Critical Zone Observatory LiDAR

Mapping Project Report
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Project Manager: Qinghua Guo

University of California - Merced
P.O. Box 2039
Merced, CA 95344

e-mail: qguo@ucmerced.edu
Phone: (209) 228-2911
Fax: (209) 228-4047

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Note: This document has been altered from the original to only include information pertaining to the Jemez, Arizona CZO LIDAR flight. This Document is intended for the PI's of the Jemez CZO site and their collaborators.

1. LiDAR System Description and Specifications

Two different sensors were used for this survey, an Optech GEMINI Airborne Laser Terrain Mapper (ALTM) S/N 06SEN195 or an ALTM3100 S/N 03SEN144 (as indicated) and mounted in either a twin-engine Cessna Skymaster (N337P) or Piper Twin PA-31 Chieftain (N931SA or N31PR). The instrument nominal specifications are listed in table 1.

Operating Altitude	150 - 4000 m, Nominal
Horizontal Accuracy	1/5,500 x altitude (m AGL); 1 sigma
Elevation Accuracy	5 - 30 cm; 1 sigma
Range Capture	Up to 4 range measurements, including 1st, 2nd, 3rd, last returns
Intensity Capture	12-bit dynamic range for all recorded returns, including last returns
Scan FOV	0 - 50 degrees; Programmable in increments of ±1degree
Scan Frequency	0 – 70 Hz
Scanner Product	Up to Scan angle x Scan frequency = 1000
Roll Compensation	±5 degrees at full FOV – more under reduced FOV
Pulse Rate Frequency	33 - 167 kHz
Position Orientation System	Applanix POS/AV 510 OEM includes embedded BD950 12-channel 10Hz GPS receiver
Laser Wavelength/Class	1047 nanometers / Class IV (FDA 21 CFR)
Beam Divergence nominal (full angle)	Dual Divergence 0.25 mrad (1/e) or 0.80 mrad (1/e)

Table 1 – Optech GEMINI specifications.

See http://www.optech.ca for more information from the manufacturer.
http://www.optech.ca/pdf/Brochures/ALTM-GEMINI.pdf

2. Description of the Project Areas of Interest (AOI).

The CZO LiDAR project consisted of eleven individual collections for six different geographic areas. These areas are Boulder Creek, Co, Shale Hills (Shavers Creek), PA, Southern Sierra Nevada, CA, Christina River Basin, PA, Jemez (Valles Caldera), NM and Luquillo, PR. Five of these areas, excluding the Puerto Rico AOI, were collected twice during the snow on / snow off or leaf on / leaf off seasons. The location of the different areas of interest is plotted in Figure 1 and the original collection dates and mapping areas are described in Table 1.

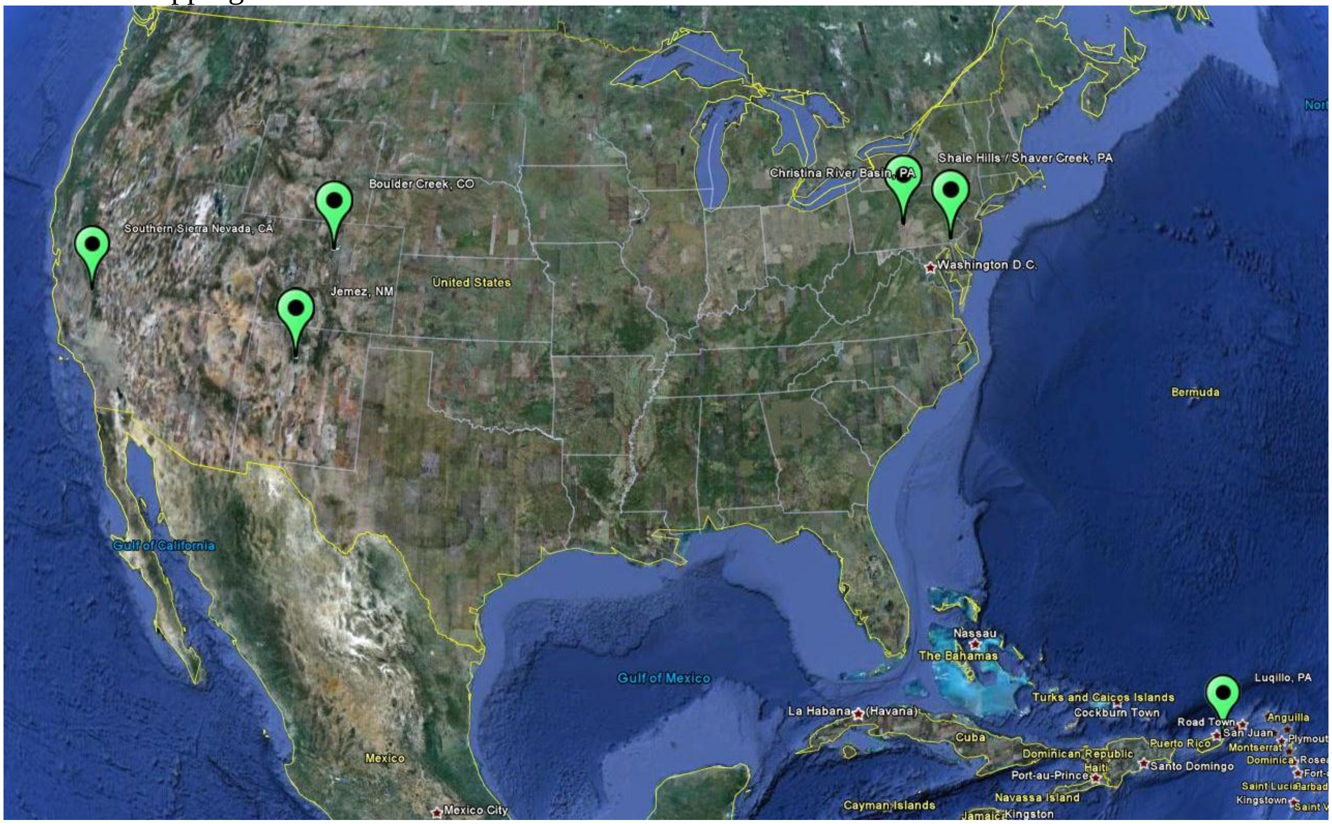


Figure 1. Location of CZO survey projects.

