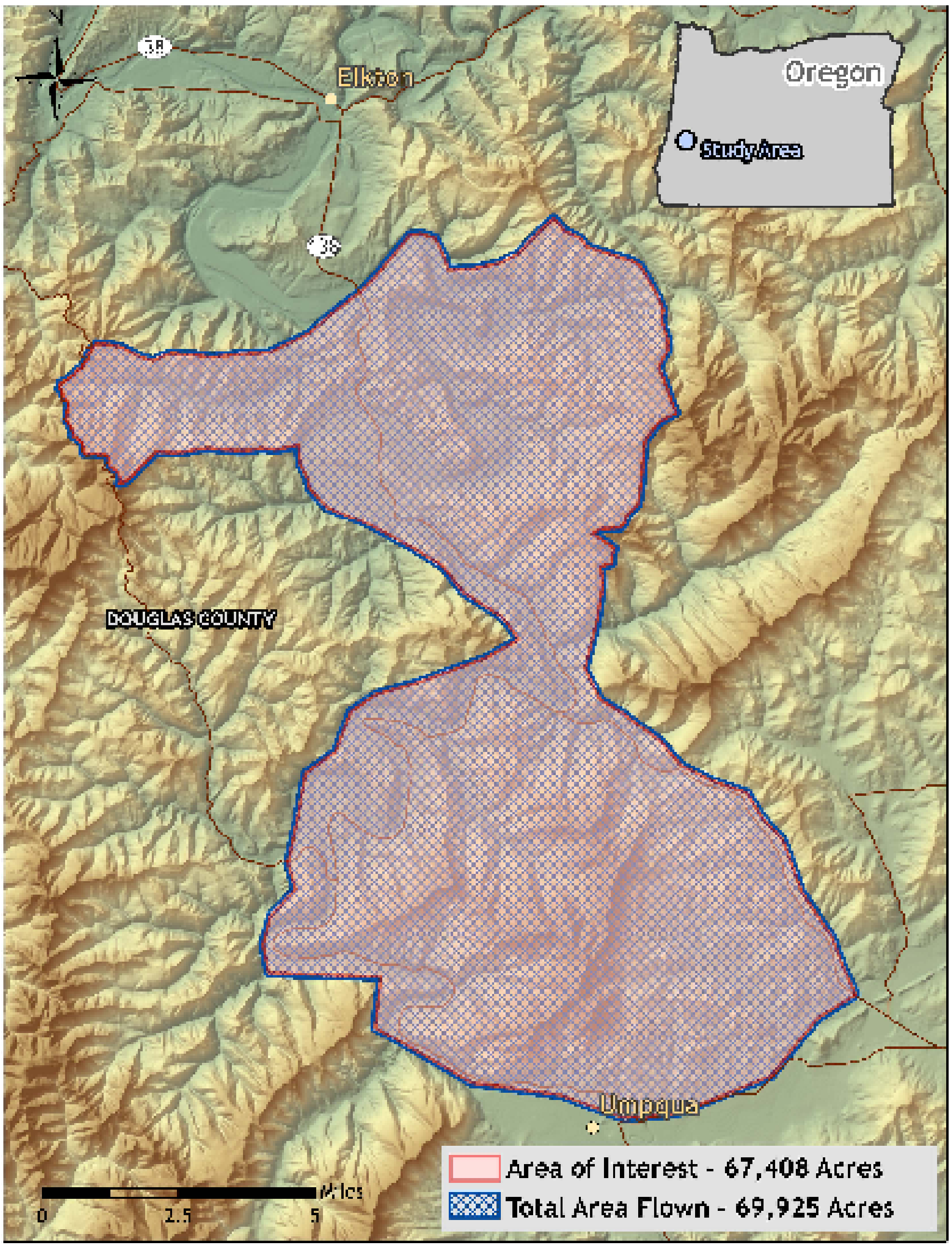
1. Overview

1.1 Study Area

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data of the U.S. Geological Survey (USGS) Umpqua River study site in collaboration with the Puget Sound LiDAR Consortium (PSLC). The extent of the requested LiDAR area of interest (AOI) totals ~67,408 acres; the map below shows both the AOI and the extent of the LiDAR area flown (TAF), covering ~69,925 acres. The area flown is greater than the original amount due to buffering of the original AOI and flight planning optimization.

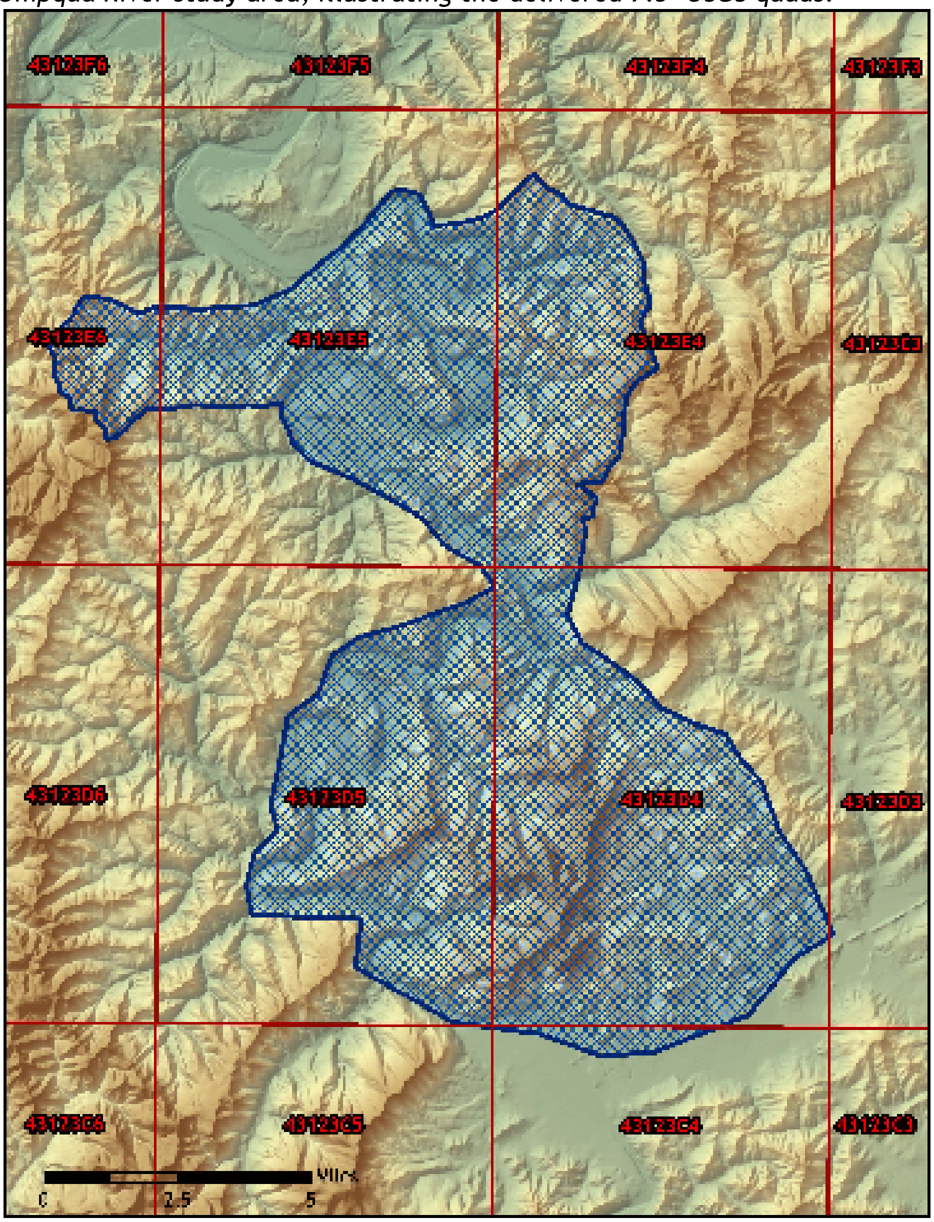
Figure1.1*. Umpqua River study area, illustrating AOI and TAF.*



7.5’ USGS quads for the Umpqua River study area data:

7.5’ USGS QUAD NAME	7.5’ USGS QUAD NUMBER
Garden Valley	43123C4
Callahan	43123C5
Sutherlin	43123D3
Tyee Mountain	43123D4
Tyee	43123D5
Yellow Butte	43123E4
Kellogg	43123E5
Old Blue	43123E6

Figure 1.2. *Umpqua River study area, illustrating the delivered 7.5’ USGS quads.*



1.2 Accuracy and Resolution

Ground-level real-time kinematic (RTK) surveys were conducted across multiple flightlines in the study areas for quality assurance purposes. The accuracy of the LiDAR data is described as standard deviations of divergence (sigma ~ σ) from RTK ground survey points and root mean square error (RMSE) which considers bias (upward or downward). These statistics are calculated cumulatively. For the Umpqua River study area, the data have the following accuracy statistics:

- RMSE of 0.04 meters
- 1-sigma absolute deviation of 0.04 meters
- 2-sigma absolute deviation of 0.08 meters

Data resolution specifications are for ≥8 pts per m^2. The total pulse density for the Umpqua River study site is 8.80 points per square meter.

1.3 Data Format, Projection, and Units

Deliverables include point data in *.las v 1.2 and ascii format, 1 meter resolution bare ground model ESRI GRIDs, 1 meter resolution highest hit surface ESRI GRID, 0.5 meter resolution intensity images in GeoTIFF format, Smoothed Best Estimate of Trajectory (5Hz frequency) information in ascii text format and a data report. Data are delivered in Universal Transverse Mercator (UTM) Zone 10; horizontal and vertical datums: NAD83 (CORS96)/NAVD88(Geoid03); Units: meters.

2. Acquisition

2.1 Airborne Survey Overview – Instrumentation and Methods

The LiDAR survey utilized a Leica ALS50 Phase II mounted in a Cessna Caravan 208B. 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 lightly variable according to distributions of terrain, land cover and water bodies.


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

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° (±14° from nadir)
Roll Compensated	Up to 15°
Overlap	100% (50% Side-lap)

The completed area was surveyed with opposing flight line side-lap of ≥50% (≥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, it is vital to have an accurate description of aircraft position and attitude. 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). **Figure 2.1** below illustrates the location of the flight lines for the Umpqua River study area.

