LiDAR Remote Sensing Data Collection:
Glass Buttes, Oregon
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Submitted to:

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TABLE OF CONTENTS

1. Overview

1.1 Study Area

Watershed Sciences, Inc. collected Light Detection and Ranging data (LiDAR) of the Glass Buttes study area for ORMAT. The requested LiDAR Area of Interest (AOI) totals approximately 84,849 acres, and was buffered to ensure data coverage, resulting in a Total Area Flown (TAF) of 86,631 acres. This report reflects statistics for the overall LiDAR survey.

Figure 1.1. Glass Buttes study area, displayed over a 30-meter DEM.
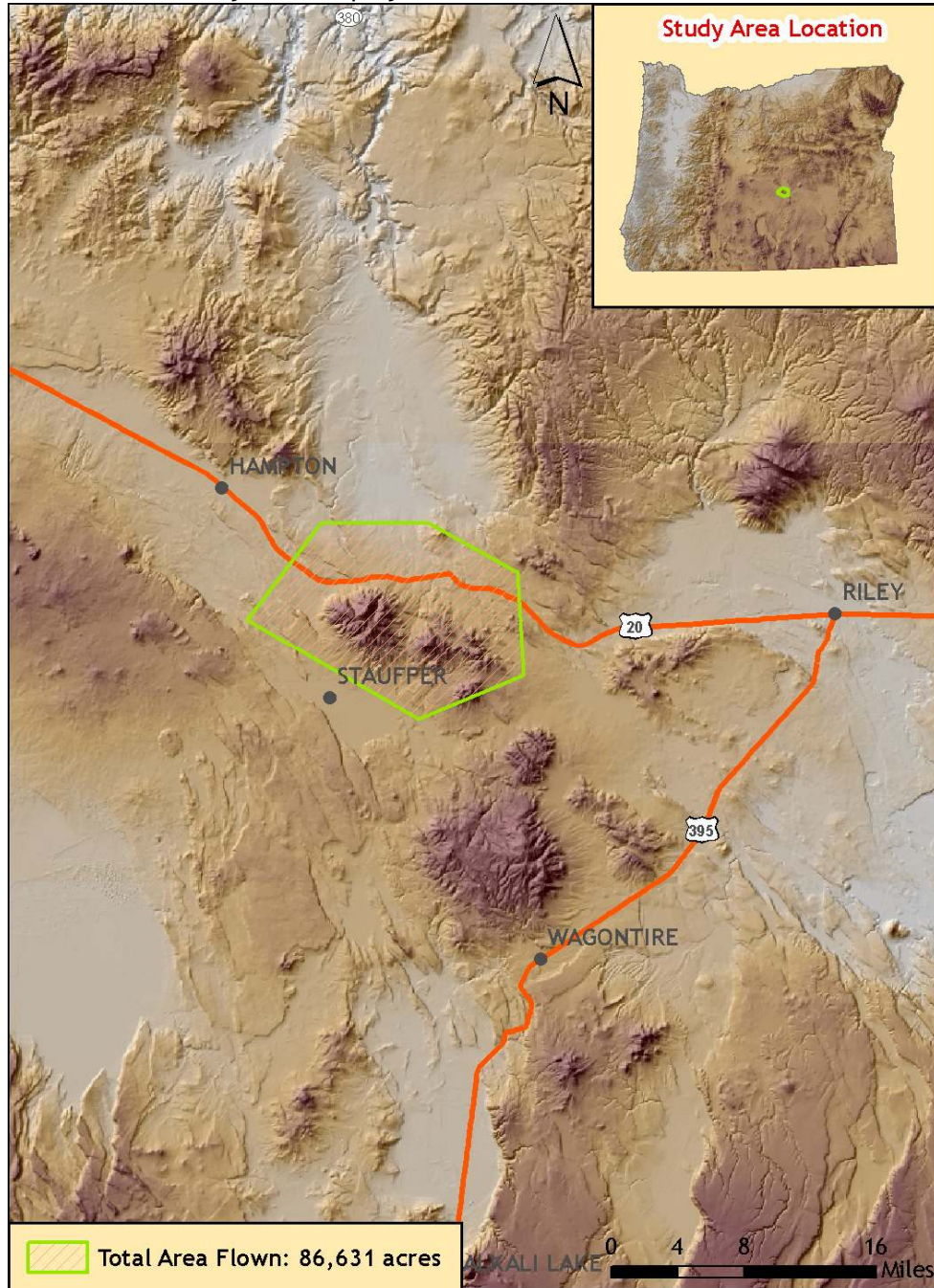
1.3 Accuracy and Resolution

Real-time kinematic (RTK) surveys were conducted in 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 Glass Buttes data have the following accuracy statistics:

RMSE	1-sigma absolute deviation	2-sigma absolute deviation
0.03 meter	0.02 meter	0.05 meter

Data resolution specifications are for ≥8 points per square meter. Total average and ground pulse density statistics Glass Buttes are as follows:

Total Pulse Density	Ground Pulse Density
9.26 points per square meter	2.02 points per square meter

1.4 Data Format, Projection, and Units

Glass Buttes data are delivered in UTM Zone 11; NAD83(HARN); NAVD88(Geoid 03). **Horizontal units are meters, vertical units are in meters.**

Deliverables include:

- All return point data in *.las v 1.2 format
- Ground classified point data in *.last v 1.2 format
- 1-meter resolution bare ground model ESRI GRID
- 1-meter resolution above ground model ESRI GRID
- 0.5-meter resolution intensity images in GeoTIFF format
- Shapefile of delivery area in 750 m x 750 m tile delineations
- Data Report summarizing data acquisition, processing, and summary statistics.

2. Acquisition

2.1 Airborne Survey Overview – Instrumentation and Methods

The LiDAR survey utilized a Leica ALS60 sensor mounted in Cessna Caravan 208B. The Leica ALS60 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] (see **Table 2.1**). These settings are developed to yield points with an average native pulse density of ≥8 points per square meter over terrestrial surfaces. Some types of surfaces (i.e., dense vegetation or water) may return fewer pulses than the laser originally emitted. Therefore, the delivered density can be less than the native density and vary according to distributions of terrain, land cover, and water bodies.

The Cessna Caravan is a powerful and stable platform, ideal for the mountainous terrain of the Pacific Northwest. The Leica ALS60 sensor head installed in the Caravan is shown on the right.

The area of interest 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, an accurate description of aircraft position and attitude is vital. Aircraft position is described as x, y, and z and measured twice per second (2 Hz) by an onboard differential GPS unit. Aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll, and yaw (heading) from an onboard inertial measurement unit (IMU).

Table 2.1 LiDAR Survey Specifications

Sensor	Leica ALS60
Survey Altitude (AGL)	900 m
Pulse Rate	>105 kHz
Pulse Mode	Single
Mirror Scan Rate	72 Hz
Field of View	28° (±14° from nadir)
Roll Compensated	Up to 20°
Overlap	100% (50% Side-lap)

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

2.2 LiDAR Acquisition

LiDAR data were collected for the Glass Buttes study area between May 8 and May 14, 2010. Flightlines are illustrated in the figure below.