Table 1. Description of original CZO LiDAR collection targets.

Sub-projects	PIs	subareas	First Collection	Second Collection
Boulder Creek, CO	Suzanne Anderson Greg Tucker	1	25-Apr-10 to 10-May-10 372.25 km²	22-Aug-10 to 5-Sep-10 494.03 km²
Shale Hills, PA	Chris Duff	1	1-Jul-10 to 31-Jul-10 169.81 km²	1-Dec-10 to 31-Dec-10 169.81 km²
Southern Sierra, CA	Roger Bales Ryan Lucas	6	1-Mar-10 to 7-Mar-10 30.95 km²	8-Aug-10 to 12-Aug-10 30.95 km²
Christina River Basin, PA	Jim Pizzuto	3	15-Mar-10 to 19-Mar-10 121.28 km²	1-Jul-10 to 31-Jul-10 121.28 km²
Jemez, NM	Jon Pelletier Jon Chorover	1	10-Mar-10 to 20-Mar-10 49.94 km²	28-Jun-10 to 3-Jul-10 49.94 km²
Luquillo, PR	Fred Scatena	1	16-Jul-10 to 14-Dec-10 180.38 km²	-

3. Airborne Survey Planning and Collection.

The survey planning was performed with a target point density of 8 to 10 points per meter square, considering nominal values of 600m for flight altitude above the terrain, a swath overlap of 50%, and a pulse repetition frequency (PRF) of 100 kHz which yields a good tradeoff between point density and precision. The mean ground speed was considered as 60 m/s for the flights performed with the Cessna 337 skymaster and 65 m/s for the flights performed with the Piper PA-31 Chieftain. The scan angle and scan frequency were adjusted to ensure a uniform along-track and across-track point spacing, the overall targeted point density, and a scan product (frequency x angle) within 75-85% of the system maximum of 1000. The beam divergence was set to narrow divergence (0.25 mrad). Table 2 lists the requested and effective survey dates for each sub-projects, the specifics of each sub-project planning and collection are presented in the subsequent sections.

Table 2. CZO LiDAR requested and collection dates.

#	Sub-project	CZO requested dates	Survey dates
2	Jemez, NM / snow-on	10-Mar-10 to 20-Mar-10	27-Mar-10 to 3-Apr-10
5	Jemez, NM / snow-off	28-Jun-10 to 3-Jul-10	29-Jun-10 to 8-Jul-10

3.3 Jemez, NM snow-on and snow-off collection

The Boulder Creek CZO sub-project consisted of two collections during the snow-on and snow-off seasons of the same area of interest (AOI). The AOI is a single rectangular polygon with 246.347 km^2 of surface area located 9 Miles west of Los Alamos, and 35 miles Northwest of Santa Fe. The location and extent of the AOI polygon is illustrated in Figure 9. Due to the required flying height above mean sea level to perform this survey, it was flown employing a Piper PA-31 Chieftain twin engine aircraft. The planned survey parameters and survey totals are presented in Table 14. The snow-off collection was performed in conjunction with a survey of the entire Valles Caldera National Preserve and the Frijoles canyon watershed.

