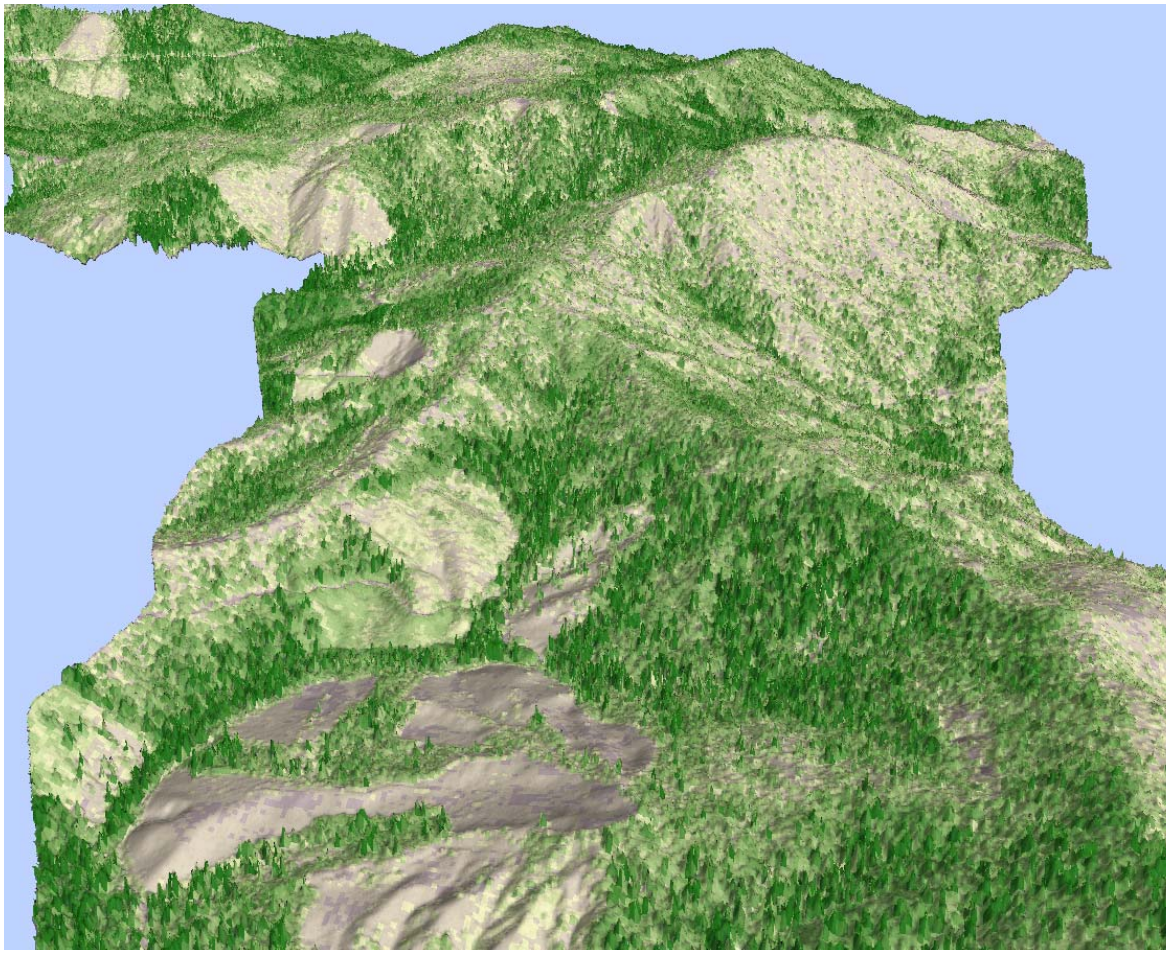
LiDAR Remote Sensing Data Collection
Biscuit Fire Study Area, Oregon



Oblique view in the Biscuit Fire Study Area: Above Ground ESRI Grid (1-meter resolution) derived from all LiDAR points

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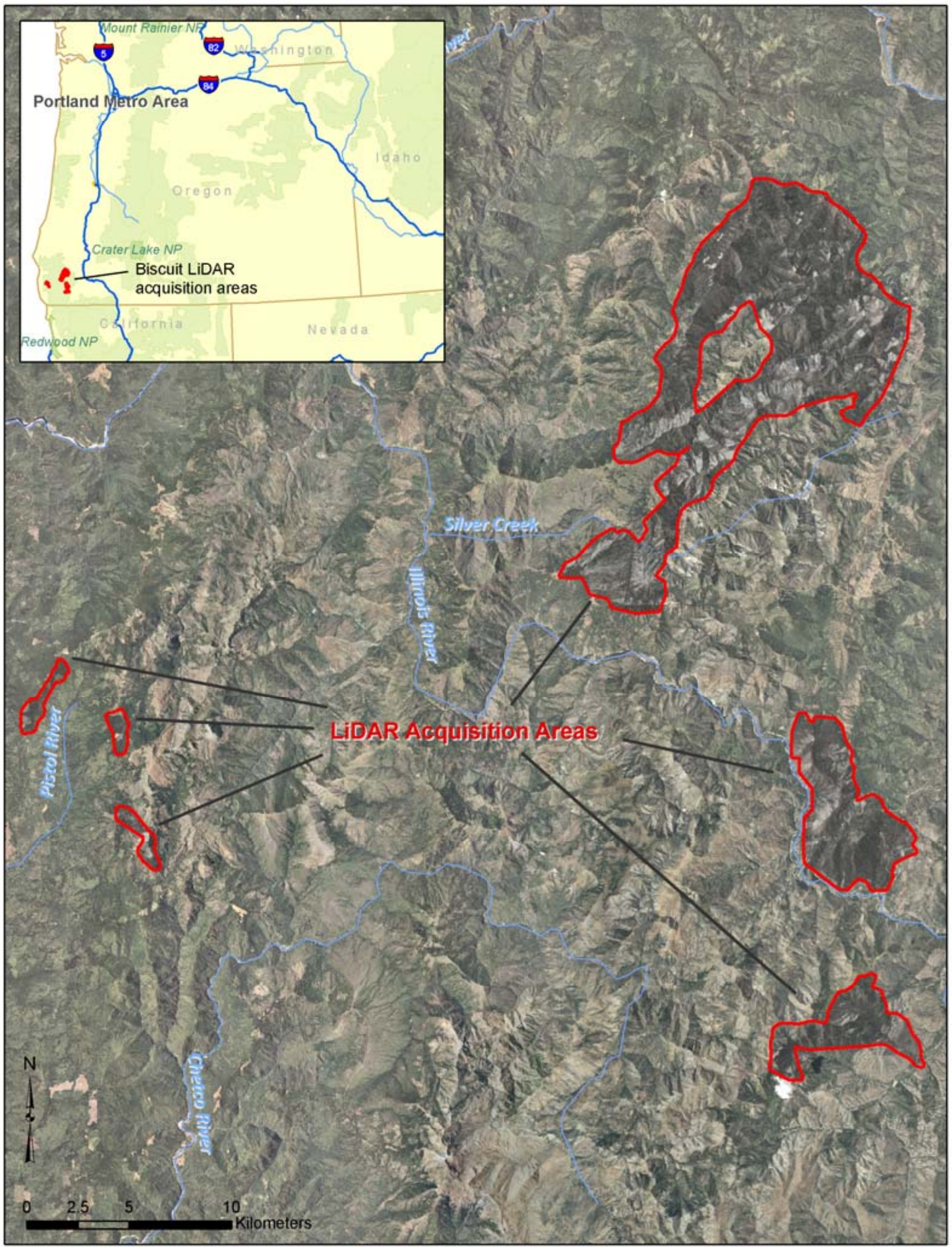
1. Overview

