# Airborne lidar sampling of the Canadian boreal forest: Planning, execution & initial processing

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## Abstract

During the summer of 2010, a transcontinental aerial survey mission was performed to acquire 24,000 line km of lidar transects covering >15,000 km$^2$ representing all ecozones within Canada's boreal forest. The coverage equates to ~21 million 'lidar plots' at the 25 m grid cell resolution. Each 'plot' contains the position and intensity of 1000 to 2000 laser points, which describe the terrain surface and 3D canopy structure, which will be used to predict forest inventory attributes and to support calibration of wide area satellite-based imagery. Furthermore, in similar fashion to geo-located permanent sample plots, the lidar transect flight path from 2010 can be re-surveyed in the future to facilitate monitoring of forest development and change in a consistent and quantifiable manner. The paper describes the mission planning criteria, survey logistical considerations and customised transect data processing routines.

## 1. Introduction

Canada's boreal forests cover approximately 3,070,000 km$^2$ (Brandt, 2009) and span almost 5000 km from Newfoundland to the Yukon. Monitoring remote and extensive forest resources across such a large area is challenging. While satellite remote sensing is used to meet some information needs, some form of calibration and validation data are required. Further, many scientific questions require plot-level information to relate conditions in a spatially referenced manner. The utility of integrating lidar sampling data with satellite imagery to investigate temporal canopy changes over a study area within Canada's boreal forest has been demonstrated (Wulder *et al.* 2007). Similarly, lidar sampling has also been shown to facilitate the scaling of forest attributes from the plot scale to an entire Province (~50,000 km$^2$) (Hopkinson *et al.* 2011). A systematic collection of lidar transect data representing the entire Canadian boreal forest is envisioned to provide a widely distributed sampling of information that may be used to support calibration / validation activities for monitoring programs, to support research, and to offer experience and insights in support of repeat lidar-based monitoring efforts.

A lidar project requiring coordination at the continental scale of Canada's land mass poses unique challenges. To plan and execute such a mission, the Canadian Forest Service (CFS) initiated partnerships with experienced lidar forestry researchers at the University of British Columbia (UBC) and the Applied Geomatics Research Group (AGRG) in Nova Scotia. This paper will summarize the key elements of the mission planning, data collection, and initial post-processing. Some of the challenges faced and solutions implemented at each stage of the project will be highlighted.

## 2. Mission Planning

The concept was to adopt the C-CLEAR (Canadian Consortium for Lidar Environmental Applications Research) collaborative research support framework, while using the AGRG airborne lidar equipment and research personnel to facilitate data acquisition and processing. C-CLEAR lidar missions are conducted annually across Canada and occasionally into the Arctic, so this model provided the ideal basis for a boreal-wide transect sampling mission from one side of Canada to the other. The first mission planning task was to identify priority areas and then to map out an approximate route to be taken by the survey aircraft.

The goal of the transect planning was to ensure that a broad sample of boreal conditions was captured, limit the amount of flying over areas with existing management inventories, and to avoid flying too frequently over sparsely tree areas. The first task was to identify and target boreal ecoregions that displayed >50% forest cover to ensure lidar transect sampling was productive; i.e. no point sampling large areas with no forest cover. Given that some forest areas can undergo active forestry operations, these areas are often described within existing forest inventory databases. Therefore, to focus the sampling in ecoregions with minimal existing inventory data, areas displaying more than 75% managed forest cover were excluded. To enable comparisons between lidar transect data and available plot-level image and field data across the country, the National Forest Inventory (NFI) grid node locations (Gillis *et al.* 2005) were used to guide the specific positioning of transect locations. In addition to the national-level sampling, more intensive lidar transect data collection was conducted in the Liard and Hyland Highlands ecoregions in the southern Yukon Territory to facilitate: a) a statistically significant spatial sampling of the forest cover attributes for these ecoregions; and b) some plot-level ground calibration of the lidar transect data for a range of forest attributes (e.g. Morrison *et al.* 2011).

