Canadian boreal forest LiDAR transect sampling flights; research data collection and processing report

Submitted to:

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Prepared by:

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Summary:

Early in 2010, Drs Wulder, Coops and Hopkinson embarked on a discussion concerning the feasibility of a national airborne lidar mission to sample representative regions of the Canadian Boreal Forest. The question and the partnership was logical as all three researchers have been working for some years on lidar canopy sampling over smaller regions, whilst being active in lidar boreal forest attribute modeling. The concept was to adopt the C-CLEAR (Canadian Consortium for LiDAR Environmental Applications Research) collaborative research support framework, while using the AGRG (Applied Geomatics Research Group) airborne lidar survey and human resources to facilitate the data acquisition and processing logistics. This report summarises the main elements of the mission from planning to execution to primary lidar data output.

Over a period of 67 days from June 14th to August 20th, 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. 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 700km 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 aircraft maintenance and servicing at Fredericton, Calgary and Yellowknife airports.

Based on early discussions regarding optimal survey configuration, the nominal flight parameters under ideal conditions were chosen to be: a) a flying altitude of 1200 m agl; b) a velocity of 150knts; c) a pulse repetition frequency (PRF) of 70 kHz; and d) a scan angle of ± 15^o. These parameters produce a nominal multiple return density of ~2.82pts/m^2. Due to adverse weather, high relief, excessive fire and smoke activity, restricted airspace, deviations from this 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. 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 is minimally impacted and will likely increase despite adjusted scan angles. Where relief has required a reduction in PRF, data density has decreased.

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 need to be stopped and restarted on several occasions in some flights (up to six time 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. These strips of data were processed by integrating GPS and IMU (Inertial Measurement Unit) data with the laser range and scanner data to generate LAS binary data files containing all the laser point position, intensity and scan angle information. 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 the ground and break the large files down into smaller manageable files of 20 million data points. Following post-processing of the 69 LAS master files, 1017 LAS sub files were created containing a total of approximately 20 billion data points.

Various challenges were encountered during the execution of this project. Weather has been highlighted above but this was to be expected. However, 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. The usual 'gremlins' associated with high tech were frequently encountered causing minor hardware and software malfunctions that required frequent troubleshooting. One problem that plagued early missions was an erratic GPS data gap error. After extensive troubleshooting, it was found that corroded ground terminals on a radio antenna were causing a ground loop that passed unfiltered signals into the GPS antenna, thus masking out satellite signal. A further logistical challenge encountered was concerning the reliability or currency of data contained with the latest Transport Canada Flight Supplement. On three occasions, information concerning fuel and service availability was found not to represent the true situation. All such challenges were to be expected on a project of this scale but they emphasise the necessity of adaptability and planned contingency; i.e. one cannot enter into a project of national scope and covering remote parts of Canada and assume everything will go to plan. It won't!

The report is broken down in nine sections, each dealing with a specific stage of the project planning, acquisition and processing workflow (Figure 1). Methods, observations and challenges encountered that are pertinent to each stage within the workflow are presented within each section.

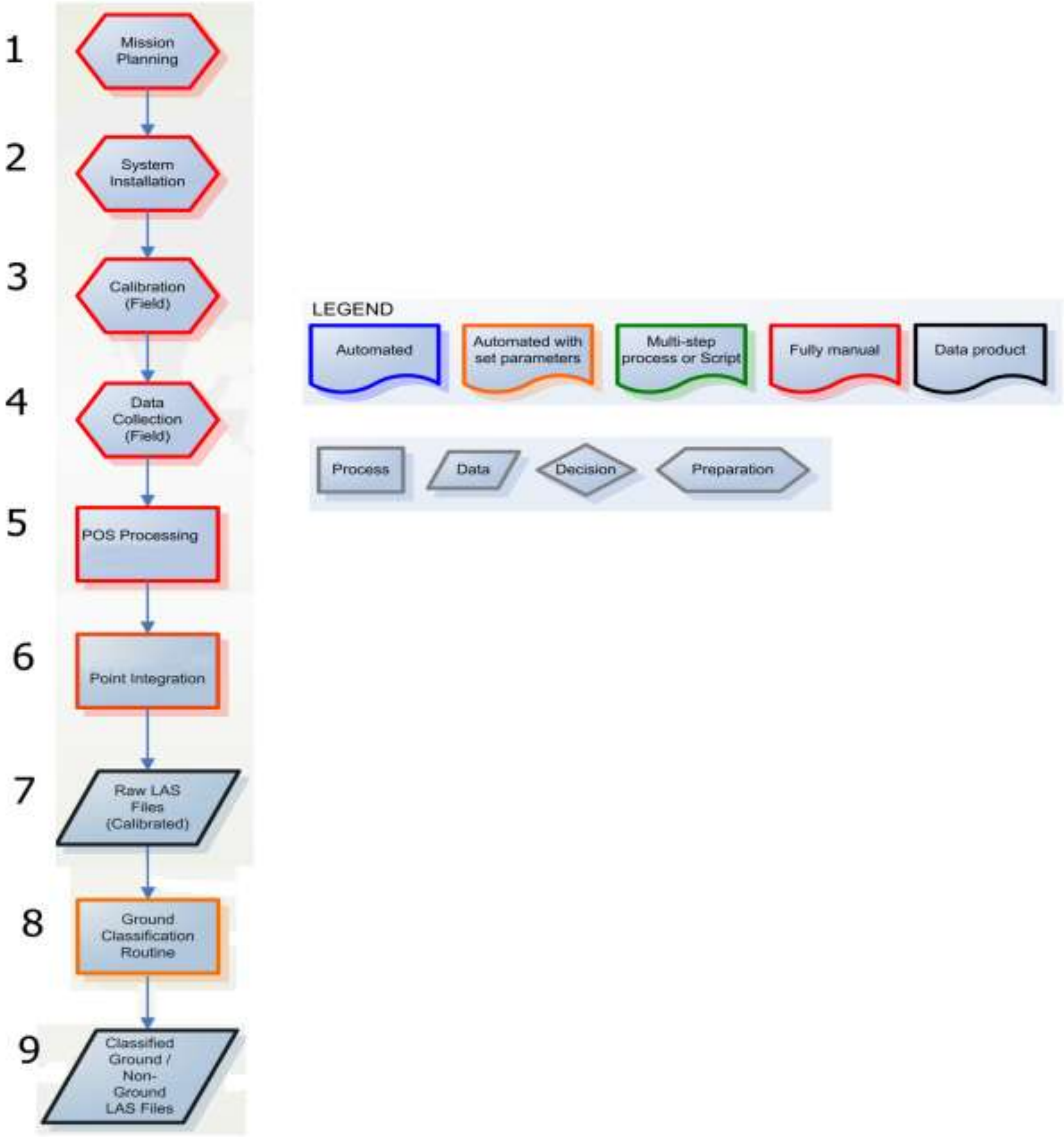


Figure 1. Workflow diagram for CFS boreal lidar sampling transects data collection and processing. Numbered steps will be discussed in the following text

1. Mission Planning

Based on early discussions concerning CFS priorities, the areas illustrated in Figure 2 were used to guide the location of survey transects. The priority area is layer one (red), which represents ecoregions that are greater than 85% boreal, greater than 50% forested, and less than 75% managed forest. The lower priority, layer two (pink) represents similar attributes but with a reduced forest cover (35%>50%). Layer three (cross hatchings) is again similar but is characterised by a reduced surface water area thus offering the potential for more intensive sampling. Ultimately, the Liard ecoregion in the Watson Lake area of the southern Yukon was chosen for more intensive sampling due to its proximity to other C-CLEAR objectives and the ability to keep a field crew on site for an extended period.

