Data Collection and Processing Report
LiDAR survey of five fault segments (Eastern Clarence, Western Clarence, Central Eastern Awatere, West Wairau and East Hope-Conway) of the Marlborough Fault System on the Northwestern portion of New Zealand's South Island

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1. LiDAR System Description and Specifications

This survey was performed with two different sensors:

1) Optech 3100EA Airborne Laser Terrain Mapper (ALTM) serial number 05SEN178 mounted in a twin-engine Cessna 402B (Tail Number NZPVC). This ALTM was leased from New Zealand Aerial Mapping (http://nzam.com) and was used on the first two survey flights due to a New Zealand Customs Service delay in releasing the NCALM ALTM. The nominal specifications for the 3100EA are listed below in Table 1

2) Optech Gemini ALTM serial number 06SEN195 mounted in the same aircraft as above. This ALTM was used for the final four survey flights after its release from Customs Service. Its nominal specifications are listed below in Table 2.

Operating Altitude	80-3500 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 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 - 50 - 70 - 100 kHz
Position Orientation System and GPS	Applanix POS/AV OEM includes embedded 12-channel dual frequency 2 Hz (GPS) receiver
Laser Wavelength/Class	1064 nanometers / Class IV (FDA 21 CFR)
Beam Divergence nominal (full angle)	Dual Divergence 0.3 mrad (1/e) or 0.80 mrad (1/e)

Table 1 – Optech ALTM 3100EA specifications.

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 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 – 50 – 70 – 100 – 125 – 142 - 167 kHz
Position Orientation System	Applanix POS/AV 510 OEM includes embedded BD960 72-channel 10Hz (GPS/GLONASS) 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 2 – Optech ALTM GEMINI specifications.

See http://www.optech.ca for more information from the manufacturer.

2. Areas of Interest.

The goal of this project was to perform a LiDAR survey over a distance of 254 km on five fault segments of the Marlborough Fault System on New Zealand's southern Island (Eastern Clarence; Western Clarence; Central Eastern Awatere; West Wairau and East Hope-Conway). LiDAR observations were planned for a 1.2 kilometer wide (nominal) corridor centered on each fault at a shot density ≥ 12 shots/m².

A Google Earth image of the faults that were surveyed is shown below in Figure 1.

Figure 1 – Location of the five fault segments on New Zealand's South Island (Google Earth).

3. Data Collection

3.1 Survey Dates

The LiDAR survey took place on six flights from March 13, 2014 through March 20, 2014 (DOY 072 - 079). No flights took place on DOY 73 – 76 due to bad weather and the switching of sensors.

3.2 Airborne Survey Parameters

Survey parameters are provided in Table 3 below. DOY is the Day Of Year; EOT is aircraft Engine On Time in hours; OAT is aircraft On Air Time in hours (wheels up until wheels down); LOT is Laser-On Time in hours; Flying Height in MSL Mean Sea Level (feet); PRF is Pulse Rate Frequency. PRF value of 125 MP indicates that the GEMINI system was operating in fixed Multi-Pulse Mode which allows the laser-measured ranges to be twice as long as what the speed-of-light allows for a given altitude – the aircraft was nominally at 1400 m AGL Above Ground Level for lines flown at this setting.

Flight	DOY	ALTM	EOT	OAT	LOT	Fault	Flying Height	PRF kHz	Scanner Half-Angle x Frequency
1	71	3100EA 05SEN178	4.8	4.2	2.02	W Wairau	5000	100	16°x50 Hz
						C E Awatere	7500-9000	100/70	16°x50 Hz
2	72	3100EA 05SEN178	4.7	4.25	2.48	E Clarence	8000	70	16°x50 Hz
						W Clarence	8000	70	16°x50 Hz
						E Hope-Conway	7000	70	16°x50 Hz
3	77	GEMINI 06SEN195	3.05	2.6	1.3	West Wairau	5000	100	16°x50 Hz
4	77	GEMINI 06SEN195	5.9	5.4	3.27	C E Awatere	7500-8500	125 MP	16°x50 Hz
						E Clarence	8000	125 MP	16°x50 Hz
						W Clarence	8000	125 MP	16°x50 Hz
5	78	GEMINI 06SEN195	6.3	5.9	3.55	C E Awatere	7500-8500	125 MP	16°x50, 10°x50 Hz
						E W Clarence	8000	125 MP	16°x50, 10°x50 Hz
						W Clarence	8000	125 MP	16°x50, 10°x50 Hz
						E Hope-Conway	7000	125 MP	16°x50, 10°x50 Hz
6	79	GEMINI 06SEN195	2.35	1.9	0.72	C E Awatere	7500-8500	125 MP	16°x50, 10°x50 Hz
						E Hope-Conway	7000	125 MP	16°x50, 10°x50 Hz

Table 3 –Survey parameters.

