2014 Data Collection and Processing Report for the Project: "Full Waveform LiDAR Survey of Tahoe National Forest"
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1. LiDAR and Digitizer System Description and Specifications

This survey was performed with an Optech Gemini Airborne Laser Terrain Mapper (ALTM) serial number 06SEN195 equipped with an Optech 12-bit waveform digitizer and mounted in a twin-engine Piper Navajo PA-31 (Tail Number N931SA) leased from Marc Inc. (Jackson, MS). The ALTM nominal specifications are listed below in Table 1 and the digitizer nominal specifications follow in Table 2.

Operating Altitude	150-4000 m, Nominal
Horizontal Accuracy	1/5,500 x altitude (m AGL); 1 sigma
Elevation Accuracy	5 - 35 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 72-channel 10Hz (GPS) receiver
Laser Wavelength/Class	1064 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.

Parameter	Specification
Sample Interval	1 ns
Maximum Acquisition and recording rate	Variable, up to 100 kHz At higher laser PRF automatically sub-samples 1:2, 1:3, as required
Record Length: T0 Return	 40 ns 440 ns (Total)
Full-Scale Input Range	0-1 V
Data Storage	Removable SSD
Operating temperature	0-35 degree C
Power	<200 W
Relative Humidity	0-98% non-condensing

Table 2 – Optech 12-bit Digitizer specifications.

See http://www.ncalm.cive.uh.edu/publications/documents/NCALM-WP-2013-01.pdf for more information on the waveform digitizer; also see http://www.optech.com/ for more information from the manufacturer.

2. Area of Interest.

The requested survey area consisted of the remainder of a large complex polygon lying roughly between Truckee and Grass Valley, CA enclosing approximately 3500 square km of the Tahoe National Forest (TNF) and a smaller irregular polygon enclosing approximately 137 square km area part of the Sierra Nevada Adaptive Management Project (SNAMP). The actual flight-planned area for all polygons is over 5250 square km (larger than the contracted value due to the expansion of the requested area by the project PI and the reality of using the most efficient flight plan given the area of interest.

Figure 1 (below) is a Google Earth image showing coverage polygons in various colors flown in the **2013 campaign**:

a) Green polygon – requested 2013 TNF polygon (3500 square km of LiDAR at 7-8 points per square meter)
b) Purple polygon – expanded 2014 survey area equal to approximately 5078 square km.
c) Red polygon – 2013 SNAMP area (~137 square km of LiDAR at 9-10 points per square meter); CASI hyperspectral images at 1 m resolution were also completed in this SNAMP area.
d) Yellow and red polygons show the TNF area that was flown, processed, and delivered in 2013.