Given AGRG is located in Nova Scotia, on the east coast of Canada, it was decided to initiate data collection here, then traverse across country toward to the Yukon Territory in the north west, with the objective being to capture as much of the target coverage as possible on the outbound leg and fill any large gaps on the return; i.e. fly the full width of the boreal zone two times. The planned survey route was constrained by the operational limitations of the survey aircraft and the presence of suitably equipped airports located to allow adequate sampling of the target areas whilst maintaining progress across the country. Given the strong latitudinal gradients in forest cover in the boreal zone, it was essential that transect sampling had a north-south component to it, thus dictating a ‘zig-zag’ flight pattern from east to west and back again.

AGRG’s survey plane is a twin engine PA-31 Piper Navajo operated by Scotia Flight Centre. Many remote northern airports in Canada have gravel airstrips and only carry jet fuel for helicopters and fixed wing aircraft with turboprop engines. The Navajo cannot use jet fuel and gravel airstrips should be avoided as it has long twin bladed propellers which mobilise dust and debris, and thus could possibly damage the aircraft or the lidar equipment. Furthermore, when fully laden the Navajo requires a runway exceeding ~ 1,100 m in length. While most airports in southern Canada and major northern towns can accommodate these operational considerations, airport options at the northern extent of the boreal forest target zone were limited.

In addition to the spatial sampling and airport location criteria summarized above, further constraints that needed to be factored into the planning were:

1. Based on a flying speed of 150 knots and endurance of 4.5 hours the planned distance between take off and landing should not exceed ~ 1000 km;
2. Due to budgetary limitations, total survey flying time should not exceed 100 hours;
3. Survey routes must avoid restricted airspace.
4. Transects to be collected between late June and end of August

All ecoregion, NFI, and airport locations and attributes were loaded into a GIS and the criteria described above used to design an optimal survey route. Based on desired cost-effective sampling requirements, sensor and survey setting influences to point cloud attributes (Hopkinson, 2007; Næsset, 2009; Evans *et al.* 2009), and the operational envelope of the AGRG airborne laser terrain mapper (ALTM) 3100C (Optech Inc. Toronto, Ontario), the chosen flight parameters under ideal conditions were:

1. flying altitude of 1200 m agl;
2. velocity of 150knts;
3. pulse repetition frequency (PRF) of 70 kHz;
4. scan angle of ± 15$^{o}$.

Under typical operational conditions, these parameters will generate a swath width of ~640 m and provide a nominal multiple return point density of ~2.8 pts/m$^2$ over flat forest covered terrain. The initial survey plan prior to execution is illustrated in Figure 1 and the associated planned flight times in Table 1. Should the above survey parameters not be possible, the following guidelines were to be used:

1. Multiple return data density must never drop below 1pt/m$^2$;
2. Swath width must always exceed 400m at ground level;
3. Scan angle will not exceed 20 degrees nor fall below 10 degrees;
4. PRF will remain at 70kHz unless high relief necessitates either 50kHz or 33kHz;
5. Survey configuration adopted for all transects will be noted and reported.

