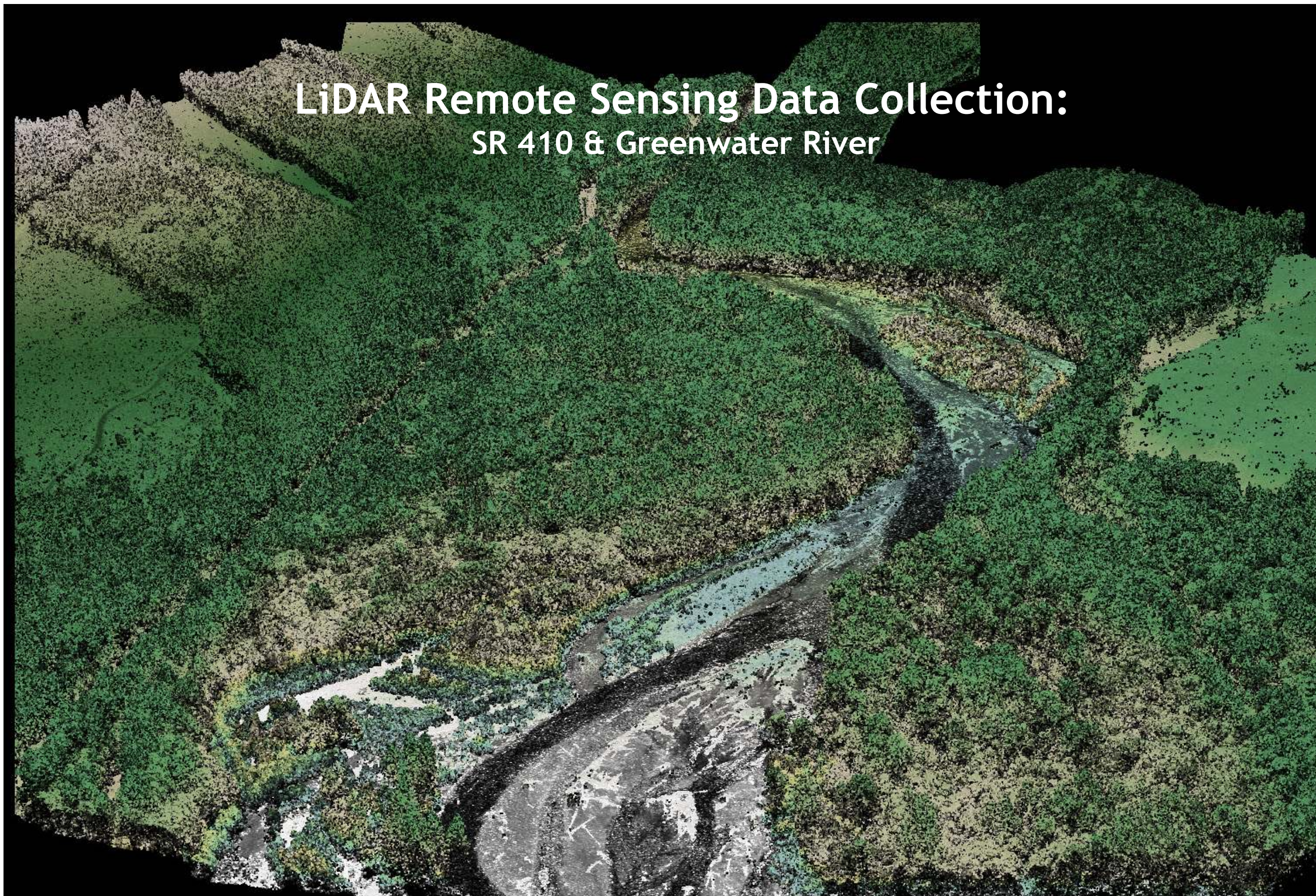
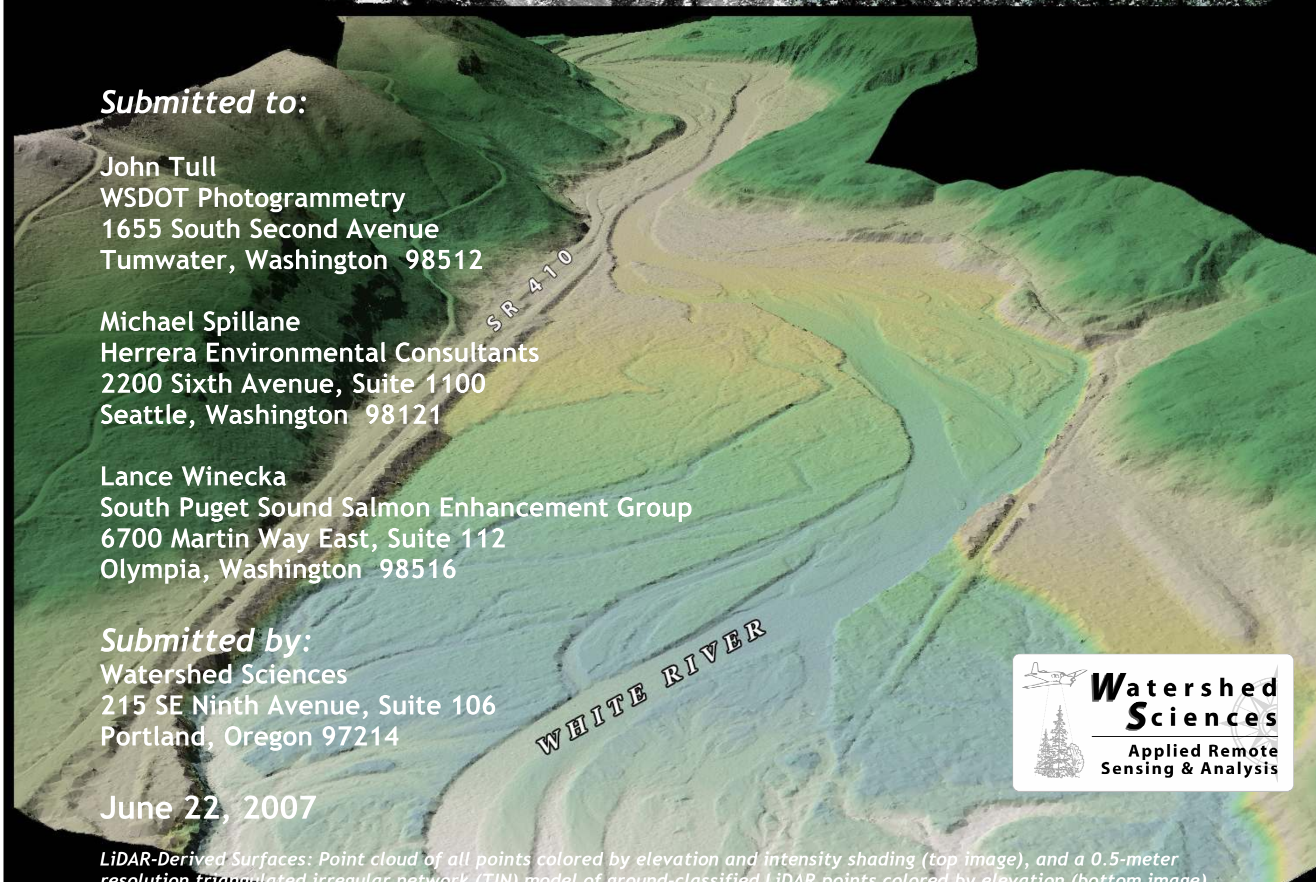
LiDAR Remote Sensing Data Collection:

