Quality assurance and quality control procedures of airborne scanning LiDAR for a nation-wide carbon inventory of planted forests

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Abstract

To meet Kyoto Protocol obligations, New Zealand is required to estimate forest carbon stock change over the first commitment period (2008-2012). New Zealand has three categories of forest, namely: natural forest; forests planted prior to 1990; and forests planted in non-forest land after 31 December 1989. The forests planted after 31 December 1989 are called 'Kyoto forests'. The Kyoto forest carbon inventory system involves use of discrete return airborne LiDAR covering circular plots located on a 4 km grid. The plots are 0.06 ha in area. This paper describes the quality assurance and quality control procedures being used to ensure that the LiDAR data meet contract specifications. To be fit-for-purpose for forest carbon inventory the key LiDAR quality characteristics include: positional accuracy; first return density greater than three points per m^2; no data decimation; correct file naming; and consistent classification of the ground returns within the point cloud.

Keywords: QA/QC, LiDAR, forest inventory, carbon, Kyoto Protocol

1. Introduction

New Zealand is a signatory to the Kyoto Protocol and the United Nations Framework Convention on Climate Change. A requirement under Article 3.3 of the Protocol is annual greenhouse gas reporting of carbon stock changes arising from land use, land-use change and forestry (LULUCF) activities. Reporting is required for the Protocol's first commitment period, from 2008 to 2012. Good Practice Guidance (IPCC 2003) for LULUCF activities requires carbon stock changes be estimated in an unbiased, transparent, and consistent manner. Further, a process and plan for implementing QA/QC (quality assurance and quality control) procedures is necessary to meet good practice.

To meet LULUCF reporting requirements, New Zealand is classifying forests into three categories: natural forest; forests planted prior to 1990; and forests planted after 31 December 1989 into non-forest land. The latter category is referred to as 'Kyoto forests'. Forests to be measured by New Zealand under the Protocol are defined by the following parameters: minimum area of 1 ha; at least 30 % canopy cover; at least 5 m in height (or the potential to reach this height under current management); and a width of at least 30 m. New Zealand planted forests are comprised predominantly (89 %) of radiata pine (*Pinus radiata*), with the remainder made up of other species, mostly (6 %) Douglas-fir (*Pseudotsuga menziesii*).

A plot-based forest inventory system has been developed for the New Zealand Kyoto forests.

Circular plots, 0.06 ha in area, are being located within these forests on a systematic 4 km grid. As field access to these mostly privately-owned forests is not guaranteed, LiDAR is being used to characterise all plots.

Airborne LiDAR provides a flexible data collection system. The laser signal can penetrate the forest canopy so that ground measurements can be made. Further, data collection is independent of sun angle and night collection is feasible. Over the past few years there have been considerable advances in LiDAR systems which have resulted in improved LiDAR positional accuracy and increased surface point density. This has resulted in cm-level ranging accuracies, significantly increased pulse rate frequencies (greater than 150 kHz) and provision for LiDAR intensity signals (as opposed to ranging observation only). The flexibility of airborne LiDAR, coupled with a high level of positional accuracy and point density, make LiDAR systems an attractive data acquisition tool for forest carbon inventory.

Although field-based carbon estimation is still an essential element of forest carbon inventory, the integration of LiDAR into such activities provides an opportunity to reduce total inventory cost and the need for extensive field-based sampling. Investigations into the potential of airborne LiDAR for forest carbon inventory have been undertaken (Drake *et al.* 2002, Nelson *et al.* 2003, Patenaude *et al.* 2004, and Stephens *et al.* 2007). In temperate deciduous woodland, LiDAR metrics explained 74% of the variation in above-ground carbon estimates, and 85% of the variation in above-ground estimates at the stand level (Patenaude *et al.* 2004). For planted forests in New Zealand, a study by Stephens *et al.* (2007) determined that total carbon per plot could be predicted by LiDAR metrics with a reasonable level of precision (R^2=0.87; RMS error=19 t (carbon) per ha (16%)).

For greenhouse gas inventory, quality control is defined as the routine technical activities used to measure and control the quality of the inventory as it is being developed. Quality assurance is defined as the system of review procedures conducted by personnel not directly involved in the inventory compilation/development process (IPCC 2003). These definitions differ with those used in the remote sensing industry (ILMB 2006; Stoker *et al.* 2007). The IPCC QA/QC definitions are used in the paper, where QC activities take place before the LiDAR acquisition mission, and the internal and external QA activities occur largely after the mission.