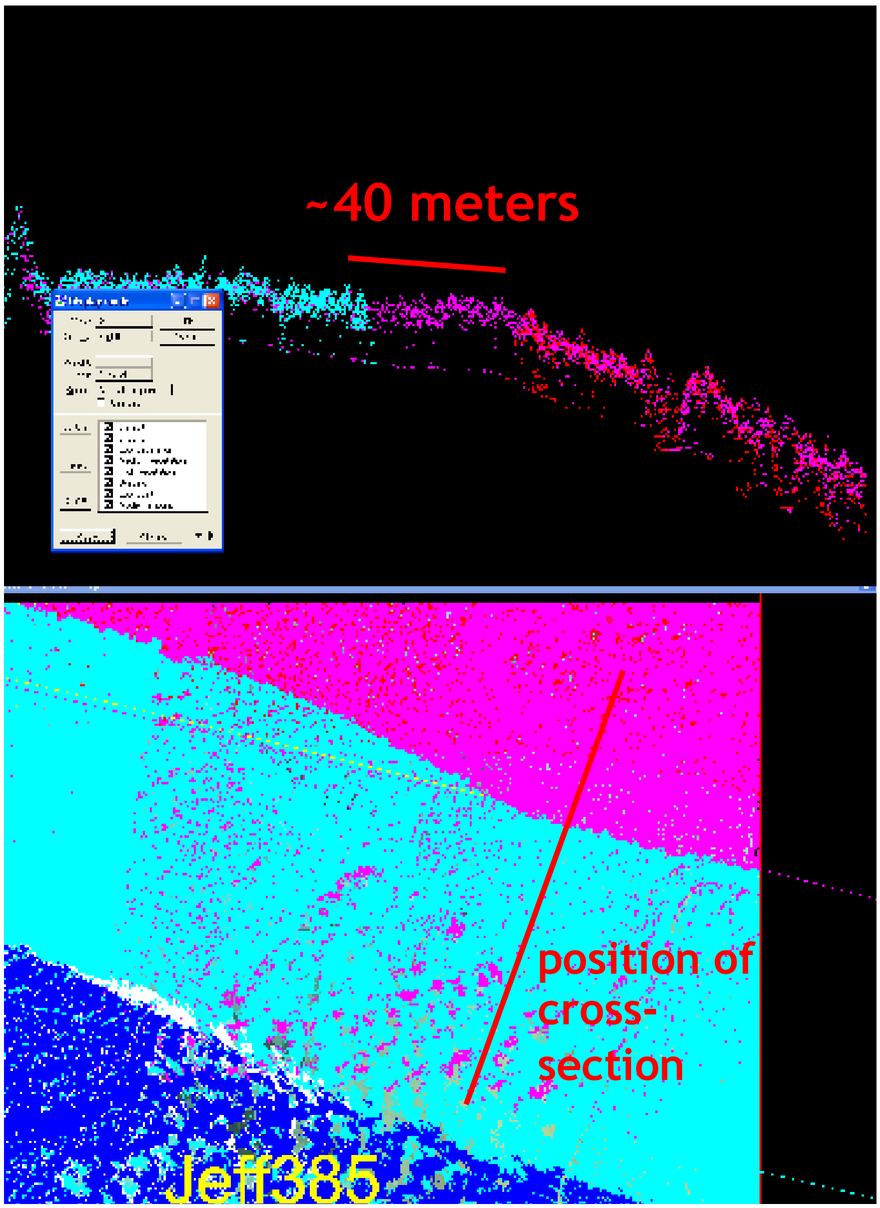
[1] Nadir refers to the perpendicular vector to the ground directly below the aircraft. Nadir is commonly used to measure the angle from the vector and is referred to a "degrees from nadir".

***Figure 2.1**. Actual flightlines for the Umpqua River study area (161 total flightlines).*

2.1.1 Acquisition Specifics

The data provided were collected between April 21 and July 13, 2009. In portions of the LiDAR dataset, acquisition conditions resulted in slivers of single-swath coverage. In areas of significant terrain change, aircraft attitude changes necessary for terrain-following can result in fluctuation of swath width, (i.e. as the aircraft pitches up and down, the footprint of the laser swath on the ground narrows and widens correspondingly). Flight planning seeks to minimize or eliminate this artifact in the data. Nevertheless, actual conditions at the time of acquisition occasionally dictate otherwise.

Figure 2.2 *Single swath sliver in point data. Points are colored by individual 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 2.2** and shown in **Figure 2.3**. 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.

Table 2.2. *Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data for the Umpqua river study area.*

	Datum NAD83(HARN)		GRS80
Base Station ID	**Latitude (North)**	**Longitude (West)**	**Ellipsoid Height (m)**
JC_EG1	43 24 22.24444	123 22 54.74972	102.255
JCALR1	43 33 20.27900	123 33 16.31182	46.643
JCMSD1	43 33 20.20783	123 33 16.38757	46.581
JCMSD3	43 28 32.48390	123 28 57.69701	51.799
JCRT_1	43 28 32.51418	123 28 57.82397	51.706

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 ($\sigma \le 1.5$ cm ~ 0.6 in). 2,832 RTK ground points were collected throughout the study areas and compared to LiDAR data for accuracy assessment. Detailed views of base station locations and RTK points are shown in **Figures 2.3** through **2.5**.

Trimble GPS survey equipment configured for collecting RTK data.

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

***Figure 2.3**. Base station and RTK point locations in the Umpqua River study area; color image is a NAIP Orthoimage.*

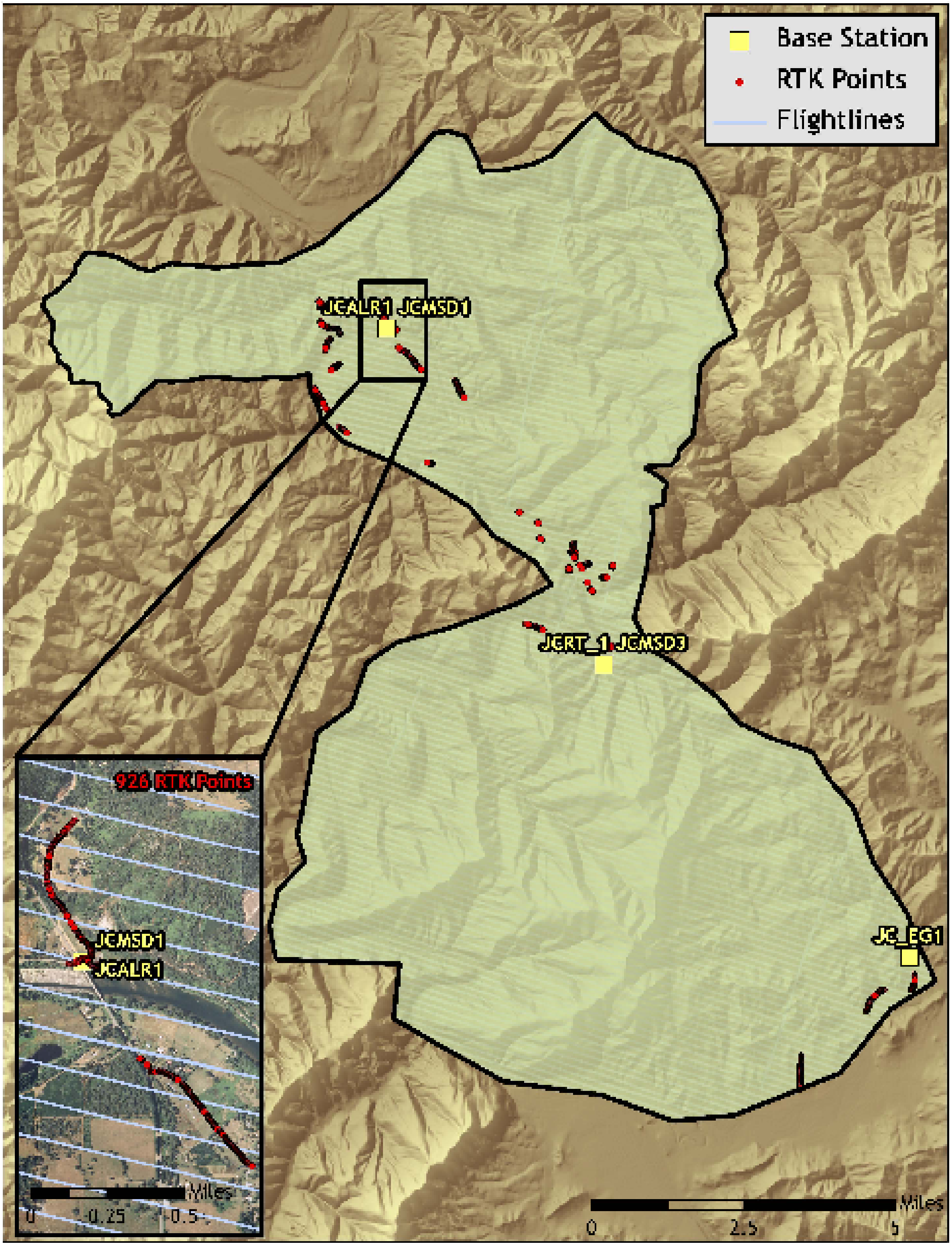


Figure 2.4. *RTK point locations in the Umpqua River study area; color images are NAIP Orthoimages.*