SR 410 & Greenwater River





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LiDAR-Derived Surfaces: Point cloud of all points colored by elevation and intensity shading (top image), and a 0.5-meter resolution triangulated irregular network (TIN) model of ground-classified LiDAR points colored by elevation (bottom image)

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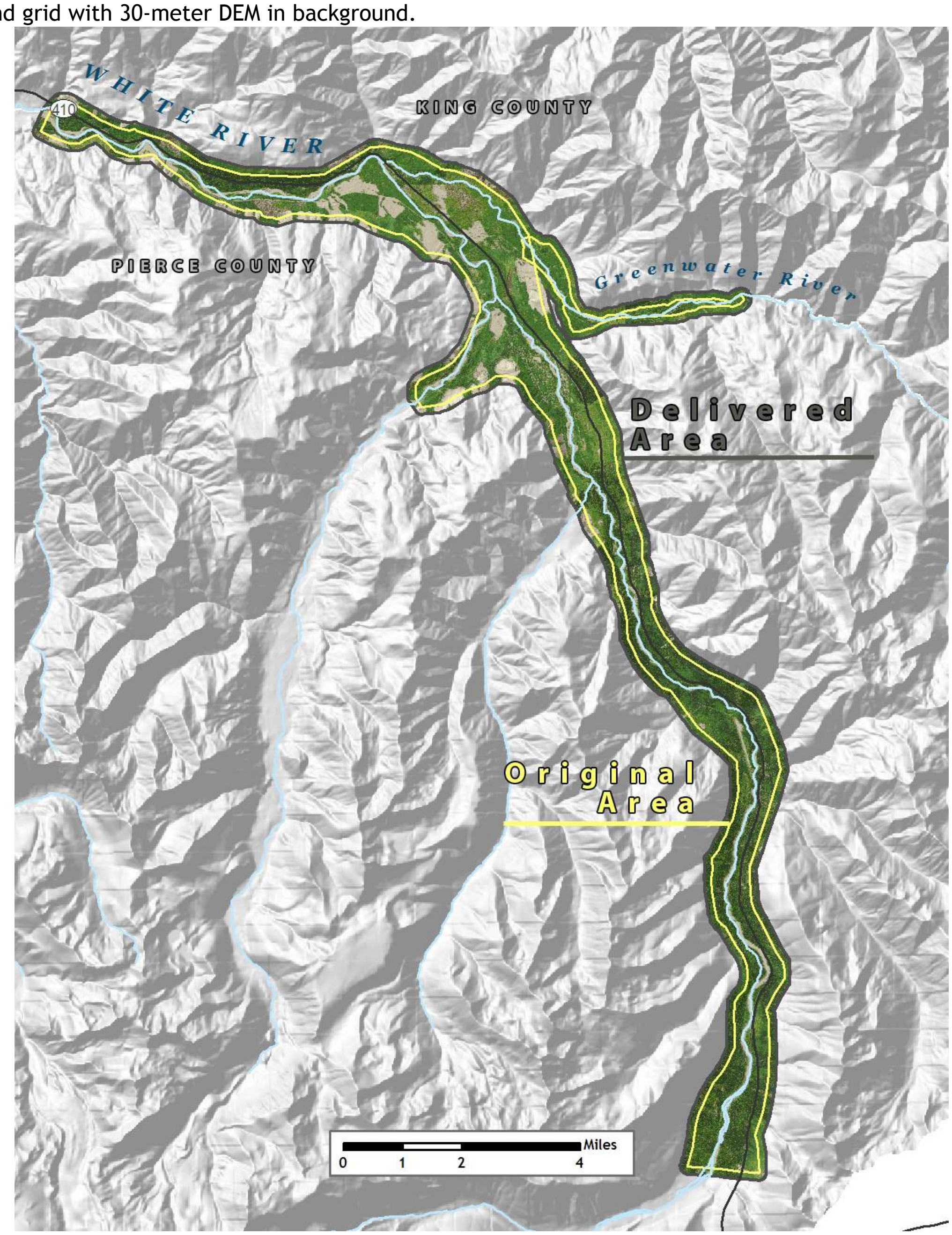
1. Introduction

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data of the SR410 and Greenwater River study areas May 22-25, 2007 for The Washington Department of Transportation (WSDOT) and the South Puget Sound Salmon Enhancement Group (SPSSEG) respectively. For the purposes of this report, the study area will be called SR 410 for simplicity. The survey area is located at the southern border of King County and the northern border of Pierce County, and follows SR410 and the White River for approximately 25 miles. The map below (**Figure 1**) shows the extent of the LiDAR acquisition area.

Figure 1. Extent of delivered LiDAR area, ~18,943 total acres. Image shows 3-foot resolution Above Ground grid with 30-meter DEM in background.



The original SR410 acreage totaled ~13,277 acres and the Greenwater area ~594 acres, for a total of ~13,871 acres. The delivered acreage for the study areas shown above is ~18,943 acres, 5,072 acres greater than the original amount, due to buffering of the original study areas and flight planning optimization.

Laser points were collected over the study areas using a LiDAR laser system set to acquire points with full overlap (i.e., ≥50% side-lap) to ensure complete coverage and minimize laser shadows created by buildings and tree canopies. A real-time kinematic (RTK) survey was conducted throughout the study area 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). For the SR410 study area, the data have an RMSE of 0.10 feet, a 1-sigma absolute deviation of 0.10 feet and a 2-sigma absolute deviation of 0.20 feet.

Deliverables include point data in ASCII format, 1.5-foot resolution laser intensity images, 3-foot resolution bare ground model ESRI GRID, and 3-foot resolution Highest Hit vegetation (above ground) model ESRI GRID. Data are delivered in Washington State Plane North (FIPS 4601) coordinate system in the NAD83/NAVD88 datum (Geoid 03) with units in US survey feet.