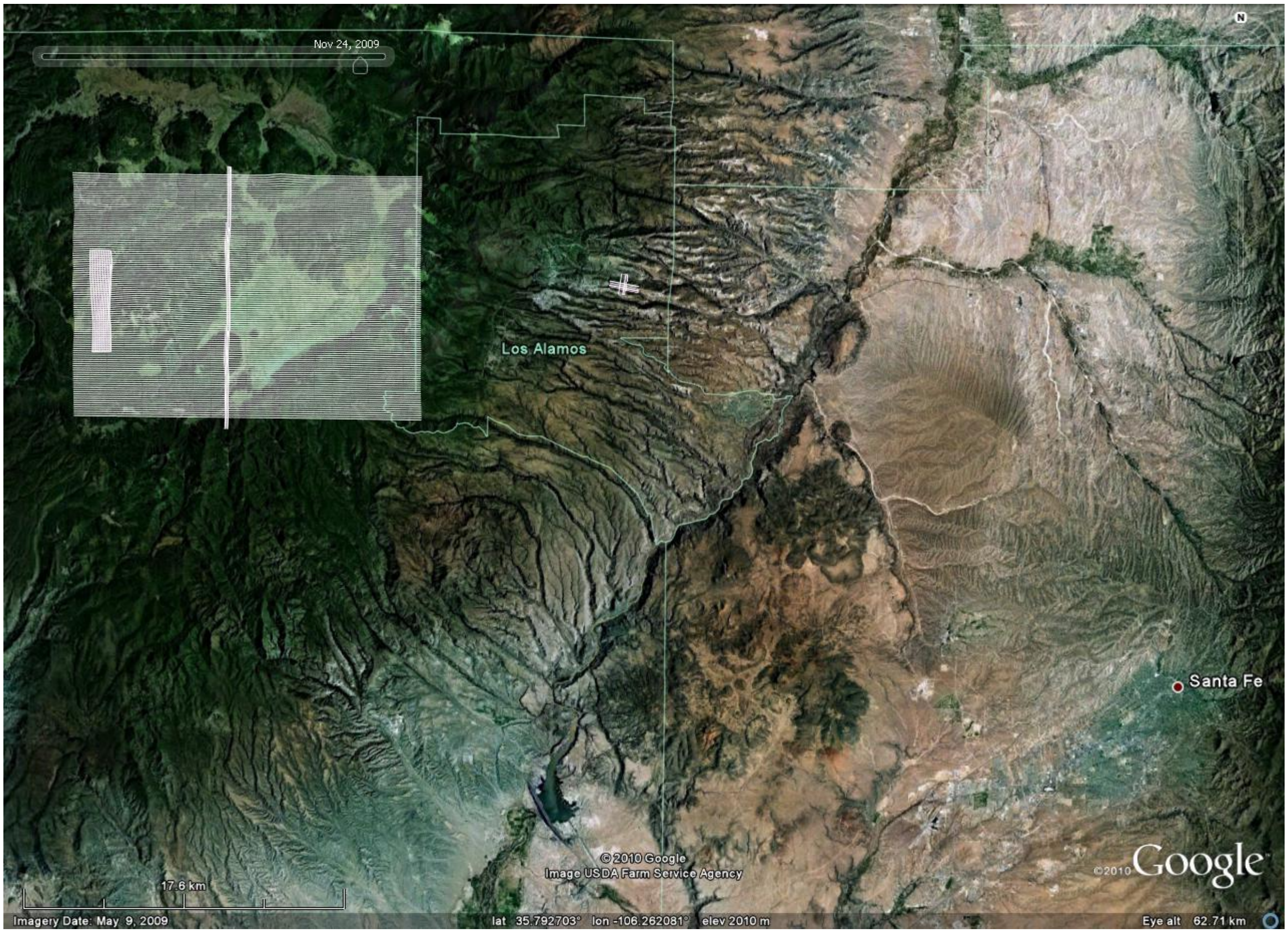


Figure 9. Area of interest (AOI) for the Jemez, NM snow-on and snow-off surveys and flight lines for the snow-on collection.

Table 14. Flight parameters, Sensor settings and survey totals for the snow-on collection*.

Nominal Flight Parameters		**Equipment Settings**		**Planned Survey Totals**	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	1
Flight Speed	65 m/s	Beam Divergence	0.25 mrad	Total Passes	113
Swath Width	233.26 m	Scan Frequency	60 Hz	Total Length	2136.692 km
Swath Overlap	50%	Scan Angle	± 14°	Total Flight Time	18.576 hrs
Point Density	10.28 p/m²	Scan Cutoff	± 3°	Total Laser Time	9.131 hrs
Cross-Track Res	0.254 m	Scan Offset	0°	Total Swath Area	249.202 km^2
Down-Track Res	0.383m			Total AOI Area	246.347 km^2

* based on plan: czo_Jemez_NM_v5.pln

3.3.1 Snow-on collection

The snow-on collection was performed between March 27 and April 3rd. There were a total of 11 flights, which are summarized in Table 15. Data was collected with the Gemini 06SEN/CON195 system installed on the PA-31 tail number N31PR.

Table 15. CZO Jemez, NM, snow-on collection flights.

Flight	Date (local)	DoY	Data Logging (GMT)		Flight	LOT	Observations	Digitizer
			Start	Stop	time (h)	(h)		(Gb)
F01	27-Mar-10	86	14:20:35	16:14:48	1.52	0.44		NA
F02	28-Mar-10	87	14:31:24	18:49:58	3.95	1.76		NA
F03	28-Mar-10	87	20:45:22	00:18:22	3.35	1.23		NA
F04	29-Mar-10	88	15:02:50	16:26:50	1.21	0.24		NA
F05	29-Mar-10	88	19:35:15	23:32:50	3.66	1.49		NA
F06	30-Mar-10	89	14:51:23	17:42:26	2.55	0.94		NA
F07	31-Mar-10	90	14:24:00	18:09:00	3.75	1.51		NA
F08	31-Mar-10	90	20:30:00	0:14:50	3.75	1.37		NA
F09	1-Apr-10	91	14:41:30	17:00	2.31	0.66		NA
F10	2-Apr-10	92	14:20:30	17:00	2.66	1.09		NA
F11	3-Apr-10	93	14:34:38	16:30	1.92	0.50		NA
					30.63	11.23		

3.3.2 Snow-off collection

The snow-off collection was performed in conjunction with a survey for the Valles Caldera National Preserve which included the park boundaries and the Frijoles Canyon. Figure 10 shows the planed flight lines for the survey and the CZO AOI.

