LiDAR Remote Sensing Data Collection:
ROGUE RIVER – SISKIYOU NATIONAL FOREST
Ashland, Oregon Study Area

Submitted to:

Michael Golden
Remote Sensing Specialist
USDA Forest Service
R6 Regional Office
333 Southwest First Avenue
Portland, Oregon 97208

Steve Bulkin
Forest Silviculturist / Biologist
USDA Forest Service
Rogue River National Forest
333 West 8th Street
Medford, Oregon 97501

Submitted by:

Watershed Sciences
4605 NE Fremont, Suite 211
Portland, Oregon 97213

LiDAR-Derived Surface: Point cloud of LiDAR laser points shown over 0.5-meter resolution bare ground model, Ashland, Oregon Study Area

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1. Purpose

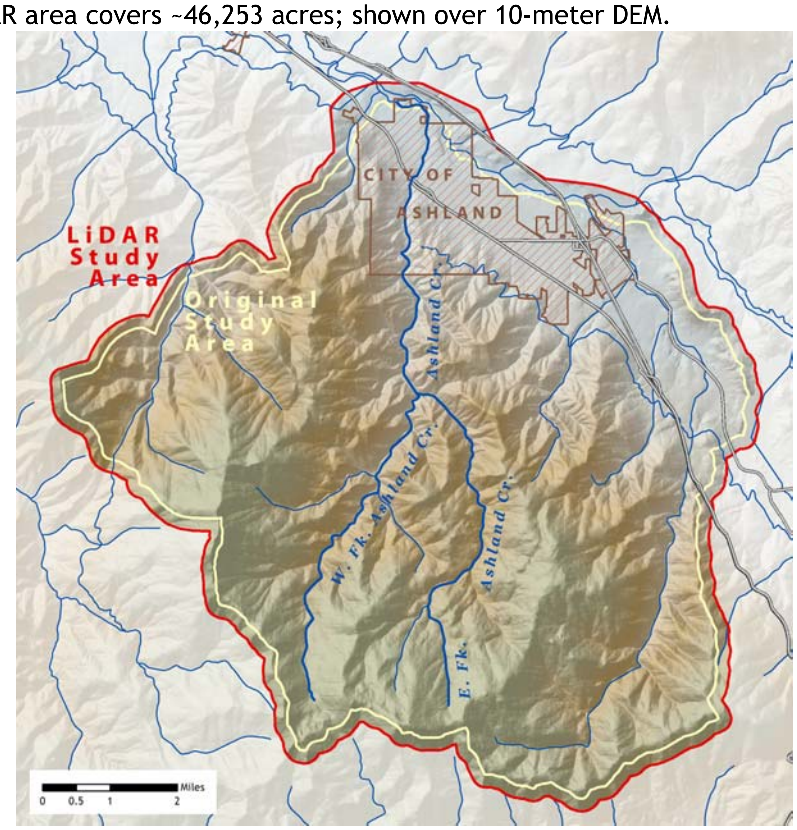
To map forest and vegetation stand structure in the forest and to provide an accurate ground model for the Rogue River-Siskiyou National Forest, near Ashland, Oregon.

2. Introduction

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data of the Ashland study area in the Rogue River-Siskiyou National Forest on July 1st-4th, 2006 (Julian Days 182-185). The survey area encompassed the city of Ashland as well as the Ashland Creek Watershed, resulting in a delivered LiDAR area of 46,253 acres.

Laser points were collected over the study area using an Optech ALTM 3100 LiDAR system. Full overlap (i.e. 50% sidelap) ensured complete coverage and minimized 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). The data have a 1σ of 0.04 meters, 2σ of 0.09 meters, and a standard deviation and RMSE both of 0.04 meters. Deliverables include ESRI grids and surface intensity images for the entire study area. Data are reported in Universal Transverse Mercator (UTM) Coordinate System, Zone 10, NAD83/NAVD88 datum, with units in meters.

Figure 1. Full extent of the Ashland, Oregon Study Area: original study area covered 41,137; delivered LiDAR area covers ~46,253 acres; shown over 10-meter DEM.



3. Acquisition

3.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey utilized an Opetch ALTM 3100 mounted in the belly of a Cessna Grand Caravan 208B. The survey was conducted on July 1st-4th, 2006 (Julian Days 182-185). Quality control (QC) pre-mission flights were performed based on manufacturer's specifications prior to the survey. The QC flight was conducted at the Ashland, Oregon Airport using known surveyed control points. The positional accuracy of the LiDAR (x, y, z) returns are checked against these known locations to verify the calibration and to report base accuracy.