2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

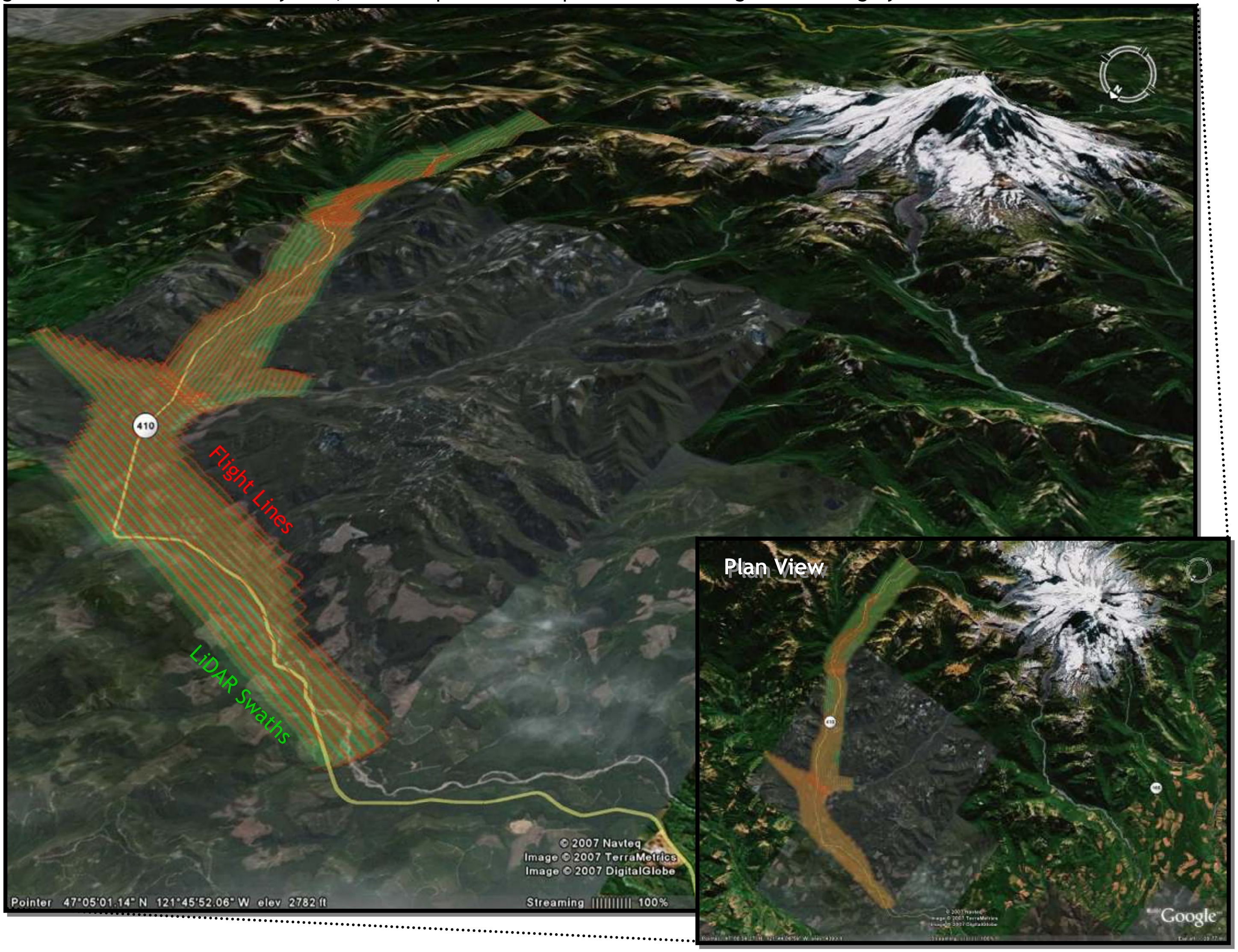
The LiDAR survey utilized a Leica ALS50 Phase II laser system mounted in Cessna Caravan 208. The survey was conducted May 22-25, 2007.

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 ±15^{o} from nadir[1]. These settings yielded points with an average native density of ≥8 points per square meter. The native pulse density is the number of pulses emitted by the LiDAR system from the aircraft. 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 entire 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).

[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. Flightline swaths for SR 410 study area, shown in plan and oblique views over Google Earth imagery.



2.2 Ground Survey – Instrumentation and Methods

During the LiDAR missions over the study area, multiple static (1 Hz recording frequency) ground surveys were conducted over monuments with known coordinates. Coordinates are provided in **Table 1** and shown in **Figure 4**. 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 1. Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data for all study areas.

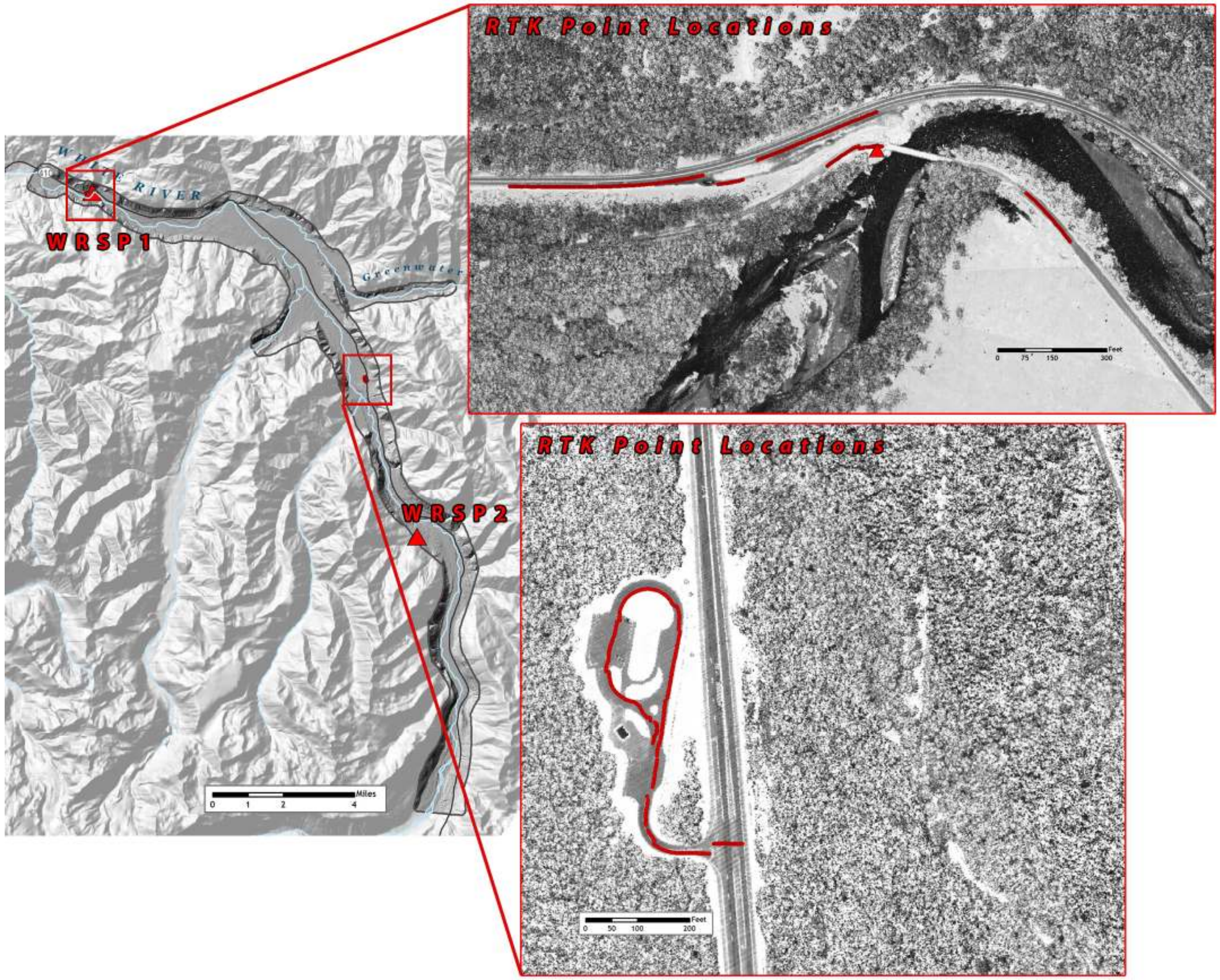
		Datum NAD83(CORS96)		GRS80
Study Area	Base Station ID	Latitude (North)	Longitude (West)	Ellipsoid Height (m)
SR410	WRSP1	47°09'52.83565"N	121°44'42.80759"W	437.163
SR410	WRSP2	47°01'17.62705"N	121°33'15.52408"W	790.433

A Thales Z-max DGPS unit is 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 ($\sigma \leq 1.5$ cm ~ 0.6 in). **Figure 4** shows examples of RTK point locations in the Ellsworth Creek study area.

Figure 3. RTK surveys utilize a base GPS unit that is set up and connected to a radio and antenna. The roving GPS unit is attached to a field data logger and receives a kinematic correction to collect field RTK data.

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

Figure 4. Base station locations and RTK point collection in the SR410 study area, shown over 3-foot resolution bare ground model; RTK detail images shown over 1.5-foot resolution intensity images.