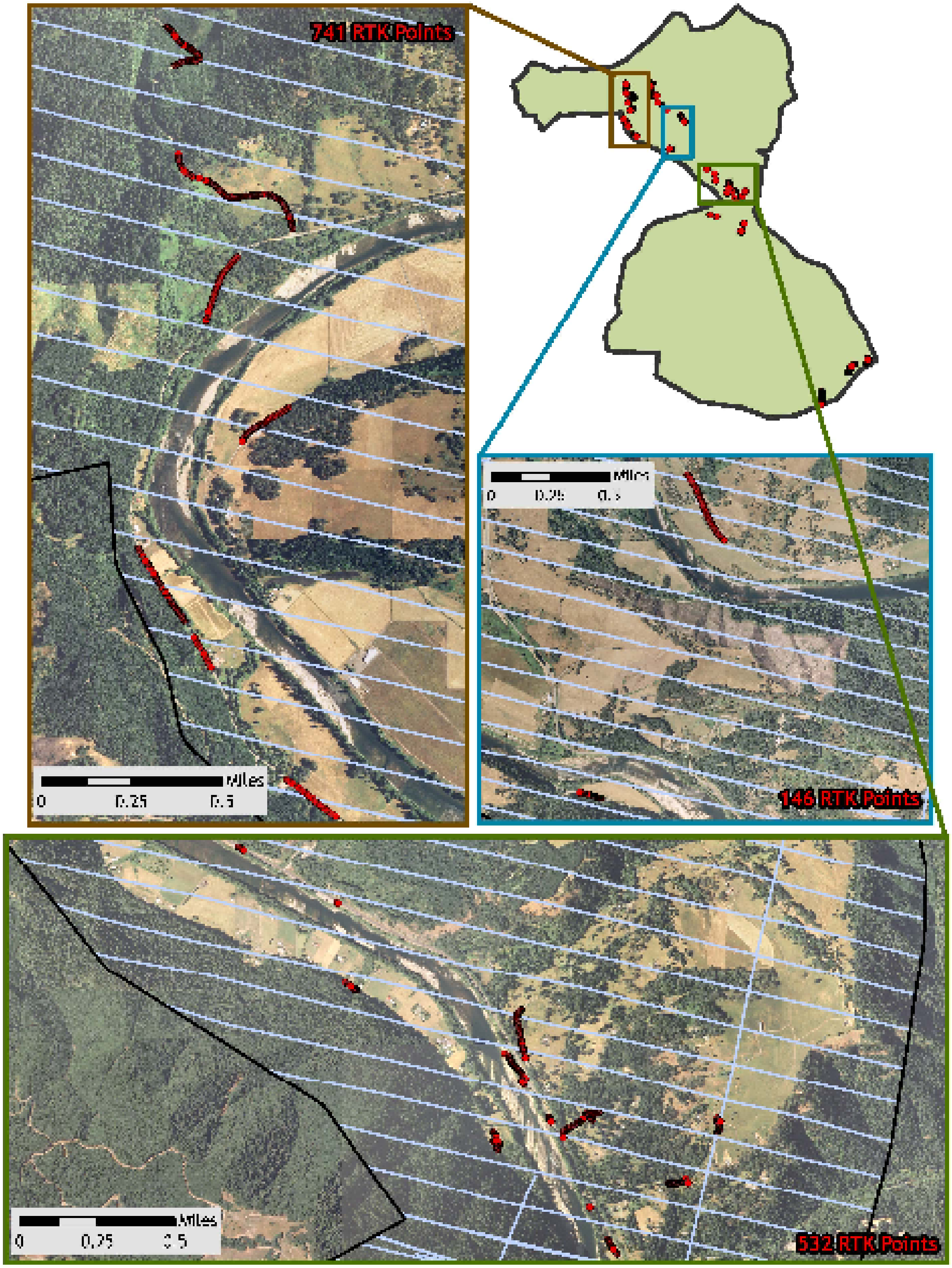
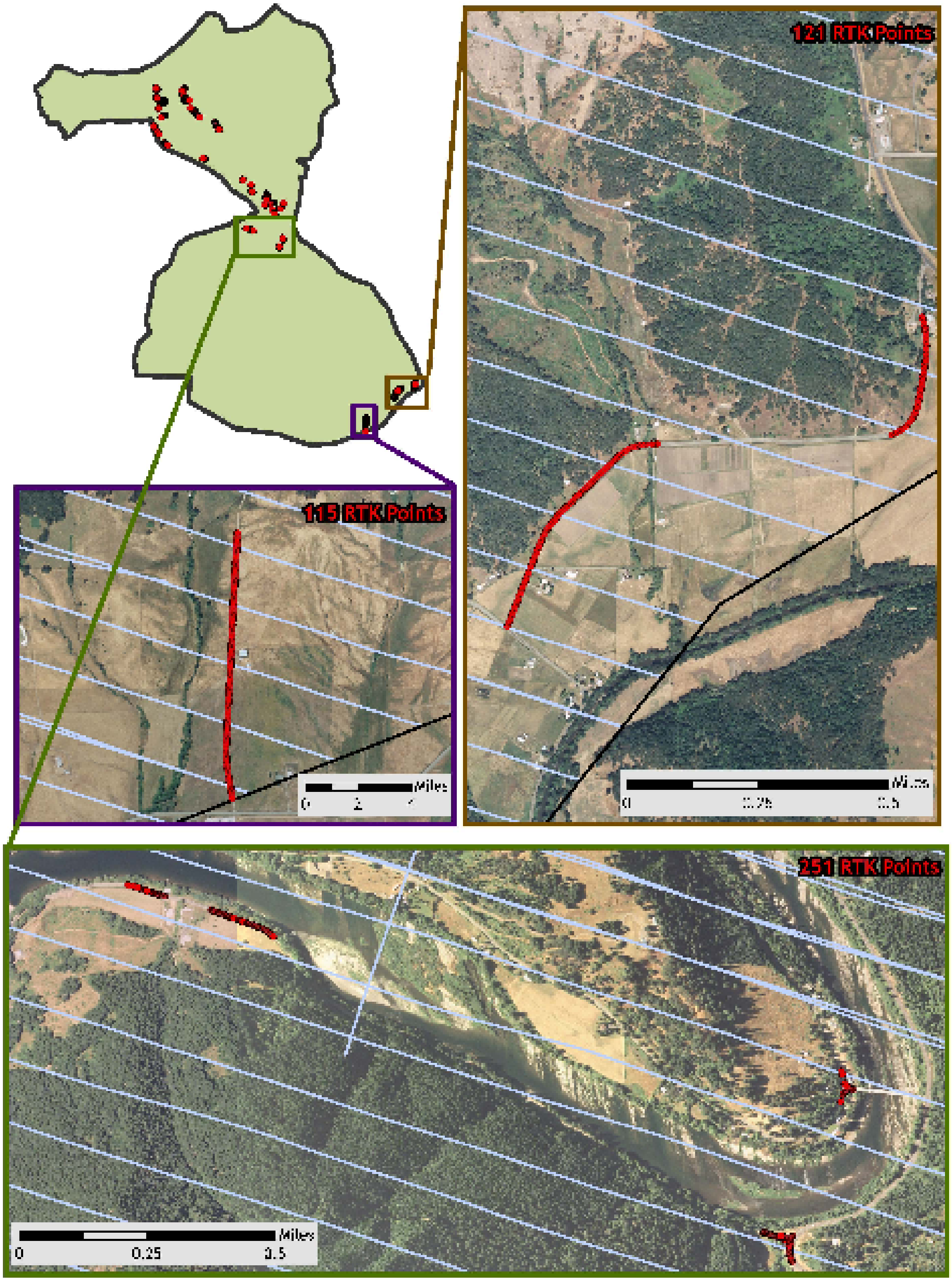


Figure 2.5. *RTK point locations in the Umpqua River study area; color image are NAIP Orthoimages.*



3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.
   Software: Waypoint GPS v.8.10, Trimble Geomatics Office v.1.62

2. Develop a smoothed best estimate of trajectory (SBET) file that blends the post-processed aircraft position with attitude data. Sensor head position and attitude are calculated throughout the survey. The SBET data are used extensively for laser point processing.
   Software: IPAS v.1.4

3. Calculate laser point position by associating the SBET position to each laser point return time, scan angle, intensity, etc. Creates raw laser point cloud data for the entire survey in *.las (ASPRS v1.2) format.
   Software: ALS Post Processing Software

4. Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter for pits/birds. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).
   Software: TerraScan v.9.001

5. Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are performed on ground classified points from paired flight lines. Every flight line is used for relative accuracy calibration.
   Software: TerraMatch v.9.001

6. Position and attitude data are imported. Resulting data are classified as ground and non-ground points. Statistical absolute accuracy is assessed via direct comparisons of ground classified points to ground RTK survey data. Data are then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction. Ground models are created as a triangulated surface and exported as ArcInfo ASCII grids at a 3-foot pixel resolution.
   Software: TerraScan v.9.001, ArcMap v9.3, TerraModeler v.9.001

3.2 Aircraft Kinematic GPS and IMU Data

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

3.3 Laser Point Processing

Laser point coordinates are 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) are assigned an associated (x, y, z) coordinate along with unique intensity values (0-255). The data are output into large LAS v. 1.2 files; each point maintains the corresponding scan angle, return number (echo), intensity, and x, y, z (easting, northing, and elevation) information.

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

Once the laser point data are imported into bins in TerraScan, a manual calibration is 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 is resolved and corrected if necessary.

The LiDAR points are then filtered for noise, pits and birds by screening for absolute elevation limits, isolated points and height above ground. Each bin is then inspected for pits and birds manually; spurious points are removed. For a bin containing approximately 7.5-9.0 million points, an average of 50-100 points are 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.

The internal calibration is refined using TerraMatch. Points from overlapping lines are tested for internal consistency and final adjustments are made for system misalignments (i.e., pitch, roll, heading offsets and mirror scale). Automated sensor attitude and scale corrections yield 3-5 cm improvements in the relative accuracy. Once the system misalignments are corrected, vertical GPS drift is then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy. At this point in the workflow, data have passed a robust calibration designed to reduce inconsistencies from multiple sources (i.e. sensor attitude offsets, mirror scale, GPS drift) using a procedure that is comprehensive (i.e. uses all of the overlapping survey data). Relative accuracy screening is complete.

The TerraScan software suite is designed specifically for classifying near-ground points (Soininen, 2004). The processing sequence begins by 'removing' all points that are not 'near' the earth based on geometric constraints used to evaluate multi-return points. The resulting bare earth (ground) model is visually inspected and additional ground point modeling is performed in site-specific areas (over a 50-meter radius) to improve ground detail. This is 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 includes known vegetation (i.e., understory, low/dense shrubs, etc.) and these points are reclassified as non-grounds. Ground surface rasters are 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 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 (i.e., ~ 1/3000th 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 can be maintained.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 14^{o}$ 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 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 2,832 RTK points that are distributed throughout multiple flight lines across the study areas.
6. 50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the most nadir portion of one flight line coincides with the edge (least nadir) portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.
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 that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets are calculated and applied to resolve misalignments. The raw divergence between lines is computed after the manual calibration is completed and reported for each study area.

2. Automated Attitude Calibration: All data are tested and calibrated using TerraMatch automated sampling routines. Ground points are classified for each individual flight line and used for line-to-line testing. ***The resulting overlapping ground points (per line) total 713,772,756 points from which to compute and refine relative accuracy***. System misalignment offsets (pitch, roll and heading) and mirror scale are solved for each individual mission. The application of 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 areas 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 accuracies have been determined for the Umpqua River study area; the statistics are based on the comparison of 161 flightlines and 713,722,756 points. For flightline coverage, see **Figure 2.1** in Section 2.1.