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data for the USDA Forest Service on September 19-23, 2007. The Areas of Interest (AOIs) collectively cover 36,837 acres (6 sites) within the Biscuit Fire region of Southwest Oregon (Figure 1). The overriding objective of the LiDAR acquisition was to provide accurate vegetation and bare earth terrain models to be used in the evaluation of landscape patterns on forestland affected by the fire of July, 2002.

Figure 1. Area of Interest (36,837 acres)



2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

The full survey was conducted on September 19-23, 2007 (Julian Days 262-266). The LiDAR survey uses a Leica ALS50 Phase II laser mounted in a Cessna Caravan 208B. The sensor scan angle was ±14° from nadir[1] with a pulse rate designed to yield an average native density (number of pulses emitted by the laser system) of ≥ 4 points per square meter over terrestrial surfaces. The Leica ALS50 Phase II system allows up to four range measurements (returns) per pulse, and all discernable laser returns are processed for the output dataset. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses than the laser originally emitted. These discrepancies between 'native' and 'delivered' density will vary depending on terrain, land cover and the prevalence of water bodies.

To accurately solve for laser point position (geographic coordinates x, y, z), the positional coordinates of the airborne sensor and the attitude of the aircraft are recorded continuously throughout the LiDAR data collection mission. Aircraft position is 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). To allow for post-processing correction and calibration, aircraft/sensor position and attitude data are indexed by GPS time.

2.2 Ground Survey – Instrumentation and Methods

The following ground survey data are collected to enable the geo-spatial correction of the aircraft positional coordinate data collected throughout the flight, and to allow for quality assurance checks on final LiDAR data products.

2.2.1 Survey Control

Simultaneous with the airborne data collection mission, we conduct a static (1 Hz recording frequency) survey of the horizontal and vertical positions of one or more survey control base stations established over monuments with known coordinates. Indexed by time, these GPS data are used to correct the continuous onboard measurements of aircraft position recorded throughout the mission. Multiple sessions are processed over the same monument to confirm antenna height measurements and reported position accuracy. After the airborne survey, these static GPS data are processed using triangulation with Continuously Operating Reference Stations (CORS) stations, and checked against the Online Positioning User Service (OPUS[2]) to quantify daily variance. Controls are located within 13 nautical miles of the mission 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".
[2] Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

Survey control coordinates for the Biscuit Fire Study Area are listed in Table 1.