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.7.60
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.1.0
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 v1.1) 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.6.009
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.6.009
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. Highest Hit model surfaces are developed from all points and exported as ArcInfo ASCII grids. Intensity images (GeoTIFF format) are created with averages of the laser footprint.
   Software: TerraScan v.6.009, ArcMap v9.1
7. The bin-delineated LAS files are imported into 0.9375' USGS Quad delineation and converted to ASCII format.
   Software: TerraScan v.6.009

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.7.60 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.1.0 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 estimate 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 POSPAC 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. 1.1 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 (i.e. > 40 GB). To facilitate laser point processing, bins (polygons) are created to divide the dataset into manageable sizes (< 500 MB). The processing bins are approximately ~0.56 km^2 each, or 750 meters to a side.

Flightlines and LiDAR data are then reviewed to ensure complete coverage of the study area 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. Vegetation surface rasters area developed from highest hit algorithms.

4. LiDAR Accuracy

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 were taken in the all study area and are compared to LiDAR point data. <u>The root mean square error (RMSE) is reported for the study area, along with 1- and 2-sigma absolute deviation values</u>.

Table 2. 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	Effect
GPS (Static/Kinematic)	Long Base Lines	None	
	Poor Satellite Constellation	None	
	Poor Antenna Visibility	Reduce Visibility Mask	Slight
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings	Large
	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. <u>Low Flight Altitude</u>: 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. <u>Focus Laser Power at narrow beam footprint</u>: 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 ±15° 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 13 km (8 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 a total of 897 RTK points distributed throughout multiple flight lines.
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 over 95 million 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 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 statistics and graphs for all study areas are reported and shown below in **Figures 5-7.**

Figure 5. SR 410 Study Area: Relative accuracy per flight line with overlapping point totals listed as ‘n’.

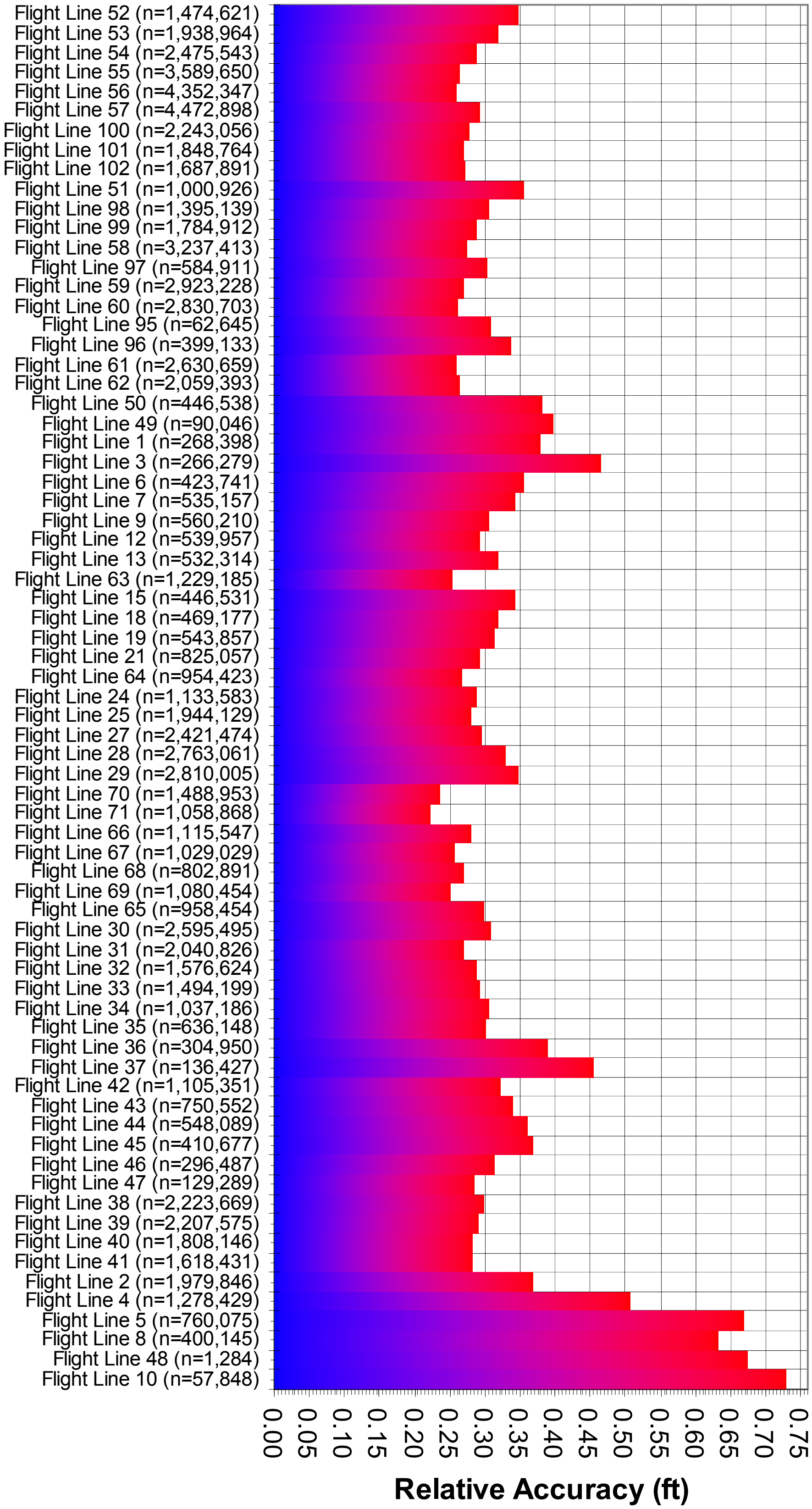


Figure 6. SR410 Study Area: Distribution of relative accuracies per flight line.