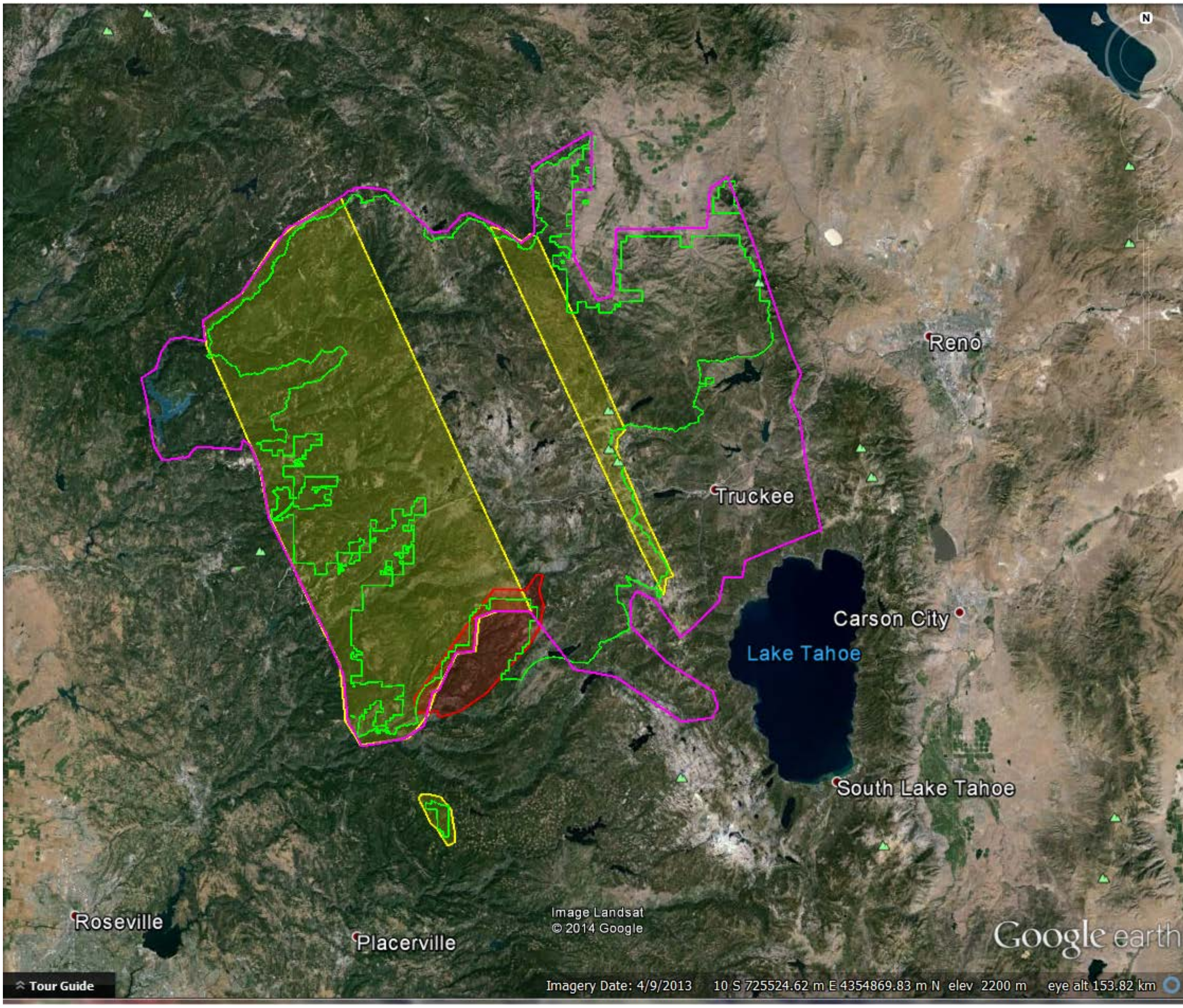

Figure 1 – The 2013 TNF polygon is shown in green; the expanded 2014 TNF polygon is shown in purple; yellow outlines show 2013 completed parts of the TNF; red polygon shows 2013 completed SNAMP LiDAR and hyperspectral imagery.

Figure 2 (below) illustrates the LiDAR coverage area in blue for the **2014 campaign** inside the expanded area (purple). Push – pins indicate the locations of GPS reference stations.

Note the small non-contiguous area to the south of the main polygon. This area is included in the 2014 deliverables.