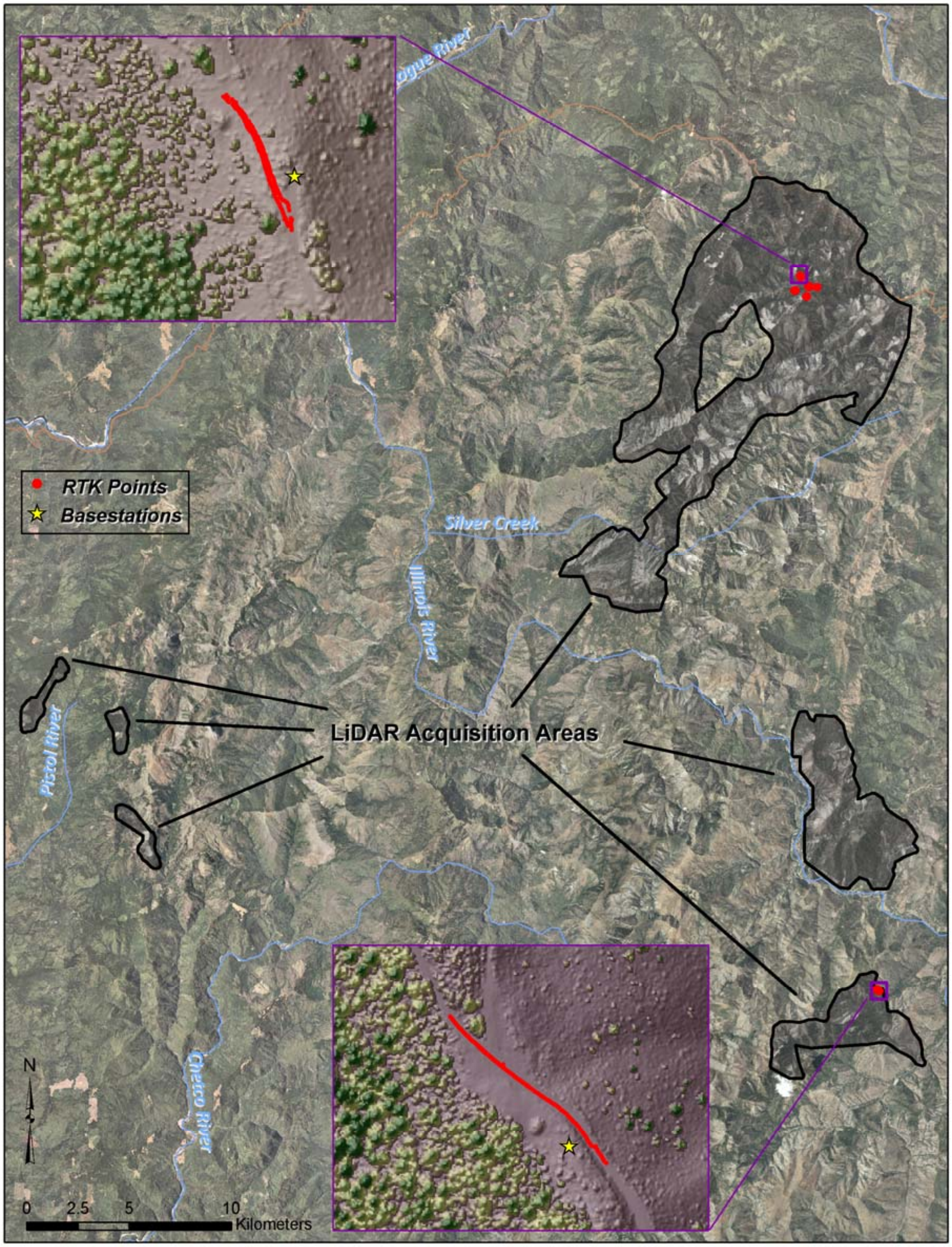
Table 1. Base Station Survey Control Coordinates for the Biscuit Fire Study Area.

	Datum NAD83 (CORS 96)		GRS80
Base Station ID	**Latitude (North)**	**Longitude (West)**	**Ellipsoid Height (m)**
BCJR1	42° 34' 0.69792"	123° 46' 50.55745"	1269.692
BCJR2	42° 34' 0.23707"	123° 46' 50.34025"	1270.315
BCJR3	42° 15' 10.45641"	123° 43' 50.89041"	928.365
BCJR4	42° 15' 10.15893"	123° 43' 50.85717"	929.402
BCJR5	42° 23' 53.55850"	124° 12' 53.67403"	1022.742

2.2.2 RTK Surveying

Ground truth points are collected using a GPS based real-time kinematic (RTK) survey. For an RTK survey, the ground crew uses a roving unit to receive radio-relayed corrected positional coordinates for all ground points from a GPS base unit set up over a survey control monument. The roving unit records precise location measurements with an error (σ) of ≤ 1.5 cm (0.6 in). 673 RTK ground points were collected in the Biscuit Fire Study Area (see **Figure 2**).

Figure 2. RTK and base station locations for study area. RTK detail view shown over 1-meter LiDAR highest hit hillshade with NAIP 2005 as background. Red dots represent the 673 RTK ground points used for the LiDAR point accuracy assessment.



3. LiDAR Data Processing, Accuracy, and Resolution

3.1 Work Flow Overview and Applications

Aircraft Kinematic GPS and IMU Data

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 post-processed aircraft position with attitude data. Sensor heading, position, and attitude are calculated throughout the survey.

   Software: IPAS v.1.0

Laser Point Processing

3. Calculate laser point position by associating 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 subset bins (less than 500 MB, to accommodate file size constraints in processing software). Filter for noise and perform manual relative accuracy calibration. Ground points are then classified for individual flight lines to be used for relative accuracy testing and calibration.

   Software: TerraScan v.6.009

LiDAR Accuracy Assessment

5. Test relative accuracy using ground classified points per each flight line. Perform automated line-to-line calibrations 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. Import position and attitude data. Classify ground and non-ground points. Assess statistical absolute accuracy via direct comparisons of ground classified points to ground RTK survey data. Convert data to orthometric elevations (NAVD88) by applying a Geoid03 correction. Create ground model as a triangulated surface and export as ArcInfo ASCII grids at the specified pixel resolution.

   Software: TerraScan v.6.009, ArcMap v9.2

3.2 Aircraft Kinematic GPS and IMU Data

LiDAR survey datasets are referenced to the 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 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 x, y, z coordinates 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 for subsequent processing. 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 area and positional accuracy of the laser points.

Laser point data are imported into processing bins in TerraScan, and manually calibrated to assess the system offsets for pitch, roll, heading and scale (mirror flex). Using a geometric relationship developed by Watershed Sciences, each of these offsets is resolved and corrected if necessary.

LiDAR points are then filtered for noise, artificial low points ('pits') or non-terrestrial high points (e.g., birds, clouds, vapor, haze) by screening for absolute elevation limits, isolated points and height above ground. Each bin is then inspected for remaining spurious points which are then manually removed. In 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.

Where there is dense vegetation and/or at breaks in terrain, steep slopes and at bin boundaries, the delivered density can be significantly less than the native density. In areas where it is determined that the ground surface model has failed, supervised classifications are performed by 'reseeding' the ground surface model with gound points.

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 scale). Automated sensor attitude and scale corrections yield 3-5 cm improvements in the relative accuracy. Once system misalignments are corrected, vertical GPS drift is then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy.

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 to improve ground detail. This manual editing of ground occurs in areas with known ground modeling deficiencies, such as bedrock outcrops, cliffs, deeply incised stream banks, and dense vegetation. In some cases, automated ground point classification includes known vegetation (i.e., understory, low/dense shrubs, etc.). These points are manually reclassified as non-ground. 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), supervised classifications are performed by 'reseeding' the ground model. Ground surface rasters are developed from triangulated irregular networks (TINs) of ground points.