3.3 Reference GPS

Nine GPS reference station locations were used during the survey; seven of them being part of the New Zealand Active Control Network (PositioNZ). The remaining two stations were set by the NCALM field crew: one (BLEN) at the operational airport in Blenheim and the other at the Hanmer Springs airstrip. All GPS reference observations were logged at 1 Hz with Trimble NetR9 GPS receivers and geodetic antennas. Table 4 (below) gives the coordinates of the stations in the IGS08 Reference Frame Epoch 2014.2081

NAME	Operating Agency	Decimal Degrees	Height (m)	X	Y	Z
CMBL	GNSS offline	-41.749041867 174.213801039	256.001	-4741514.346	480471.603	-4225019.001
KAIK	GNSS on-line	-42.425462822 173.533653844	314.762	-4685479.510	531055.307	-4280818.963
LKTA	GNSS on-line	-42.783367075 172.266329297	712.978	-4646207.689	630972.472	-4310354.372
MAHA	GNSS offline	-41.291385444 173.793816972	441.986	-4771501.641	518871.952	-4187083.410
NLSN	GNSS on-line	-41.183503231 173.433729306	302.143	-4775888.454	549740.197	-4177981.002
WEST	GNSS on-line	-41.744741211 171.806222367	665.352	-4717762.491	679316.977	-4224935.154
WITH	GNSS offline	-41.560654044 173.984196206	423.836	-4753506.408	500939.330	-4209496.407
BLEN	NCALM	-41.513889111 173.863862386	43.078	-4755584.984	511259.320	-4205356.008
HNMR	NCALM	-42.550786067 172.822200800	343.879	-4669215.822	588021.135	-4291104.932

Table 4 –Survey parameters.

Figure 2 (below) show the relative locations of the reference stations and the faults. Yellow push-pins indicate on-line GNS stations (data available on-line), Blue push-pins are off-line GNS stations (special data request from GNS) and pink push-pins indicate NCLAM stations.

