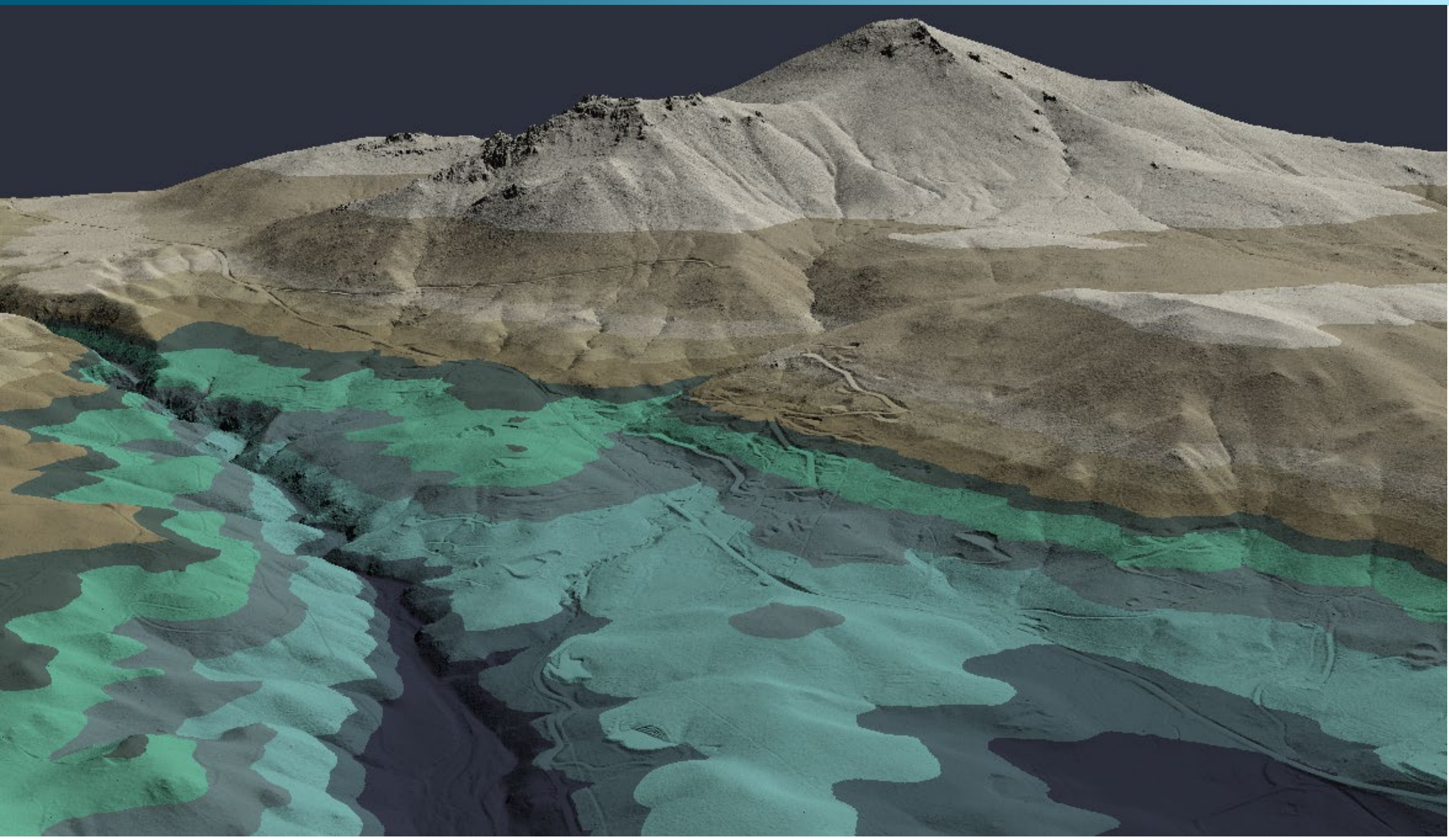
December 13, 2023



UCSD Fire Threat North Sierra Nevada (Phase 1A), California

2022 – 2023 Cumulative Lidar Technical Data Report

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Cover Photo: A view looking northwest over the UCSD Fire Threat North Sierra Nevada (Phase 1A) project area. The image was created from the lidar bare earth model colored by elevation.

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Introduction

This photo, taken by NV5 Geospatial acquisition staff shows a view of snow and trees in an area of the Plumas National Forest affected by the Dixie Fire in 2021.

In October 2021, NV5 Geospatial (NV5) was contracted by the University of California, San Diego (UCSD) to collect Light Detection and Ranging (lidar) data and digital imagery beginning in the fall of 2021 and extending into the summer of 2022 for the UCSD Fire Threat North Sierra Nevada (Phase 1A) site in California. The area near the Sierra Nevada Mountains in California contains the perfect conditions for wildfires, having dry highly combustible vegetation and dry weather conditions with occasional thunderstorms during the summer. The survey follows the Caldor, Tamarack, and Dixie fires of July to September 2021 and encompasses approximately 13,767 square miles of an area generally consisting of the US Forest Service CALVEG North Sierran ecoregion in California. This area of interest is characterized by high threat to wildfire as defined by the California Public Utilities Commission. Data were collected to aid UCSD in assessing the topographic and geophysical properties of the study area in support of their fire threat assessment initiative, furthering understanding and mitigation efforts associated with the extreme fire risks posed to this ecoregion.

This report accompanies the delivered lidar data and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including lidar accuracy and density. Acquisition dates and acreage are shown in Table 1, deliverable projection information is shown in Table 2, a complete list of contracted deliverables provided to UCSD is shown in Table 3, and the project extent is shown in Figure 1. This report encompasses the lidar full phase 1A project area, which is made up of 22 deliveries. Reference the report labeled “39806_UCSD_California_Fires_Orthos_Report.pdf” for a summary of the orthoimagery dataset.

Table 1: Acquisition dates, acreage, and data types collected on the UCSD Fire Threat North Sierra Nevada (Phase 1A) site by delivery area.

UTM Zone	Project Site	Buffered Sq. Miles	Aerial Acquisition Dates	Data Type
UTM 10	**D1A**	190	11/7/2021, 11/11/2021	NIR - Lidar
UTM 10	**D1B**	538	11/7/2021 - 11/8/2021, 11/11/2021, 11/23/2021, 11/28/2021 - 11/29/2021	NIR - Lidar
UTM 10	**D2**	475	11/8/2021, 11/23/2021, 11/25/2021 – 11/20/2021	NIR - Lidar
UTM 10	**D3**	475	11/24/2021 – 11/27/2021	NIR - Lidar
UTM 10	**D4**	627	11/16/2021, 11/24/2021 – 11/27/2021	NIR - Lidar
UTM 10	**D5**	585	11/16/2021, 11/23/2021 – 11/25/21, 11/29/2021 – 12/1/2021	NIR - Lidar
UTM 10	**D6**	688	11/23/2021 – 11/25/2021, 11/29/2021 – 12/1/2021	NIR - Lidar
UTM 10	**D7**	665	11/23/2021, 11/29/2021 – 12/2/2021	NIR - Lidar
UTM 10	**D8**	598	11/3/2021, 11/5/2021, 11/8/2021, 11/11/2021, 11/22/2021 – 11/25/2021, 11/28/2021 - 11/30/2021	NIR - Lidar
UTM 10	**D9**	559	11/29/2021 – 11/30/2021, 12/4/2021 – 12/5/2021	NIR - Lidar
UTM 10	**D10**	472	11/3/2021, 11/5/2021, 11/8/2021, 11/11/2021, 11/22/2021 – 11/25/2021, 11/29/2021 – 11/30/2021	NIR - Lidar
UTM 10	**D11**	554	11/3/2021, 11/5/2021, 11/8/2021, 11/12/2021, 11/22/2021 – 11/23/2021, 11/25/2021	NIR - Lidar
UTM 10	**D12**	505	11/8/2021, 11/12/2021, 11/15/2021 – 11/17/2021, 11/22/2021 – 11/23/2021, 11/25/2021 - 11/26/2021	NIR - Lidar
UTM 10	**D13**	468	11/12/2021 -11/13/2021, 11/15/2021 – 11/18/2021, 11/20/2021, 11/24/2021	NIR - Lidar
UTM 10	**D14, 19, 20a**	1,837	11/12/2021, 11/17/2021 - 11/18/2021, 11/20/2021 - 11/24/2021, 11/29/2021, 6/2/2022, 6/16/2022, 6/20/2022 – 6/21/2022, 6/28/2022 – 6/29/2022, 7/1/2022, 7/7/2022, 8/3/2022 – 8/4/2022, 8/19/2022 - 8/20/2022, 8/22/2022	NIR - Lidar
UTM 10	**D15 - 18**	2,136	11/3/2021, 11/5/2021, 11/8/2021, 11/12/2021, 11/18/2021, 11/22/2021, 11/24/2021, 11/29/2021 – 11/30/2021, 12/4/2021 – 12/5/2021, 5/26/2022 – 5/27/2022, 6/1/2022 – 6/2/2022, 6/15/2022 – 6/17/2022, 6/20/2022 – 6/21/2022, 6/28/2022 – 7/1/2022, 7/7/2022, 8/19/2022	NIR - Lidar
UTM 11	**D20b-22**	2,000	11/17/2021 - 11/18/2021, 11/21/2021, 6/1/2022, 6/2/2022 – 6/3/2022, 6/16/2022, 6/28/2022, 7/1/2022 – 7/6/2022, 7/30/2022, 8/20/2022 – 8/23/2022	NIR - Lidar
UTM 10 & UTM 11	**Cumulative**	13,267	11/3/2021 – 8/23/2022	NIR - Lidar

Deliverable Products

Table 2: Deliverable product projection information

Projections	Horizontal Datum	Vertical Datum	Units
UTM Zone 10 and 11 North	NAD83 (2011)	NAV88 (GEOID18)	Meters

Table 3: Products delivered to UCSD for the UCSD Fire Threat North Sierra Nevada (Phase 1A) site

Product Type	File Type	Product Details
Points	LAS v.1.4 (*.las), Point Format 6	• All Classified Returns
Rasters	0.5 meter GeoTiffs (*.tif)	• Bare Earth Digital Elevation Model (DEM) • Hydroflattened Bare Earth Model (DEM) • Highest Hit Digital Surface Model (DSM) • Intensity Images • Normalized Digital Surface Model* • Normalized Digital Surface Model (NDSM) Slope Model* • Bare Earth Slope Model* • Bare Earth Aspect Model* • Bare Earth East Aspect Model* • Bare Earth North Aspect Model* • Bare Earth Hillshades* • Topographic Position Index* • Topographic Openness Index*
Vectors	Shapefiles (*.shp)	• Full Project UTM 10 Tile Index • Full Project UTM 11 Tile Index • Full Project UTM 10 Buffered Boundary • Full Project UTM 11 Buffered Boundary • Ground Survey data • 3D Hydrobreaklines and Bridge Breaklines
Metadata	Extensible Markup Language (*.xml)	• Metadata
Reports	Adobe Acrobat (*.pdf)	• Lidar Technical Data Report

*The first delivery (D1A) did not include these deliverables

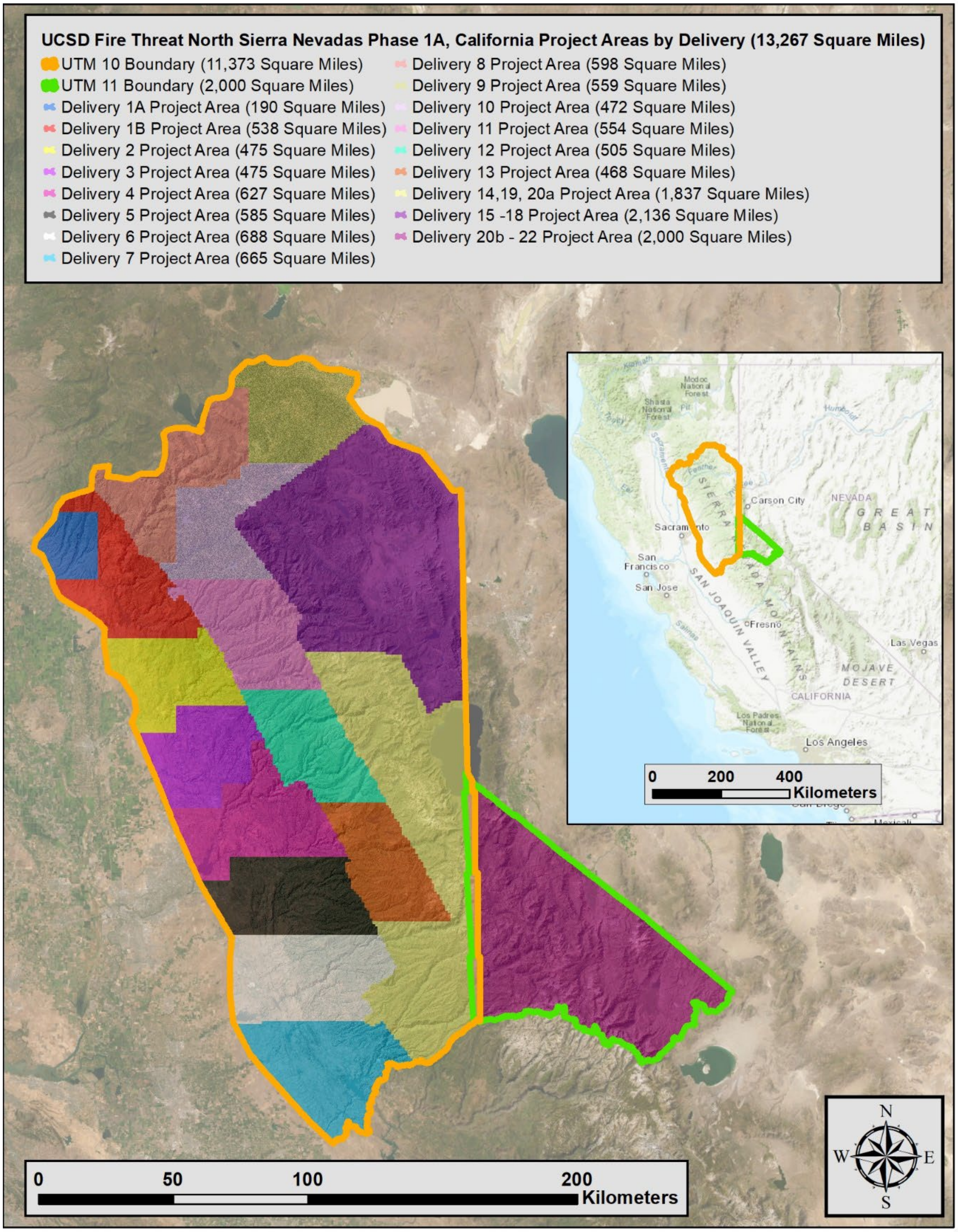


Figure 1: Location map of the UCSD Fire Threat North Sierra Nevada (Phase 1A) site in California

NV5 Geospatial's ground acquisition equipment set up in the UCSD Fire Threat North Sierra Nevada (Phase 1A) Lidar study area.

Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the UCSD Fire Threat North Sierra Nevada (Phase 1A) lidar study area at the target point density of ≥ 8.0 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications. Figure 2 shows these optimized flight paths and dates.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne Survey

Lidar

The lidar survey was accomplished using a Riegl VQ-1560ii-S system mounted in a Cessna Caravan. Table 4 summarizes the settings used to yield an average pulse density of ≥ 8 pulses/m^2 over the UCSD Fire Threat North Sierra Nevada (Phase 1A) project area. The Riegl VQ-1560ii-S laser system can record unlimited range measurements (returns) per pulse, however a maximum of 15 returns can be stored due to LAS v1.4 file limitations. 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. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset. Figure 2 shows the flightlines acquired using these lidar specifications.

Table 4: Lidar specifications and aerial survey settings

Parameter	NIR Laser
Acquisition Dates	11/3/2021 – 8/23/2022
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser Channel	VQ-1560ii-S
Maximum Returns	15
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2,500 m
Survey speed	145 knots
Field of View	58.5º
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	757 kHz
Pulse Length	3.0 ns
Laser Pulse Footprint Diameter	57.5 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.23 mrad
Swath Width	2,800 m
Swath Overlap	55%
Intensity	16-bit
Vertical Accuracy	$RMSE_Z$ (Non-Vegetated) ≤ 10 cm
NVA Accuracy	NVA (95% Confidence Level) ≤ 19.6 cm
VVA Accuracy	VVA (95th Percentile) ≤ 30 cm

Riegl VQ-1560ii-S

All areas were surveyed with an opposing flight line side-lap of ≥55% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and z), the positional coordinates of the airborne sensor and the orientation of the aircraft to the horizon (attitude) 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, and 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 and sensor position and attitude data are indexed by GPS time.

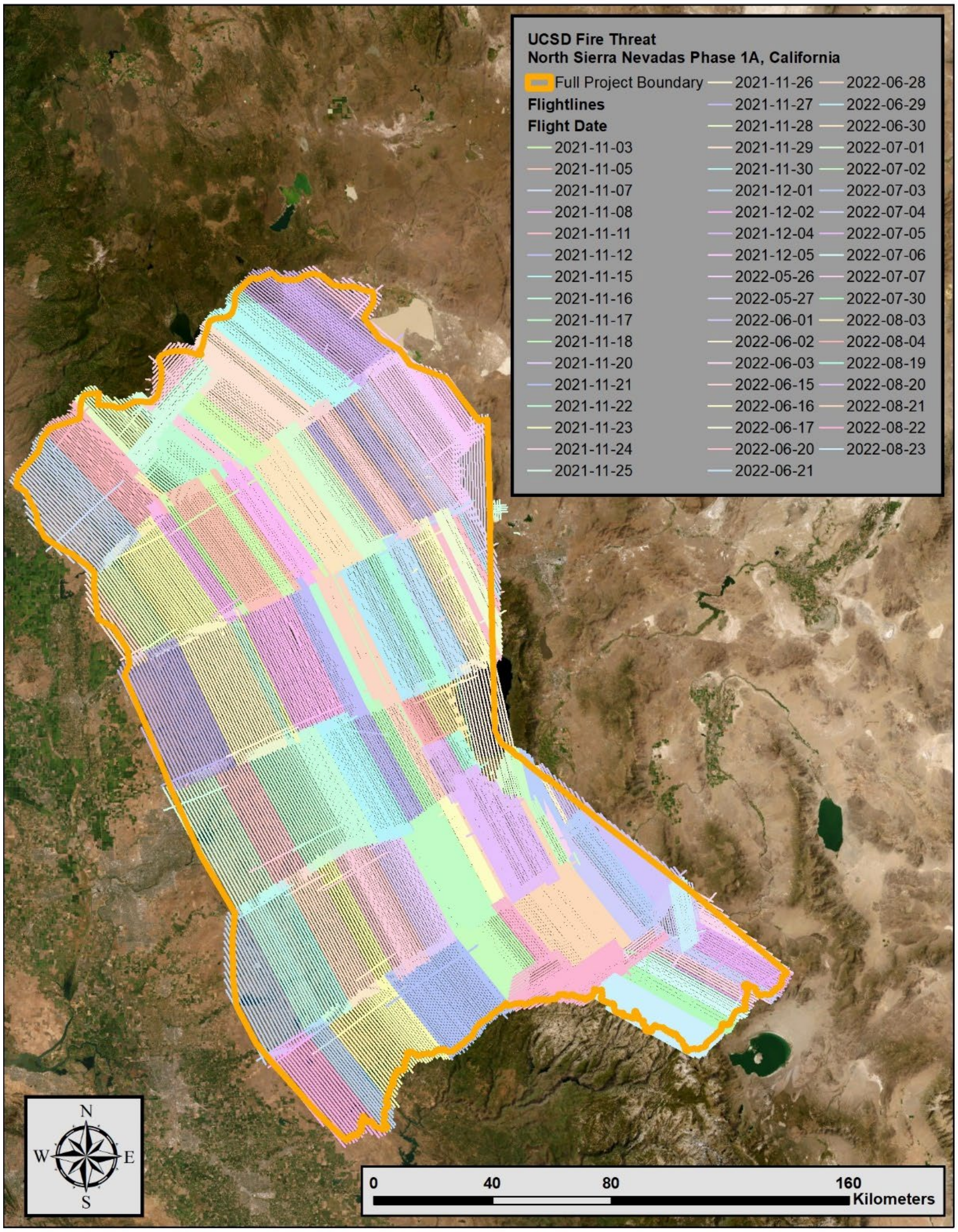


Figure 2: Flightlines map

Ground Survey

Ground control surveys, including monumentation, aerial targets and ground survey points (GSPs) were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data.

Existing USGS Monument

NV5 Geospatial-Established Monument

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK), post processed kinematic (PPK), fast static (FS), and total station (TS) survey techniques.

Base station locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 Geospatial utilized 20 permanent real-time network (RTN) base stations (8 from the California Surveying and Drafting Supply and 12 from the Hexagon SmartNet network, and 1 from NGS), 30 new monuments, and 3 existing monuments (including 2 from the California Department of Transportation (CDOT) and 1 from USGS) for the UCSD Fire Threat North Sierra Nevada (Phase 1A) Lidar project (Table 5). NV5 Geospatial established 28 new monuments using 6" mag hub nails with orange survey washers and set 2 monuments using 5/8" x 30" rebar topped with stamped 2 ½ " aluminum caps. Evon Silvia (CAPLS#9401) oversaw and certified the ground survey.

Table 5: Base station positions for the UCSD Fire Threat North Sierra Nevada (Phase 1A) acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Owner	Type
CH1F	39° 45' 41.22825"	-121° 52' 00.85247"	34.785	CSDS	RTN
GV1K	39° 13' 58.76859"	-121° 02' 34.75684"	794.139	CSDS	RTN
LD1J	38° 08' 13.57317"	-121° 15' 14.58255"	-6.810	CSDS	RTN
MD1I	37° 38' 55.34920"	-120° 58' 39.86345"	6.466	CSDS	RTN
OR1J	39° 30' 18.80455"	-121° 33' 09.27255"	40.770	CSDS	RTN
SS1H	38° 39' 58.90613"	-120° 56' 14.91233"	457.080	CSDS	RTN
YC1H	39° 08' 43.40979"	-121° 38' 33.44751"	-3.477	CSDS	RTN
SACR	38° 39' 17.97072"	-121° 21' 15.19293"	7.472	CSDS	RTN
CACH	39° 42' 50.90381"	-121° 48' 18.99053"	43.933	SMARTNET	RTN
CACR	40° 18' 34.61612"	-121° 13' 44.72082"	1365.022	SMARTNET	RTN
CAEG	38° 22' 51.96521"	-121° 21' 54.25715"	-9.318	SMARTNET	RTN
CAOD	37° 46' 09.98122"	-120° 50' 16.01202"	21.51	SMARTNET	RTN

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Owner	Type
CAOV	39° 29' 46.71485"	-121° 36' 35.12665"	38.645	SMARTNET	RTN
CAPV	38° 41' 50.41539"	-120° 49' 27.00363"	530.245	SMARTNET	RTN
CARK	38° 47' 25.35750"	-121° 18' 45.30085"	18.867	SMARTNET	RTN
CASV	40° 22' 44.64976"	-120° 27' 55.97377"	1232.010	SMARTNET	RTN
NVCC	39° 10' 50.94034"	-119° 45' 55.01467"	1419.708	SMARTNET	RTN
NVSP	39° 31' 42.90057"	-119° 42' 06.76297"	1326.85	SMARTNET	RTN
P143	38° 45' 36.58617"	-119° 45' 53.35829"	1734.144	SMARTNET	RTN
P147	39° 56' 14.57671"	-120° 17' 03.83554"	2489.452	SMARTNET	RTN
CMBB	38° 02' 03.02146"	-120° 23' 09.69394"	696.297	NGS	RTN
89PLU	40° 06' 31.21167"	-120° 54' 27.16654"	1054.746	CDOT	AL Cap
CLAPPE	40° 00' 32.98259"	-121° 11' 27.36742"	762.831	CDOT	Brass Cap
UCSD_FIRE_01	39° 56' 56.34188"	-121° 03' 08.06376"	1091.912	NV5	Set Nail
UCSD_FIRE_02	39° 56' 53.63000"	-120° 55' 28.47964"	1015.157	NV5	Set Nail
UCSD_FIRE_03	39° 03' 22.38766"	-121° 19' 19.98511"	69.955	NV5	Set Nail
UCSD_FIRE_04	39° 27' 12.43661"	-121° 16' 55.40021"	601.255	NV5	Set Nail
UCSD_FIRE_05	39° 05' 19.17748"	-120° 57' 15.16457"	663.274	NV5	Set Nail
UCSD_FIRE_07	38° 50' 30.36441"	-120° 53' 19.21374"	562.810	NV5	Set Nail
UCSD_FIRE_08	38° 26' 08.11181"	-120° 33' 04.97841"	933.475	NV5	Set Nail
UCSD_FIRE_09	40° 10' 51.54205"	-120° 36' 28.94102"	1509.712	NV5	Set Nail
UCSD_FIRE_10	40° 03' 19.84580"	-121° 35' 39.71582"	1357.788	USGS	AL Cap
UCSD_FIRE_11	39° 58' 59.31845"	-121° 16' 55.60642"	633.738	NV5	Set Nail
UCSD_FIRE_12	39° 53' 59.64192"	-121° 31' 11.52379"	1050.214	NV5	AL Cap
UCSD_FIRE_13	39° 35' 09.29564"	-121° 04' 40.80538"	1192.909	NV5	AL Cap
UCSD_FIRE_14	39° 44' 42.08712"	-120° 35' 18.38238"	1314.227	NV5	Set Nail
UCSD_FIRE_15	39° 55' 44.76796"	-120° 30' 41.24853"	1737.423	NV5	Set Nail
UCSD_FIRE_16	39° 27' 31.03713"	-120° 55' 42.51351"	1355.708	NV5	Set Nail
UCSD_FIRE_17	39° 29' 49.67239"	-121° 01' 29.97635"	943.067	NV5	Set Nail
UCSD_FIRE_18	38° 15' 00.69728"	-119° 12' 50.23061"	1967.256	NV5	Set Nail
UCSD_FIRE_19	38° 31' 00.70864"	-119° 27' 29.73751"	1638.472	NV5	Set Nail
UCSD_FIRE_20	38° 20' 59.69831"	-119° 26' 25.42930"	2221.712	NV5	Set Nail

Monument ID	Latitude	Longitude	Ellipsoid (meters)	Owner	Type
UCSD_FIRE_21	38° 39' 25.85446"	-119° 32' 14.17068"	1507.619	NV5	Set Nail
UCSD_FIRE_22	38° 33' 54.47169"	-120° 16' 02.83325"	2065.460	NV5	Set Nail
UCSD_FIRE_23	38° 54' 37.48592"	-120° 30' 38.81412"	1474.628	NV5	Set Nail
UCSD_FIRE_24	39° 07' 00.80841"	-120° 28' 57.43896"	1705.348	NV5	Set Nail
UCSD_FIRE_25	39° 08' 20.28952"	-120° 38' 56.34450"	1486.127	NV5	Set Nail
UCSD_FIRE_26	39° 30' 12.25792"	-120° 47' 00.55736"	1690.256	NV5	Set Nail
UCSD_FIRE_27	39° 29' 42.05156"	-120° 24' 41.70659"	2058.234	NV5	Set Nail
UCSD_FIRE_28	39° 36' 49.89251"	-120° 36' 05.03954"	1663.162	NV5	Set Nail
UCSD_FIRE_29	39° 35' 44.98466"	-120° 06' 19.14701"	2557.078	NV5	Set Nail
UCSD_FIRE_30	38° 33' 26.21883"	-119° 48' 28.92870"	2523.271	NV5	Set Nail
UCSD_FIRE_31	38° 19' 40.91922"	-119° 38' 11.13639"	2918.578	NV5	Set Nail
UCSD_FIRE_87	38° 15' 10.51824"	-119° 12' 40.11244"	2000.638	NV5	Set Nail

NV5 Geospatial utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project is shown in Table 6.