3.4 LiDAR Accuracy Assessment

Quality assurance for LiDAR datasets uses data from the real-time kinematic (RTK) ground survey conducted in the study area. Absolute accuracy assessments compare known RTK ground survey points to the closest laser points. The vertical accuracy of the LiDAR data is described as the mean and standard deviation (sigma ~ σ) of divergence of LiDAR point coordinates from RTK ground survey point coordinates. To provide a sense of the model predictive power of the dataset, we also calculate the root mean square error (RMSE) for vertical accuracy. These statistics assume the error distribution for x, y, and z are normally distributed, thus we also consider the skew and kurtosis of distributions when evaluating error statistics. Statements of statistical accuracy apply to fixed terrestrial surfaces only. In this project, a total of 673 RTK GPS measurements were collected on asphalt points distributed among multiple flight swaths.

Laser point absolute accuracy is largely a function of laser noise and relative accuracy. Prior to evaluations of accuracy, however, we perform a number of noise filtering and calibration procedures to minimize these sources of error.

3.4.1 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. Typical laser noise evaluated over multiple projects has been approximately 2 cm.

3.4.2 Relative Accuracy

Relative accuracy refers to the internal consistency of the data set - the ability to place a laser point in the same location over multiple flight lines, GPS conditions, and aircraft attitudes. Affected by system attitude offsets, scale, and GPS/IMU drift, internal consistency 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). See Appendix A for further information on sources of error and operational measures that can be taken to improve relative accuracy.

Calibration for relative accuracy is typically performed in the following sequence:

1. <u>Manual System Calibration:</u> 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. System misalignment offsets (pitch, roll and heading) and scale are solved for each individual mission and applied to respective mission datasets. 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 used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration is the final step employed for relative accuracy calibration.

4. Study Results

Summary statistics for point resolution and accuracy (relative and absolute) of the LiDAR data collected in the Biscuit Fire Study Area are presented below in terms of central tendency, variation around the mean, and the spatial distribution of the data (for point resolution by bin). All resulting parameters met or exceeded the specifications of the contract.

4.1 Data Summary

Table 2. Resolution and Accuracy - Specifications and Achieved Values

	Targeted	Achieved
Resolution:	$\geq$ 8 points/m^2	8.59 points/m^2
Vertical Accuracy (1 σ)	<13 cm	0.007 m (7 cm)

4.2 Data Density/Resolution

Data Resolution for the Biscuit Fire Study Area:

- Average Point (First Return) Density = 8.59 points/m^2
- Average Ground Point Density = 0.96 points/m^2

Figure 3. Density distribution for first return laser points.

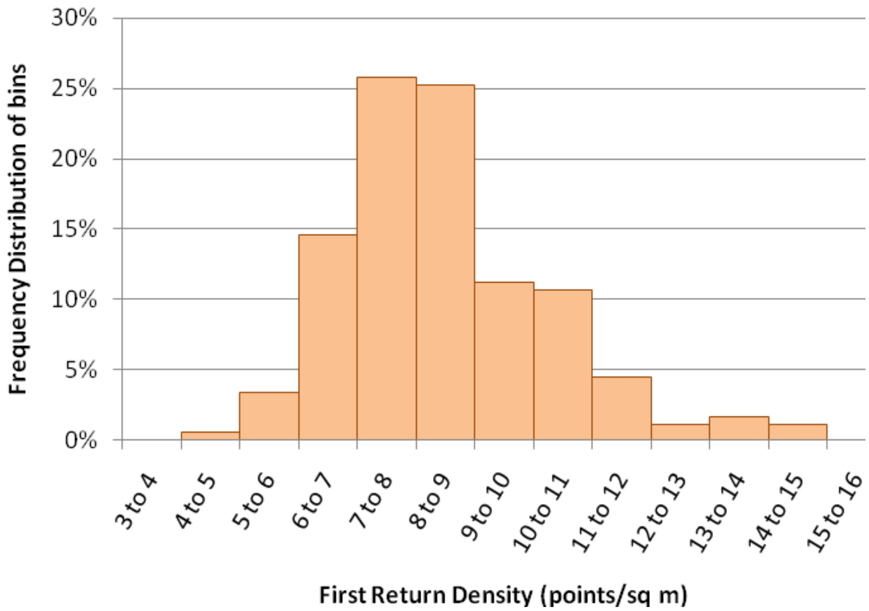


Figure 4. Density distribution for ground-classified laser points.

