



Applied
Remote Sensing
and Analysis

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USFS Region 5 LiDAR

Delivery 3 – Northern California

Technical Data Report



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Cover Photo: View looking southeast down the Trinity River flowing through the Hyampom Valley. Image created from the bare-earth model with LiDAR point cloud of vegetation. RGB values assigned with 2009 NAIP Imagery.

INTRODUCTION

View of terrain near the Sims Fire study area in Northern California



In August 2012, WSI (Watershed Sciences, Inc.) was contracted by 3Di West, in conjunction with the USDA Forest Service (USFS), to collect Light Detection and Ranging (LiDAR) data for multiple areas throughout USFS Region 5, including sites in the Inyo, Mendocino, Klamath, Shasta-Trinity, Sierra, Six Rivers, and Sequoia National Forests. The LiDAR data were collected to aid in identifying ecological restoration opportunities by assessing forest structural complexity, mapping geomorphic features, and quantifying acreages of highly suitable wildlife habitat.

This report accompanies the third delivered LiDAR data set for 4 areas of interest (AOIs) in Northern California: Sims Fire, East Branch East Weaver, Gopher Hill, and Bean Hill (Figure 1). It documents data acquisition procedures, processing methods, and results of all accuracy assessments. Project specifics for this delivery are shown in Table 1, and a complete list of contracted deliverables provided to 3Di West can be found in Table 2.

Table 1: Acquisition dates, acreages, and data types collected on the USFS Region 5 LiDAR site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Delivery 1 (Northern California)	51,711	54,914	10/14-17/2012	LiDAR
Delivery 2 (Central Sierra)	152,437	61,620	11/13-27/2012	
East Branch East Weaver	2,464	2,794	10/14/2012	
Sims Fire	122,168	126,436	10/18-19/2012 10/21/2012 10/28-30/2012 11/1-6/2012 12/7-10/2012 12/13/2012	
Gopher Hill	406	564	11/26/2012	
Bean Hill	77	143	11/26/2012	

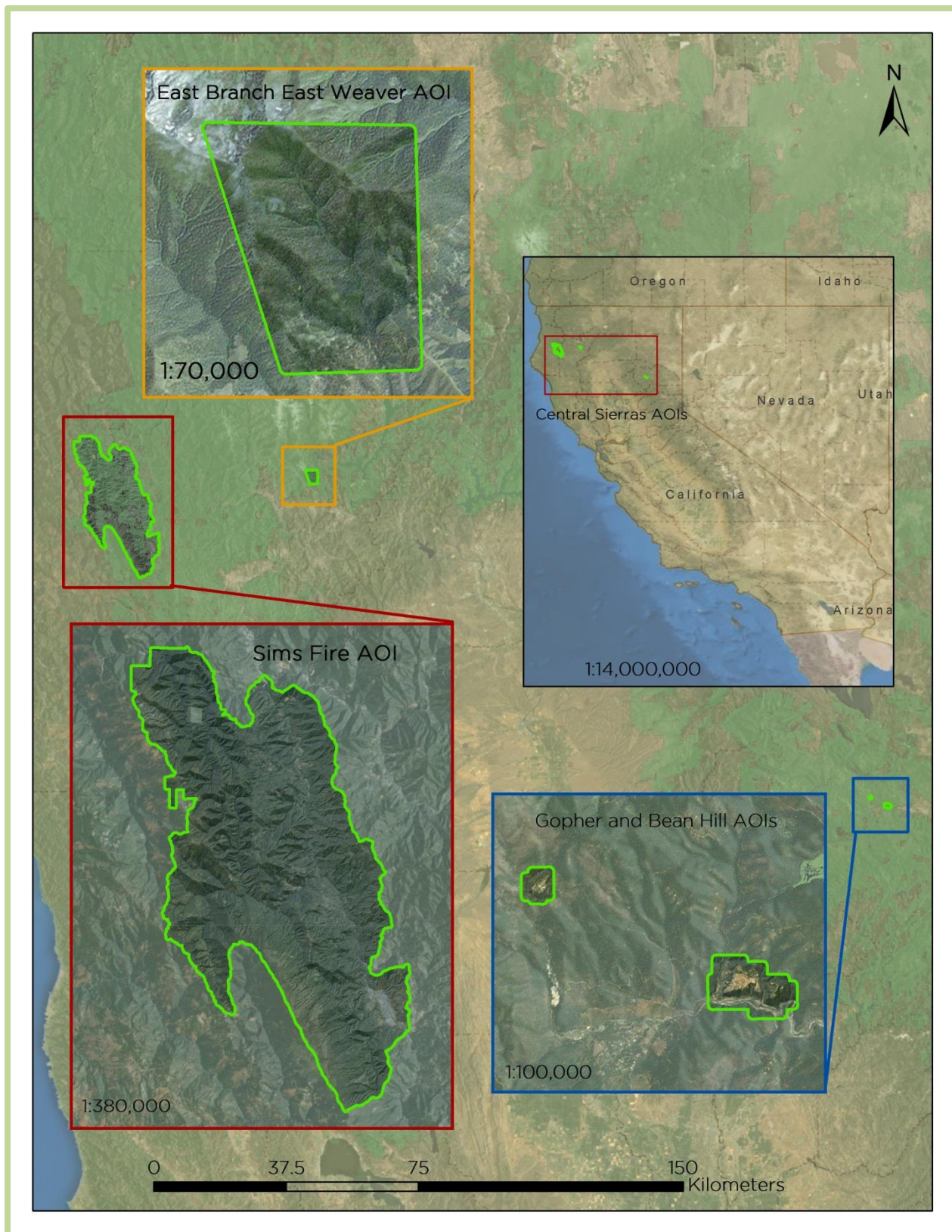


Figure 1: Location map of the Delivery 3 USFS Region 5 LiDAR sites in Northern California

Table 2: Products delivered to 3Di West for the 4 Northern California AOIs (Delivery 3)

Projection: UTM Zone 10 North Horizontal Datum: NAD83 (CORS96) Vertical Datum: NAVD88 (GEOID03) Units: Meters	
LAS Files	LAS v 1.2 <ul style="list-style-type: none"> • All Returns
Rasters	1 Meter ESRI Grids and GeoTIFFs <ul style="list-style-type: none"> • Bare Earth Model • Highest Hit Model 1 Meter GeoTIFFs <ul style="list-style-type: none"> • Intensity Images
Vectors	Shapefiles (*.shp) <ul style="list-style-type: none"> • Site Boundary • LiDAR Index • DEM/DSM Index • Smooth Best Estimate Trajectory (SBETs) • Flightlines • Flight Swaths Geodatabase (*.gdb) <ul style="list-style-type: none"> • Ground points



Leica ALS50 LiDAR sensor installation



Planning

In preparation for data collection, WSI reviewed the project area using Google Earth, and flightlines were developed using ALTM-NAV Planner (v.3.0) software. Careful planning by acquisition staff entailed adapting the pulse rate, flight altitude, scan angle, and ground speed to ensure complete coverage of the LiDAR study areas at the target point density of ≥ 8 pulses per square. Efforts are taken to optimize flight paths by minimizing flight times while meeting all accuracy specifications.

Factors such as satellite constellation availability and weather windows must be considered. Any weather hazards and conditions affecting the flight were continuously monitored due to their impact on the daily success of airborne and ground operations. In addition, a variety of logistical considerations require review: private property access, potential air space restrictions, and availability of company resources (both staff and equipment). Significant effort was made to acquire all LiDAR areas with no snow on the ground. Acquisition of the Bluff Creek, Slides Glade, Deadman Creek, Moores Flat Hyd Mine, and Michigan Bluff Hyd Mine AOIs are still outstanding and acquisition is dependent on snow melt.

Ground Survey

Ground survey data is used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on the final LiDAR data. Ground professionals set permanent survey monuments and collect real time kinematic (RTK) surveys to support the airborne acquisition process.



Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground control points using RTK survey techniques. Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for RTK coverage. WSI occupied 4 existing monuments, including three NGS monuments, and established 7 new monuments for the Delivery 3 area of the survey (Table 3, Figure 2). New monumentation was set using 5/8" x 30" rebar topped with stamped 2" aluminum caps.

To correct the continuous onboard measurements of the aircraft position recorded throughout the missions, WSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. After the airborne survey, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS¹) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

RTK Surveys

For the real time kinetic (RTK) check point data collection, a Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All RTK measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK data, the rover would record data while stationary for five seconds, then calculate the pseudorange position using at least three one-second epochs. Relative errors for the position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted.

RTK positions were collected on paved roads and other hard surface locations such as gravel or stable dirt roads that also had good satellite visibility. RTK measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. The distribution of RTK points depends on ground access constraints and may not be equitably distributed throughout the study area. See Figure 2 for the distribution of RTK in this project.

¹ OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. <http://www.ngs.noaa.gov/OPUS>.

Table 3: Monuments established for the Northern California Delivery 3 LiDAR acquisition. Coordinates are on the NAD83 (CORS96) datum, epoch 2002.00

Monument ID	Monument Origin	Latitude	Longitude	Ellipsoid (meters)
DH6531	NGS	40 53 15.88630	-123 36 11.10993	156.970
SR_12	New WSI	40 51 01.75635	-123 33 27.97462	494.596
SR_13	New WSI	40 50 19.94893	-123 43 13.00377	1451.809
KS0531	NGS	39 56 32.59114	-120 57 12.33373	1018.021
MINE_01	New WSI	39 56 56.24662	-121 03 03.59741	1094.058
LU2289	NGS	40 39 07.51122	122 56 30.81067	478.731
SR_14	New WSI	40 47 14.59291	-123 41 07.21712	1564.425
SR_15	New WSI	40 40 21.70425	-123 35 57.95568	1476.592
SR_17	New WSI	40 37 41.89450	-123 28 16.44261	353.581
SR_18	New WSI	40 42 02.18201	-123 31 48.96728	544.815
PT1253_WV7AIR	Trinity County	40 44 21.67943	-122 55 37.85999	630.829

All static surveys were collected with Trimble model R7 GNSS receivers equipped with a Zephyr Geodetic Model 2 RoHS antenna. A Trimble model R8 GNSS receiver was used to collect RTK. All GNSS measurements were made with dual frequency L1-L2 receivers with carrier-phase correction. See Table 4 for Trimble unit specifications.