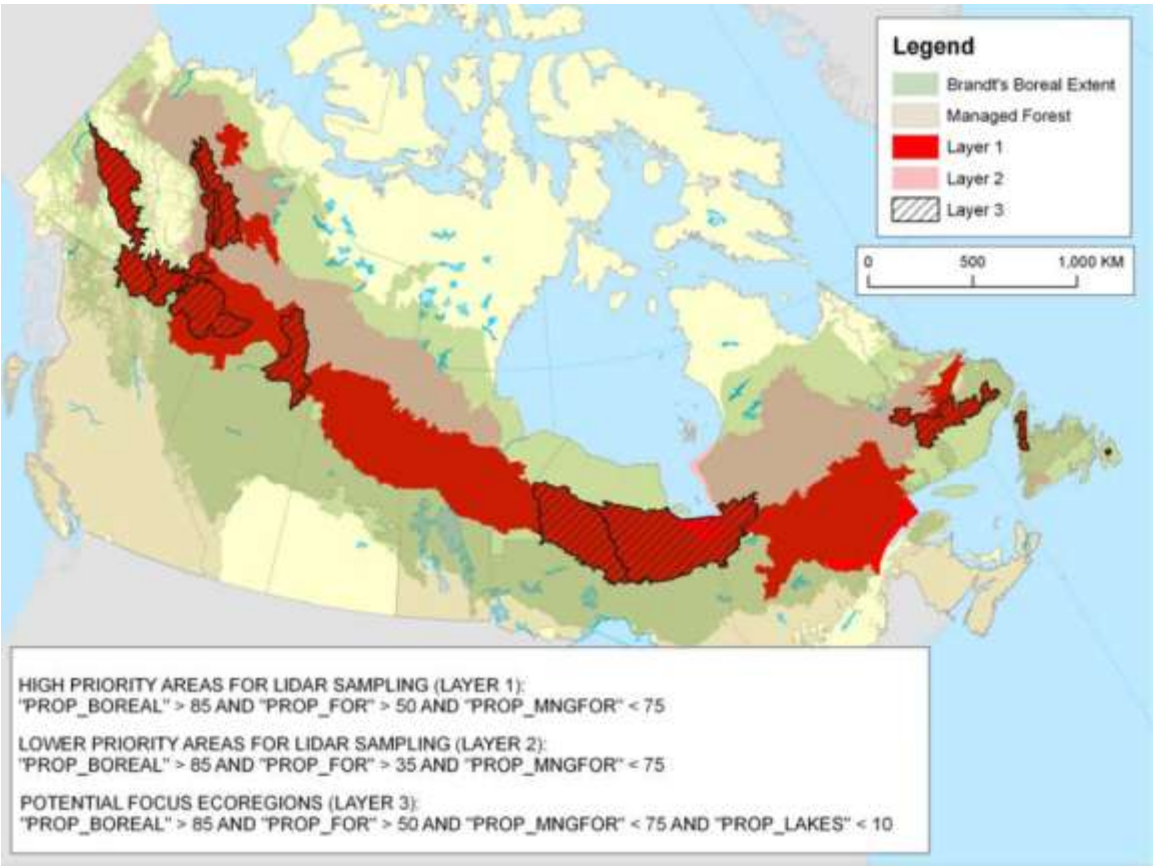
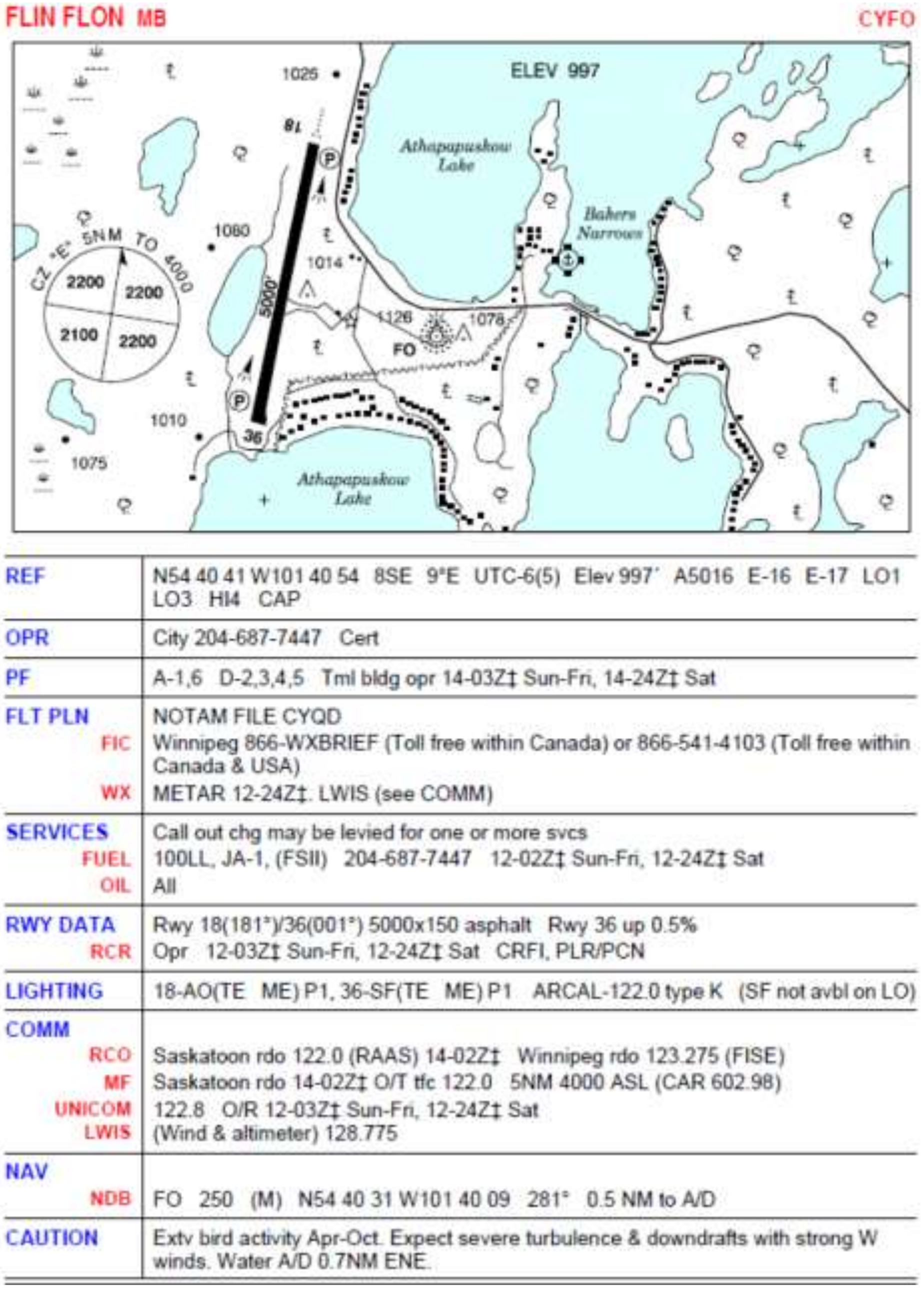


Figure 2. Priority and potential focus areas to guide mission planning for lidar transects, as defined by CFS (Wulder).

Criteria for the transect sampling campaign were to sample as much of the prioritized area as possible by flying north and south across the boreal zone whilst tracking east to west and back. The broad limitation was to perform the data collection between June to September and to keep the total flying time to around 100 hrs. In initial discussions it was also indicated that >=5pts/m^2 was desired. The location and route of planned survey lines was determined by the proximity of suitable airports to the priority area and the distances between them. Furthermore, planned routes were to fly along the NFI (National Forest

Inventory) grid where possible to ensure correspondence between these forestry datasets. It was a priori known that planned flight lines might not correspond exactly with actual as surveyed flight lines due to weather (low cloud, rain, thunder storms, high turbulence), fire/smoke, air traffic, restricted air space and technical glitches on the aircraft or the ALTM (Airborne Laser Terrain mapper). Nonetheless, the survey plan needed to be realistic and achievable under ideal conditions.



FLIN FLON MB **CYFO**

REF	N54 40 41 W101 40 54 8SE 9°E UTC-6(5) Elev 997' A5016 E-16 E-17 LO1 LO3 HI4 CAP
OPR	City 204-687-7447 Cert
PF	A-1,6 D-2,3,4,5 Tml bldg opr 14-03Z‡ Sun-Fri, 14-24Z‡ Sat
FLT PLN	NOTAM FILE CYQD
FIC	Winnipeg 866-WXBRIEF (Toll free within Canada) or 866-541-4103 (Toll free within Canada & USA)
WX	METAR 12-24Z‡. LWIS (see COMM)
SERVICES	Call out chg may be levied for one or more svcs
FUEL	100LL, JA-1, (FSII) 204-687-7447 12-02Z‡ Sun-Fri, 12-24Z‡ Sat
OIL	All
RWY DATA	Rwy 18(181°)/36(001°) 5000x150 asphalt Rwy 36 up 0.5%
RCR	Opr 12-03Z‡ Sun-Fri, 12-24Z‡ Sat CRFI, PLR/PCN
LIGHTING	18-AO(TE ME) P1, 36-SF(TE ME) P1 ARCAL-122.0 type K (SF not avbl on LO)
COMM	
RCO	Saskatoon rdo 122.0 (RAAS) 14-02Z‡ Winnipeg rdo 123.275 (FISE)
MF	Saskatoon rdo 14-02Z‡ O/T tfc 122.0 5NM 4000 ASL (CAR 602.98)
UNICOM	122.8 O/R 12-03Z‡ Sun-Fri, 12-24Z‡ Sat
LWIS	(Wind & altimeter) 128.775
NAV	
NDB	FO 250 (M) N54 40 31 W101 40 09 281° 0.5 NM to A/D
CAUTION	Extv bird activity Apr-Oct. Expect severe turbulence & downdrafts with strong W winds. Water A/D 0.7NM ENE.

Figure 3. Page copied from Transport Canada Flight Supplement illustrating airport information used for mission planning purposes. The most critical requirements being an asphalt runway exceeding 3,500' in length and 100LL fuel services.

All route planning was initially performed in ArcMap using the provided priority areas and the airports database from the Transport Canada Flight Supplement (an example of which is provided in Figure 3). For an airport to be suitable, it needed to meet the following criteria:

1) Have a long enough runway for a fully laden Piper Navajo to land and take off (>3,500’);
2) Suitable airports were identified to query airports with suitable runway lengths The runway surface material needed to be asphalt or concrete, as the survey plane had two bladed propellers which are longer than three bladed propllors and given it is a low wing monoplane, there is a high risk of damaging the props with flying gravel/earth and/or having debris enter into the aircraft through the survey window and potentially damage the ALTM.
3) Airport services need to provided aviation fuel for a regular piston engine (100LL);
4) Finally, airport locations were checked for accommodation facilities should there be a need to stay.