Table 1. LiDAR Data Acquisition Specifications

Laser Pulse Repetition Rate	70,000 pulses per second (70 kHz)
Operating Altitude	1100 m AGL
Flight Speed	105 knots
Scan Angle	+/-14° from Nadir
Scan Pattern	Sawtooth
Laser Footprint Diameter on Ground (at 1000 m AGL)	30 cm
Number of Returns Collected Per Laser Pulse	Up to 4
Multi-Swath Pulse Density	≥7.5 pulse/m^2
Intensity Range	8 bits
Adjacent Swath Overlap (Side-Lap)	≥50%
Number of GPS Base Stations Used	2
Maximum Distance From Airborne to Ground GPS	<10 miles
GPS PDOP During Acquisition	≤3.0
GPS Satellite Constellation During Acquisition	≥6
RTK Quality Control Data Points Collected	859
RTK Data RMSE	≤0.04 meters

The Optech ALTM 3100 system was set to acquire 70,000 laser pulses per second (i.e. 70kHz pulse repetition rate) and flown at 1,100 meters above ground level (AGL), capturing a scan angle of +/-14° from nadir[1], to yield points with an average density of ≥7.5 points per square meter. The entire area was surveyed with opposing flight line sidelap 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 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 a second (2 Hz) by an onboard differential GPS unit. Aircraft attitude

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

is measured 200 times a second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU).

Throughout the survey, two dual frequency DGPS base stations at monuments placed by Watershed Sciences and corrected by the Online Positioning User Service (OPUS), recorded fast static (1 Hz) data.

Table 2. Base Station Surveyed Coordinates: Watershed Sciences Placed Monuments

Survey Date / Julian Day	Point ID (OPUS Corrected)	NAD83/NAVD88		
		Latitude (North)	Longitude (West)	Ellipsoid Height (m)
July 1-4, 2006 / JD 182-185	Ashland 1	42 8'32.33669"	122 37'29.21920"	672.396
July 1-4, 2006 / JD 182-185	Ashland 2	42 12'57.92842"	122 42'24.45226"	534.905

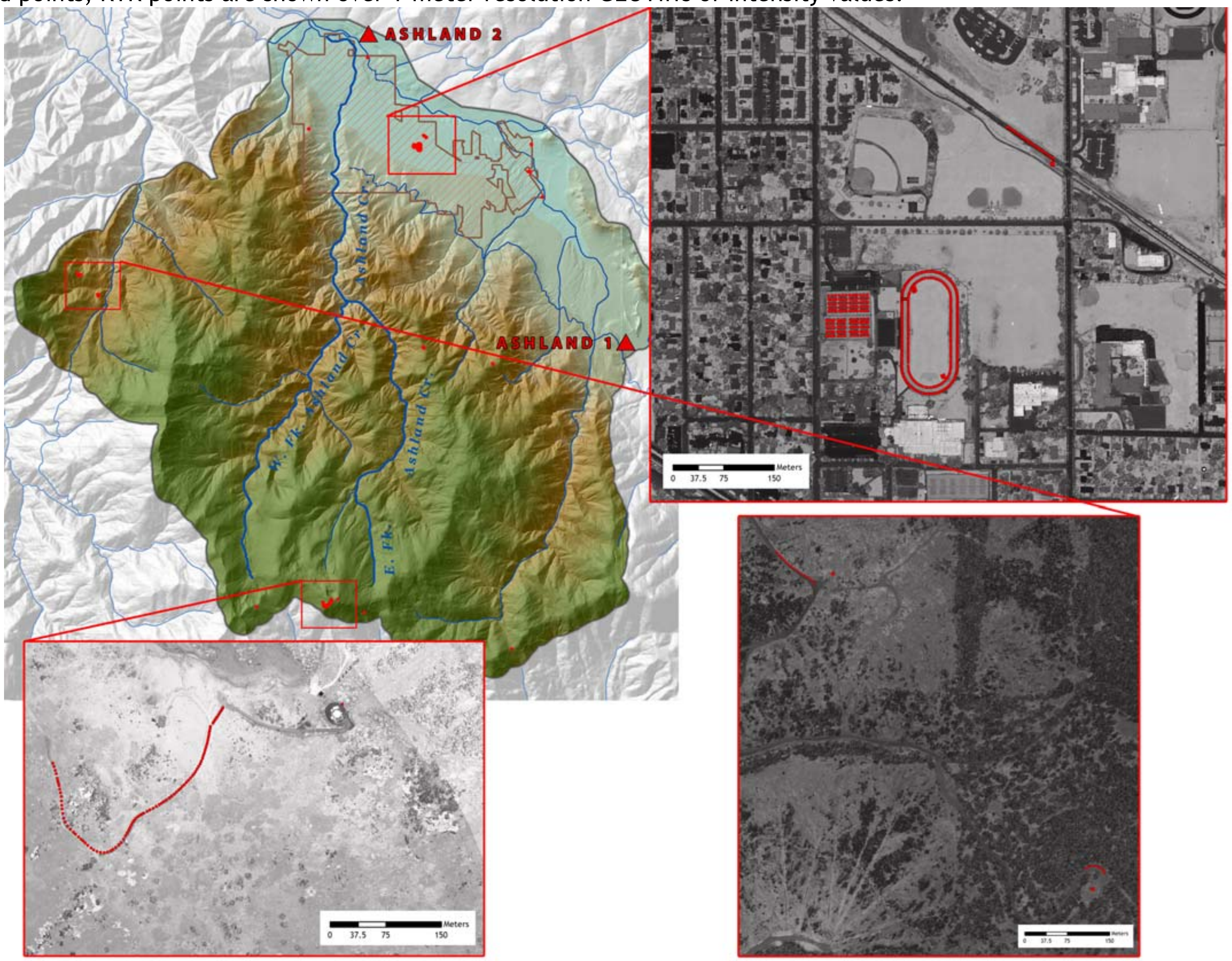
The station locations are shown on the map below (Figure 3). The fast static ground GPS data were used to calculate a kinematic correction for the aircraft position.