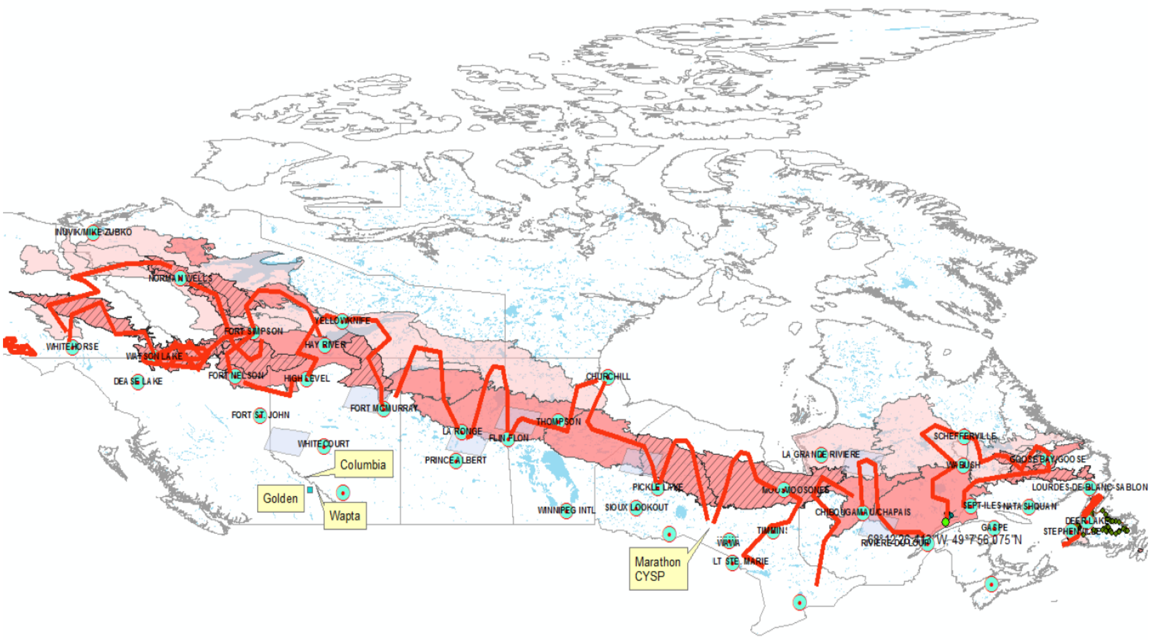


Figure 1: Planned survey transects (red lines) across the boreal forest area of interest (priority increasing from light to dark pink ecoregions). Airports meeting suitability criteria are illustrated as blue/red circles.

Table 1: Planned survey transects illustrating the anticipated data acquisition, transit and total flight time listed sequentially from east to west across Canada.

| Missions | Survey hrs | Transit hrs | Total hrs |
|---|---|---|---|
| Mobilization/Installation | 0 | 4.0 (NB – NS x2) | 4.0 |
| Calibration (NS x 2) | 10 | 0 | 10 |
| 1 Schefferville | 3.75 | 2.25 (NS – QB) | 6.0 (two flights) |
| 2 Goose bay | 2.75 | 0.5 | 3.25 |
| 3 Sept Isle | 2.5 | 2.5 (QB – NS) | 5.0 |
| 4 NFLD South | 0.75 | 2.5 (shared) | 0.75 |
| 5 NFLD North | 2.0 | 2.5 (NFLD – NS) | 4.5 |
| 6 RDL - Chibougama | 4.5 | 2.5 (NS – QB) | 7.0 (two flights) |
| 7 Timmins | 4.0 | 0.5 | 4.5 |
| 8 Moosonee | 3.0 | 0.5 | 3.5 |
| 9 Marathon | 3.25 | 0.5 | 3.75 |
| 10 Pickle | 3.75 | 0.5 | 4.25 |
| 11 Churchill | 3.5 | 0.5 | 4.0 |
| 12 Flin Flon | 3.0 | 0.5 | 3.5 |
| 13 LaRonge | 4.0 | 0.5 | 4.5 |
| 14 Ft McMurray | 4.0 | 0.5 | 4.5 |
| 15 Yellowknife | 3.0 | 0.5 | 3.5 |
| 16 South (100 hr) | 2.5 | 5.0 (transit service) | 7.5 (two flights) |
| 17 Ft Nelson | 1.0 | 4.0 (transit service) | 5.0 |
| 18 Ft Simpson | 1.5 | 0.5 | 2.0 |
| 19 Watson Lake | 2.0 | 0.5 | 2.5 |
| ELH1 Watson | 2.5 | 0.5 | 3.0 |
| ELH2 Watson | 3.25 | 0.5 | 3.75 |
| 20 Whitehorse | 3.25 | 0.5 | 3.75 |
| 21 Norman Wells | 3.75 | 0.5 | 4.25 |
| 22 Ft Simpson | 3.0 | 0.5 | 3.5 |
| 23 Hay River | 2.75 | 0.5 | 3.25 |
| Return Nova Scotia | 0 | 16.5 | 16.5 (~ 4 - 5 flights) |
| Mission total | 83.25 | 48.25 | 131.5 |

## 3. Data Collection

Over a period of 67 days from June 14$^{th}$ to August 20$^{th}$, 2010, the AGRG undertook 34 individual survey flights traversing 13 UTM zones and over 24,000 km of the Canadian Boreal Forest from Newfoundland (56$^{o}$ W, UTM zone 21) in the east to the Yukon (138$^{o}$ W, UTM zone 8) in the west (Figure 2). All provinces and territories were represented apart from Prince Edward Island and Nunavut (where there is minimal to no boreal forest cover) and the longitudinal gradient sampled represents 23% of the Earth's circumference between latitudes 43$^{o}$ N and 65$^{o}$ N. Survey flights ranged from one to five hours in duration, averaging three hours and 700 line kilometres in length. The entire mission took 127 hrs of flying (including transits). Of this, approximately 91 was used for transect data collection and nine for sensor calibration at the start and end of the mission. Three stops totalling ten days were performed en route for scheduled aircraft maintenance and servicing at Fredericton, Calgary, and Yellowknife airports.