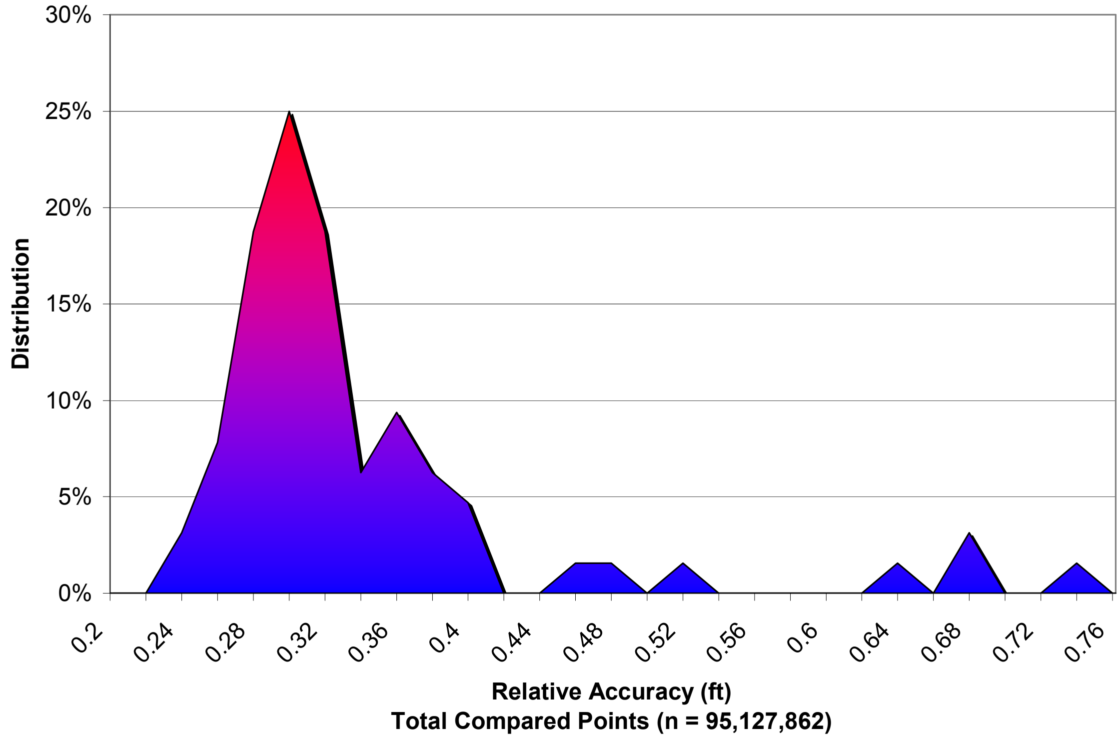
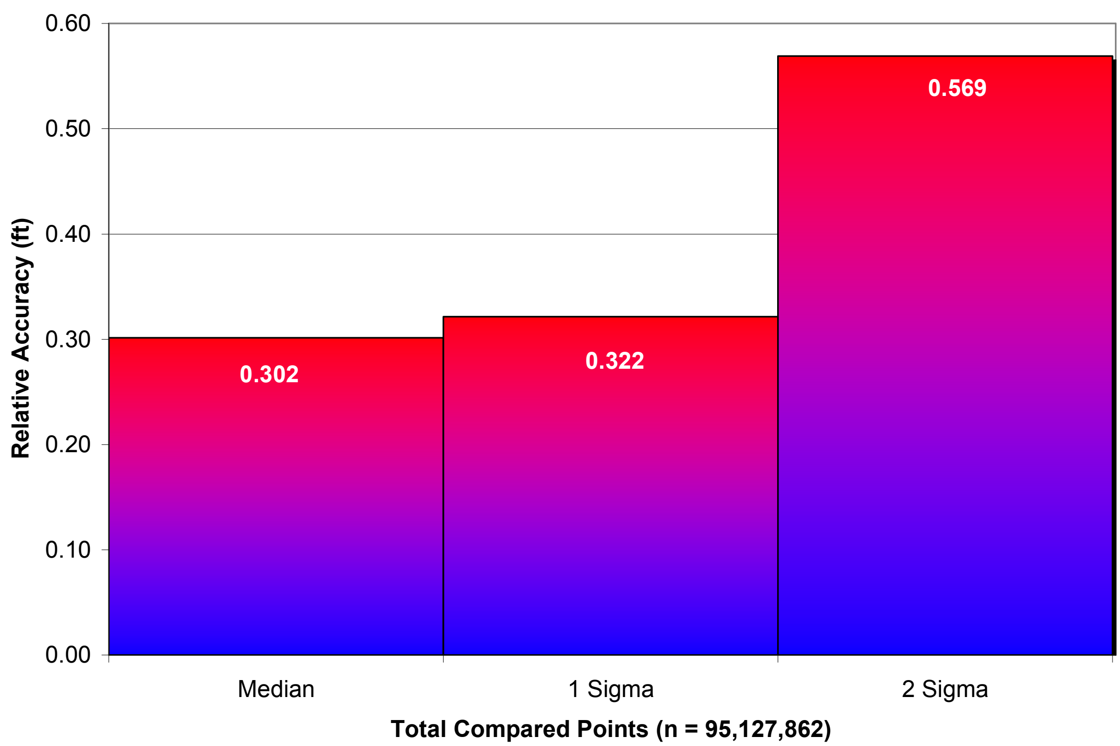


Figure 7. SR410 Study Area: Statistical relative accuracies.



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 3** and shown in **Figures 8-9**.

Table 3. SR410 Study Area: Absolute Accuracy – Deviation between laser points and RTK survey points.

Sample Size (n): 897	
Root Mean Square Error (RMSE): 0.10 feet	
Standard Deviations	**Deviations**
1 sigma (σ): 0.10 feet	**Minimum Δz:** -0.29 feet
2 sigma (σ): 0.20 feet	**Maximum Δz:** 0.43 feet
	Average Δz: -0.01 feet

Figure 8. Ellsworth Creek Study Area: Histogram Statistics

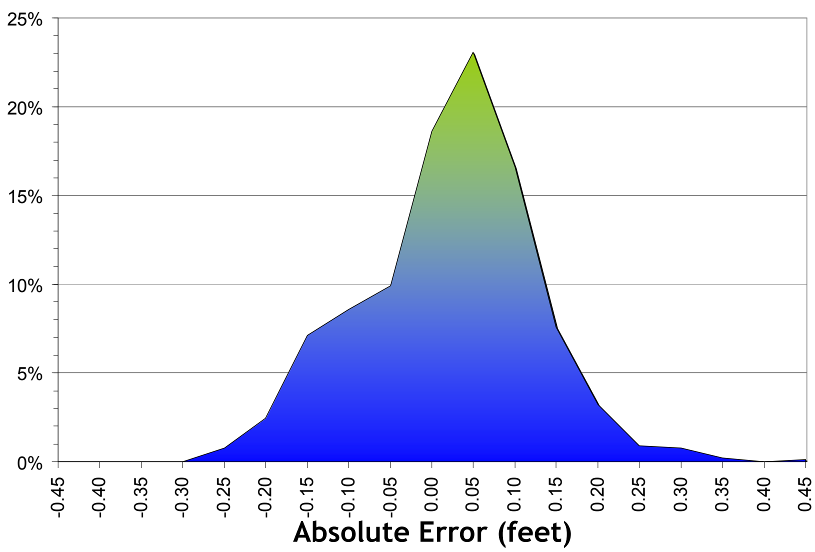
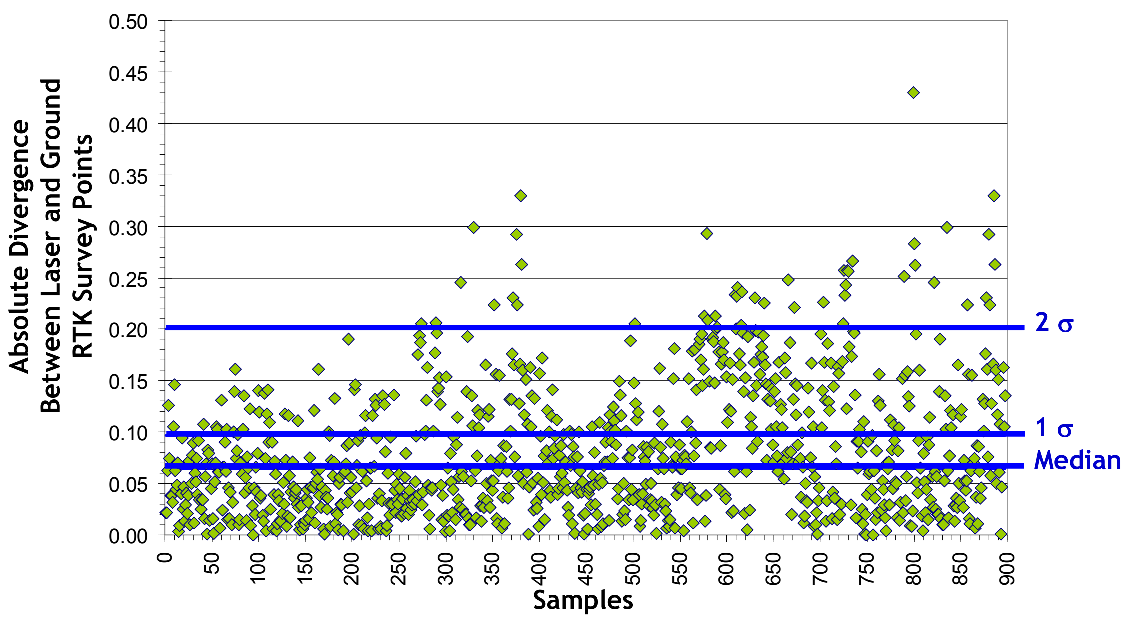


Figure 9. Ellsworth Creek Study Area: Point Absolute Deviation Statistics



4.2 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 Geiod03 model is applied to each point. The data are delivered in Washington State Plane North (FIPS 4601) coordinate system in the NAD83/NAVD88 datum (Geoid 03) with units in US survey feet.