3.2 Ground Survey – Instrumentation and Methods

Two Thales Z-max units were used for the ground survey portion of the survey. To collect accurate ground surveyed points, a GPS base unit was set up to broadcast a kinematic correction to a roving GPS unit. The ground crew used a roving unit to receive radio-relayed kinematic corrected positions from the base unit. 859 RTK points were collected throughout the study area and were used to assess the LiDAR data accuracy; these points' locations are shown on the map below (Figure 3).

Figure 2. RTK surveys utilize a base GPS unit that is set up and connected to the radio and antenna. The roving GPS unit is attached to a field data logger and receives a kinematic correction to collect field RTK data.

Figure 3. Location of RTK survey point collection and base stations: Study area and base stations are shown over 1-meter resolution ESRI grid of Bare Ground points; RTK points are shown over 1-meter resolution GEOTiffs of intensity values.



4. LiDAR Data Processing

4.1 Applications and Work Flow Overview

1. POSGPS: Monument static GPS data are processed with aircraft GPS data to resolve kinematic corrections.
2. POSProc: Aircraft attitude data are incorporated with post processed aircraft kinematic GPS data.
3. REALM: Laser point data are calculated for the entire survey in *.las format.
4. TerraScan: Data are imported, manually calibrated and filtered for pits/birds.
5. TerraMatch: Internal consistencies derived from GPS and IMU drift are measured and corrected.
6. TerraScan: Develop ground models, statistical accuracy assessments, Geoid03 application, projection changes and transformations.
7. TerraModel: Develop TINs, contours and rasters.
8. ArcGIS: View and mosaic raster data.