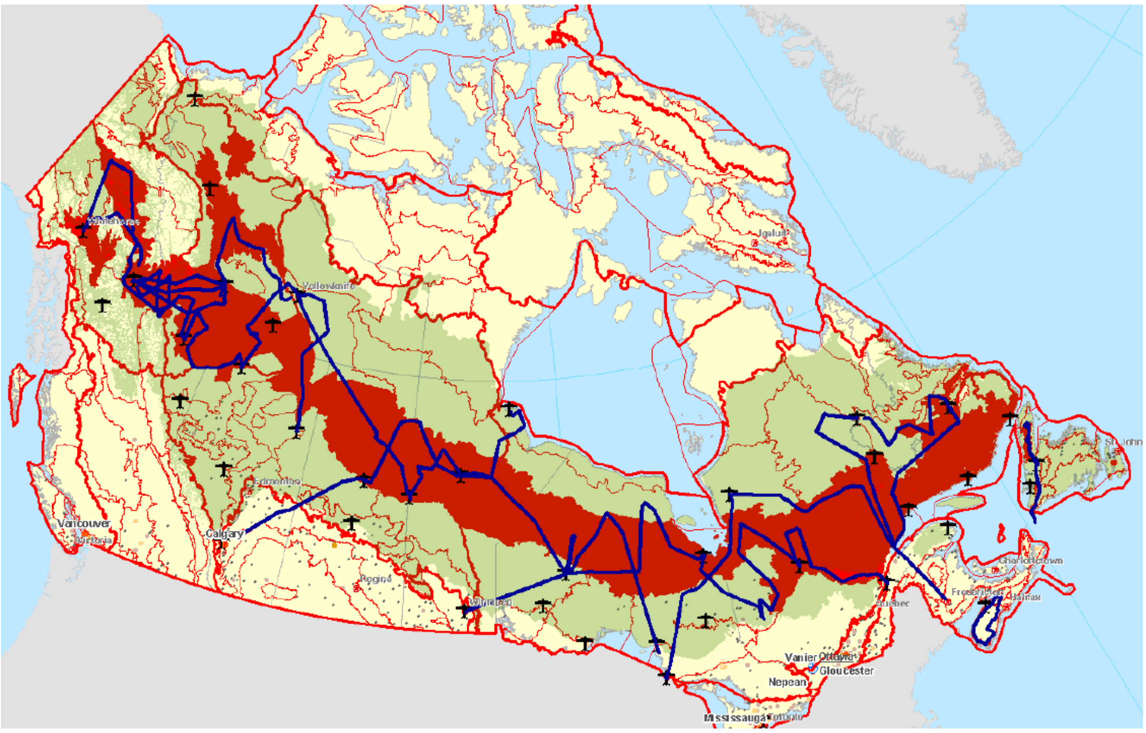


Figure 2: The final lidar sampling transect locations across Canada's Boreal Forest. Area in green represents Canada's boreal forest cover (Brandt, 2009), and the red area illustrates priority ecoregions.

Fire activity in the Boreal Forest during July and August of 2010 was unusually high and this directly impacted approximately one third of the flights by substantially reducing visibility, and forcing diversions away from dense smoke, closed runways and restricted airspace surrounding water bomber activity. A technical problem discovered during calibration and initial test flights was an erratic GPS data gap error due to corroded ground terminals on a radio antenna that passed unfiltered radio signals into the GPS antenna. This intermittent issue resulted in some short data gaps and down time, but did not impact the final data quality. A further logistical challenge encountered concerned the reliability of data contained within the latest Transport Canada Flight Supplement. On three occasions, information concerning fuel and airport service availability was found to be incorrect or out of date. Such minor challenges were expected on a project of this scale but they emphasize the necessity of adaptability and planned contingency.