Table 6: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.020 m
1.96 * St Dev $_{z}$:	0.050 m

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

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3: FGDC Standards Website

For the UCSD Fire Threat North Sierra Nevada (Phase 1A) Lidar project, the monument coordinates contributed no more than 5.6 cm of positional error to the geolocation of the final ground survey points and lidar, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK), post-processed kinematic (PPK), fast-static (FS), and total station (TS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. PPK and FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK and PPK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. All GSP 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. See Table 7 for Trimble unit specifications.

Forested checkpoints are collected using total stations in order to measure positions under dense canopy. Total station backsight and setup points are established using GNSS survey techniques.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP 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. GSPs were collected within as many flightlines as possible; however, the distribution of GSPs depended on ground access constraints and monument locations and may not be equably distributed throughout the study area (Figure 3).

Table 7: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R8 Model 3	Integrated Antenna	TRMR8_GNSS3	Rover
Trimble R10 Model 2	Integrated Antenna	TRMR10-2	Rover or Static
Trimble R12	Integrated Antenna	TRMR12	Rover or Static
Nikon X-Series Total Station	N/A	N/A	VVA
Nikon NPL-322+ 5” P Total Station	N/A	N/A	VVA
Trimble M3 Total Station	N/A	N/A	VVA

Land Cover Class

In addition to ground survey points, land cover class checkpoints were collected throughout the study area to evaluate vertical accuracy. Vertical accuracy statistics were calculated for all land cover types to assess confidence in the lidar derived ground models across land cover classes (Table 8, see Lidar Accuracy Assessments, page 23).

Table 8: Land Cover Types and Descriptions

Land cover type	Land cover code	Example	Description	Accuracy Assessment Type
Shrub	SH		Low growth shrub	VVA
Tall Grass	TG		Herbaceous grasslands in advanced stages of growth	VVA
Forest	FR		Forested areas	VVA
Bare Earth	BARE, BE		Areas of bare earth surface	NVA
Urban	UA		Areas dominated by urban development, including parks	NVA

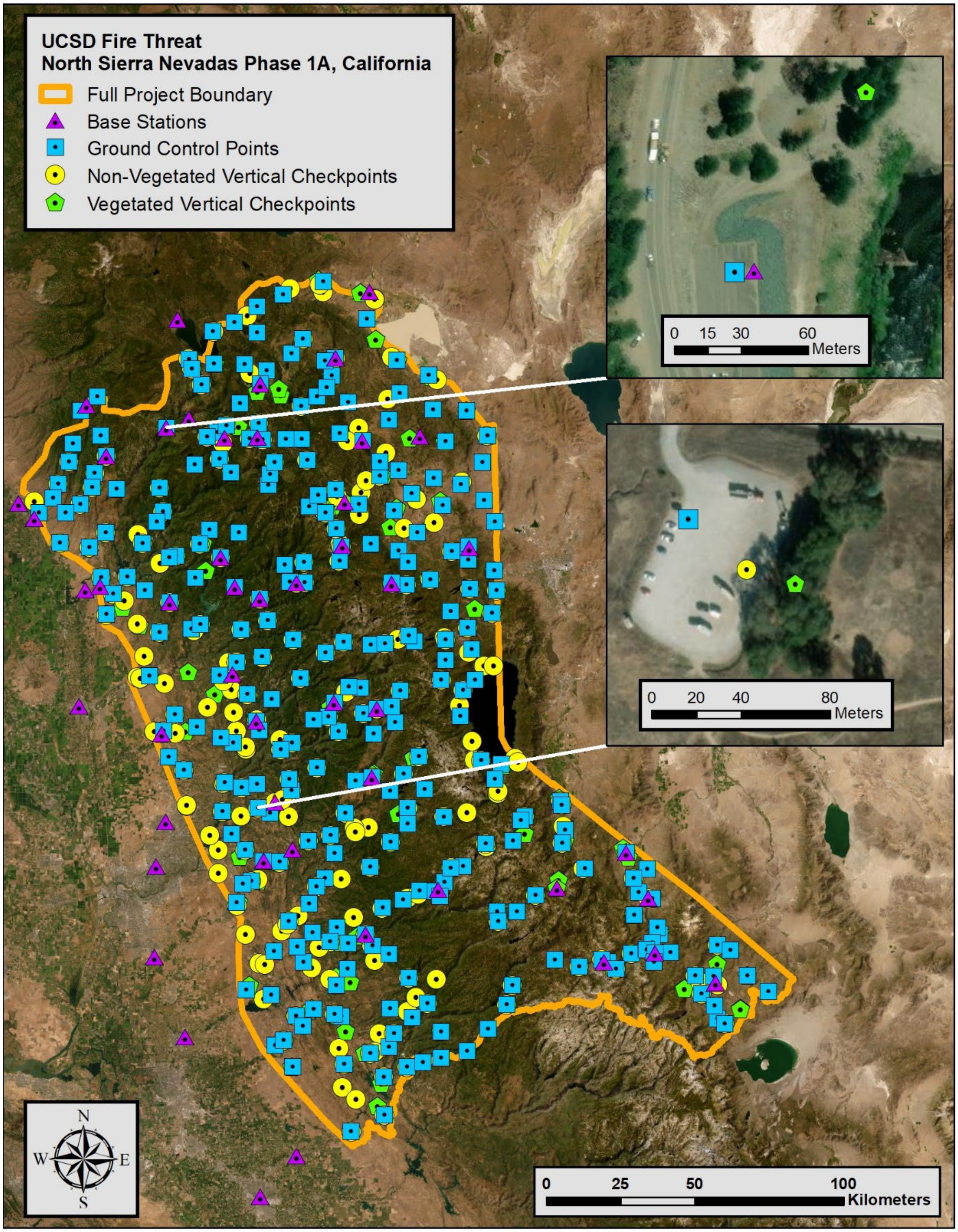
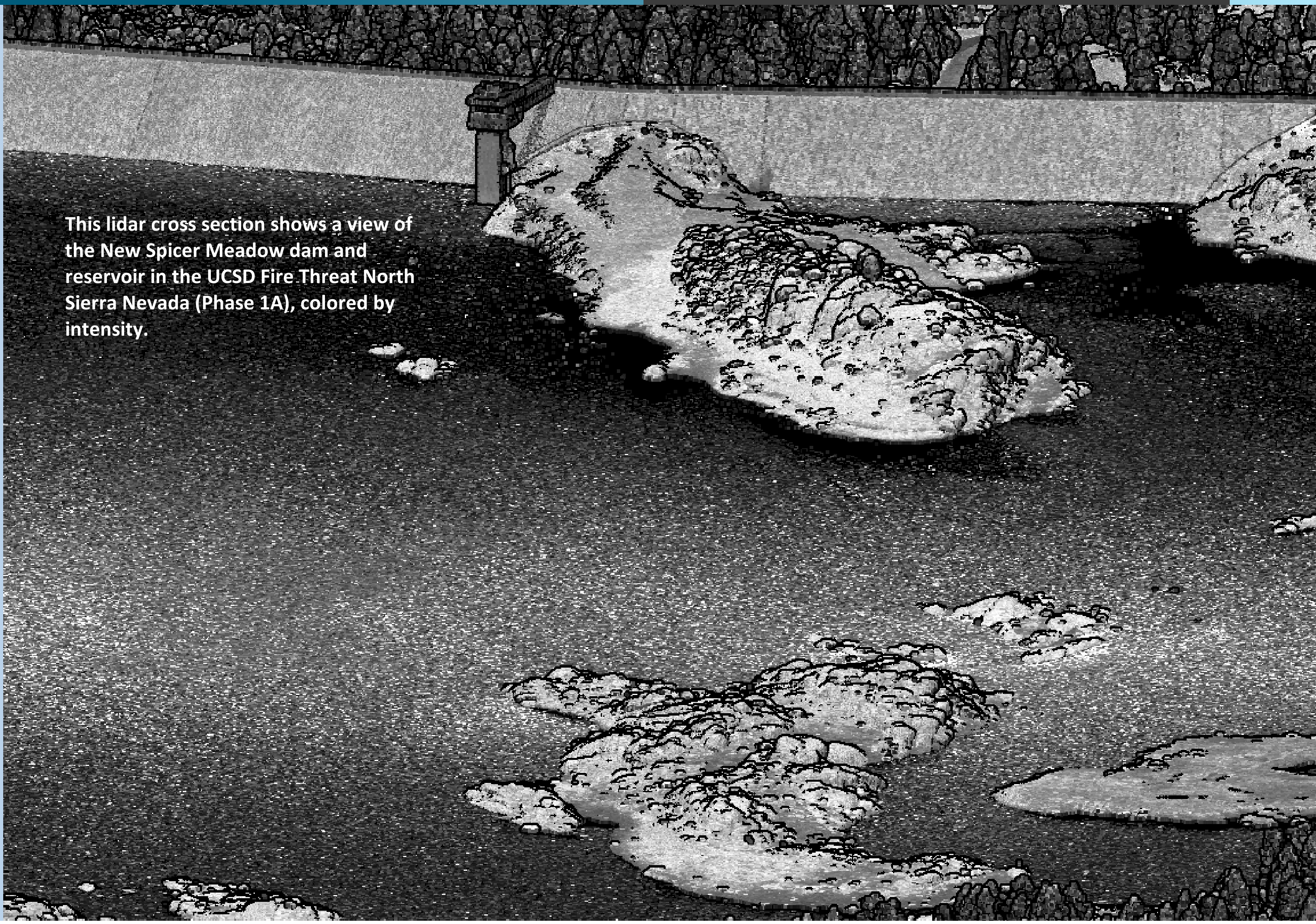


Figure 3: Ground survey location map



This lidar cross section shows a view of the New Spicer Meadow dam and reservoir in the UCSD Fire Threat North Sierra Nevada (Phase 1A), colored by intensity.

NIR Lidar Data

Upon completion of data acquisition, NV5 Geospatial processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and lidar point classification (Table 9). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 10.

Table 9: ASPRS LAS classification standards applied to the UCSD Fire Threat North Sierra Nevada (Phase 1A) dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
1W	Edge Clip/Withheld	Laser returns at the outer edges of flightlines that are geometrically unreliable
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7W	Noise/Withheld	Laser returns that are often artificial points below the ground surface
9	Water	Laser returns that are determined to be water using automated and manual cleaning algorithms
17	Bridge	Bridge decks
18W	High Noise/Withheld	Laser returns that are often associated with birds or scattering from reflective surfaces.
20	Ignored Ground	Ground points proximate to water's edge breaklines; ignored for correct model creation
21	Snow	Laser returns in the presence of snow for D20 - D22
22	Temporal Exclusion	Data excluded due to temporal variation with adjacent lift

Table 10: Lidar processing workflow

Lidar Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	POSPac MMS v.8.9
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. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiUnite v.1.0.3
Import raw laser points into manageable blocks to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.19.005
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	StripAlign v.2.21
Classify resulting data to ground and other client designated ASPRS classifications (Table 3). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.003
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as Cloud Optimized GeoTIFFs at a 0.5 meter pixel resolution.	LAS Product Creator 4.0 (NV5 Geospatial proprietary) ArcMap v. 10.8.1
Bare Earth raster models were utilized in production of Aspect, Aspect East, Aspect North, Hillshade, Slope, Openness, and Topographic Position index Rasters.	OpenHydro (NV5 Proprietary)
Bare Earth and Highest Hit raster models were utilized in production of Normalized Digital Surface and Normalized Digital Surface Slope Raster Models	OpenHydro (NV5 Proprietary)
Export intensity images as Cloud Optimized GeoTIFFs at a 0.5 meter pixel resolution.	LAS Product Creator 4.0 (NV5 Geospatial proprietary)

Feature Extraction

Hydroflattening and Water's Edge Breaklines

The UCSD Fire Threat North Sierra Nevada (Phase 1A)River and other water bodies within the project area were flattened to a consistent water level. Bodies of water that were flattened include lakes and other closed water bodies with a surface area greater than 2 acres, all streams and rivers that are nominally wider than 30 meters, all non-tidal waters bordering the project, and select smaller bodies of water as feasible. The hydroflattening process eliminates artifacts in the digital terrain model caused by both increased variability in ranges or dropouts in laser returns due to the low reflectivity of water.