The NFI plot database was also brought into the ArcMap project to assist in precisely locating the planned flight trajectory. Polyline shape files were drawn to represent optimal routes between suitable airports. The routes were chosen to meet the following criteria:

1) Using an estimated velocity of 150knts, the planned route distance needed to be kept to a maximum endurance of 4.5 hrs minus a 45 minute margin for safety. This resulted in an upper limit line length of ~ 1000 km between airports for each leg;
2) Routes needed to make east to west progress but attempt to represent the north to south gradient of forest conditions with the priority area; i.e. the route needed to zig zag across the country;
3) The total line lengths should not exceed an on survey time of approximately 100 hours based on budgetary limitations;
4) Planned survey routes needed to fly over as many NFI plots (and ecomonitor sites) as convenient;
5) Routes should avoid restricted airspace (if known) such as military bases and airport control zones.

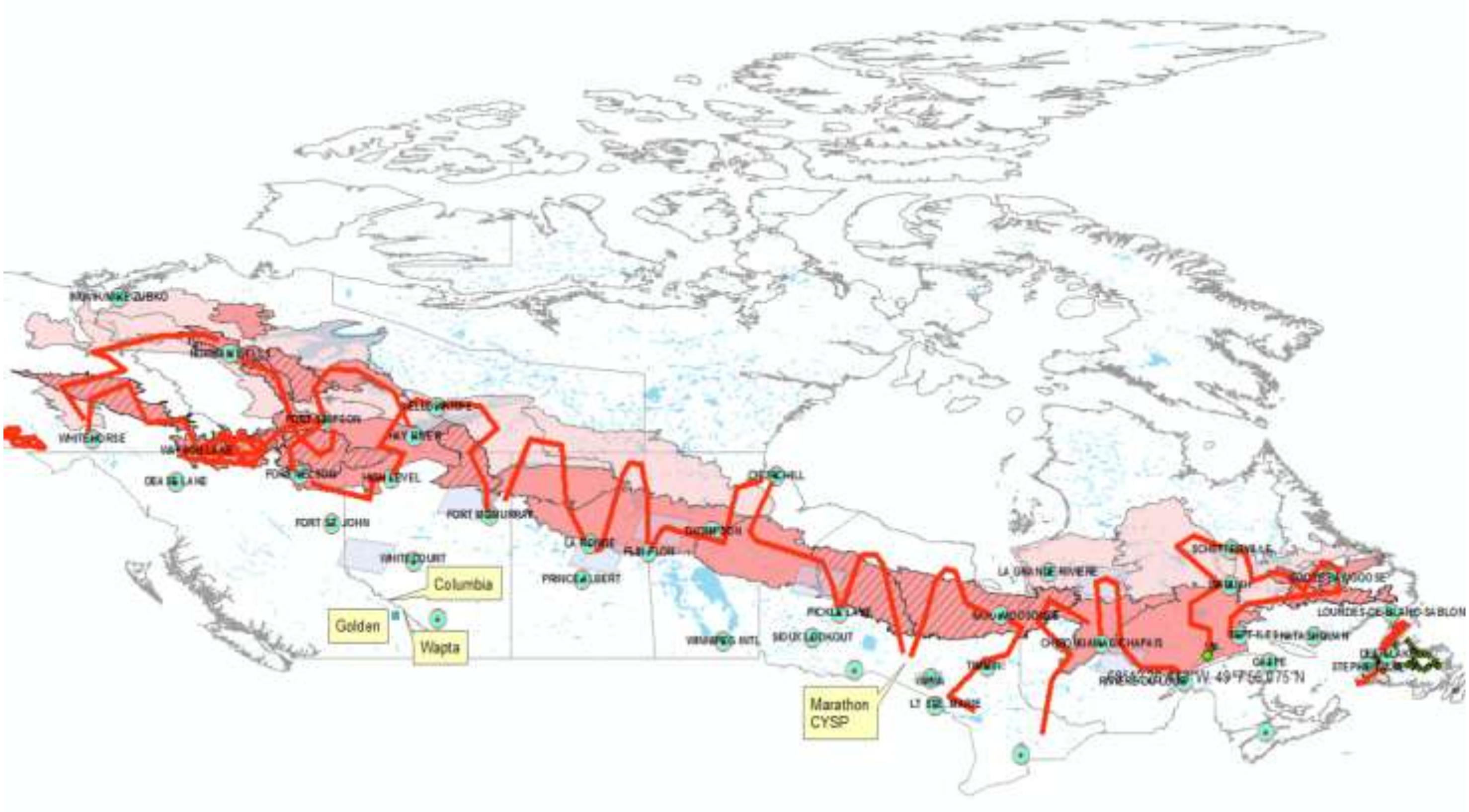
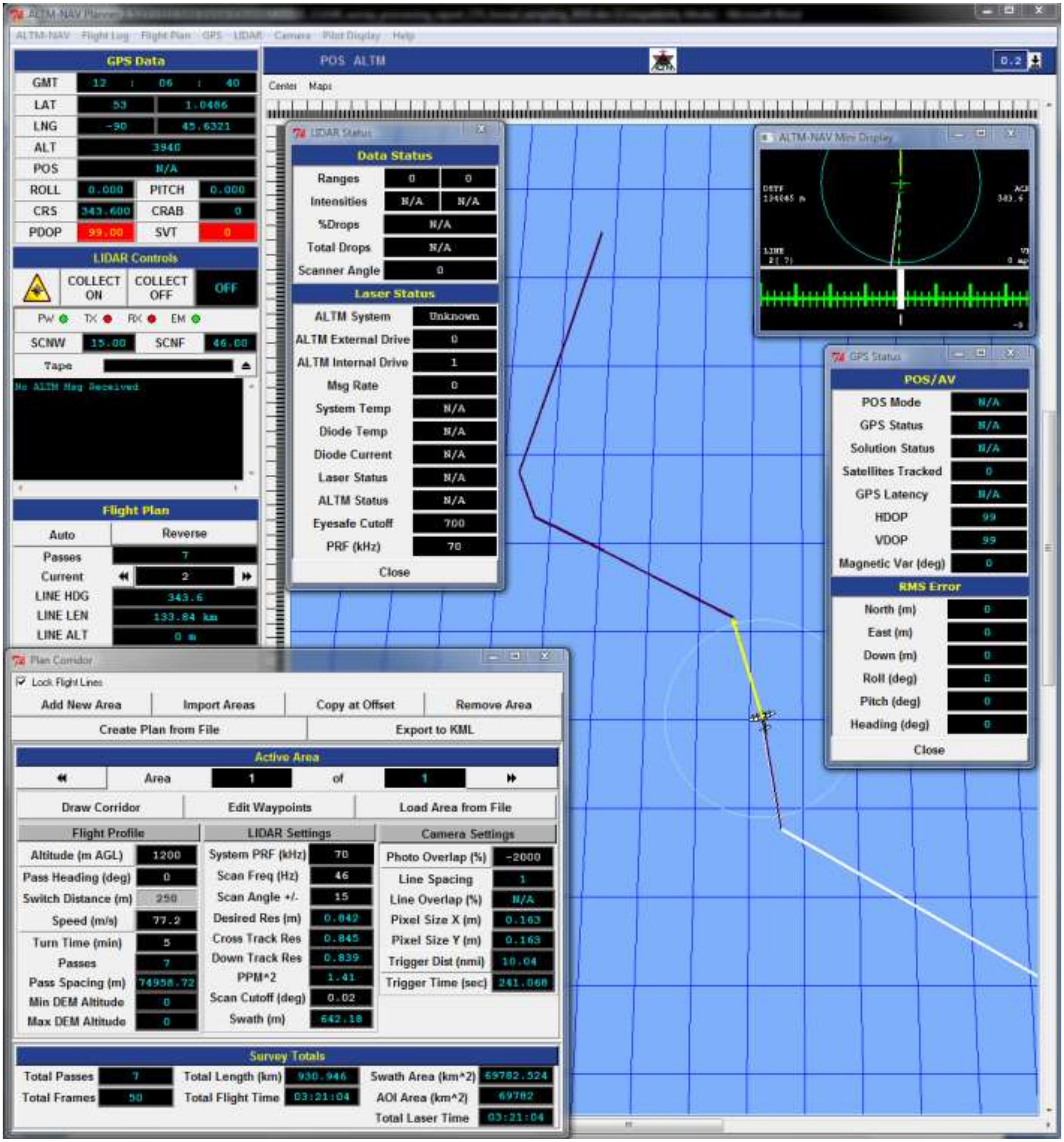


Figure 4. Planned survey transects (red lines) across the prioritized boreal forest area of interest (priority increasing from light to dark pink to cross hatched ecozones). Airports meeting suitability criteria are illustrated as blue/red circles.

The shape file routes (Figure 4.) meeting these criteria were imported into the ALTM Nav Planner software (Optech, Ontario) to generate route waypoints and then optimal survey parameters were entered (Figure 5). The process of route selection was iterative, as once a route across the country had been defined, it needed to be entered into the survey planning software to calculate actual flying times. Once total times were available, this guided the decision to either extend or reduce the length of some legs, as appropriate. Once created, the planned survey legs were exported to Google earth for sharing amongst the team and to facilitate near real time comparisons between actual and planned flight data.