Table 4: Trimble equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2	TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2	TRM_R8_GNSS	RTK

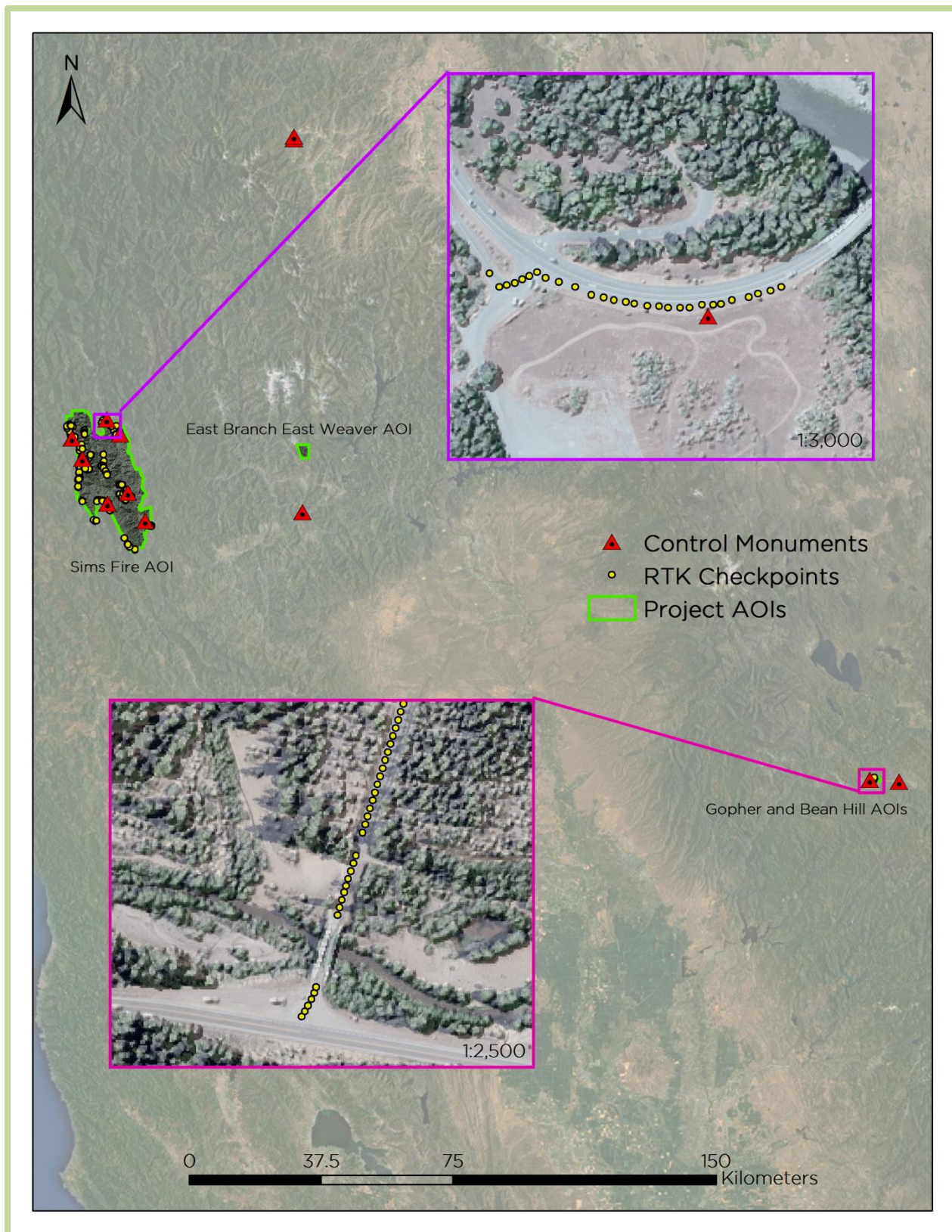


Figure 2: Basestation and RTK checkpoint location map

Airborne Survey

LiDAR

The LiDAR surveys were accomplished with either a Leica ALS50 Phase II or Leica ALS60 system mounted in a Cessna Caravan. Table 5 summarizes the settings used to yield an average pulse density of ≥ 8 pulses/m² over the USFS Region 5 LiDAR terrain. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses to the LiDAR sensor 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.

Table 5: LiDAR survey settings and specifications for delivered AOIs

LiDAR Survey Settings & Specifications				
AOI	East Branch East Weaver	Sims Fire	Gopher Hill	Bean Hill
Sensor	Leica ALS50	Leica ALS50/ALS60	Leica ALS50	Leica ALS50
Survey Altitude (AGL)	900 m	900 m	900 m	900 m
Target Pulse Rate	98.0-105.9 kHz	98.0-105.9 kHz	98.0-105.9 kHz	98.0-105.9 kHz
Sensor Configuration	SPiA*	SPiA*	SPiA*	SPiA*
Laser Pulse Diameter	21 cm	21 cm	21 cm	21 cm
Field of View	30°	30°	30°	30°
GPS Baselines	≤ 13 nm	≤ 13 nm	≤ 13 nm	≤ 13 nm
GPS PDOP	≤ 3.0	≤ 3.0	≤ 3.0	≤ 3.0
GPS Satellite Constellation	≥ 6	≥ 6	≥ 6	≥ 6
Maximum Returns	4	4	4	4
Intensity	8-bit	8-bit	8-bit	8-bit
Resolution/Density	~ 8 pulse/m ²	~ 8 pulse/m ²	~ 8 pulse/m ²	~ 8 pulse/m ²
Accuracy	RMSE _z ≤ 15 cm	RMSE _z ≤ 15 cm	RMSE _z ≤ 15 cm	RMSE _z ≤ 15 cm

*SPiA – single pulse in air.

To reduce laser shadowing and increase surface laser painting, all areas were surveyed with an opposing flight line side-lap of $\geq 50\%$ ($\geq 100\%$ overlap). The Leica laser systems record up to four range measurements (returns) per pulse. All discernible laser returns were processed for the output dataset.

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 were recorded continuously throughout the LiDAR data collection mission. Position of the aircraft was 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). To allow for post-processing correction and calibration, aircraft/sensor position and attitude data are indexed by GPS time.

View looking northwest up the Hyampom Valley toward the Hyampom Airport. Image created from LiDAR point cloud with RGB values assigned with 2009 NAIP Imagery.



LiDAR Data

Upon the LiDAR data's arrival to the office, WSI processing staff initiates a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks include GPS control computations, kinematic corrections, calculation of laser point position, calibration for optimal relative and absolute accuracy, and classification of ground and non-ground points (Table 6). Processing methodologies are tailored for the landscape and intended application of the point data. A full description of these tasks can be found in Table 7.

Table 6: ASPRS LAS classification standards applied to the USFS Region 5 LiDAR datasets

Classification Number	Classification Name	Classification Description
1	Default/ Unclassified	Laser returns that are not included in the ground class and not dismissed as Noise or Withheld points
2	Ground	Ground that is determined by a number of automated and manual cleaning algorithms to determine the best ground model the data can support
7	Noise	Low points and/or noise
11	Withheld	Laser returns that have intensity values of 0 or 255

Table 7: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.	Waypoint GPS v.8.3 Trimble Business Center v.2.80 Blue Marble Desktop v.2.5
Develop a smoothed best estimate of trajectory (SBET) file that blends 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.	IPAS TC v.3.1
Calculate laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v. 1.2) format. Data are converted to orthometric elevations (NAVD88) by applying a Geoid12 correction.	ALS Post Processing Software v.2.74
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).	TerraScan v.12.004
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 calculated on ground classified points from paired flight lines and results are applied to all points in a flight line. Every flight line is used for relative accuracy calibration.	TerraMatch v.12.001
Classify resulting data to ground and other client designated ASPRS classifications (Table 6). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground RTK survey data.	TerraScan v.12.004 TerraModeler v.12.002
Generate bare earth models as triangulated surfaces. Highest hit models were created as a surface expression of all classified points (excluding the noise and withheld classes). All surface models were exported as GeoTIFFs at a 1 meter pixel resolution.	TerraScan v.12.004 ArcMap v. 10.0 TerraModeler v.12.002

View overlooking the former Spanish Creek hydraulic mine site, which is now the Gopher Hill Landfill. Image created from LiDAR point cloud colored by elevation and intensity.



LiDAR Density

The average cumulative first-return density for the delivered AOIs was 12.58 points/m² (Table 8). The pulse density distribution will vary within the study area due to laser scan pattern and flight conditions. Additionally, some types of surfaces (i.e. breaks in terrain, water, steep slopes) may return fewer pulses to the sensor (delivered density) than originally emitted by the laser (native density).

The statistical distribution of cumulative first returns (Figure 3) and cumulative classified ground points (Figure 4) are portrayed below. Also presented are the spatial distribution of average first return densities (Figure 5 and 6) and ground point densities (Figure 7 and 8) for each 100 square meter cell. Statistical histograms for individual AOIs can be seen in Appendix A.