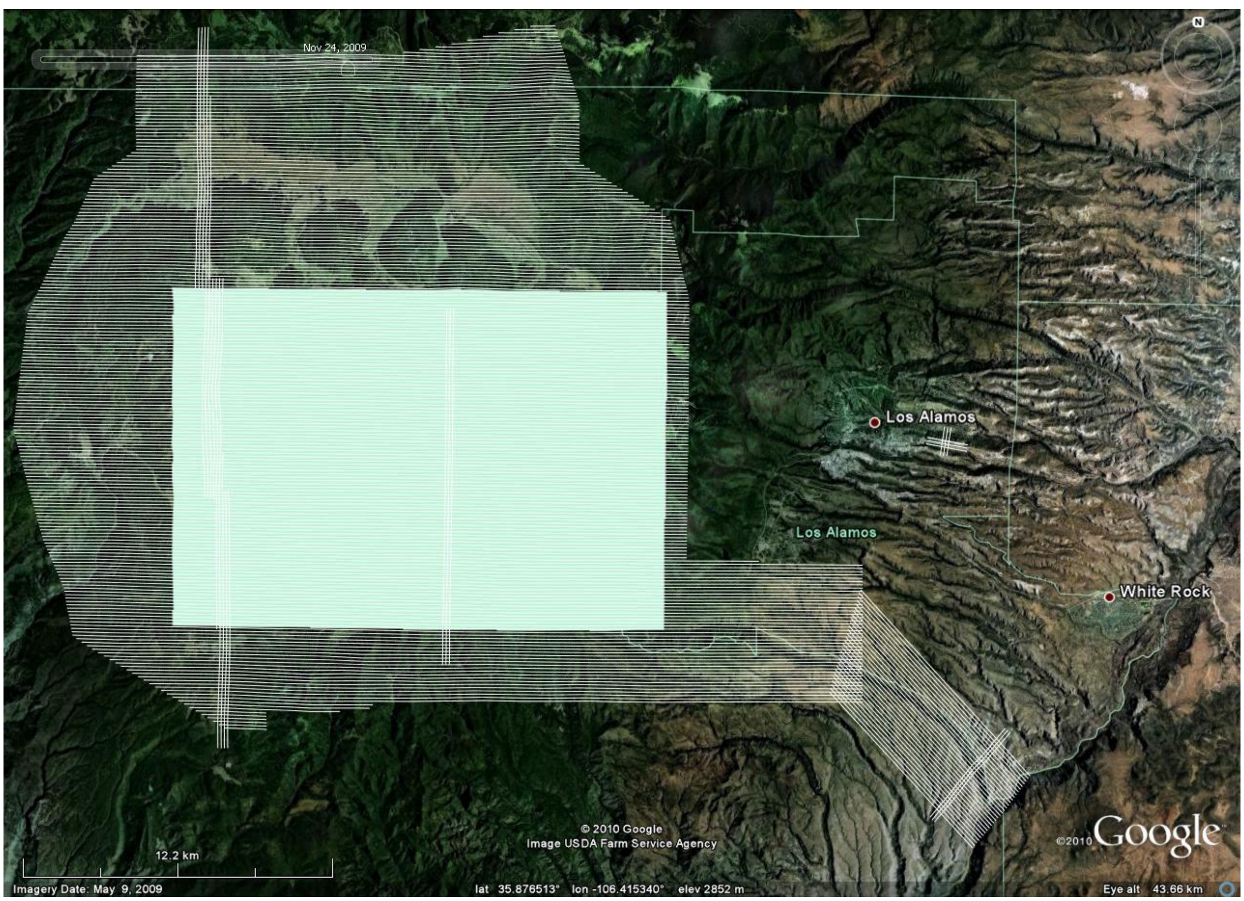


Figure 10. Area of interest (AOI) for the CZO Jemez collection overlaid with the Valles Caldera Preserve plan.

The entire collection was performed between June 29 and July 8. There were a total of 14 flights, the collection was uneventful and the details of each flight are summarized in Table 16. Data was collected with the Gemini 06SEN/CON195 system installed on the PA-31 tail number N931SA.

Table 16. CZO Jemez, NM, snow-off collection flights.

Flight	Date (local)	DoY	Data Logging (GMT)		Flight	LOT	Observations	Digitizer
			Start	Stop	time (h)	(h)		(Gb)
F01	29-Jun-10	180	19:06:45	21:48:01	2.26	1.20		NA
F02	30-Jun-10	181	13:16			0.03	Mapping mission aborted	NA
F03	30-Jun-10	181	20:59:30	1:19:30	1.24	2.09		NA
F04	1-Jul-10	182	13:20:15	14:10:45	0.45	0.04	Mapping mission aborted	NA
F05	1-Jul-10	182	20:18:30	0:58:04	4.12	2.70		NA
F06	2-Jul-10	183	20:05:15	0:14:20	3.88	1.84		NA
F07	4-Jul-10	185	13:40:14	18:52:30	4.88	2.96		NA
F08	4-Jul-10	185	21:27:15	1:50:01	4.06	2.04		NA
F09	5-Jul-10	186	13:44:30	18:23:50		2.39		NA
F10	5-Jul-10	186	21:36:30	2:09:50	2.21	2.29		NA
F11	6-Jul-10	187	13:47:45	18:47:30	4.68	2.60		NA
F12	6-Jul-10	187	21:47:45	1:50:45	3.78	2.02		NA
F13	7-Jul-10	188	13:52:10	18:29:32	4.33	2.46		NA
F14	8-Jul-10	189	13:34:45	15:31:05	1.69	0.60		NA
					37.58	25.27		

3.3.3 GPS stations

Data from a total of three GPS ground stations were used for aircraft trajectory determination. Two of these stations (KLAM and SAF) were setup by NCALM at the Santa Fe and Los Alamos airports and one that is part of the NGS CORS network (NMSF).The location of the stations relative to the project AOI is presented on Figure 11 and the coordinates of the stations are summarized in Table 17.

Table 17. Coordinates of GPS stations used to derive aircraft trajectories for the Boulder, CO sub-project.

GPS station	NMSF	SAF $_{\text{snow-on}}$	SAF $_{\text{snow-off}}$	KLAM $_{\text{snow-on}}$	KLAM $_{\text{snow-off}}$
Operating agency	NM DOT	NCALM	NCALM	NCALM	NCALM
Latitude	35.673784	35.61541	35.61998	35.88178	35.88179
Longitude	-105.958592	-106.08089	-106.08090	-106.27866	-106.27868
Ellipsoid Height (m)	2097.242	1902.952	1911.259	2168.706	2168.821