As a backup, the aircraft had its own GPS navigation system. A script was developed by Neville Crasto (a grad student of Hopkinson's and member of the survey team) that converted ALTM Nav planner files to the Garmin GPS file format required by the aircraft aviation GPS Navigation receiver. This provided a backup that would have enabled continued data collection should anything happen en route that required manual firing of the ALTM without the benefit of the operations laptop. All aviation charts covering the route were obtained and checked for additional aviation specific information about hazards and features en route.



GPS Data

GMT 12 : 06 : 40
LAT 53 1.0486
LNG -90 45.6321
ALT 3940
POS N/A
ROLL 0.000 PITCH 0.000
CRS 343.600 CRAB 0
PDOP 99.00 SVT 0

LIDAR Controls

OFF
SCNW 15.00 SCNF 46.00
Tape

```
No ALTM Msg Received
```

Flight Plan

Passes 7
Current 2
LINE HDG 343.6
LINE LEN 133.84 km
LINE ALT 0 m

LIDAR Status

Data Status

Ranges 0 0
Intensities N/A N/A
%Drops N/A
Total Drops N/A
Scanner Angle 0

Laser Status

ALTM System Unknown
ALTM External Drive 0
ALTM Internal Drive 1
Msg Rate 0
System Temp N/A
Diode Temp N/A
Diode Current N/A
Laser Status N/A
ALTM Status N/A
Eyesafe Cutoff 700
PRF (kHz) 70

GPS Status

POS/AV

POS Mode N/A
GPS Status N/A
Solution Status N/A
Satellites Tracked 0
GPS Latency N/A
HDOP 99
VDOP 99
Magnetic Var (deg) 0

RMS Error

North (m) 0
East (m) 0
Down (m) 0
Roll (deg) 0
Pitch (deg) 0
Heading (deg) 0

Plan Corridor

☑ Lock Flight Lines

Active Area

Area 1 of 1

Flight Profile		LIDAR Settings		Camera Settings	
Altitude (m AGL)	1200	System PRF (kHz)	70	Photo Overlap (%)	-2000
Pass Heading (deg)	0	Scan Freq (Hz)	46	Line Spacing	1
Switch Distance (m)	250	Scan Angle +/-	15	Line Overlap (%)	N/A
Speed (m/s)	77.2	Desired Res (m)	0.842	Pixel Size X (m)	0.163
Turn Time (min)	5	Cross Track Res	0.845	Pixel Size Y (m)	0.163
Passes	7	Down Track Res	0.839	Trigger Dist (nmi)	10.04
Pass Spacing (m)	74958.72	PPM^2	1.41	Trigger Time (sec)	241.068
Min DEM Altitude	0	Scan Cutoff (deg)	0.02		
Max DEM Altitude	0	Swath (m)	642.18		

Survey Totals

Total Passes	7	Total Length (km)	930.946	Swath Area (km^2)	69782.524
Total Frames	50	Total Flight Time	03:21:04	AOI Area (km^2)	69782
				Total Laser Time	03:21:04

Figure 5. Screen grab of ALTM Nav route planning, sensor and flight configuration software. The flight survey configuration illustrated is that for the transect from Pickle lake, Ontario to Churchill, Manitoba. Due to real time changing conditions, this transect (like most) was not acquired exactly according to plan.

Based on the need for multiple returns per square meter for subsequent lidar metric modeling, the optimal flying altitude above ground level was limited to less than 1500m using a nominal PRF of 70kHz. Furthermore, due to the desire for uniform sampling geometry and high canopy penetration, the optimal scan angle needed to be kept below 15 degrees. These operational requirements provided strict limits on the flying envelope that were not ideal from a regular transit perspective. Normally, when flying long transits in remote areas, the plane would fly higher to increase fuel efficiency and endurance, while increasing the margin of safety should a malfunction occur mid air.

It was a priori known that it would be impossible to stick to the optimal survey route or configuration, as weather would force the plane to fly lower or to divert around rain showers/storm cells, and high relief terrain would be impossible to follow. Consequently, the optimal parameters were used as a guide only. If terrain relief dictated, the PRF would be dropped to 50kHz to enable range collection when altitude locally exceeded 1600m agl. While scan width would never decrease, in cases where cloud ceilings forced the plane to fly low to the ground, the scan width would be widened to ensure an adequate swath at ground level. Under both compensation scenarios, the scanner oscillation frequency would be optimized to mitigate the x and y point spacing variability.

Below is the optimal survey configuration and decision criteria for all transect sampling flights unless safety is compromised or otherwise impossible due to unforeseen reasons.

All CFS transects were planned using the following optimal parameters:

PRF = 70kHz
Altitude ~ 1200 (metres above ground level)
Scan angle ±15º
~3 multiple returns per m^2

The following guidelines to be followed if the above survey parameters were not possible:

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.

While the original request by CFS was for $>5pts/m^2$, this was not a practical target density using the available ALTM 3100 hardware considering the operational constraints of needing to sample the entire Boreal Forest within around 100 hrs of acquisition time. To fly low enough to obtain this density, while maintaining reasonable canopy sampling geometry (scan angle < 20 degrees) would have compromised flight safety, burned too much fuel and reduced the chances of overflying NFI plots due to the minimal swath at ground level. Hence, $3pts/m^2$ was considered a more realistic target. Furthermore, given the ultimate data product was to be aggregated to a 20 or 25m grid cell level to approximate field plot and Landsat TM footprint dimensions, the suggested density still ensured a minimum of 1000 points within each aggregated grid cell for subsequent lidar metric extraction. Given the statistical approach that will be adopted in modeling at the national scale, a higher density sampling is unlikely to yield improved model calibration results. Higher density could facilitate more physical modeling approaches (e.g. for ray tracing or individual stem/crown mapping applications) but the potential advantage this would provide was likely not feasible given the operational cost and downstream computing resources required at the national scale.

The final route and survey plan from airport to airport across the Boreal Forest is illustrated in Figure 4 and summarised in Table 1.

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**

Table 1. Planned survey transect illustrating the anticipated data acquisition, transit and total flight time listed sequentially from east to west across Canada. The routes associated with these legs are illustrated in Figure 4.

2. Sensor Installation

The LiDAR sensor used for the mission was an Airborne Laser Terrain Mapper (ALTM) 3100C (Figure 6) integrated with a Rollei 39MP AiC digital camera with RGB lens. The ALTM 3100, has a range in PRF of 33, 50, 70 and 100 kHz; a useful scan angle range from zero (profile) up to 30^{o} from nadir; and operational envelope of 80 m agl to 3500 m agl; and selectable narrow and wide beam divergences of 0.3 and 0.8 mRad, respectively. The 1/e laser pulse footprint diameter is approximately 1/1000 the flying altitude such that in the standard narrow beam divergence mode the footprint will have a width of approximately 30 cm at 1000 m agl. The Applied Geomatics Research Group (AGRG) obtained the ALTM 3100C through a CFI grant in 2004 to support in house research and to support national collaborative research partnerships through C-CLEAR.

Figure 6. The Optech Airborne Laser terrain Mapper (ALTM) 3100 used for the national mapping campaign.

The aircraft used for the missions was a twin engine PA31 Piper Navajo, call sign C-FEHB) (Figure 7), owned by Scotia Flight Centre (Nova Scotia) and operated by Capital Airways (Fredericton, New Brunswick). When in survey configuration, the Navajo can carry two flight crew (pilot and co-pilot), two survey crew in the rear, the ALTM / camera hardware, basic personal belongings and minimal supplemental survey equipment. For remote long distance surveys, the Navajo is not the ideal platform; especially as when in survey configuration and due to having a two bladed prop, it cannot safely land on gravel runways. However, it is far more economical than the ideal aircraft (e.g. a de Havilland Twin Otter) at about 1/3 the operational cost over equivalent ferry distances. The Navajo was just about suitable for this scale of project. A smaller aircraft could have been used but not without increasing the safety risks and significantly reducing operational capability; especially regarding payload, endurance and power requirements.

Figure 7. The PA31 Piper Navajo (C-FEHB) used for the survey missions.

The ALTM was installed in the Navajo in June, 2010, shortly before the survey flights commenced. As illustrated in Figure 8 the computer control rack is mounted in the centre of the aircraft behind the pilot seat, while the sensor head is aft above a standard camera hole. The ALTM operator (Allyson Fox for the most part) was seated behind the rack and next to the sensor head so that the hardware could be monitored. The aircraft is not pressurised and given the sensor head passes through a hole in the fuselage, cold drafts can enter into the cabin and chill the equipment, which can lead to instrument failure. Ti mitigate this, all gaps are taped and insulated. The most common hardware fault is due to cable damage. On long survey missions, where the hardware will be installed for prolonged periods, the risk of such damage is enhanced. To reduce this likelihood, all cables are routed behind the chairs, tie wrapped into bundles and taped to the floor where they cross trafficked areas.

Figure 8. The interior of the survey plane illustrating the locations of the sensor head (rear starboard side) and the control rack (centre port side). The only difference between this configuration and that used during the boreal forest missions, was that a camera control rack was mounted above the ALTM rack plus the RGB digital camera was mounted ahead of the ALTM sensor head.

Following installation, the offset between the GPS antenna mounted on the exterior fuselage of the aircraft and the sensor head is accurately measured. The process of surveying these offsets using a Total Station is illustrated in Figure 8 for a Twin Otter. This step ensures that the post-processed laser range, IMU and scanner data can be accurately registered to the trajectory of the GPS antenna.