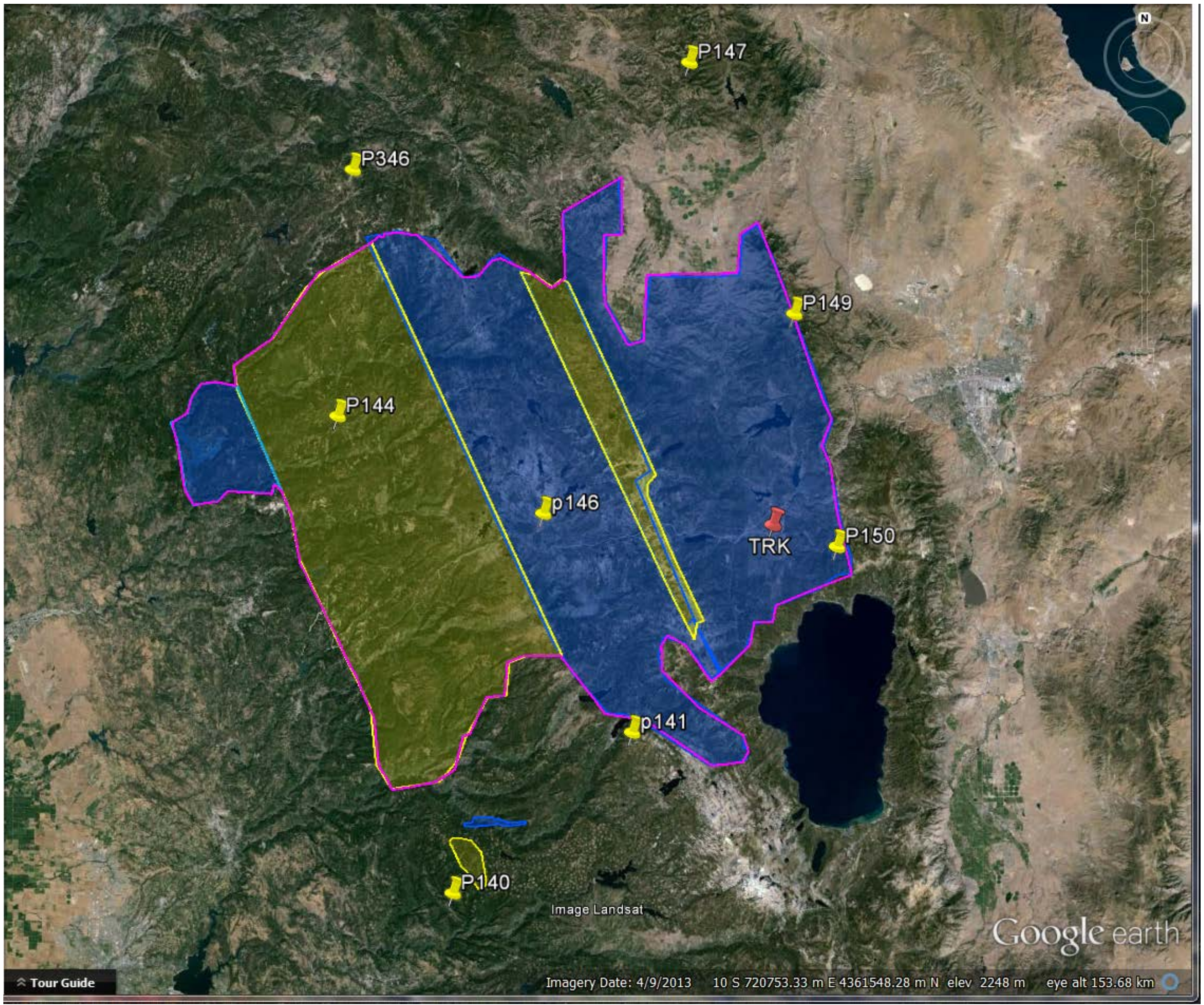

Figure 2 - 2014 LiDAR coverage in blue, 2013 LiDAR coverage in yellow, GPS locations indicated by push pins.

3. Data Collection

a) Survey Dates: The 2014 TNF survey began on June 10, 2014 and the final flight was on June 30, 2014. (DOY 161 through 181). Twenty-nine flight missions took place over these 21 days. Together with the 17 flight missions flown in 2013 the total number of missions required totaled forty-six.

b) Airborne Survey Parameters: Survey parameters for the 2014 TNF full waveform survey are provided in Table 3 below.

Nominal Flight Parameters		Equipment Settings		Survey Totals	
Flight Altitude	600 m	Laser PRF	100 kHz	Total Flight Time	128.1 hrs.
Flight Speed	+/- 60 m/s	Beam Divergence	0.33 mrad	Total Laser Time	80.7 hrs.
Swath Width	390-520m	Scan Frequency	45 Hz	Total Swath Area	5078 km^2
Swath Overlap	Min 50 %	Scan Angle (TNF)	± 18°	Scan Angle (SNAMP)	± 18°
Point Density (TNF)	8.56 p/m^2	Scan Cutoff	1.0°		

Table 3 – 2014 Nominal flight parameters, equipment settings and survey totals; actual parameters vary with considerably with the mountainous terrain.