Figure 2.1. *Flightlines displayed over a 30-meter DEM.*
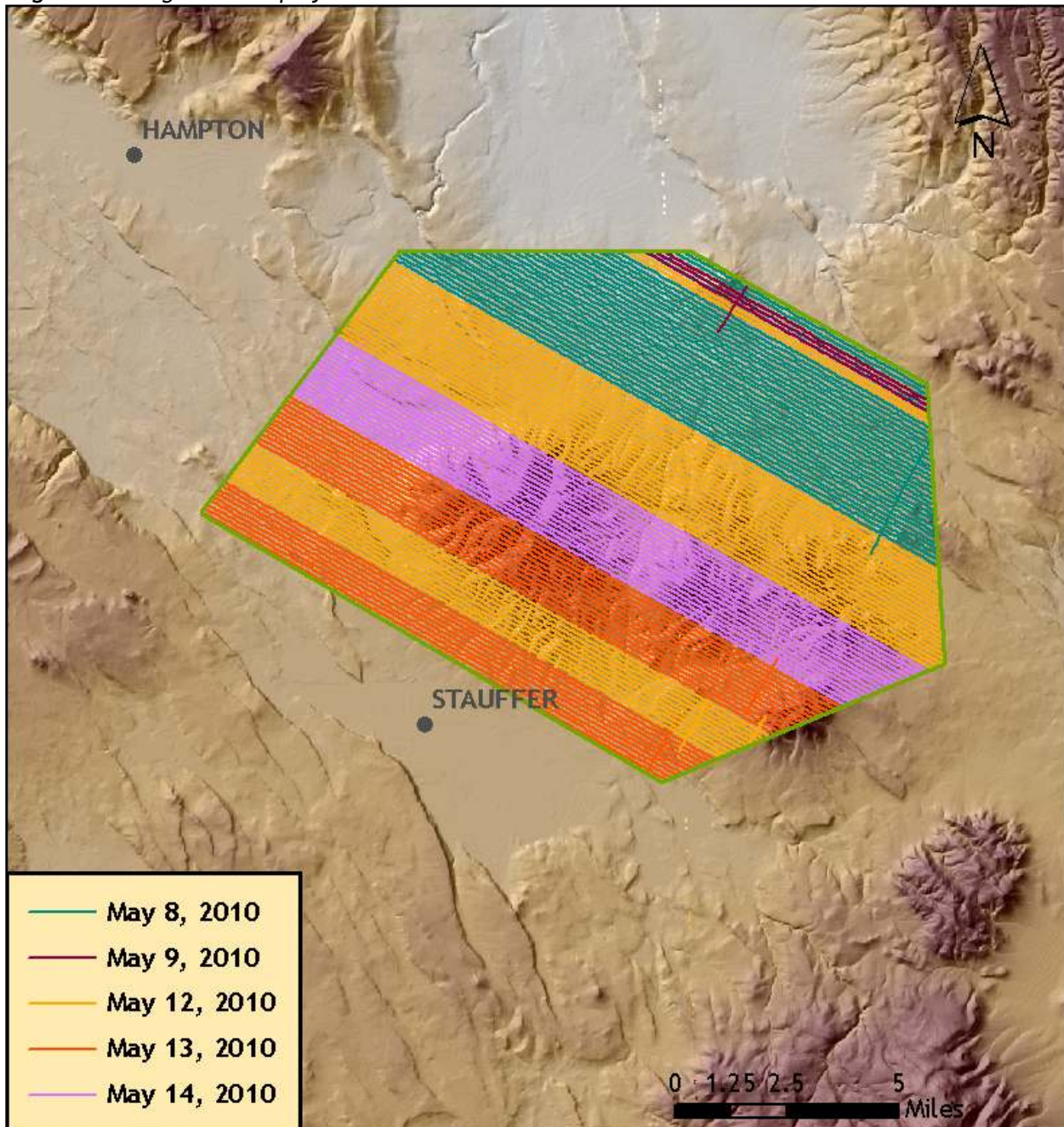
## 2.3 Ground Survey – Instrumentation and Methods

During the LiDAR survey, static (1 Hz recording frequency) ground surveys were conducted over monuments with known coordinates. Base station coordinates are provided in the table below. After the airborne survey, the static GPS data were processed using triangulation with CORS stations and checked against the Online Positioning User Service (OPUS[2]) to quantify daily variance. Multiple sessions were processed over each monument to confirm antenna height measurements and reported position accuracy. Base stations are listed in **Table 2.2** below and shown in **Figure 2.2**.

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

|	Datum NAD83(HARN)		GRS80
Base Station ID	**Latitude (North)**	**Longitude (West)**	**Ellipsoid Height (m)**
PA0519	43 35 24.51127	119 58 58.79200	1339.149
GB_RI1	43 34 07.55173	120 08 08.23125	1354.525
GB_RI2	43 34 08.32424	120 08 08.23902	1354.557
GB_RI3	43 33 02.18955	119 56 14.55878	1403.158

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

Figure 2.2. GPS base station locations in the Glass Buttes study area, displayed over a 30-meter DEM.

Trimble GPS survey equipment configured for static survey data.
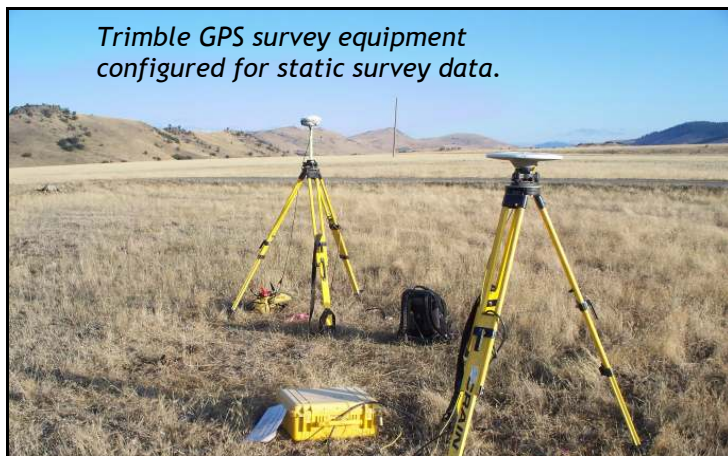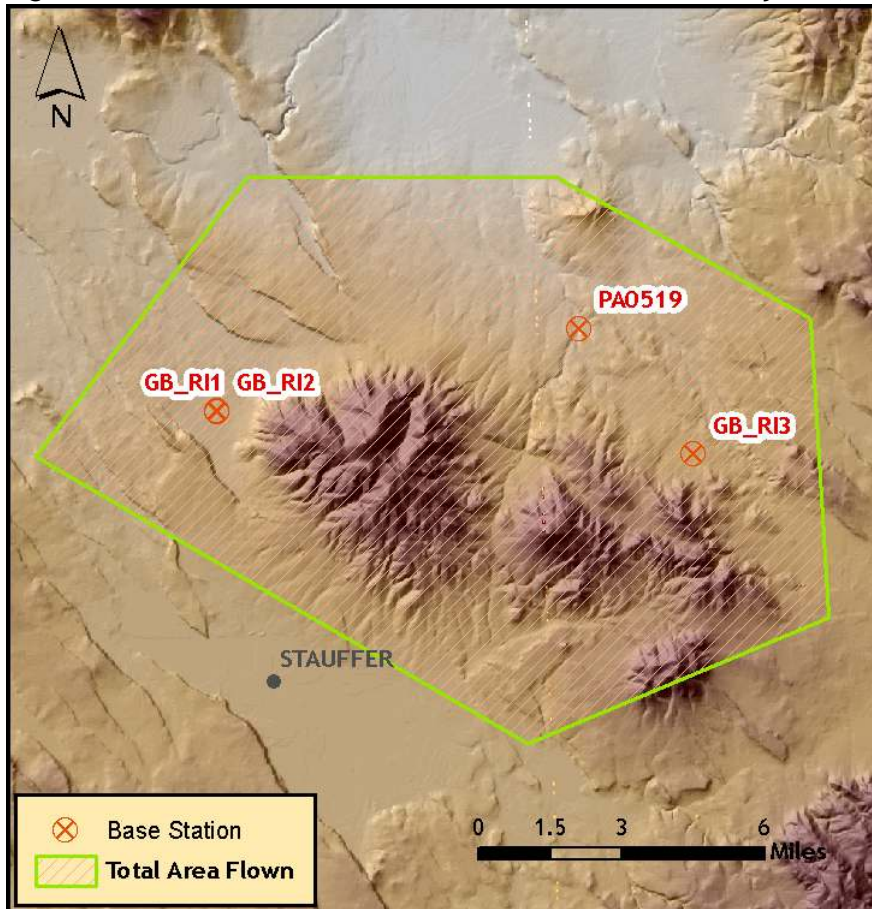
Multiple differential GPS units were used in the ground based real-time kinematic (RTK) portion of the survey. To collect accurate ground surveyed points, a GPS base unit was set up over monuments to broadcast a kinematic correction to a roving GPS unit. The ground crew used a roving unit to receive radio-relayed kinematic corrected positions from the base unit. This RTK survey allowed precise location measurement ($\sigma \leq 1.5$ cm). **Figure 2.3** shows a subset of these RTK locations.