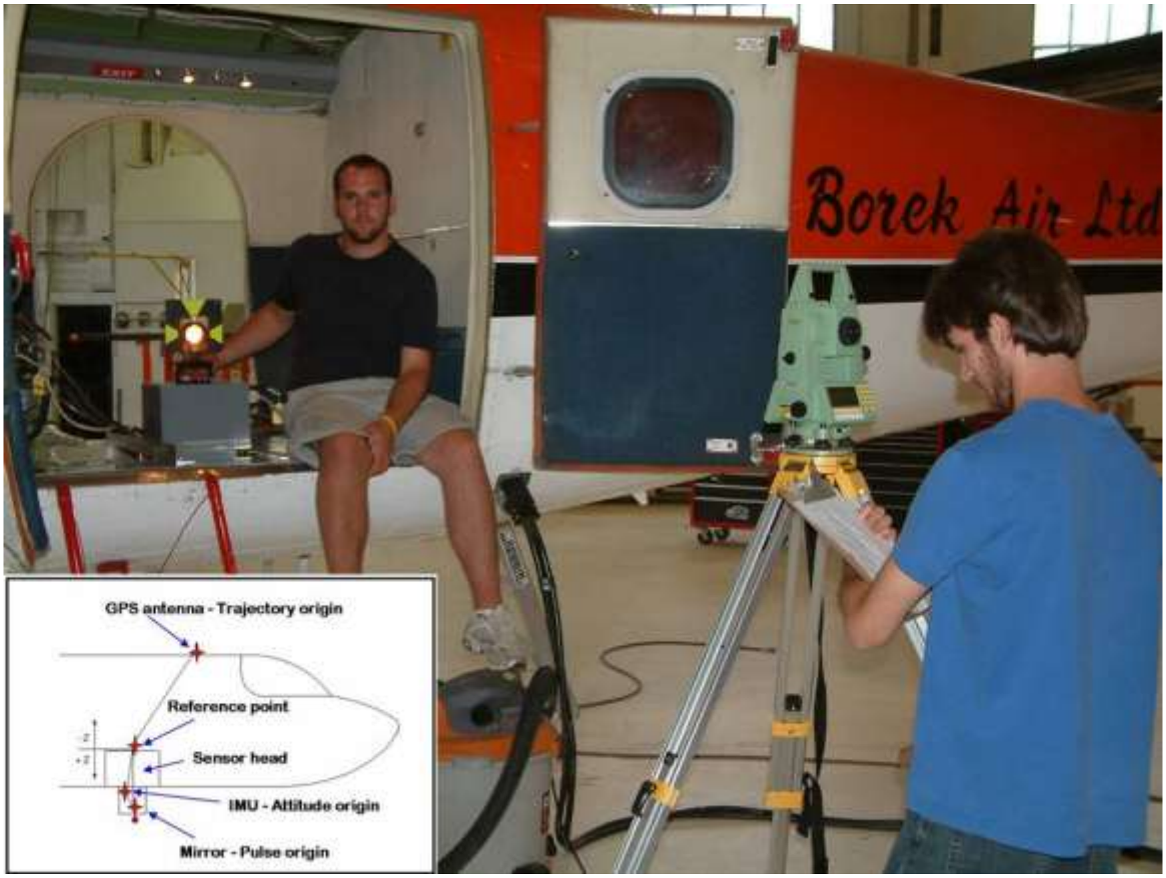


Figure 8. An example illustrating the installation of the ALTM in a Twin Otter C-GKBG survey aircraft (Kenn Borek Air – Calgary). AGRG graduate students (Pete Horne, SMU and Tristan Goulden, Dalhousie) are surveying in the GPS eccentricity offsets to register the ALTM, GPS antenna and flight axis.

3. Calibration

Before the installed ALTM can be used for survey data collection, the boresight misalignments between the IMU and laser scanner need to be ascertained. The three misalignment components (pitch, roll and heading) correspond to the three rotational axes of the aircraft in flight and are illustrated in Figure 9. In practice, these alignments are typically calibrated in systematic fashion using known targets before and after every mission, and then again for actual survey data using a statistical bundle adjustment approach. Given the data collected for this project had no overlapping swath data, there was no possibility for bundle adjustment and so system calibration over targets was the only calibration method available. This was performed in June prior to the mission and again at the end of August following the mission. Both calibrations were carried out over AGRG's previously surveyed bldg and runway targets in the Annapolis Valley.

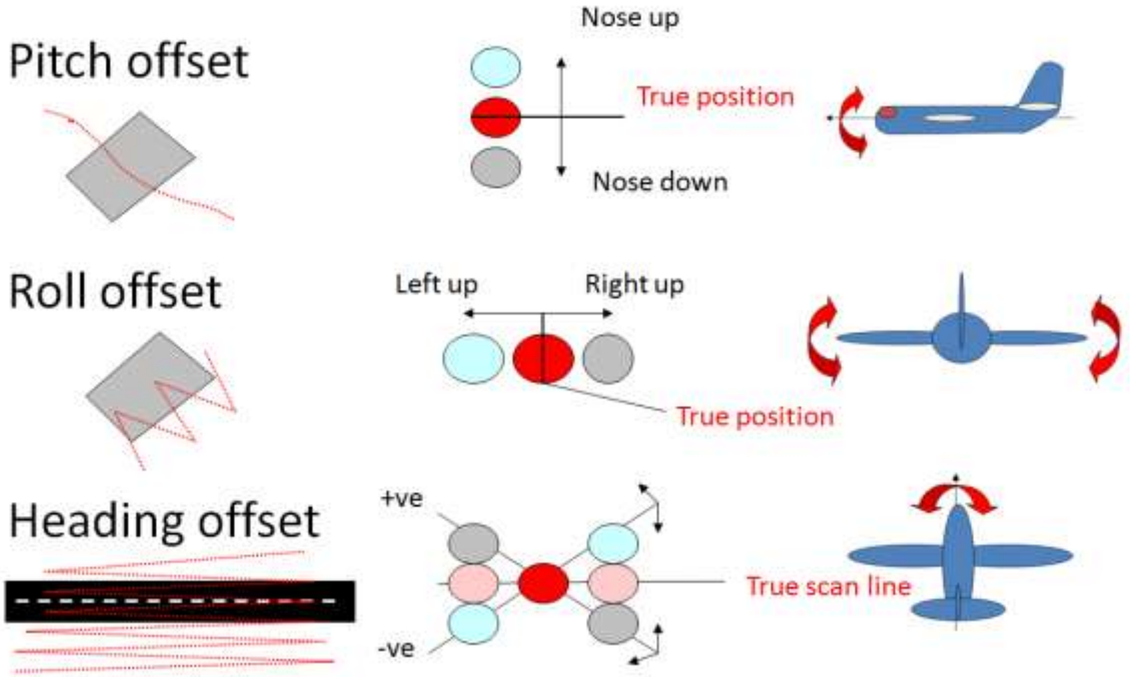


Figure 9. Boresight misalignments that must be calibrated prior to a following each survey mission. Pitch and roll are calibrated over building edges, while heading along a runway edge.

A fourth element of standard system calibration is scanner scale factor. This is a multiplication factor of the observed scan angle to account for any drift or wear in the electro-optical scanner mechanism. Pitch and roll misalignments are calibrated by aligning observed laser point data with known building edge break lines (in our case, the Middleton Campus building). Heading and scale factor are calibrated over the surveyed Waterville Runway, the airport from which we operate locally in the Annapolis Valley. Heading is calibrated by aligning the edge of surveyed runway target with the observed interface between the grass and asphalt runway in the intensity data. Any heading offset will manifest as a positive offset at one end of the runway and a negative offset at the other. A perfect heading calibration will display no offset (a uniform offset will indicate that heading is correct, while pitch is incorrect). Scanner scale factor is calibrated using the surveyed runway elevation data. If the scale factor is too high, this will elevate the point cloud at the edges of the scan relative to the runway control surface, or if the scale factor is too low, the point cloud elevations will be lower than the target surface. Scale factor is calibrated when there is no bias along the full width of the scan (a positive bias at one end and a negative bias at the other indicates there is a roll calibration error).

The ALTM was assumed to be operating well within calibration for the full duration of the mission, as none of the boresight misalignment or scale factor parameters displayed any significant difference between the June and August calibration runs.

4. Data Collection

Over a period of 67 days from June 14th to August 20th, 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° W, UTM zone 21) in the east to the Yukon (138° W, UTM zone 8) in the west. 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° N and 65° N. Survey flights ranged from one to five hours in duration, averaging three hours and 700km 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 aircraft maintenance and servicing at Fredericton, Calgary and Yellowknife airports. The lidar sampling transects are illustrated in Figure 10 and data collection summary is provided in Table 2.