- Project Average = 0.06 m
- Median Relative Accuracy = 0.06 m
- 1σ Relative Accuracy = 0.07 m
- 2σ Relative Accuracy = 0.09 m
-

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

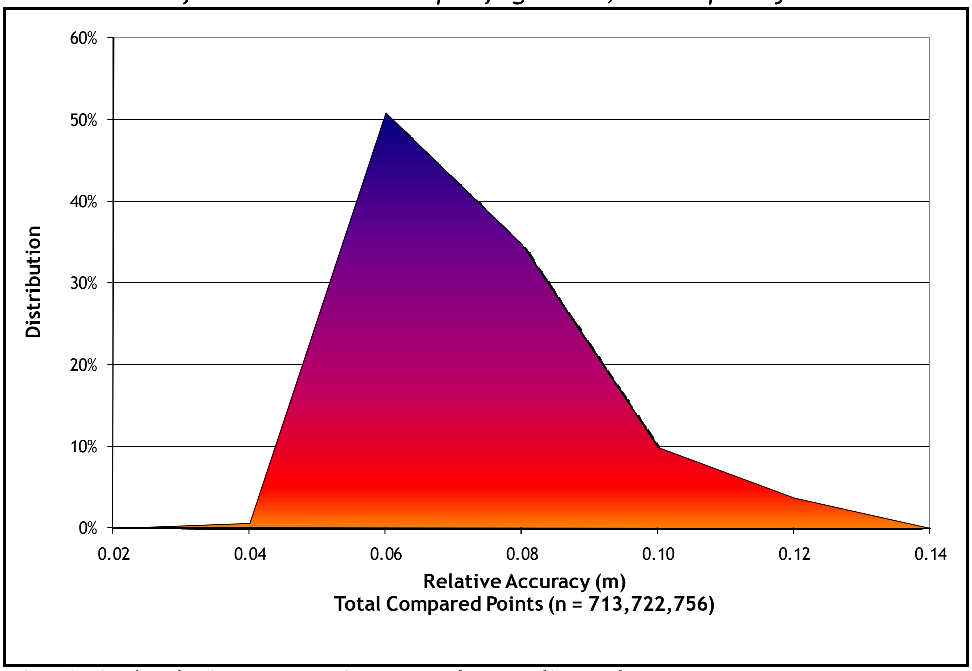
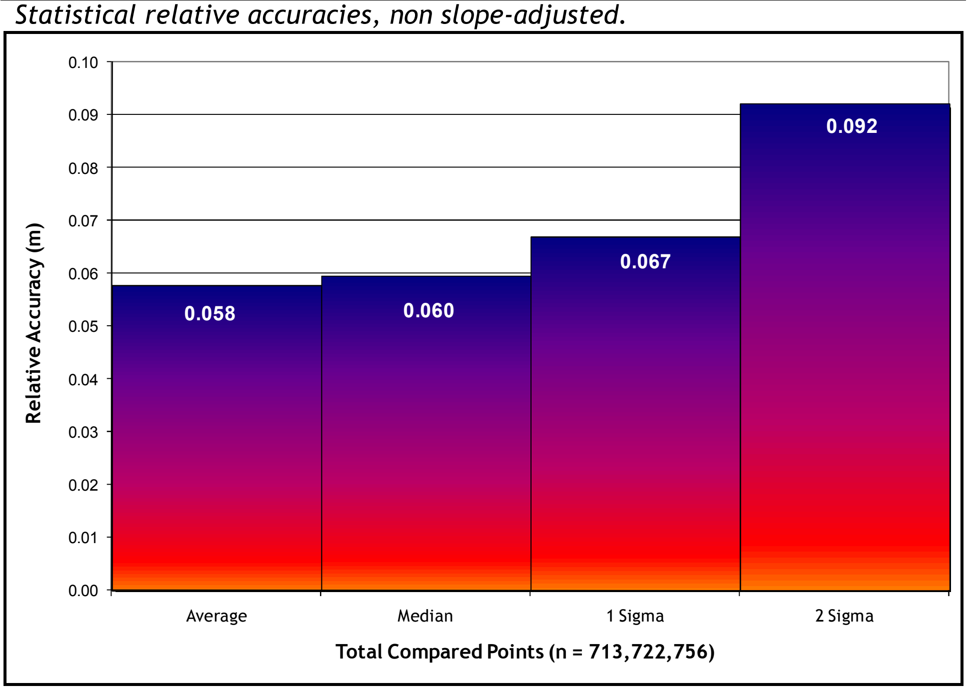


***Figure 4.2**. Statistical relative accuracies, non slope-adjusted.*



4.1.2 Absolute Accuracy

The final quality control measure is a statistical accuracy assessment that compares known RTK ground survey points to the closest laser point. Accuracy statistics are reported in **Table 4.2** and shown in **Figures 4.3-4.4.** Accuracy statistics have been developed for the entire study area.

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

Sample Size (n): 2,832	
Root Mean Square Error (RMSE): 0.04 meters	
Standard Deviations	**Deviations**
1 sigma (σ): 0.04 meters	**Minimum Δz:** -0.16 meters
2 sigma (σ): 0.08 meters	**Maximum Δz:** 0.21 meters
	Average Δz: 0.03 meters

Figure 4.3. Study Areas: *Histogram Statistics*

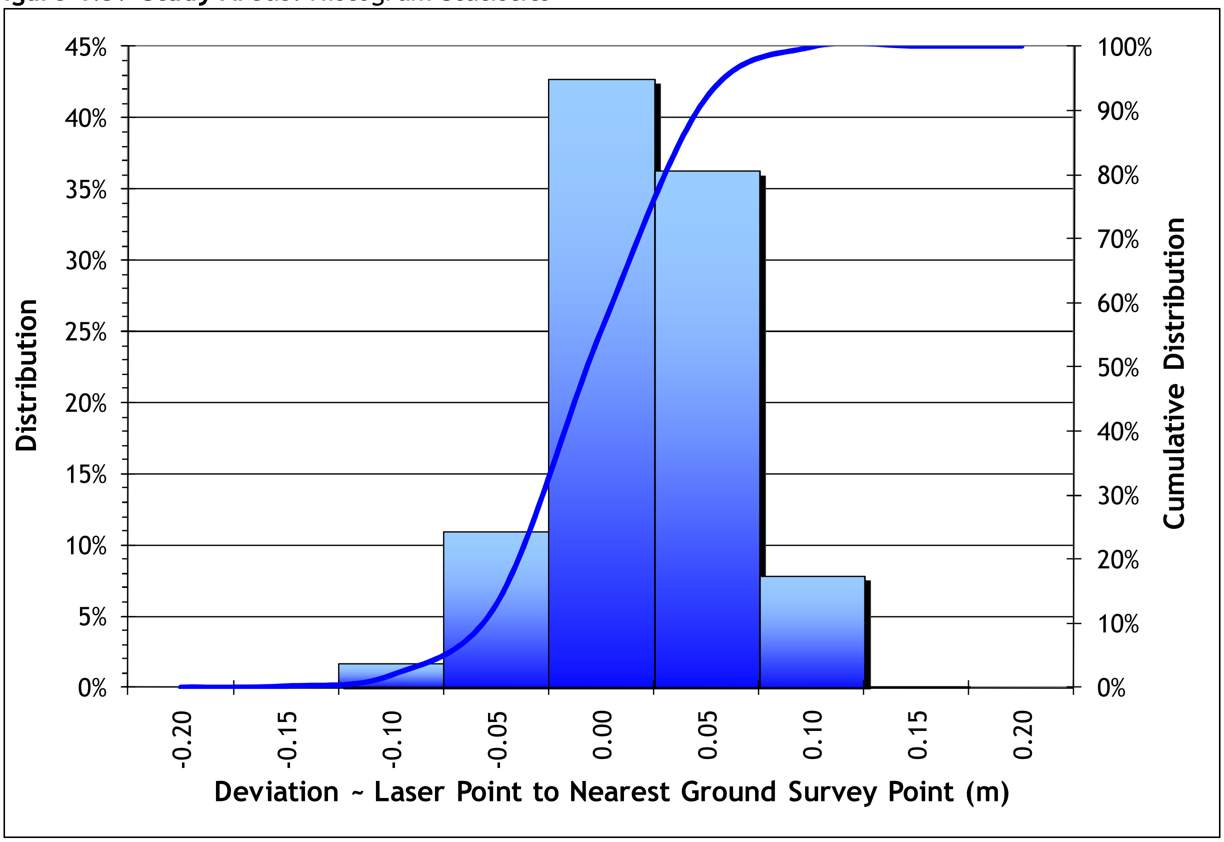
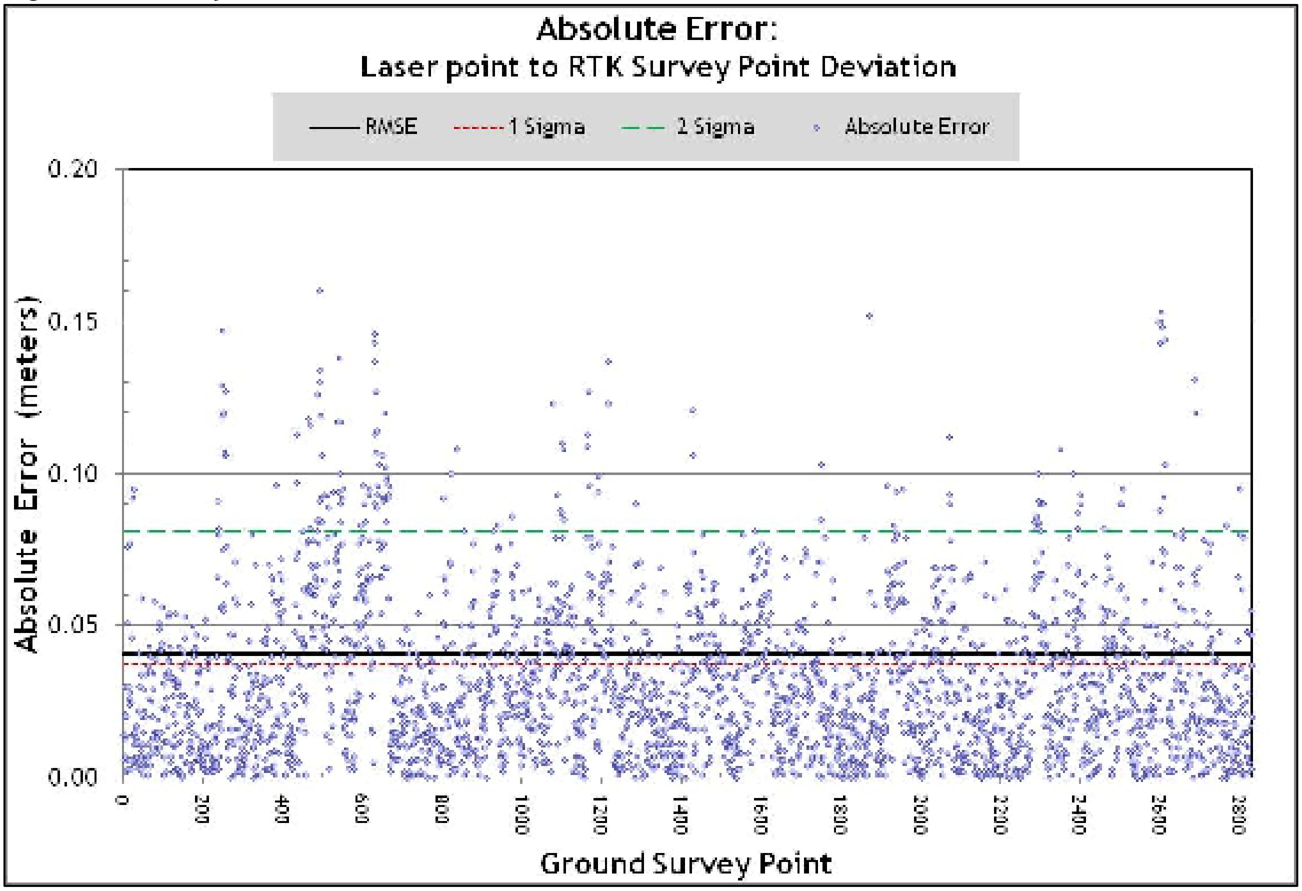