4.2 Aircraft Kinematic GPS and IMU Data

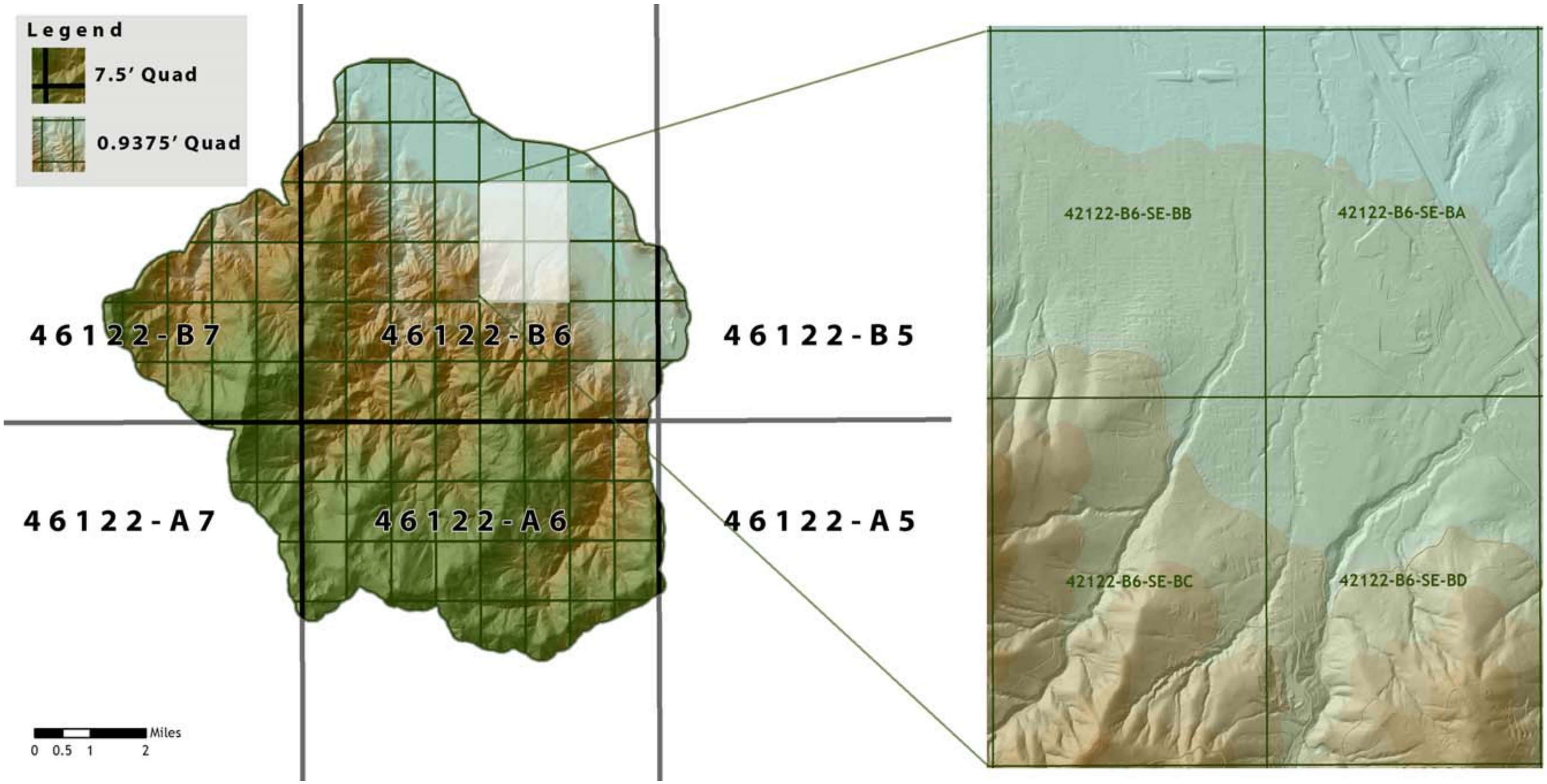
LiDAR survey datasets are referenced to 1Hz static ground GPS that are set up prior to the LiDAR aircraft survey flight. While surveying, the aircraft collects 2Hz kinematic GPS data. The onboard inertial measurement unit (IMU) collects 200 Hz aircraft attitude data. POSGPS v. 4.2 is used to process the kinematic corrects for the aircraft. The static and kinematic GPS data are then post-processed after the survey to obtain accurate GPS solution and aircraft positions during times of the survey. POSProc v. 4.2 is used to develop a trajectory file that includes corrected aircraft position and attitude information. The trajectory data for the entire flight survey session is incorporated into a final trajectory file that contains accurate and continuous aircraft positions and attitudes.

4.3 Laser Point Processing

Laser point coordinates were computed using the REALM v. 3.5.2 software suite based on independent data from the LiDAR system (pulse time, scan angle), aircraft attitude, and aircraft position. Laser point returns (first through fourth) are assigned an associated (x, y, z) coordinate, along with unique intensity values (1-255). The data are output into one very large LAS v. 1.0 file format; each point has a corresponding scan angle, return number (echo), intensity, and x,y,z (easting, northing, and elevation) information.