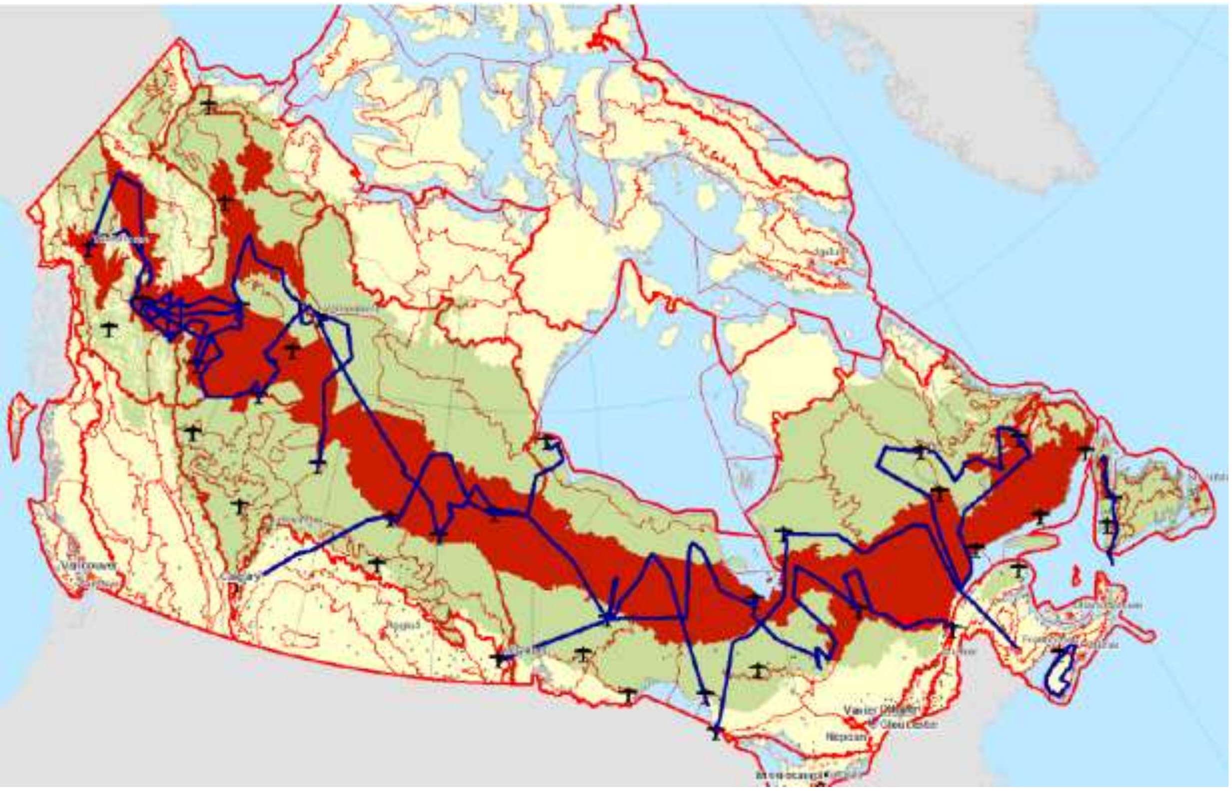


Figure 10. The final lidar sampling transect locations across Canada's Boreal Forest.

The planned flight parameters for ideal survey conditions were: a) a flying altitude of 1200 m agl; b) a velocity of 150knts; c) a pulse repetition frequency (PRF) of 70 kHz; d) a scan angle of ± 15°; and a nominal multiple return density of ~2.82pts/m^2. Due to adverse weather, high relief, excessive fire and smoke activity, restricted airspace, deviations from this 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. 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 often increased despite adjusted scan angles. Where variable terrain relief demanded a reduction in PRF, data density has decreased.

		Survey Flights				**Config**			**Notes:**
Transect	**Sections**	**JD**	**Objective**	**Province**	**Flying hrs**	**Alt (m agl)**	**PRF (kHz)**	**scan (deg)**	
		165	Transit	NB - NS	0.9				
		165	Calibration	NS	2.0				Photo calibration
		166	Calibration	NS	2.4				Laser calibration
NS_Test	1	167	Test transect	NS	3.8	1000-1300	70	15	POS data gaps
		169	Transit	NS - QB	2.3				
T01	1	171	Baie Comeau - Goose bay	QB / NFL	3.4	1000-1200	70	15	POS data gaps
T02	3	172	Goose bay - Schefferville	QB / NFL	3.2	900-1300	70	15/20	POS data gaps / Nav crash
T03	1	172b	Schefferville - Baie Comeau	QB / NFL	3.7	900-1400	70	15	Lots of turbulence
		173	Transit	QB - NB	1.5				
		173b	Test flight	NB	0.9				Troubleshooting GPS / IMU hardware
		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	Low ceilings, poor weather
T05	1	192	NW Newfoundland	NFL	1.9	600-1200	70	15/20	Low ceilings, poor weather
		200	Transit	NS - QB	2.0				Poor weather, no surveys
T06	2	201	Riviere du loop - Chibougamau	QB	3.3	450-1250	70	15	Low ceilings/restricted airspace forced plane down/divert, poor weather
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	Nav crash mid survey
T09	2	203b	Moosonee - Pickle lake	ON	4.1	1000-1300	70	15	Rain showers / diversion in flight plan
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	Low ceilings, poor weather
T12	1	204b	Winnipeg - Thompson	MB	2.6	700-1150	70	15	Low ceilings
T13	3	205	Thompson - La Ronge	MB / SK	3.2	600-1050	70	15	Low ceilings/smoke
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				No data on transit due to poor visibility
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	Low ceilings / smoke
T18	6	212	Ft Nelson - Whitehorse	BC / YK	4.4	1200-1500	50	15	Hilly terrain/ fires around Watson lake/ excessive smoke / runway closed
T19	1	213	Whitehorse - Watson Lake	YK	3.8	1050-1600	50	15	Hilly terrain / lots of smoke
T20	2	213b	Liard ecozone loop (Watson lake)	YK	3.2	900-1900	50	15	Hilly terrain / lots of smoke
T21	3	214	Watson Lake - Ft Simpson	YK / NWT	2.0	600-1800	70/50	15/20	Hilly terrain / low visibility
T22	3	214b	Ft Simpson south loop	NWT	0.9	1400-1500	50	20	
T23	2	214c	Ft Simpson - Watson Lake **(plots)**	NWT / YK	1.9	900-1900	70/50	15	Hilly terrain / low visibility
		215	Aborted	YK	0.2				Aborted due to local fires/smoke
T24	4	215b	Watson Lake - Ft Simpson **(plots)**	YK / NWT	2.5	1200-1400	70/50	15/17	Low visibility due to haze / smoke
T25	1	215c	Ft Simpson - Yellowknife	NWT	3.6	1200-1300	70	15	diverted due to rain showers / haze
		216+	Aircraft service (Yellowknife)	NWT	0.0				
T26	2	218	Yellowknife - Flin Flon	NWT / MB	4.5	1200-1400	70	15	diverted due to fires / smoke
T27	1	218b	Flin Flon - Thompson	MB	2.1	1200-1300	70	15	diverted due to fires / smoke
T28	1	219	Thompson - Churchill	MB	2.0	1200-1250	70	15	POS system crash
T29	1	219b	Churchill - Thompson	MB	2.3	1000-1300	70	15	High winds / turbulence
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	Low ceilings / rain showers
T32	3	223	Sioux Ste Marie - La Grand Riv.	ON / QB	3.7	1000-1400	70	15	Ground fog / low ceilings in places
T33	4	223b	La Grande Riviere - Fredericton	QB / NB	5.1	850-1400	70	15	Low ceilings / rain showers
		230	Transit	NB - NS	0.8				
		230	Calibration	NS	5.0				Photo & laser calibration
		232	Transit	NS - NB	0.9				
TOTAL		**67**			**126.7**				

Table 2. Lidar survey transect IDs, timing, flying hours, survey configuration and notes concerning problems encountered during acquisition.

The backup GPS waypoint files generated during planning were never needed for the purpose of resolving ALTM problems but the pilots did load up the backup plans along with our survey plan for each leg, to provide some redundancy. In practice, this was found to be extremely useful, as it gave the pilots more survey information than they would typically have, and enabled linkage of our survey plan with other pertinent aviation feature information accessible from their GPS receiver database. When it came to making last minute decisions in the face of deteriorating visibility or hazards in the planned survey zone, this meant that the entire flight crew was adequately informed as to the route ahead and options in real time. Given the remote nature of the surveys and the hazardous weather and terrain conditions encountered, these elements of contingency proved highly valuable and reassuring. Another ‘old school’ backup in our possession was two sets of up to date hard copy Canadian aviation charts and flight supplements.

The GPS backup, the charts and additional supplement information came in very useful on several occasions, as there were indeed some quite frantic instances in the plane. For example, on occasion, we were up to 90 minutes from a suitable airport only to encounter unforecasted rapidly deteriorating visibility that forced last minute decisions regarding staying on route or aborting/diverting for the sake of safety. This was no minor issue, as whilst on survey, we heard of three aircraft crashes causing fatalities in the general area where we were operating. One of these was a water bomber fighting the fires we were trying to avoid, and another was a private pilot flying into Ft Simpson on the same day we were there. Needless to say, such occurrences led to a certain amount of apprehension for some members of the crew (not least the pilot!)

Several challenges were encountered during the execution of this project. Weather has been highlighted above but this was to be expected. However, fire activity in the Boreal Forest during July and August of 2010 was unusually high and this directly impacted up to 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. The usual ‘gremlins’ associated with high tech were frequently encountered causing minor hardware and software malfunctions that required frequent troubleshooting. One problem that plagued early missions was an erratic GPS data gap error. After extensive troubleshooting, it was found that corroded ground terminals on a radio antenna were causing a ground loop that passed unfiltered signals into the GPS antenna, thus masking out satellite signal. A further logistical challenge encountered was concerning the reliability or currency of data contained with the latest Transport Canada Flight Supplement. On three occasions, information concerning fuel and service availability was found not to represent the true situation. All such challenges were to be expected on a project of this scale but they emphasise the necessity of adaptability and planned contingency; i.e. one cannot enter into a project of national scope and covering remote parts of Canada and assume everything will go to plan.