Due to adverse weather, high relief, excessive fire and smoke conditions, temporary airspace restrictions and airport closures, deviations from the optimal plan were necessary for 24 of the 34 flights. For example, whilst all 34 flights were conducted between altitudes of 450 to 1900 m agl, 11 flights encountered altitudes <900 m agl, and three >1500 m agl (Table 2). Scan angle was kept fixed at 15$^{o}$ for all but four of the flights and PRF kept at 70 kHz for all but seven. Low ceilings forced a scan widening of up to 20$^{o}$, while high relief dictated a reduction in PRF to 50 kHz. In cases where ceilings or visibility reduced the flying height, data density was minimally impacted and typically increased despite adjusted scan angles. Where relief required a reduction in PRF, data density systematically decreased.

Table 2: Lidar survey transect IDs, timing, flying hours, survey configuration.

| | | | Survey Flights | | | Survey configuration | | |
|---|---|---|---|---|---|---|---|---|
| Transect | Strips | JD | Objective/Route | Province | Flying hrs | Alt (m agl) | PRF (kHz) | scan (deg) |
| | | 165 | Transit + Calibration | NB - NS | 2.9 | | | |
| | | 166 | Calibration | NS | 2.4 | | | |
| Test | 1 | 167 | Test transect | NS | 3.8 | 1000-1300 | 70 | 15 |
| | | 169 | Transit | NS - QB | 2.3 | | | |
| T01 | 1 | 171 | Baie Comeau - Goose bay | QB / NFL | 3.4 | 1000-1200 | 70 | 15 |
| T02 | 3 | 172 | Goose bay - Schefferville | QB / NFL | 3.2 | 900-1300 | 70 | 15/20 |
| T03 | 1 | 172b | Schefferville - Baie Comeau | QB / NFL | 3.7 | 900-1400 | 70 | 15 |
| | | 173 | Transit | QB - NB | 1.5 | | | |
| | | 173b | Test flight | NB | 0.9 | | | |
| | | 174+ | Aircraft service (Fredericton) | NB | 0.0 | | | |
| | | 186 | Transit | NB - NS | 0.8 | | | |
| | | 187 | Transit | NS - NFLD | 2.6 | | | |
| T04 | 1 | 188 | SW Newfoundland | NFL | 1.6 | 700-1000 | 70 | 15 |
| T05 | 1 | 192 | NW Newfoundland | NFL | 1.9 | 600-1200 | 70 | 15/20 |
| | | 200 | Transit | NS - QB | 2.0 | | | |
| T06 | 2 | 201 | Riviere du loop - Chib | QB | 3.3 | 450-1250 | 70 | 15 |
| T07 | 2 | 201b | Chibougamau - Val D'Or | QB | 4.0 | 1000-1300 | 70 | 15 |
| T08 | 2 | 203 | Val D'Or - Moosonee | QB / ON | 2.1 | 1000-1200 | 70 | 15 |
| T09 | 2 | 203b | Moosonee - Pickle lake | ON | 4.1 | 1000-1300 | 70 | 15 |
| T10 | 1 | 203c | Pickle Lake north loop | ON / MB | 1.7 | 1100-1250 | 70 | 15 |
| T11 | 2 | 204 | Pickle Lake - Winnipeg | MB | 2.0 | 500-600 | 70 | 15 |
| T12 | 1 | 204b | Winnipeg - Thompson | MB | 2.6 | 700-1150 | 70 | 15 |
| T13 | 3 | 205 | Thompson - La Ronge | MB / SK | 3.2 | 600-1050 | 70 | 15 |
| T14 | 1 | 205b | La Ronge - Calgary | SK / AB | 3.0 | 1000-1300 | 70 | 15 |
| | | 206+ | Aircraft service (Calgary) | AB | 0.0 | | | |
| | | 210 | Transit | AB | 2.4 | | | |
| T15 | 2 | 210b | Ft McMurray - Yellowknife | AB / NWT | 3.2 | 900-1250 | 70 | 15 |
| T16 | 3 | 211 | Yellowknife - High Level | NWT / AB | 2.5 | 1150-1300 | 70 | 15 |
| T17 | 2 | 211b | High Level - Ft Nelson | AB / BC | 3.0 | 750-1000 | 70 | 15 |
| T18 | 6 | 212 | Ft Nelson - Whitehorse | BC / YK | 4.4 | 1200-1500 | 50 | 15 |
| T19 | 1 | 213 | Whitehorse - Watson Lake | YK | 3.8 | 1050-1600 | 50 | 15 |
| T20 | 2 | 213b | Liard ecozone loop (Watson) | YK | 3.2 | 900-1900 | 50 | 15 |
| T21 | 3 | 214 | Watson Lake - Ft Simpson | YK / NWT | 2.0 | 600-1800 | 70/50 | 15/20 |
| T22 | 3 | 214b | Ft Simpson south loop | NWT | 0.9 | 1400-1500 | 50 | 20 |
| T23 | 2 | 214c | Ft Simpson - Watson (plots) | NWT / YK | 1.9 | 900-1900 | 70/50 | 15 |
| | | 215 | Aborted | YK | 0.2 | | | |
| T24 | 4 | 215b | Watson - Ft Simpson (plots) | YK / NWT | 2.5 | 1200-1400 | 70/50 | 15/17 |
| T25 | 1 | 215c | Ft Simpson - Yellowknife | NWT | 3.6 | 1200-1300 | 70 | 15 |
| | | 216+ | Aircraft service (Yellowknife) | NWT | 0.0 | | | |
| T26 | 2 | 218 | Yellowknife - Flin Flon | NWT / MB | 4.5 | 1200-1400 | 70 | 15 |
| T27 | 1 | 218b | Flin Flon - Thompson | MB | 2.1 | 1200-1300 | 70 | 15 |
| T28 | 1 | 219 | Thompson - Churchill | MB | 2.0 | 1200-1250 | 70 | 15 |
| T29 | 1 | 219b | Churchill - Thompson | MB | 2.3 | 1000-1300 | 70 | 15 |
| T30 | 1 | 219c | Thompson - Pickle Lake | MB / ON | 2.9 | 1200-1250 | 70 | 15 |
| T31 | 3 | 220 | Pickle Lake - Sioux Ste Marie | ON | 4.8 | 600-1250 | 70 | 15 |
| T32 | 3 | 223 | Sioux Ste Marie - La Grnd Riv. | ON / QB | 3.7 | 1000-1400 | 70 | 15 |
| T33 | 4 | 223b | La Grnde Riviere - Fredericton | QB / NB | 5.1 | 850-1400 | 70 | 15 |
| | | 230+ | Transit + Calibration | NS - NB | 6.7 | | | |
| TOTAL | | 67 | | | 126.7 | | | |