Hydroflattening of closed water bodies was performed through a combination of automated and manual detection and adjustment techniques designed to identify water boundaries and water levels. Boundary polygons were developed using an algorithm which weights lidar-derived slopes, intensities, and return densities to detect the water's edge. The water edges were then manually reviewed and edited as necessary.

Once polygons were developed the initial ground classified points falling within water polygons were reclassified as water points to omit them from the final ground model. Elevations were then obtained from the filtered lidar returns to create the final breaklines. Lakes were assigned a consistent elevation for an entire polygon while rivers were assigned consistent elevations on opposing banks and smoothed to ensure downstream flow through the entire river channel.

Water boundary breaklines were then incorporated into the hydroflattened DEM by enforcing triangle edges (adjacent to the breakline) to the elevation values of the breakline. This implementation corrected interpolation along the hard edge. Water surfaces were obtained from a TIN of the 3-D water edge breaklines resulting in the final hydroflattened model (Figure 4).

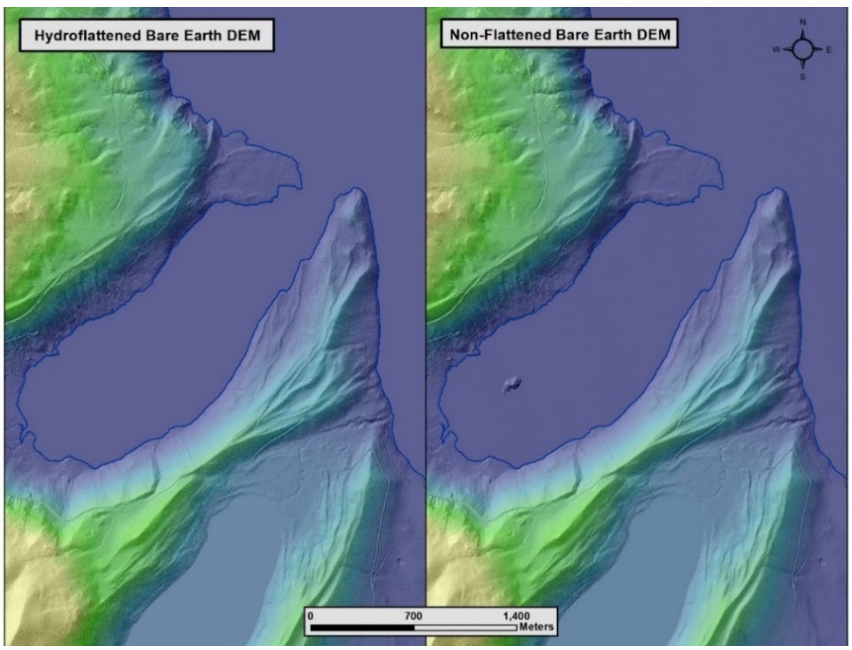
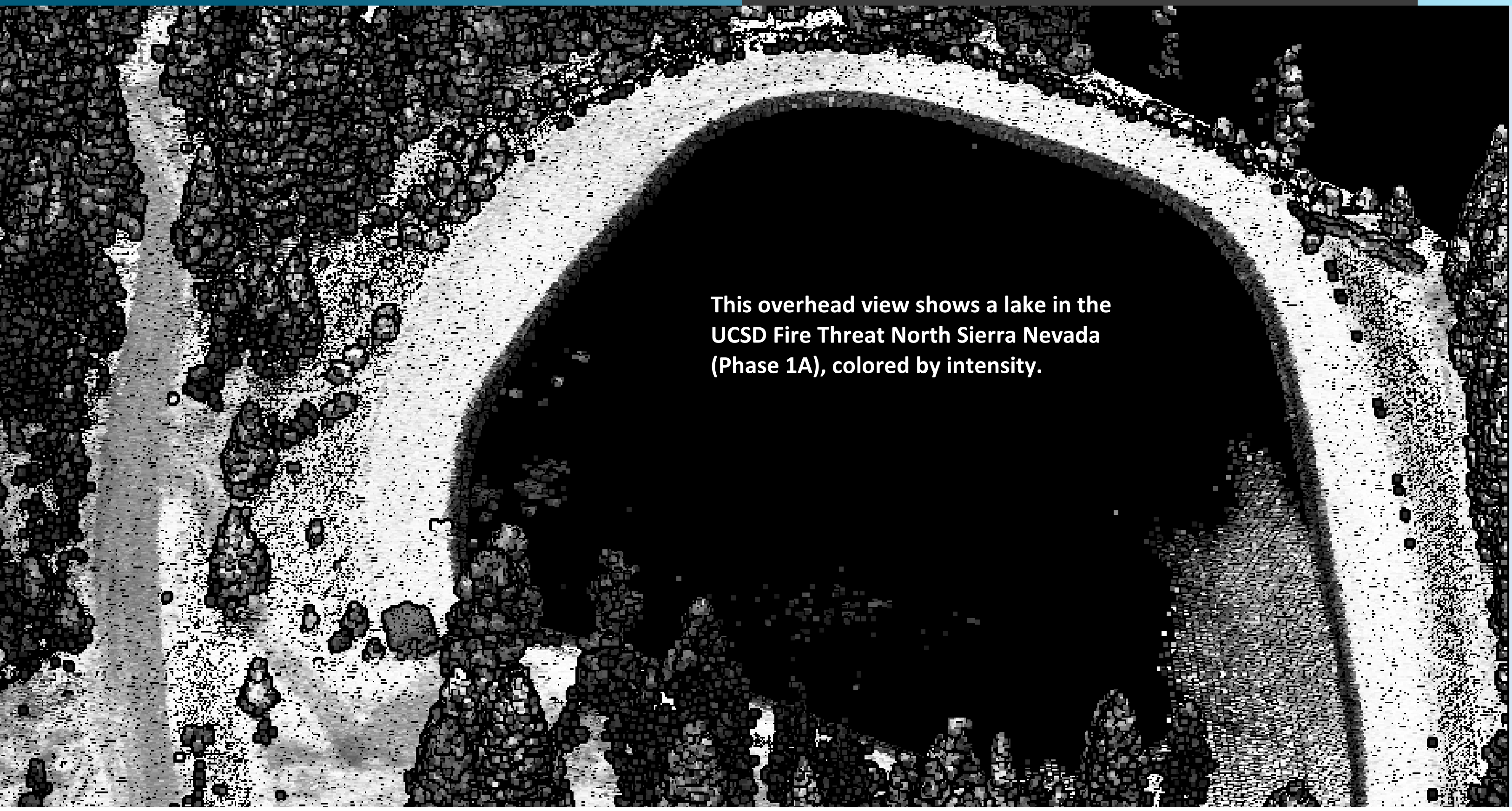


Figure 4: Example of hydroflattening in the UCSD Fire Threat North Sierra Nevada (Phase 1A) Lidar dataset



Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 . First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser.

First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas, the highest feature could be a tree, building, or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of lidar data for the full UCSD Fire Threat North Sierra Nevada (Phase 1A) project was 16.93 points/m^2 while the average ground classified density was 6.07 points/m^2 (Table 11). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 5 through Figure 7.

Table 11: Average lidar point densities

Delivery	Classification	Point Density	Delivery	Classification	Point Density
D1A	First-Return	14.14 points/m^2	D9	First-Return	18.31 points/m^2
D1A	Ground Classified	5.57 points/m^2	D9	Ground Classified	7.51 points/m^2
D1B	First-Return	16.52 points/m^2	D10	First-Return	21.57 points/m^2
D1B	Ground Classified	5.75 points/m^2	D10	Ground Classified	6.66 points/m^2
D2	First-Return	15.28 points/m^2	D11	First-Return	19.02 points/m^2
D2	Ground Classified	5.51 points/m^2	D11	Ground Classified	4.23 points/m^2
D3	First-Return	13.53 points/m^2	D12	First-Return	18.28 points/m^2
D3	Ground Classified	6.08 points/m^2	D12	Ground Classified	4.76 points/m^2
D4	First-Return	14.99 points/m^2	D13	First-Return	19.69 points/m^2
D4	Ground Classified	5.04 points/m^2	D13	Ground Classified	6.59 points/m^2
D5	First-Return	15.23 points/m^2	D14, 19, 20a	First-Return	18.59 points/m^2
D5	Ground Classified	5.97 points/m^2	D14, 19, 20a	Ground Classified	5.43 points/m^2
D6	First-Return	14.16 points/m^2	D15 - 18	First-Return	18.78 points/m^2
D6	Ground Classified	6.11 points/m^2	D15 - 18	Ground Classified	6.41 points/m^2
D7	First-Return	13.46 points/m^2	D20b -22	First-Return	21.46 points/m^2
D7	Ground Classified	6.75 points/m^2	D20b -22	Ground Classified	10.94 points/m^2
D8	First-Return	21.84 points/m^2	Cumulative	First-Return	16.93 points/m^2
D8	Ground Classified	7.07 points/m^2	Cumulative	Ground Classified	6.07 points/m^2