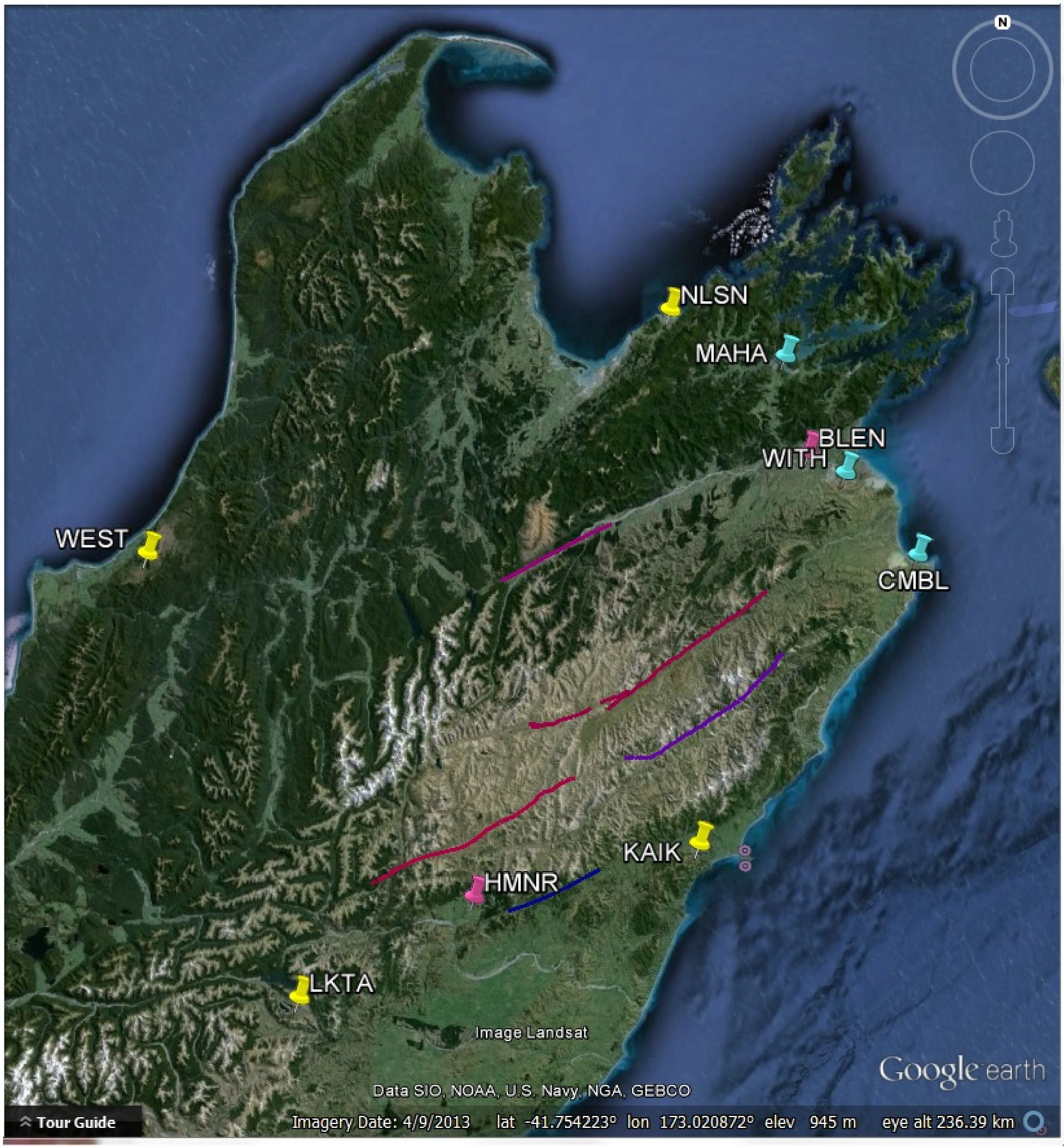

Figure 2 – GPS Reference station locations with respect to the five fault segments on New Zealand's South Island (Google Earth).

4. GPS/IMU Data Processing

Coordinate values for PositioNZ stations at EPOCH 2014.2081 were obtained via e-mail from GNS Science (http://www.gns.cri.nz/). NCALM stations were then positioned relative to the PositioNZ network via GrafNav software (http://www.novatel.com/products/software/grafnav/)