Table 8: Average LiDAR point densities

AOI	Point Density (points/m ²)				
	Cumulative	East Branch East Weaver	Sims Fire	Gopher Hill	Bean Hill
First-Return	12.58	29.66	13.20	9.10	10.21
Ground Classified	1.71	2.01	1.25	0.52	0.63

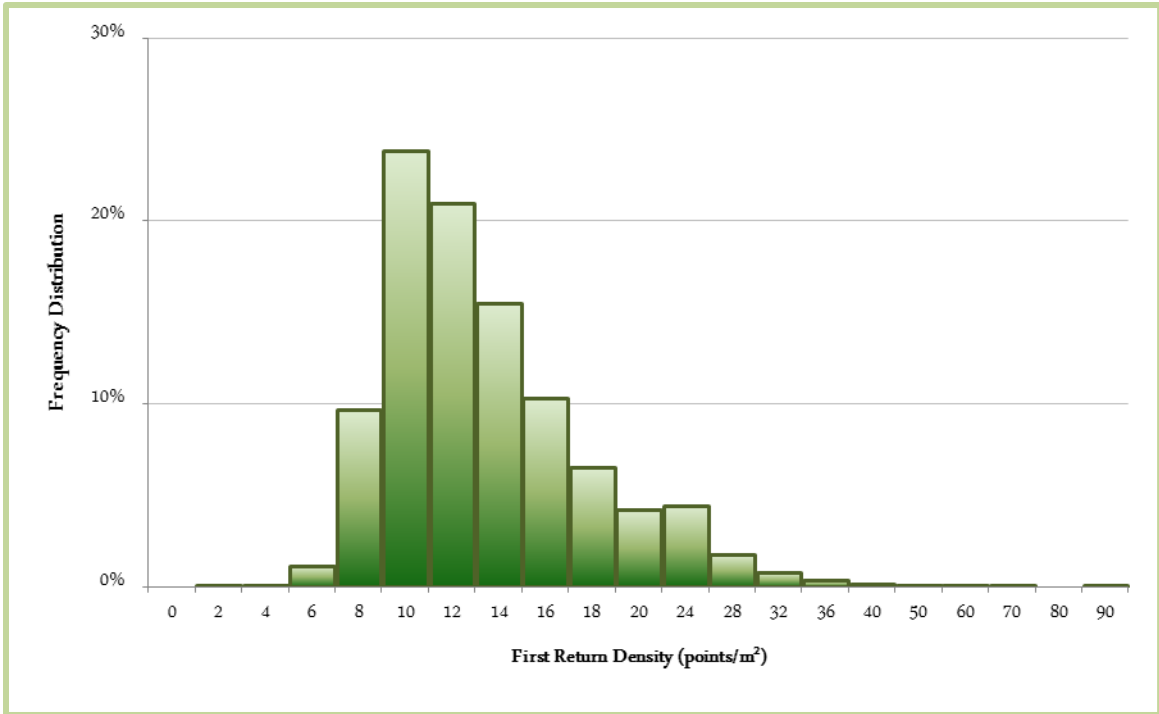


Figure 3: Cumulative frequency distribution of first return densities (native densities) of the 1m gridded study area for the 4 delivered AOIs

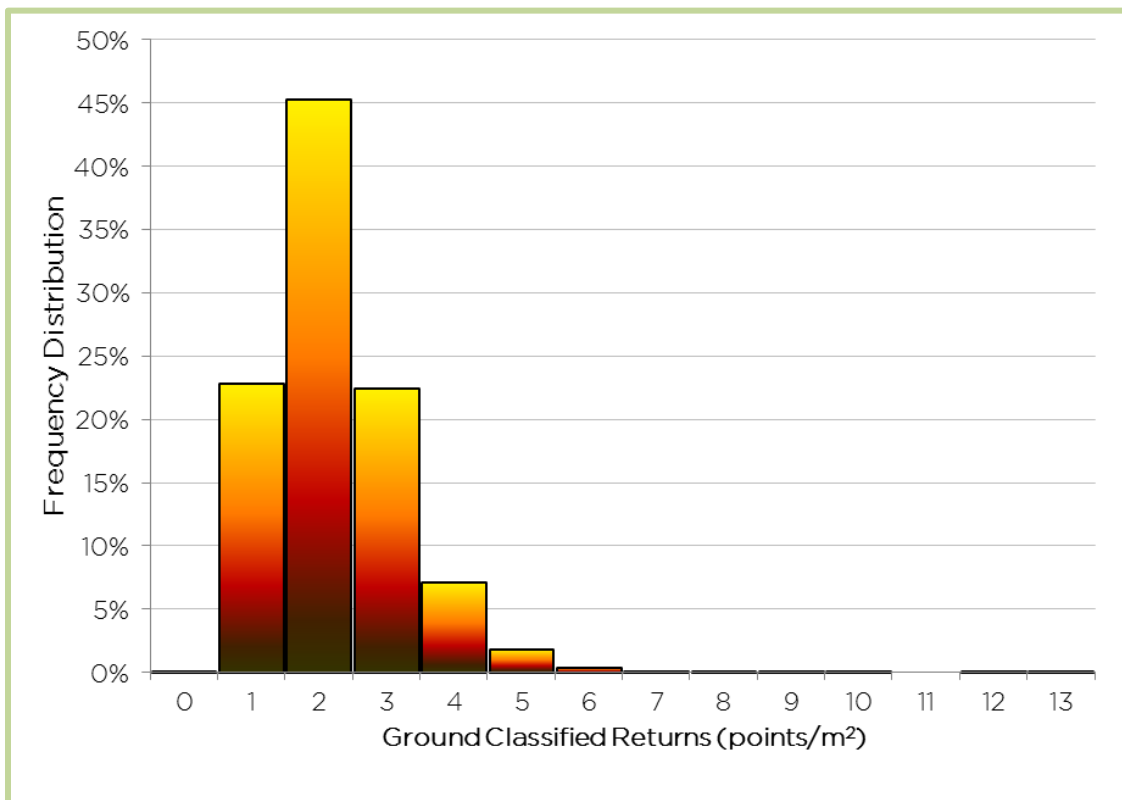


Figure 4: Cumulative frequency distribution of ground return densities of the 1m gridded study area for the 4 delivered AOIs