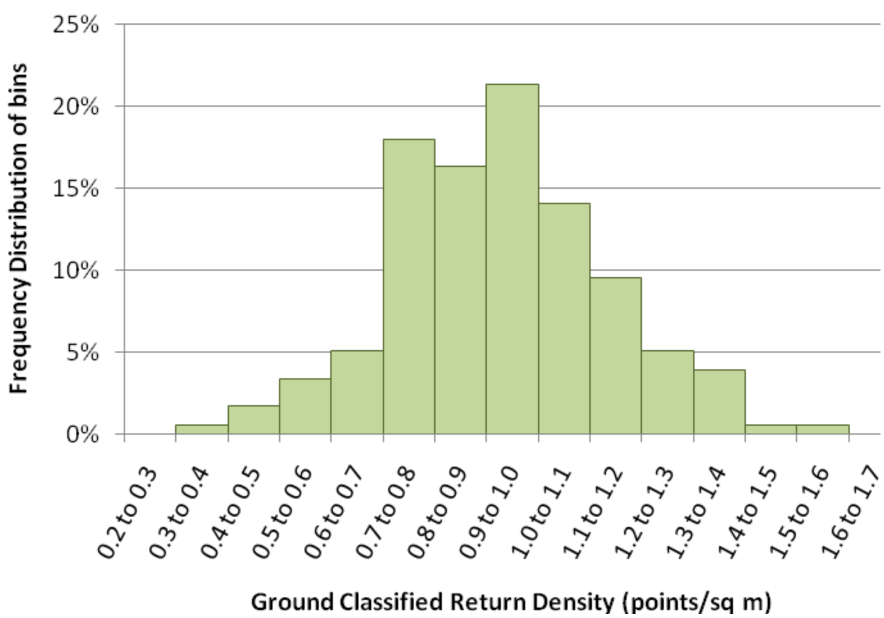
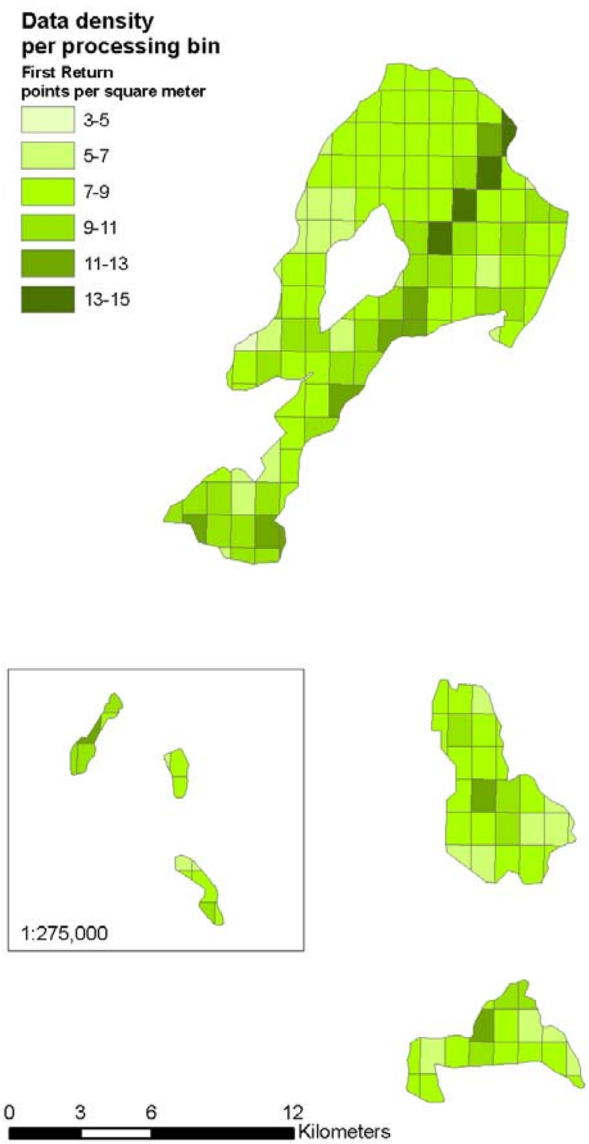
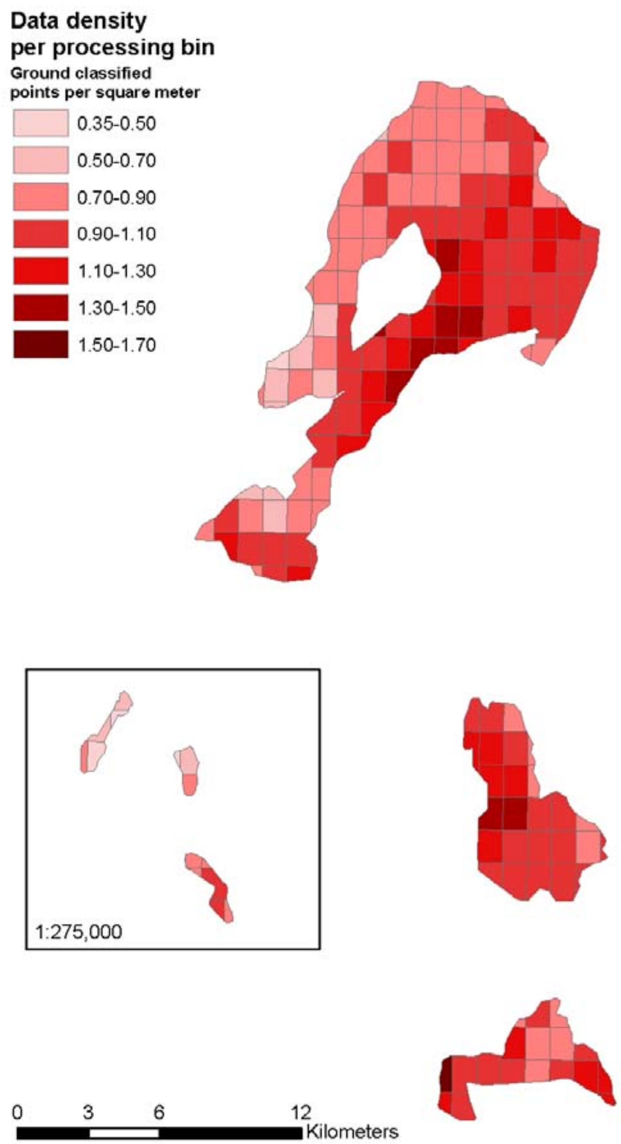


Figure 5. First return and ground-classified data density in the study area, per processing bin.





4.3 Relative Accuracy (Internal Consistency) Calibration Results

Relative accuracies for the Biscuit Fire Study Area:

- o Project Average = 0.6 cm
- o Median Relative Accuracy = 0.5 cm
- o 1σ Relative Accuracy = 0.7 cm
- o 2σ Relative Accuracy = 1.4 cm

Figure 6. Statistical relative accuracies, non slope-adjusted.

