Natural Resources Canada
Ressources naturelles Canada

GEOMATICS CANADA
OPEN FILE 32

# Assessment of UAV-based photogrammetry for snow-depth mapping: data collection and processing

**R.A. Fernandes, F. Canisius, S.G. Leblanc, M. Maloley, S. Oakes, C. Prévost, and C. Schmidt**

**2017**

Canada

**GEOMATICS CANADA**
**OPEN FILE 32**

# Assessment of UAV-based photogrammetry for snow-depth mapping: data collection and processing

**R.A. Fernandes, F. Canisius, S.G. Leblanc, M. Maloley, S. Oakes, C. Prévost, and C. Schmidt**

**2017**



doi: 10.4095/300553

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

**Recommended citation**
Fernandes, R.A., Canisius, F., Leblanc, S.G., Maloley, M., Oakes, S., Prévost, C., and Schmidt, C., 2017. Assessment of UAV-based photogrammetry for snow-depth mapping: data collection and processing; Geomatics Canada, Open File 32, 50 p. doi: 10.4095/300553

Publications in this series have not been edited; they are released as submitted by the author.

## Contents

List of Figures

List of Tables

# 1 Introduction

Snow depth (SD) is defined as the vertical distance from the snow surface to the underlying surface (ground, glacier ice or sea ice) (World Meteorological Organization, http://www.wmo-sat.info/oscar/variables/view/206). SD information is widely used for flood forecasting, water quantity assessments, road and building safety assessment, habitat assessment, and climate studies (GCOS, 2014). SD is measured synoptically at the global level using standardized methods and equipment (WMO, 2008). In Canada, the synoptic network is supplemented by numerous regional mesonet SD measurement networks in support of flood forecasting, avalanche forecasting and hydroelectricity production and local networks related to land use such as mining, transportation and skiing.

SD measurement is typically performed using rulers, fixed stakes, or fixed near-surface (<5m above ground level) remote sensing with laser or ultrasonic technology (Lee et al. 2015). Ruler measurements have a precision of +/-0.5cm and an accuracy determined primarily by sampling design (NOAA, 2013). Lee et al. 2015 reported an instrument uncertainty between 1.33cm and 1.81cm for stakes and between 1,55cm and 2.17 for SD sensors in comparison to reference ruler. This uncertainty does not include the additional uncertainty due to the spatially limited sampling of such measurement devices or errors when reading rulers. For example, Prokop et al. (2008) used 1.5m resolution LIDAR SD measurements over 100m snow covered forested and open area transects found that uncertainty in estimating SD with a single measurement ranged from 10cm to 80cm and only dropped below 5m with ~20measurements . Current synoptic SD sampling is biased to flat open areas (for fixed sensors) and accessible areas (for manual ruler measurements) (GCOS, 2010; Gruenewald, T. and Lehning, M., 2015,).

Remote sensing measurements from airborne platforms offer a means for reducing the uncertainty due to biased and insufficient spatial sampling. These include the use of LIDAR and digital cameras to derive digital surface models (DSMs) from which SD is estimated using multi-temporal differences. Unmanned aerial vehicles (UAV) are especially attractive as they offer relatively low cost and easy to operate platforms that fly low and slow enough to provide high spatial resolution measurements with a dense spatial sampling. These systems typically acquire spatially redundant sampling of digital imagery from professional or consumer grade digital cameras. Photogrammetric algorithms (e.g. Structure From Motion , SFM, Dellaert et al. 2000) are then applied to produce a DSM.

Nolan et al. (2014) first used SFM to map SD from data acquired from an aircraft mounted professional digital camera (34 MP pixel Nikon D800E). They reported a difference of ~10cm (1 sigma) between SD from multi-date DSMs with between 6cm to 20cm ground sampling distance (GDS) and in-situ measurements. The aircraft based system was able to map regional extents but was costly and required expert operation that may not be feasible for applications such as local flood assessment. The system was also not tested in forests where the resolution may be inadequate to map SD on or under the canopy. Subsequently, there have been a number of studies evaluating the use of UAV based image acquisitions with the same DSM differencing technique (De Michele et al. 2015; Harder et al. 2016). These studies are promising since they report differences on the order of 10cm (1 sigma) compared to snow depth rulers or stakes. However the studies are not comprehensive: they both used fixed wing UAV systems that are both not as widely available as multi-rotor systems and cannot hover, they both used costly Real Time Kinematic positioning of the UAV, they used a relatively high elevation of 100m or above, a full season of acquisitions was only reported at one flat site, and most importantly no evaluation of performance with vegetation or rough micro-topography was performed.

The goal of this report is to describe the planning, acquisition and processing (to date) of UAV imagery and associated in-situ and SFM based DSMs for snow depth estimation over a range of terrain, snow and sky conditions in southern Canada. A qualitative assessment of data and derived DSM quality is performed. A subsequent phase will perform a quantitative analysis of DSM and SD retrieval as a function of land cover, snow and sky conditions.

# 2 Methods

## 2.1 Study Sites

### 2.1.1 Study Region Selection

Study regions were selected within driving distance of Canada Centre for Mapping and Earth Observation (CCMEO) headquarters in Ottawa, Canada (hereafter labelled 'Gatineau') and Fredericton, New Brunswick (hereafter labelled 'Acadia'). Sites were selected with the following constraints and criteria:

Constraints:

1. Federal government property.
2. Qualify for Transport Canada conditions for operation of a UAV less than 2kg.
3. Within 30 minutes driving distance for easy access.
4. Provide a unique land cover and terrain condition.
5. At least 1ha.

Criteria:

1. Potential to quality for operation without a special flight operation certificate (SFOC)
2. Close (<100m) from an all-weather road.
3. Ability to place permanent markers in-situ.
4. Availability of permanent locations that can serve as ground control targets.
5. Close to other sites.

The first three constraints resulted in a limited set of potential study regions. Transport Canada regulations (http://www.tc.gc.ca/civilaviation/regserv/affairs/exemptions/docs/en/2880.htm ) require operation away from controlled air space that was an issue both near Ottawa and Fredericton leading to study region selection away from the cities themselves. Figure 1 shows the final selected study regions. Most selection criteria were satisfied except for the need for an SFOC at Gatineau due to the density of built up areas close to federal lands. Study region selection was optimized for scientific activities. In practice, legal UAV surveys could be conducted over other regions, including built-up floodplains, with adequate certification.