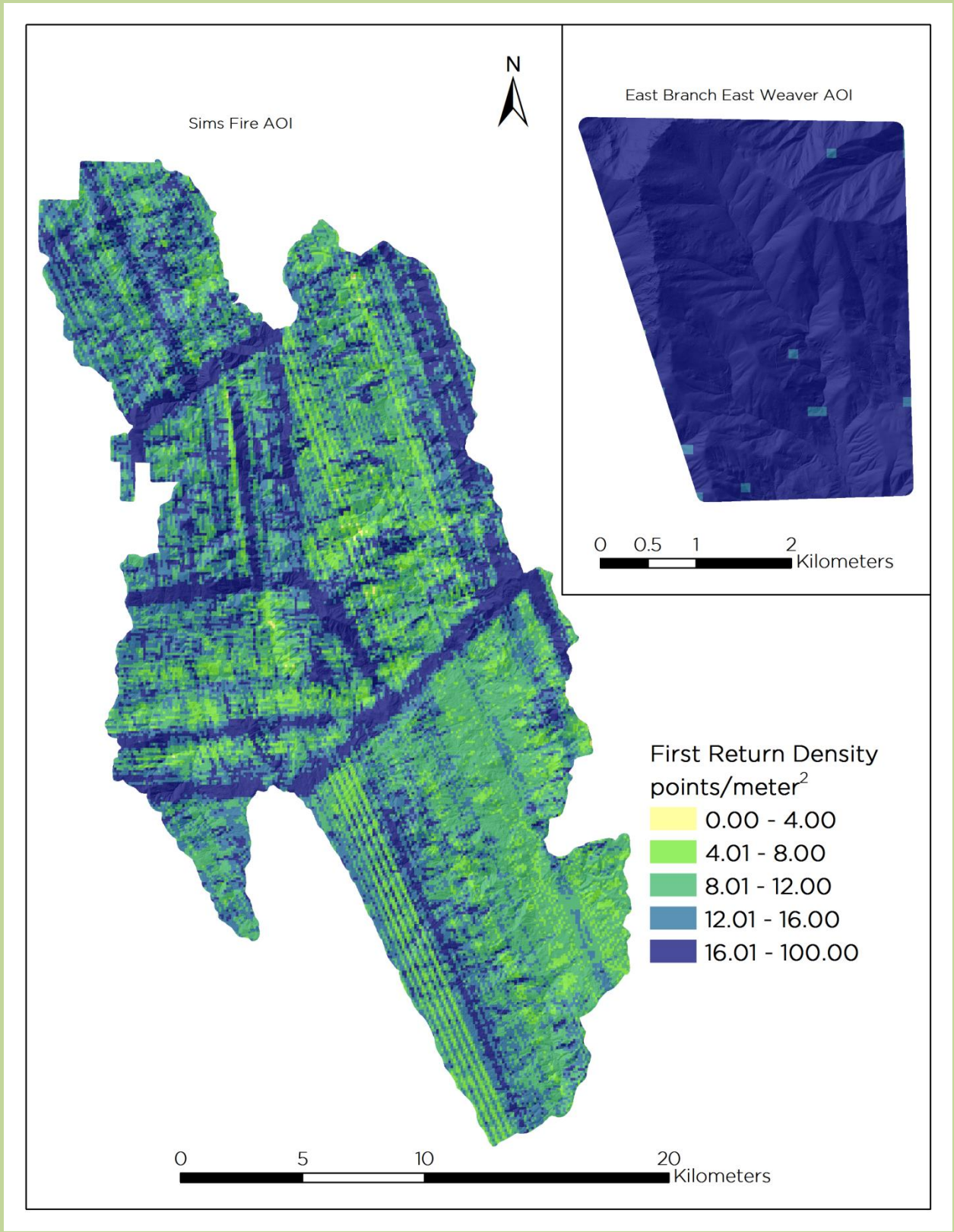


Figure 5: Native density maps for the Sims Fire and East Branch East Weaver AOIs

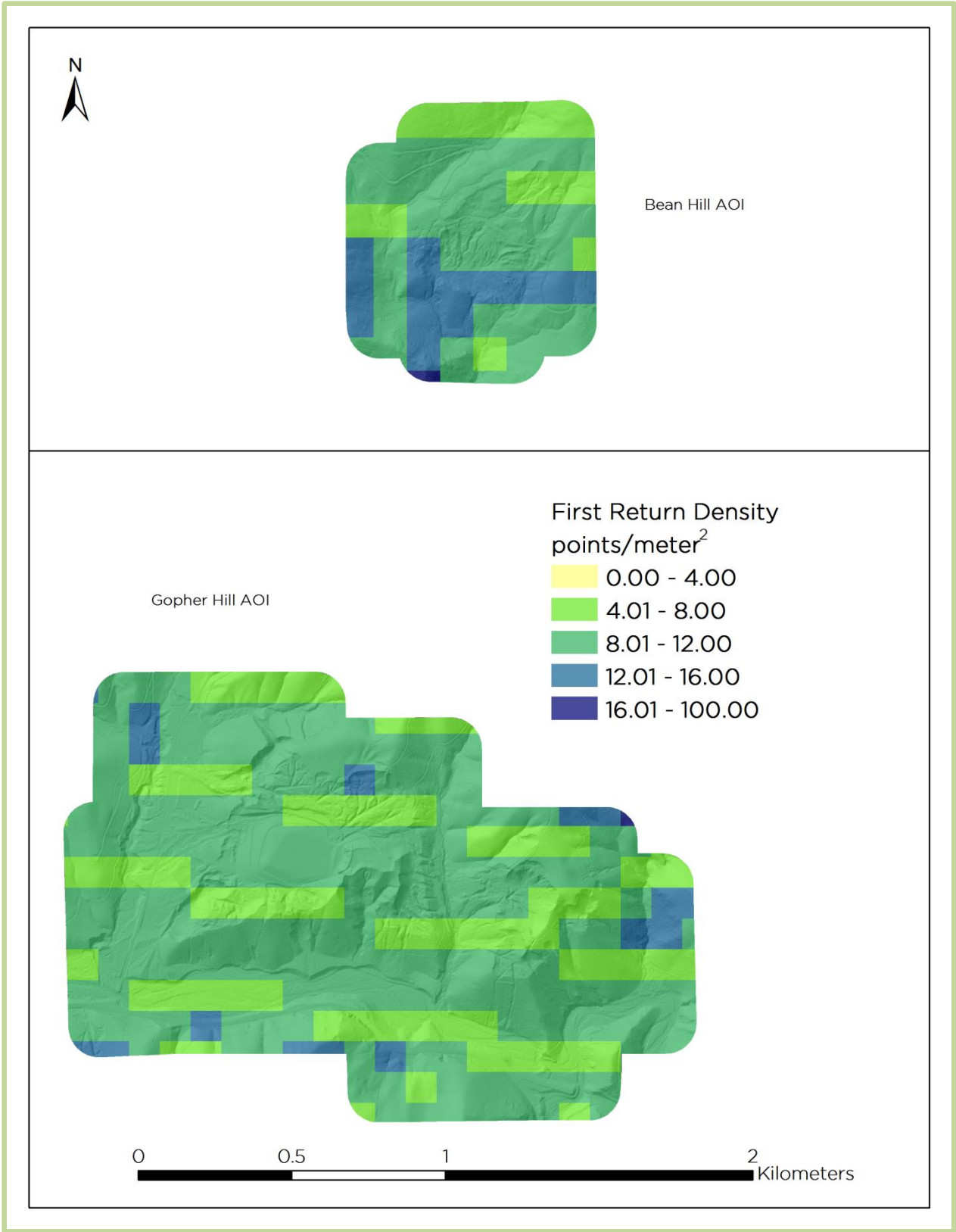


Figure 6: Native density maps for the Gopher and Bean Hill AOIs

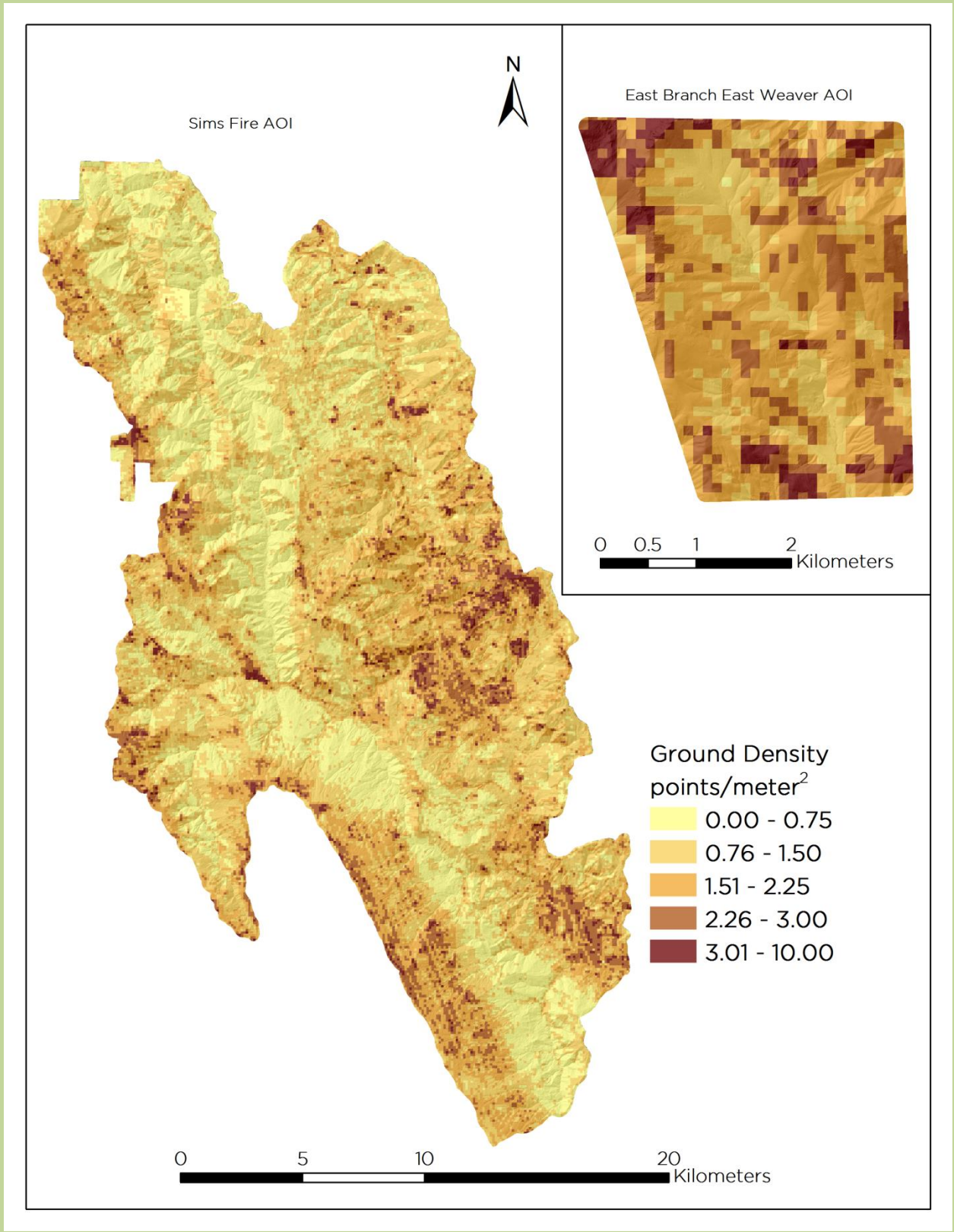


Figure 7: Ground density maps for the Sims Fire and East Branch East Weaver AOIs



Figure 8: Ground density maps for the Gopher and Bean Hill AOIs

LiDAR Accuracy Assessments

The accuracy of LiDAR data collection can be described in terms of *absolute accuracy* (the consistency of the data with external data sources) and *relative accuracy* (the consistency of the dataset with itself).

LiDAR Absolute Accuracy

Vertical absolute accuracy was primarily assessed from RTK ground check point (GCP) data collected on open, bare earth surfaces with level slope (<20°). Fundamental Vertical Accuracy (FVA) reporting is designed to meet guidelines presented in the National Standard for Spatial Data Accuracy (FGDC, 1998). FVA compares known RTK ground survey check points to the triangulated ground surface generated by the LiDAR points. FVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a “very high probability” of measuring the ground surface and is evaluated at the 95% confidence interval (1.96σ).

Absolute accuracy is described as the mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates. These statistics assume the error for x, y, and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the delivered AOIs, 7,281 RTK ground check points were collected in total resulting in an average accuracy of 0.001 meters (Table 9, Figure 9). Because RTK ground check points are not distributed evenly throughout the AOIs, individual AOI absolute accuracies were not calculated.

Table 9: Cumulative absolute accuracy statistics

Absolute Accuracy	Cumulative
Sample	7,281
Average	0.001 m
Median	0.003 m
RMSE	0.027 m
1σ	0.027 m
2σ	0.053 m

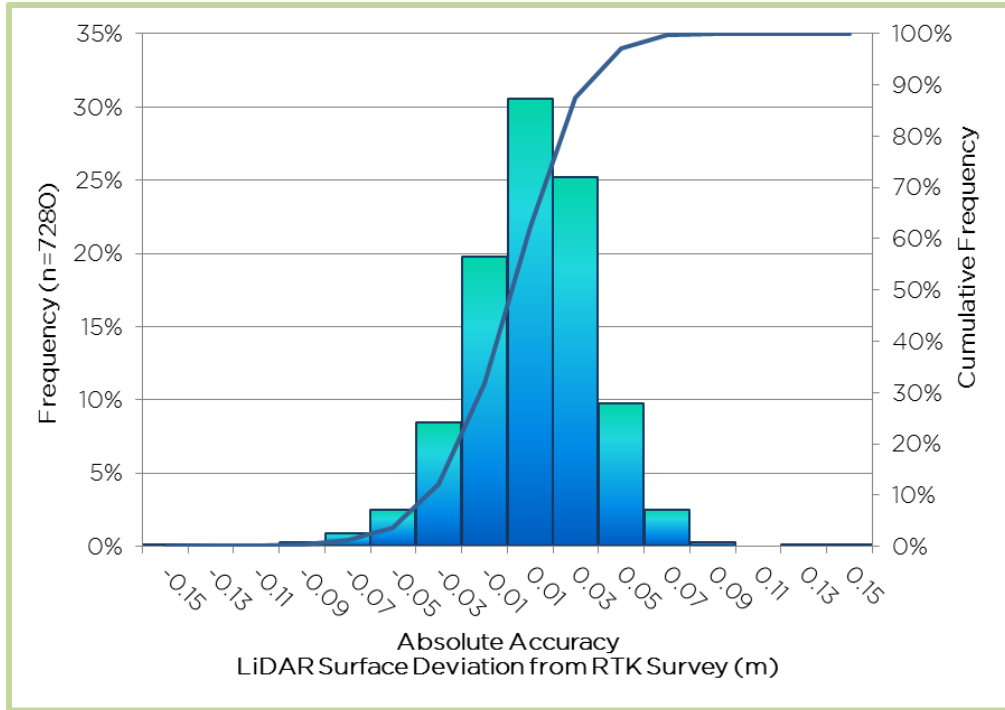


Figure 9: Frequency histogram for LiDAR surface deviation from RTK values

LiDAR Relative Accuracy

Relative accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath divergence is low (<0.10 meters). The relative accuracy is computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average relative accuracy across all delivered AOIs was 0.051 meters (Table 10, Figure 10). Frequency plots by individual AOI can be seen in Appendix B. See Appendix C for further information on sources of error and operational measures used to improve relative accuracy.