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

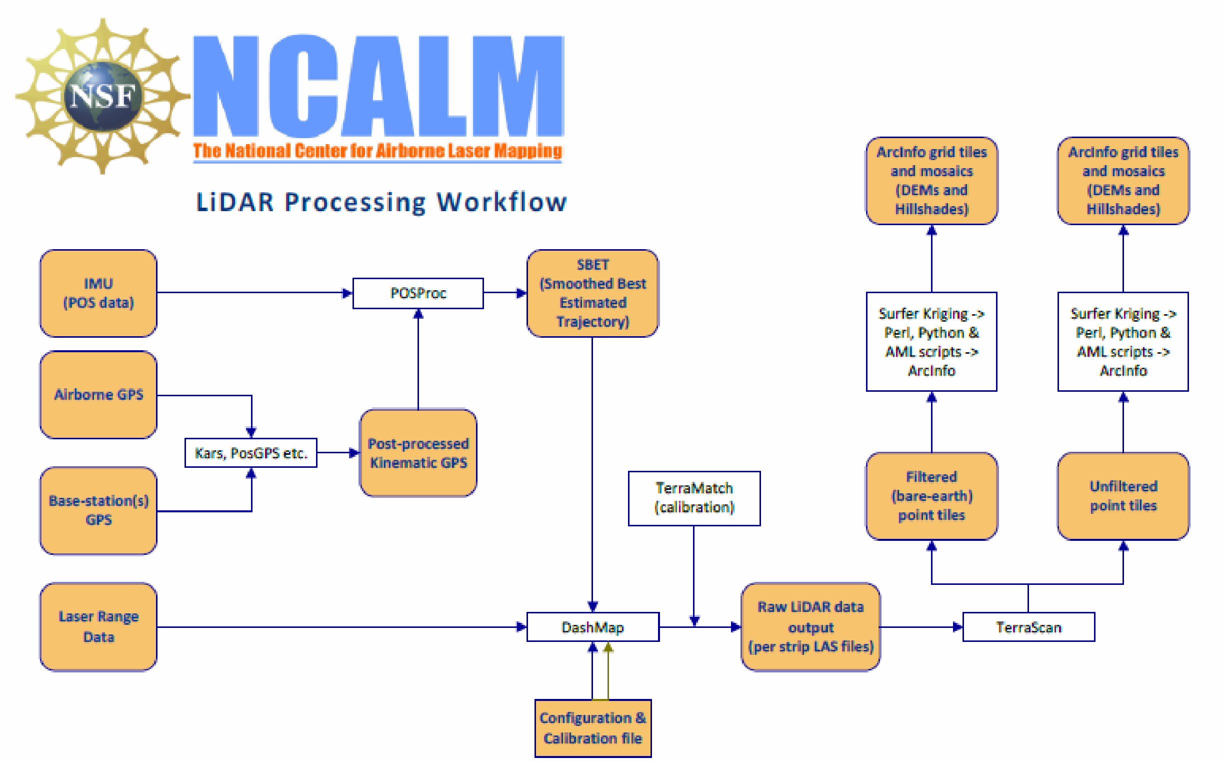

Figure 3 - NCALM LiDAR Processing Workflow

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 used to do the ground point 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 TerraScan Version 14.008 see http://www.terrasolid.com/products/terrascanpage.html

6. Accuracy assessment

6.1 Relative accuracy

System calibration of the 3 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 combined with perpendicular cross lines are used as input to TerraMatch (Version 14.003). The calibration values are checked on a flight-flight basis.

After the optimized values for the bore-sight angles and mirror scale are calculated for each flight, the flight line surfaces are compared in the overlap zones in order to quantify height mismatch of adjacent flight lines. **For this project a typical flight line height mismatch (delta Z) in relatively flat overlap areas is 0.02 – 0.05 meters; in steep terrain delta Z increases to 0.05 – 0.12 meters.**

6.2 Absolute accuracy

In order to assess the absolute accuracy of the LiDAR, >2300 check points were collected on Highway 63 west of Renwick. NCALM field personnel mounted a GPS antenna on a vehicle and drove a 4 km section of this highway. The survey aircraft then collected LiDAR observations over the check points at several different altitudes and two different Pulse Rate Frequencies. The nearest neighbor LiDAR shot elevation was then differenced from the check point elevation, the standard deviation of these differences was computed and results are presented below in Table 5.

PRF	AGL (m)	STD (m)
100 KHz	1220	0.068
125 KHz	975	0.089
125 KHz	1200	0.139
125 KHz MP	1800	0.165

Table 5 –Accuracy assessment.

Absolute accuracy is certainly less on steep terrain and under canopy.

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**: IGS08 (2014.2081)
b) **Vertical Datum:** NZVD2009 (NZGEOID 2009)
c) **Projection:** UTM Zone 59S
d) **Units:** Meters.
e) **File Formats:**

1. Discrete return point cloud in LAS format (Version 1.2), classified as ground or non-ground, in 1 km square tiles.
2. ESRI format 0.5-m DEM from ground classified points.
3. ESRI format 0.5-m Hillshade raster from ground classified points
4. ESRI format 0.5-m DEM from all points (canopy included).
5. ESRI format 0.5-m Hillshade raster from all points (canopy included).

f) **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 723000 through 724000, and northing equals 5398000 through 5399000 then the tile filename incorporates 723000_5398000. The ESRI DEMs are single mosaic files created by combining together the 1KM tiles.

8. Notes

1. The height values for all points in this project (LAS flight strips, LAS point cloud tiles, DEMs) are orthometric heights. They were computed per the equation h = H + N where h=ellipsoid height, H=orthometric height, N=geoid height as computed by geoid model NZGEOID2009 and the IGS08 ellipsoid height. These heights are not strictly equivalent to any local New Zealand MSL datum because they lack the additional required offset correction to any existent MSL datum. See http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/mean-sea-level-datums for more information.

2. "*NZGD2000 is essentially coincident with the World Geodetic System 1984 (WGS84). This is the reference system that is used by GPS receivers. It means that for most practical purposes WGS84 coordinates can be assumed to be the same as NZGD2000 coordinates.*" Italics from http://www.linz.govt.nz/geodetic/datums-projections-heights/geodetic-datums/new-zealand-geodetic-datum-2000

3. The horizontal reference frame for these data is the IGS08, Epoch 2014.2081 (date of survey) because *"The NZGD2000 coordinate of a point nominally represents its location*

on 1 January 2000 in terms of ITRF96 at epoch 2000.0" Italics from http://www.linz.govt.nz/geodetic/datums-projections-heights/geodetic-datums/new-zealand-geodetic-datum-2000/deformation-model.