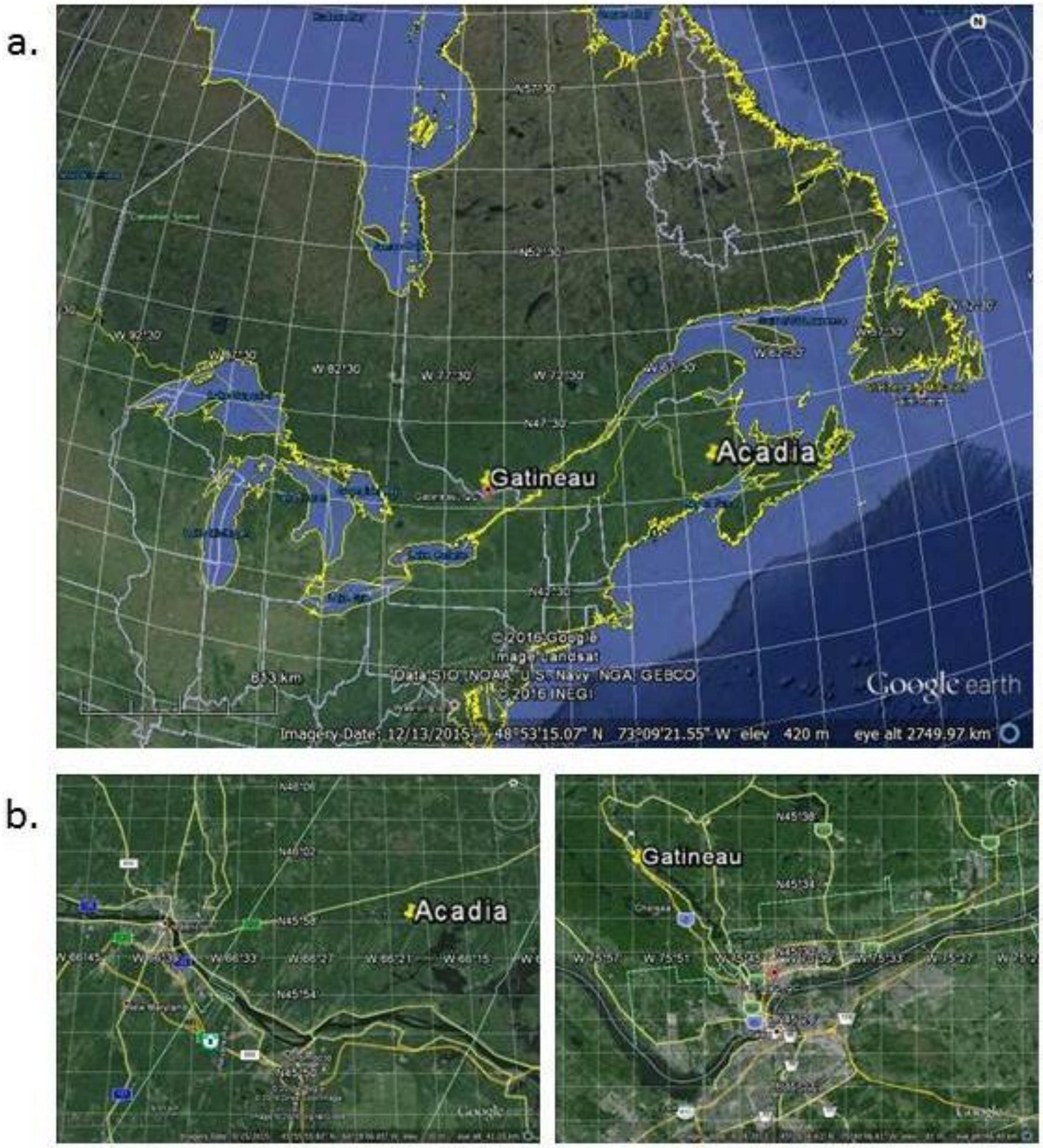


Figure 1. UAV study regions showing a) location within Canada and b) location with reference to nearby cities.

### 2.1.2 Gatineau Study Region

Gatineau, shown in Figure 2, corresponds to managed pastureland in the Southern Laurentians Ecoregion of the Boreal Shield ecozone. Native vegetation is mixed forest although the study region has been converted to pasture land use for at least 100 years. Surficial material corresponds to till overlain with humo-ferric podzols characteristic of agricultural terrain. Local topography was flat to undulating.

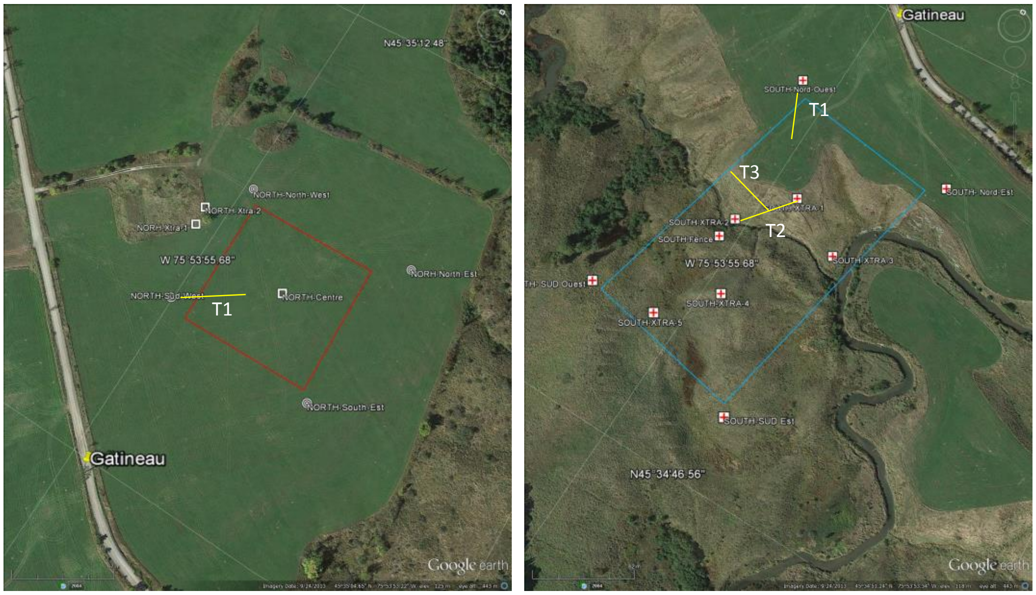


**Figure 2. Gatineau study region with two study sites, North (left panel) and South (right panel). Polygons indicate the site boundaries for SD mapping Lines indicate SD transects and makers indicate Ground control points.**

This ecoregion is characterized by warm summers and cold winters with substantial snow. Climate normals between 1981 and 2010 at the Gatineau airport ~7km from the study region, Figure 3, indicates snowfall from October until April with rain possible year round although winter rains are infrequent. As indicated in Figure 4, snow depth starts at ~2cm in November, ranges between 30 and 40cm during the winter and 0cm by the end of April. Total snowfall is 187mm/year.

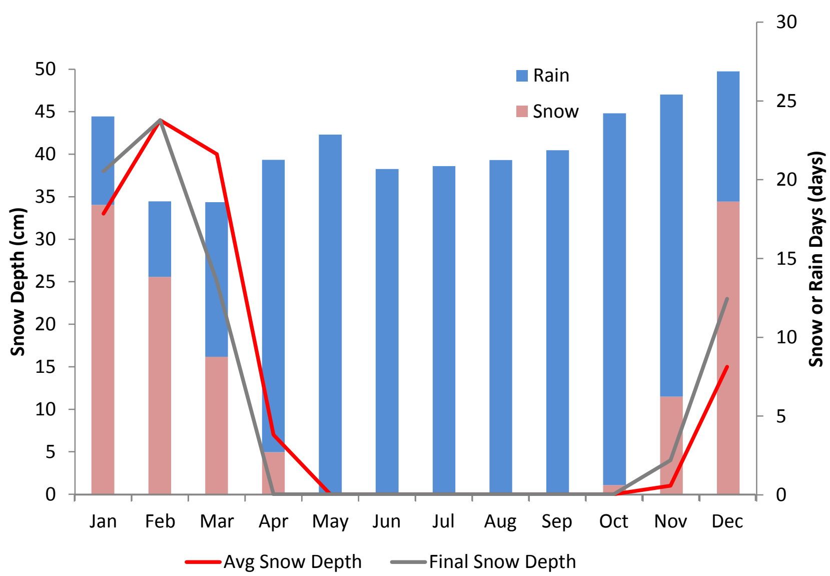


**Figure 3. Climate normal between 1981 and 2010 for snow depth and rain and snowfall days for Gatineau taken from the Chelsea, Quebec synoptic station.**

Two study sites were selected in Gatineau: North and South. The North site corresponded to a 1ha square placed in the centre of a gently sloping grass field. The site was selected to correspond to a typical climate station installation as well as to represent flat pasture land. The South site corresponded to a stream valley bounded in the north by a similar field to the North site and on the south by sparse tree cover. The site included topographic crests and hollows that should, respectively lose and gain snow due to wind redistribution and a north and south facing slope that should experience late and early melt respectively. There was substantial shrub cover (<1.35m) within a buffer of ~20m around the stream and some lower (<50m) shrub cover in the valley. Figure 4 shows winter landscape photographs of both sites taken from in-situ SD measurement transects.