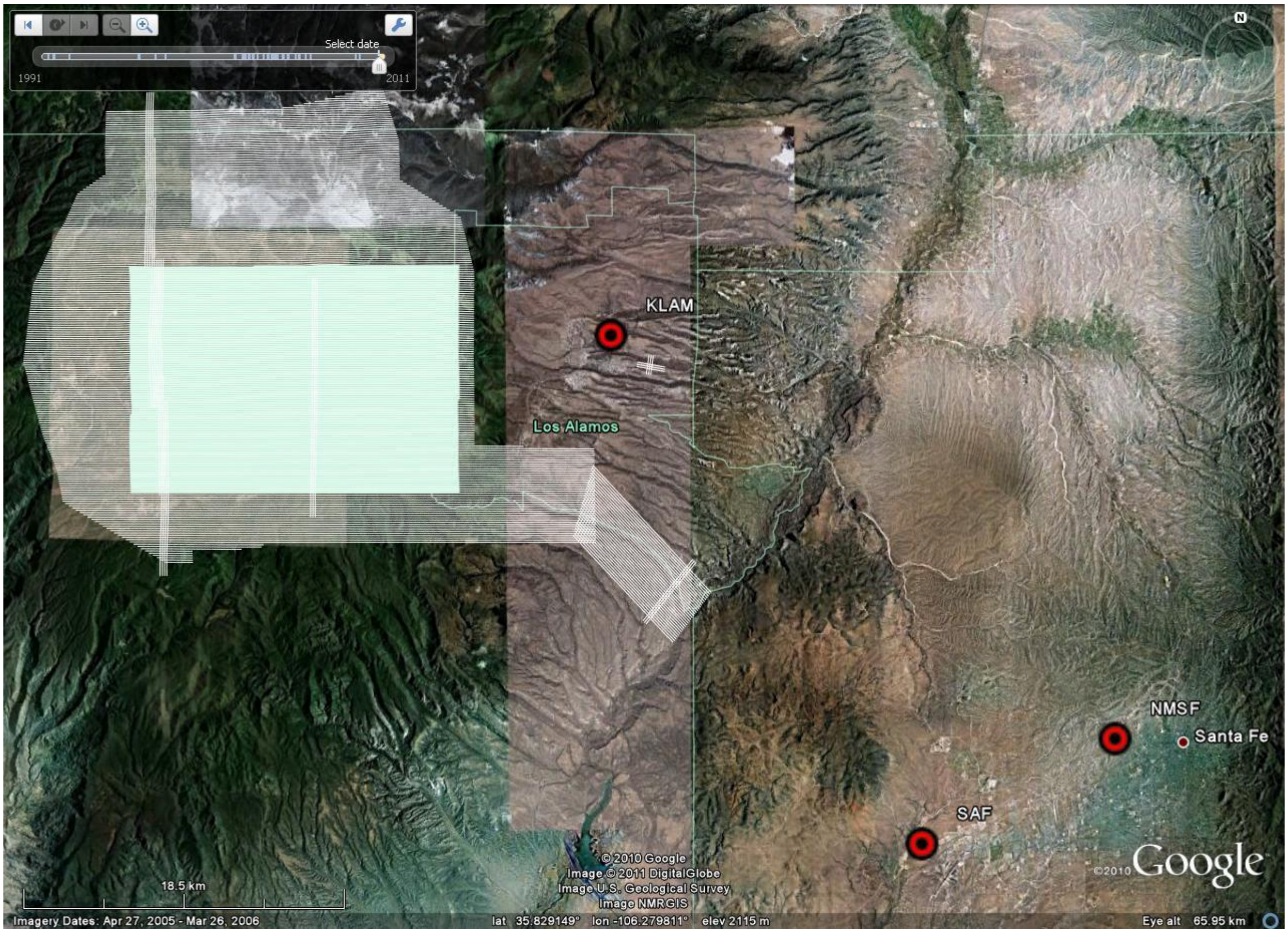
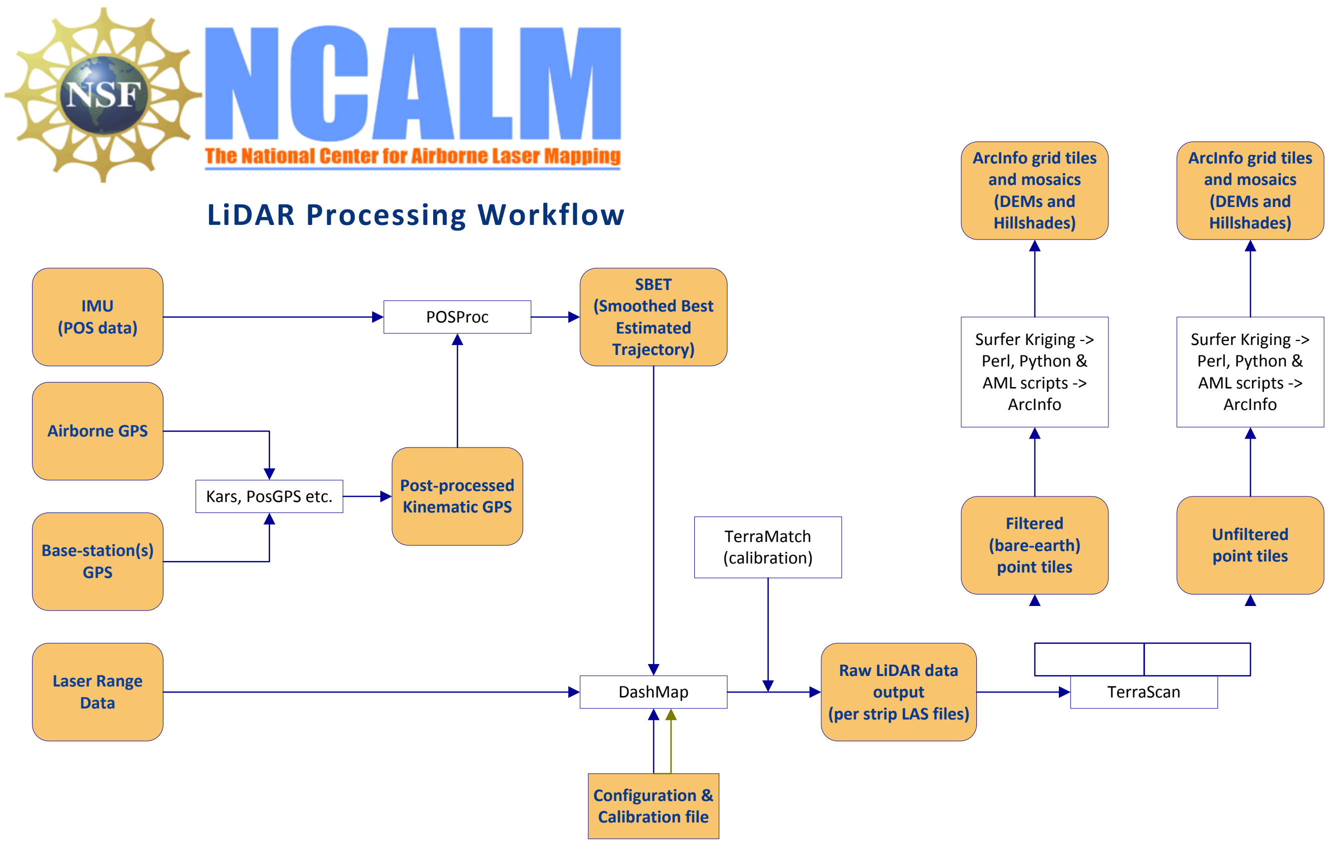


