Critical Zone Observatory LiDAR

Mapping Project Report
January 14, 2011

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

Mapping Project Report Table of Contents

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 1^{st}, 2^{nd}, 3^{rd}, 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.

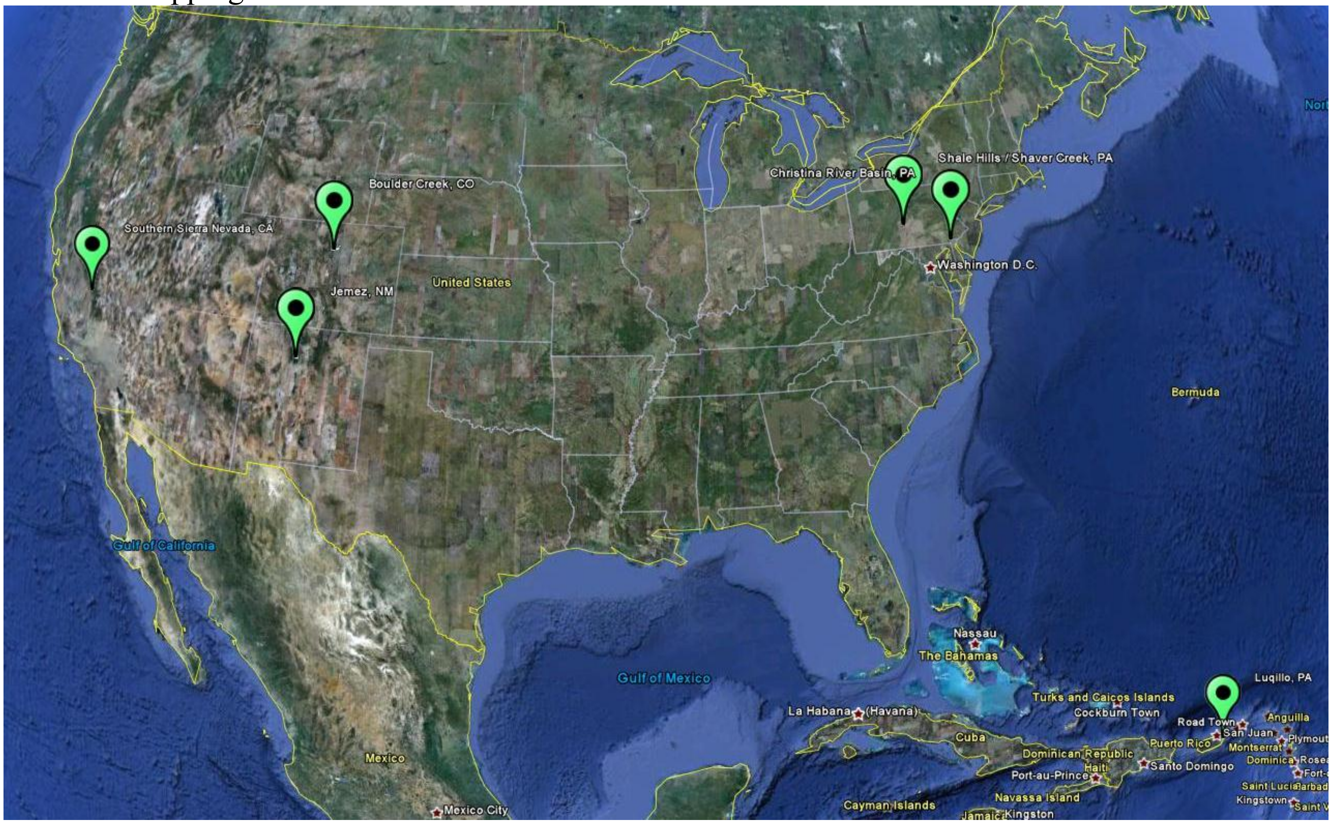


Figure 1. Location of CZO survey projects.

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
1	Southern Sierra Nevada, CA / snow- on	1-Mar-10 to 7-Mar-10	14-Mar-10 to 24-Mar-10
2	Jemez, NM / snow-on	10-Mar-10 to 20-Mar-10	27-Mar-10 to 3-Apr-10
3	Christina River Basin, PA / leaf-off	15-Mar-10 to 19-Mar-10	7-Apr-10 to 8-Apr-10
4	Boulder Creek, CO / snow-on	25-Apr-10 to 10-May-10	28-Apr-10 to 21-May-10
5	Jemez, NM / snow-off	28-Jun-10 to 3-Jul-10	29-Jun-10 to 8-Jul-10
6	Shale Hills, PA / leaf-on	1-Jul-10 to 31-Jul-10	14-Jul-10 to 16-Jul-10
7	Christina River Basin, PA / leaf-on	1-Jul-10 to 31-Jul-10	17-Jul-10 to 18-Jul-10
8	Luquillo, PR	16-Jul-10 to 14-Dec-10	26-Jul-10 to 30-Jul-10
9	Southern Sierra Nevada, CA / snow-off	8-Aug-10 to 12-Aug-10	5-Aug-10 to 15-Aug-10
10	Boulder Creek, CO / snow-off	22-Aug-10 to 5-Sep-10	21-Aug-10 to 26-Aug-10
11	Shale Hills, PA / leaf-off	1-Dec-10 to 31-Dec-10	3-Dec-10 to 9-Dec-10
12	Luquillo, PR / retry	1-Feb-11 to 28-Feb-11	

3.1 Southern Sierra Nevada, CA snow-on and snow-off collection

The Southern Sierra Nevada sub-project consisted of seven areas of interest (AOI): Bull (area1), Courtwright Road (area2), Providence (area3), San Joaquin Range (area4), Soaproot Saddle (area5), Wolverton and Tokopah (area6). Because of their proximity and topographic conditions the Wolverton and Tokopah AOIs were flown as a single polygon. The total surveyed area for the Southern Sierra Nevada was larger than originally requested by CZO. This sub-project was flown employing a Piper PA-31 Chieftain twin engine aircraft, the sensor configuration used for both snow-on and snow-off is presented in Table 3.

Table 3. Flight parameters, Sensor settings and survey totals (single collection)*.

Nominal Flight Parameters		Equipment Settings		Planned Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	6
Flight Speed	65 m/s	Beam Divergence	0.25 mrad	Total Passes	125
Swath Width	233.26 m	Scan Frequency	55 Hz	Total Length	632.757 km
Swath Overlap	50%	Scan Angle	± 14°	Total Flight Time	12.87 hrs
Point Density	10.27 p/m²	Scan Cutoff	3°	Total Laser Time	2.71 hrs
Cross-Track Res	0.233 m	Scan Offset	0°	Total Swath Area	73.798 km²
Down-Track Res	0.418 m			Total AOI Area	58.369 km²

* based on plan: czo_sierranevada_3.pln

The locations of the seven areas of interest for the Southern Sierra Nevada CZO sub-project are shown in Figure 2. Close-up views of the areas of interest showing the polygon outlines and the planned flight lines are presented in Figure 3. The survey quantities (number or lines, line lengths, areas and time) for each area of interest are summarized in Table 4.

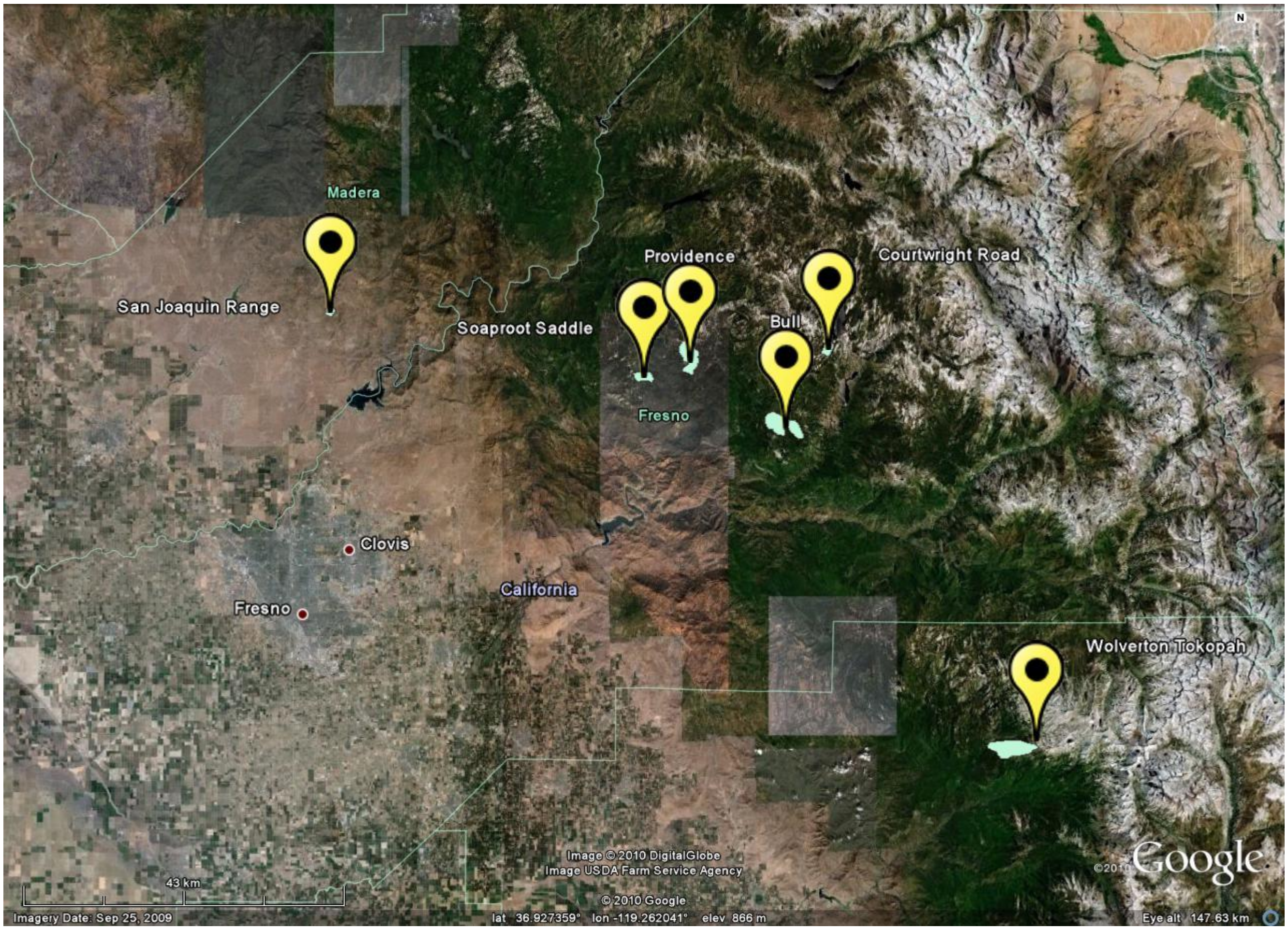


Figure 2. Location of the Areas of Interest for the CZO Southern Sierra Nevada, CA sub-project.

Table 4. Planned survey quantities per AOI (single collection).