North

South
Transect 1

South
Transect 2 & 3

**Figure 4. Landscape photographs of Gatineau North and South sites taken from in-situ SD transects.**

### 2.1.3 Acadia Study Region

As shown in Figure 5, Acadia corresponds to managed forest in the Maritime Lowlands region of the Atlantic Maritime ecozone. Native vegetation is mixed forest although the study region included sites that were harvested with only stumps remaining, harvested with debris, spruce plantation and mature mixedwood forest. Surficial material corresponds to- humo-ferric podzols but with compacted subsoils with relatively poor drainage. Local topography was hummocky.

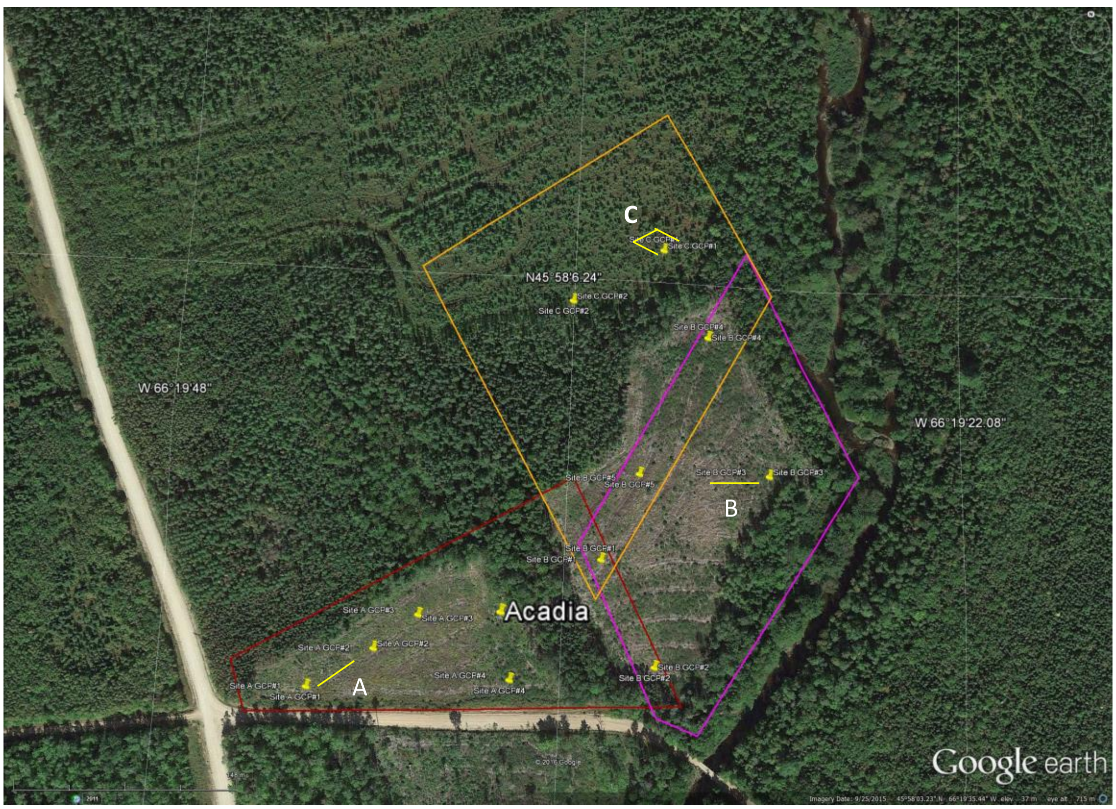


**Figure 5. Acadia study region indicating three sites: A (red polygon), B (pink polygon), C (yellow polygon). Ground control points and SD transects are also indicated by markers and lines respectively**

This ecoregion is characterized by moderate summers and mild winters with substantial snow. Snow depth measurements are not conducted at the nearby Fredericton synoptic station. Climate normals between 1981 and 2010 at Moncton Aiport,~60km from the study region, Figure 7, indicates snowfall from November until May with rain possible year round including frequent winter rain. As indicated in Figure 7, snow depth starts at ~6cm in November, ranges between 30 and 45cm during the winter and 0cm by the end of April.    The snow depth climatology is very similar to that of Gatineau although the total snowfall of 246mm/yr  is ~30% larger.

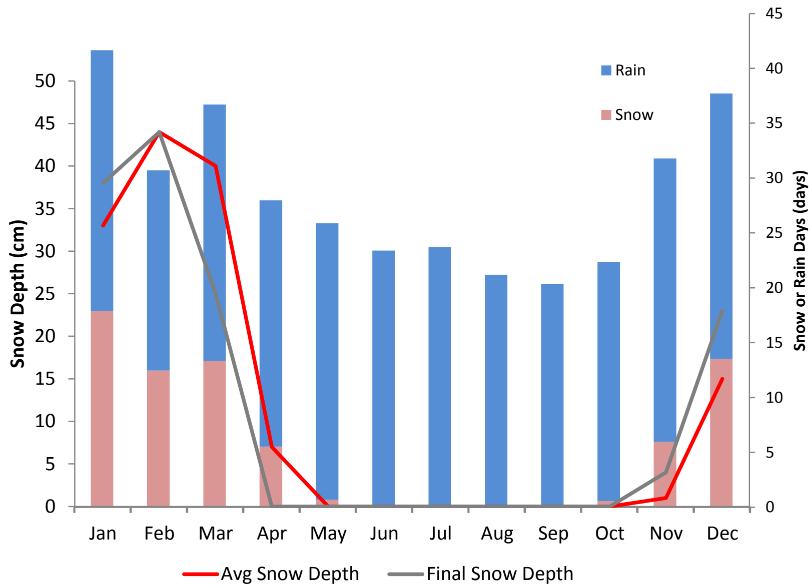


**Figure 6.  Climate normals from 1981 to 2010 for snow depth and rain and snowfall days for Acadia taken from the Moncton. New Brunswick synoptic station.**

Three study sites were selected in Acadia: A, B and C.  The sites are indicated with coloured polygons in Figure 5 and shown using landscape photographs in Figure 7.  All three sites were on flat terrain in terms of macro-topography.  Site A corresponded to a recent (<2 years old) triangular clear cut of ~75ha with residual stumps but with shrubs and standing debris removed.    The site was selected to correspond to a recently disturbed site within managed forests.  Site B corresponds to an older (<5 years old) square clear cut of ~0.75ha with residual standing stems, trunks and ground debris and substantial shrub cover (<2m).  The site was selected to correspond to a naturally disturbed site within forested land cover.  Site C was a white spruce regeneration stand of ~ 0.6ha planted on the same terrain conditions as Site B but without residual stems and with only low (<1m) shrubs.  The site was selected to correspond to a medium density managed forest or even to urban forest orchards.  All three sites were bordered by mature mixed wood strips on the order of 20m in height.  These strips were included in each site to characterize snow depth estimating in transitions between forest and open land cover conditions.