Emphasis on the development of QA/QC procedures for LiDAR data have been in support of topographic mapping. Csanyi *et al.* (2007) describe LiDAR ground targets designed for topographic mapping to support geodetic grade LiDAR surveys (digital surface mapping with very accurate elevations and horizontal positions).

This paper describes the QA/QC procedures used to ensure that discrete return LiDAR data acquired of forest carbon inventory plots met the aerial survey contract specifications.

2. Method

2.1 Study area

LiDAR data for this project was acquired across New Zealand, which is centered on 41^0 S and 174^0 E (Figure 1). A total of 758 inventory sites, located on a 4 km grid, were surveyed.

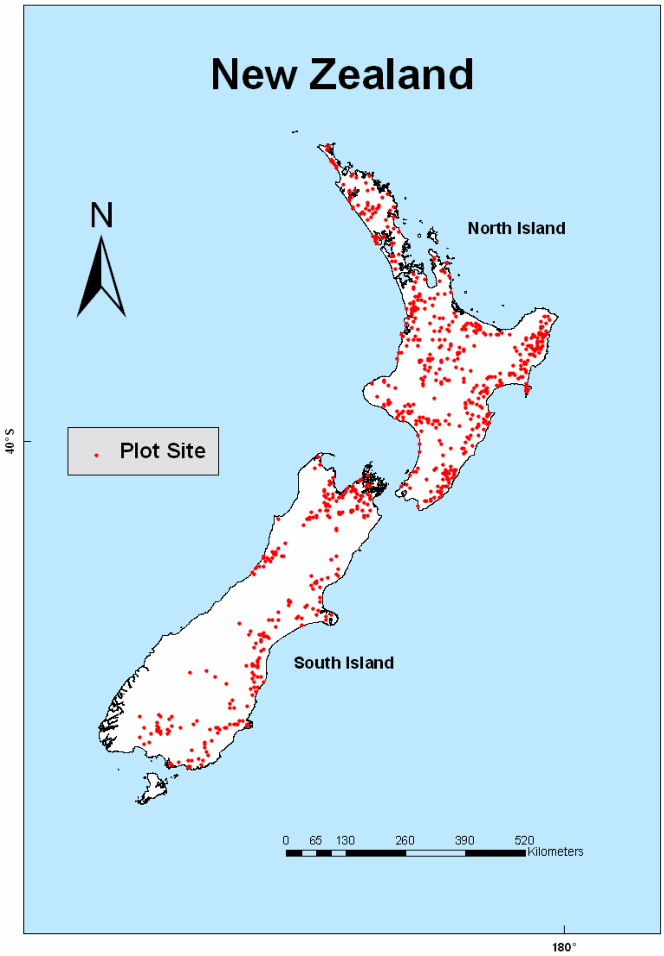

Figure 1: The location of the inventory plots across New Zealand.

2.2 Project specifications

The data acquisition specifications for this project included:

- A total of 758 sites to be flown, each site covering a circular area with a radius of 85 m, where the site centre is the middle of a 0.06 ha circular forest inventory plot.
- For each plot site the first return density for each site to be at least three points per m^2
- Digital colour imagery is to be collected concurrently with the LiDAR data
- Data are to be acquired over a three month period (February to April 2008), with data supplied at regular intervals. QA to be undertaken within 10 days of receipt of data.
- Both sensors (LiDAR and digital colour photography) to acquire data along the full length of all flight lines
- Data to be in the NZ Transverse Mercator (NZTM) projection and NZGD2000 geodetic datum
- Project report and metadata documents to describe the capture method, sensor calibration procedures, data processing, contractor QA/QC approach and the outputs supplied to the client.
- No data decimation is to occur, except for atmospheric outliers.
- Data and information to be supplied in specified file formats, with the LiDAR data to be delivered in the LAS 1.0 format.

2.3 LiDAR system and data processing overview

The LiDAR survey was flown using a Cessna 207 aircraft. An Optech ALTM 3100EA LiDAR sensor was mounted in the aircraft, along with an integrated Rollei AIC digital camera. Table 1 summarises the LiDAR and flight parameters used to achieve a target point spacing of 0.5m. The digital camera was used in tandem with the LiDAR sensor. The resulting colour photography had a ground resolution of 0.2 m and a forward overlap of 30 per cent. The system also utilised an Applanix 510 Position and Orientation System (POS) that uses the GPS and IMU sensors, and a GPS-based computer controlled navigation system.