Sub areas	Bull	Courtwright Road	Providence	San Joaquin	Soaproot Saddle	Wolverton Tokopah
Total Passes	24	11	23	14	13	40
Total Length [km]	101.614	20.271	87.6	14.789	27.704	380.779
Total Flight Time [hrs]	02:23:45	00:55:49	02:14:33	01:09:46	01:08:38	04:59:56
Total Laser Time [hrs]	00:26:03	00:05:12	00:22:28	00:03:48	00:07:06	01:37:38
Total Swath Area [km^2]	11.851	2.364	10.217	1.725	3.231	44.41
Total AOI Area [km^2]	9.333	2.101	8.055	1.335	2.84	34.705

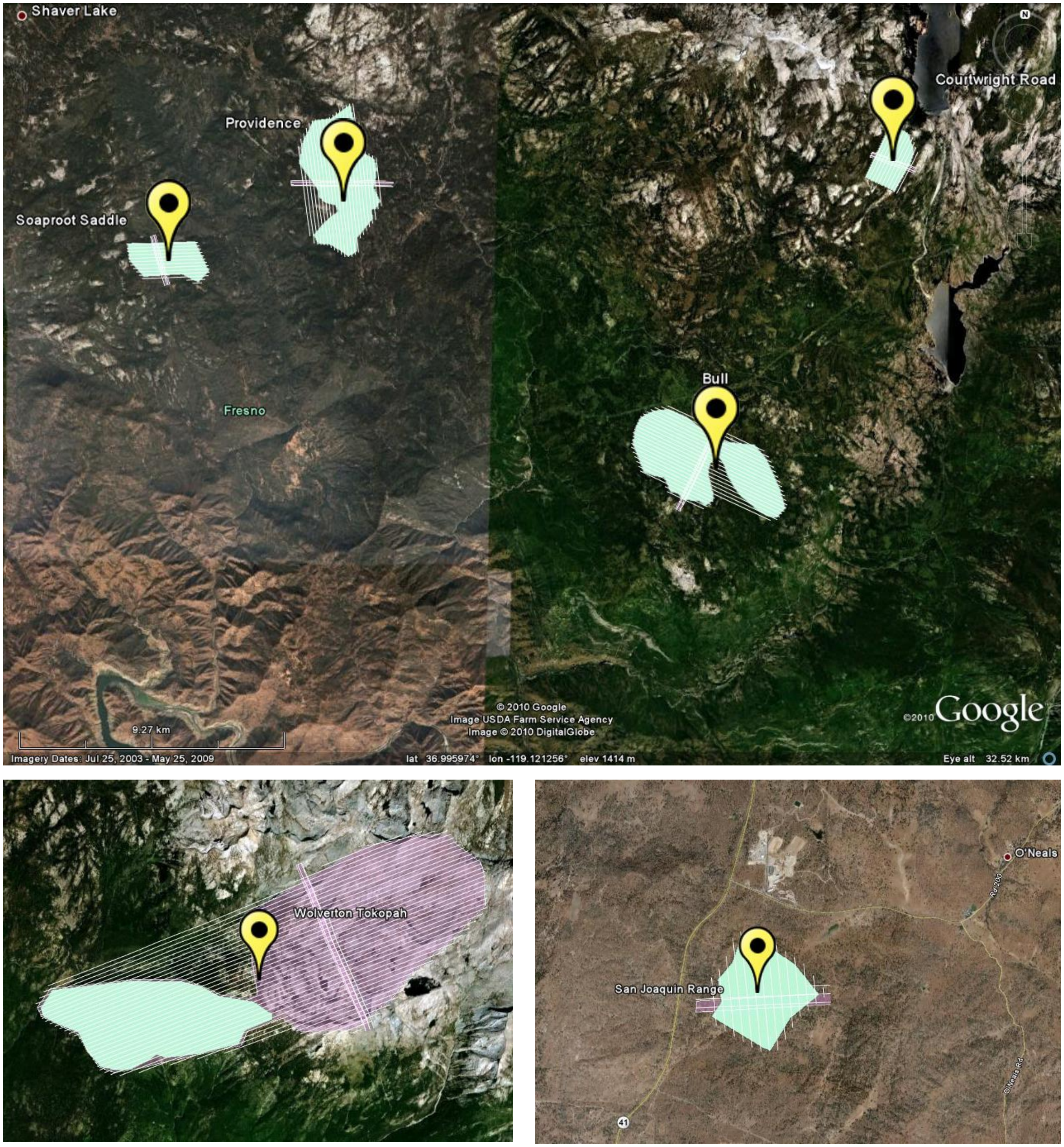


Figure 3. Planned flight lines for the Areas of Interest for the CZO Southern Sierra Nevada, CA sub-project.

3.1.1 Snow-on collection

The snow-on collection took place between March 14 and 24; there were a total of 11 flights, which are summarized in Table 5. After a preliminary processing of the data collected on the second flight, a problem with the return intensity was found. Technical support from the manufacturer was requested, after inspection the solution was to replace the intensity and logic boards of the system. Flights resumed on March 19th with an attempt to map the Soaproot area but the mission was aborted because of low clouds and haze that severely limited the visibility above the project areas. The data collected on the second flight for the Courtwright and Providence AOIs were discarded and recollected on flights 8 and 9. On flight 10, the first attempt to map the Bull area, however low clouds rendered the data unusable and the area was reflown on flight 11. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the PA-31 tail number N31PR.

Table 5. CZO Southern Sierra Nevada, CA, snow-on collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Area	Digitizer (Gb)
F01	14-Mar-10	73	16:47:52	20:47:55	4.06	0.25	San Joaquin Range	4.4
F02	15-Mar-10	74	14:52:31	19:50:52	4.61	0.79	Courtwright Providence	10.3+4.1
F03	19-Mar-10	78	0:22	1:35	0.87	0.00	Attempt Soaproot	
F04	20-Mar-10	79	14:45:30	18:53:40	3.77	0.69	Wolverton-Tokopah	1.1
F05	20-Mar-10	79	20:50:00	0:05:41	2.84	0.55	Wolverton-Tokopah	11.1
F06	21-Mar-10	80	15:30:05	18:58:40	3.12	0.68	Wolverton-Tokopah	8.9
F07	21-Mar-10	80	19:39:31	22:19:22	2.34	0.34	Wolverton-Tokopah	
F08	22-Mar-10	81	19:09:10	19:16:30	3.75	0.57	Wolverton-Tokopah , Providence	9.9
F09	23-Mar-10	82	15:06:40	19:40:11	4.23	0.58	Providence, Courtwright, Soaproot	12.5
F10	23-Mar-10	82	21:49:30	1:34:50	3.27	0.62	Bull (clouds)	11.6
F11	24-Mar-10	83	14:56:18	18:30:25	3.21	0.63	Bull	10.1
					36.06	5.68		

3.1.2 Snow-off collection

The snow-off collection started on August 5th mapping the San Joaquin and Providence area, however, ground crews were not ready to do the ground-truth measurements and subsequent flights were delayed until August 13th, the last collection was flown on August 15th. The collection was uneventful and the details of each flight are summarized in Table 6. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the PA-31 tail number N931SA.

Table 6. CZO Southern Sierra Nevada, CA, snow-off collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Area	Digitizer (Gb)
F01	5-Aug-10	217	17:52:05	22:25:10	4.17	0.93	San Joaquin Range, Providence	10.1
F02	13-Aug-10	225	22:55:25	3:10:22	3.96	0.69	Soaproot, Wolverton, Tokopah and Courtwright	7.7
F03	14-Aug-10	226	15:46:04	19:14:37	3.19	0.90	Wolverton, Tokopah	9.3
F04	15-Aug-10	227	15:54:44	19:27:11	3.28	1.03	Wolverton, Tokopah	

F05	15-Aug-10	227	21:20:04	0:34:00	2.89	0.74	Bull
					17.48	4.30	

3.1.3 GPS stations

Data from a total of six GPS ground stations were used for aircraft trajectory determination. Four of these stations are part of UNAVCO PBO GPS network (P307, P572, P629 and MUSB), 2 other stations (KFAT and Reedley) were setup by NCALM near the Fresno and Reedley airports. The location of the stations relative to the project AOIs is presented on Figure 4 and the coordinates of the stations are summarized in Table 7.

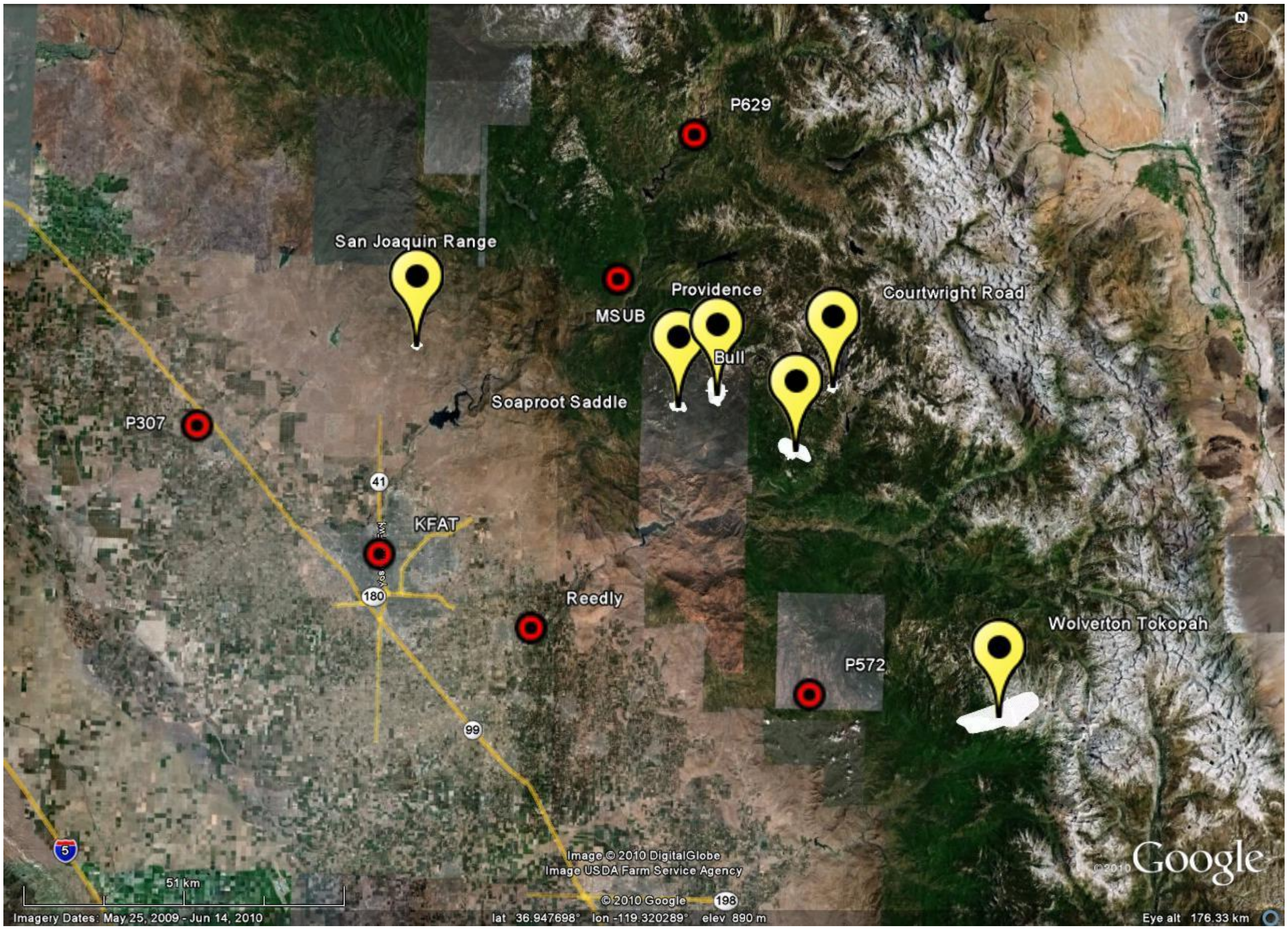


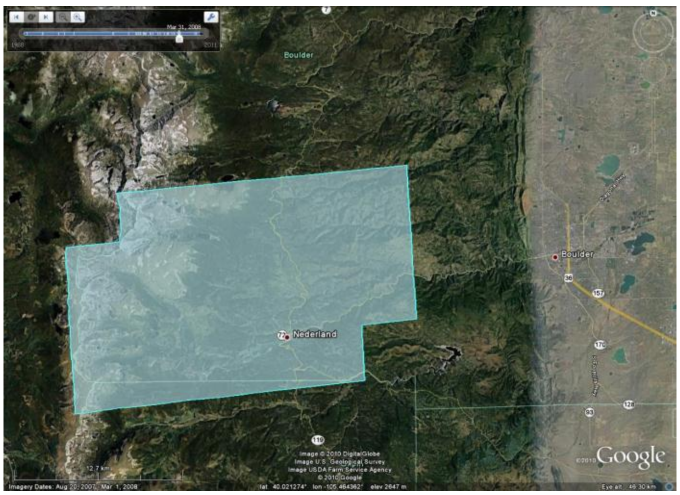
Figure 4. Location of the GPS stations used to derive aircraft trajectories for the Southern Sierra, CA sub-project.