A.

B.

C.

**Figure 7.** View of Acadia sites taken from in-situ SD transects on February, 10, 2016

### 2.2 Ground Control Points

Ground control points (GCPs) correspond to targets identified in each UAV flight acquisition located with known accuracy. GCPs are required for three purposes:

i) Horizontal Geolocation: The UAV system flown in this project (Section 3) uses a consumer grade GPS/GLONASS receiver. The accuracy of this device is not specified but is typically on the order of 2.37–4.65 meters (90% Circular Error Probable, CEP, http://water.usgs.gov/osw/gps/). Considering that SD can vary substantially within 1m it was decided to use post processing of acquired imagery with in-situ GCPs to improve absolute geolocation. A requirement of <10cm 90% C.E.P. was specified corresponding to the likely sampling uncertainty of in-situ SD measurements.

ii) Camera calibration: The software used for producing DSMs (PIX4DMapper 2.0) includes automated calibration of actual camera parameters based on nominal parameters provided and GCPs.

iii) SD estimation: SD estimation is performed by taking the difference of DSMs from snow free and snow covered acquisitions. The typical vertical accuracy of commercial grade GPS systems is ~3m (90% CEP http://water.usgs.gov/osw/gps/). This accuracy is clearly inadequate considering that SD changes <10cm should be measured. Rather, both DSMs require an absolute accuracy on the order of 1cm (1σ) to provide a reasonable estimate of SD changes.

While all three requirements for GCPs are important the need for GCPs for SD estimation is most critical. A two level approach to geolocation was adopted within each sub-site. In the first stage between 3 and 10 targets were placed in-situ with geolocation known to ~2cm (90%CEP) using post-processing (Prevost et al. 2016a,b ). In the second stage DSMs were co-registered using ~100 targets identified in images acquired by UAV immediately before and after snow cover.

### 2.2.1 Level 1 Geolocation

Three types of targets were deployed (Figure 8): flat, disks on poles, cones on poles. Flat targets corresponds to 30cm square plywood painted red with black cross marking and a center 0.5” mounting hole. Flat targets were placed on fence posts or on the snow surface at a known elevation prior to flights and then removed to prevent snow accumulation. The pole mounted targets were placed on wooden or metal poles at a known elevation above the local snow free surface. Red disk targets of 8cm and 15cm were tested, mounted on horizontal pivots to shed snow. The 15cm targets had 2cm black disks at the center. Cone targets were 15cm tall by 10cm diameter cones with a 2cm wide cross terminating 2cm below the tip to present a red center point. Flat and cone targets included cross-markings, disk targets had a 2cm diameter black center. Due to logistics many of the targets were placed during the measurement campaign so that they were not present in all acquisitions.

The position of GCPs were all established based on long (>6 hours) static GPS survey using Ashtech Pinwheel antennas and Ashtech dual frequency Zxtreme receivers. Processing of the resulting RINEX files was performed after acquisition using NRCAN Precision Point Processing (PPP) service. Two types of GCPs were located. Those using existing targets as in Figure 8a (fence posts, bridge roofs) were located by placing the GCP antenna on the target. Other targets were located at the snow free surface and the GCP height was then determined by ruler measurement. A GCP report was logged with each location using the NRCan PPP service.

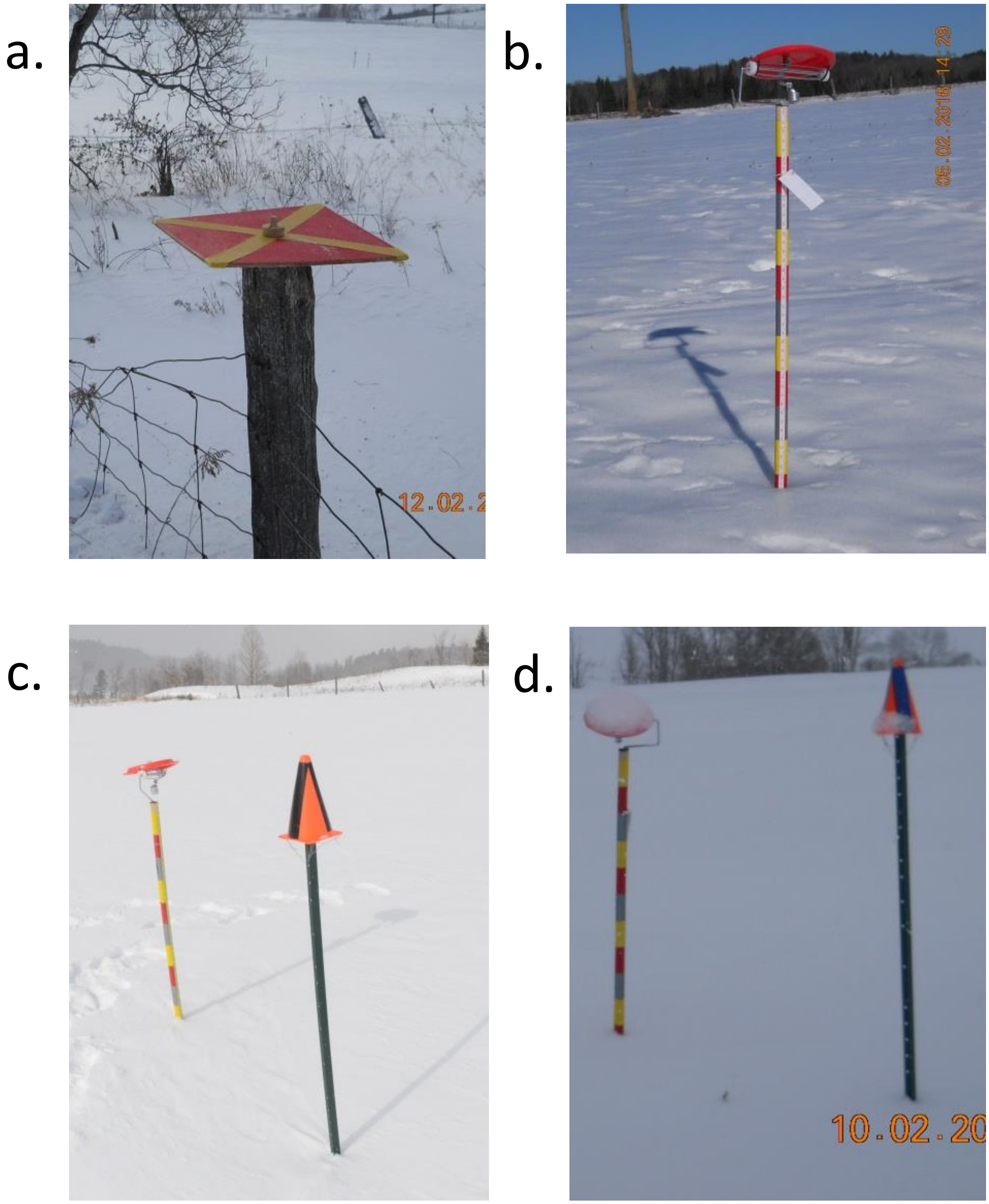


**Figure 8. In-situ GCP targets: a) Flat, b) Disk on Pole, c) Disk and Cone on Pole, snow free d) Disk and cone on pole after 15cm snowfall.**

### 2.2.2 Level 2 Geolocation

Level 2 Geolocation is implemented to improve the temporal consistency of geolocation between acquisitions. This approach exploited multiple (~100) matches between image pairs identified visually by an operator of the PIX4DMapper software. A single clear sky snow covered acquisition was used as a base image for all other images to allow for differencing between arbitrary dates without significant effort to find new matching targets. The snow free images were separately georeferenced to snow covered images since many persistent targets could only be easily identified with snow present when the contrast between them and the background was high.