Table1: Summary of narrow beam, discrete return, LiDAR data and flight details

System	Wavelength	Scan angle	Pulse frequency	Scan frequency	Swath width	Footprint diameter*	Ground speed	Flying height**
Optech ALTM 3100EA	1064 nm	± 6 deg	70 kHz	53Hz	170 m	0.27 m	105 knots	1200 m

* beam divergence based on full width and half height of beam; ** height above ground level

The POS data were processed using Applanix POSPac software and the LiDAR 3D point cloud generation was completed using DASHMap™ software. LiDAR point cloud classification, product generation and orthophoto production was accomplished using the TerraSolid suite of LiDAR processing software.

2.4 QA/QC activities undertaken by contractor

Data acquisition and pre-processing began with the application of rigorous sensor calibration procedures to ensure relative accuracy of the point cloud with absolute positional accuracy being maintained through adopting “procedures that have been demonstrated to produce data with particular horizontal and vertical accuracy values” (FGDC 1998).

Sensor calibration was a key QC activity. LiDAR boresight alignment and scanner scale parameters were determined from LiDAR data collected over a calibration range located close to the aircraft operating base. The calibration range was flown at regular intervals during the aerial acquisition phase of the project. These data were used to confirm whether or not the boresight alignment and scanner scale parameters varied over time. The LiDAR point intensity data were also monitored by reviewing histograms of point intensity values within a subset of the calibration range, and checking for changes in their shape and statistical characteristics.

The absence of a suitable network of continuously operating GPS reference network base stations in New Zealand, and the geographic extent of the project, made it necessary to use advanced Precise Point Positioning (PPP) algorithms during the post-processing of the POS GPS data. To monitor the performance of the PPP output, base stations were operated from time to time throughout the project. When collected, the base station data were used to generate differential GPS (dGPS) based sensor trajectories and these were then used in the QA of the PPP based sensor trajectories.

Following the generation of the LiDAR point cloud with DASHMap™ software, QA of the collected data for swath width/site coverage and point cloud density was undertaken after loading the LiDAR data into TerraScan LiDAR processing software. The target outgoing pulse point density of four points per square metre (with a minimum of three points) in a single flight line required the aircraft pilot and sensor operator to be vigilant in maintaining correct ground speed, altitude and track over steeply undulating terrain.

Rigorous folder and file naming conventions built around unique site identifies and acquisition dates was used to track the data from its raw state after off-load from storage devices on the aircraft through to delivered products. The products were delivered in blocks created on the date of acquisition and were accompanied by ISO 19115 compliant metadata XML files containing both mandatory and optional field entries.

2.5 QA activities undertaken by client

QA activities undertaken by the client involved use of the FUSION LiDAR visualisation and analysis software (McGaughey *et al.* 2004) and ERDAS IMAGINE software. Batch processing of LiDAR data with the FUSION software was undertaken to assess data for all flight lines and all classified sites. The batch processing produced HTML QA reports, which contained numeric and image outputs.

For each LiDAR flight line and each site datasets, FUSION was used to determine first return (pulse) density, return density, and to produce an intensity image of the area covered by the datasets. A ground surface model was also created with FUSION from the flight line and site LiDAR datasets. The ground surface model is generated by filtering the LiDAR point cloud to identify ground returns. The filtering method used is an adaptation of the iterative method developed by Kraus and Pfeifer (1998). The FUSION filtering method is described in Andersen *et al.* 2006.

The FUSION LiDAR data viewer was used to visually assess the site point cloud LiDAR data classified by the contractor as ground surface. This was accomplished by comparing the classified data with the independently created (using FUSION) ground surface model, and by rotating the point cloud to establish if there were any points at an elevation less than those classified as ground surface. These assessments were undertaken for five per cent of the plot sites.

The ground surface model for the flight lines were exported from FUSION as a Surfer ASCII grid file. In ERDAS the elevations along the centreline of the flight line ground surface models were adjusted by applying an elevation offset obtained from reference to a 10 cm contour Geoid separation model. Then the adjusted elevations were compared with elevations for the same centreline sampling area in a national 15 m digital elevation model. This model has a vertical uncertainty of ±10 m. Flight line elevation comparisons were to provide a ‘reasonableness’ check of LiDAR-derived elevations against a nation-wide digital elevation model.