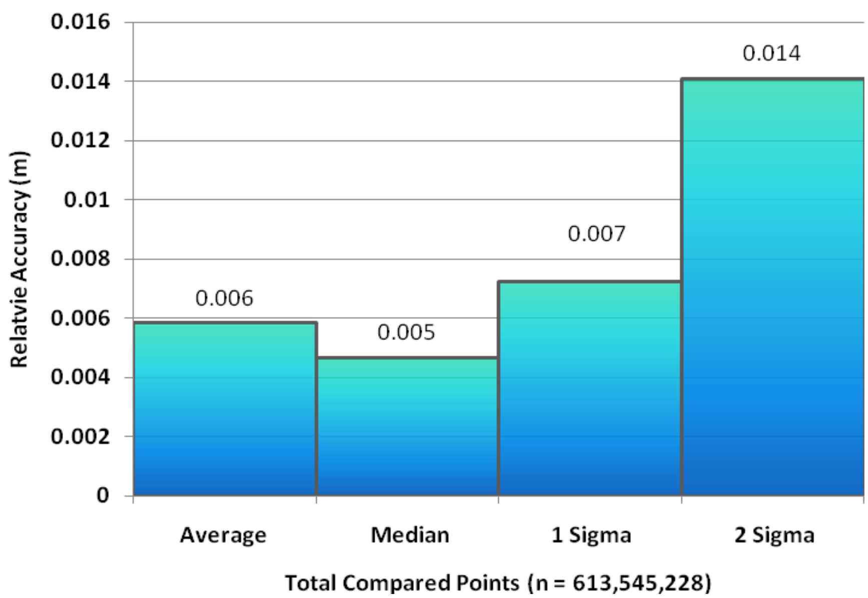
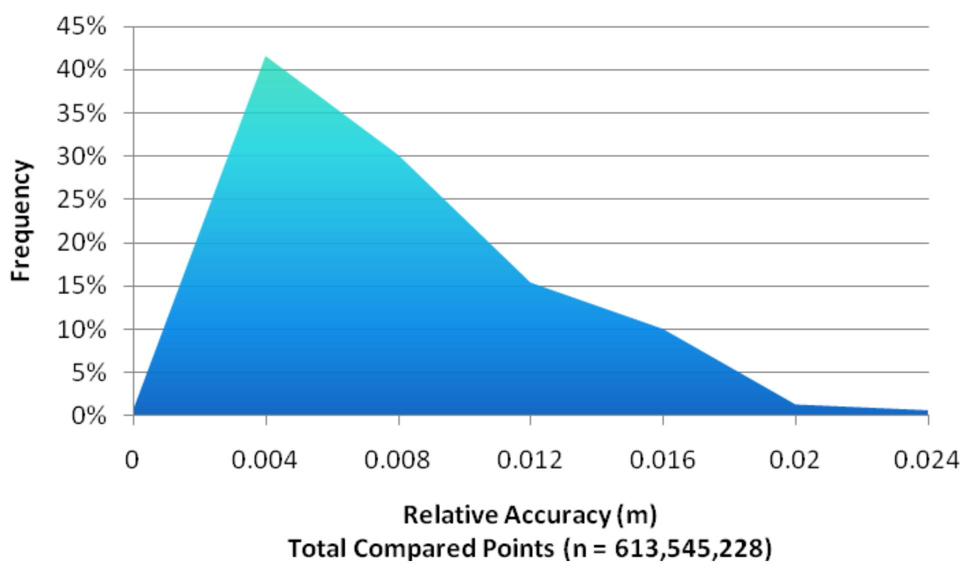


Figure 7. Distribution of relative accuracies per flight line, non slope-adjusted.



4.4 Absolute Accuracy

Table 3. Absolute Accuracy – Deviation between laser points and RTK survey points.

RTK Survey Sample Size (n): 673	
Root Mean Square Error (RMSE) = 0.04 m (4 cm)	Average Δz = -0.005 m (-0.5 cm)
Standard Deviations 1 sigma (σ) = 3.9 cm 2 sigma (σ): 8.2 cm	Minimum Δz = -0.113 m (-11.3 cm) Maximum Δz = 0.101 m (10.1 cm)

Figure 8. Absolute Accuracy **-** Histogram Statistics, based on asphalt points

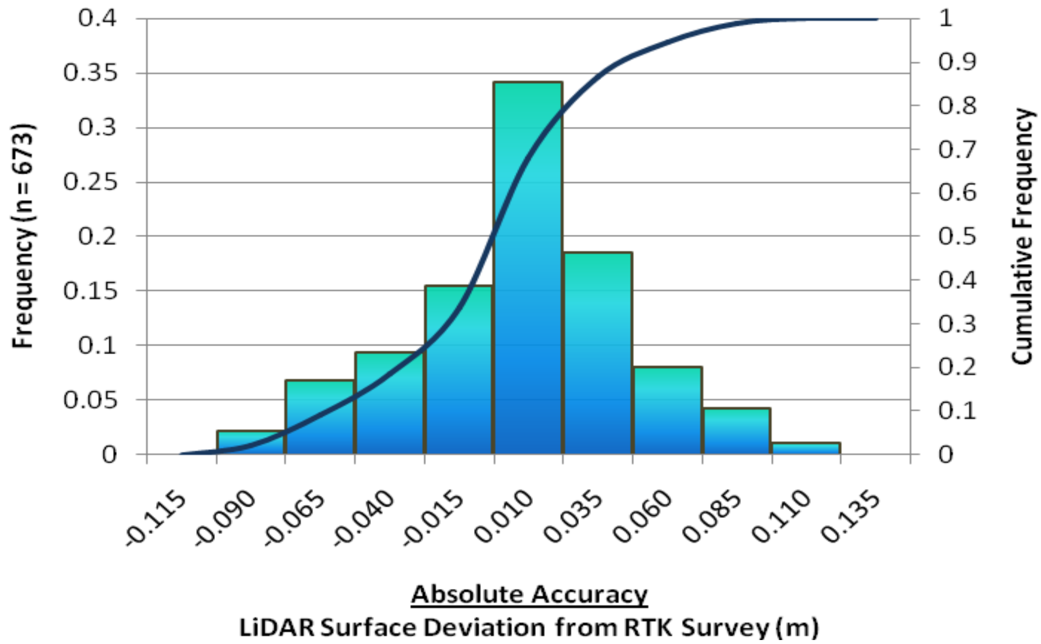
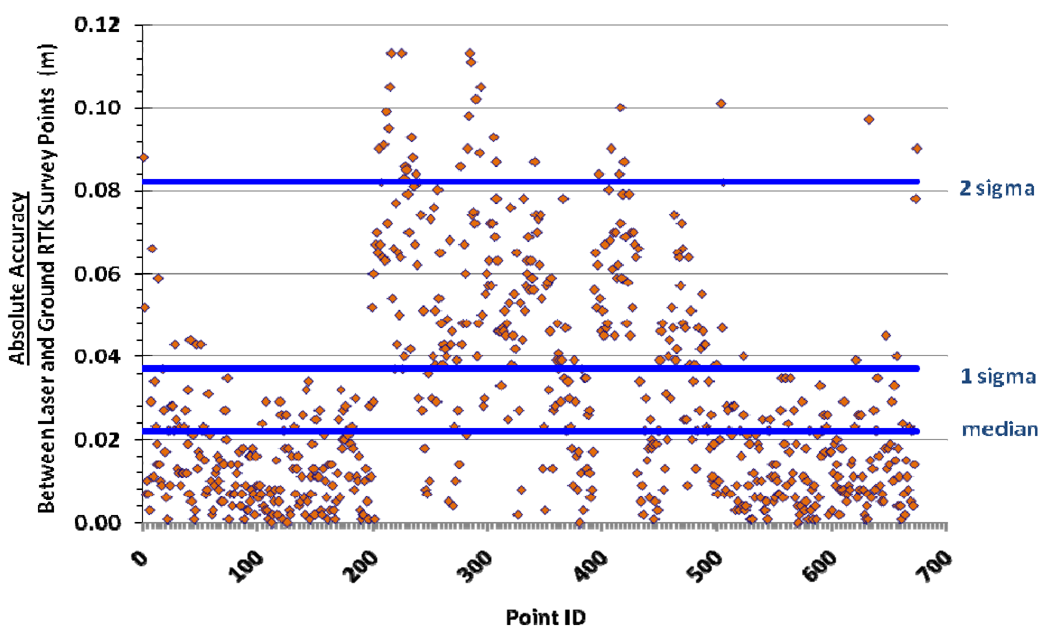