## 2.3 Data Acquisition

UAV acquisitions were performed on a trial basis in Gatineau in November, 2015 and then systematically from the end of January, 2016 with the goal of at least one survey per week keeping in mind data could not be acquired during precipitation, winds in excess of 20km/hr, or temperatures below 15dC. Data was acquired both in-situ and using a UAV simultaneously but taking care that the in-situ observer was not moving during UAV imaging of the observer.

### 2.3.1 UAV Measurements

The trial acquisitions used an earlier version of the Phantom 2 UAV system (P2, *www.dji.com/product/phantom-2*) with the aim of testing flight planning and post-processing software. Systematic acquisitions were performed using the Phantom 3 Professional UAV (P3, *www.dji.com/product/phantom-3-pro*).

The P3P had a mass of 1280g with a nominal maximum flight duration of 23minutes and operating temperature of 0dC to 40dC. The P3P camera has a 94d FOV f/2.8 20mm lens (35mm format equivalent) focused at infinity. The camera used a Sony ExMORE 1/2.3" sensor with 124Mpixels. It was operated in 4K video mode (4096x2160p) with output in MP4 format except for the November Gatineau surveys where still images were saved as JPEGs. The instrument was operated at a nominal speed of ~3.5m/s in air temperatures as low as -15dC for 17minute flights without issues.   Surveys were nominally scheduled twice a week during forecasted clear sky precipitation free conditions and aborted in the event of precipitation, extreme cold or wind speeds exceeding 20km/hr.  The P3P was purchased for ~$1500.00 CAD including four batteries.  Each flight consumed 1 battery with a 30% margin of safety.

The P2 was manually flown at ~50m elevation and between 3m/s and 5m/s.  The P3P was controlled by the Litchee application (*https://*flylitchi.com/) to give 4K Video acquisitions at 50m elevation with the camera at nadir and a flight line spacing that provided an across track overlap of 60% (initial flights were conducted at 40%).  Additional acquisitions with the P3P were performed later at 15m elevation in the 2016 winter period over in-situ snow depth stakes with the camera at 45$^{o}$ downward zenith angle.  Figures 9 and 10 show the flight plans over Gatineau and Acadia respectively. Additional details are provided in Maloley et al. (2016).


**Figure 9.  Final P3P flight plans for Gatineau corresponding to study sites (upper row) and in-situ SD stakes (lower row).**

**Figure 10. Final P3P flight plans for Acadia.**

### 2.3.2 In-situ Measurements

In-situ snow depth measurements were acquired within 30minutes over UAV flights in most cases (see Table 1).

Stake measurements were performed along transects indicated in Figure 11 Typically twelve stakes were placed with a ~2m spacing along linear transects as in Figure 12. Two exceptions were Acadia C where stakes were placed in a horseshoe pattern to fall within canopy gaps, and Gatineau South T3 where only 8 stakes were placed to minimize survey time.

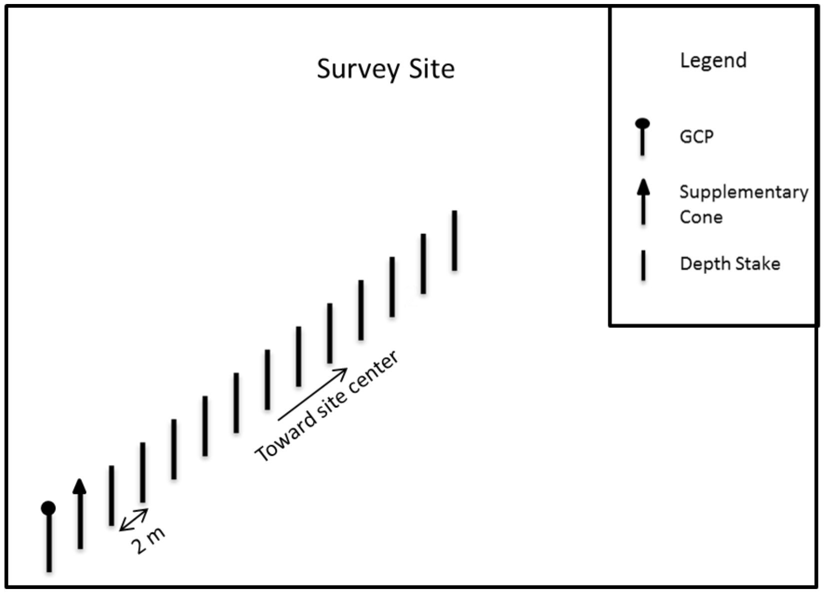


**Figure 11. Components and layout of a snow depth transect.**

Stakes were either 36" (Acadia) or 48" (Gatineau) tall and placed at least 6" in the ground approximately perpendicular in orientation. Each stake had two horizontal bars of red all-weather tape (Tuk tape) 100m wide with the first at the stake top and the second having upper edge 50 cm from the stake top (Figure 12). Acadia stakes were natural in colour but Gatineau stakes were black to improve contrast with snow.

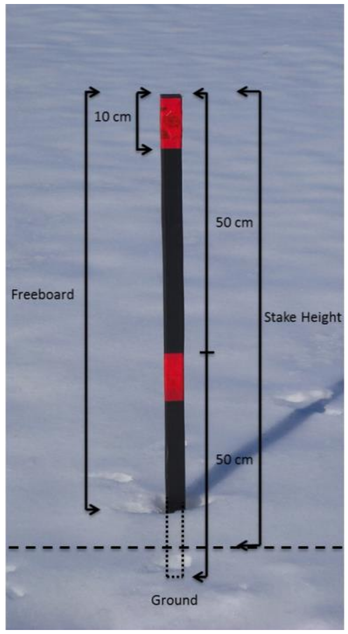


**Figure 12. Snow depth stake dimensions.**

Digital images (>=12MPixel) were acquired for each stake in-situ using a NIKON D7000 or D300 with telephoto lens and manual focus. A protocol for computing the distance from the top of each stake to the snow surface with an error of less than 1cm was devised and applied (Oakes et al., 2016). These measurements were converted to absolute snow depth once snow free conditions allow for survey of stake height and orientation. We expect an error of less than 2cm (90% ile) for point snow depth estimation. This error is within the natural variability of snow depth between stakes. In addition to the SD stakes, a ruler based SD measurement was conducted at the first GCP pole to provide a verification of the SD stake depths.

### 2.4 UAV Post Processing

UAV missions resulted in a single MP4 movie per acquisition. Each MP4 movie was processed separately of other acquisitions using customized software to extract frames in JPEG format. The extracted JPEG images were processed by PIX4DMapper Pro 2.0 software (www.pix4d.com) to extract geolocated tie points, a densified point cloud, an orthoimage and a DSM using structure from motion (SFM). Details regarding UAV processing and sensitivity of results to software parameters are provided in Maloley et al (2016). A brief description of the processing steps is provided below.

1. Frame extraction: Frames were extracted from MP4 or .MOV files using PIX4D with a subsampling interval of 24. This processes included EXIF tags on frames.