5. Deliverables and Specifications

5.1 Point Data (per 0.9375' USGS Quad delineation)

- ASCII space delimited: All points with data fields: *Class, Easting, Northing, Elevation, Intensity*
- ASCII space delimited: Ground-classified points with data fields: *Easting, Northing, Elevation*
- ASCII space delimited: Ground-classified keypoints with data fields: *Easting, Northing, Elevation*

5.2 Vector Data

- Total Area Flown
  - Study Area delineation in shapefile format
  - 0.9375' USGS Quad delineation in shapefile format
  - 7.5' USGS Quad delineation in shapefile format

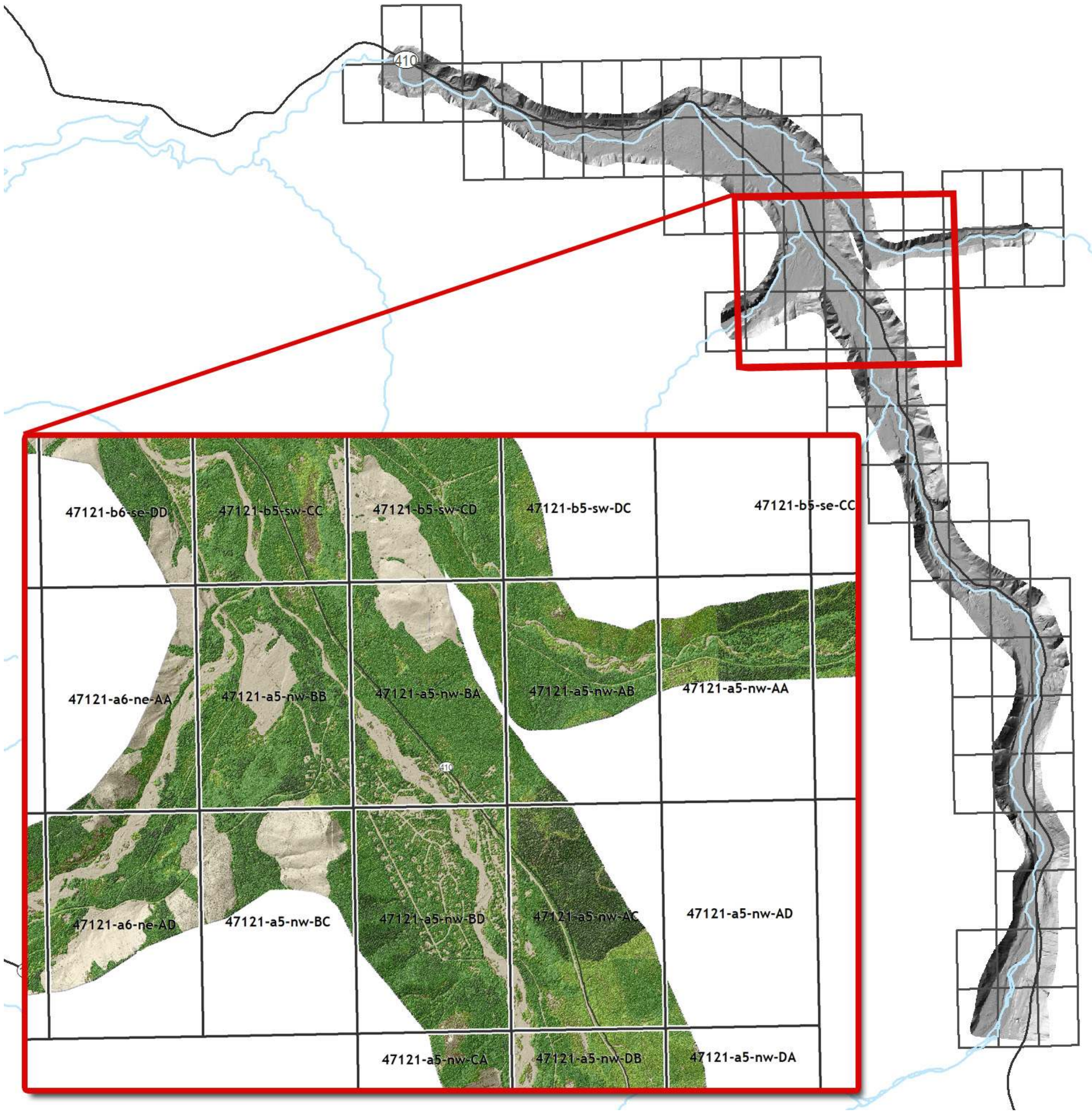
5.3 Raster Data

- ESRI GRIDs of LiDAR dataset:
  - Bare Earth Modeled Points (3-foot pixel resolution) delivered in 7.5'-minute USGS Quad delineation;
  - Vegetation Modeled Points- Highest Hit model (3-foot pixel resolution) delivered in 7.5'-minute USGS Quad delineation;
- Surface intensity images in GEOTIFF format, 1.5-foot resolution delivered in 0.9375' USGS Quad delineation

5.4 Data Report

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

Figure 10. Example of 0.9375' USGS Quad Delineations. LiDAR Points and Intensity GeoTIFFs are delivered in this delineation due to size constraints. (ESRI GRIDs are delivered in full 7.5' USGS Quad delineations).



6. Selected Images

6.1 Plan View Data

An example area is presented to show the following plan view datasets (see **Figures 11-13):**

- Bare earth 3-foot pixel resolution ESRI Grids,
- Highest Hit vegetation 3-foot resolution ESRI Grids, and
- 1.5-foot pixel resolution Intensity GeoTIFFs.

Figure 11. Bare Earth 3-foot resolution ESRI grid showing detail of Huckleberry Creek's confluence with the White River in the central portion of the **SR410 Study Area.**