Table 7. Coordinates of GPS stations used to derive aircraft trajectories.

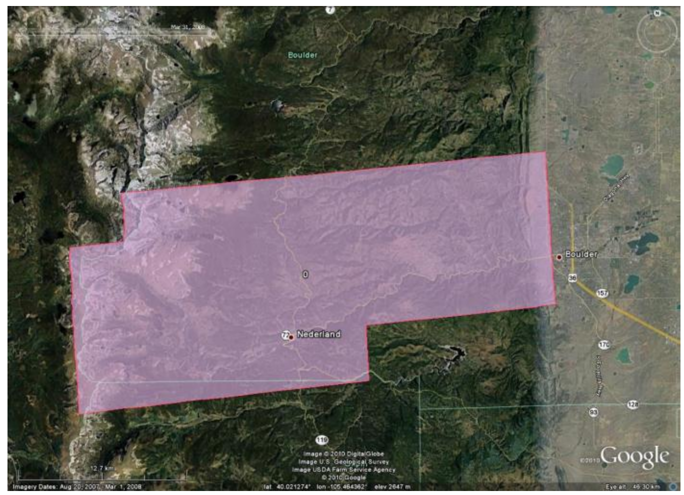
GPS station	P307	P572	P629	MUSB	KFAT	Reedley
Operating agency	UNAVCO	UNAVCO	UNAVCO	UNACO	NCALM	NCALM
Latitude	36.94727	36.585511	37.3758664	37.1699409	36.7711458	36.6710278
Longitude	-120.057919	-118.954581	-119.179372	-119.309351	-119.726092	-119.45100
Ellipsoid Height (m)	49.5085	1167.945	2725.6721	2042.5353	68.366	85.061

3.2 Boulder Creek, CO snow-on and snow-off collection

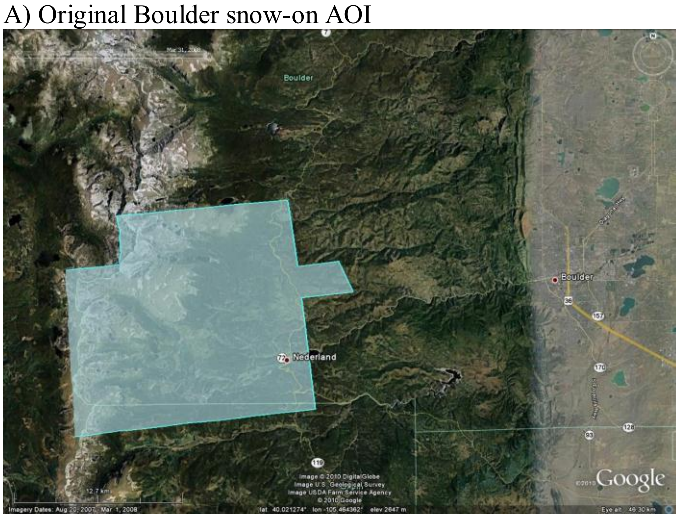
The Boulder Creek CZO sub-project consisted on two collections, one during the snow-on season and the other during snow-off conditions. The original snow-on collection had a surface area of 372.25 km^2 and the original snow-off was 494.03 km^2. However the areas of interest for both domains were adjusted based on the snow conditions at the time of the winter collection; reducing the area of the winter survey and increasing the area of the summer collection, but maintaining the total area. These changes are illustrated in Figure 5 and summarized in Table 8. 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 parameter and survey totals are presented in Tables 9 and 10 and illustrated with Figures 6 and 7.



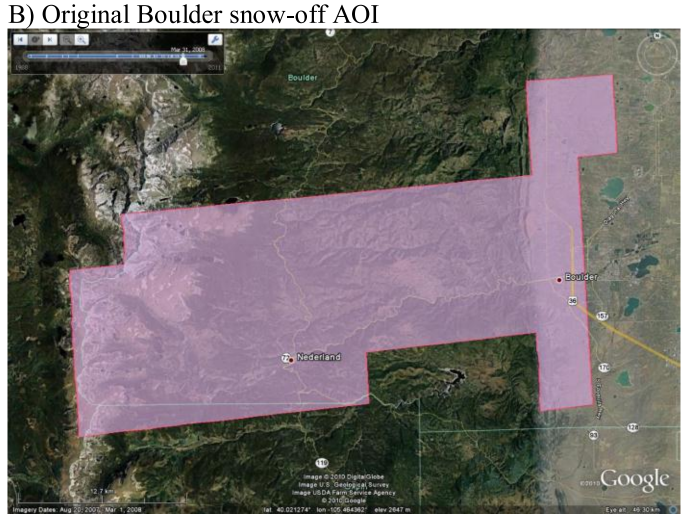
A) Original Boulder snow-on AOI



B) Original Boulder snow-off AOI



C) Final Boulder snow-on AOI



D) Final Boulder snow-off AOI

Figure 5. Original and final areas of interest for the Boulder, CO snow-on and snow-off surveys.

Table 8. Changes to the original Boulder Creek, CO Areas of Interest (AOI)s.

	Snow-on		Snow-off		Snow-on + Snow-off	
	Original	Surveyed	Original	Surveyed	Original	Surveyed
Area (km^2)	372.250	265.442	494.026	598.922	866.276	864.364

Table 9. 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	125
Swath Width	255.07 m	Scan Frequency	60 Hz	Total Length	2111.943 km
Swath Overlap	50%	Scan Angle	± 14°	Total Flight Time	19.54 hrs
Point Density	10.28 p/m²	Scan Cutoff	± 2°	Total Laser Time	9.03 hrs
Cross-Track Res	0.254 m	Scan Offset	0°	Total Swath Area	269.336 km^2
Down-Track Res	0.383m			Total AOI Area	265.442 km^2

* based on plan: CZO_CO_Boulder_Winter_v3.pln

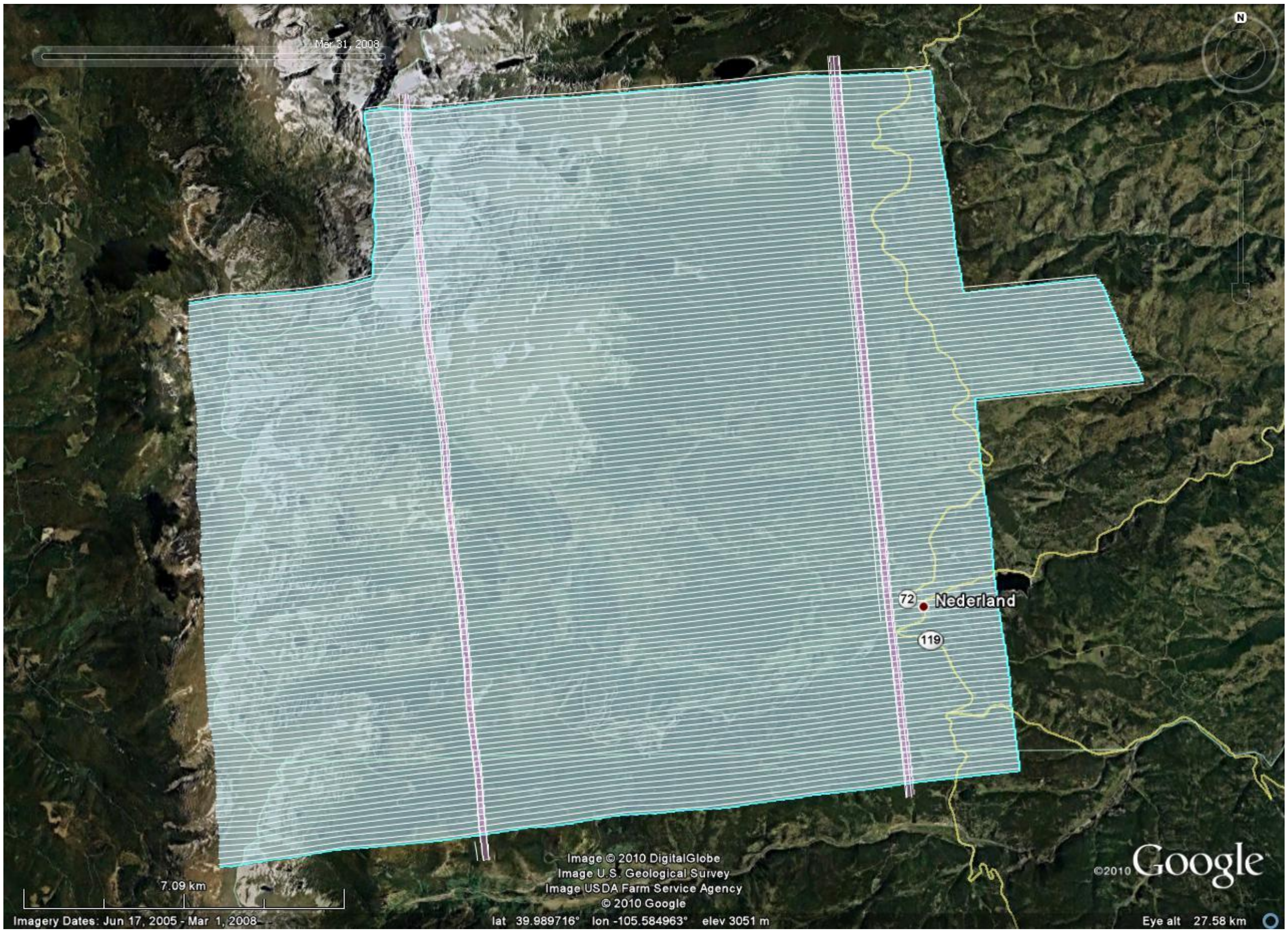


Figure 6. Planned flight lines for the CZO Boulder CO snow-on collection.

Table 10. Flight parameters, Sensor settings and survey totals for the snow-off collection*.