Table 10: Relative accuracy (in meters) by AOI

Absolute Accuracy	Cumulative	East Branch East Weaver	Sims Fire	Gopher Hill	Bean Hill
Sample Size	1,545	63	493	10	7
Average (m)	0.051	0.065	0.057	0.043	0.036
Median (m)	0.047	0.065	0.057	0.040	0.036
RMSE (m)	0.049	0.065	0.059	0.043	0.037
1σ (m)	0.017	0.004	0.012	0.006	0.003
1.96σ (m)	0.033	0.009	0.024	0.012	0.005

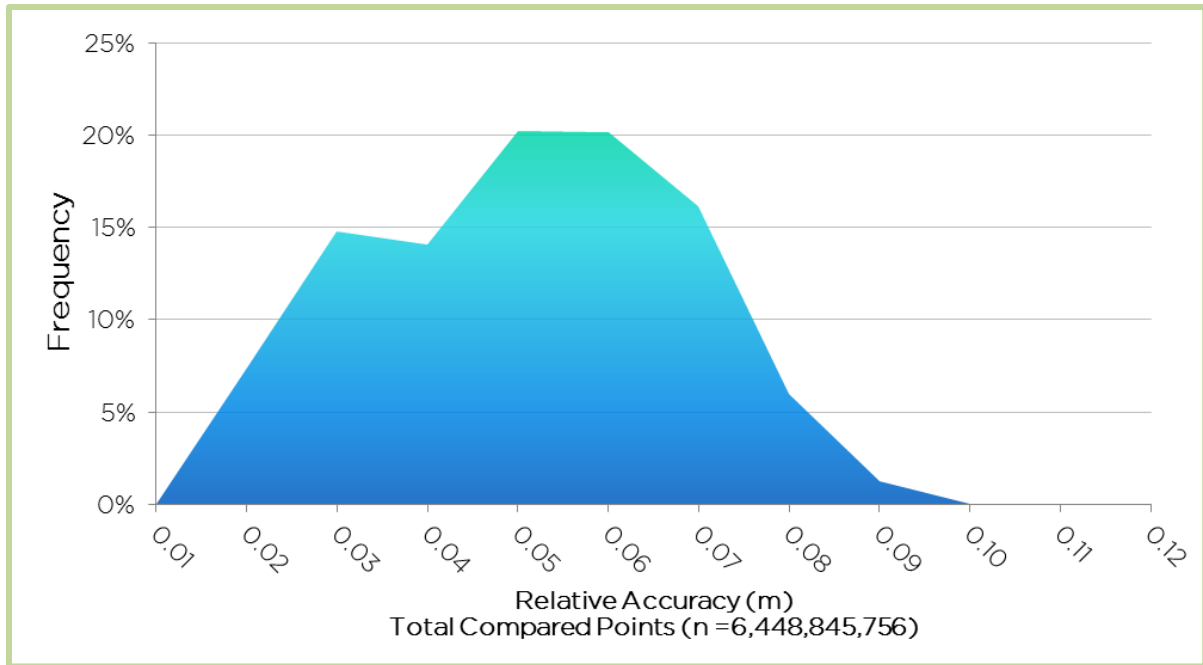


Figure 10: Frequency plot for relative accuracy between flight lines across all delivered AOIs



SELECTED IMAGES

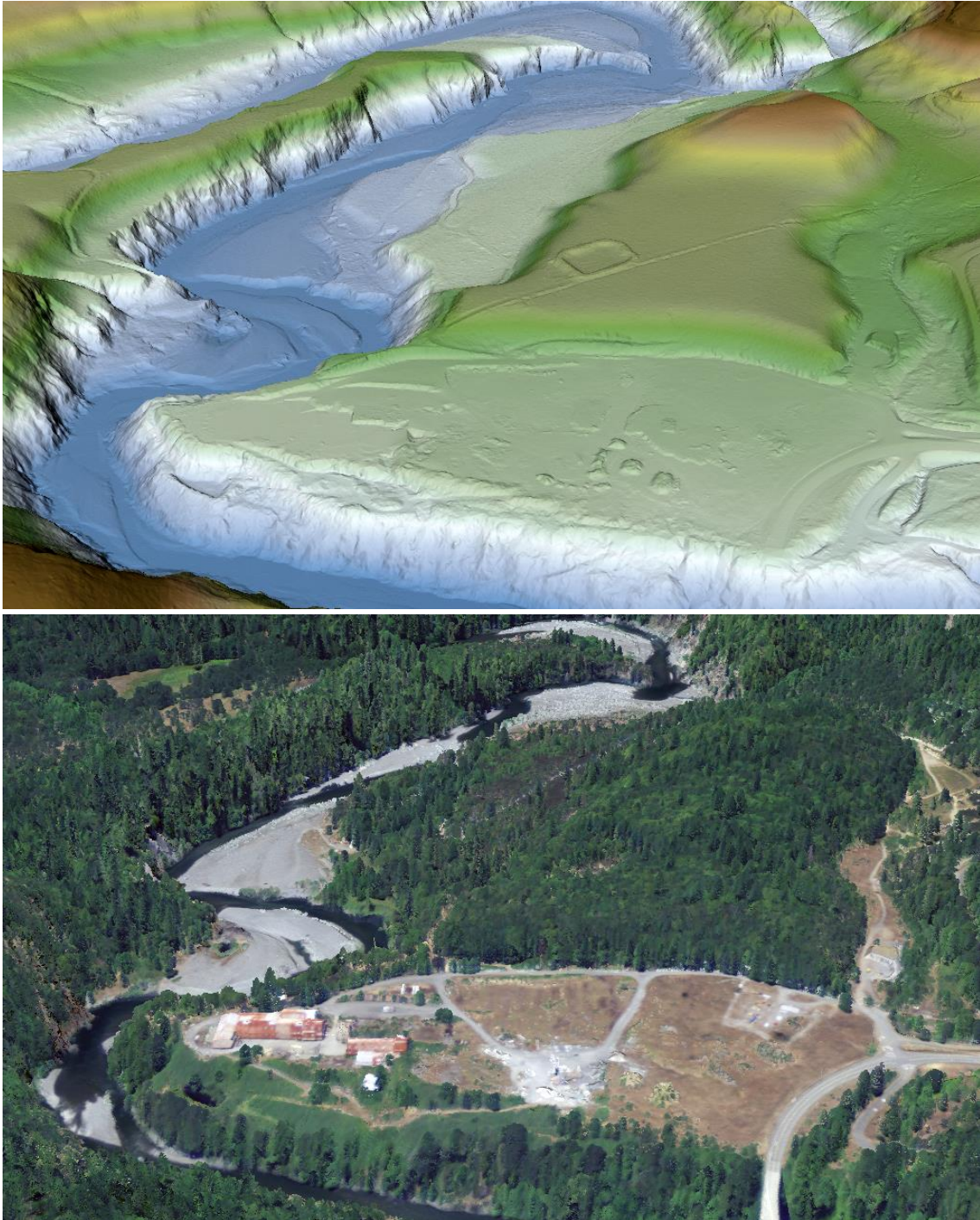


Figure 11: View looking south over an industrial site at the head of South Fork Trinity Wild and Scenic River. Top image created from LiDAR-derived bare-earth model colored by elevation. Bottom image created from LiDAR point cloud colored by 2009 NAIP imagery.

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

1.96-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.

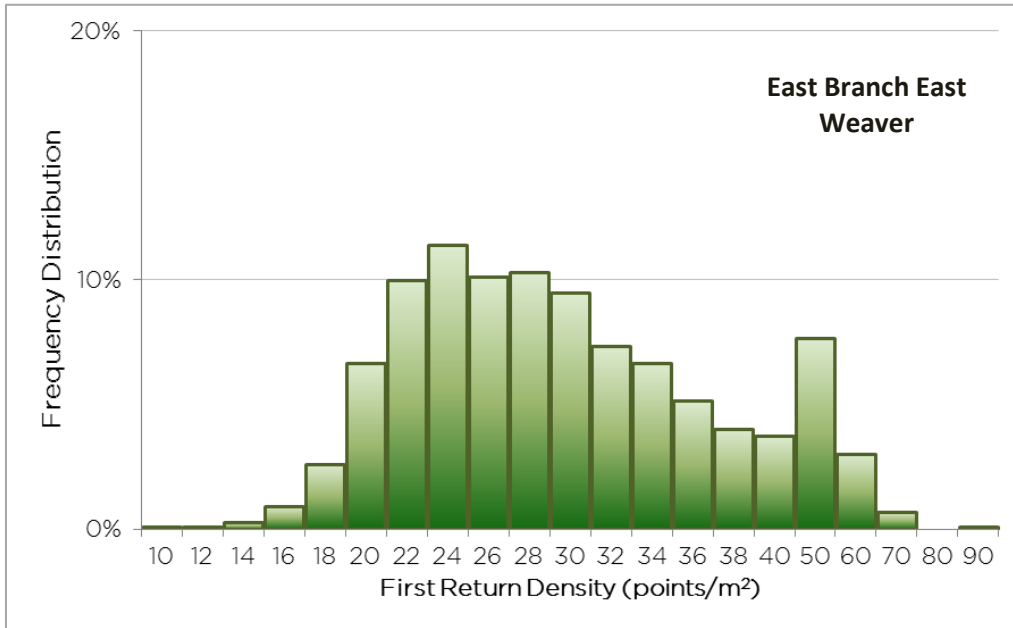
Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