Figure 11. Location of the GPS stations used to derive aircraft trajectories for the Jemez, NM sub-project.

4. Data Processing and Product Generation.

The following diagram shows a general overview of the NCALM LiDAR data processing workflow:



4.1. GPS & INS Navigation Processing.

Reference coordinates for all NCALM stations are derived from observation sessions taken over the project duration and submitted to the NGS on-line processor OPUS which processes static differential baselines tied to the international CORS network. All coordinates are relative to the NAD83 (CORS96) Reference Frame.

Airplane trajectories for all survey flights are processed using KARS software (Kinematic and Rapid Static) written by Dr. Gerry Mader of the NGS Research Laboratory. KARS kinematic GPS processing uses the dual-frequency phase history files of the reference and airborne receivers to determine a fixed integer ionosphere-free differential solution. All available GPS reference stations for each flight are used to create individual differential solutions and then these solutions are differenced and compared for consistency. The standard deviation of the component differences (Easting, Northing, and Height) between individual solutions is generally between 5 – 25 mm horizontally and 15 – 55 mm vertically. Typical values (Shale Hills flight on DOY 338) are 6 mm Easting, 8 mm

Northing, and 21 mm upping. The quality-checked individual solutions are then combined into a final solution using an unweighted averaging algorithm.

Table 30 (below) gives the average Positional Dilution of Precision (PDOP - which is a measure of the strength of the satellite geometry) and the average Root Mean Square (RMS) of the phase residuals from the KARS kinematic processing for each survey flight. These values have a strong correlation with the overall precision of the GPS trajectory and a direct correlation with the accuracy of the LiDAR shots.

Table 30. Average PDOP and Average RMS from kinematic processing on a flight by flight basis.

Flight	Date	DOY	Aircraft	PDOP	RMS (meters)
Jemez Snow-on_F01	27-Mar-10	86	31PR	1.9	0.013
Jemez Snow-on_F02	28-Mar-10	87	31PR	2.1	0.017
Jemez Snow-on_F03	28-Mar-10	87	31PR	2.3	0.019
Jemez Snow-on_F04	29-Mar-10	88	31PR	2.8	0.020
Jemez Snow-on_F05	29-Mar-10	88	31PR	1.9	0.025
Jemez Snow-on_F06	30-Mar-10	89	31PR	2.2	0.017
Jemez Snow-on_F07	31-Mar-10	90	31PR	1.8	0.011
Jemez Snow-on_F08	31-Mar-10	90	31PR	2.4	0.012
Jemez Snow-on_F09	1-Apr-10	91	31PR	2.4	0.018
Jemez Snow-on_F10	2-Apr-10	92	31PR	2.7	0.015
Jemez Snow-on_F11	3-Apr-10	93	31PR	1.9	0.012
Jemez Snow-off_F01	29-Jun-10	180	931SA	1.7	0.015
Jemez Snow-off_F02	30-Jun-10	181	931SA	1.7	0.019

Jemez Snow-off_F04	1-Jul-10	182	931SA	1.7	0.024
Jemez Snow-off_F06	2-Jul-10	183	931SA	1.8	0.035
Jemez Snow-off_F07	4-Jul-10	185	931SA	2.1	0.031
Jemez Snow-off_F08	4-Jul-10	185	931SA	1.8	0.018
Jemez Snow-off_F09	5-Jul-10	186	931SA	2.2	0.015
Jemez Snow-off_F10	5-Jul-10	186	931SA	1.8	0.012
Jemez Snow-off_F11	6-Jul-10	187	931SA	1.5	0.010
Jemez Snow-off_F12	6-Jul-10	187	931SA	1.9	0.031
Jemez Snow-off_F13	7-Jul-10	188	931SA	2.2	0.015
Jemez Snow-off_F14	8-Jul-10	189	931SA	1.6	0.012

After GPS processing, the trajectory and the inertial measurement unit (IMU) data collected during the flight are input into APPLANIX software POSPac (MMS 5.2) which implements a Kalman Filter algorithm to produce a final, smoothed, and complete navigation solution including both aircraft position and orientation at 200 Hz. This final navigation solution is known as the SBET (Smoothed Best Estimated Trajectory). The SBET and the raw laser range data were combined using Optech's DashMap processing program to generate the laser point dataset in LAS format.