Nominal Flight Parameters		Equipment Settings		Planned Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	2 (continuous)
Flight Speed	65 m/s	Beam Divergence	0.25 mrad	Total Passes	183
Swath Width	255.07 m	Scan Frequency	60 Hz	Total Length	4800.206 km
Swath Overlap	50%	Scan Angle	± 14°	Total Flight Time	36.04 hrs
Point Density	10.28 p/m²	Scan Cutoff	± 2°	Total Laser Time	20.51 hrs
Cross-Track Res	0.254 m	Scan Offset	0°	Total Swath Area	612.17 km^2
Down-Track Res	0.383m			Total AOI Area	598.922 km^2

* based on plan: CZO_CO_Boulder_Summer_v1.pln

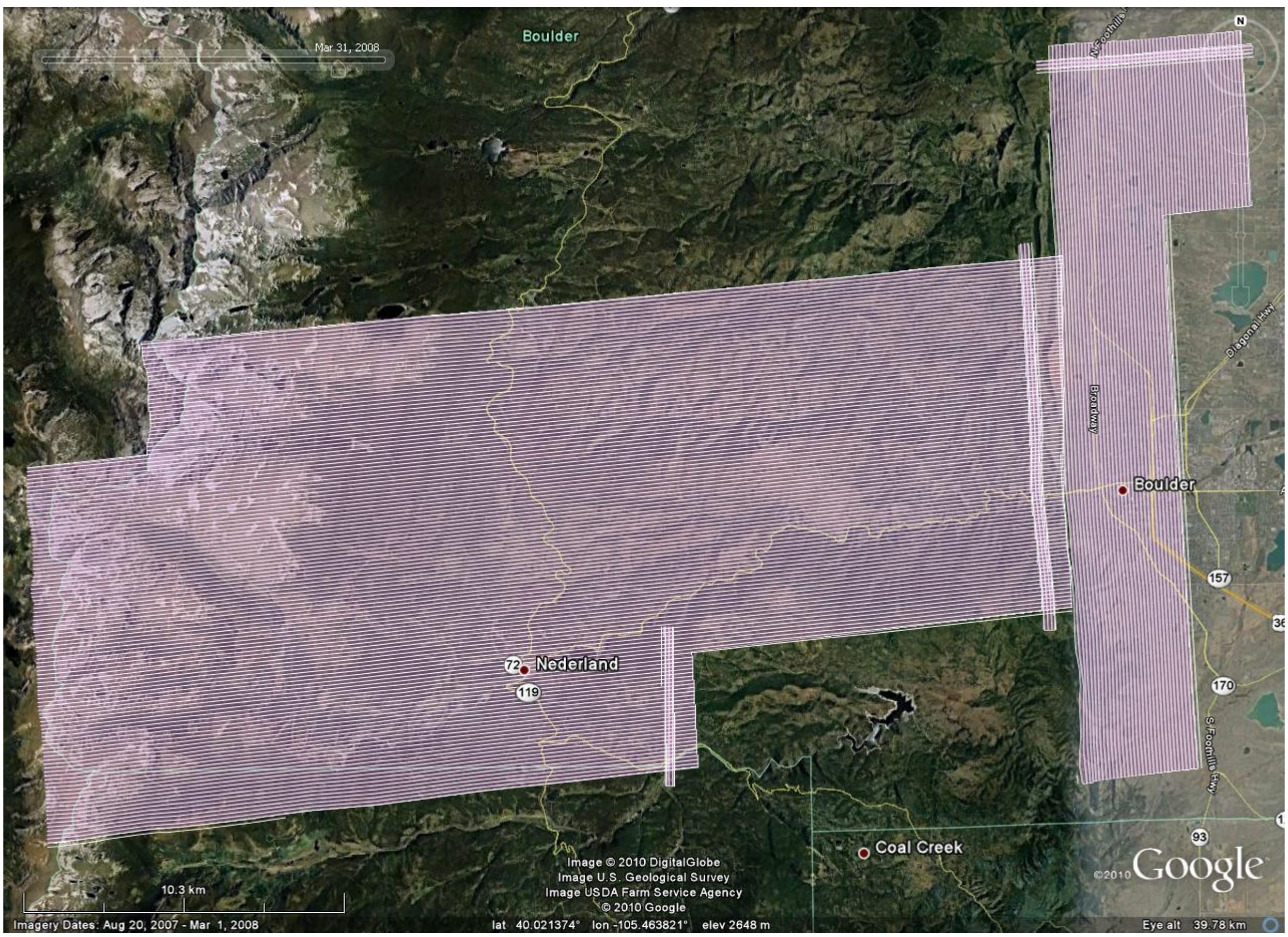


Figure 7. Planned flight lines for the CZO Boulder CO snow-off collection.

3.2.1 Snow-on collection

The snow-on collection started on April 28 but due to bad mountain weather and equipment malfunctions it was completed until May 21. There were a total of 9 flights, which are summarized in Table 11. Collection started with the Gemini 06SEN/CON195 system installed on the PA-31 tail number N31PR. During the fourth flight a problem with the intensity board was detected, an extinction test was performed on flight number five and an additional collection with intensity malfunction was performed on flight number 6. It was then decided to send the system to Canada for servicing and a loaner system was requested. The loaner system an ALTM 3100 S/N 03SEN/CON144 arrived on May 20th and flights resumed that same day. The project was completed on May 21st.

Table 11. CZO Boulder, CO, snow-on collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	28-Apr-10	118	14:51:48	16:16:31	0.79	0.16	Aborted due to bad weather	NA
F02	5-May-10	125	13:36:10	17:24:19	3.47	1.88		NA
F03	7-May-10	127	15:25:45	16:01:01	0.42	0.03		NA
F04	9-May-10	129	14:00:25	15:49:34	1.45	0.66	Intensity issue detected	NA
F05	9-May-10	129	20:30:31	21:09:00	0.42	0.21	Extinction test	NA
F06	9-May-10	129	23:21:06	3:12:15	3.60	2.39		NA
F07	20-May-10	140	21:12:12	1:38:00	4.12	2.47	Replace Gemini by ALTM 3100	NA
F08	21-May-10	141	13:29:18	18:03:32	4.28	2.43		NA
F09	21-May-10	141	20:34:27	23:38:10	2.72	1.32		NA
					21.28	11.54		

Note: Due to the 11 days gap between data collections, the snow accumulation has changed the topography of some areas in significant ways. The topographic change can be tracked in the point cloud and in some (limited) areas the offset is visible in the DEM hill shade as well.

The LAS point tiles were assigned the following flight line numbering scheme in order to facilitate the distinction between different survey dates:

DoY	Line ID range
125a	100-199
125b	200-299
129a	700-799
129c	600-699
140	300-399
141a	400-499
141b	500-599

3.2.2 Snow-off collection

The snow-off collection was performed between August 21 and 26. The collection was uneventful and the details of each flight are summarized in Table 12. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the PA-31 tail number N931SA.

Table 12. CZO Boulder, CO, snow-off collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	21-Aug-10	233	15:12:27	19:42:48	4.24	2.56		18.6
F02	21-Aug-10	233	23:00:32	2:45:18	3.46	2.15		0.1
F03	22-Aug-10	234	18:45:10	22:52:40	3.88	2.24		18.3
F04	23-Aug-10	235	14:30:06	19:09:32	4.41	2.21		18.6
F05	24-Aug-10	236	19:38:52	23:53:57	3.99	2.45		18.8+3.0
F06	25-Aug-10	237	14:07:02	18:34:48	4.20	2.82		18.2
F07	25-Aug-10	237	21:49:59	1:15:15	3.48	2.04		11.9+6.5
F08	26-Aug-10	238	14:00:53	18:21:18	4.09	2.68		18.5+5.5
F09	26-Aug-10	238	19:54:24	0:01:10	3.92	2.81		12.5+11.0
					35.69	21.97		

3.2.3 GPS stations

Data from a total of four GPS ground stations were used for aircraft trajectory determination. Two of these stations are part of the NGS CORS network (TMGO and DSCR), one is part of the UNAVCO PBO network (P041), and an additional station (KBDU) was setup by NCALM at the Boulder airport. The location of the stations relative to the project AOI is presented on Figure 8 and the coordinates of the stations are summarized in Table 13.

Table 13. Coordinates of GPS stations used to derive aircraft trajectories for the Boulder, CO sub-project.

GPS station	TMGO	DSRC	P041	$KBDU_{snow\text{-}on}$	$KBDU_{snow\text{-}off}$
Operating agency	NGS	NOAA/ESRL	UNAVCO	NCALM	NCALM
Latitude	40.130929	39.991425	39.949492	40.0394297	40.0394297
Longitude	-105.232699	-105.261021	-105.194266	-105.2258217	-105.2258217
Ellipsoid Height (m)	1673.858	1657.176	1728.8417	1612.555	1612.555

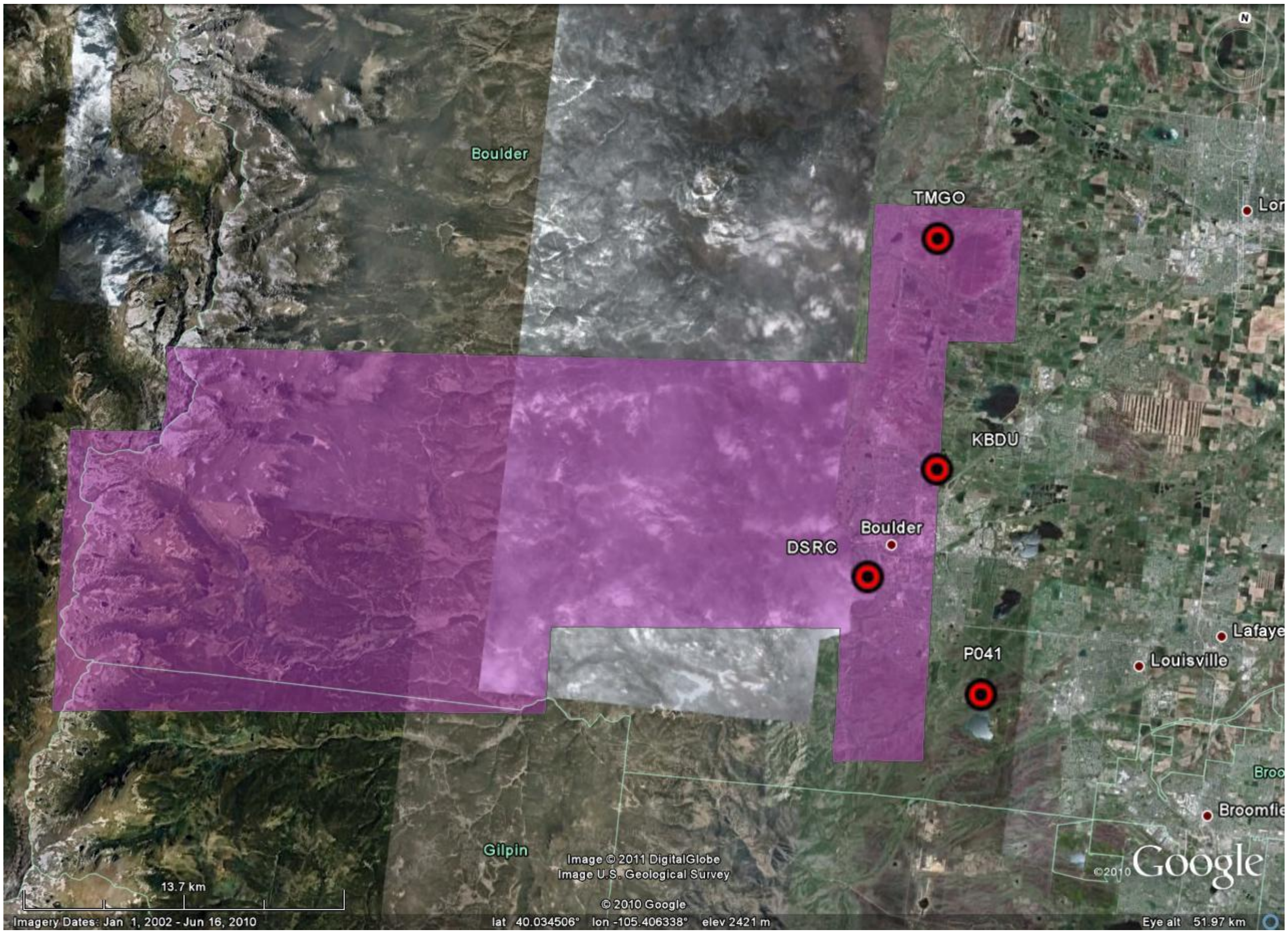


Figure 8. Location of the GPS stations used to derive aircraft trajectories for the Boulder, CO sub-project.