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

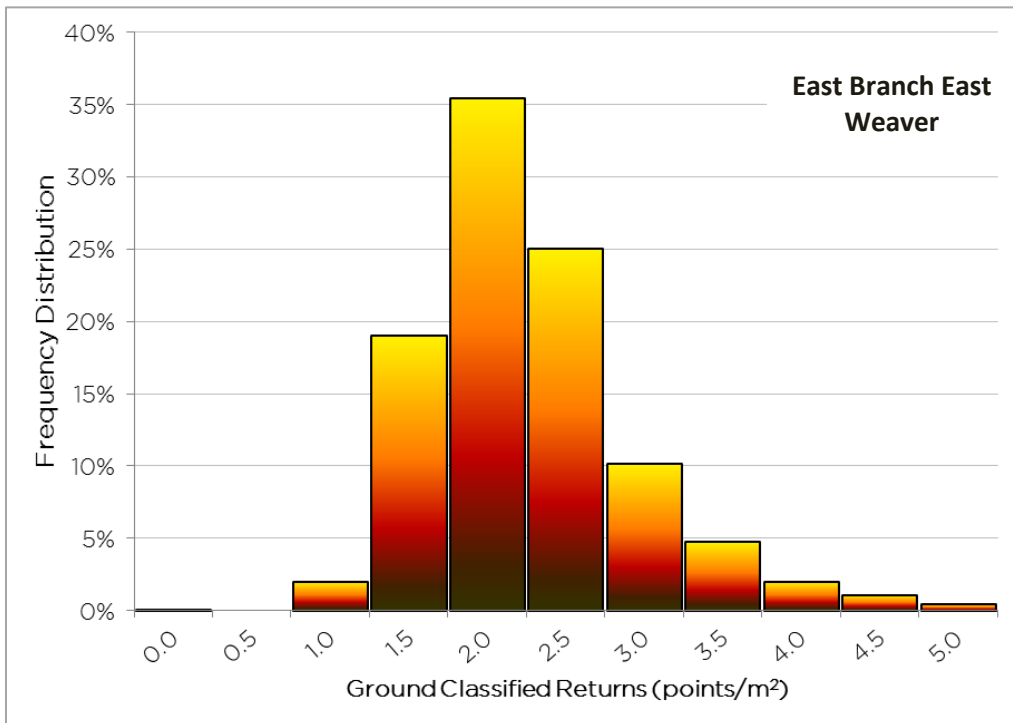
DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

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.

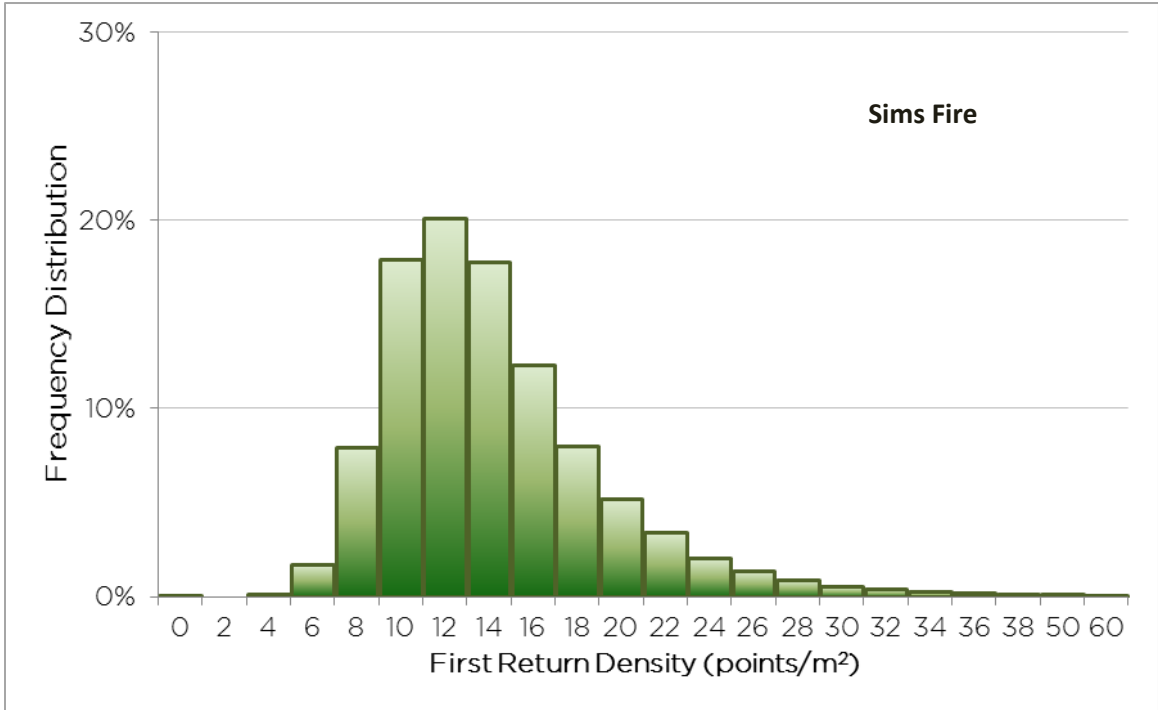
APPENDIX A



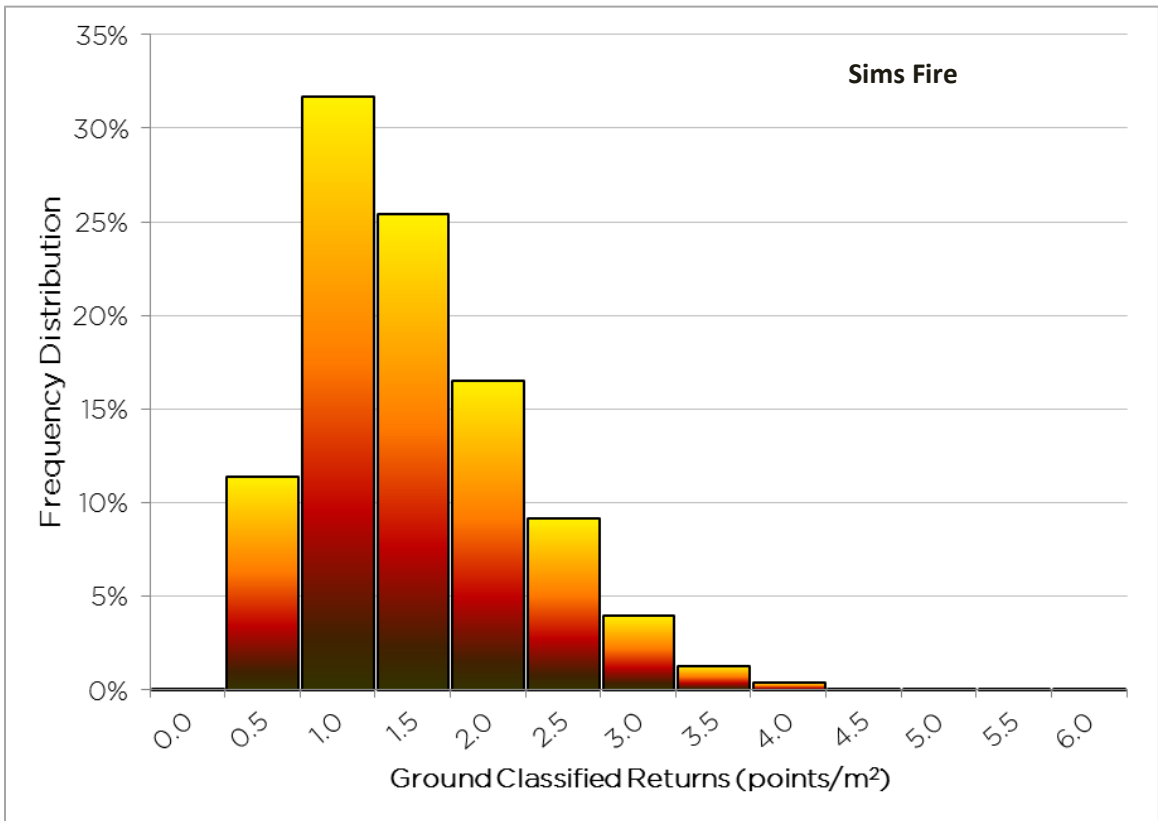
Frequency distribution of first return densities (native densities) of the 1-m gridded study area for the East Branch East Weaver AOI



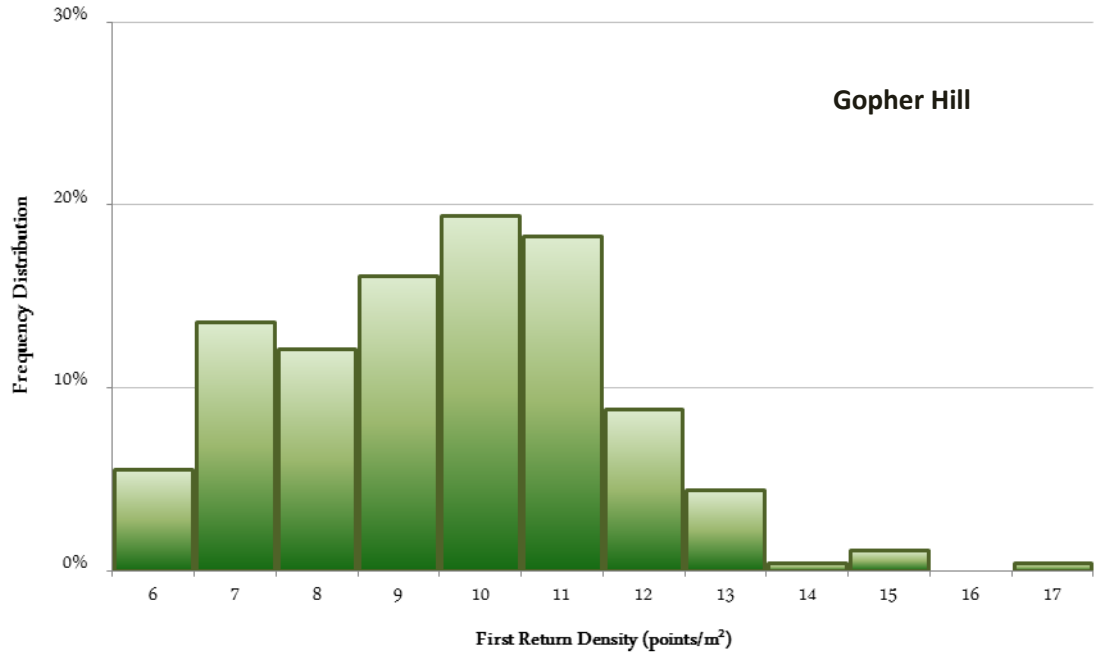
Frequency distribution of ground return densities of the 1-m gridded study area for the East Branch East Weaver AOI