4.2. Calibration, Validation, and Accuracy Assessment

Bore sight calibration was done for each flight by surveying crossing flight-lines with the ALTM over near-by residential neighborhoods and also on the project polygon and using TerraMatch software (http://www.terrasolid.fi/en/products/terramatch) to calculate calibration values. Residential neighborhoods are utilized because building rooftops provide ideal surfaces (exposed, solid, and sloped in different aspects) for automated calibration.

TerraMatch uses least-squares methods to find the best-fit values for roll, pitch, yaw, and scanner mirror scale by analyzing the height differences between computed laser surfaces of rooftops and ground surfaces from individual crossing and/or overlapping flight lines. TerraMatch is generally run on several different areas for each flight. TerraMatch routines also provide a measurement for the mismatch in heights of the overlapped portion of adjacent flight strips.

Range calibration was done for each project by collecting check points on nearby roads with vehicle-mounted GPS. These road sections containing check points were then surveyed with the ALTM. Overflying check points for range calibration purposes was not done on every flight as this value remains very stable over many flights, but rather was done at least twice for each project.

Below is Table 31 which contains a column (Average height mismatch in overlap) for the magnitude (in meters) of the mismatch in heights of the overlapped portion of adjacent flight strips and cross-lines. There is a value taken from an average of all checked areas for each flight. In general flight line overlap is checked in at least three different areas per flight.

The Check-Points: # of differences column contains the total number of differences formed from check points and their nearest neighbor LiDAR shot for the entire mission across all flights.

The Check-Points: RMS of height differences column contains the RMS of the differences between the heights of the check points and their nearest neighbor LiDAR shot.

Taken together with the manufacturer's system accuracy specification and the accuracy of the GPS trajectory these numbers provide a general accuracy framework for the delivered DEM on a flight by flight and project by project basis. This does not imply that the derived DEM maintains this level of accuracy in all locations.

Table 31. Average height differences (in meters) between surfaces from adjacent swaths and cross lines in the overlap for each flight; RMS of the height differences (in meters) between check points and LiDAR points for each project.

Flight	Average height mismatch in overlap	Check Points	
		Number of differences	RMS of height differences

Jemez Snow-on_F01	0.024	1230	0.034
Jemez Snow-on_F02	0.041		
Jemez Snow-on_F03	0.038		
Jemez Snow-on_F04	0.032		
Jemez Snow-on_F05	0.038		
Jemez Snow-on_F06	0.043		
Jemez Snow-on_F07	0.049		
Jemez Snow-on_F08	0.058		
Jemez Snow-on_F09	0.052		
Jemez Snow-on_F10	0.031		
Jemez Snow-on_F11	0.043		

Jemez Snow-off_F01	0.042	858	0.054
Jemez Snow-off_F02	0.053		
Jemez Snow-off_F04	0.045		
Jemez Snow-off_F06	0.058		
Jemez Snow-off_F07	0.043		
Jemez Snow-off_F08	0.054		
Jemez Snow-off_F09	0.044		
Jemez Snow-off_F10	0.039		
Jemez Snow-off_F11	0.059		
Jemez Snow-off_F12	0.047		
Jemez Snow-off_F13	0.049		
Jemez Snow-off_F14	0.032		

NCALM makes every effort to produce the highest quality LiDAR data possible but every LiDAR point cloud and derived DEM will have visible artifacts if it is examined at a sufficiently fine level. Examples of such artifacts include visible swath edges, corduroy (visible scan lines), and data gaps. A detailed discussion on the causes of data artifacts and how to recognize them can be found here: http://ncalm.berkeley.edu/reports/GEM_Rep_2005_01_002.pdf ,
and a discussion of the procedures NCALM uses to ensure data quality can be found here: http://ncalm.berkeley.edu/reports/NCALM_WhitePaper_v1.2.pdf

NCALM cannot devote the required time to remove all artifacts from data sets, but if researchers find areas with artifacts that impact their applications they should contact NCALM and we will assist them in removing the artifacts to the extent possible – but that this may well involve the PIs devoting additional time and resources to this process.

4.3 Classification

TerraSolid's TerraScan software was used to classify the raw laser point into the following categories: ground, non-ground (default) and artifacts (aerial/isolated points, low points)

Because of the large size of the LiDAR dataset the processing had to be done in tiles. Each survey segment was imported into TerraScan projects consisting of 1000m x 1000m tiles aligned with the 1000 units in UTM coordinates.

The classification process was executed by a TerraScan macro that was run on each individual tile data and the neighboring points within a 40m buffer. The overlap in processing ensures that the filtering routine generate consistent results across the tile boundaries.

The classification macros consist of the following general steps:

1) *Initial set-up and clean-up.* All four pulses are merged into the "Default" class to be used for the ground classification routine. A rough minimum elevation threshold filter is applied to the entire dataset in order to eliminate the most extreme low point outliers.

2) *Low and isolated points clean-up*. At this step the macro is searching for isolated and low points using several iterations of the same routines.

The "Low Points" routine is searching for possible error points which are clearly below the ground surface. The elevation of each point (=center) is compared with every other point within a given neighborhood and if the center point is clearly lower than any other point it will be classified as a "low point". This routine can also search for groups of low points where the whole group is lower than other points in the vicinity.

The "Isolated Points" routine is searching for points which are without any neighbors within a given radius. Usually it catches single returns from high above ground but it is also useful in the case of isolated low outliers that were not classified by the Low Points routine.

Typically the Isolated routine was run twice and the Low routine three times.

Search for: Groups of Points
Max Count (maximum size of a group of low points): 5 – 5 - 5
More than (minimum height difference): 0.2 m – 0.5m – 0.5m
Within (xy search range): 5.0 m – 5.0m – 10.0m

3) *Ground Classification*. This routine classifies ground points by iteratively building a triangulated surface model. The algorithm starts by selecting some local low points assumed as sure hits on the ground, within a specified windows size. This makes the algorithm particularly sensitive to low outliers in the initial dataset, hence the requirement of removing as many erroneous low points as possible in the first step.