Figure 4.4. Study Areas: *Point Absolute Deviation Statistics*



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 lightly variable according to distributions of terrain, land cover and water bodies. Density histograms and maps (**Figures 4.5-4.8**) have been calculated based on first return laser point density and ground-classified laser point density.

Table 4.3. *Average density statistics for the Umpqua River study area.*

Average Pulse Density (per square meter)	Average Ground Density (per square meter)
8.80	1.45

4.2.1 First Return Laser Pulses per Square Meter

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

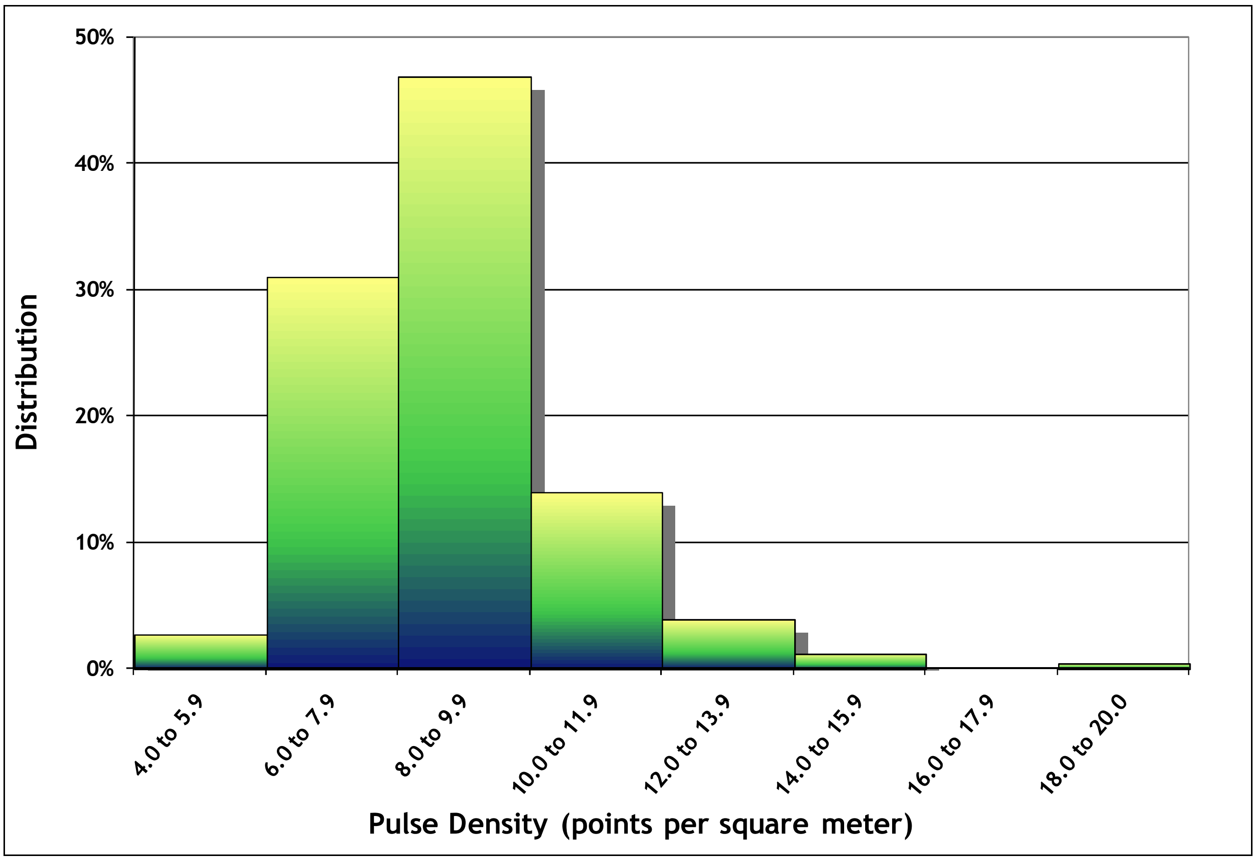
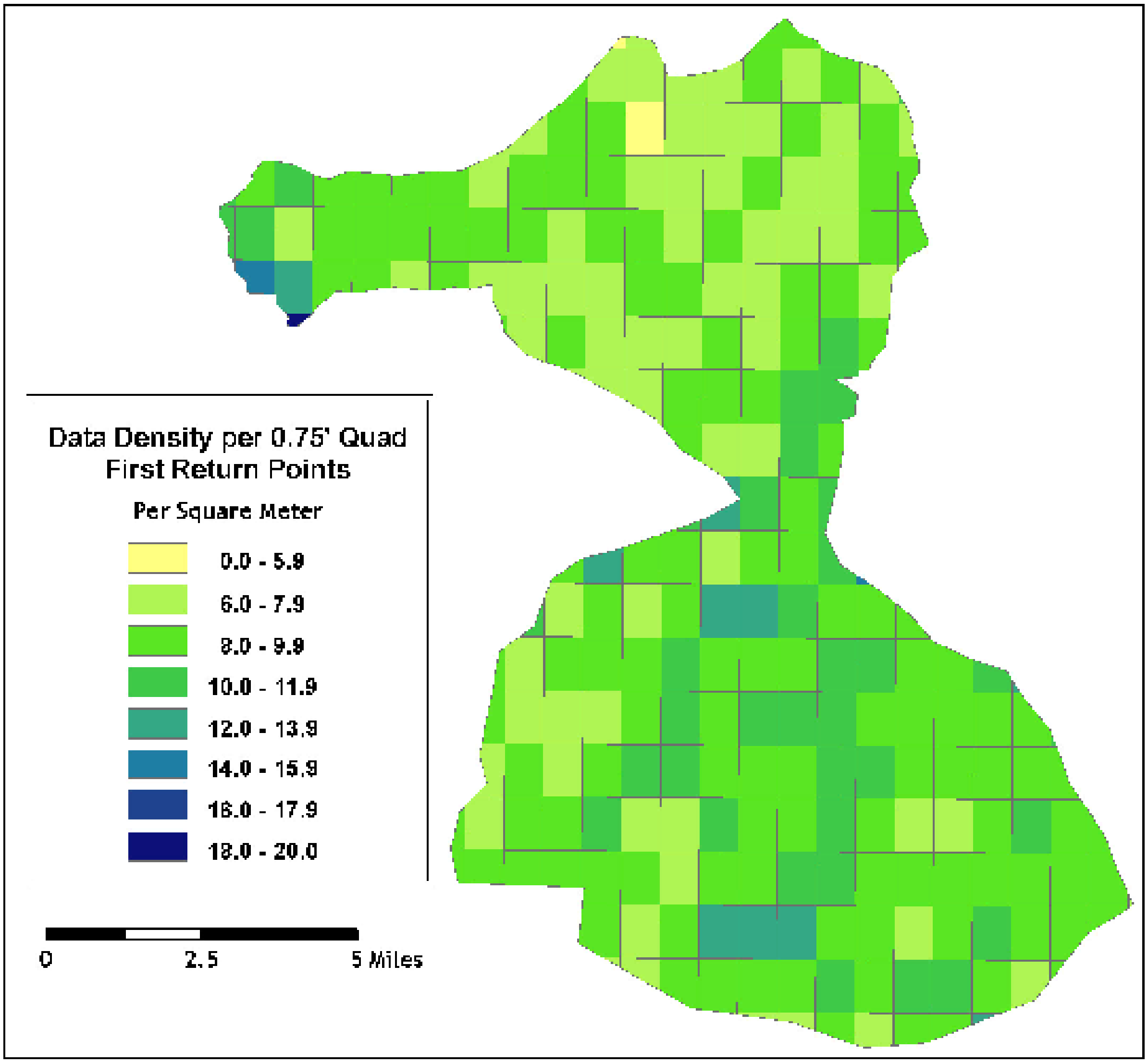


Figure 4.6. *Image shows first return laser point data density per 0.75' USGS Quad*



4.2.2 Classified Ground Points per Square Meter

Ground classifications are derived from ground surface modeling. Supervised classifications were performed by reseeding of 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. Ground point density information is summarized below.