The initial laser point file is too large to process. To facilitate laser point processing, bins (polygons) were created to divide the dataset into manageable sizes (less than 500 MB and approximately 1 km^2 each). Flight lines and LiDAR data were then reviewed to ensure complete coverage of the study area and positional accuracy of the laser points. These processing bins were ultimately aggregated into areas of 0.9375-minute quadrangles (1/64th of a standard USGS 7.5-minute quadrangle; see Figure 4 below).

Figure 4. Delivered delineations: 0.9375-minute quadrangles, shown over 1-meter resolution ESRI grid of Bare Ground points.



Once the laser point data are imported into bins in TerraScan, a manual calibration test is performed to assess the system offsets for pitch, roll, yaw and 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, and spurious points are removed. For a bin measuring 1 km^2, an average of 20-40 points are found to be artificially low or high.

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, yaw and scale offsets). Once these misalignments are corrected, GPS drift can then be resolved and removed. The resulting dataset is internally calibrated using both manual and automated routines. At this point in the workflow, remaining data have passed initial screening and are deemed accurate.

The TerraScan software suite is designed specifically for classifying near-ground laser points (Soinenen, 2004). The processing sequence begins by 'removing' all points that are not 'near' the earth based on evaluation of the multi-return layers. The resulting bare earth (ground) model is visually inspected and additional ground 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.

Custom vegetation modeling is also performed using Fusion v.2.1 deforestation algorithms (Haugerud and Harding, 2001; Andersen et al. 2003; McGaughey and Carson, 2003; McGaughey, in progress[2]).

4.4 Laser Point Accuracy

Laser point absolute accuracy is largely a function of internal consistency and laser noise:

- **Absolute Accuracy**: This is the comparison of laser points to real time kinematic (RTK) ground level survey data.

- **Internal Consistency**: Internal consistency refers to the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes. The data were analyzed for internal consistency between opposing and orthogonal flight lines and passed divergence test requirements of less than 0.070 meters per any one overlapping flight line.

- **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) will experience higher laser noise. The laser noise range for this mission varies between 0.040 - 0.050 meters.

[2] McGaughey*, in progress*. Fusion v. 1.7 development and testing.

Table 3. 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
Internal Consistency	Poor System Calibration	Recalibration IMU and sensor offsets/settings	Large
	Inaccurate System	None	
Laser Noise	Poor Laser Timing	None	
	Poor Laser Reception	None	

4.4.1 Internal Consistency

Internal consistency is the measure of swath to swath reproducibility. Simply stated, internal consistency is the divergence in points within an overlapping area. If the system is well calibrated, then divergence between lines in overlapping areas should be low. Internal consistency is affected by system misalignments in pitch, roll, yaw and scale. Further, GPS and IMU drift also affects internal consistency.

Quality Control Measures to Optimize Internal Consistency:

1. Manual System Calibration: We utilize a calibration procedure for each mission that involves solving geometric relationships that relate measured swath to swath deviations in terms of misalignments of system. Corrected scale, pitch, roll and yaw offsets are calculated and applied to correct measured misalignments.
2. Fly Low: We target terrain following at 1100 meters above ground level (AGL) flight altitudes. Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 1/3000th AGL flight altitude). It follows that lower flight altitudes decrease laser noise on surfaces with even the slightest relief.
3. Increase Laser Power: To record a measurement accurately, a laser return must be received by the system above a power threshold. The strength of the laser return is a function of laser emission power, flight altitude and the reflectivity of the target. While we cannot control surface reflectivity, we can increase emitted laser power (and maintain low flight altitudes ~ see above).
4. Reduce Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±14^{o} from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
5. High Data Resolution: While resolution does not directly affect laser spot *accuracy*, it dramatically increases testing capabilities. Targets are more fully resolved and the probability for penetration to ground is increased. Laser spot comparisons are more proximate to ground survey points, improving point to point comparisons. Small features (e.g., tree tops, roof peaks, terrain breaks, etc.) are more easily resolved, increasing the absolute accuracy of the overall

dataset by reducing interpolation between points during the TIN creation process.