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.

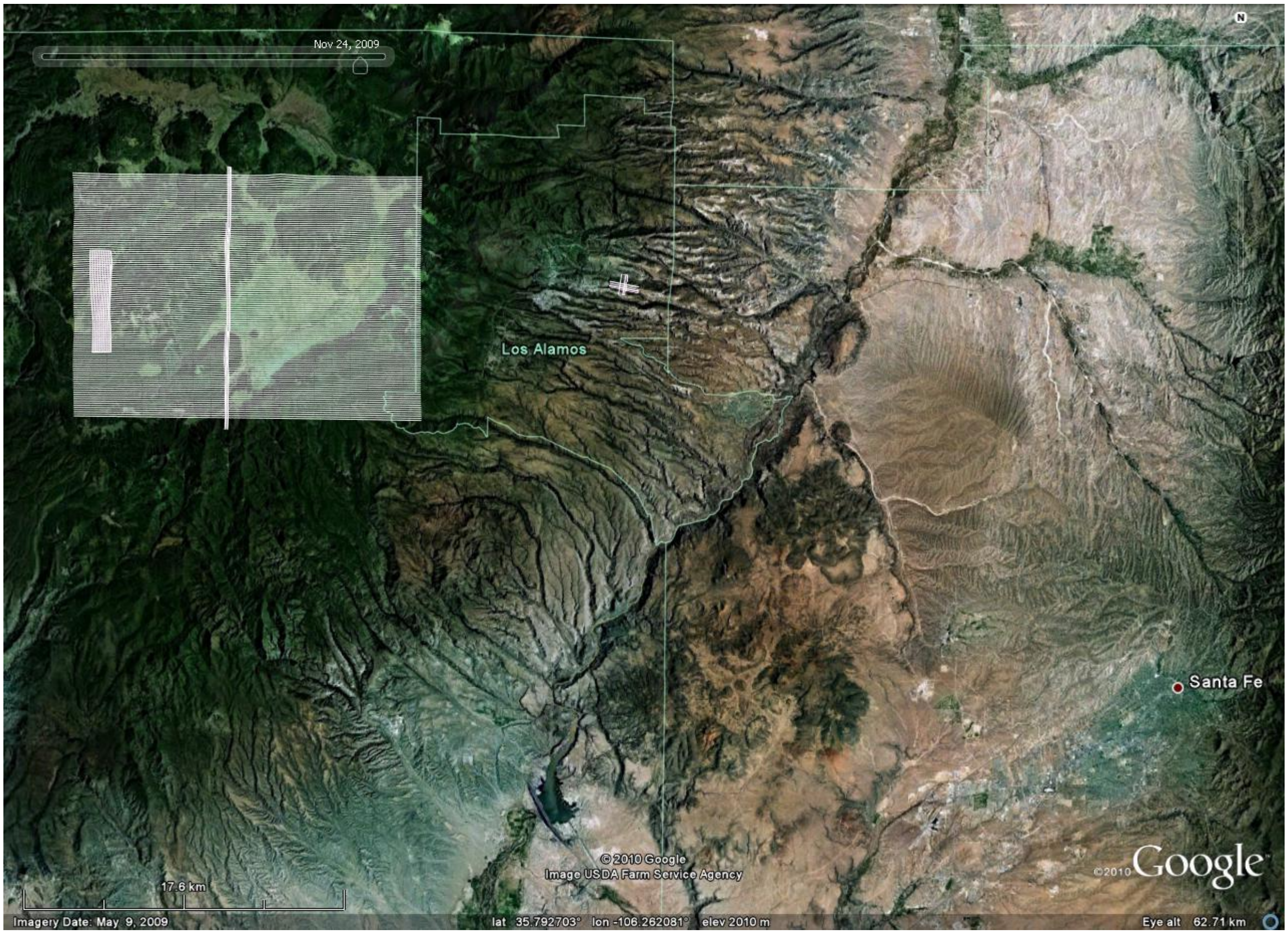


Figure 9. Area of interest (AOI) for the Jemez, NM snow-on and snow-off surveys and flight lines for the snow-on collection.

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) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (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.

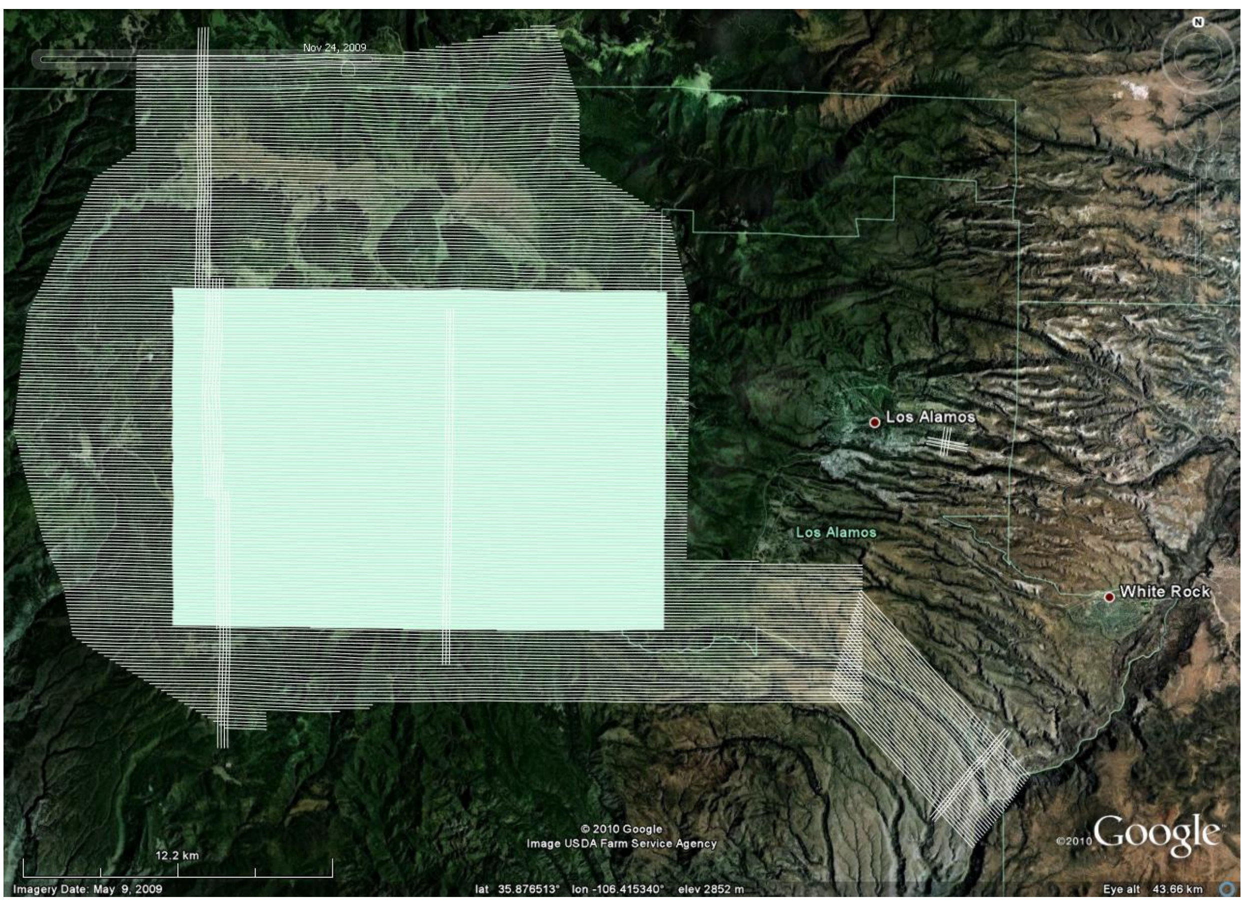


Figure 10. Area of interest (AOI) for the CZO Jemez collection overlaid with the Valles Caldera Preserve plan.

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 $_{snow-on}$	SAF $_{snow-off}$	KLAM $_{snow-on}$	KLAM $_{snow-off}$
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

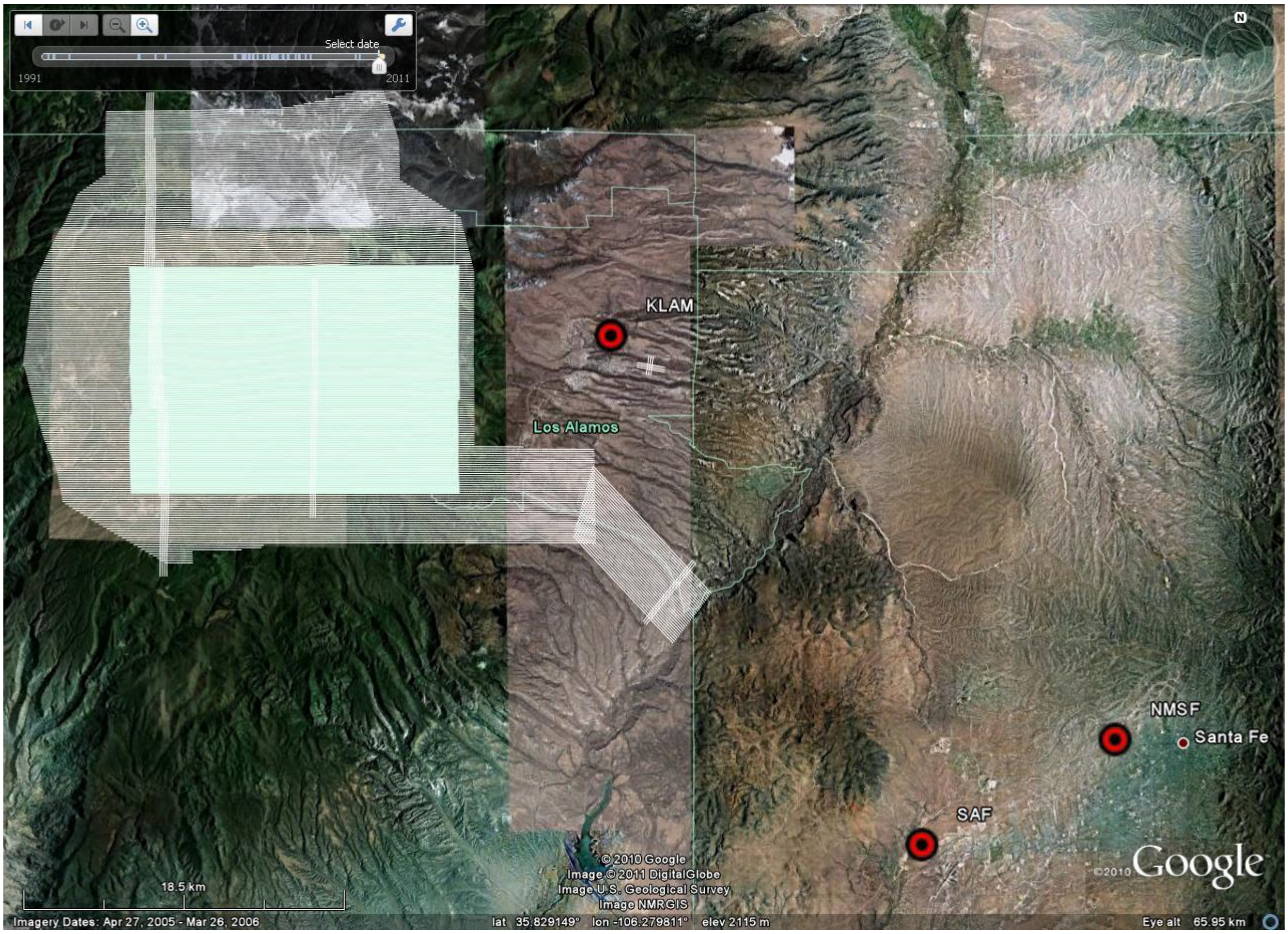


Figure 11. Location of the GPS stations used to derive aircraft trajectories for the Jemez, NM sub-project.