Figure 2.3. *Sample selection of RTK point locations in the study area, displayed over NAIP orthoimages.*
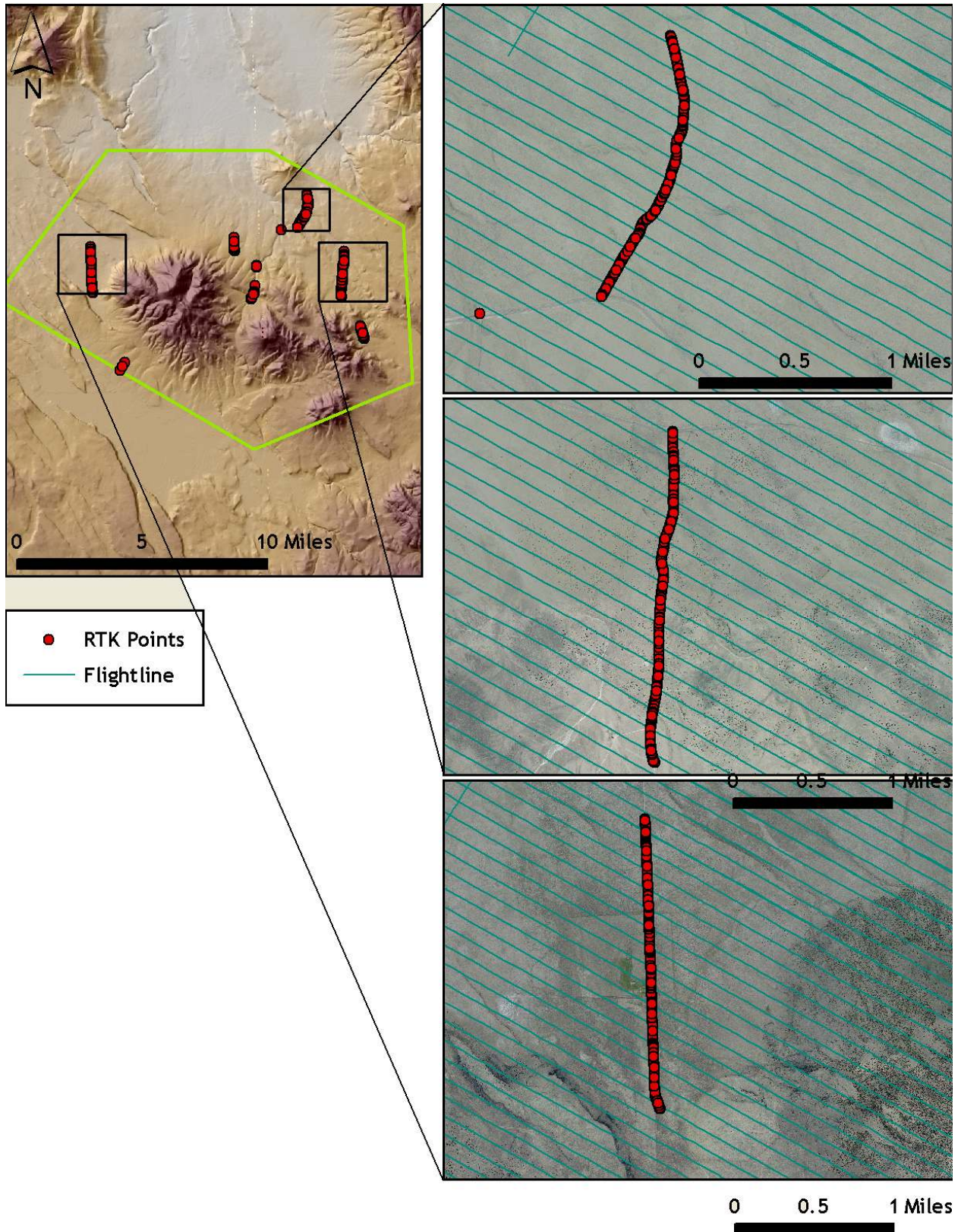
3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolved kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.
   Software: Waypoint GraphNav v.8.10, Trimble Geomatics Office v.1.63

2. Developed a smoothed best estimate of trajectory (SBET) file blending post-processed aircraft position with attitude data. Sensor head position and attitude were calculated throughout the survey. The SBET data were used extensively for laser point processing.
   Software: IPAS Pro v.1.3

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

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

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

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

3.2 Aircraft Kinematic GPS and IMU Data

LiDAR survey datasets were referenced to 1 Hz static ground GPS data collected over a pre-surveyed monument with known coordinates. While surveying, the aircraft collected 2 Hz kinematic GPS data and the inertial measurement unit (IMU) collected 200 Hz attitude data. Waypoint GraphNav v.8.10 was used to process the kinematic corrections for the aircraft. The static and kinematic GPS data were then post-processed after the survey to obtain an accurate GPS solution and aircraft positions. IPAS Pro v.1.3 was used to develop a trajectory file including corrected aircraft position and attitude information. The trajectory data for the entire flight survey session were incorporated into a final smoothed best estimated trajectory (SBET) file containing accurate and continuous aircraft positions and attitudes.

3.3 Laser Point Processing

Laser point coordinates were computed using the IPAS and ALS Post Processor software suites based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point returns (first through fourth) were assigned an associated (x, y, and z) coordinate along with unique intensity values (0-255). The data were output into large LAS v. 1.2 files; each point maintaining the corresponding scan angle, return number (echo), intensity, and x, y, and z (easting, northing, and elevation) information.

Flightlines and LiDAR data were then reviewed to ensure complete coverage of the study area and positional accuracy of the laser points.

Once the laser point data were imported into TerraScan, a manual calibration was performed to assess the system offsets for pitch, roll, heading and mirror scale. Using a geometric relationship developed by Watershed Sciences, each of these offsets was resolved and corrected if necessary.

The LiDAR points were then filtered for noise, pits and birds by screening for absolute elevation limits, isolated points and height above ground. The data were then inspected for pits and birds manually, and spurious points were removed. For a .las file containing approximately 7.5-9.0 million points, an average of 50-100 points were typically found to be artificially low or high. These spurious non-terrestrial laser points must be removed from the dataset. Common sources of non-terrestrial returns are clouds, birds, vapor, and haze.

Internal calibration was refined using TerraMatch. Points from overlapping lines were tested for internal consistency and final adjustments made for system misalignments (i.e., pitch, roll, heading offsets and mirror scale). Automated sensor attitude and scale corrections yielded 3-5 cm improvements in the relative accuracy. Once the system misalignments were corrected, vertical GPS drift was resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy. In summary, the data must complete a robust calibration designed to reduce inconsistencies from multiple sources (i.e., sensor attitude offsets, mirror scale, GPS drift).