File names and geographic position of all ploy data were checked using ARCInfo software. This was accomplished by comparing post-processing plot location shapefiles with shapefiles (with file names and spatial location) of plots to be surveyed.

3. Results

3.1 Sensor calibration

The LiDAR sensor calibration range was flown four times through the course of the acquisition. Height difference statistics between 600 ground surveyed points of the calibration range and the LiDAR point cloud were calculated following the checking of the boresight alignment and scanner scale parameters. Table 2 summaries these statistics and the range of return pulse intensity values for two of the calibration sorties. These are typical of the values obtained for each of the calibration flights.

Table 2: Summary of sensor calibration output for two calibration sorties

Sortie	Flightline	Height difference mean (m)	Height difference Std Dev. (m)	Return pulse intensity range (min-max)
080127	1	-0.002	0.06	1.4 to 6.8
	2	-0.018	0.02	1.5 to 7.2
080213	1	0.002	0.03	0.7 to 6.7
	2	-0.05	0.02	0.6 to 6.6

3.2 Precise Point Positioning

The expected accuracy of the precise point positioning method is 10 to 40 cm, subsequent to the convergence of the processing algorithms. This expectation was tested on six occasions through the course of the project where a GPS base station receiver was operated. Table 3 shows typical positional difference statistics between PPP and dGPS processed sensor trajectories. These results are in accord with expectations and confirm the validity of using PPP for this project.

Table 3: Summary of PPP v dGPS sensor trajectory for two sorties

Sortie	Duration of sortie (hr:min)	Easting difference mean (m)	Northing difference mean (m)	Height difference mean (m)	Easting difference Std Dev (m)	Northing difference Std Dev (m)	Height difference Std Dev (m)
080214	2:20	0.06	-0.19	-0.16	0.02	0.01	0.06
080314	3:10	0.22	0.12	0.10	0.10	0.12	0.09

All files were named in according to client specifications and the plot sites were found to be in the correct geographic position.

3.3 Assessment of LiDAR first return (pulse) density

A summary of the LiDAR return density results are provided in Table 4. In a few instances point densities were less than the minimum required. This occurred because of strong winds encountered by the aircraft, making it difficult to maintain the planned ground speed of 105 knots. Sites with a density less than three were re-flown.

Table 4: Summary of first return (pulse) LiDAR densities (returns per m^2)

Data delivery date	Number of sorties	Number of plots flown	Maximum return density	Minimum return density	Mean return density	Plots to re-fly
14-03-08	2	24	6.67	2.62	3.55	3
31-03-08	2	69	7.55	3.00	3.66	0
11-04-08	12	228	4.47	2.98	3.91	1
17-04-08	8	178	6.41	3.06	4.09	0
30-04-08	2	29	5.39	3.04	3.96	0
14-05-08	4	87	5.87	3.12	3.99	0
28-05-08	4	107	6.04	3.23	4.16	0
11-06-08	3	36	5.23	3.68	4.22	0

Intensity images (created with a dynamic range of 0-100) and the orthophotographs were of high quality. An example of the data acquired, and generated in this project, is illustrated in

Figure 2.

3.4 Assessment of LiDAR-derived ground surface models

Visual comparison of the contractor ground-classified data for the sites with the client created ground surface model showed no discernable difference between the two. Elevation profile differences for a typical flight line in steeply undulating hill country are shown in Figure 3.