2. An initial point cloud was produced resulted in nominal georeferencing of frames.

3. Geolocation targets were identified in frames by an analyst and the PIX4D geolocation processing (Step 1) was completed. This produced a georeferencing report giving the absolute geolocation accuracy at the GCPs.

4. Tie points were then automatically identified by PIX4D and used by the software to refine the camera attitude and position for each image.

5. A point cloud was generated by iteratively using an image matching algorithm to identify a spatially dense sampling of points on multiple images and performing bundle adjustment on all locations with at least 3 overlapping images.

6. An orthoimage and DSM was generated using inverse distance weighting for DSM.

7. Visual quality assessment was performed using output PIX4D reports.

# 3 Results

## 3.1 Ground Control Points

Details regarding GCP location acquisition and results of processing are given for Gatineau and Acadia in separate technical reports (Prevost et al. 2015ab). Table 1 and Table 2 summarizes the location and precision of each GCP in Gatineau and Acadia, respectively. The 95% worst case error was less than 25mm at all sites and typically corresponded to a lateral rather than vertical error vector.

**Table 1 Gatineau GCPs.**

| Name | Type | Easting UTM m18 N Nad 83 SCRS | Northing UTM m18 N Nad 83 SCRS | Height m EIL | Height m (CGVD28) orthometric | 95% error mm |
|---|---|---|---|---|---|---|
| NORTH-NordOuest | Disc | 429892.54 | 5048359.30 | 104.56 | 137.58 | 20.50 |
| NORTH-NordEst | Disc | 430025.42 | 5048365.12 | 101.62 | 134.64 | 20.50 |
| NORTH-SudOuest | Disc | 429883.81 | 5048256.87 | 101.72 | 134.74 | 12.70 |
| NORTH-SudEst | Disc | 430007.13 | 5048242.58 | 100.64 | 133.66 | 12.30 |
| Permanent 6 | Plate | 429804.37 | 5047823.59 | 99.11 | 132.14 | 8.00 |
| Permanent 1 | Plate | 429869.04 | 5048327.09 | 105.98 | 139.00 | 7.20 |
| Permanent 2 | Plate | 429866.13 | 5048308.18 | 105.23 | 138.25 | 7.90 |
| Permanent 3 | Plate | 429887.87 | 5048128.66 | 101.13 | 134.15 | 11.00 |
| Permanent 4 | Plate | 430042.93 | 5048105.21 | 96.66 | 129.68 | 8.60 |
| Permanent 5 | Plate | 429813.02 | 5047819.51 | 99.51 | 132.54 | 7.80 |
| SOUTH-NordEst | Disc | 429999.08 | 5048015.00 | 94.55 | 127.57 | 10.60 |
| SOUTH-NordOuest | Disc | 429856.69 | 5048037.64 | 97.96 | 130.98 | 10.30 |
| SOUTH-Post | Plate | 429867.06 | 5047893.53 | 90.49 | 123.51 | 11.10 |
| SOUTH-SudEst | Disc | 429950.01 | 5047925.11 | 85.59 | 118.61 | 12.90 |
| SOUTH-SudOuest | Disc | 429808.19 | 5047815.16 | 98.63 | 131.65 | 16.40 |
| SOUTH-XTRA1 | Plate | 429903.63 | 5047949.43 | 93.93 | 126.96 | 17.10 |

| | | | | | | |
|---|---|---|---|---|---|---|
| SOUTH-XTRA2 | Plate | 429869.61 | 5047911.95 | 85.58 | 118.60 | 18.30 |
| SOUTH-XTRA3 | Plate | 429942.82 | 5047782.40 | 92.09 | 125.12 | 9.90 |
| SOUTH-XTRA4 | Plate | 429893.05 | 5047855.78 | 94.98 | 128.01 | 9.80 |
| SOUTH-XTRA5 | Disc | 429859.27 | 5047818.29 | 91.67 | 124.70 | 12.70 |

**Table 2. Acadia GCPs.**

| Name | Description | Easting UTM m18 N Nad 83 SCRS | Northing UTM m18 N Nad 83 SCRS | Height m EIL | Height m (CGVD28) orthometric | 95% error mm |
|---|---|---|---|---|---|---|
| A1 | Disc | 706970.655 | 5093702.761 | 11.941 | 33.807 | 24.60 |
| A2 | Disc | 707005.814 | 5093733.502 | 11.228 | 33.093 | 23.2 |
| A3 | Disc | 707044.191 | 5093762.504 | 10.073 | 31.937 | 21.50 |
| A4 | Disc | 707108.749 | 5093720.754 | 6.625 | 28.488 | 22.85 |
| B1 | Plate | 707169.568 | 5093806.322 | 6.733 | 28.594 | 7.89 |
| B2 | Plate | 707217.232 | 5093739.042 | 0.76 | 22.621 | 14.40 |
| B3 | Plate | 707283.873 | 5093874.287 | 5.836 | 27.694 | 19.30 |
| B4 | Plate | 707233.297 | 5093970.592 | 9.222 | 31.08 | 8.12 |
| B5 | Plate | 707188.183 | 5093868.607 | 8.818 | 30.678 | 14.50 |
| C1 | Plate | 707201.75 | 5094033.735 | 11.961 | 33.819 | 18.20 |
| C2 | Disc | 707134.322 | 5093992.106 | 12.409 | 34.269 | 23.80 |

### 3.2 In-situ Stakes

The freeboard for each in-situ stake was computed by image interpretation. The uncertainty of the freeboard is primarily due to deciding the intersection point of the snowpack and the stake. This was estimated at ~1cm worst case. Figures 13 and 14 show stake freeboard for different dates at two sites for Gatineau and Acadia, respectively. At this time snow depth cannot be derived until snow free conditions in April, 2016. However, temporal changes in snow depth can be inferred from changes in freeboard.

The Gatineau results in Figure 13 correspond to an 11 day interval during which 22mm or rain and 26cm of snowfall were recorded at Chelsea climate station. The North site shows a consistent snow depth decrease on the order of 5cm while a similar open field transect (T1) at the South site shows little or no increase in snow depth. These results highlight the spatial variation in snowpack accumulation between sites and climate stations and between sites in similar weather and land cover conditions. They also indicate that rain on snow can result in substantial changes in snow depth – either due to changes in snow density or snow melt.

In contrast to Gatineau, Acadia showed increasing snow depths between 5cm to 10cm over a 21 day period at the sites shown in Figure 14. During this period the Fredericton station recorded 12.6mm of rain and 76cm of snowfall. While the large snowfall resulted in a net increase in snow depth at all sites it is noteworthy that the increase was much less than the total snowfall amount. This is due to changes in snow density as rain was not significant. However, between the 18th and 23 of February, when snowfall was <4cm in total, snow depth did not change substantially suggesting that snowfall measurements at climate stations can indicate large values for fresh snowfall when density is low.