3.4 Christina River Basin, PA leaf-off and leaf-on collection

The Christina River Basin, PA sub-project consisted of two collections during the leaf-off and leaf-on seasons of three areas of interest (36.857, 41.243, and 43.184 km²) located west of West Chester, PA and Northwest of Wilmington, DE, as illustrated in Figure 12. The leaf-off collection was flown employing a Piper PA-31 Chieftain aircraft, while the leaf-on survey was collected using a Cessna 337 Skymaster aircraft.

3.4.1 Leaf-off mission planning and collection

The leaf-off survey was planned to be collected with a Piper PA-31 Chieftain aircraft; the flight parameters, sensor settings and survey totals for the CZO CRB leaf-off collection are summarized in Table 18. The collection was performed on April 7 and 8. There were a total of 4 flights, which are summarized in Table 19. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the PA-31 tail number N31PR.

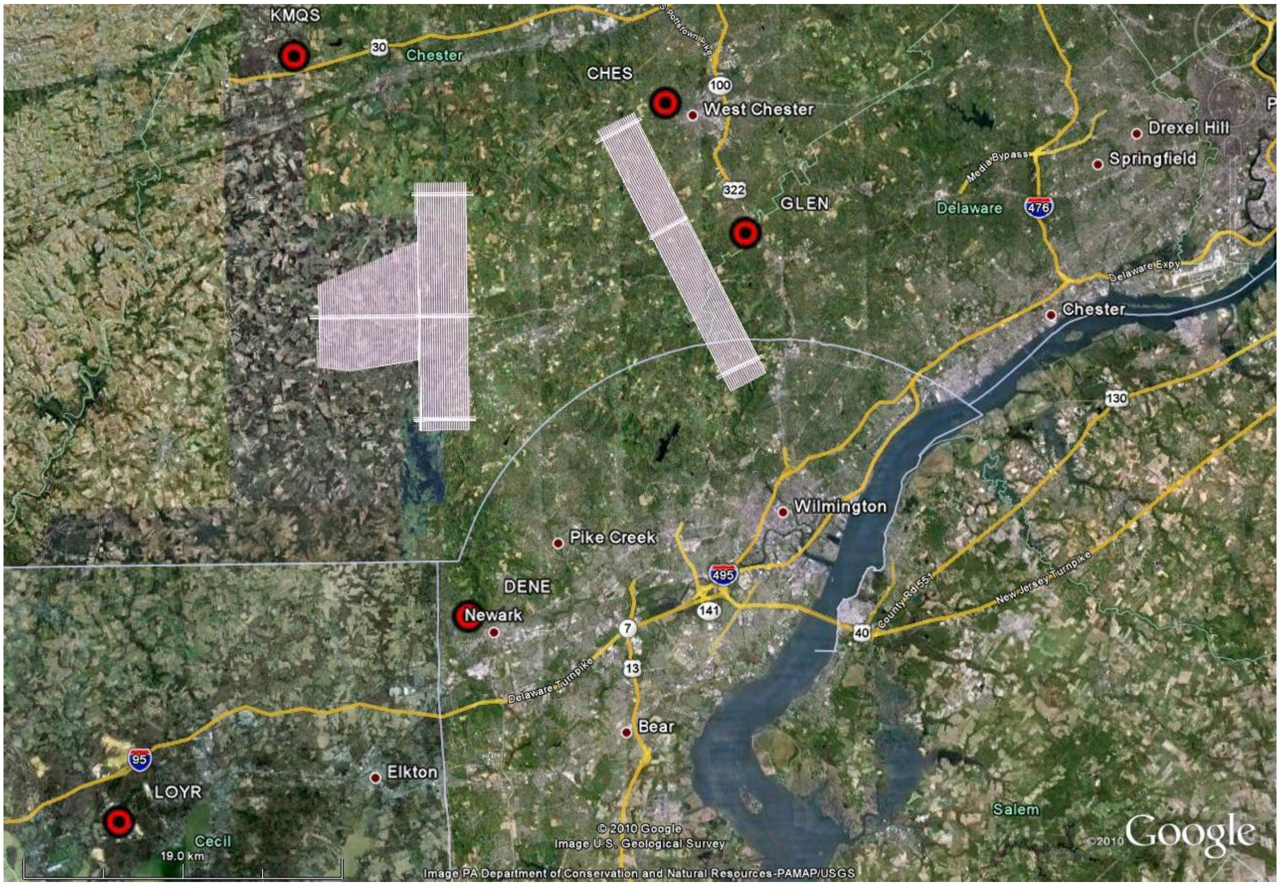


Figure 12. Areas of interest (AOIs), flight lines and GPS stations for the Christina River Basin, PA surveys.

Table 18. Flight parameters, Sensor settings and survey totals (single collection)*.

Nominal Flight Parameters		Equipment Settings		Planned Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	3
Flight Speed	65 m/s	Beam Divergence	0.25 mrad	Total Passes	102
Swath Width	233.26 m	Scan Frequency	60 Hz	Total Length	1090.940 km
Swath Overlap	50%	Scan Angle	± 14°	Total Flight Time	13.071 hrs
Point Density	10.27 p/m²	Scan Cutoff	± 3°	Total Laser Time	4.662 hrs
Cross-Track Res	0.254 m	Scan Offset	0°	Total Swath Area	127.234 km^2
Down-Track Res	0.383 m			Total AOI Area	121.284 km^2

* based on plan: CZO_PA_CRB_v2.pln

Table 19. CZO CRB, PA, leaf-off collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	7-Apr-10	97	13:49:44	18:32:10	4.36	1.47		18.7
F02	7-Apr-10	97	19:34:38	23:56:30	4.03	1.74		18.6
F03	8-Apr-10	98	13:53:13	18:20:30	4.13	1.98		18.4
F04	8-Apr-10	98	19:41:31	21:27:55	1.47	0.40		5.5
					13.98	5.58		

3.4.2 Leaf-on mission planning and collection

The leaf-on survey was planned to be collected with a Cessna 337 Skymaster aircraft; the flight parameters, sensor settings and survey totals for the CZO CRB leaf-off collection are summarized in Table 20. The collection was performed on July 17 and 18. There were a total of 3 flights, which are summarized in Table 21. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the Cessna 337 tail number N337P.

Table 20. Flight parameters, Sensor settings and survey totals (leaf-on)*.

Nominal Flight Parameters		Equipment Settings		Planned Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	3
Flight Speed	60 m/s	Beam Divergence	0.25 mrad	Total Passes	86
Swath Width	277.04 m	Scan Frequency	55 Hz	Total Length	921.987 km
Swath Overlap	50%	Scan Angle	± 14°	Total Flight Time	11.366 hrs
Point Density	10.27 p/m²	Scan Cutoff	± 2°	Total Laser Time	4.268 hrs
Cross-Track Res	0.25 m	Scan Offset	0°	Total Swath Area	127.714 km^2
Down-Track Res	0.386 m			Total AOI Area	121.284 km^2

* based on plan: CZO_PA_CRB_v3.pln

Table 21. CZO CRB, PA, leaf-on collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	17-Jul-10	198	15:08:18	17:28:35	2.16	0.99		19.1
F02	17-Jul-10	198	19:34:45	23:49:53	3.99	1.84		14
F03	18-Jul-10	199	13:18:56	18:00:58	4.46	2.45		19.6+9.9
					10.61	5.28		

3.4.3 GPS stations

Data from a total of five GPS ground stations were used for aircraft trajectory determination, two of these stations were only operated for either the leaf-off or leaf-on (GLEN during leaf-off and KMQS for the leaf-on collection). Three stations (CHES, DENE, and LOYR) are part of the NGS CORS network, the other two (GLEN and KMQS) were setup by NCALM; KMQS was set at the Chester county airport. The location of the stations relative to the project AOI is presented on Figure 12 and the coordinates of the stations are summarized in Table 22.

Table 22. Coordinates of GPS stations used to derive aircraft trajectories for the Christina river basin sub-project.

GPS station	CHES	DENE	LOYR	GLEN	KMQS
Operating agency	NGS	NGS	NGS	NCALM	NCALM
Latitude	39.951644	39.676736	39.569091	39.880768	39.980074
Longitude	-75.600320	-75.743008	-75.987499	-75.545362	-75.861468
Ellipsoid Height (m)	109.466	6.562	-14.736	97.186	159.854

3.5 Shale Hills, PA leaf-off and leaf-on collection

The Shale Hills (Shavers Creek), PA CZO sub-project consisted of two collections during the leaf-off and leaf-on seasons of the same area of interest (AOI). The AOI is a single irregular polygon with 169.80901 km^2 of surface area located 10 miles southwest of State College, PA. The location and extent of the AOI polygon, the planned flight lines and the location of the GPS stations is illustrated in Figure 13. This survey was flown on a Cessna 337, the survey parameters are presented in Table 23.

Table 23. Flight parameters, Sensor settings and survey totals (based on single collection)*.

Nominal Flight Parameters		Equipment Settings		Planned Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	1
Flight Speed	60 m/s	Beam Divergence	0.25 mrad	Total Passes	86
Swath Width	277.04 m	Scan Frequency	55 Hz	Total Length	1433.066 km
Swath Overlap	50%	Scan Angle	± 15°	Total Flight Time	13.986 hrs
Point Density	10.28 p/m²	Scan Cutoff	± 2°	Total Laser Time	6.634 hrs
Cross-Track Res	0.25 m	Scan Offset	0°	Total Swath Area	198.508 km^2
Down-Track Res	0.386m			Total AOI Area	191.629 km^2