## 4. Transect Data Processing

### 4.1 Flight light trajectories

Given the need to adapt the sensor and flying configuration to accommodate changing external conditions such as cloud, smoke and terrain relief, the ALTM sensor needed to be stopped and restarted on several occasions in some flights (up to six times in the extreme case). Therefore, during the 34 survey flights, there were actually 69 individual strips of lidar collected, the longest of these being a continuous data stream exceeding four hours in duration. All data were checked in the field shortly after download from the ALTM but final processing took place in the AGRG lab in Nova Scotia.

After download and archival of raw data, the first data processing task was to compute the smoothed best estimated trajectory (sbet) containing both position and orientation data. The ALTM GPS receiver (Trimble BD9500) collected real time GPS signals at 1Hz for the antenna location on top of the aircraft. Meanwhile, multi-axial aircraft accelerations and attitude shifts were recorded at 200Hz at an inertial measurement unit (IMU) located within the sensor head adjacent to the scanner mirror. Trajectory processing uses a Kalman filter to integrate these two data streams to simultaneously estimate and predict the true position and orientation of the aircraft platform. Given the impracticality (high cost and time requirement) of setting up ground base stations at hundreds of locations across Canada, it was originally intended to process all GPS data using Precise Point Positioning (PPP) but after some experimentation it was found that the Canadian active control station (CACS) network and United States continuously operating reference station (CORS) data enabled reasonably accurate differential correction of the airborne GPS trajectory using a 'virtual base station' solution (Boba *et al.* 2008). While the base lines were actually up to several hundred kms in some cases, this capability meant that all points on all trajectories were differentially corrected to accurately known base station locations such that positional errors are anticipated to be better than PPP and likely within 1m throughout

### 4.2 Points integration

The software used to integrate the raw laser scanner and sbet data was 'Dashmap', a proprietary point processing software package developed by Optech Inc (Toronto, Ontario). Typical user configurable processing settings are the boresight alignment and hardware calibration parameters, factory defaults, range, scanner and altitude masks, atmospheric settings, and intensity normalisation. Output parameters, such as geographic extent, decimation, datum, projection and zone, file formats/paths, etc can also be user defined.