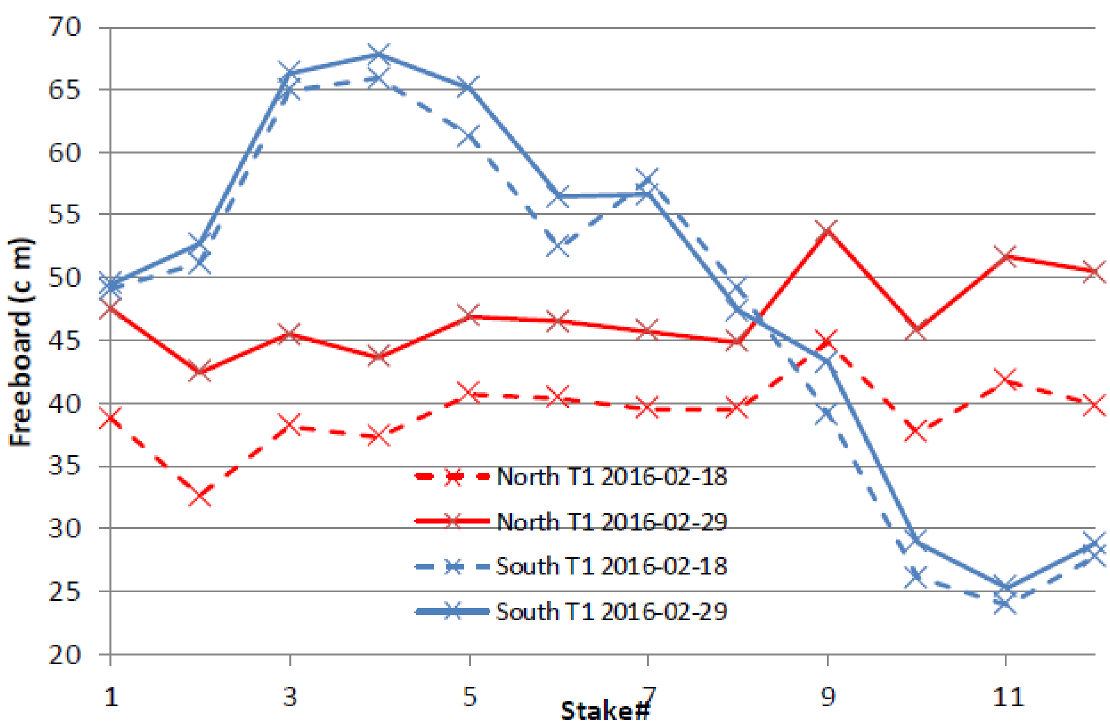


**Figure 13. Gatineau now depth stake freeboard for 18 and 29 February, 2016.**

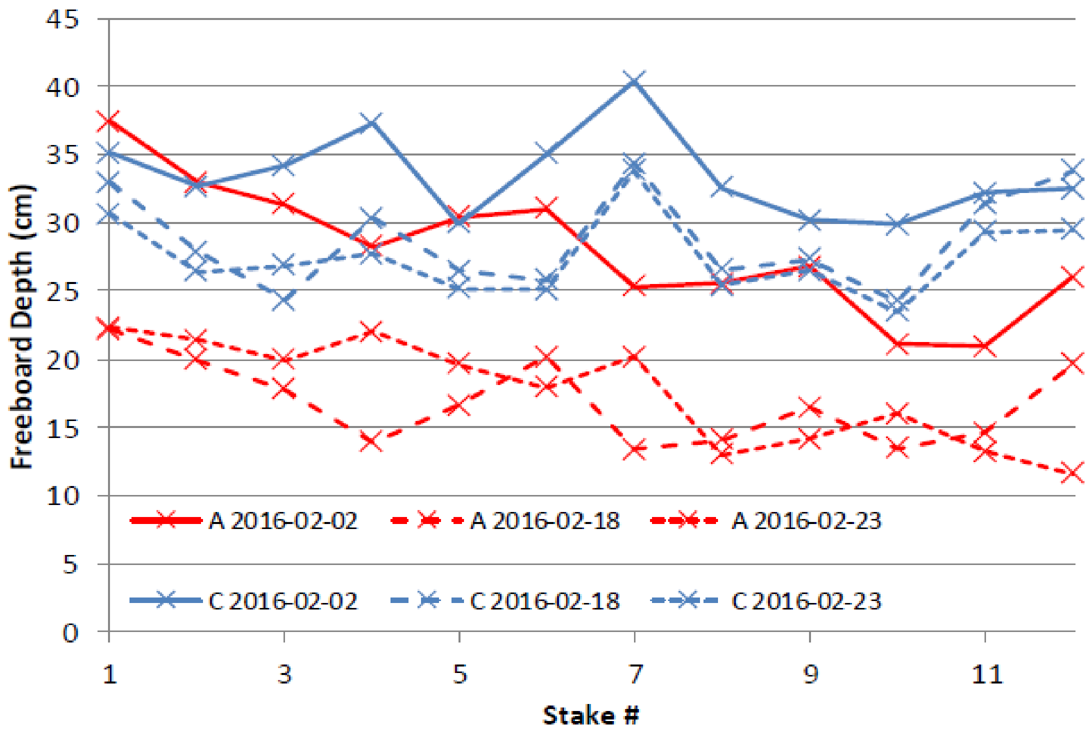


**Figure 14. Acadia snow depth stake freeboard for 02, 18 and 23 February, 2016..**

### 3.3 UAV Acquisitions

As of March 6, 2016 6 surveys were completed at each site as indicated in Table 3. Bi-weekly flights continue at each site until 100% snow free conditions.

**Table 3. UAV acquisitions and processing as of March 6, 2016.**

| Site | Date | Sky | Surface | DSM | Notes |
|---|---|---|---|---|---|
| Acadia A | 2016-01-22 | Clear | Fresh snow | No | Initial flight plan |
| Acadia A | 2016-02-02 | Clear | Fresh snow | No | Initial flight plan, oblique view |
| Acadia A | 2016-02-10 | Partly cloudy | Snow | Yes | Final flight plan |
| Acadia A | 2016-02-12 | Clear | Snow | No | No flights too cold |
| Acadia A | 2016-02-18 | Clear | Icy snow | Yes | Final flight plan |
| Acadia A | 2016-02-19 | Clear | Snow | No | No flights too cold |
| Acadia B | 2016-01-22 | Clear | Fresh snow | No | Initial flight plan |
| Acadia B | 2016-02-02 | Clear | Fresh snow | No | Initial flight plan, oblique view |
| Acadia B | 2016-02-10 | Partly cloudy | Snow | Yes | Final flight plan |
| Acadia B | 2016-02-12 | Clear | Snow | No | No flights too cold |
| Acadia B | 2016-02-18 | Clear | Icy snow | No | Final flight plan |

| | | | | | |
|---|---|---|---|---|---|
| Acadia B | 2016-02-19 | Clear | Snow | No | No flights too cold |
| Acadia B | 2016-02-22 | Clear | Icy snow | No | Final flight plan |
| Acadia C | 2016-01-22 | Clear | Fresh snow | No | Initial flight plan |
| Acadia C | 2016-02-02 | Clear | Fresh snow | No | Initial flight plan, oblique view |
| Acadia C | 2016-02-10 | Partly cloudy | Snow | Yes | Final flight plan |
| Acadia C | 2016-02-12 | Clear | Snow | No | No flights too cold |
| Acadia C | 2016-02-18 | Clear | Icy snow | Yes | Final flight plan |
| Acadia C | 2016-02-19 | Clear | Snow | No | No flights too cold |
| Acadia C | 2016-02-22 | Clear | Icy snow | No | Final flight plan |
| Gatineau N | 2015-11-04 | Clear | No snow | Yes | Manual flight P2 |
| Gatineau N | 2016-01-27 | Clear | Icy snow | No | No snow depth, initial flight plan. |
| Gatineau N | 2016-02-01 | Overcast | snow | No | Initial flight plan |
| Gatineau N | 2016-02-02 | Clear | snow | Yes | Initial flight plan |
| Gatineau N | 2016-02-05 | Clear | snow | No | Final flight plan |
| Gatineau N | 2016-02-05 | Clear | snow | No | Final flight plan |
| Gatineau S | 2015-11-04 | Clear | No snow | Yes | Manual flight P2 |
| Gatineau S | 2016-01-27 | Clear | Icy snow | No | initial flight plan. |
| Gatineau S | 2016-02-01 | Overcast | snow | No | Initial flight plan |
| Gatineau S | 2016-02-02 | Clear | snow | Yes | Initial flight plan |
| Gatineau S | 2016-02-05 | Clear | snow | No | Final flight plan |
| Gatineau S | 2016-02-05 | Clear | snow | No | Final flight plan |