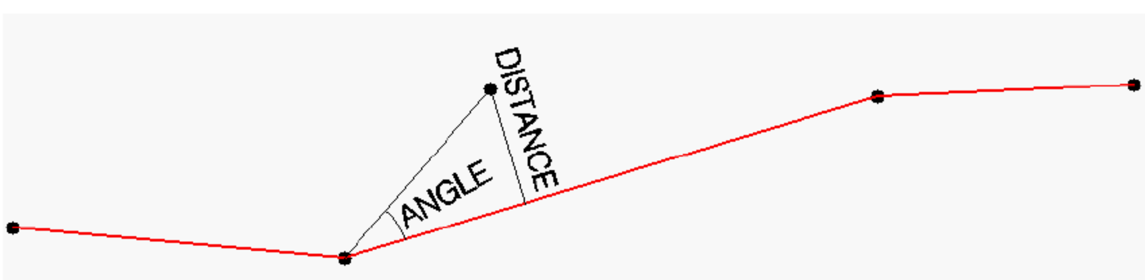


Figure 16. Ground classification parameters

The routine builds an initial model from selected low points. Triangles in this initial model are mostly below the ground with only the vertices touching ground. The routine then starts molding the model upwards by iteratively adding new laser points to it. Each added point makes the model follow ground surface more closely. Iteration parameters determine how close a point must be to a triangle plane so that the point can be accepted to the model. Iteration angle is the maximum angle between point, its projection on triangle plane and closest triangle vertex. The smaller the Iteration angle, the less eager the routine is to follow changes in the point cloud. Iteration distance parameter makes sure that the iteration does not make big jumps upwards when triangles are large. This helps to keep low buildings out of the model. The routine can also help avoiding adding unnecessary point density into the ground model by reducing the eagerness to add new points to ground inside a triangle with all edges shorter than a specified length.

Typical Ground classification parameters used:

Max Building Size (window size): 40.0 m
Max Terrain Angle: 88.0
Iteration Angle: 6.20 deg
Iteration Distance: 2.0 m
Reduce iteration angle when edge length < : 5.0 m

These parameters where adjusted where required by the specific topography of some areas, in order to better capture the true ground surface.

4) *Below Surface removal*. This routine classifies points which are lower than other neighboring points and it is run after ground classification to locate points which are below the true ground surface. For each point in the source class, the algorithm finds up to 25 closest neighboring source points and fits a plane equation through them. If the initially selected point is above the plane or less than "Z tolerance", it will not be classified. Then it computes the standard deviation of the elevation differences from the neighboring points to the fitted plane and if the central point is more than "Limit" times standard deviation below the plane, the algorithm it will classify it into the target class.

Typical "Below Surface" classification parameters used:

Source Class: Ground
Target Class: Low Point
Limit: 8.00 * standard deviation
Z tolerance: 0.10 m

5) *Above ground clean-up*. This last step applies a height above ground threshold (typically 60m) to the points left in the "Default" class in order to eliminate systemic, grouped high point clusters that sometime may appear in the raw LiDAR data. This ensures that the "unfiltered" dataset is free from artifacts due to these types of clusters.

5. Deliverables Description.

All deliverables were processed with respect to NAD83 (CORS96) reference frame. The projection is the appropriate UTM zone with units in meters. Heights are NAVD88 orthometric heights computed from GRS80 ellipsoid heights using NGS GEOID03 model.

Deliverable 1 is the point cloud in LAS (V 1.0 or 1.2) format of the individual flight strips; elevations have been transformed to the NAVD88 Vertical Datum (GEOID03). These flight strips are NOT classified as ground or non-ground, but rather the classification field contains the default value as populated by the manufacturer's software (Optech's DashMap ver. 5.1) which is equivalent to the stop number.

Deliverable 2 is the point cloud in LAS format, classified by automated routines in TerraScan (http://www.terrasolid.fi/en/products/terrascan) as ground or non-ground in tiles created from the combined flight strips. The tiles follow a naming convention using the lower left UTM coordinate (minimum X, Y) as the seed for the file name as follows: XXXXXX_YYYYYYY. For example if the tile bounds coordinate values from easting equals 269000 through 270000, and northing equals 4947000 through 4948000 then the tile filename is 269000_4947000.las

Deliverable 3 is the ESRI format DEM mosaic derived from deliverable 2 using default-class (first-stop) points at 1 meter node spacing. Elevation rasters are first created using Golden Software's Surfer 8 Kriging algorithm using the following parameters:

```
Gridding Algorithm: Kriging
Variogram: Linear
Nugget Variance: 0.15 m
MicroVariance: 0.00 m
SearchDataPerSector: 7
SearchMinData: 5
SearchMaxEmpty: 1
SearchRadius: 5m
```

The resulting Surfer grids are transformed into ArcInfo binary DEMs and hill shades using in-house Python and AML scripts.

Deliverable 4 is the ESRI format DEM mosaic derived from deliverable 2 using only ground-class points. The rasters are first created using Golden Software's Surfer 8 Kriging algorithm using the following parameters:

```
Gridding Algorithm: Kriging
Variogram: Linear
Nugget Variance: 0.15 m
MicroVariance: 0.00 m
SearchDataPerSector: 7
SearchMinData: 5
SearchMaxEmpty: 1
SearchRadius: 25m or 40m
```

The resulting Surfer grids are transformed into ArcInfo binary DEMs and hill shades using in-house Python and AML scripts.

During processing, a scan cutoff angle of 2.0 degrees was used to eliminate points at the edge of the scan lines. This was done to improve the overall DEM accuracy as points farthest from the scan nadir are the most affected by scanner errors and errors in heading, pitch, and roll.