* based on plan: CZO_PA_ShaversCreek_v2.pln

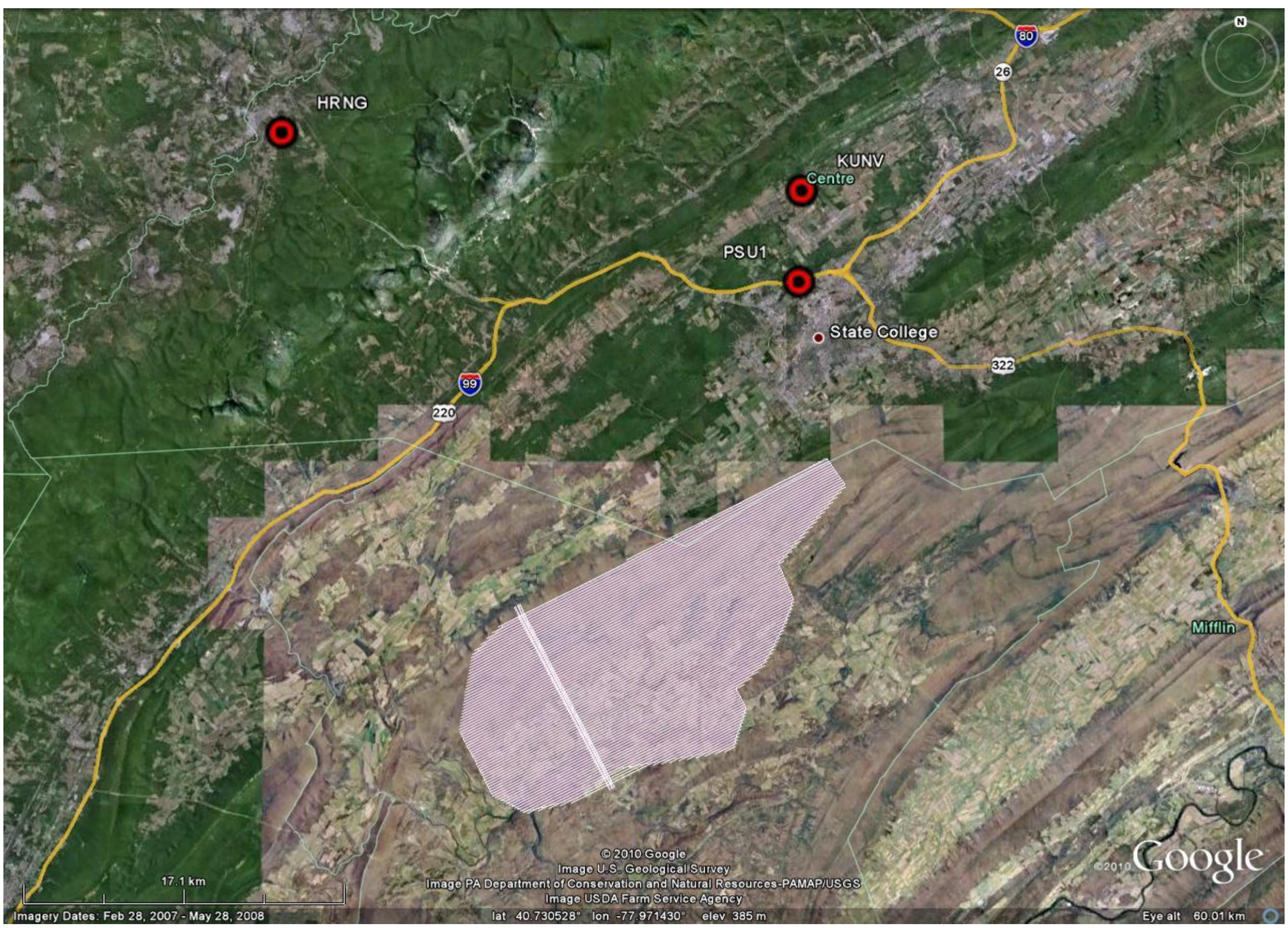


Figure 13. Area of interest (AOI), flight lines and GPS stations for the Shale Hill, PA CZO sub-project.

3.5.1 Leaf-on collection

The leaf-on collection was performed between July 14 and 17. There were a total of 4 flights, which are summarized in Table 24. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the Cessna 337 tail number N337P.

Table 24. Shale Hills, leaf-on collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	14-Jul-10	195	20:14:55	0:37:55	4.13	2.42		21.0+13.0
F02	15-Jul-10	196	12:48:35	17:21:01	2.01	2.01		20.1
F03	15-Jul-10	196	20:33:40	1:42:26	4.85	2.82		
F04	16-Jul-10	197	15:34:05	17:46:40	0.83	0.83		
					11.82	8.07		

3.5.2 Leaf-off collection

The leaf-on collection was performed between December 3rd and 9th. There were a total of 7 flight attempts, two of which were aborted due to bad weather conditions. The flights are summarized in Table 25. Data was collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the Cessna 337 tail number N337P.

Table 25. Shale Hills, leaf-on collection flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	3-Dec-10	337					Aborted due to bad weather	
F02	4-Dec-10	338	18:13:00	20:16:24	2.80	1.80		18.9+5.0
F03	5-Dec-10	339	15:26:00	18:39:00	2.78	1.56		18.6+15.4
F04	6-Dec-10	340	17:10:05				Aborted due to bad weather	
F06	8-Dec-10	342	19:45:00	23:01:45	2.89	1.42		17.4+14.1
F07	9-Dec-10	343	13:54:32	17:00:45	2.71	0.83		14.7
F08	9-Dec-10	343	19:06:48	23:17:00	3.84	2.09		18.4
					15.03	7.71		

3.5.3 GPS stations

Data from a total of three GPS ground stations were used for aircraft trajectory determination, two of these stations (HRN6 and PSU1) are part of the NGS CORS network, and the KUNV station was set by NCALM at the State College airport. The location of the stations relative to the project AOI is presented on Figure 13 and the coordinates of the stations are summarized in Table 26.

Table 26. Coordinates of GPS stations used to derive aircraft trajectories for the Shale Hills sub-project.

GPS station	HRN6	PSU1	KUNV
Operating agency	USCG	PADT	NCALM
Latitude	40.877838	40.80686	40.851527

Longitude	-78.181271	-77.84998	-77.848183
Ellipsoid Height (m)	589.387	312.461	341.537

3.6 Luquillo, Puerto Rico

The Luquillo Puerto Rico CZO sub-project consisted of a single collection of an area of interest (AOI) over El Yunque National Forest, located on the East end of the main island. The original requested area covered 180.356 km^2, the final AOI is a single irregular polygon with 217.107 km^2 of surface area. The location and extent of the AOI polygon, the planned flight lines and the location of the GPS stations is illustrated in Figure 14. This survey was flown on a Cessna 337, the survey parameters are presented in Table 27.

Figure 14. Area of interest (AOI), flight lines and GPS stations for the Luquillo, Puerto Rico CZO sub-project.

Table 27. Flight parameters, Sensor settings and survey totals.

Nominal Flight Parameters		Equipment Settings		Planned Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	# Sub areas	1
Flight Speed	60 m/s	Beam Divergence	0.25 mrad	Total Passes	120
Swath Width	277.04 m	Scan Frequency	55 Hz	Total Length	1909.931 km
Swath Overlap	50%	Scan Angle	± 15°	Total Flight Time	19.08 hrs
Point Density	10.28 p/m²	Scan Cutoff	± 2°	Total Laser Time	8.84 hrs

Cross-Track Res	0.25 m	Scan Offset	0°	Total Swath Area	264.564 km^2
Down-Track Res	0.386m			Total AOI Area	218.134 km^2

* based on plan: CZO_PR_Luquillo_V1.pln

3.6.1 First collection attempt

The first collection attempt was performed between July 25 and the 31st, despite the seven days deployed in the field there were only four successful flights, data for these flights are summarized in Table 28, and the areas for which data was collected are illustrated in Figure 15. Data were collected with the Gemini 06SEN/CON195 and digitizer 08DIG017 system installed on the Cessna 337 tail number N337P.

Table 28. Luquillo, PR Survey flights.

Flight	Date (local)	DoY	Data Logging (GMT) Start	Stop	Flight time (h)	LOT (h)	Observations	Digitizer (Gb)
F01	26-Jul-10	207	18:26:00				Aborted due to bad weather	
F02	27-Jul-10	208	9:51:45	12:32:00	1.77	0.58		5.6
F03	28-Jul-10	209	10:00:00	11:00:40	0.79	0.09	Aborted due to bad weather	
F04	28-Jul-10	209	20:19	23:16:00	2.77	0.77		8.8
F05	29-Jul-10	210	10:17:50	14:09:20	3.64	1.50		16.5
F06	30-Jul-10	211	10:02:40	12:12:30	2.04	0.59		6.5
					11.01	3.52		

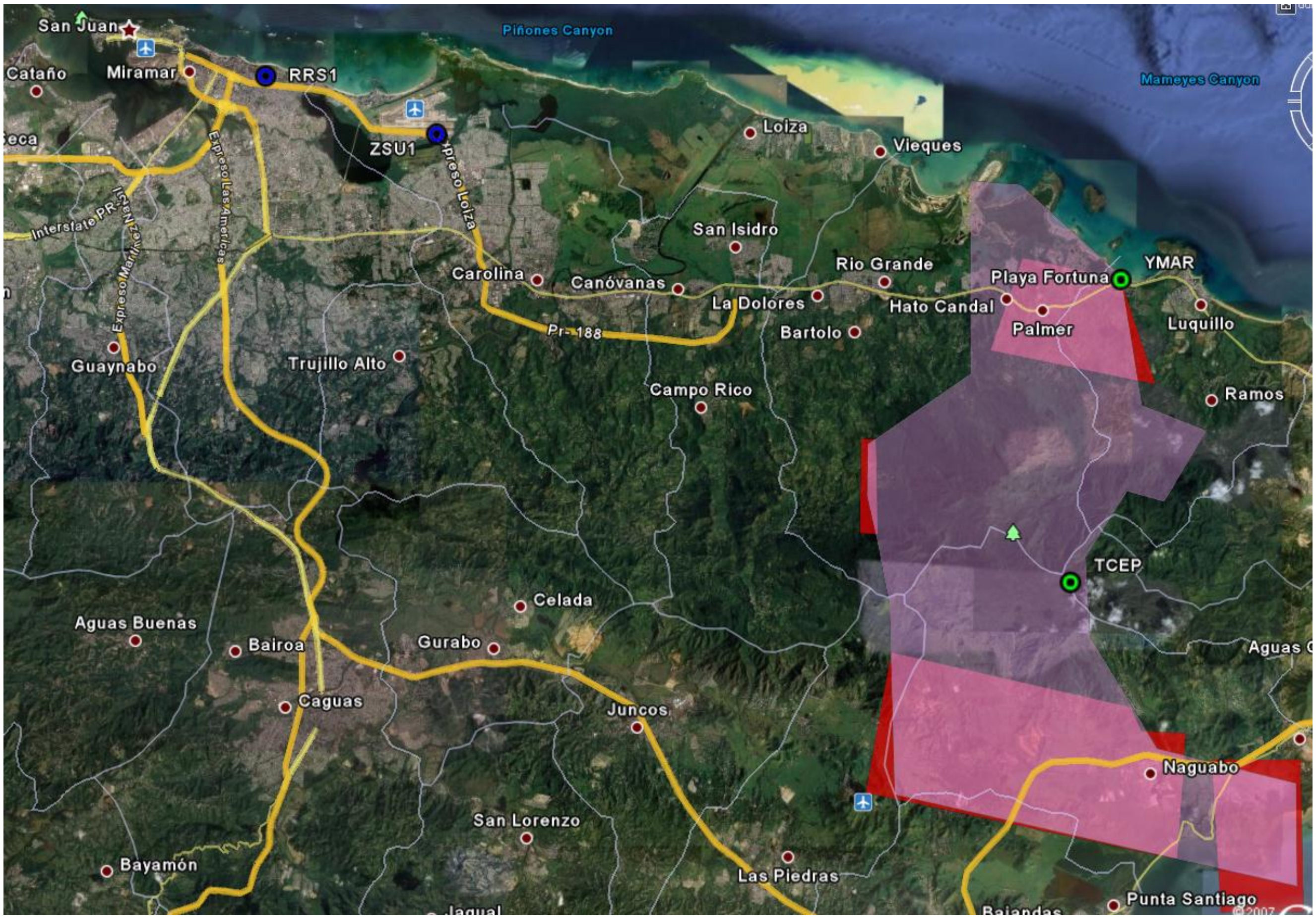


Figure 15. Area of interest (AOI), and surveyed area for during the first collection attempt of the Luquillo, Puerto Rico CZO sub-project.