5. Trajectory Processing

Preliminary trajectory and point integration processing was carried out while in the field to ensure no major problems and that the sensor was functioning correctly. All final data processing stages were conducted back at the lab in Nova Scotia.

After download and archival of raw data files from the sensor (Range = laser scanner data and POS = GPS and IMU data), the first data processing task is to compute the smoothed best estimated trajectory (sbet) containing both position (GPS) and orientation (IMU) information. The onboard GPS receiver (Trimble BD9500) collects real time GPS signals at 1Hz for the antenna location on top of the aircraft. Meanwhile, multi-axial aircraft accelerations and attitude shifts are recorded at 200Hz at the 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. Several options are available for this data processing step, as illustrated in Figure 11.

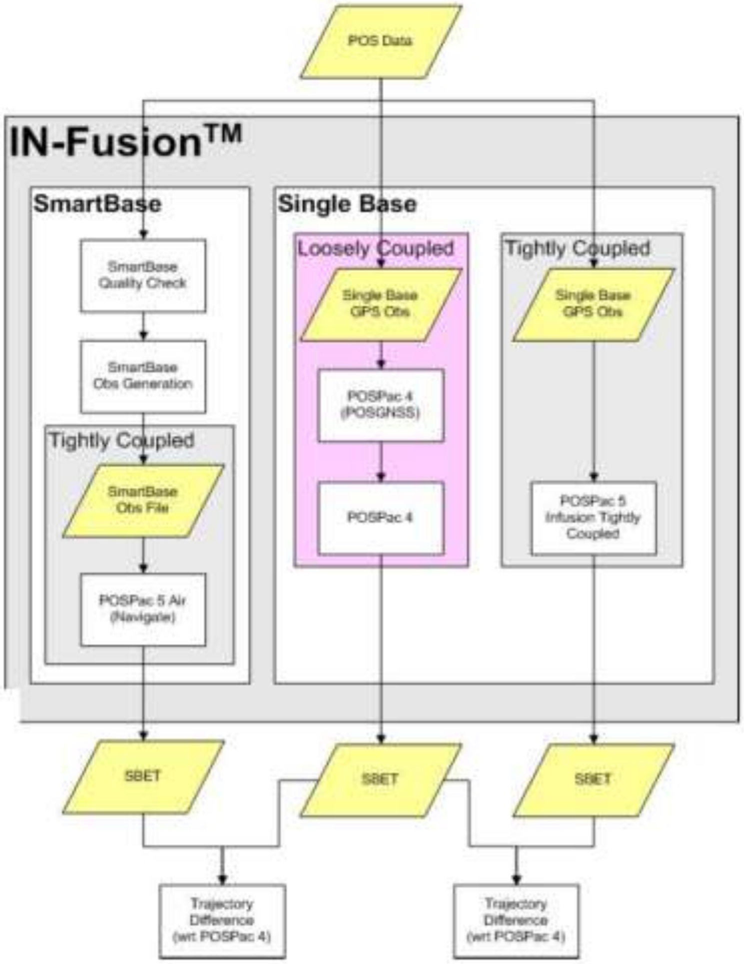


Figure 11. Trajectory (sbet) processing options within Applanix POS MMs software (multi base option not shown).

The software used for the sbet processing was POS MMs v5.3 (Applanix Corp., Ontario). 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 some nearby US continuously operating reference station (CORS) data enabled reasonably accurate differential correction of the airborne GPS trajectory using the 'Smartbase' tool with POS MMS. While the base lines were actually up to several hundred kms in some cases, this capability meant that all points on all trajectories were in fact differentially corrected to accurately known base stations such that positional errors are anticipated to be better than PPP and likely within 1m throughout.

However, given the automated nature of base station selection, download and coordinate definition using the Smartbase tool within POS MMS, this meant that all trajectories were automatically referenced to the ITRF (WGS84) reference frame, as opposed to the desired NAD83CSRS datum. Given the size of the project and number of files, and the desire for as much automation in the processing workflow as possible, this datum was used throughout. This does not introduce any error but there is a slight shift in position of up to 2m in places between WGS84 and NAD83, and this must be borne in mind for any subsequent comparative data analysis.

A unique and valuable attribute of 'tightly coupled' processing, is that both the GPS positions and the IMU attitude data are processed simultaneously, which, in theory, produces a more accurate trajectory. This was the approach adopted for all trajectories. Overall, the reported trajectory RMSEs were within 20cm. However, a cautionary note is that the RMSE computed in this software is not relative to any absolute 'truth' rather it is computed by comparing the forward and reverse trajectory before they are combined. If both initial trajectories are highly coincident, the reported RMSE will be low and assumed accuracy high. However, this is a relative measure of accuracy and there is no operational way of estimating the true level of error. Nonetheless, considering the long base lines and long trajectories containing sections of long straight lines, reported errors within 20cm are considered good for these sbets.

Following processing of the sbets, they were exported to shape files for comparison with original flight plans and subsequent post-processing. A quirk of this process that was established after all shape files had been exported was that the UTM zone was set to the start point of the trajectory, which could be a long way from the start point of data acquisition and outside the UTM zone representing most of the lidar data. This could be manually remedied by editing the zone information in ArcCatalog.

Unfortunately, of the 34 trajectories processed, one was partially lost due to data corruption during ftp file transfer from the internal POS computer hard-drive inside the ALTM. This meant that the associated laser data had no geographic reference and could not be outputted. The total loss of data amounted to between one and two hours on the final leg approaching Ft Nelson after leaving Yellowknife.

6. Points Integration

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.

The software used to integrate the laser scanner 'range' file with the previously processed sbet was Dashmap, proprietary point processing software develop by Optech Inc (Toronto, Ontario). The general points processing workflow is illustrated in Figure 12, along with the three primary software packages used in pre-processing. The range file is downloaded and decoded form the ALTM hard-drive using Optech's proprietary 'decode' software, which essentially parses the file to something that can be read into Dashmap. As discussed in the previous section, the sbet is generated using the Applanix POS MMS software. Dashmap is then used to integrate the sbet and range file, and set the points integration and output parameters. Typical user configurable processing settings are the calibration parameters (discussed in section 3), 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.

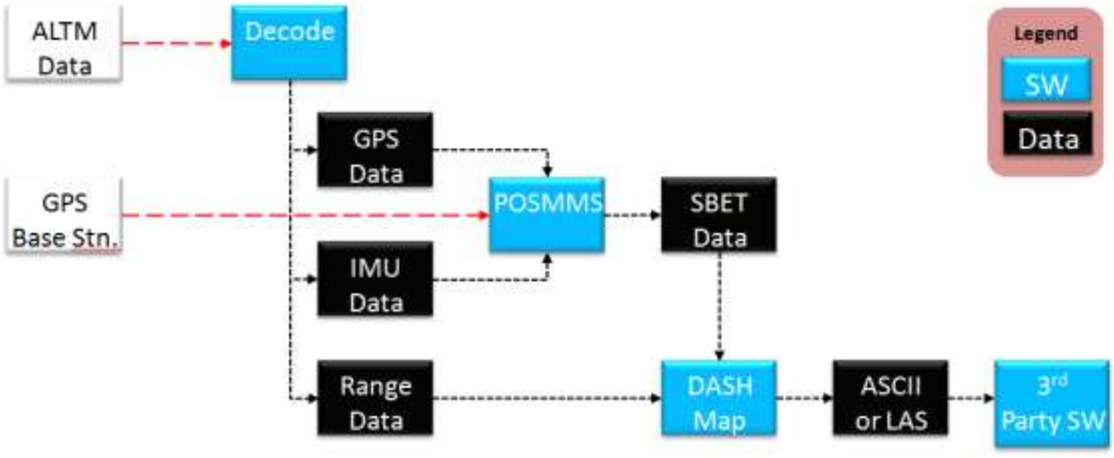


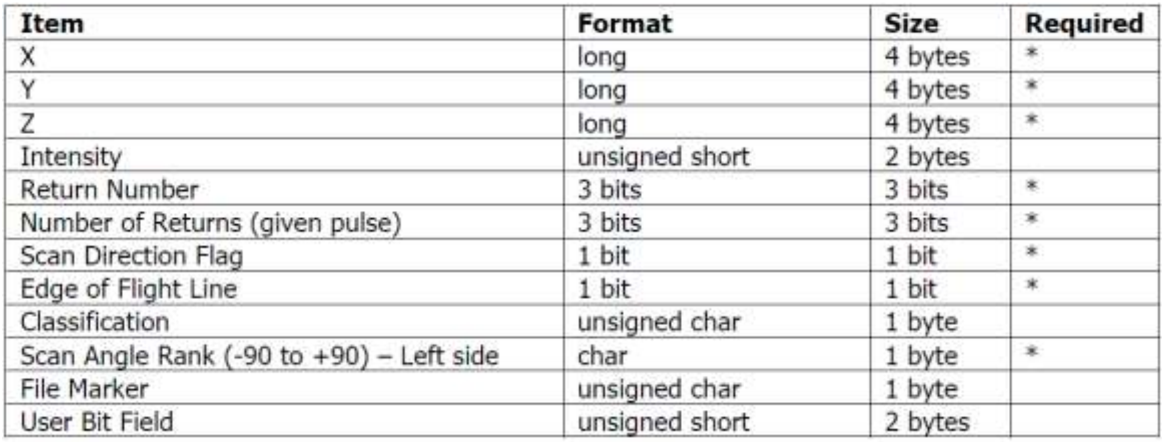
Figure 12. The ALTM proprietary pre-processing workflow. For this project, the 3rd party software used following pre-processing was the lasline tool discussed below.