The total required flight time for the combined 2013-2014 TNF and SNAMP survey is 191.8 hours. The total Laser-on time for the entire survey (2013-2014) was 128.2 hours.

c) Ground GPS: Nine GPS reference station locations were used during the survey; eight of them being part of UNAVCO's PBO network (see http://pbo.unavco.org/ for more information from UNAVCO). The remaining station was set by the NCALM field crew at the operational airport in Truckee, CA using a Trimble NetR9 dual-frequency receiver and Zephyr Geodetic2 antenna. All GPS reference observations were logged at 1 Hz. Table 4 (below) gives the coordinates of the stations and Figure 2 (above) shows the project area and the GPS reference station locations.

GPS station	Operating Agency	Latitude	W Longitude	Ellipsoid Height(m)
KTRK	NCALM	39 19 9.22626	120 8 50.41067	1776.259
P346	UNAVCO	39 47 40.94164	120 52 2.81632	2037.871
P140	UNAVCO	38 49 45.23204	120 41 35.44677	1079.775
P141	UNAVCO	39 2 47.86372	120 23 8.04872	2170.917
P144	UNAVCO	39 28 0.11980	120 53 34.69557	1437.406
P146	UNAVCO	39 20 14.85533	120 32 14.22617	2347.831
P147	UNAVCO	39 56 14.57705	120 17 3.83537	2489.443
P149	UNAVCO	39 36 7.65353	120 6 17.85644	2635.242
P150	UNAVCO	39 17 32.55505	120 2 1.81957	2619.643

Table 4 – GPS Coordinates of ground reference stations. NAD_83 (2011) (EPOCH: 2010.0000)

4. GPS/IMU Data Processing

Reference coordinates for all 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. For further information on OPUS see http://www.ngs.noaa.gov/OPUS/ and for more information on the CORS network see http://www.ngs.noaa.gov/CORS/

Airplane trajectories for this survey were processed using KARS (Kinematic and Rapid Static) software written by Dr. Gerald 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 high-accuracy fixed integer ionosphere-free differential solution at 1 Hz. All final aircraft trajectories for this project are blended solutions from the appropriate stations.

After GPS processing, the trajectory solution and the raw inertial measurement unit (IMU) data collected during the flights are combined in APPLANIX software POSPac MMS (Mobile Mapping Suite Version 5.2). POSPac MMS 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 an SBET (Smoothed Best Estimated Trajectory).

5. LiDAR Data Processing Overview

The following diagram (Figure 3) shows a general overview of the NCALM LiDAR data processing workflow