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

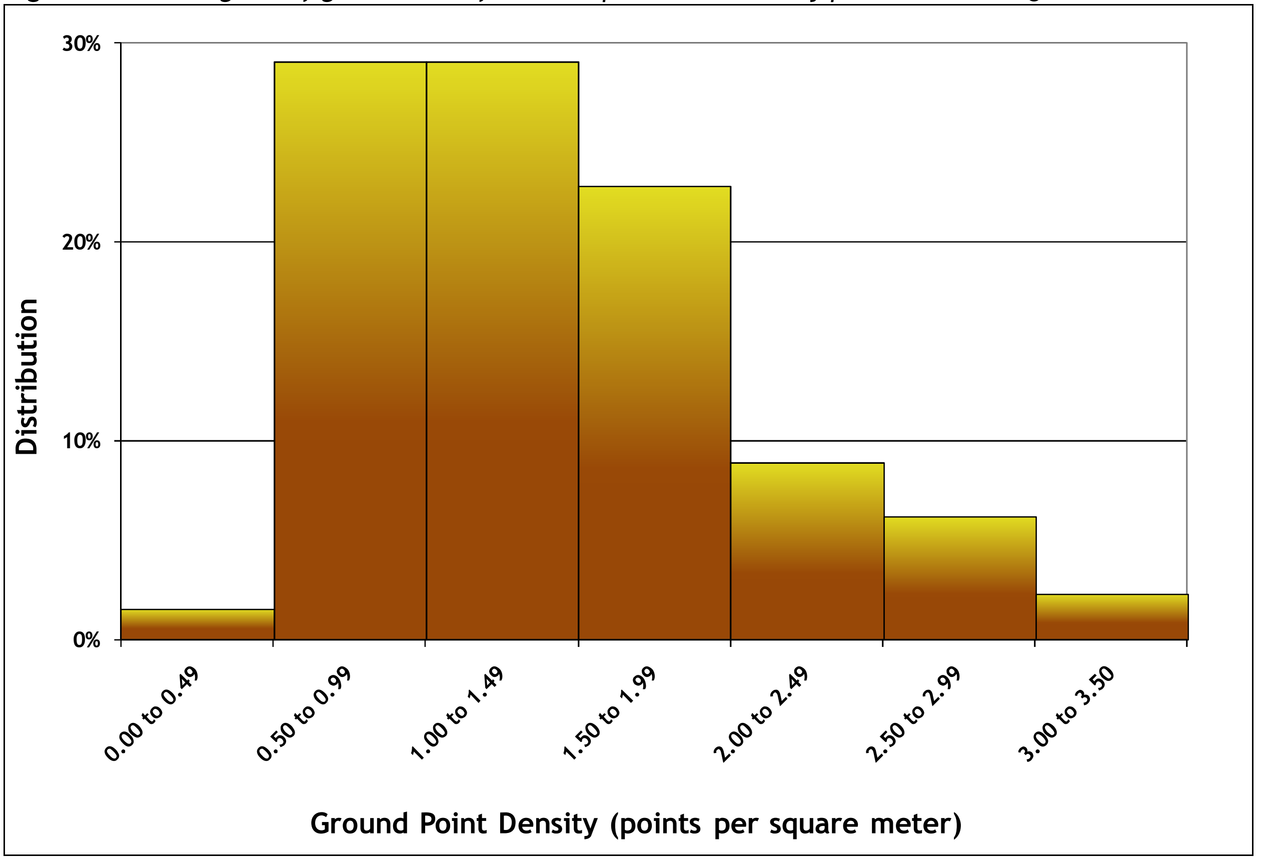
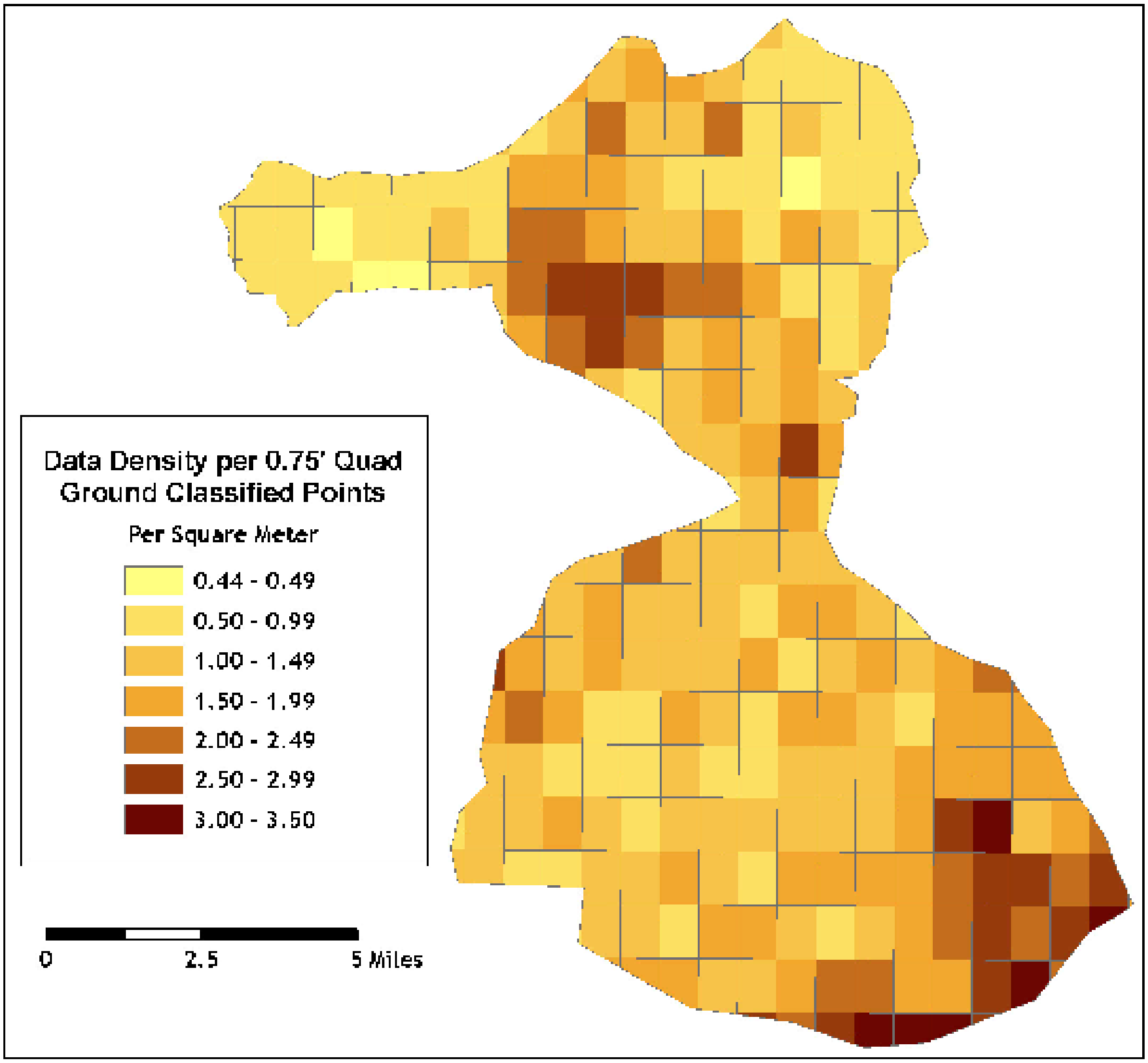


Figure 4.8. Image shows ground-classified laser point data density per 0.75' USGS Quad.



Selected Samples of Data Density

Figure 4.9. *Quadrant containing overlapping flightlines resulting in high pulse density.*

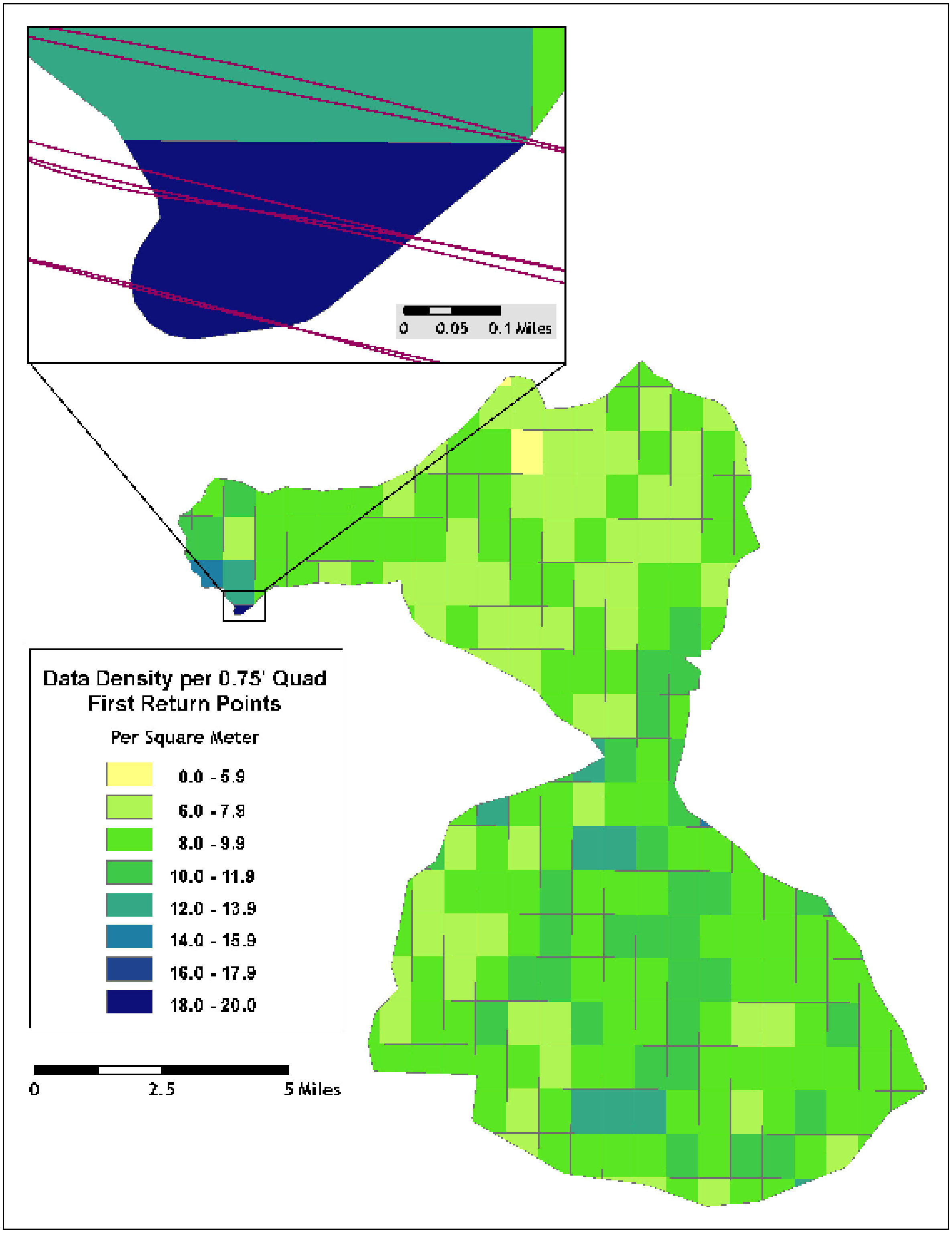
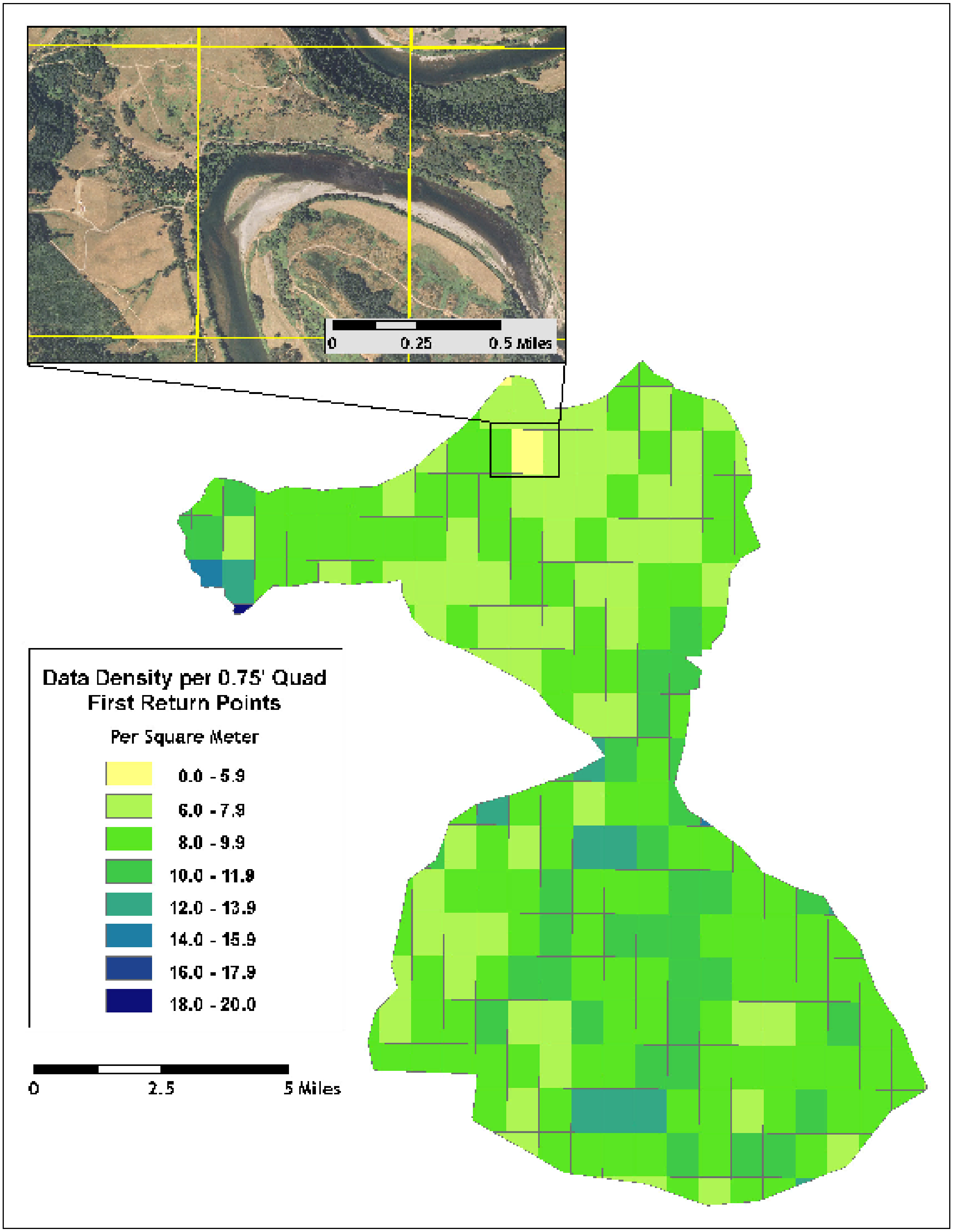