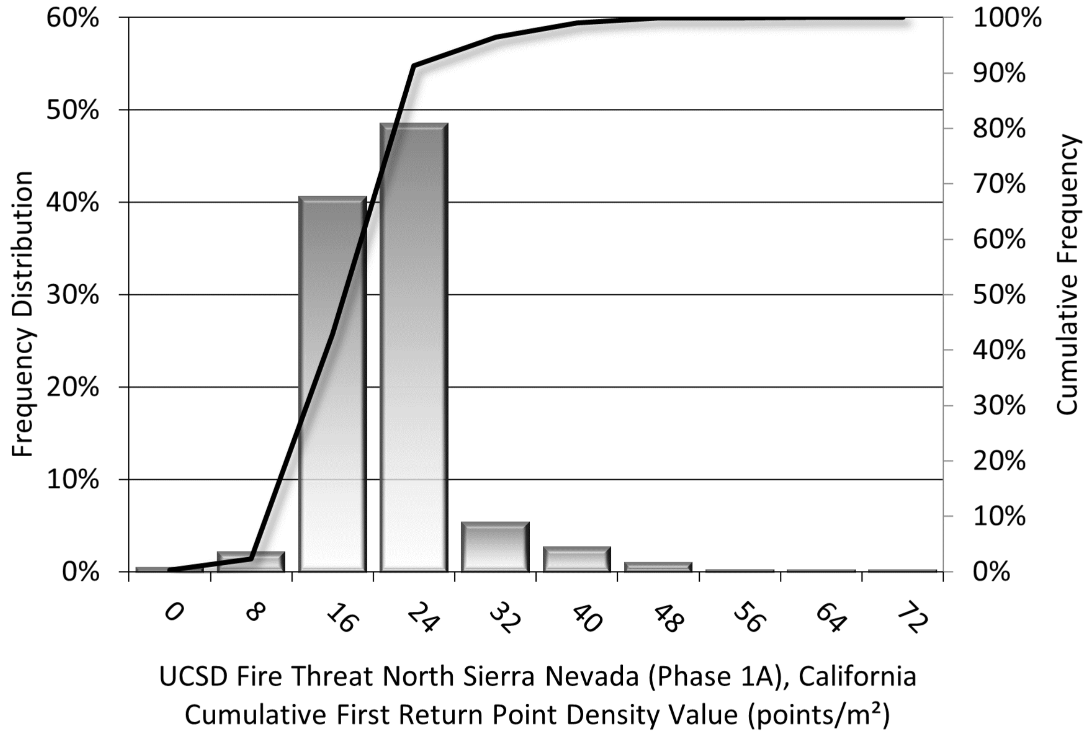


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

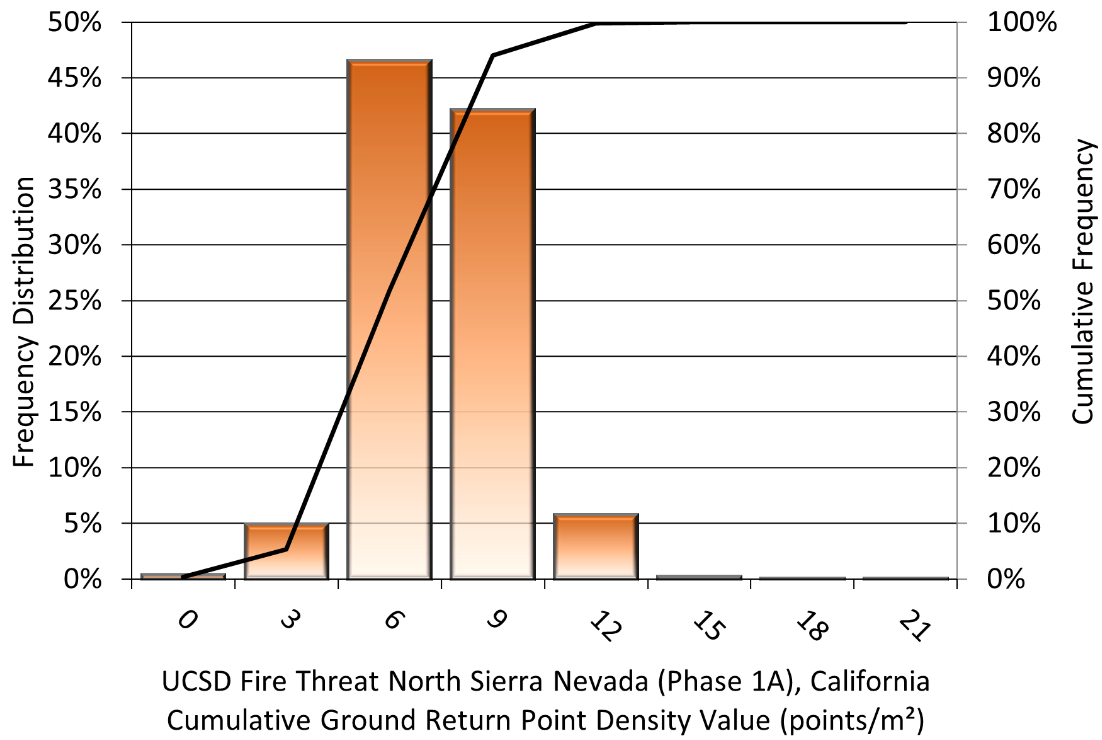


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

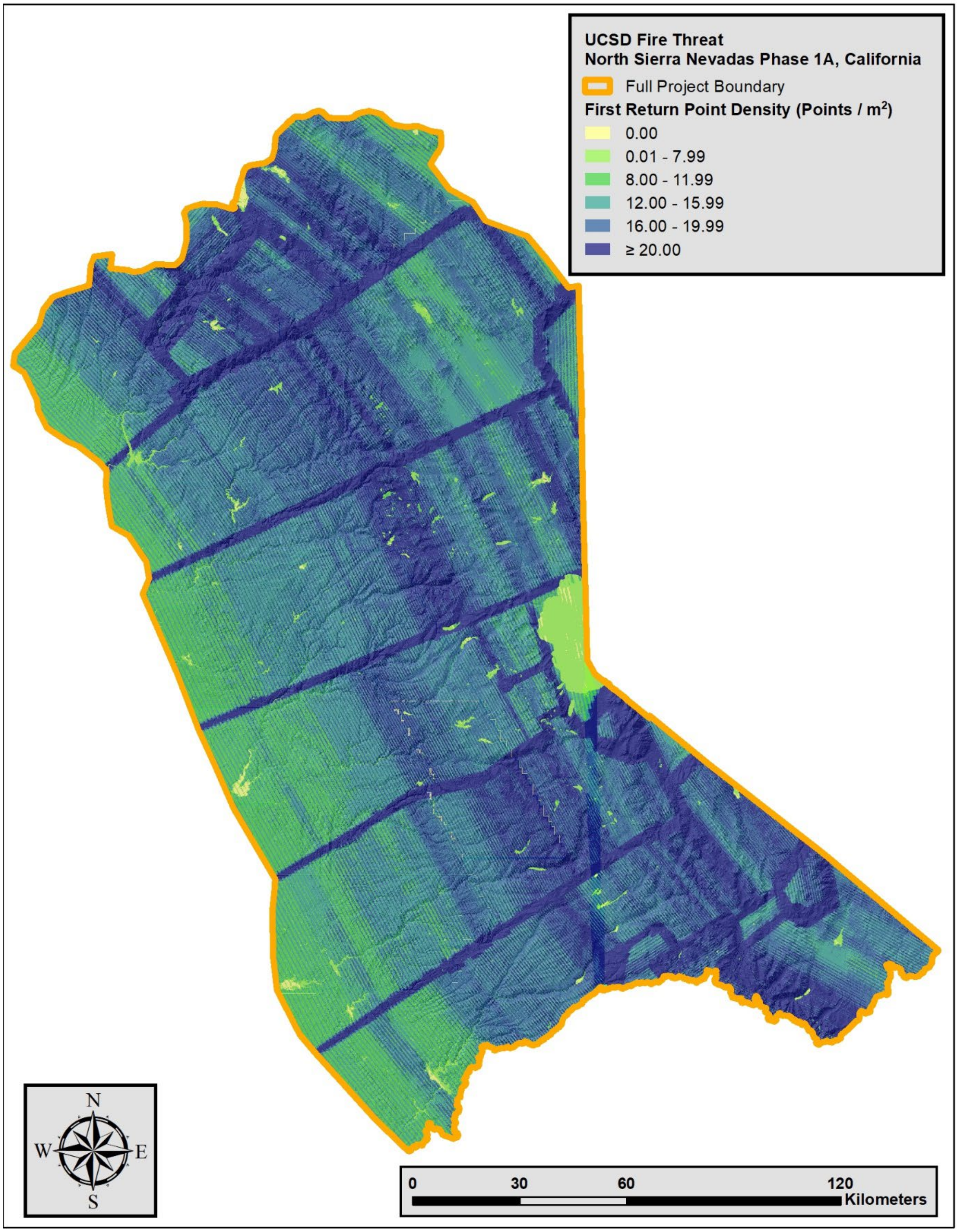


Figure 7: First return point density map for the UCSD Fire Threat North Sierra Nevada (Phase 1A) site (100 m x 100 m cells).

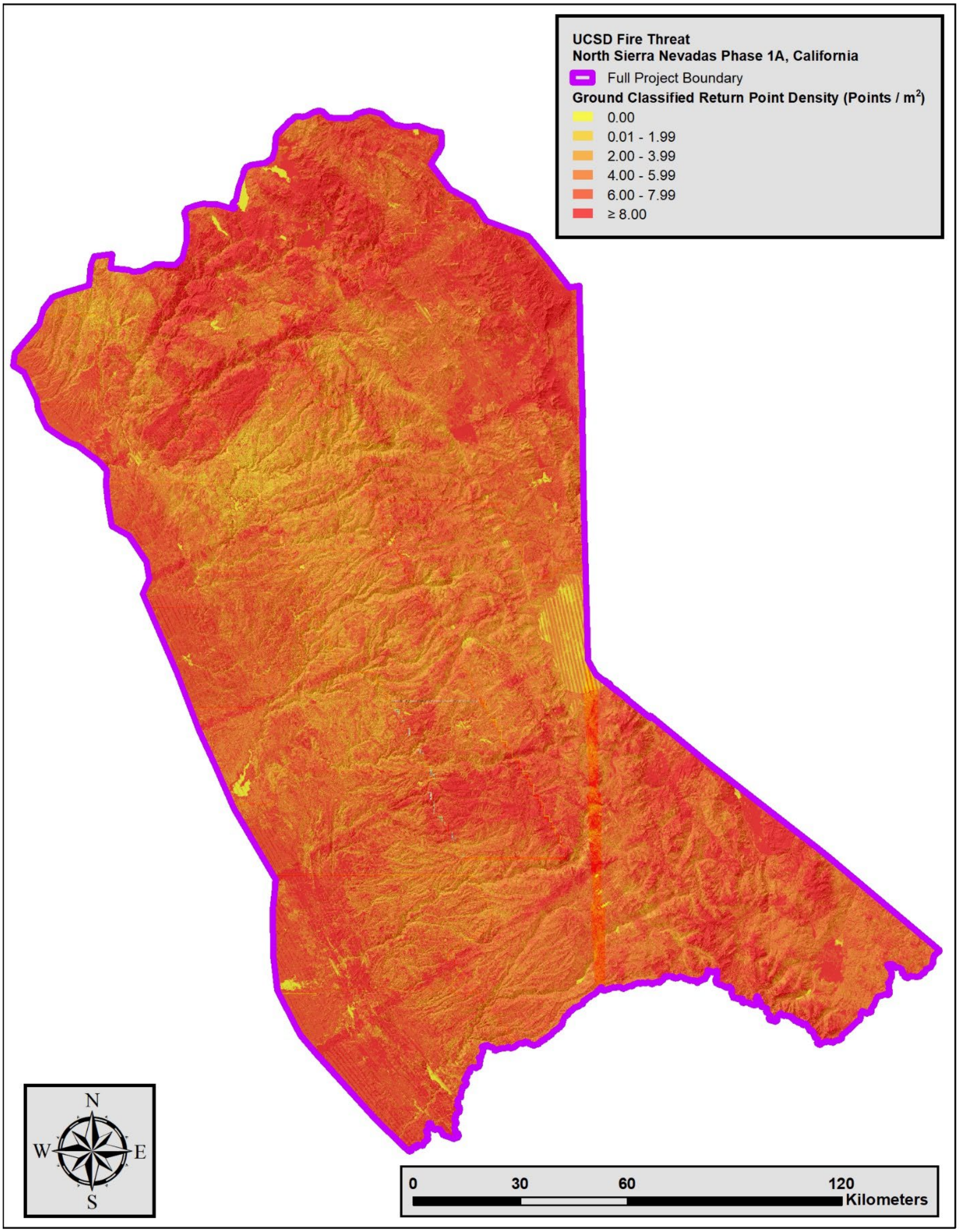


Figure 8: Ground classified point density map for the UCSD Fire Threat North Sierra Nevada (Phase 1A) site (100 m x 100 m cells).

Lidar Accuracy Assessments

The accuracy of the 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). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

Lidar Non-Vegetated Vertical Accuracy

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. NVA compares known ground checkpoint data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. NVA is a measure of the accuracy of lidar point data in open areas where the lidar system has a high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 12 through Table 16.

The mean and standard deviation (sigma, σ) of divergence of the ground surface model from quality assurance point coordinates are also considered during accuracy assessment. The number of points evaluated for NVA is large enough that the error for x, y, and z is approximately normally distributed. The skew and kurtosis of distributions are also considered when evaluating error statistics in order to better evaluate the magnitude and distribution of the estimated error. For the UCSD Fire Threat North Sierra Nevada (Phase 1A) survey, 259 ground checkpoints were withheld from the calibration and post processing of the lidar point cloud, with a resulting cumulative non-vegetated vertical accuracy of 0.060 meters as compared to classified LAS, and 0.064 meters as compared to the bare earth DEM, with 95% confidence (Figure 9, Figure 10).

NV5 Geospatial also assessed absolute accuracy using 292 ground control points overall. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset, and therefore have been provided in Table 12 and Figure 11.

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[3] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 12: Absolute accuracy results (D1 through D3)

Delivery	Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
D1A	Sample	7 points	7 points	7 points
D1A	95% Confidence (1.96*RMSE)	0.064 m	0.088 m	0.053 m
D1A	Average	-0.020 m	-0.018 m	-0.016 m
D1A	Median	-0.011 m	-0.007 m	-0.018 m
D1A	RMSE	0.033 m	0.045 m	0.027 m
D1A	Standard Deviation (1σ)	0.028 m	0.044 m	0.024 m
D1B	Sample	12 points	12 points	12 points
D1B	95% Confidence (1.96*RMSE)	0.059 m	0.058 m	0.059 m
D1B	Average	-0.019 m	-0.018 m	-0.021 m
D1B	Median	-0.011 m	-0.015 m	-0.023 m
D1B	RMSE	0.030 m	0.030 m	0.030 m
D1B	Standard Deviation (1σ)	0.024 m	0.025 m	0.023 m
D2	Sample	16 points	16 points	10 points
D2	95% Confidence (1.96*RMSE)	0.049 m	0.056 m	0.074 m
D2	Average	0.001 m	-0.003 m	-0.006 m
D2	Median	0.005 m	0.000 m	-0.004 m
D2	RMSE	0.025 m	0.028 m	0.038 m
D2	Standard Deviation (1σ)	0.026 m	0.029 m	0.039 m
D3	Sample	17 points	17 points	11 points
D3	95% Confidence (1.96*RMSE)	0.041 m	0.042 m	0.039 m
D3	Average	0.005 m	0.003 m	0.004 m
D3	Median	-0.003 m	-0.004 m	0.002 m
D3	RMSE	0.021 m	0.021 m	0.020 m
D3	Standard Deviation (1σ)	0.021 m	0.022 m	0.020 m

Table 13: Absolute accuracy results (D4 through D7)

Delivery	Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
D4	**Sample**	22 points	22 points	13 points
D4	**95% Confidence (1.96*RMSE)**	0.041 m	0.042 m	0.055 m
D4	**Average**	-0.011 m	-0.010 m	-0.002 m
D4	**Median**	-0.017 m	-0.010 m	-0.011 m
D4	**RMSE**	0.021 m	0.022 m	0.028 m
D4	**Standard Deviation (1σ)**	0.018 m	0.020 m	0.029 m
D5	**Sample**	15 points	15 points	14 points
D5	**95% Confidence (1.96*RMSE)**	0.049 m	0.048 m	0.085 m
D5	**Average**	-0.004 m	-0.006 m	-0.013 m
D5	**Median**	-0.010 m	-0.005 m	-0.019 m
D5	**RMSE**	0.025 m	0.024 m	0.043 m
D5	**Standard Deviation (1σ)**	0.025 m	0.025 m	0.043 m
D6	**Sample**	16 points	16 points	17 points
D6	**95% Confidence (1.96*RMSE)**	0.039 m	0.041 m	0.032 m
D6	**Average**	-0.006 m	-0.005 m	0.007 m
D6	**Median**	-0.006 m	-0.005 m	0.011 m
D6	**RMSE**	0.020 m	0.021 m	0.016 m
D6	**Standard Deviation (1σ)**	0.020 m	0.021 m	0.015 m
D7	**Sample**	16 points	16 points	16 points
D7	**95% Confidence (1.96*RMSE)**	0.060 m	0.058 m	0.067 m
D7	**Average**	0.018 m	0.018 m	-0.002 m
D7	**Median**	0.018 m	0.020 m	0.002 m
D7	**RMSE**	0.030 m	0.029 m	0.034 m
D7	**Standard Deviation (1σ)**	0.025 m	0.024 m	0.035 m