6. Quality GPS: Fly during optimal GPS conditions (e.g., 6 or great satellites and PDOP less than 3.5, preferably 3.0). Before each flight, the PDOP (Position Dilution of Precision) was determined for the survey day. During all flight times, two (2) dual frequency DGPS base stations recording at 1–second epochs were utilized and a maximum baseline length between the aircraft and the control points was less than 10 miles at all times.
7. Ground Survey Data: Accuracy: Ground survey points themselves should be accurate (i.e., <1.5 cm RMSE). This is accomplished by surveying at optimal PDOP ranges and minimizing base lines between GPS rover and base.
8. Ground Survey Data: Sample Size and Distribution: Robust statistics are, in part, a function of sample size (n) and sample distributions. RTK survey points are n=859 and distributed throughout multiple flight lines.
9. 50% Side-Lap (100% Overlap): Optimize overlapping areas for relative accuracy testing. Prevent laser shadowing and 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 50% overlap, with terrain followed acquisition, eliminates the chance for data gaps.
10. Opposing Flight Lines: All overlapping flight lines are opposing. Pitch, roll and yaw errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.
11. Automated System Calibration: Using TerraMatch's automated sampling routines, all overlapping areas are tested for internal consistency. Data are assessed and optimized for scale, pitch, roll and yaw system misalignments. Automated system calibration is a refinement to the manual system calibration and allows for slight alignments based upon millions of discrete comparisons over varied terrain and GPS conditions.