The TerraScan software suite is designed specifically for classifying near-ground points (Soininen, 2004). The processing sequence 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 manually 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; lower flight altitudes decrease laser noise on all surfaces.
2. Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes maintained.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 14^o$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. Quality GPS: Acquisition occurred during optimal GPS conditions (e.g., 6 or more satellites and PDOP [Position Dilution of Precision] less than 3.0). 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 point was less than 24 km (13 nautical miles).
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.
6. 50% Side-Lap (100% Overlap): Overlapping areas were optimized for relative accuracy testing. Laser shadowing was minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the most nadir portion of one flight line coincides with the edge (least nadir) portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.
7. Opposing Flight Lines: All overlapping flight lines are opposing. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

Relative Accuracy Calibration Methodology

1. Manual System Calibration: Calibration procedures for each mission require solving geometric relationships relating measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration and reported for the study area.
2. Automated Attitude Calibration: All data were tested and calibrated using TerraMatch automated sampling routines. Ground points were classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and mirror scale were solved for each individual mission. Attitude misalignment offsets (and mirror scale) occurs for each individual mission. The data from each mission were then blended when imported together to form the entire area of interest.
3. Automated Z Calibration: Ground points per line were utilized to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Relative Accuracy Calibration Results

Relative accuracy statistics are based on the comparison of 117 flightlines and over 3 billion points. **Figures 4.1** and **4.2** show the distribution and the statistical analyses.

- o Project Average = 0.04 meters
- o Median Relative Accuracy = 0.03 meters
- o 1σ Relative Accuracy = 0.04 meters
- o 2σ Relative Accuracy = 0.05 meters

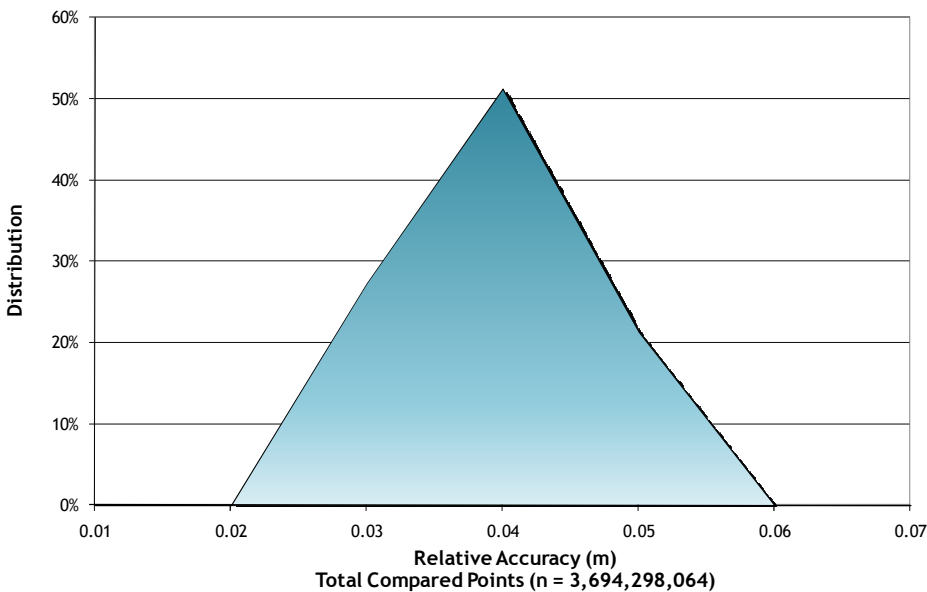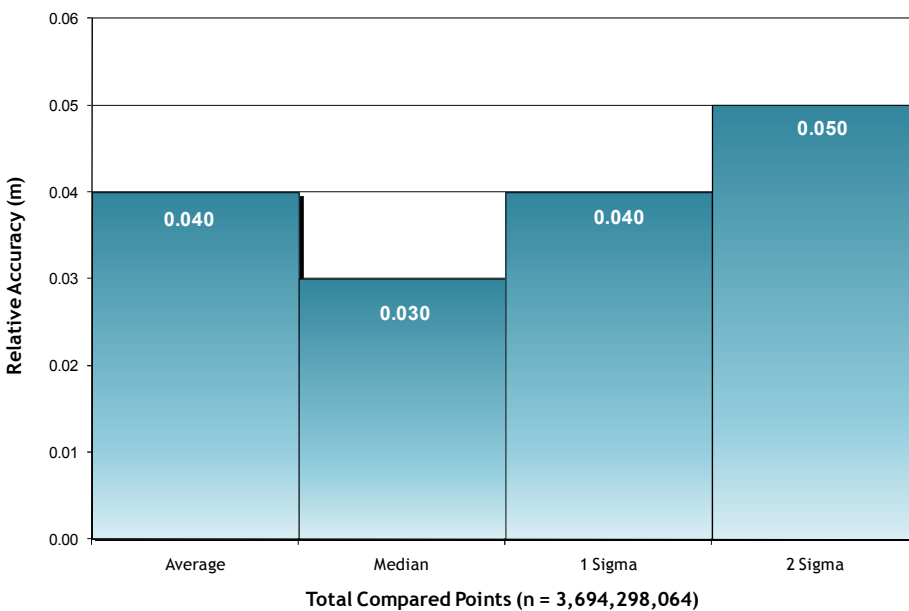***Figure 4.1***. *Distribution of relative accuracies, non slope-adjusted.*

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

4.1.2 Absolute Accuracy

Absolute accuracy compares known Real Time Kinematic (RTK) ground survey points to the closest laser point. For the Glass Buttes study area, 1,695 RTK points were collected. Absolute accuracy is reported in **Figure 4.3** and **4.4,** below.

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

Sample Size (n): 1,695	
Root Mean Square Error (RMSE): 0.03 m	
Standard Deviations	**Deviations**
1 sigma (σ): 0.02 m (0.06 ft)	**Minimum Δz:** -0.12 m (-0.39 ft)
2 sigma (σ): 0.05 m (0.16 ft)	**Maximum Δz:** 0.12 m (0.39 ft)
	Average Δz: 0.02 m (0.07 ft)