Figure 4.10. *Quadrant exhibiting low pulse density as a result of a water body.*



5. Data Specifications

	Targeted	Achieved
Resolution:	>8 points/m^2	8.80 points/m^2
Vertical Accuracy (1 σ):	<15 cm	4 cm

6. Projection/Datum and Units

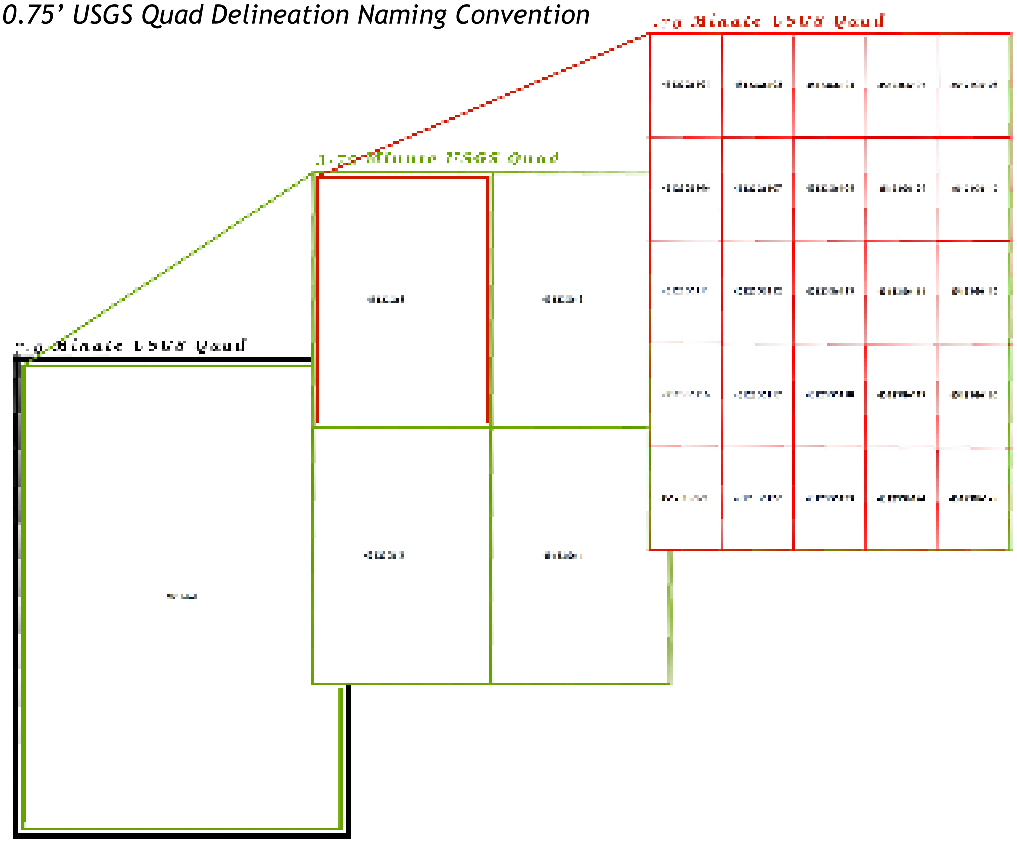
The data were processed as ellipsoidal elevations and required a Geoid transformation to be converted into orthometric elevations (NAVD88). In TerraScan, the NGS published Geiod03 model is applied to each point. The data were processed using meters in the Universal Transverse Mercator (UTM) Zone 10 and NAD83 (CORS96)/NAVD88 datum and converted to the projection below below.

	Projection:	UTM Zone 10
Datum	**Vertical:**	NAVD88 Geoid03
	Horizontal:	NAD83 (HARN)
	Units:	Meters

7. Deliverables

All Deliveries of the Umpqua River study area conform to the following tiling scheme:

Figure 7.1. *0.75' USGS Quad Delineation Naming Convention*



7.1 Point Data (per 0.75' USGS Quads ~ 1/100th Quads)

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

- LAS v 1.2 Format – all returns
- ASCII Format – all returns and all ground classified returns
- Smoothed Best Estimate of Trajectory Point Files in ASCII format

7.2 Vector Data

- Areas of Interest in shapefile format
  - 3.75' USGS Quad delineation in shapefile format
  - 0.75' USGS Quad delineation in shapefile format

7.3 Raster Data

- ESRI GRIDs of LiDAR dataset, delivered **per 3.75' USGS Quads ~ 1/4th Quads**):
  - Bare Earth Modeled Points (1 meter resolution),
  - Vegetation Modeled Points- Highest Hit model (1 meter resolution),
- Surface intensity images in GEOTIFF format (0.5 meter resolution), delivered **per 0.75' USGS Quads ~ 1/100th Quads**)

7.4 Data Report

- Full Report containing introduction, methodology, accuracy, and example imagery
  - Word Format (*.doc)
  - PDF Format (*.pdf)

8. Selected Images

Example areas are presented to show paired, same-scene 3-D oblique and plan view imagery (see **Figures 8.1-8.3**).

Figure 8.1. *Plan view showing a section of Myrtle Island on the Umpqua River (top image is derived from highest hit classified LiDAR points, middle image is derived from ground-classified LiDAR points, and bottom image is derived from NAIP Orthoimagery).*