Table 14: Absolute accuracy results (D8 through D11)

Delivery	Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
D8	**Sample**	9 points	9 points	8 points
D8	**95% Confidence (1.96*RMSE)**	0.036 m	0.047 m	0.053 m
D8	**Average**	-0.003 m	-0.007 m	0.010 m
D8	**Median**	0.001 m	0.003 m	0.009 m
D8	**RMSE**	0.019 m	0.024 m	0.027 m
D8	**Standard Deviation (1σ)**	0.019 m	0.024 m	0.027 m
D9	**Sample**	7 points	7 points	12 points
D9	**95% Confidence (1.96*RMSE)**	0.066 m	0.066 m	0.041 m
D9	**Average**	0.023 m	0.022 m	-0.002 m
D9	**Median**	0.034 m	0.029 m	-0.003 m
D9	**RMSE**	0.034 m	0.034 m	0.021 m
D9	**Standard Deviation (1σ)**	0.027 m	0.028 m	0.022 m
D10	**Sample**	8 points	8 points	11 points
D10	**95% Confidence (1.96*RMSE)**	0.033 m	0.035 m	0.057 m
D10	**Average**	0.012 m	0.010 m	0.013 m
D10	**Median**	0.009 m	0.009 m	0.014 m
D10	**RMSE**	0.017 m	0.018 m	0.029 m
D10	**Standard Deviation (1σ)**	0.012 m	0.016 m	0.027 m
D11	**Sample**	8 points	8 points	12 points
D11	**95% Confidence (1.96*RMSE)**	0.038 m	0.077 m	0.075 m
D11	**Average**	0.008 m	0.010 m	0.025 m
D11	**Median**	0.008 m	0.002 m	0.022 m
D11	**RMSE**	0.019 m	0.039 m	0.038 m
D11	**Standard Deviation (1σ)**	0.018 m	0.041 m	0.031 m

Table 15: Absolute accuracy results (D11 through D20a)

Delivery	Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
D12	**Sample**	7 points	7 points	11 points
D12	**95% Confidence (1.96*RMSE)**	0.063 m	0.072 m	0.054 m
D12	**Average**	-0.018 m	-0.019 m	-0.005 m
D12	**Median**	-0.010 m	-0.010 m	-0.011 m
D12	**RMSE**	0.032 m	0.037 m	0.028 m
D12	**Standard Deviation (1σ)**	0.029 m	0.034 m	0.028 m
D13	**Sample**	28 points	28 points	30 points
D13	**95% Confidence (1.96*RMSE)**	0.084 m	0.089 m	0.083 m
D13	**Average**	-0.026 m	-0.031 m	-0.015 m
D13	**Median**	-0.030 m	-0.032 m	-0.017 m
D13	**RMSE**	0.043 m	0.045 m	0.042 m
D13	**Standard Deviation (1σ)**	0.035 m	0.034 m	0.040 m
D14, 19, 20a	**Sample**	9 points	9 points	14 points
D14, 19, 20a	**95% Confidence (1.96*RMSE)**	0.065 m	0.080 m	0.074
D14, 19, 20a	**Average**	-0.017 m	-0.023 m	-0.011 m
D14, 19, 20a	**Median**	-0.006 m	-0.015 m	-0.018 m
D14, 19, 20a	**RMSE**	0.033 m	0.041 m	0.038 m
D14, 19, 20a	**Standard Deviation (1σ)**	0.030 m	0.036 m	0.037 m
D15 - 18	**Sample**	35 points	35 points	53 points
D15 - 18	**95% Confidence (1.96*RMSE)**	0.075 m	0.072 m	0.077 m
D15 - 18	**Average**	0.010 m	0.011 m	0.005 m
D15 - 18	**Median**	0.004 m	0.006 m	-0.001 m
D15 - 18	**RMSE**	0.038 m	0.037 m	0.039 m
D15 - 18	**Standard Deviation (1σ)**	0.037 m	0.035 m	0.040 m

Table 16: Absolute accuracy results (D20b through D22, Cumulative)

Delivery	Parameter	NVA, as compared to classified LAS	NVA, as compared to bare earth DEM	Ground Control Points
D20b - 22	Sample	27 points	27 points	41 points
D20b - 22	95% Confidence (1.96*RMSE)	0.065 m	0.066 m	0.071 m
D20b - 22	Average	-0.020 m	-0.015 m	-0.029 m
D20b - 22	Median	-0.023 m	-0.023 m	-0.032 m
D20b - 22	RMSE	0.033 m	0.034 m	0.036 m
D20b - 22	Standard Deviation (1σ)	0.027 m	0.030 m	0.022 m
Cumulative	Sample	259 points	259 points	292 points
Cumulative	95% Confidence (1.96*RMSE)	0.060 m	0.064 m	0.068 m
Cumulative	Average	-0.005 m	-0.006 m	-0.005 m
Cumulative	Median	-0.004 m	-0.004 m	-0.008 m
Cumulative	RMSE	0.030 m	0.032 m	0.035 m
Cumulative	Standard Deviation (1σ)	0.030 m	0.032 m	0.034 m

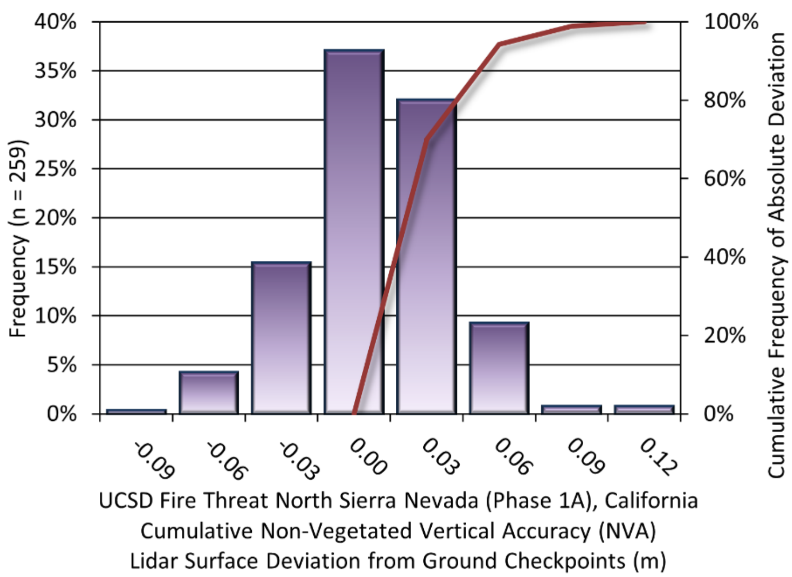

Figure 9: Frequency histogram for lidar classified LAS deviation from cumulative ground checkpoint values (NVA)

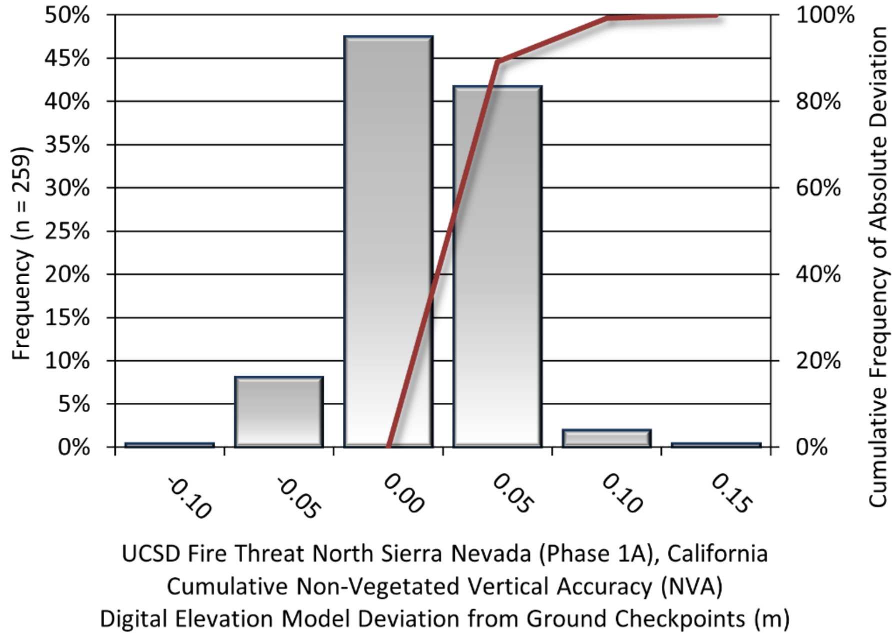

Figure 10: Frequency histogram for the lidar bare earth DEM surface deviation from cumulative ground checkpoint values (NVA)

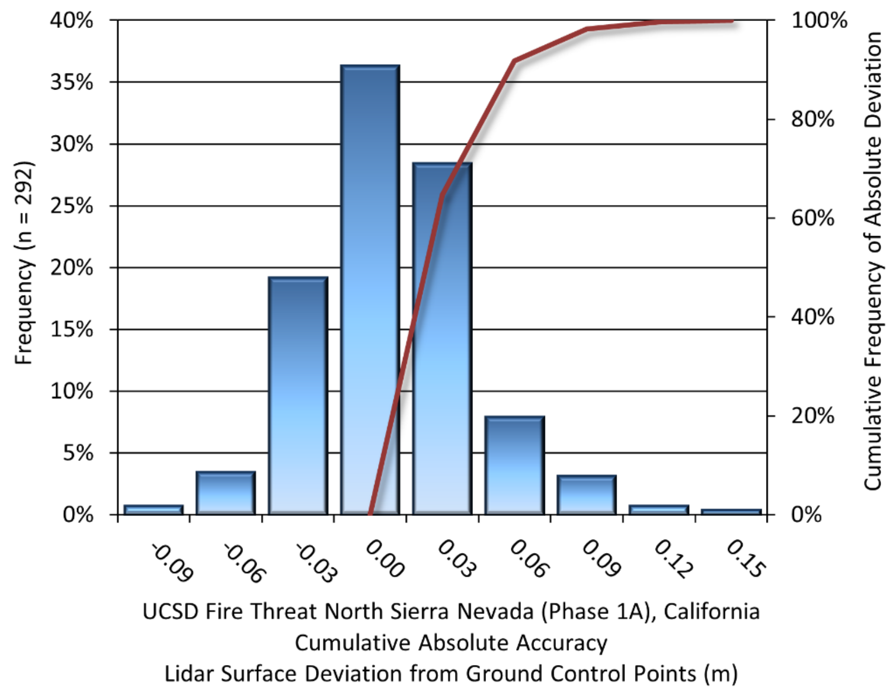

Figure 11: Frequency histogram for the lidar surface deviation from cumulative ground control point values

Lidar Vegetated Vertical Accuracy

NV5 Geospatial also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground checkpoint data collected over vegetated surfaces using land class descriptions to the triangulated ground surface generated by the ground classified lidar points. Unlike in non-vegetated areas, the errors associated with data collected in vegetated areas cannot be assumed to approximate a normal distribution. Therefore, accuracy in vegetated areas is evaluated using the 95th percentile (the value for which 95% of absolute values of errors will be less than or equal to) rather than the 95% confidence level. For the overall UCSD Fire Threat North Sierra Nevada (Phase 1A) survey, 185 vegetated checkpoints were collected, with a resulting cumulative vegetated vertical accuracy of 0.180 meters as compared to the classified LAS, and 0.180 meters as compared to the bare earth DEM evaluated at the 95th percentile (Table 17 through Table 21, Figure 12, and Figure 13).