Figure 9. Absolute Accuracy - Absolute Deviation, based on asphalt points



4.5 Projection/Datum and Units

Table 4. Projection, Datum and Units

Projection:		UTM Zone 10 North
Datum	**Vertical:**	NAVD88 Geoid03
	Horizontal:	NAD83
Units:		Meters

5. Deliverables

Point Data:	**Delivered in 1/4th (3.75') USGS quad delineation:** • Ground Classified Points (ASCII text format) **Delivered in 1/100th (0.75') USGS quad delineation:** • All four laser returns with intensity values (Las v 1.1 and ASCII text format)
Raster Data:	**Delivered in 1/4th (3.75') USGS quad delineation:** • ESRI GRID of Bare Earth Modeled LiDAR data (1-meter resolution) • ESRI GRID of Highest Hit (First Return) Vegetation Surface Modeled LiDAR data (1-meter resolution) • ESRI GRID Vegetation Surface Model (1 meter resolution) • GeoTIFF of Laser Return Intensities (1 meter resolution)

Vector Data:	• Bin delineations of LiDAR points (shapefile format)
	  o 3.75' USGS quad delineation
	  o 0.75' USGS quad delineation
	• SBET (5Hz) with GPS time; X,Y,Z; and angular pitch, roll, heading in degrees

Reporting:	**In .pdf and .doc formats:**
	• Methods and Results
	• Accuracy Assessments
	  - Internal Consistency
	  - Absolute Accuracy Analysis
	• Metadata

6. Selected Images

Figure 10. Detail of Highest Hit and Bare Earth LiDAR DEM for a selected region of the Biscuit Fire Study Area (top image derived from all points, bottom image derived from ground-classified points).