The main Dashmap output definitions for this project were the file format (LAS 1.0), UTM projection (eastings and northings) and the UTM zone for each strip. Because a given transect could cross multiple UTM zones, there were some challenges with zones being incorrectly defined, but these issues were resolved by manually over-riding the default output settings. In total, 69 LAS binary strip files were generated and outputted, containing an average of 300 million points each, ranging from a few million up to around a billion. Both the trajectory outputs and the point cloud data were horizontally and vertically referenced to the International Terrestrial Reference Frame (ITRF), which is equivalent to the WGS84 ellipsoidal datum.

For each emitted laser pulse, there was the possibility of up to four measured returns (first, intermediate, last and single). The echo classification, intensity and scan angle for each pulse are embedded within a LAS file. The LAS binary format is described on the ASPRS web site: http://www.asprs.org/a/society/committees/standards/lidar_exchange_format.html

### 4.3 Ground Classification

Individual strip file sizes could exceed 30GB and were too large to be handled in most software environments. Therefore a tool was developed to clean the data, classify ground returns, and break the large files down into smaller manageable files of 20 million data points.

'Lasline' is a tool developed partially to support the analysis presented here as well as an AGRG project with Nova Scotia Power Inc. to sample and inventory Provincial biomass (Hopkinson *et al.* 2011). Lasline takes raw LAS binary transect files of any size as input then executes the following operations:

1. Data cleaning: isolating high and low laser pulse returns that either float well above the canopy surface or penetrate well below the true ground surface. Such data errors occur due to bird strikes, atmospheric vapour/clouds/aerosols, and/or multi-path of the laser pulse.
2. Ground classification: Ground returns were classified from the transect point cloud using a variant of the algorithm developed by Axelsson (1999) that is also used in Terrascan (Terrasolid, Finland). Prior to implementation, many different parameter sets were tested over various datasets to find a compromise parameter set that produced satisfactory results across a broad range of terrain and land cover scenarios. The Lasline classification routine was found to be faster than the Terrascan routine for an equivalent data volume.
3. Data output: Cleaned and re-classified LAS files were then outputted in 20 million point increments; e.g. for a raw LAS file containing 267million laser points, Lasline would output 13 complete files of 20 million points and one final file of 7 million.

These steps are currently being further expanded to automatically output grid cell-level point cloud metrics in a similar fashion to the USDA tool 'FUSION' (McGaughey, 2010). Tools already exist in house that convert point output data to models of forest biometrics, so the intent is to calibrate 'push button' tools that automate the workflow from raw LAS binary transect files through to grid-cell level forest attributes ready for input to a GIS.

## 5. Conclusion

From June to August of 2010, an unprecedented survey of 24,000 km of lidar transects covering >15,000 km$^2$ were collected across Canada's boreal forest. The size of all the LAS files exceeds 500 GB and the coverage equates to ~21 million 'lidar plots' at the 25 m grid cell resolution. Each 'plot' contains the position and intensity of 1000 to 2000 laser points, which describe the terrain surface and 3D canopy structure, which may then be used for estimating forest inventory attributes (Bater *et al*. 2011). Overall, the completed data collection closely resembled the plan in terms of coverage and timing. The results of this mission represent a rich database describing Canada's boreal forests during the summer of 2010. These data offer the potential for calibration of wide area satellite-based imagery for spatial upscaling purposes, and will support Canadian government reporting and science programs. Furthermore, in similar fashion to geo-located permanent sample plots, the lidar transect flight path from 2010, or portions thereof, can be re-surveyed in the future to facilitate monitoring of forest development and change in a consistent and quantifiable manner.

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