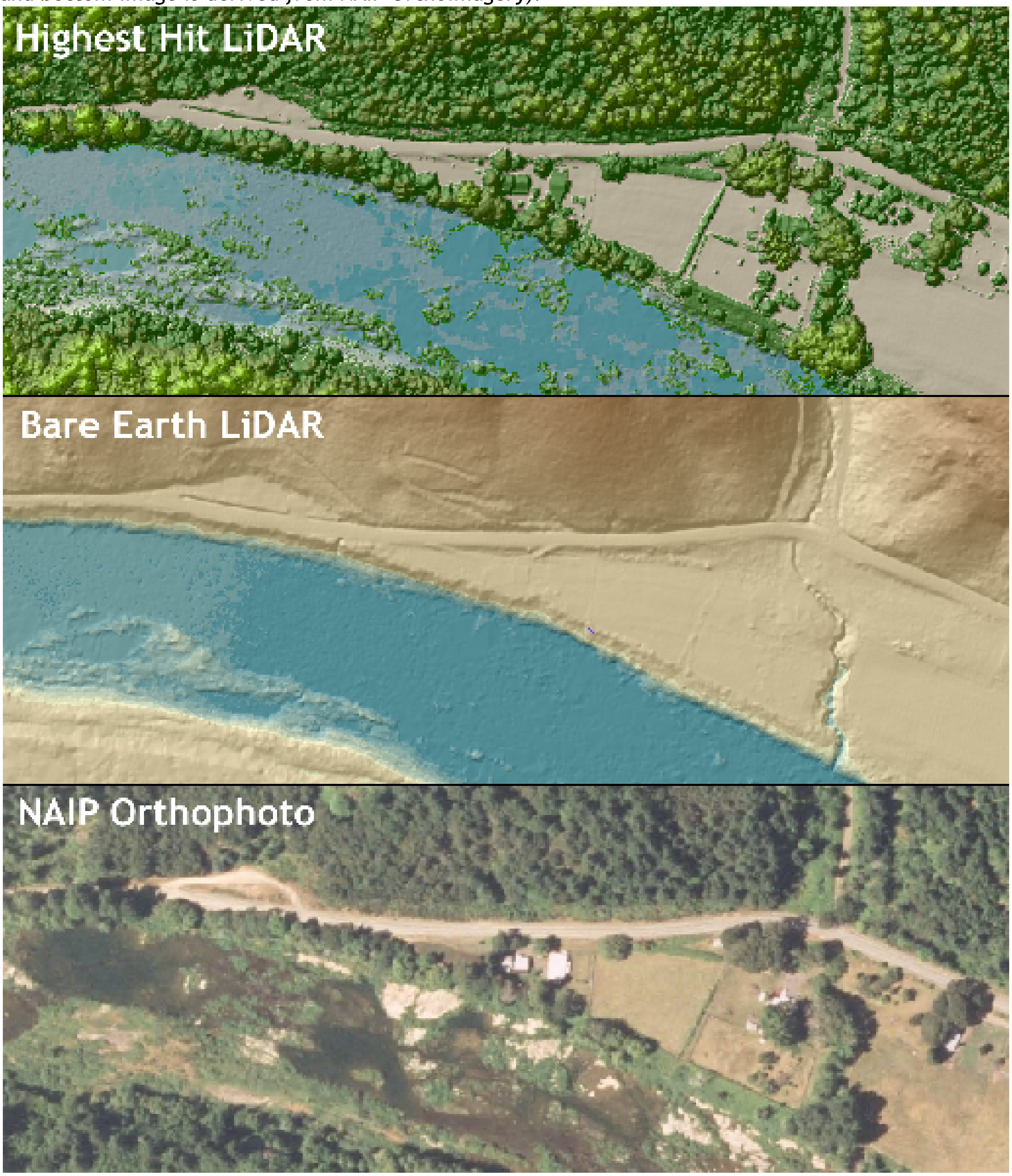


Figure 8.2. *3-D view showing the Umpqua River, just northwest of Tyee (top image is derived from NAIP Orthoimagery, middle image is derived from highest hit LiDAR points, and bottom image is derived from ground-classified classified LiDAR points).*

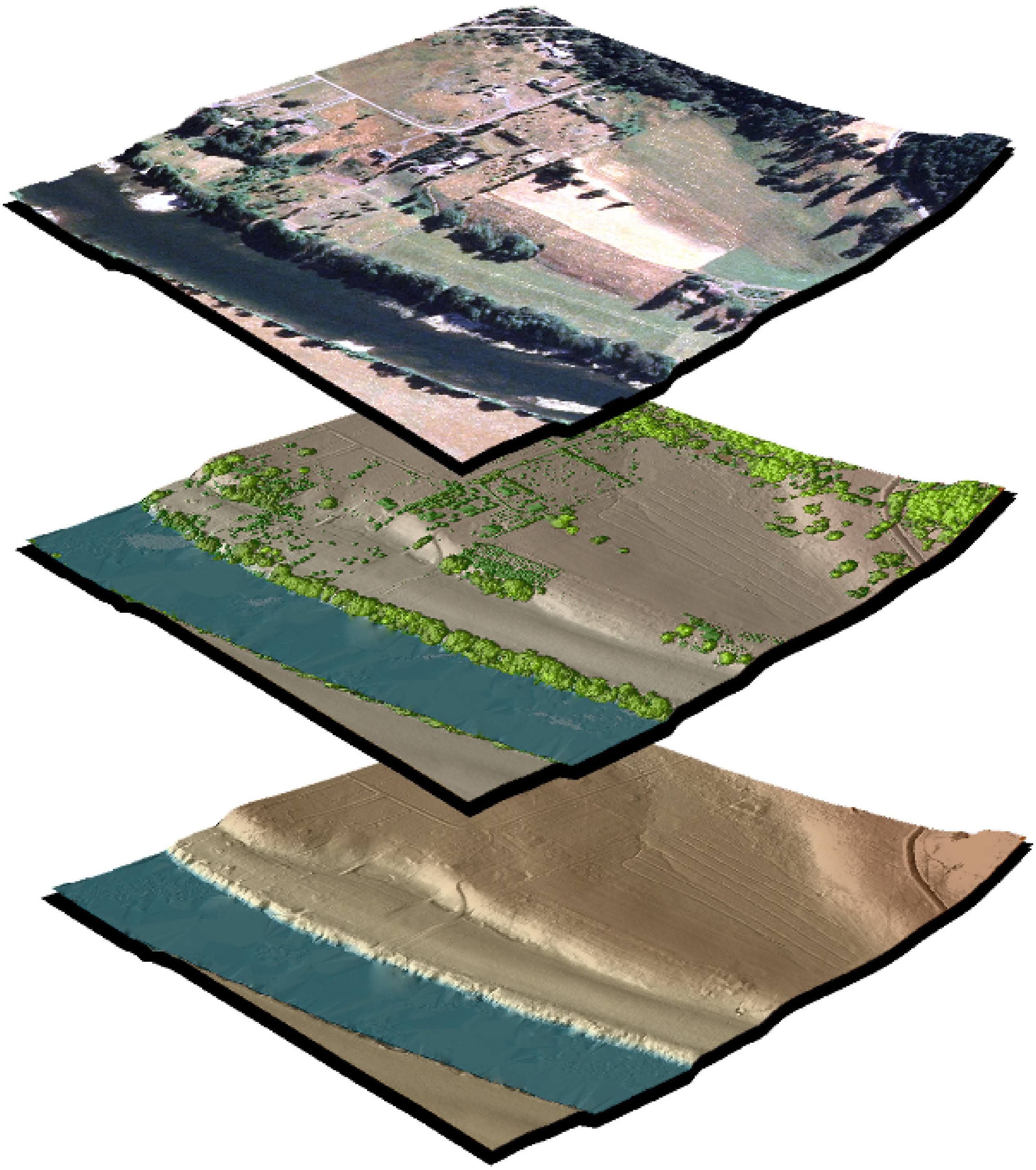
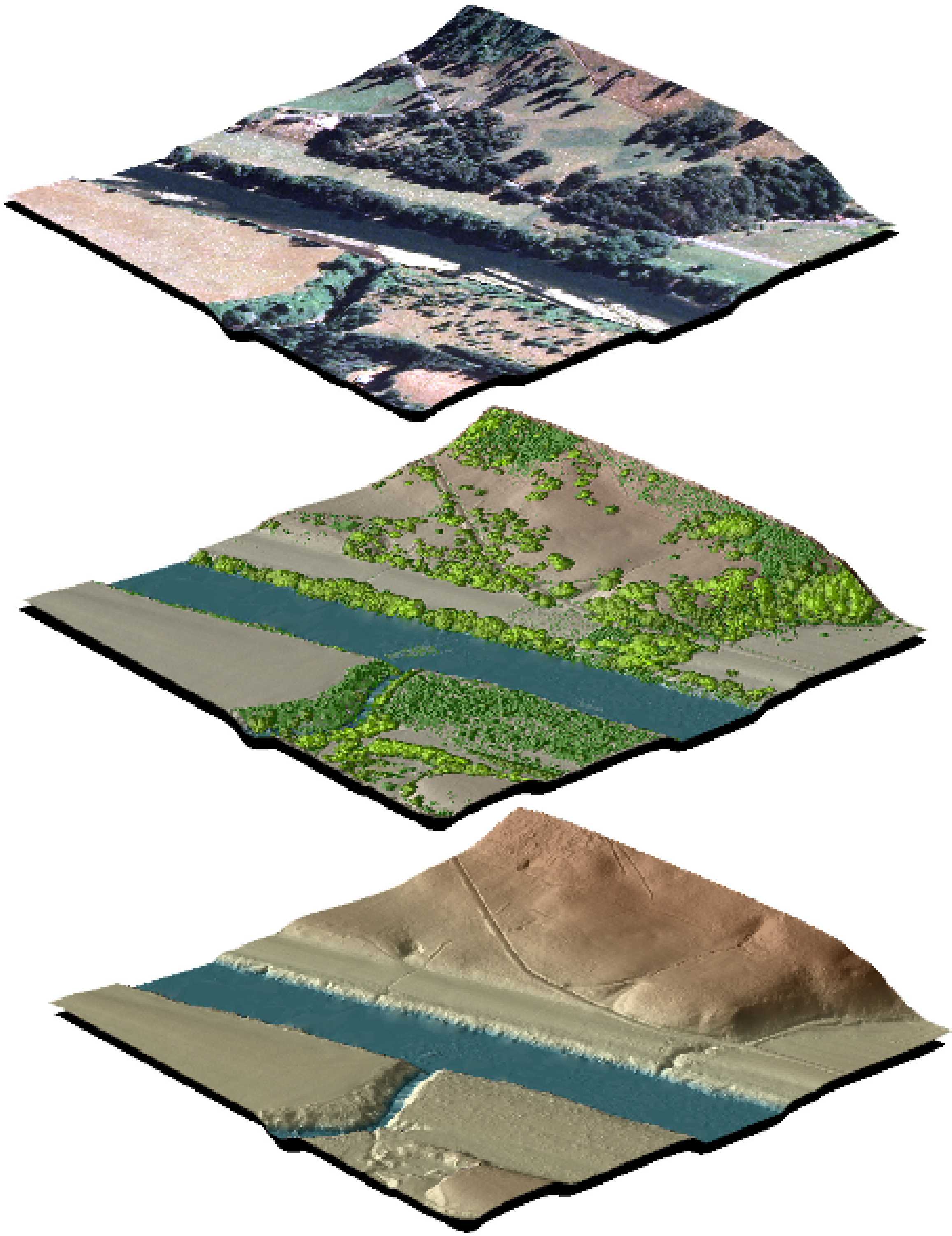


Figure 8.3. *3-D view showing the Umpqua River, just north of the Wolf Creek Bridge (top image is derived from NAIP Orthoimagery, middle image is derived from highest hit LiDAR points, and bottom image is derived from ground-classified classified LiDAR points).*



9. Glossary

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

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

<u>Root Mean Square Error (RMSE)</u>: 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.

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

<u>Pulse Returns</u>: 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.

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

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

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

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

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

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

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

<u>DTM / DEM</u>: 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.

<u>Real-Time Kinematic (RTK) Survey</u>: 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.