Table 17: Vegetated vertical accuracy results (D1 through D2)

Delivery	Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
D1A	**Sample**	1 point	1 point
D1A	**95th Percentile**	0.108 m	0.118 m
D1A	**Average**	0.108 m	0.118 m
D1A	**Median**	0.108 m	0.118 m
D1A	**RMSE**	0.108 m	0.118 m
D1A	**Standard Deviation (1σ)**	NA	NA
D1B	**Sample**	8 points	8 points
D1B	**95th Percentile**	0.104 m	0.095 m
D1B	**Average**	0.010 m	0.000 m
D1B	**Median**	0.013 m	-0.010 m
D1B	**RMSE**	0.059 m	0.053 m
D1B	**Standard Deviation (1σ)**	0.062 m	0.056 m
D2	**Sample**	7 points	7 points
D2	**95th Percentile**	0.173 m	0.155 m
D2	**Average**	0.066 m	0.064 m
D2	**Median**	0.050 m	0.032 m
D2	**RMSE**	0.095 m	0.085 m
D2	**Standard Deviation (1σ)**	0.074 m	0.061 m

Table 18: Vegetated vertical accuracy results (D3 through D6)

Delivery	Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
D3	Sample	7 points	7 points
D3	95th Percentile	0.274 m	0.271 m
D3	Average	0.080 m	0.075 m
D3	Median	0.050 m	0.027 m
D3	RMSE	0.143 m	0.142 m
D3	Standard Deviation (1σ)	0.128 m	0.130 m
D4	Sample	8 points	8 points
D4	95th Percentile	0.076 m	0.068 m
D4	Average	0.015 m	0.007 m
D4	Median	0.004 m	-0.011 m
D4	RMSE	0.045 m	0.042 m
D4	Standard Deviation (1σ)	0.045 m	0.045 m
D5	Sample	10 points	10 points
D5	95th Percentile	0.131 m	0.137 m
D5	Average	0.035 m	0.031 m
D5	Median	0.027 m	0.007 m
D5	RMSE	0.064 m	0.065 m
D5	Standard Deviation (1σ)	0.056 m	0.059 m
D6	Sample	14 points	14 points
D6	95th Percentile	0.159 m	0.156 m
D6	Average	0.073 m	0.072 m
D6	Median	0.068 m	0.080 m
D6	RMSE	0.095 m	0.094 m
D6	Standard Deviation (1σ)	0.064 m	0.063 m

Table 19: Vegetated vertical accuracy results (D7 through D10)

Delivery	Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
D7	Sample	8 points	8 points
D7	95th Percentile	0.148 m	0.138 m
D7	Average	0.081 m	0.075 m
D7	Median	0.095 m	0.085 m
D7	RMSE	0.098 m	0.092 m
D7	Standard Deviation (1σ)	0.059 m	0.057 m
D8	Sample	8 points	8 points
D8	95th Percentile	0.105 m	0.107 m
D8	Average	0.039 m	0.032 m
D8	Median	0.033 m	0.027 m
D8	RMSE	0.060 m	0.056 m
D8	Standard Deviation (1σ)	0.048 m	0.049 m
D9	Sample	10 points	10 points
D9	95th Percentile	0.169 m	0.157 m
D9	Average	0.081 m	0.080 m
D9	Median	0.097 m	0.096 m
D9	RMSE	0.101 m	0.098 m
D9	Standard Deviation (1σ)	0.064 m	0.060 m
D10	Sample	4 points	4 points
D10	95th Percentile	0.147 m	0.139 m
D10	Average	0.051 m	0.066 m
D10	Median	0.028 m	0.078 m
D10	RMSE	0.087 m	0.096 m
D10	Standard Deviation (1σ)	0.081 m	0.080 m

Table 20: Vegetated vertical accuracy results (D11 through D14, D19, D20a)

Delivery	Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
D11	Sample	7 points	7 points
D11	95th Percentile	0.141 m	0.267 m
D11	Average	0.027 m	0.031 m
D11	Median	0.013 m	0.014 m
D11	RMSE	0.084 m	0.140 m
D11	Standard Deviation (1σ)	0.086 m	0.148 m
D12	Sample	3 points	3 points
D12	95th Percentile	0.058 m	0.072 m
D12	Average	0.035 m	0.049 m
D12	Median	0.036 m	0.040 m
D12	RMSE	0.041 m	0.053 m
D12	Standard Deviation (1σ)	0.025 m	0.024 m
D13	Sample	11 points	11 points
D13	95th Percentile	0.312 m	0.367 m
D13	Average	0.065 m	0.069 m
D13	Median	0.006 m	0.009 m
D13	RMSE	0.143 m	0.165 m
D13	Standard Deviation (1σ)	0.133 m	0.158 m
D14, 19, 20a	Sample	14 points	14 points
D14, 19, 20a	95th Percentile	0.091 m	0.112 m
D14, 19, 20a	Average	0.012 m	0.007 m
D14, 19, 20a	Median	0.025 m	0.009 m
D14, 19, 20a	RMSE	0.051 m	0.058 m
D14, 19, 20a	Standard Deviation (1σ)	0.052 m	0.060 m

Table 21: Vegetated vertical accuracy results (D15 through D18, D20b through D22, Cumulative)

Delivery	Parameter	VVA, as compared to classified LAS	VVA, as compared to bare earth DEM
D15 - 18	Sample	30 points	30 points
D15 - 18	95th Percentile	0.171 m	0.181 m
D15 - 18	Average	0.041 m	0.038 m
D15 - 18	Median	0.049 m	0.050 m
D15 - 18	RMSE	0.089 m	0.091 m
D15 - 18	Standard Deviation (1σ)	0.081 m	0.084 m
D20b - 22	Sample	35 points	35 points
D20b - 22	95th Percentile	0.185 m	0.191 m
D20b - 22	Average	0.024 m	0.027 m
D20b - 22	Median	0.018 m	0.026 m
D20b - 22	RMSE	0.094 m	0.101 m
D20b - 22	Standard Deviation (1σ)	0.092 m	0.099 m
Cumulative	Sample	185 points	185 points
Cumulative	95th Percentile	0.180 m	0.180 m
Cumulative	Average	0.043 m	0.041 m
Cumulative	Median	0.036 m	0.031 m
Cumulative	RMSE	0.091 m	0.094 m
Cumulative	Standard Deviation (1σ)	0.080 m	0.085 m

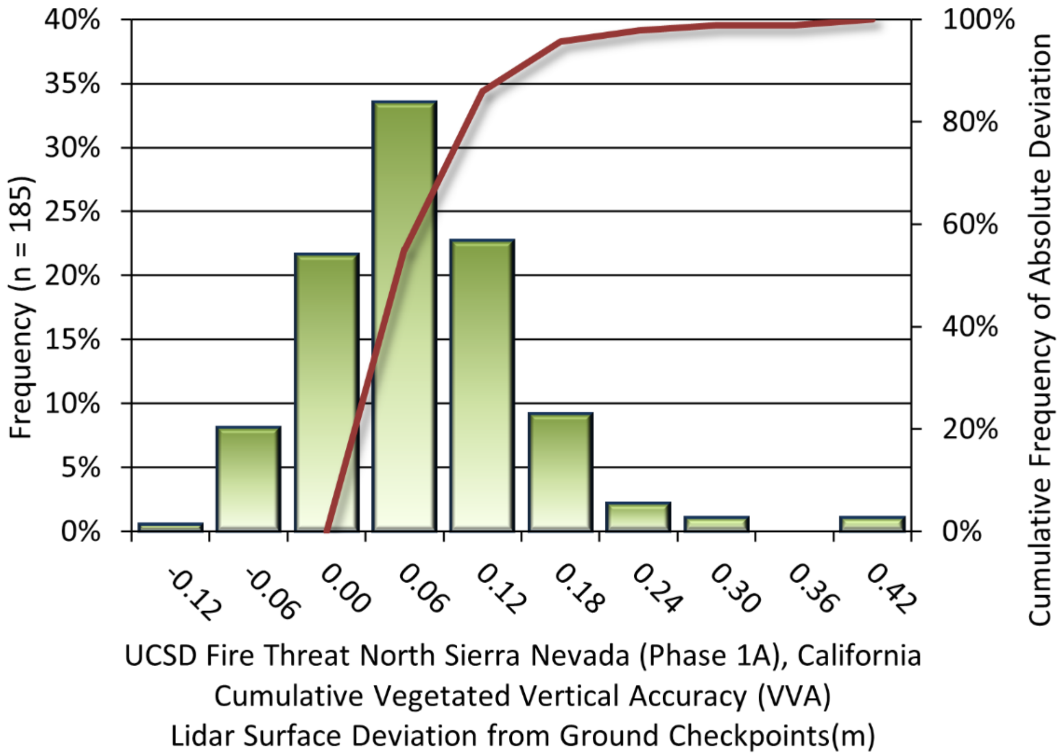

Figure 12: Frequency histogram for the lidar surface deviation from all land cover class point values (VVA)

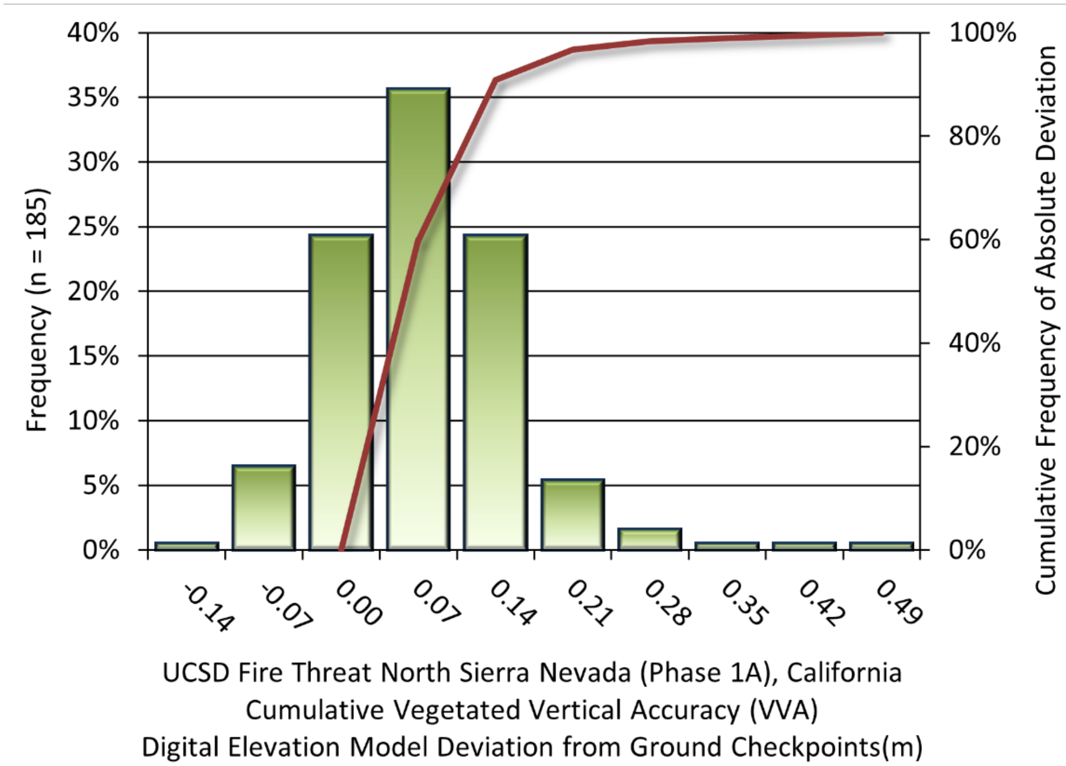

Figure 13: Frequency histogram for the lidar bare earth DEM deviation from vegetated checkpoint values (VVA)

Lidar Relative Vertical Accuracy

Relative vertical 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 vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The cumulative average (mean) line to line relative vertical accuracy for the UCSD Fire Threat North Sierra Nevada (Phase 1A) Lidar project was 0.035 meters. (Table 22 through Table 24, Figure 14).

Table 22: Relative accuracy results (D1 through D5)

Delivery	Parameter	Relative Accuracy	Delivery	Parameter	Relative Accuracy
D1A	**Sample**	34 surfaces	**D3**	**Sample**	58 surfaces
D1A	**Average**	0.037 m	**D3**	**Average**	0.033 m
D1A	**Median**	0.035 m	**D3**	**Median**	0.036 m
D1A	**RMSE**	0.039 m	**D3**	**RMSE**	0.035 m
D1A	**Standard Deviation (1σ)**	0.011 m	**D3**	**Standard Deviation (1σ)**	0.007 m
D1A	**1.96σ**	0.021 m	**D3**	**1.96σ**	0.015 m
D1B	**Sample**	81 surfaces	**D4**	**Sample**	105 surfaces
D1B	**Average**	0.037 m	**D4**	**Average**	0.034 m
D1B	**Median**	0.035 m	**D4**	**Median**	0.035 m
D1B	**RMSE**	0.038 m	**D4**	**RMSE**	0.036 m
D1B	**Standard Deviation (1σ)**	0.009 m	**D4**	**Standard Deviation (1σ)**	0.008 m
D1B	**1.96σ**	0.019 m	**D4**	**1.96σ**	0.016 m
D2	**Sample**	89 surfaces	**D5**	**Sample**	114 surfaces
D2	**Average**	0.033 m	**D5**	**Average**	0.032 m
D2	**Median**	0.035 m	**D5**	**Median**	0.033 m
D2	**RMSE**	0.035 m	**D5**	**RMSE**	0.034 m
D2	**Standard Deviation (1σ)**	0.008 m	**D5**	**Standard Deviation (1σ)**	0.007 m
D2	**1.96σ**	0.015 m	**D5**	**1.96σ**	0.013 m

Table 23: Relative accuracy results (D6 through D13)