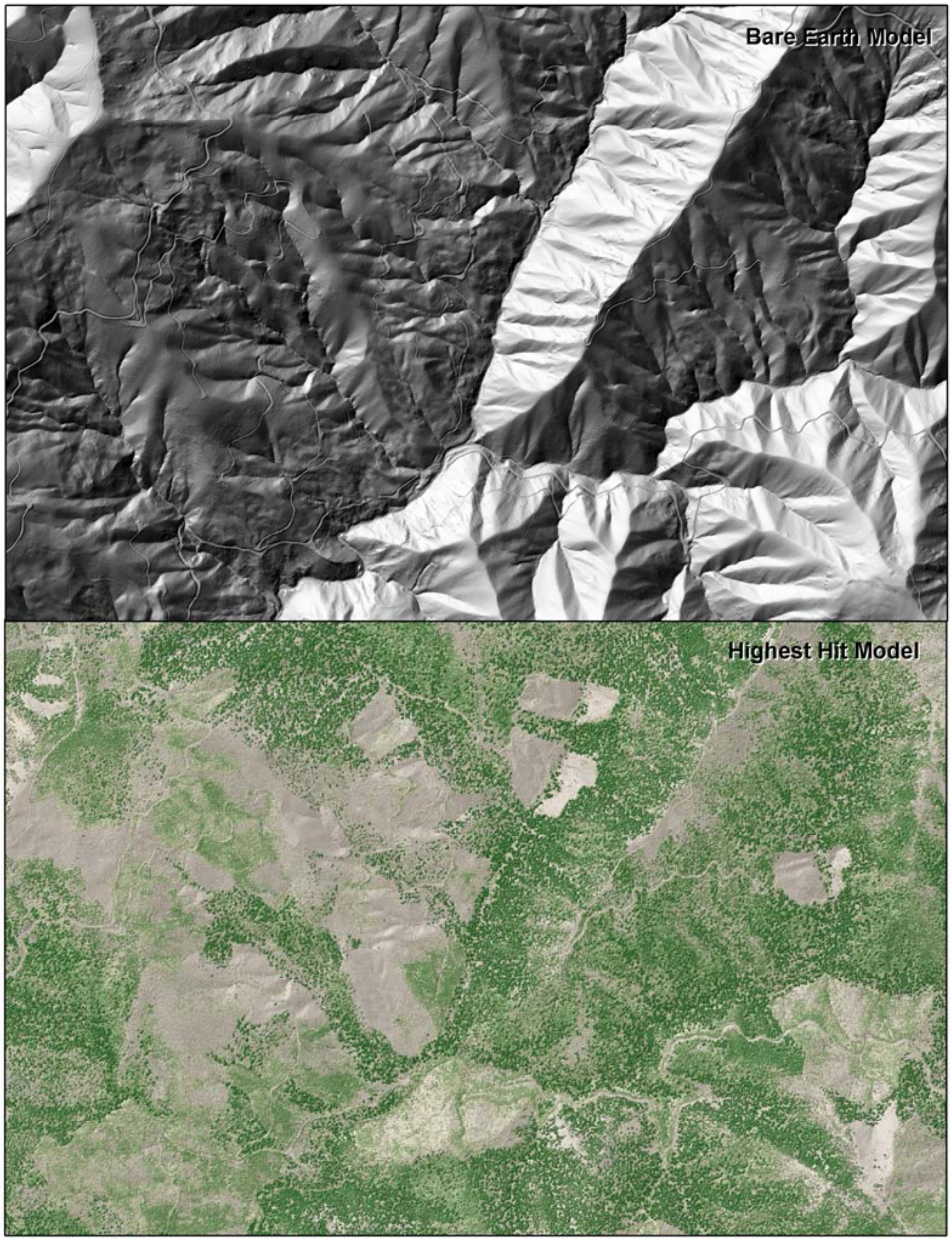
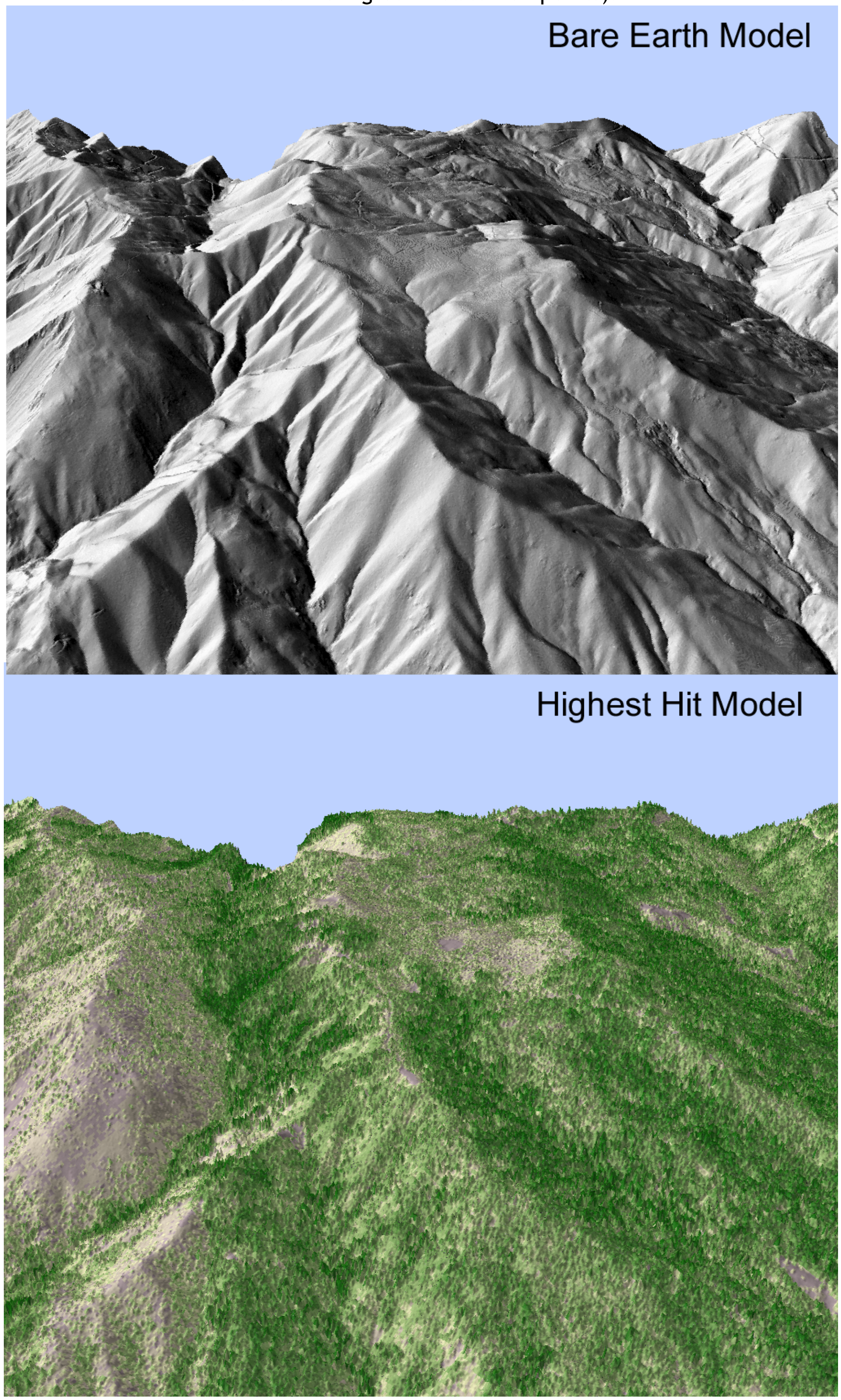


Figure 11. 3-d oblique view of LiDAR-derived surfaces (Top image derived from all points, bottom image derived from ground-classified points).



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, the Leica ALS 50 Phase II system can record *up to four* wave forms reflected back to the sensor. Portions of the wave form that return earliest are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

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

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

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

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

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

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

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

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Real-Time Kinematic (RTK) Survey: GPS surveying is conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

Citations

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

Appendix A

LiDAR accuracy error sources and solutions:

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

Operational measures taken to improve relative accuracy:

1. Low Flight Altitude: Terrain following is employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 1/3000th AGL flight altitude).
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 ±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. Ground survey RTK points are distributed to the extent possible throughout multiple flight lines and across the study area.
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.