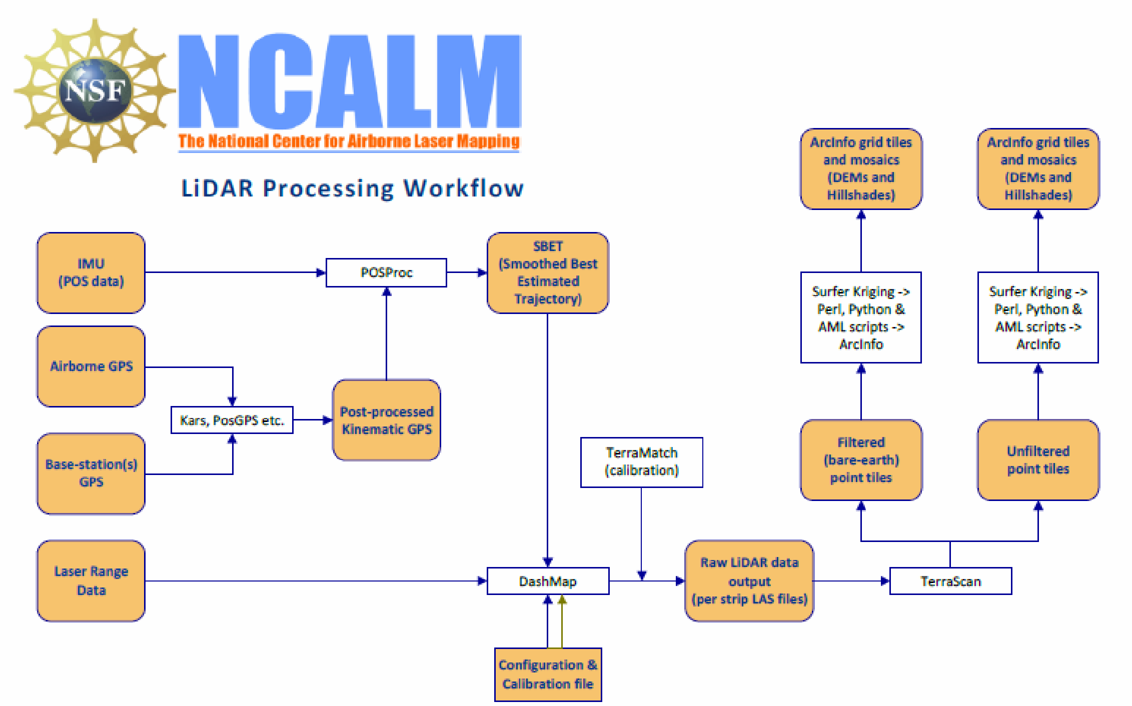

Figure 3 - NCALM LiDAR Processing Workflow

These LiDAR data were collected in flight strips and the initial observations are of course not classified but are associated with certain collection attributes such as time stamp, scan angle, intensity value, echo number (only echo, first of many, intermediate, last echo) etc. TerraSolid software is first used to do the flight strip calibration then to parse the strips into square blocks, and finally to do the ground point classification. In classification, the emphasis being on first removing blunder points and outliers and then finding the final set of ground class points from which the bare-earth DEM is constructed. Classification of the ground-class points is done by automated routines using TerraSolid Software (TerraScan Version 14.020). http://www.terrasolid.com/products.html

6. Calibration and Accuracy Assessment

System calibration of the three sensor bore-sight angles (roll, pitch, and yaw) and scanner mirror scale factor is done by automated means using TerraSolid Software (TerraMatch). Project lines and off-project lines flown with opposite headings along with perpendicular cross lines are used as input to TerraMatch (Version 14.007). The above calibration values are then optimized using an iterative least-squares algorithm on a flight by flight basis. These optimal values are then used to produce the LAS output in flight-strips for each flight.

Internal accuracy of the LiDAR can be measured by how well bare-earth surfaces derived from different and adjacent flight lines agree in elevation in the overlap zones. TerraMatch does this on a tile by tile basis for the entire project (or a smaller subset of tiles) in the following way: first calibrated flight strips are parsed into 1 km square tiles. Secondly, a mean bare-earth surface is computed for the entire tile. Next, individual flight line surfaces are computed and differenced with respect to the mean surface. Finally, the following project statistics are compiled on all test tiles and for the project.

1. Magnitude: Absolute value of the elevation difference between a strip and the mean surface.
2. Average magnitude: Mean value of absolute elevation difference values.
3. DZ: Mean value of the elevation difference between a strip and the mean surface.

Table 5 (below) gives the some statistics for a 50-tile subset of the TNF project area.

Project area	Min magnitude for individual flight strip	Max magnitude for individual flight strip	**Average Magnitude all flight strips**	Min DZ for individual flight strip	Max DZ for individual flight strip
TNF	0.040	0.107	**0.061**	-0.085	0.102

Table 5 Flight line elevation statistics.

To check absolute vertical accuracy of the ground surfaces an analysis was performed to measure vertical bias between the 2013 and the 2014 Bare Earth DEM. By subtracting the 2014 DEM from the 2013 DEM in the overlap zones **the 2013 DEM was higher by a mean value of 0.099 m.** This value was not adjusted, and will vary across individual tiles.

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 .
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 this may well involve the PIs devoting additional time and resources to this process.

7. Data Deliverables

a) **Horizontal Datum**: NAD83 (2011)
b) **Vertical Datum:** NAVD88 (GEOID 12a)
c) **Projection:** UTM Zone 10N – meters.
d) **File Formats:**

1. Point Cloud in LAS format (Version 1.2), classified as ground or non-ground, in 1 km square tiles.
2. ESRI format 1-m DEM from ground classified points.
3. ESRI format 1-m Hillshade raster from ground classified points
4. ESRI format 1-m DEM from all points (canopy included).
5. ESRI format 1-m Hillshade raster from all points (canopy included).
6. Digitizer files which include the raw intensity – time waveform data as collected by the digitizer in DF2 / IX2 formats.
7. Corrected Sensor Data (CSD) files in flight strips which contain timing, navigation, scan angle, and discrete return information (range and intensity) for each fired laser pulse as obtained from the discrete ALTM system.

e) **File naming convention:** 1 Km tiles follow a naming convention using the lower left 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 702000 through 703000, and northing equals 4328000 through 4329000 then the tile filename incorporates 702000_4328000. These tile footprints are available as an AutoCAD DXF or ESRI shapefile. The ESRI DEMs are several mosaic files created by combining together the 1KM tiles – a single mosaic proved too large for computer memory to handle efficiently.