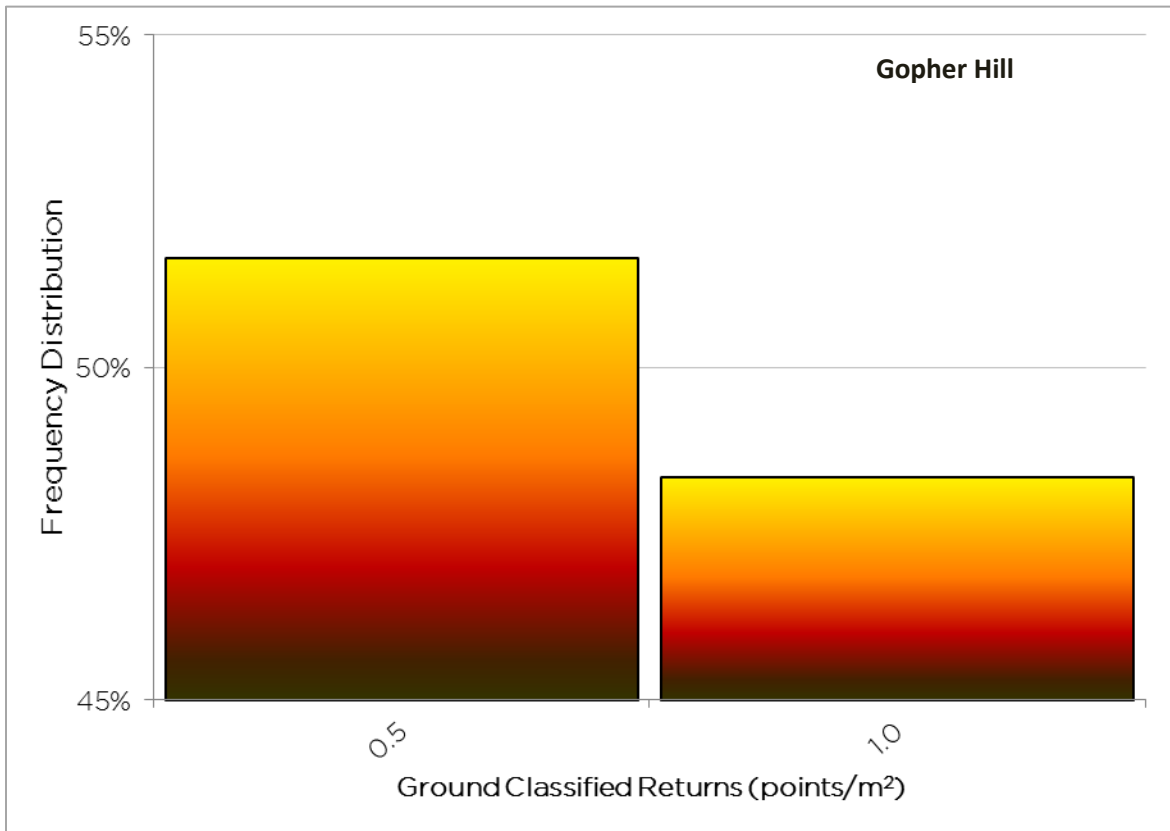
Frequency distribution of first return densities (native densities) of the 1-m gridded study area for the Sims Fire AOI



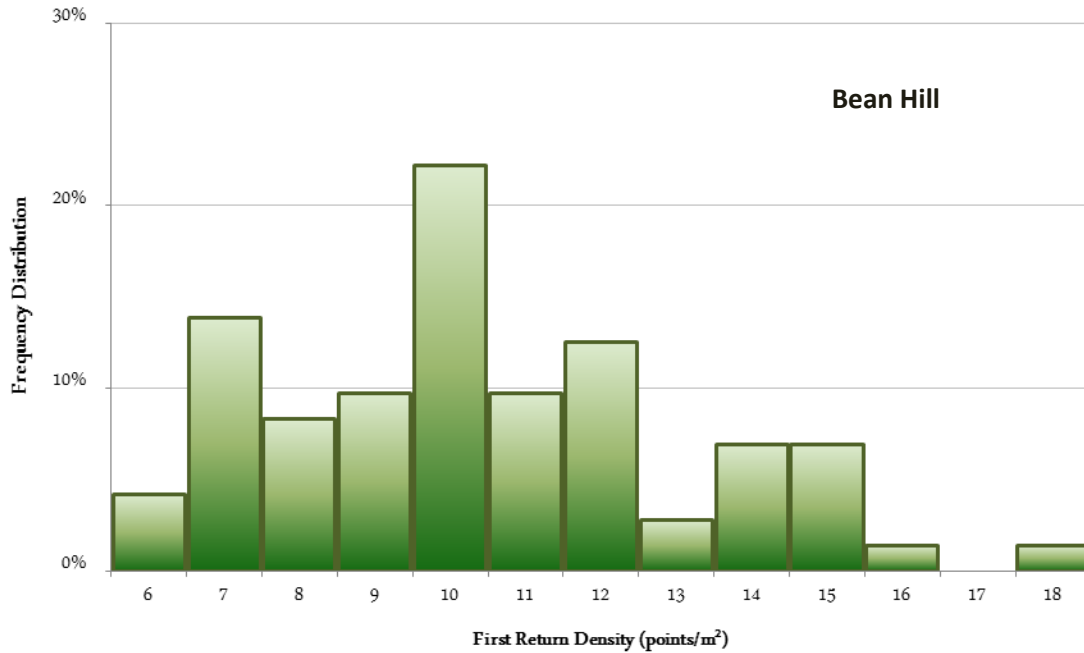
Frequency distribution of ground return densities of the 1-m gridded study area for the Sims Fire AOI



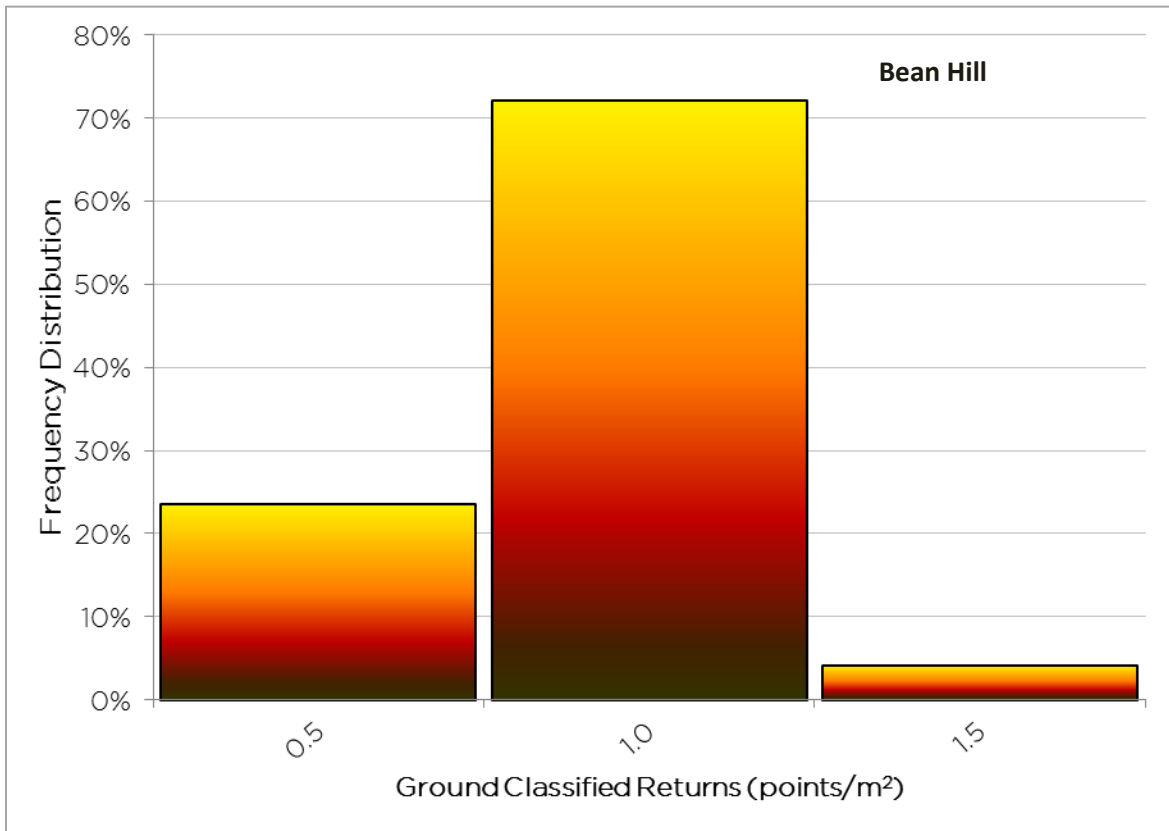
Frequency distribution of first return densities (native densities) of the 1m gridded study area for the Gopher Hill AOI



Frequency distribution of ground return densities of the 1m gridded study area for the Gopher Hill AOI