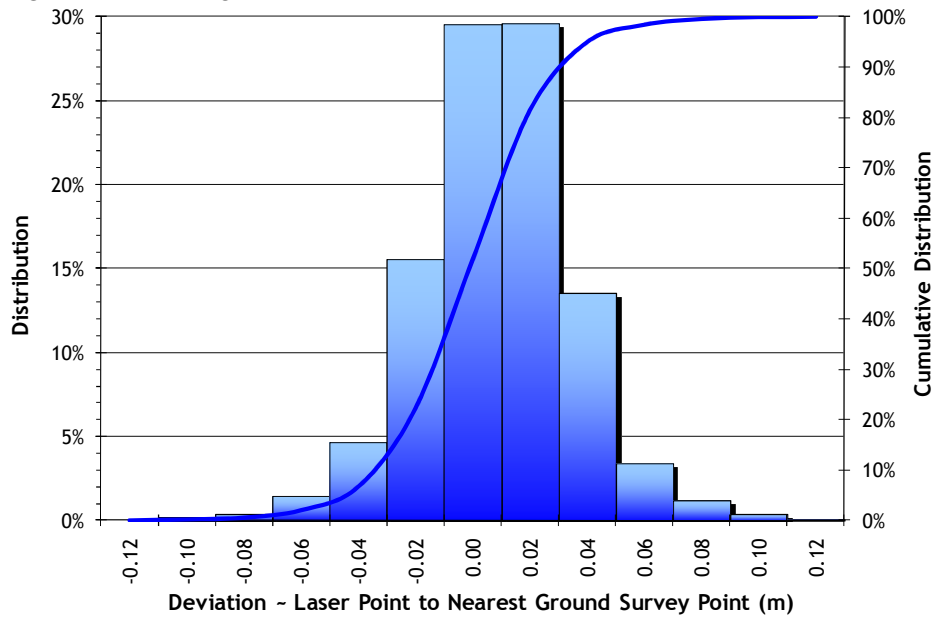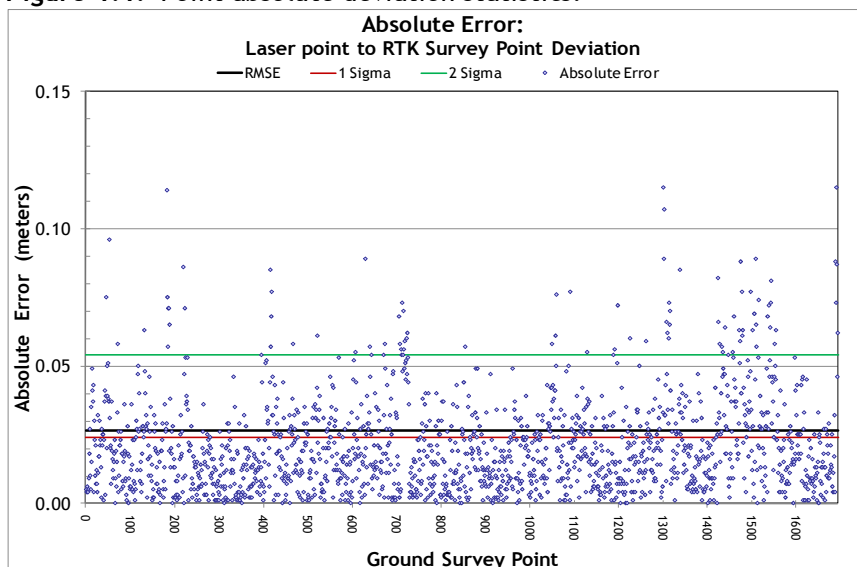*Figure 4.3*. *Histogram statistics.*

Figure 4.4. *Point absolute deviation statistics.*

4.2 Data Density/Resolution

Some types of surfaces (i.e., dense vegetation or water) may return fewer pulses than originally emitted by the laser.   Delivered density may therefore be less than the native density and vary according to distributions of terrain, land cover, and water bodies. Density histograms and maps (**Figures 4.5-4.8**) have been calculated based on first return laser point density and ground-classified laser point density.

Table 4.3. *Average densities.*

Average Pulse Density (per square m)	Average Ground Density (per square m)
9.26	2.02

4.2.1 First Return Data Density

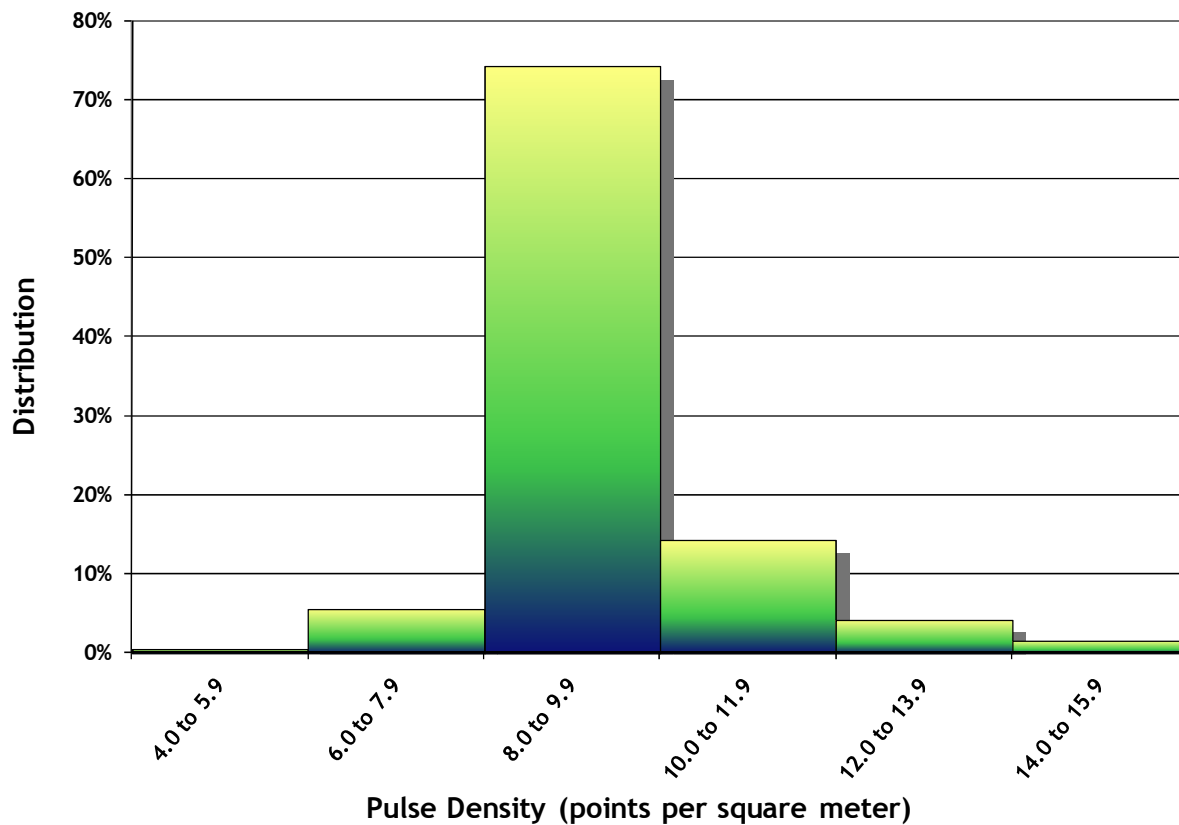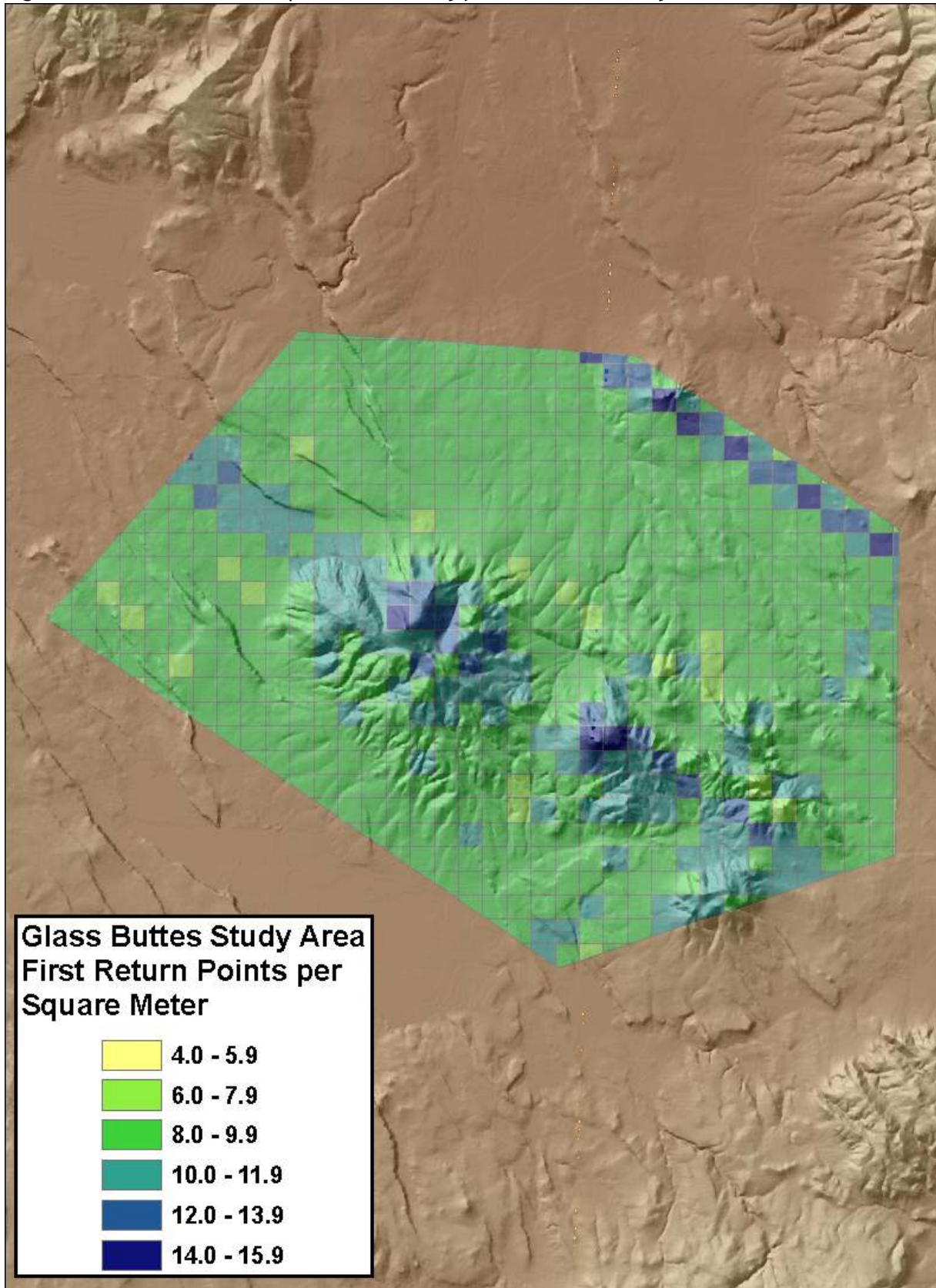*Figure 4.5*. *Histogram of first return laser point density for data Glass Buttes study area.*