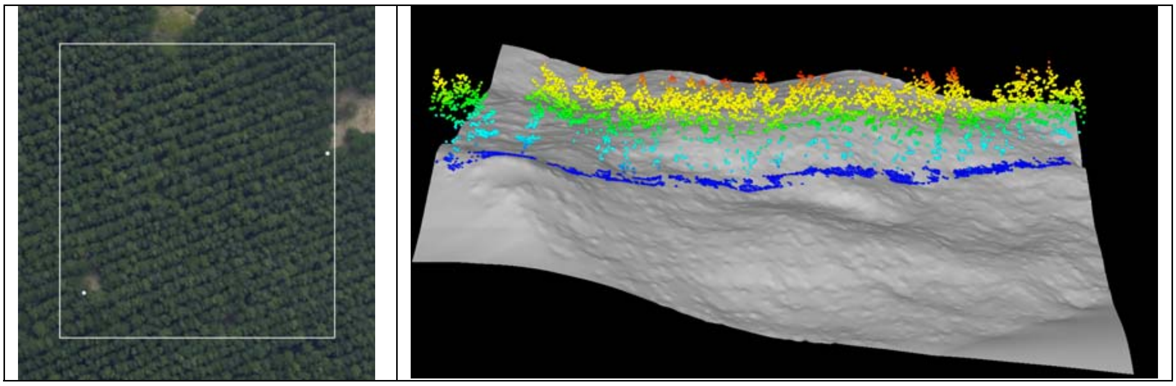

Figure 2: Left image shows an extract of a site orthophotograph. A circular plot site is located within the white rectangle. The two white points mark the ends of a transect through the site. The right image shows the client-produced ground surface model and a 5 m wide point cloud coloured using the height above ground along the transect. The first return density for the site is 3.46 points per m^2.

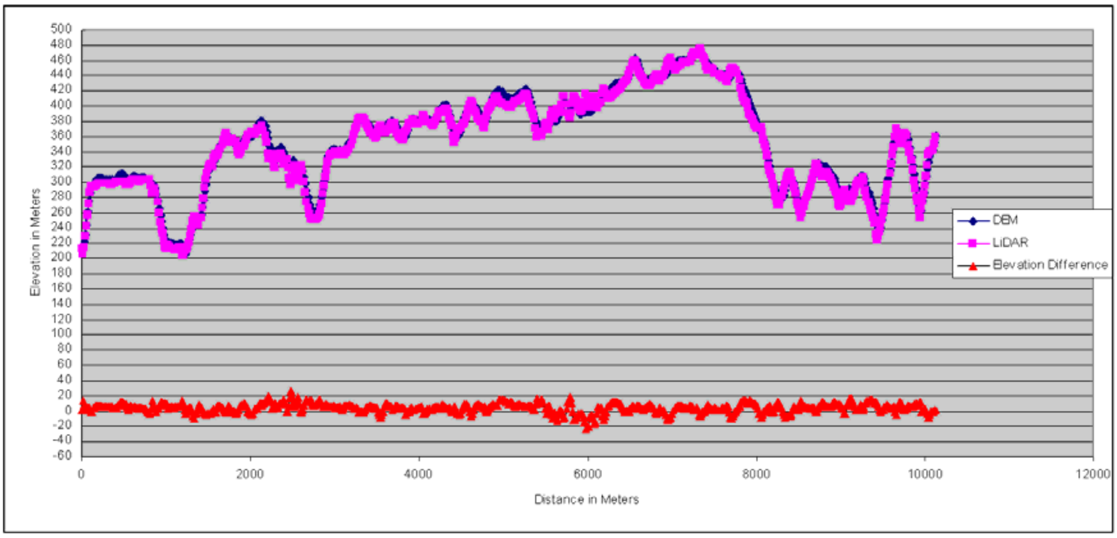

Figure 3: The top two lines show heights from Geoid-corrected LiDAR data and a corresponding profile from a national digital elevation model. The lower line shows the elevation differences between the two data sources. The large elevation difference is 25 m, 2.5 km into the flight line.

4. Discussion

Over the past decade many studies have demonstrated that airborne LiDAR can provide data appropriate for resource management, including forest inventory. Over this time LiDAR technology has been widely used for high-resolution terrain analysis and mapping. National QA/QC standards and guidelines for LiDAR data collection are well developed for terrain analysis and mapping (ILMB 2006; Stoker *et al.* 2007). However, standards and guidelines for forestry applications are not as well advanced. McGaughey *et al.* (2006) described the requirements for LiDAR data for forestry measurements and highlighted the deliverables, specific to forestry applications that should be included in data acquisition contracts.

This operational LiDAR forest inventory project involved 758 small forest sites, on land ranging from sea level and 940 m elevation, and located over a large geographic area. The QA/QC activities undertaken by the contractor were designed specifically for the project, with quality being maintained through the application of flying skill, rigorous processes and advanced technology. Further, the QA processes undertaken by the client and conducted within 10 days of data delivery, were designed to provide rapid feedback to the contractor, and to ensure that the LiDAR data were appropriate for the intended purpose, namely forest carbon inventory. The QA/QC processes documented here provide a basis for establishing forestry standards and guidelines for airborne LiDAR data acquisition and processing.

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