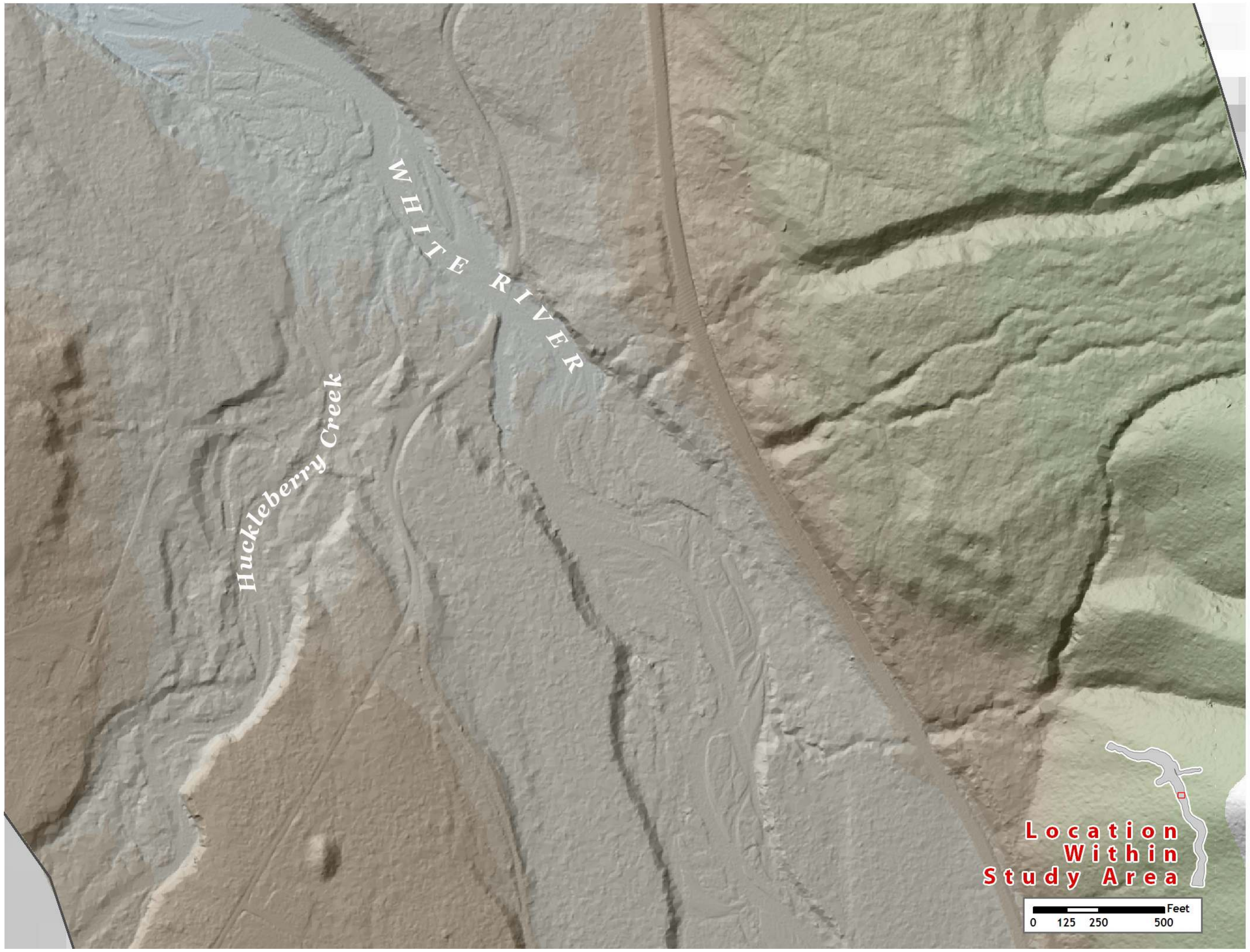
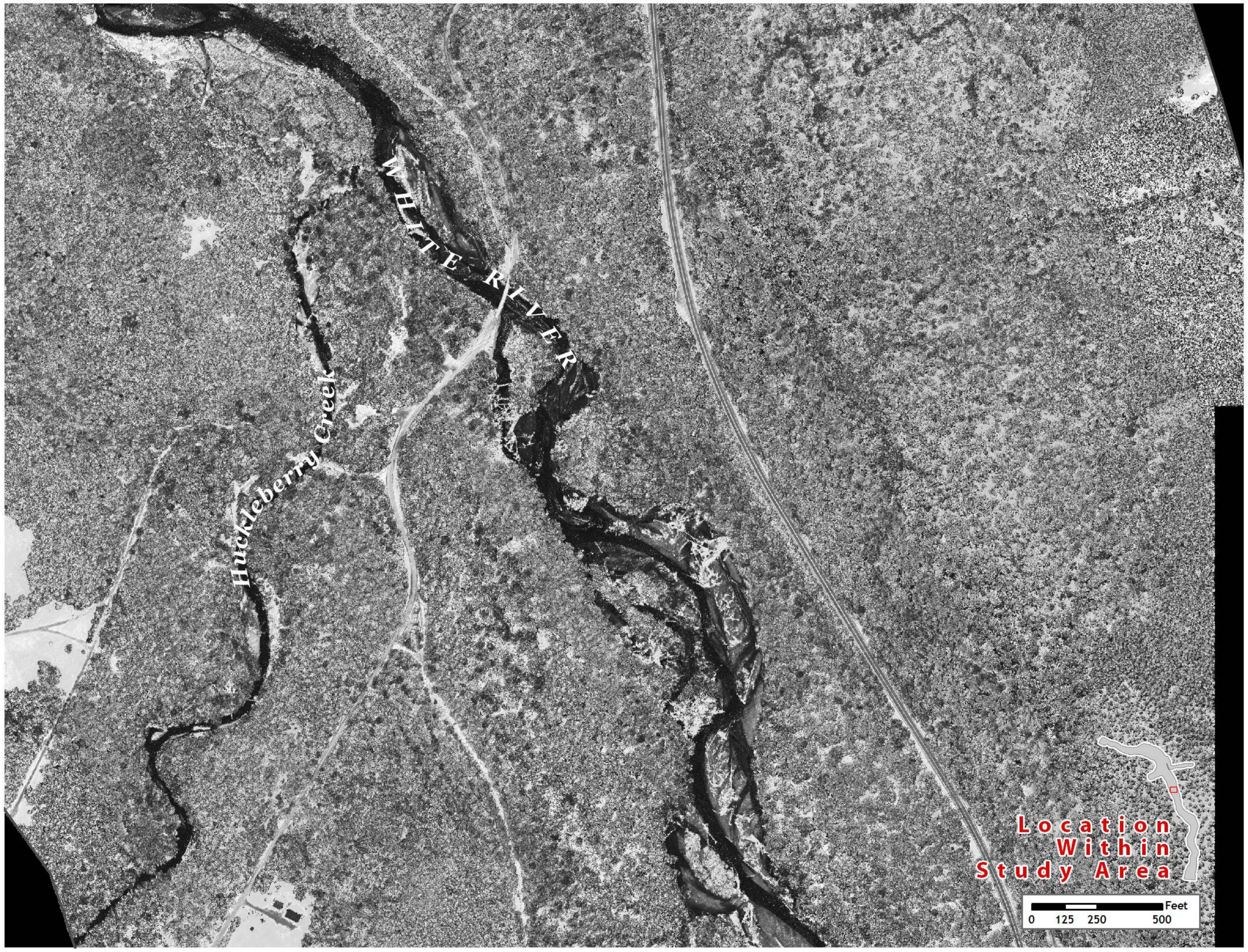


Figure 12. The Highest Hit Above Ground 3-foot resolution ESRI grid showing detail of Huckleberry Creek's confluence with the White River in the central portion of the **SR410 Study Area.** (To calculate vegetation heivalues shown in the map, the Bare Earth grid was subtracted from the Above Ground grid).

Figure 13. 1.5-foot resolution intensity image showing detail of Huckleberry Creek's confluence with the White River in the central portion of the **SR410 Study Area.**



6.2 Three Dimensional Oblique View Data Pairs

Example areas are presented to show paired, same-scene 3-D oblique view imagery (see **Figures 14-15**). These pairs depict a point cloud of all points colored by elevation and intensity shading (top image), and a 0.5-meter resolution triangulated irregular network (TIN) model of ground-classified LiDAR points colored by elevation (bottom image). *Please note that the oblique view images are not north-oriented.*

Figure 14. 3-d oblique view of LiDAR-derived surfaces in the northwestern portion of the **SR410 Study Area.** (Top image derived from all points, bottom image derived from ground-classified points).