Figure 4.6. *First return laser point data density for Glass Buttes study area.*

Glass Buttes Study Area
First Return Points per
Square Meter

	4.0 - 5.9
	6.0 - 7.9
	8.0 - 9.9
	10.0 - 11.9
	12.0 - 13.9
	14.0 - 15.9

4.2.2 Ground-Classified Data Density

Figure 4.7. Histogram of ground-classified laser point density for Glass Buttes study area.

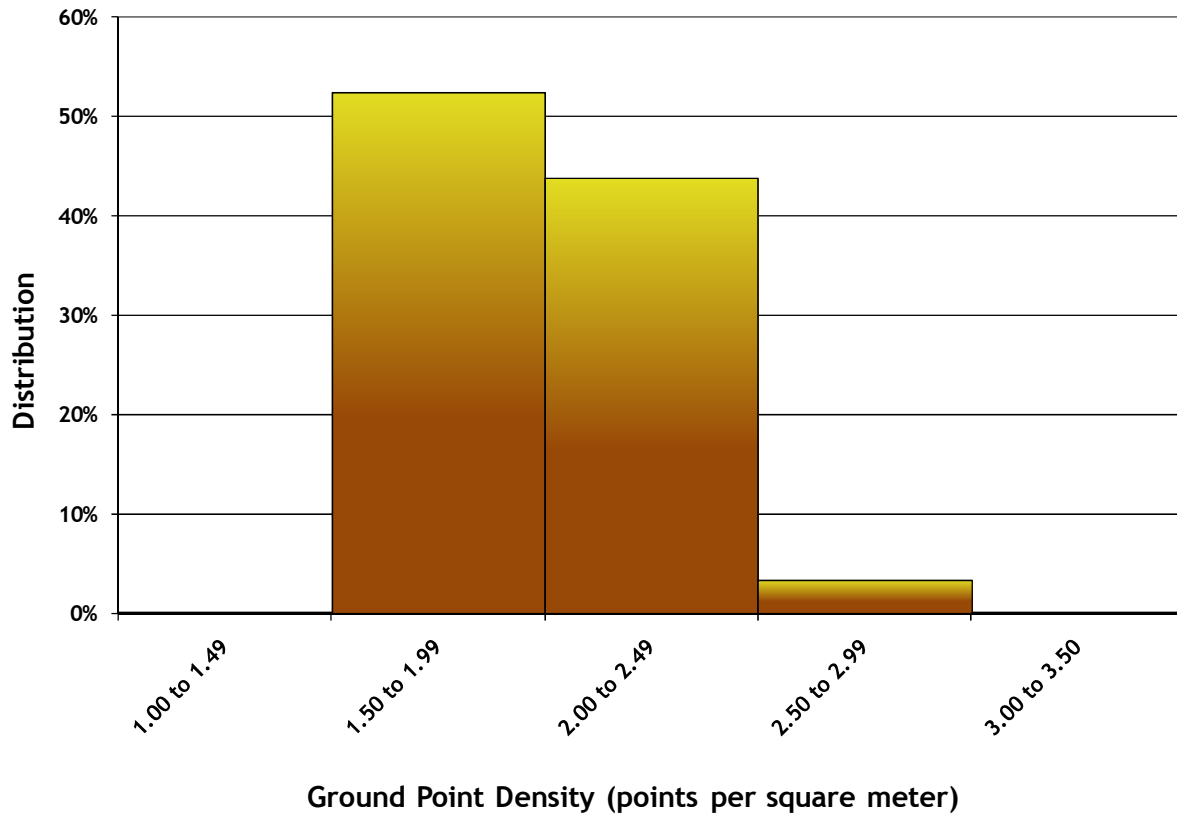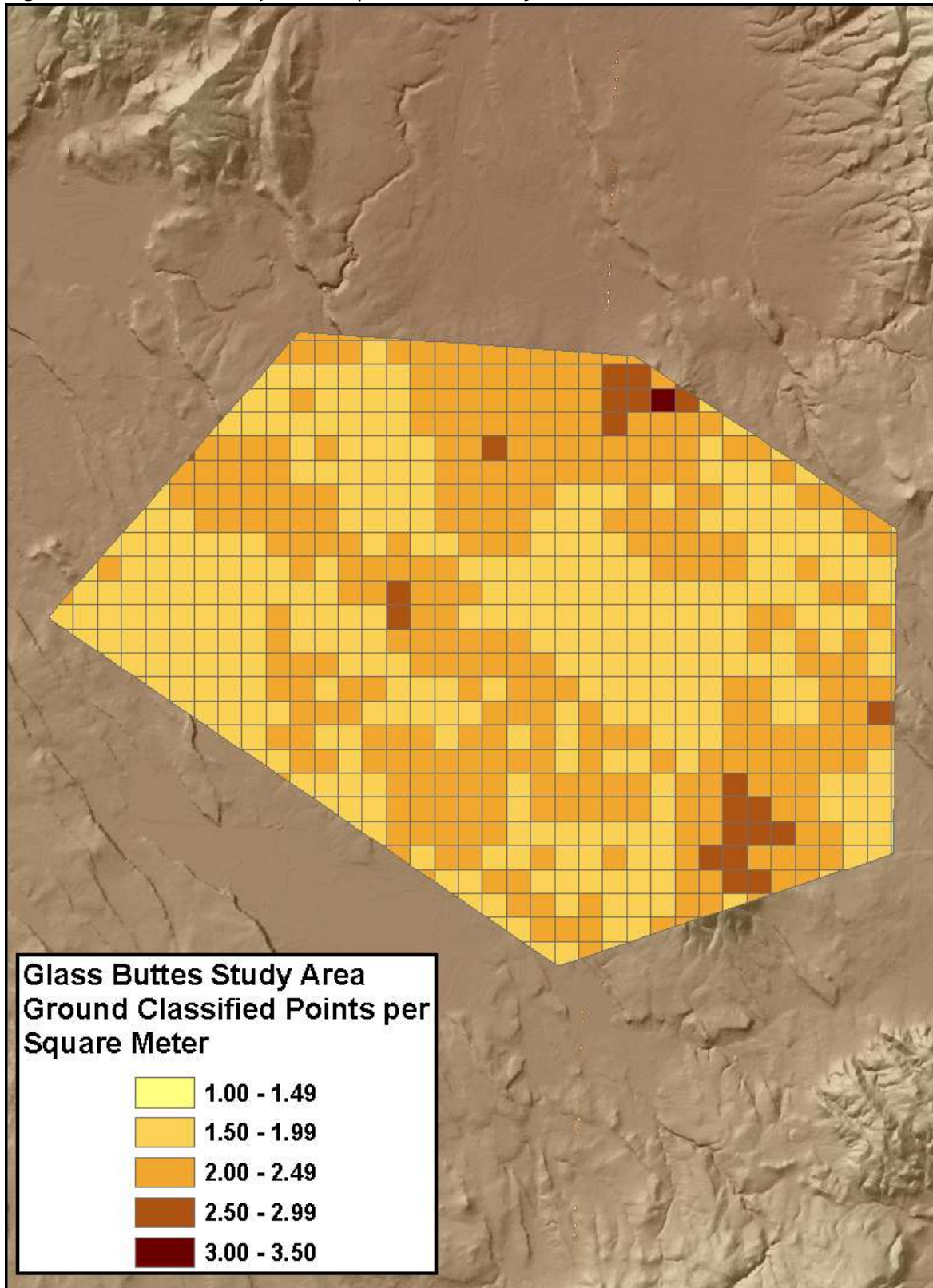*Figure 4.8*. *Ground-classified laser point data density.*