Delivery	Parameter	Relative Accuracy	Delivery	Parameter	Relative Accuracy
D6	**Sample**	97 surfaces	**D10**	**Sample**	151 surfaces
D6	**Average**	0.030 m	**D10**	**Average**	0.040 m
D6	**Median**	0.032 m	**D10**	**Median**	0.039 m
D6	**RMSE**	0.031 m	**D10**	**RMSE**	0.039 m
D6	**Standard Deviation (1σ)**	0.006 m	**D10**	**Standard Deviation (1σ)**	0.009 m
D6	**1.96σ**	0.011 m	**D10**	**1.96σ**	0.017 m
D7	**Sample**	84 surfaces	**D11**	**Sample**	94 surfaces
D7	**Average**	0.026 m	**D11**	**Average**	0.042 m
D7	**Median**	0.026 m	**D11**	**Median**	0.042 m
D7	**RMSE**	0.028 m	**D11**	**RMSE**	0.041 m
D7	**Standard Deviation (1σ)**	0.006 m	**D11**	**Standard Deviation (1σ)**	0.008 m
D7	**1.96σ**	0.011 m	**D11**	**1.96σ**	0.017 m
D8	**Sample**	185 surfaces	**D12**	**Sample**	88 surfaces
D8	**Average**	0.039 m	**D12**	**Average**	0.040 m
D8	**Median**	0.038 m	**D12**	**Median**	0.039 m
D8	**RMSE**	0.039 m	**D12**	**RMSE**	0.039 m
D8	**Standard Deviation (1σ)**	0.007 m	**D12**	**Standard Deviation (1σ)**	0.008 m
D8	**1.96σ**	0.013 m	**D12**	**1.96σ**	0.015 m
D9	**Sample**	65 surfaces	**D13**	**Sample**	83 surfaces
D9	**Average**	0.029 m	**D13**	**Average**	0.034 m
D9	**Median**	0.030 m	**D13**	**Median**	0.032 m
D9	**RMSE**	0.029 m	**D13**	**RMSE**	0.034 m
D9	**Standard Deviation (1σ)**	0.005 m	**D13**	**Standard Deviation (1σ)**	0.005 m
D9	**1.96σ**	0.009 m	**D13**	**1.96σ**	0.009 m

Table 24: Relative accuracy results (D14 through D22, Cumulative)

Delivery	Parameter	Relative Accuracy	Delivery	Parameter	Relative Accuracy
D14, 19, 20a	**Sample**	360 surfaces	**D20b - 22**	**Sample**	606 surfaces
D14, 19, 20a	**Average**	0.038 m	**D20b - 22**	**Average**	0.035 m
D14, 19, 20a	**Median**	0.036 m	**D20b - 22**	**Median**	0.034 m
D14, 19, 20a	**RMSE**	0.038m	**D20b - 22**	**RMSE**	0.036m
D14, 19, 20a	**Standard Deviation (1σ)**	0.008 m	**D20b - 22**	**Standard Deviation (1σ)**	0.008 m
D14, 19, 20a	**1.96σ**	0.016 m	**D20b - 22**	**1.96σ**	0.016 m
D15 - 18	**Sample**	292 surfaces	**Cumulative**	**Sample**	1281 surfaces
D15 - 18	**Average**	0.034 m	**Cumulative**	**Average**	0.035 m
D15 - 18	**Median**	0.033 m	**Cumulative**	**Median**	0.035 m
D15 - 18	**RMSE**	0.035 m	**Cumulative**	**RMSE**	0.037 m
D15 - 18	**Standard Deviation (1σ)**	0.008 m	**Cumulative**	**Standard Deviation (1σ)**	0.008 m
D15 - 18	**1.96σ**	0.016 m	**Cumulative**	**1.96σ**	0.016 m

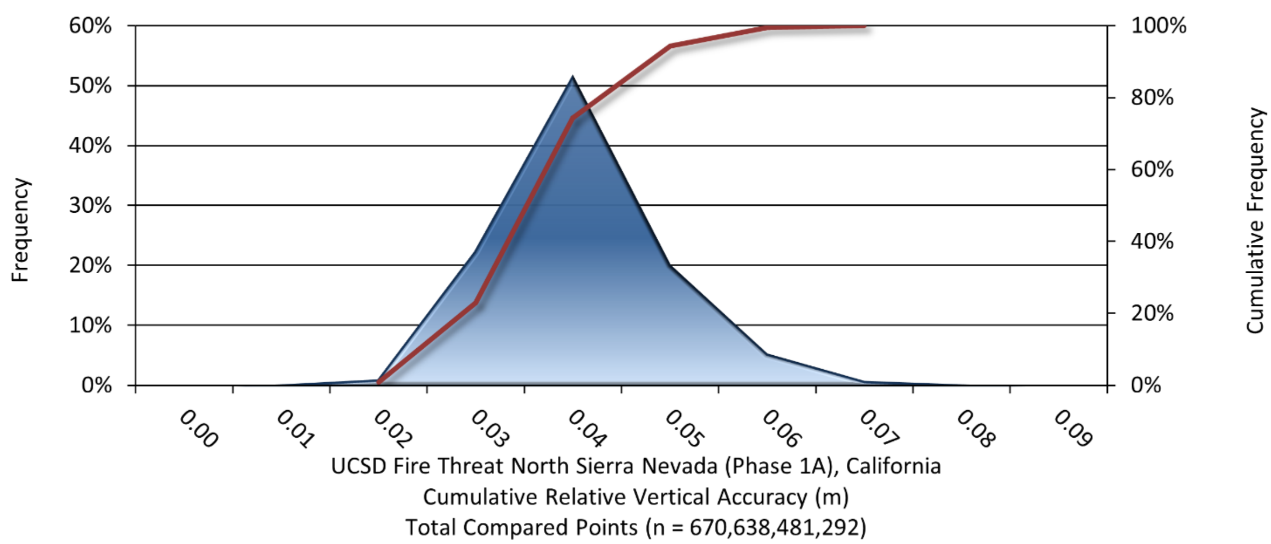

Figure 14: Frequency plot for the cumulative relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Based on a flying altitude of 2500 meters, an IMU error of 0.003 decimal degrees, and a GNSS positional error of 0.052 meters, this project was produced to meet 0.415 meters horizontal accuracy at the 95% confidence level (Table 25).

Table 25: Predicted horizontal accuracy

Delivery	Parameter	Horizontal Accuracy
D1A – D10, D12	**$RMSE_r$**	0.157 m
D1A – D10, D12	**ACC_r**	0.272 m
D11	**$RMSE_r$**	0.048 m
D11	**ACC_r**	0.082 m
D13	**$RMSE_r$**	0.165 m
D13	**ACC_r**	0.285 m
D14, 19, 20a	**$RMSE_r$**	0.156 m
D14, 19, 20a	**ACC_r**	0.270 m
D15 - 18	**$RMSE_r$**	0.235 m
D15 - 18	**ACC_r**	0.407 m
D20b - 22	**$RMSE_r$**	0.234 m
D20b - 22	**ACC_r**	0.405 m
Cumulative	**$RMSE_r$**	0.240 m
Cumulative	**ACC_r**	0.415 m

NV5 Geospatial provided lidar services for the UCSD Fire Threat North Sierra Nevada (Phase 1A) project as described in this report.

I, John English, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

John T English (Dec 13, 2023 15:45 PST) Dec 13, 2023

John English
Project Manager
NV5 Geospatial

I, Evon P. Silvia, PLS, being duly registered as a Professional Land Surveyor in and by the state of California, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work was conducted from November 3, 2021, to August 23, 2022, for the airborne survey, while field work was conducted from October 18, 2021 to October 11, 2022, for the ground survey.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the “National Standard for Spatial Data Accuracy”.

LICENSED LAND SURVEYOR
EVON PETER SILVIA
9401
STATE OF CALIFORNIA

Dec 13, 2023

Evon P. Silvia, PLS
NV5 Geospatial
Corvallis, OR 97330

Signed: Dec 13, 2023

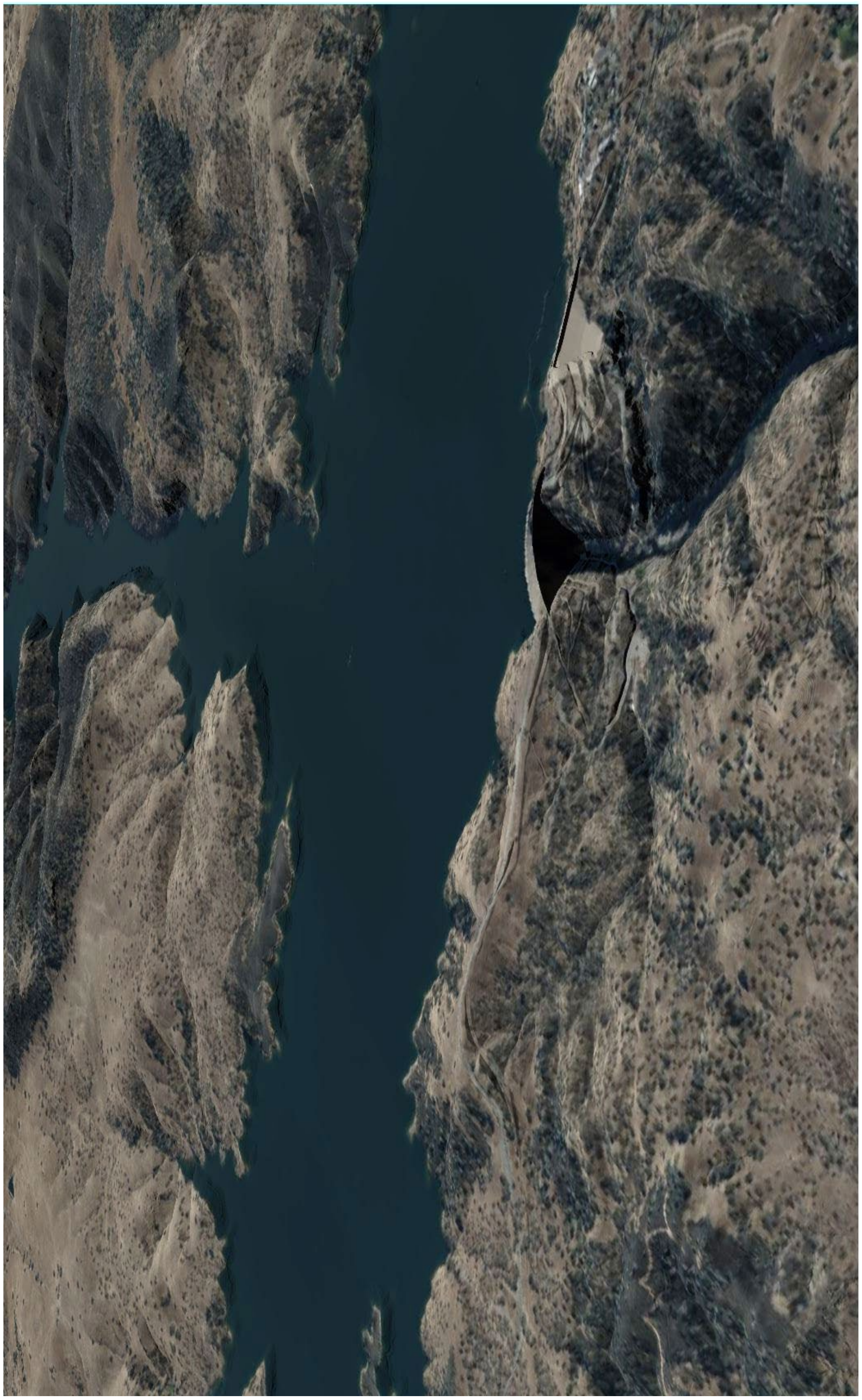

Figure 15: View looking northeast over the Melones Lake in the UCSD Fire Threat North Sierra Nevada (Phase 1A) site. The image was created from the lidar bare earth model and overlaid with Virtual Earth Imagery.

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 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Non-vegetated Vertical Accuracy (NVA) reporting.

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).

> **Absolute Accuracy:** The vertical accuracy of lidar data is described as the mean and standard deviation (sigma σ) of divergence of lidar point coordinates from 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, and thus we also consider the skew and kurtosis of distributions when evaluating error statistics. When the distribution of the positional error is normal, the skewness of the distribution is zero and positive errors are equal in magnitude and likelihood to negative errors. The excess kurtosis of a distribution approximating the normal distribution will be near zero, indicating a lack of weight in the tails of the distribution. Here, this means a low frequency of outliers that have high positional error.
>
> **Relative Accuracy:** Relative accuracy refers to the internal consistency of the data set; i.e., 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).
>
> **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 each error (the distance between an observed and known value), taking the average of these squared errors, and finally taking the square root of this average.

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

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

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.

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

Pulse Rate (PR): The rate at which laser pulses are emitted from the sensor; typically measured in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echoes) reflected back to the sensor. Portions of the wave form that return first 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.

Real-Time Kinematic (RTK) Survey: A type of surveying 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.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. This type of ground survey is accurate to 1.5 cm or less.

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

Native Lidar Density: The number of pulses emitted by the lidar system, commonly expressed as pulses per square meter.

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.

Lidar accuracy error sources and solutions:

Source	Type	Post Processing Solution
Long Base Lines	GPS	None
Poor Satellite Constellation	GPS	None
Poor Antenna Visibility	GPS	Reduce Visibility Mask
Poor System Calibration	System	Recalibrate IMU and sensor offsets/settings
Inaccurate System	System	None
Poor Laser Timing	Laser Noise	None
Poor Laser Reception	Laser Noise	None
Poor Laser Power	Laser Noise	None
Irregular Laser Shape	Laser Noise	None

Operational measures taken to improve relative accuracy:

Low Flight Altitude: Terrain following was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 1/3000th 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 (i.e., intensity) 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 ±29.25° 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.

Ground Survey: Ground survey point accuracy (<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 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 nadir portion of one flight line coincides with the swath edge 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 have opposing directions. 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.

UCSD_Fire_Threat_North_Sierra_Nevadas_CA_NIR_Cumulative_Report_Final

Final Audit Report 2023-12-13

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