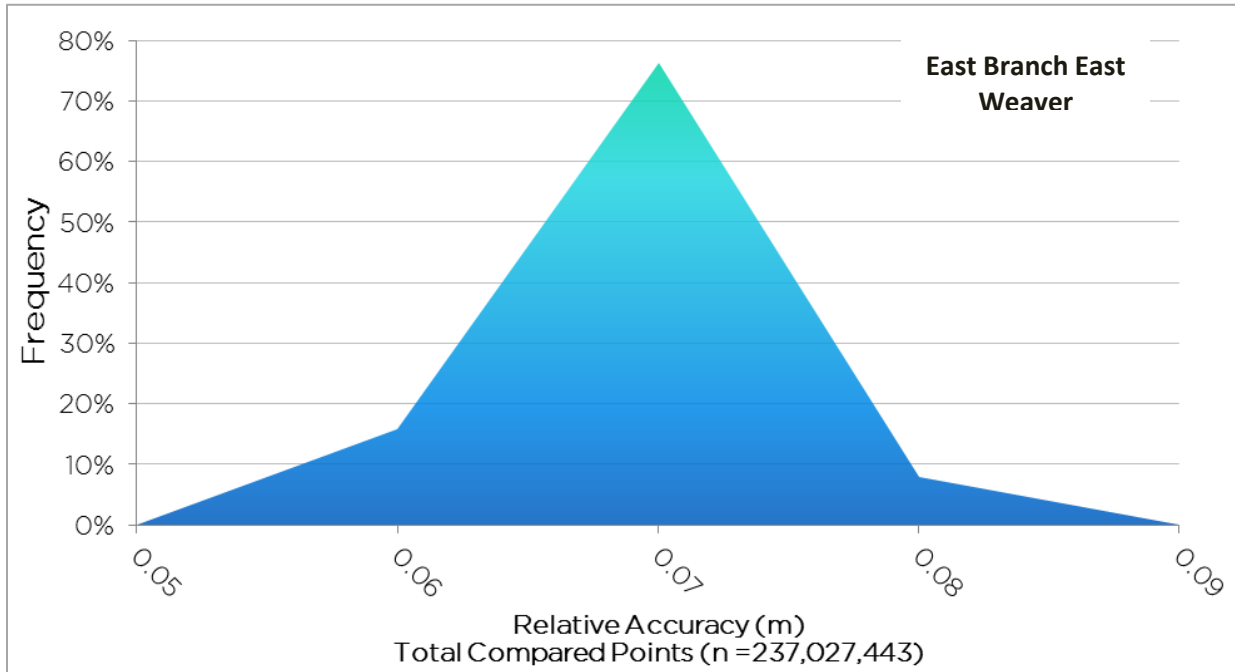


Frequency distribution of first return densities (native densities) of the 1m gridded study area for the Bean Hill AOI

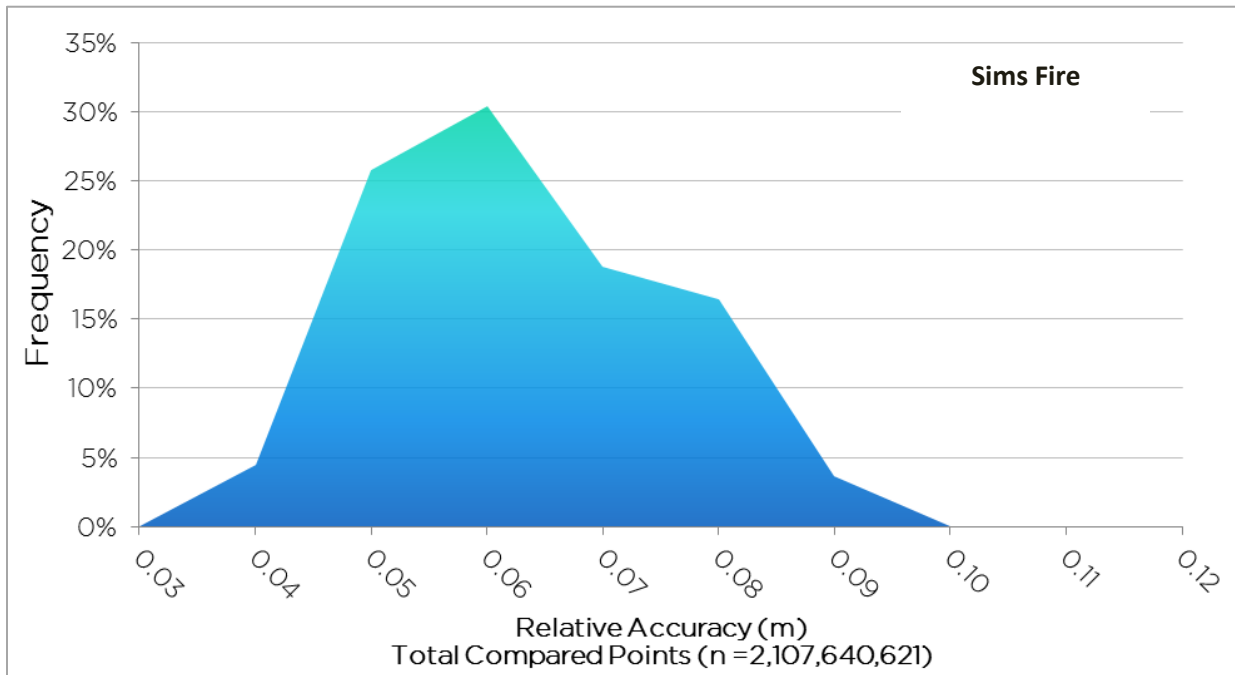


Frequency distribution of ground return densities of the 1m gridded study area for the Bean Hill AOI

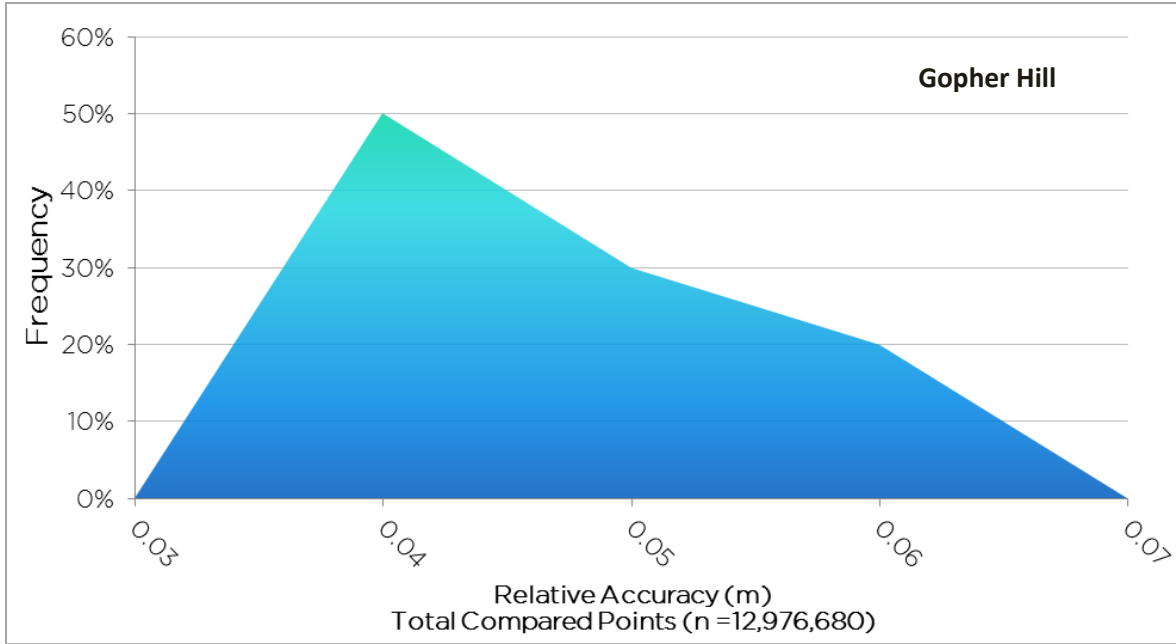
APPENDIX B



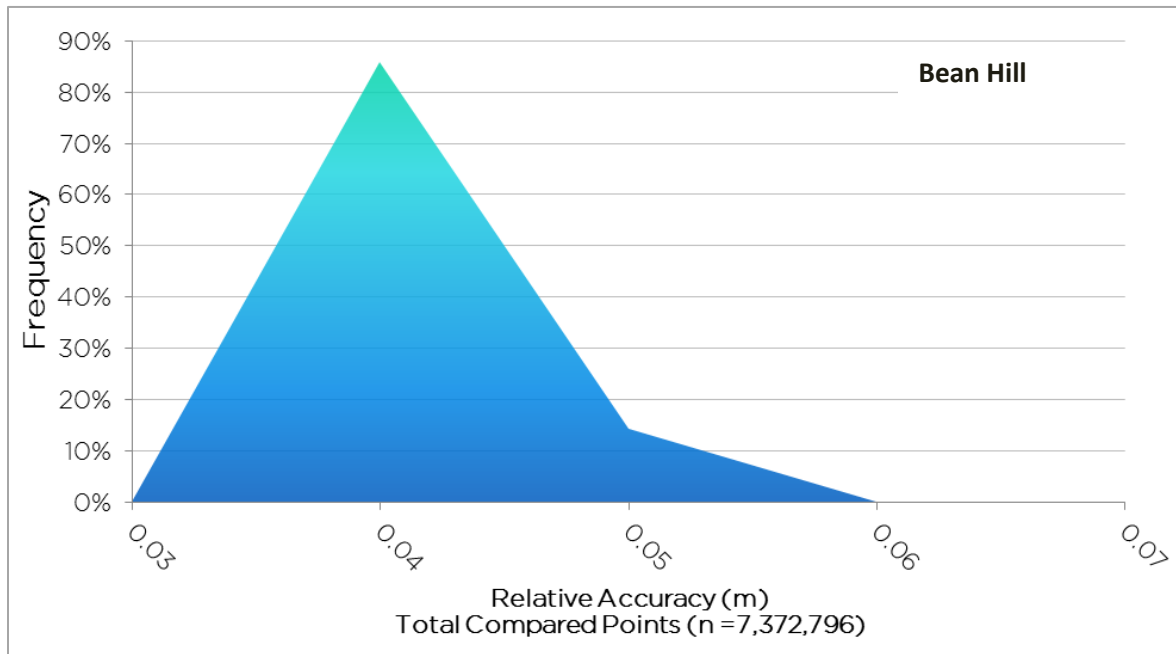
Frequency plot for relative accuracy between flight lines for the East Branch East Weaver AOI



Frequency plot for relative accuracy between flight lines for the Sims Fire AOI



Frequency plot for relative accuracy between flight lines for the Gopher Hill AOI



Frequency plot for relative accuracy between flight lines for the Bean Hill AOI

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 survey was approximately 0.02 meters.

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).

Relative Accuracy Calibration Methodology

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 were calculated and applied to resolve misalignments. The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.

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 scale were solved for each individual mission and applied to respective mission datasets. The data from each mission were then blended when imported together to form the entire area of interest.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

Absolute Accuracy

The vertical accuracy of LiDAR data is described as the mean and standard deviation (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, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y, and z are normally distributed, thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

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:

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., $\sim 1/3000^{\text{th}}$ AGL flight altitude).

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.

Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 15^{\circ}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

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.

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 survey area.

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.

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.