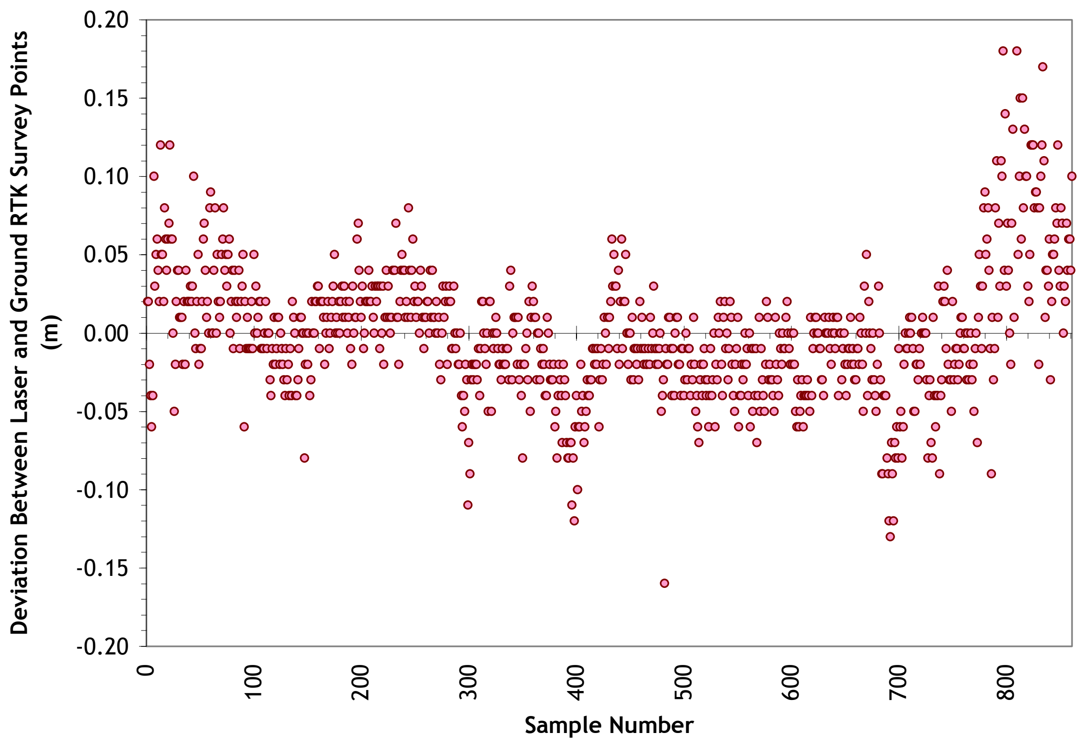
4.4.2 Absolute Accuracy

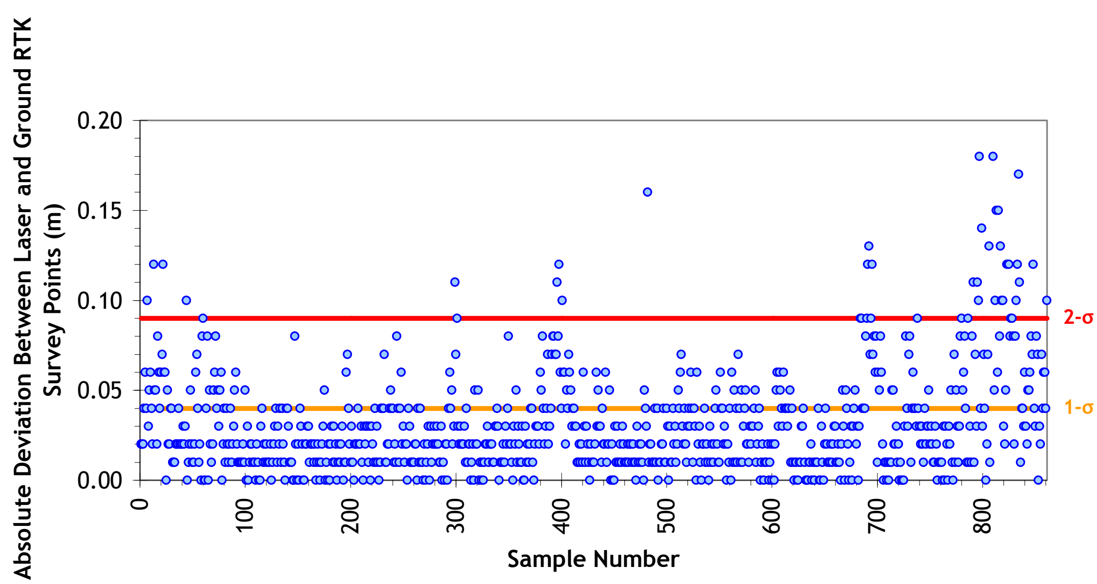
The final quality control measure is a statistical accuracy assessment that compares known RTK ground survey points to the closest laser point. Accuracy statistics are reported below.

Table 4. Absolute Accuracy – Deviation between laser points and RTK survey points.

Standard Deviation:	0.04 meters	1 sigma (σ):	0.04 meters
Average Deviation:	0 meters	2 sigma (σ):	0.09 meters
RMSE:	0.04 meters	Minimum Δz:	-0.16 meters
n:	859	Maximum Δz:	0.18 meters

Figure 5. Point Deviation Statistics





4.5 Geoid03

The data were processed as ellipsoidal elevations and required a Geoid03 transformation to convert the elevations into orthometric values. In TerraScan, the NGS published Geiod03 model (orthometric transformation) was applied to each point.

4.6 Datum and Projection

The data were processed with meters units in the UTM Coordinate System, Zone 10, NAD83/NAVD88 datum.

4.7 Raster Processing - GRIDs

The ground model rasters were created in TerraScan by creating TINs of the ground points and developing an ArcINFO GRID of the TIN. A raster of the bare ground surface was created at a 1-meter resolution, with z-units (elevation units) in meters. A Fusion v.2.1 5x5 model was used to develop a raster of buildings and vegetation (above ground surfaces) at a 1-meter resolution, with z-units (elevation units) in meters. All rasters were converted to ESRI GRID format and delivered with metadata.

5. Deliverables

All deliverables are delivered in:

- Projection: UTM Coordinate System, Zone 10
- Units: Meters
- Horizontal Datum: NAD83
- Vertical Datum: NAVD88

Points:

ASCII files of LiDAR Laser Points: Fields are Easting, Northing, Elevation, Intensity: ***Delivered by 7.5' Quad***

*.las files of LiDAR Laser Points: ***Delivered by 7.5' Quad***

Rasters:

ESRI GRIDs of LiDAR dataset

- Ground Modeled Points (1-meter resolution, z-units in meters): ***Delivered by 7.5' Quad***

- Above Ground Modeled Points (1-meter resolution, z-units in meters): ***Delivered by 7.5' Quad***

Surface intensity images in GEOTIFF format (0.5-meter resolution): ***Delivered by 0.9375' Quad***

Shapefiles:

0.9375' Quad Delineations in ESRI shapefile format
7.5' Quad Delineations in ESRI shapefile format

Survey report

Figure 6. The following image pairs show oblique-view examples of vegetation coverage and underlying bare ground surface in the Ashland study area. Each pair includes a 0.5-meter resolution bare ground model (top) paired with a point cloud of LiDAR laser points (bottom) ***of the same scene***. This image pair covers the lower extent of Ashland Creek as it runs through the City of Ashland.

Figure 7. This image pair captures the northern end of Reeder Reservoir, near the center of the LiDAR study area.

Figure 8. This image pair shows a forested area near the intersection of Neil Creek and I-5.