Glass Buttes Study Area
Ground Classified Points per
Square Meter

	1.00 - 1.49
	1.50 - 1.99
	2.00 - 2.49
	2.50 - 2.99
	3.00 - 3.50

5. Deliverables

5.1 Point Data
- All Return Point data in las v 1.2 format with RGB values (delineated in 750 m x 750 m tiles)
- Ground Classified Point data in las v 1.2 format with RGB values (delineated in 750 m x 750 m tiles)

5.2 Vector Data

- Total Area Flown (delineated in 750 m x 750 m tiles)

5.3 Raster Data
- ESRI GRID of LiDAR-derived Bare Earth Model (1-meter resolution)
- ESRI GRID of LiDAR-derived Highest Hit surface (1-meter resolution)
- Intensity Images in GeoTIFF format (0.5-meter resolution)

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

5.5 Datum and Projection

Universal Transverse Mercator (UTM) Zone 11; NAD83(CORS96); NAVD88(Geoid03). **Elevation units and horizontal units are meters.**

6. Selected Images

Figure 6.1. *Streambed near Glass buttes. Upper image is a digital elevation model derived from ground classified points. Lower image is a NAIP orthophoto draped over bare earth ground model.*
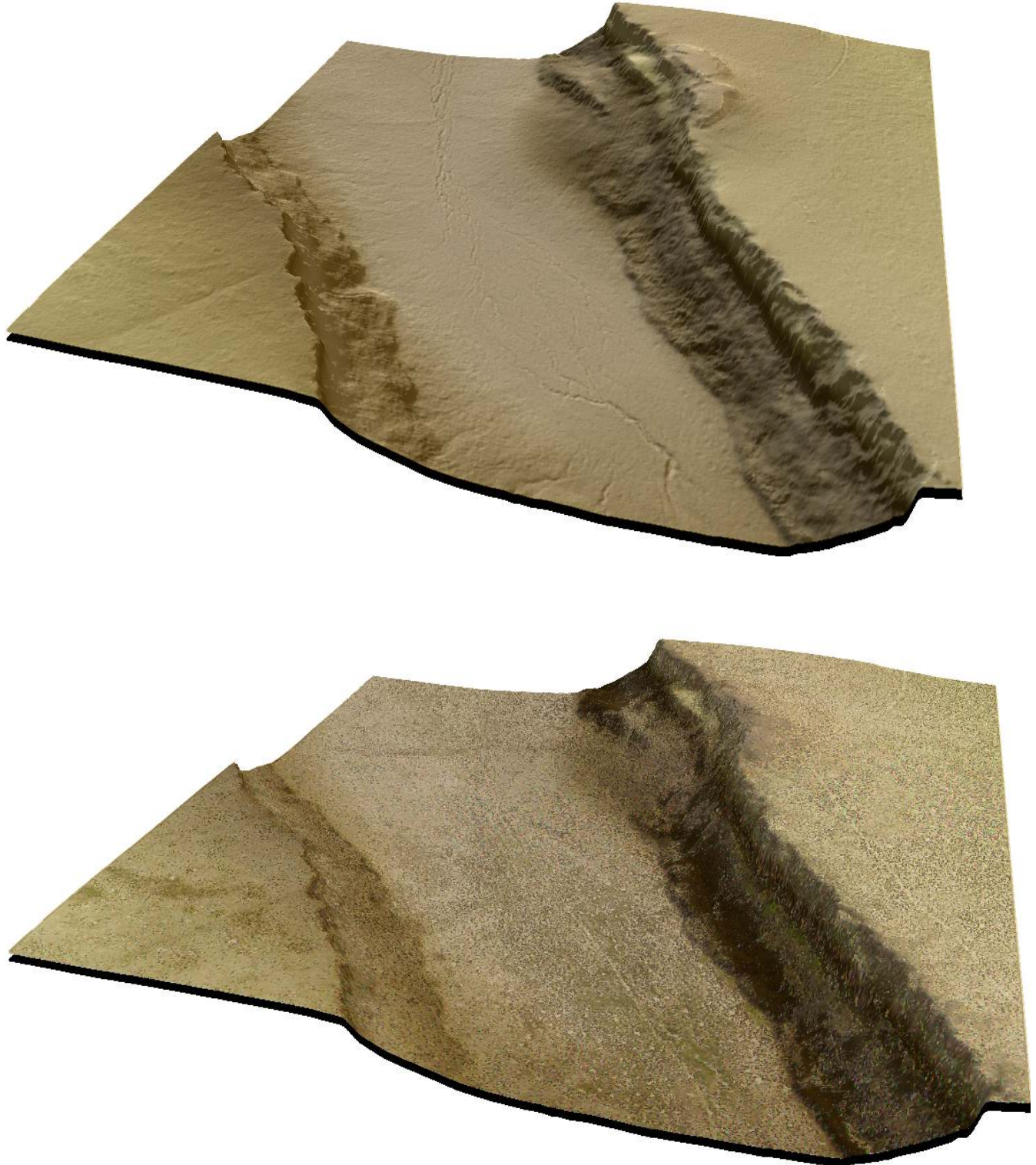
Figure 6.2. *Ridgeline approximately one mile south of Glass Buttes. Image is a three dimensional LiDAR point cloud with RGB values extracted from a NAIP orthophoto.*
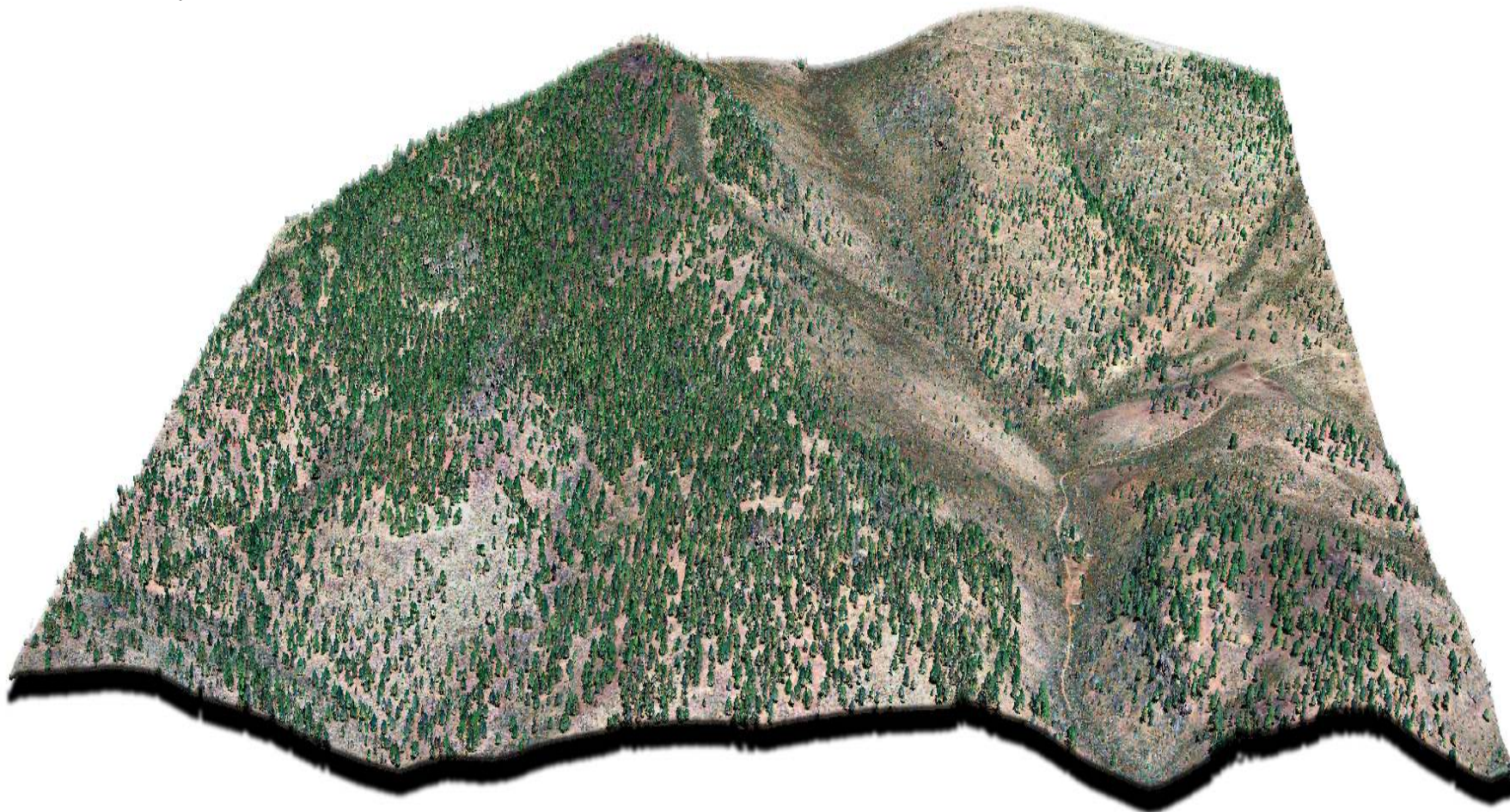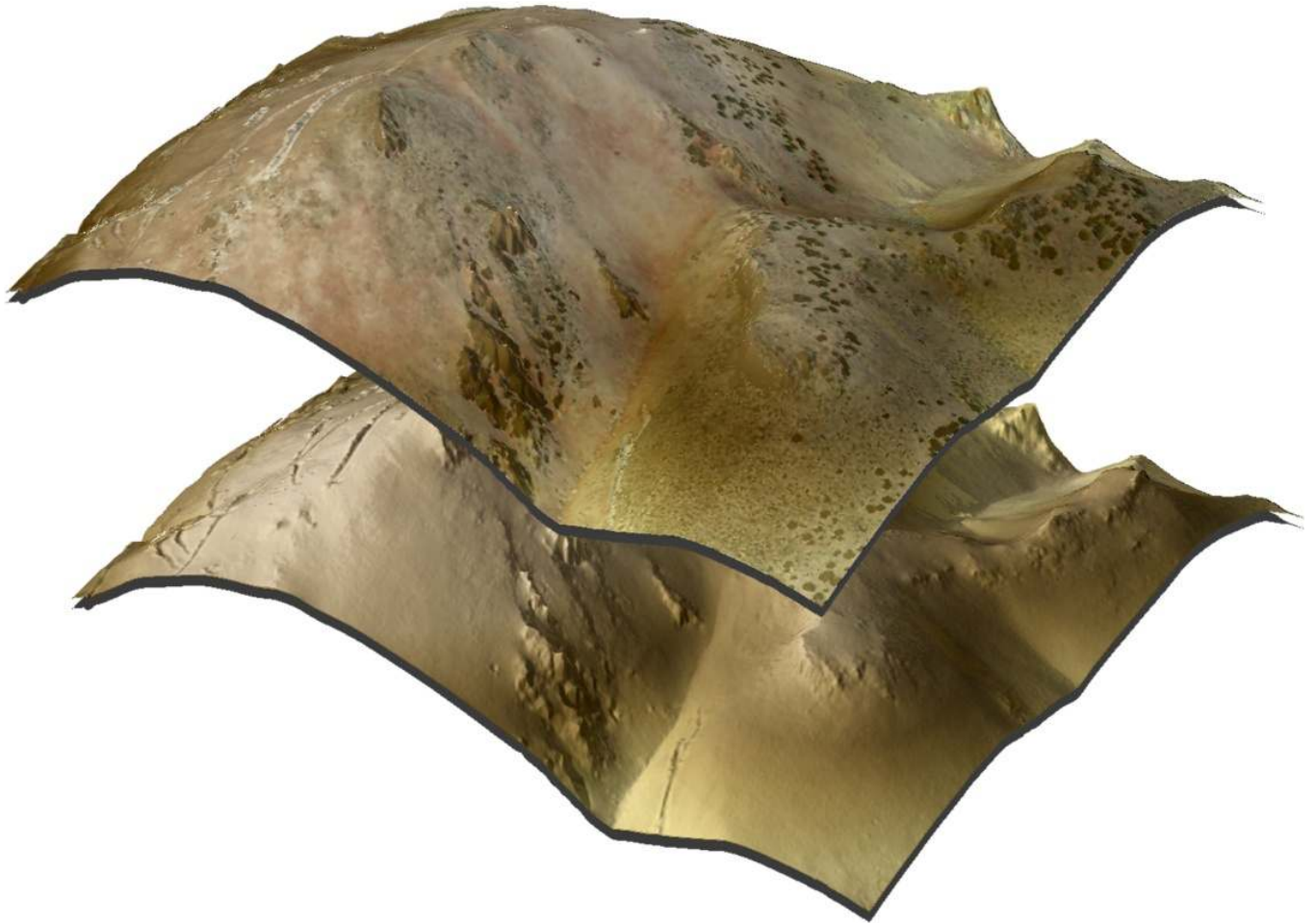
Figure 6.3. *Southeast view of Little Glass Butte, part of a series of volcanic domes that are aligned in a northwest dierection. Lower image is a digital elevation model derived from ground classified LiDAR points, upper image is a NAIP orthophoto draped over digital elevation model.*

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 pulse emitted, the Leica ALS 60 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.