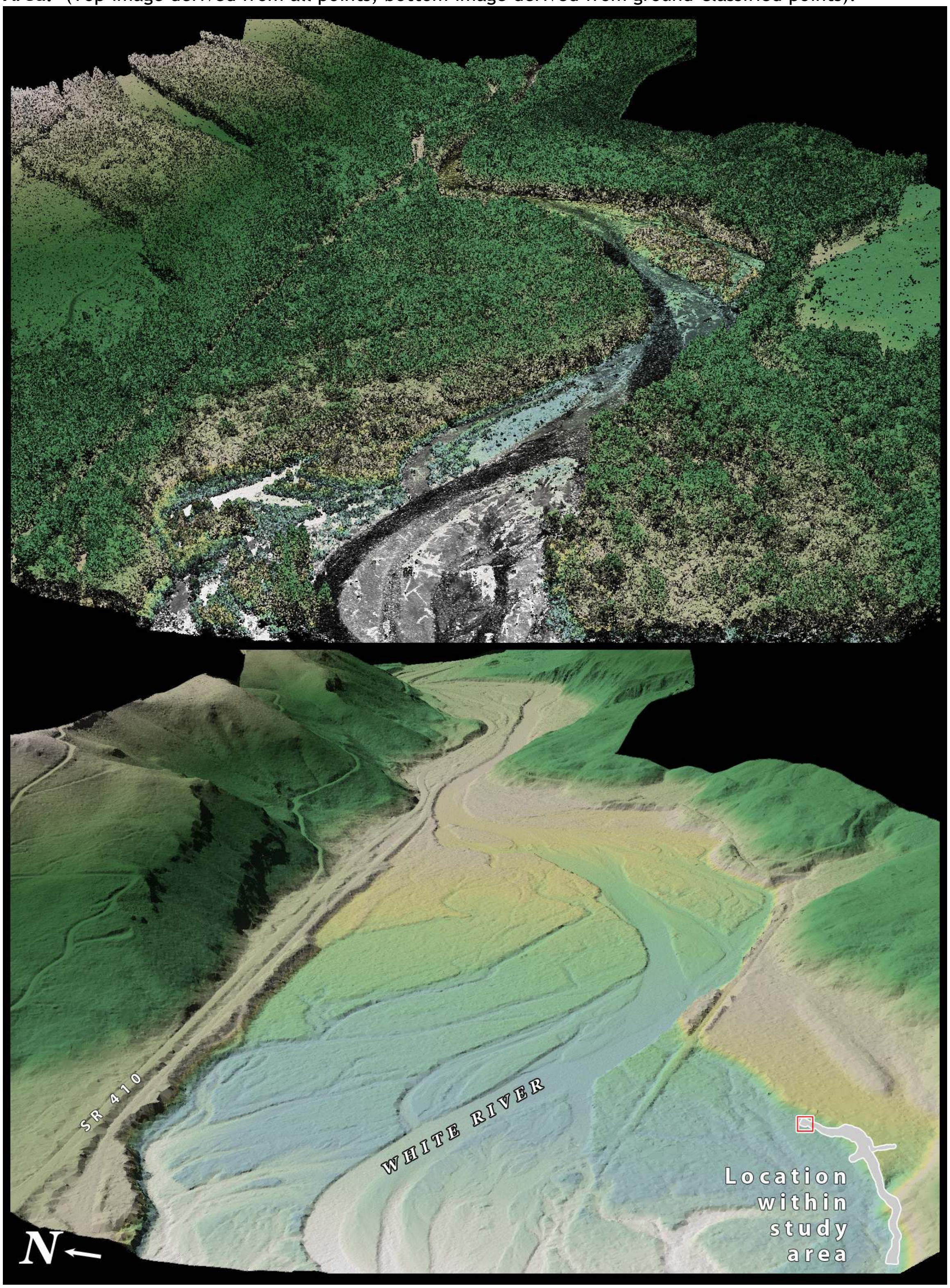
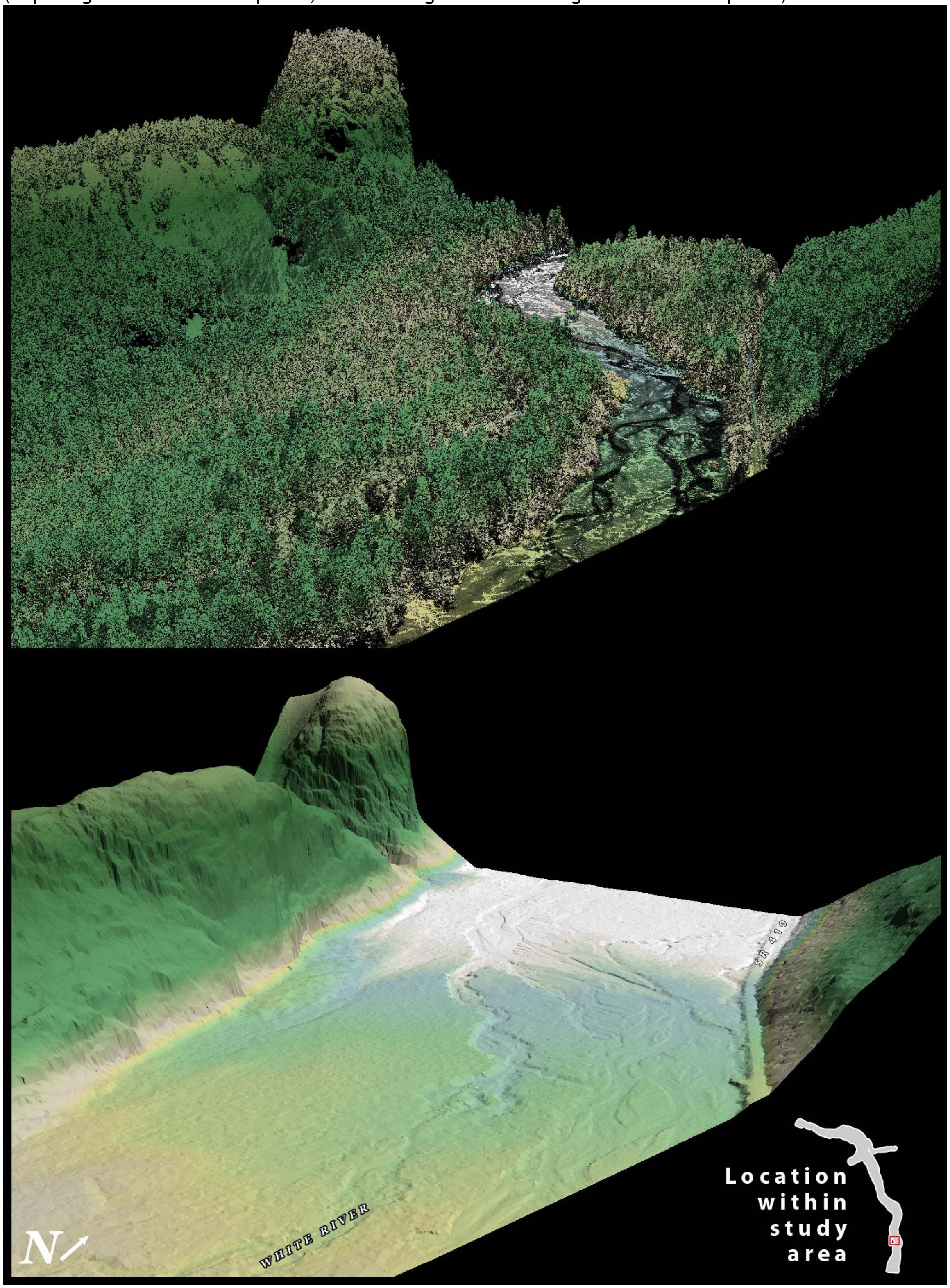


Figure 15. 3-d oblique view of LiDAR-derived surfaces in the southern portion of the **SR410 Study Area**. (Top image derived from all points, bottom image derived from ground-classified points).



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, both the Leica ALS 50 Phase II and Optech 3100 LiDAR 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.

8. Citations

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