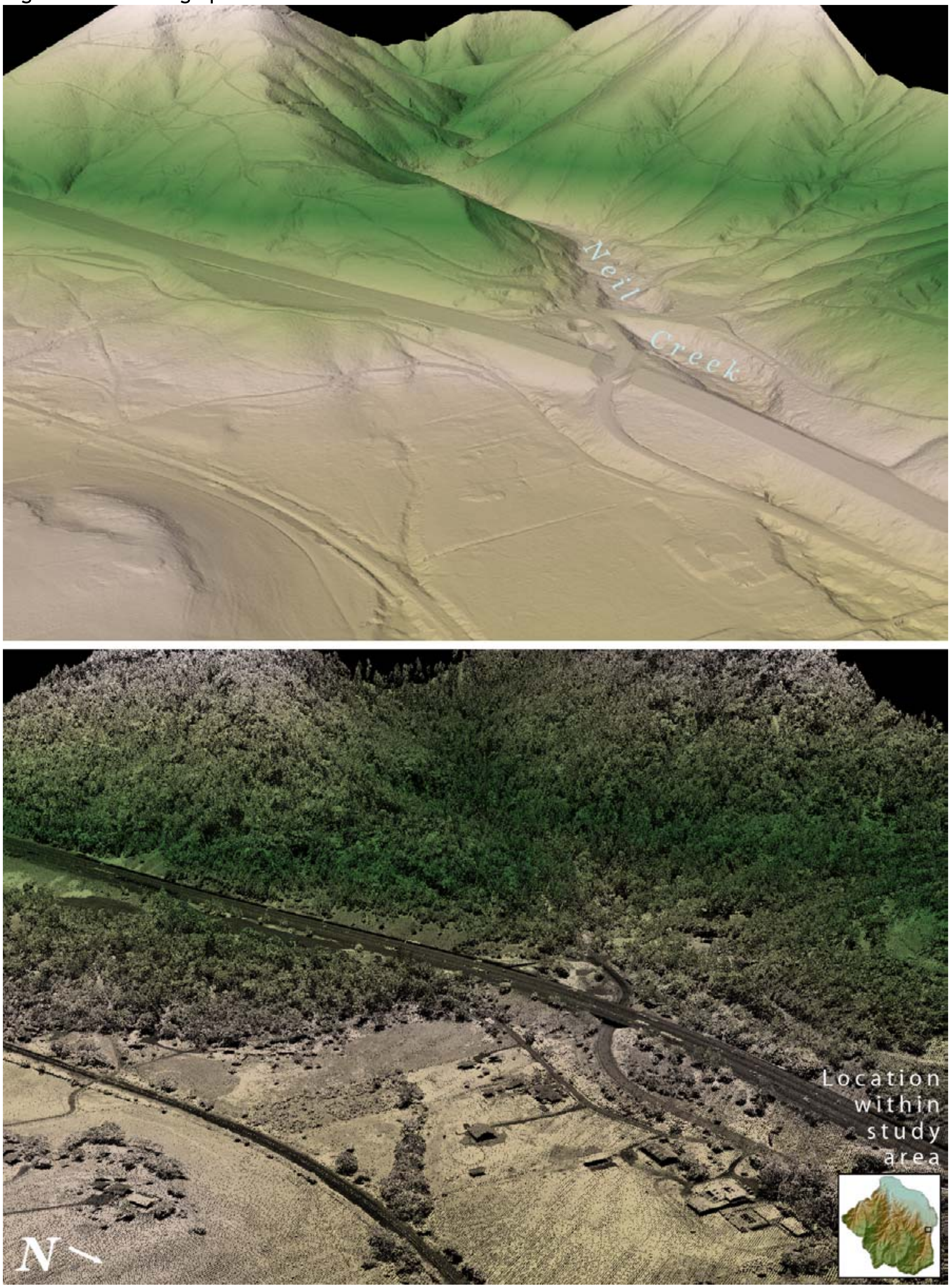


Figure 9. This image pair captures a forested reach in the upper portion of Neil Creek.

6. Glossary of Terms

- **Pulse Repetition Frequency (PRF)**: The rate at which lasers are emitted from the sensor; typically measured as pulses per second (kHz).
- **Pulse Returns**: For every laser emitted, our 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. This 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 line of flight.
- **Scan Angle**: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase beyond 15˚.
- **Overlap**: The area shared between flight lines, typically measured in percents; 100% overlap is essential to ensure complete coverage and reduce laser shadows.
- **Contours**: Lines that represent known elevations with intervals typically recorded in feet. It is standard practice to develop minimum contour intervals with data that have two sigma accuracy.
- **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.

7. Citations

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