3.6.2 GPS stations

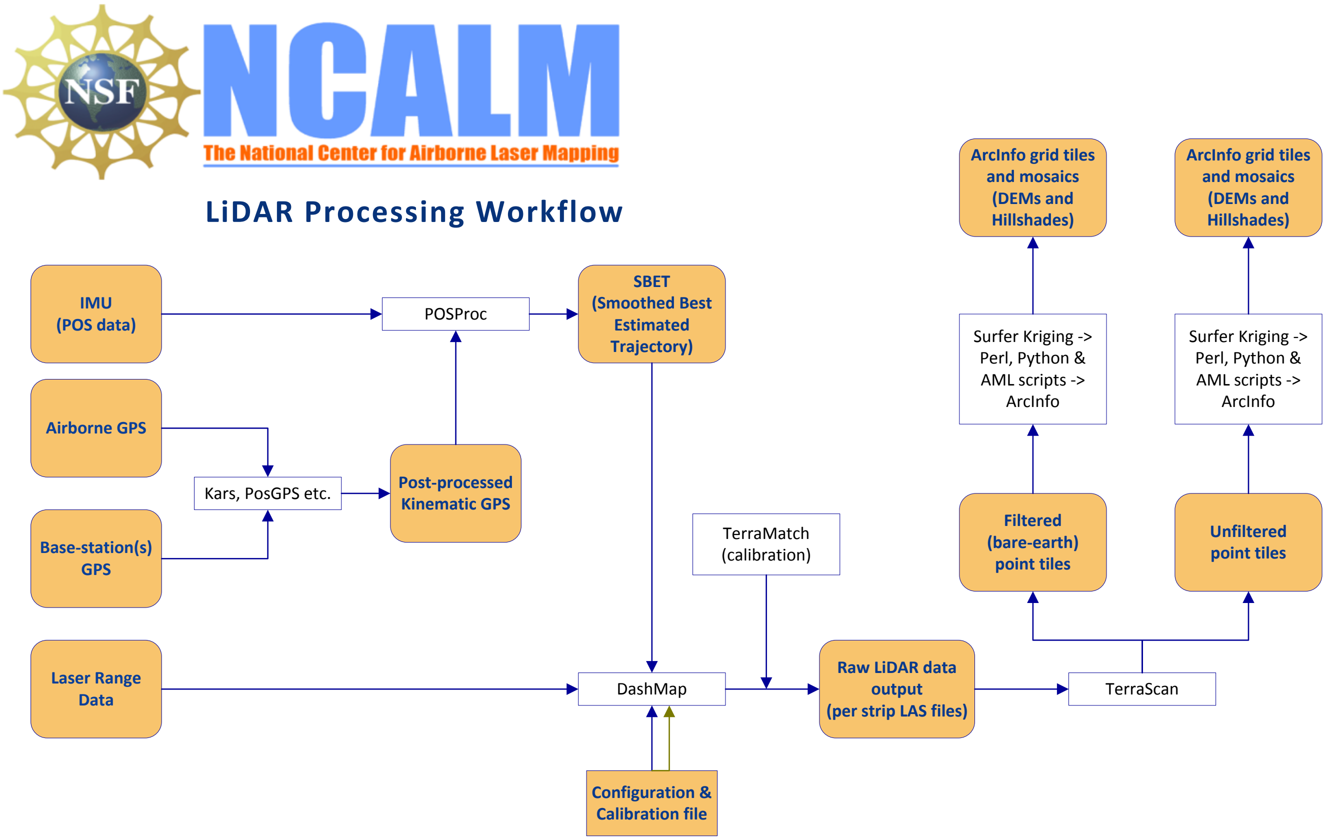
Data from a total of three GPS ground stations were used for aircraft trajectory determination. Two of these stations (YMAR and TCEP) were setup by NCALM inside the area of interest, and one that is part of the NGS CORS network (ZSU1).The location of the stations relative to the project AOI is presented on Figure 14 and the coordinates of the stations are summarized in Table 29.

Table 29. Coordinates of GPS stations used to derive aircraft trajectories for the Boulder, CO sub-project.

GPS station	ZSU1	YMAR	TCEP
Operating agency	FAA	NCALM	NCALM
Latitude	18.431334	18.381569	18.277730
Longitude	-65.993477	-65.745128	-65.763441
Ellipsoid Height (m)	-27.189	-31.652	951.004

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)
Southern Sierra Snow-on_F01	14-Mar-10	73	31PR	1.4	0.036
Southern Sierra Snow-on_F04	20-Mar-10	79	31PR	2.6	0.012
Southern Sierra Snow-on_F05	20-Mar-10	79	31PR	2.6	0.028
Southern Sierra Snow-on_F06	21-Mar-10	80	31PR	2.2	0.020
Southern Sierra Snow-on_F07	21-Mar-10	80	31PR	1.6	0.013
Southern Sierra Snow-on_F08	22-Mar-10	81	31PR	2.2	0.029
Southern Sierra Snow-on_F09	23-Mar-10	82	31PR	1.5	0.031
Southern Sierra Snow-on_F11	24-Mar-10	83	31PR	1.5	0.021
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
CRB Leaf-off_F01	7-Apr-10	97	31PR	2.1	0.018
CRB Leaf-off_F02	7-Apr-10	97	31PR	2.0	0.014
CRB Leaf-off_F03	8-Apr-10	98	31PR	2.0	0.020
CRB Leaf-off_F04	8-Apr-10	98	31PR	2.0	0.031
Boulder Snow-on_F01	28-Apr-10	118	31PR	1.4	0.011
Boulder Snow-on_F02	5-May-10	125	31PR	1.6	0.011
Boulder Snow-on_F03	7-May-10	127	31PR	2.2	0.026
Boulder Snow-on_F04	9-May-10	129	31PR	1.5	0.011
Boulder Snow-on_F05	9-May-10	129	31PR	1.7	0.012
Boulder Snow-on_F06	9-May-10	129	31PR	2.0	0.021
Boulder Snow-on_F07	20-May-10	140	31PR	2.3	0.024
Boulder Snow-on_F08	21-May-10	141	31PR	2.4	0.013
Boulder Snow-on_F09	21-May-10	141	31PR	2.5	0.023
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
Shale Hills Leaf-on_F01	14-Jul-10	195	337P	2.2	0.022
Shale Hills Leaf-on_F02	15-Jul-10	196	337P	2.0	0.019
Shale Hills Leaf-on_F03	15-Jul-10	196	337P	1.9	0.023
Shale Hills Leaf-on_F04	16-Jul-10	197	337P	1.8	0.020
CRB Leaf-on_F01	17-Jul-10	198	337P	1.6	0.032
CRB Leaf-on_F02	17-Jul-10	198	337P	2.0	0.015
CRB Leaf-on_F03	18-Jul-10	199	337P	1.9	0.019
Southern Sierra Snow-off_F01	5-Aug-10	217	931SA	1.9	0.022
Southern Sierra Snow-off_F02	13-Aug-10	225	931SA	1.5	0.019
Southern Sierra Snow-off_F03	14-Aug-10	226	931SA	1.9	0.025
Southern Sierra Snow-off_F04	15-Aug-10	227	931SA	2.0	0.027
Southern Sierra Snow-off_F05	15-Aug-10	227	931SA	2.2	0.033
Boulder Snow-off_F01	21-Aug-10	233	931SA	1.7	0.017
Boulder Snow-off_F02	21-Aug-10	233	931SA	2.4	0.014
Boulder Snow-off_F03	22-Aug-10	234	931SA	1.9	0.023
Boulder Snow-off_F04	23-Aug-10	235	931SA	1.8	0.032
Boulder Snow-off_F05	24-Aug-10	236	931SA	2.0	0.022
Boulder Snow-off_F06	25-Aug-10	237	931SA	1.9	0.018
Boulder Snow-off_F07	25-Aug-10	237	931SA	2.1	0.022
Boulder Snow-off_F08	26-Aug-10	238	931SA	2.0	0.013
Boulder Snow-off_F09	26-Aug-10	238	931SA	2.0	0.012
Shale Hills Leaf-off_F01	4-Dec-10	338	337P	1.7	0.018
Shale Hills Leaf-off_F02	5-Dec-10	339	337P	1.8	0.012
Shale Hills Leaf-off_F03	8-Dec-10	342	337P	1.9	0.019
Shale Hills Leaf-off_F04	9-Dec-10	343	337P	1.4	0.009
Shale Hills Leaf-off_F05	9-Dec-10	343	337P	1.8	0.017

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
Southern Sierra Snow-on_F01	0.034	243	0.024
Southern Sierra Snow-on_F04	0.040		
Southern Sierra Snow-on_F05	0.048		
Southern Sierra Snow-on_F06	0.042		
Southern Sierra Snow-on_F07	0.042		

Southern Sierra Snow-on_F08	0.066		
Southern Sierra Snow-on_F09	0.039		
Southern Sierra Snow-on_F11	0.048		
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		
CRB Leaf-off_F01	0.026	445	0.032
CRB Leaf-off_F02	0.027		
CRB Leaf-off_F03	0.026		
CRB Leaf-off_F04	0.023		
Boulder Snow-on_F02	0.059	814	0.077
Boulder Snow-on_F04	0.038		
Boulder Snow-on_F06	0.053		
Boulder Snow-on_F07	0.053		
Boulder Snow-on_F08	0.047		
Boulder Snow-on_F09	0.071		
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		
Shale Hills Leaf-on_F01	0.054	490	0.036
Shale Hills Leaf-on_F02	0.039		
Shale Hills Leaf-on_F03	0.037		
Shale Hills Leaf-on_F04	0.042		
CRB Leaf-on_F01	0.049	411	0.040
CRB Leaf-on_F02	0.045		
CRB Leaf-on_F03	0.032		

Southern Sierra Snow-off_F01	0.061	100	0.064
Southern Sierra Snow-off_F02	0.047		
Southern Sierra Snow-off_F03	0.048		
Southern Sierra Snow-off_F04	0.070		
Southern Sierra Snow-off_F05	0.053		
Boulder Snow-off_F01	0.034	3344	0.038
Boulder Snow-off_F02	0.033		
Boulder Snow-off_F03	0.045		
Boulder Snow-off_F04	0.031		
Boulder Snow-off_F05	0.027		
Boulder Snow-off_F06	0.059		
Boulder Snow-off_F07	0.058		
Boulder Snow-off_F08	0.059		
Boulder Snow-off_F09	0.048		
Shale Hills Leaf-off_F01	0.048	260	0.029
Shale Hills Leaf-off_F02	0.043		
Shale Hills Leaf-off_F03	0.050		
Shale Hills Leaf-off_F04	0.042		
Shale Hills Leaf-off_F05	0.046		

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.

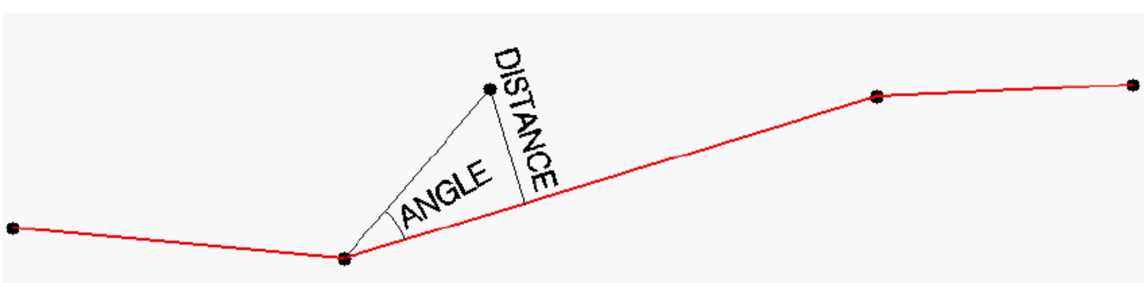


Figure 16. Ground classification parameters

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.