7. Raw LAS file output

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. There were some challenges with UTM 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. As with the trajectory outputs, the point cloud data are referenced to the International Terrestrial Reference Frame (ITRF), which is equivalent to WGS84. This is important to note, as the Dashmap output has labelled the data as being in NAD83, and this information will be embedded in the LAS file. All elevations are provided relative to the GRS80 ellipsoid.

For each emitted laser pulse, there was the possibility of up to four measured returns (first, intermediate, last and single returns). This enables further refinement or information extraction routines to be generated that require the return class information. The echo classification, intensity and scan angle for each pulse are embedded within the LAS file. The LAS 1.0 binary format contains a public header block, variable length records and actual laser point data (see Table 3). The LAS file structure is further described on the ASPRS web site:

http://www.asprs.org/society/committees/standards/asprs_las_format_v10.pdf



Item	Format	Size	Required
X	long	4 bytes	*
Y	long	4 bytes	*
Z	long	4 bytes	*
Intensity	unsigned short	2 bytes	
Return Number	3 bits	3 bits	*
Number of Returns (given pulse)	3 bits	3 bits	*
Scan Direction Flag	1 bit	1 bit	*
Edge of Flight Line	1 bit	1 bit	*
Classification	unsigned char	1 byte	
Scan Angle Rank (-90 to +90) – Left side	char	1 byte	*
File Marker	unsigned char	1 byte	
User Bit Field	unsigned short	2 bytes	

Table 3. The LAS 1.0 binary laser point data field format.

8. 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 the ground and break the large files down into smaller manageable files of 20 million data points.

Lasline is a tool developed partially to support this project as well as an AGRG project with Nova Scotia Power to sample and inventory Provincial biomass. The tool was constructed through a sub-contract to Gaiamatics (T. Milne) under the direction of C. Hopkinson. Lasline takes raw LAS binary transect files of any size as input then runs the following operations:

1) **Data cleaning:** This involved isolating high and low laser pulse returns that either floated well above the canopy surface or penetrated well below the true ground surface. Such data errors occur due to bird strike, atmospheric vapour/clouds/aerosols, and or multi-path of the laser pulse.

2) **Ground classification:** Ground returns were classified from the point cloud using a variant of the algorithm developed by Axelsson (1999) that is also used in Terrascan. 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 is several times 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.

As part of our Provincial biomass mapping program, we are currently expanding the process to automatically output cell-level point cloud metrics (i.e. similar to FUSION). Our experience with FUSION is that the data input/output procedures could be more efficient and many of the derived cloud metrics are autocorrelated and thus unusable for multivariate modeling. We already have in house tools that allow scripting of point output data to generate models of forest biometrics so the intent is to develop a tool set that automates the workflow from raw LAS binary files all the way to final forest attributes ready for input to GIS. Beta versions of these tools are anticipated by summer 2011.

9. Final LAS file output

Following post-processing of the 69 LAS master files, 1017 LAS sub files were created containing a total of approximately 20 billion data points. A summary of the processing steps and data file attributes is provided in Table 4.

Transect	**Data hrs**	**Lidar Processing**					**UTM Zone**		**Notes:**
		Trajectory export	**Range file**	**Lasline output**	**Total Size (GB)**	**# files**	**LAS file**	**Trajectory shape file**	
NS_Test	3.5	**Y**	**Y**	**Y**	17.8	35	20	20	
T01	3.1	**Y**	**Y**	**Y**	18.2	35	20	20	
T02	2.9	**Y**	**Y**	**Y**	16.8	33	20	20	
T03	3.4	**Y**	**Y**	**Y**	22.2	43	19	19	
T04	1.3	**Y**	**Y**	**Y**	3.4	7	21	21	
T05	1.6	**Y**	**Y**	**Y**	8.7	17	21	21	
T06	3.0	**Y**	**Y**	**Y**	18.4	37	19	18	
T07	3.7	**Y**	**Y**	**Y**	22.2	44	18	18	
T08	1.8	**Y**	**Y**	**Y**	8.1	17	17	17	
T09	3.8	**Y**	**Y**	**Y**	22.3	43	16	16	
T10	1.4	**Y**	**Y**	**Y**	8.7	17	15	16	
T11	1.7	**Y**	**Y**	**Y**	7.1	15	15	15	
T12	2.3	**PARTIAL**	**Y**	**PARTIAL**	10.8	21	14	14	Trajectory problems - lost southerly PCS files
T13	2.9	**Y**	**Y**	**Y**	17.5	36	14	13	
T14	2.7	**Y**	**Y**	**Y**	15.3	30	12	12	
T15	2.9	**Y**	**Y**	**Y**	20.3	40	12	12	
T16	2.2	**Y**	**PARTIAL**	**PARTIAL**	9.6	20	11	11	Southern extent lost - range file corruption
T17	2.7	**Y**	**Y**	**Y**	21.3	42	10	10	
T18	4.1	**Y**	**Y**	**Y**	21.7	45	9	9	
T19	3.5	**Y**	**Y**	**Y**	17.1	33	8	8	
T20	2.9	**Y**	**Y**	**Y**	16.7	33	9	9	
T21	1.7	**Y**	**Y**	**Y**	10.0	21	9	10	
T22	0.6	**Y**	**Y**	**Y**	1.7	4	10	10	
T23	1.6	**Y**	**Y**	**Y**	9.9	20	9	10	
T24	2.2	**Y**	**Y**	**Y**	13.5	28	9	10	
T25	3.3	**Y**	**Y**	**Y**	21.0	41	11	10	
T26	4.2	**Y**	**Y**	**Y**	18.8	38	12	13	
T27	1.8	**Y**	**Y**	**Y**	11.4	22	14	14	
T28		**X**	**Y**	**X**	na	na	15	15	Trajectory lost - corrupt PCS file
T29	2.0	**Y**	**Y**	**Y**	8.7	17	15	15	
T30	2.6	**Y**	**Y**	**Y**	16.9	33	15	15	
T31	4.5	**Y**	**Y**	**Y**	27.0	54	16	16	
T32	3.4	**Y**	**Y**	**Y**	17.3	35	17	17	
T33	4.8	**Y**	**Y**	**Y**	30.5	61	19	19	
TOTAL	**90.1**				**510.9**				

Table 4. Data attributes and processing summary, illustrating processing steps, file sizes, file number, geographic location and any major problems encountered during processing.

A note on C-CLEAR research collaboration:

The ALTM used for this study, was acquired under a 2 million dollar CFI grant awarded to the AGRG (Drs Maher and Hopkinson) to support both AGRG research and to develop a national research consortium through C-CLEAR (The Canadian Consortium for LiDAR Environmental Applications Research). As such, we are able to provide these lidar research support services on a non profit basis, thus allowing our research partners to access lidar data at a fraction of the commercial cost (typically 5% to 20%). We respectfully request that our research collaborators understand the significant effort that goes into building, maintaining and funding this consortium effort for the benefit of the Canadian research community. And further, to appreciate the time commitment involved in the mission planning, data collection and data processing and follow up assistance with analysis and the development of research questions.

We are not a service provider and do not compete with the lidar industry. We are also not a charity. Our motivation, like all academics, is to do research and to educate. As such, we expect that supporting these collaborative research initiatives will result in co-authorship on journal publications. After all, like all academics, we must compete for funding, and if our time is spent on supporting the research of others, this takes time away from our own independent research activities. If these efforts do not result in publications for the AGRG research staff and graduate students supporting them, then we appear to be academically unproductive and this reduces our ability to continue to support the research community.

Thank you for the opportunity to assist you and be involved in your research activities.

Enjoy ☺

Acknowledgements

Above: Gary and Jean-Louis piloting the Navajo over mountains in western Canada. Below: Allyson Fox operating the ALTM somewhere between Watson and Whitehorse.

Allyson Fox, lidar operations (AGRG/Acadia research associate / graduate student); Heather Morrison, field support (AGRG/Acadia graduate student); Neville Crasto, field and planning support (AGRG/Acadia graduate student); Tristan Goulden, field support (AGRG/Dalhousie graduate student); Gary Noel, pilot (Scotia Flight Centre); Jean-Louis Arsenault, co-pilot/AME (Scotia Flight Centre); Leaon Zinck (Scotia Flight Centre); Mike Dana (Capital Airways); Debby Hebb and Brenda Vienot (AGRG admin). Funding support was provided primarily by the Canadian Forest Service but the project would not have been possible without supporting funds from the Geological Survey of Canada (Mike Demuth), University of Quebec (Benoit St Onge), and Nova Scotia Power Inc. The Canada Foundation for Innovation is acknowledged for funding the purchase of the ALTM to support AGRG and C-CLEAR research activities.