8. Notes

Plan line 88 was (inadvertently) not flown in 2013. This has resulted in a swath of lower point density and some small data voids. Figure 4 (below) shows the location of the missing line in the western portion of the bare-earth DEM of the TNF.

This line was re-flown when NCALM returned to finish the survey in 2014, but was not combined into any DEM.

At some future point all data can be combined in order to produce a single seamless DEM, this requires mixing data collected in 2013 and 2014. NCALM has NOT combined these data as of the date on this report.

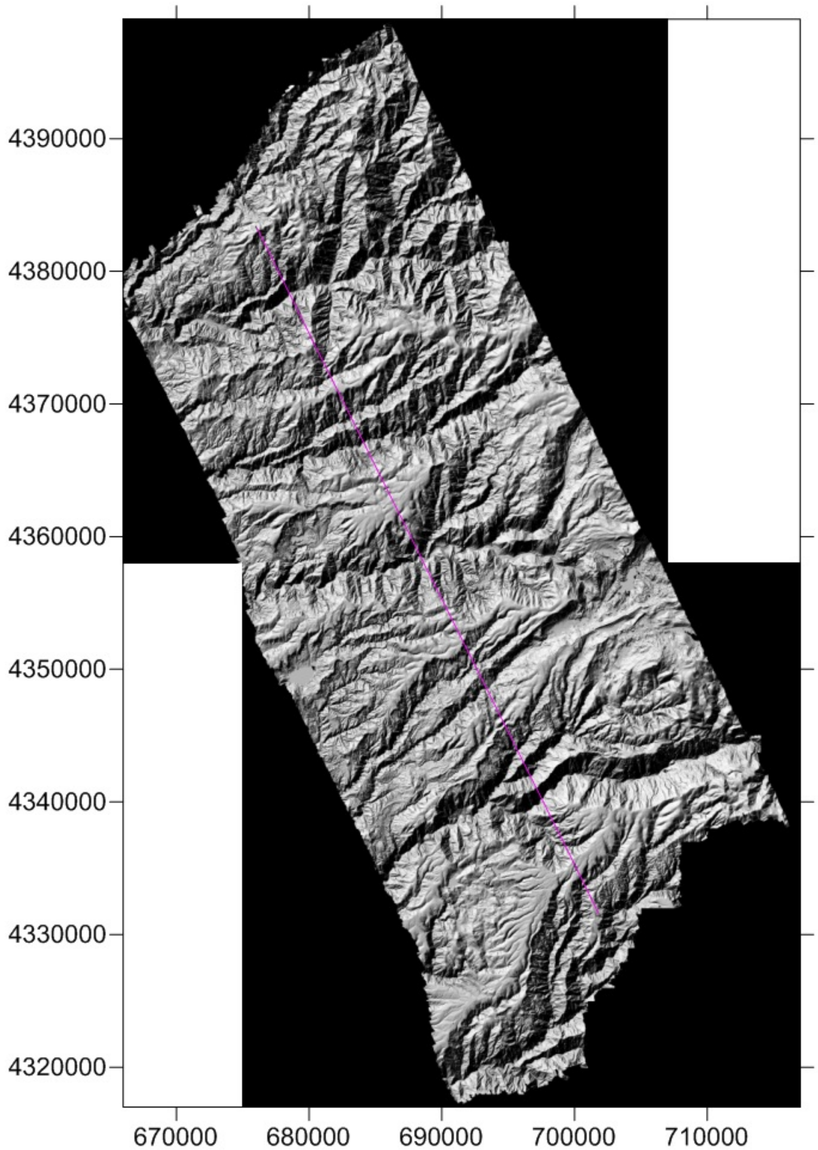

Figure 4 - Missing line 88 shown in purple overlaid onto the western portion of the TNF shaded relief image