**Table 4. UAV Acquisition processing status as of March 6, 2016.**

| Site | Date | Area | Images | GSD | Matches | GCPs | Geolocation Accuracy | | |
|---|---|---|---|---|---|---|---|---|---|
| | | km2 | count | mm | #/image | count | mm x | mm y | mm z |
| Acadia A | 2016-02-10 | 0.0614 | 734 | 19.6 | 5718 | 6 | 41.9 | 52.6 | 8.08 |
| Acadia A | 2016-02-18 | 0.062 | 733 | 21.7 | 14237 | 6 | 44.4 | 52.7 | 16.9 |
| Acadia B | 2016-02-10 | 0.079 | 685 | 21 | 7033 | 5 | 41.6 | 74.9 | 20.7 |
| Acadia B | 2016-02-18 | 0.0755 | 655 | 21.4 | 14822 | 5 | 43.9 | 72.9 | 11.5 |
| Acadia C | 2016-02-10 | 0.0709 | 695 | 18.4 | 8267 | 5 | 26.3 | 51.3 | 19.6 |
| Acadia C | 2016-02-18 | 0.0714 | 698 | 19.5 | 13930 | 5 | 38.8 | 79.9 | 8.72 |
| Gatineau N | 2016-02-02 | 0.1296 | 774 | 20.2 | 14255 | 5 | 58.01 | 240.2 | 50.19 |
| Gatineau N | 2016-02-18 | 0.1263 | 741 | 20.2 | 3526 | 6 | 66.6 | 99.5 | 58.4 |
| Gatineau S | 2016-02-02 | 0.1427 | 782 | 20.45 | 13482 | 4 | 76.44 | 83.23 | 46.45 |
| Gatineau S | 2016-02-18 | 0.1474 | 762 | 24.6 | 5438 | 8 | 85.92 | 81.11 | 16.11 |

### 3.4 PIX4DMapper Processing

UAV datasets were processed for DSM and orthoimagery using PIX4D. Processing time requirements were ~0.5 person days of initial designation of GCPs followed by between 1 to 4 days of processing on a workstation. Table 4 provides details on flights processed at this time. In addition to a data processing report and a visualization of the position of geolocated camera frames (see Figure 15 for an example), PIX4d processing results in five output raster layers shown in Figure 15 for Gatineau South on 2016-02-18: Tie Points, Point Cloud, 3D surface mesh, orthomosiac and DSM. An analysis of selected results for each of these outputs is provided below.

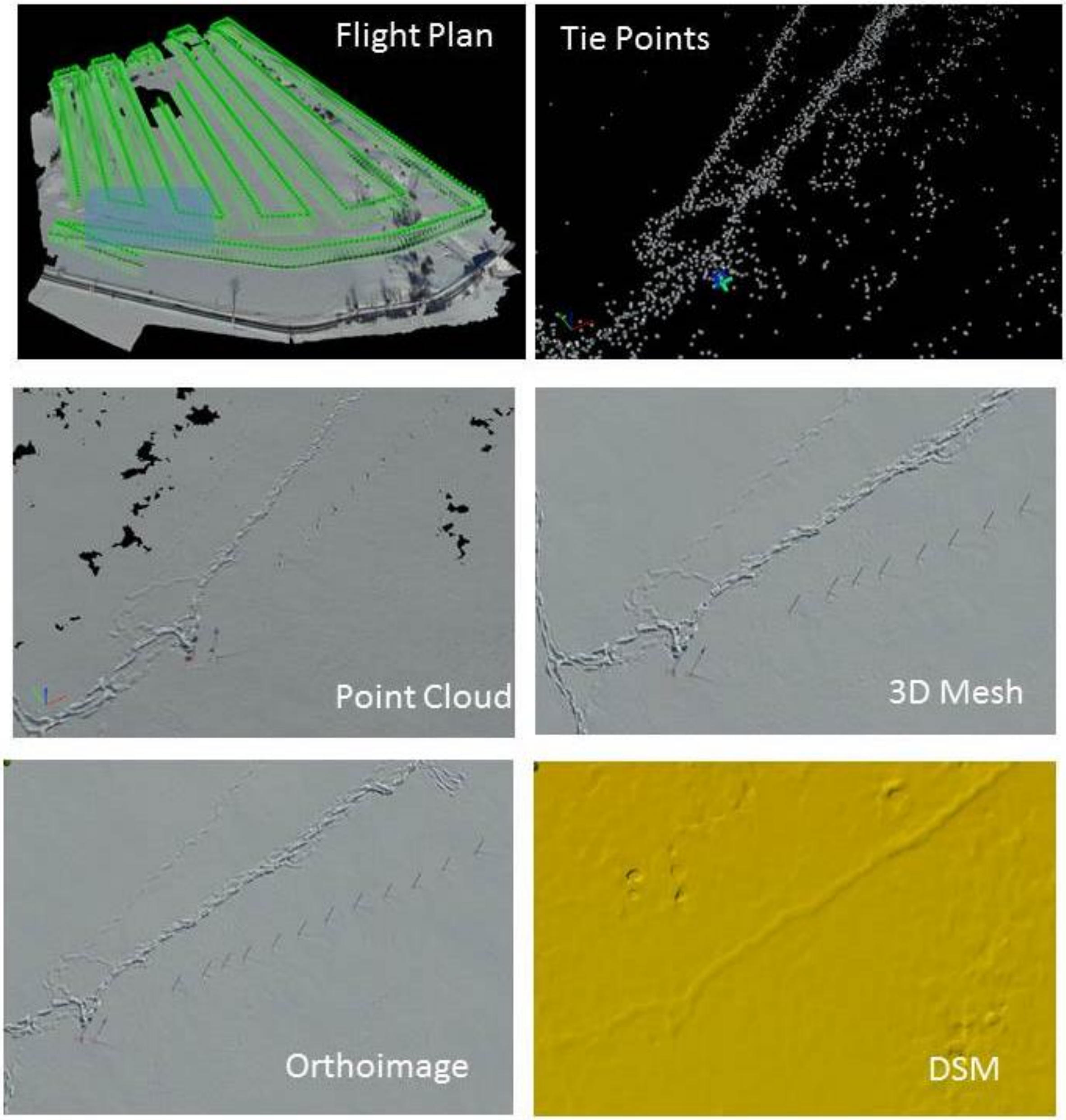


**Figure 15. PIX4D outputs for Gatineau N on 18-02-2016. Top left shows complete flight plan on orthoimage and blue shaded zone corresponding to spatial subset. Other panels show outputs for the spatial subset.**

### 3.4.1 Tie Points and Flight Tracks

Tie points are matches between pairs of images that are spatially resolved using photogrammetric bundle adjustment over all acquired images. The bundle adjustment results in a definitive track of camera position (flight track) later used for producing a dense point cloud using image matching algorithms. For example, Figure 16 shows the assumed camera position based on the UAV ephemeris data over the Acadia A site with a clear indication of badly positioned images in the foreground of the clear cut region.

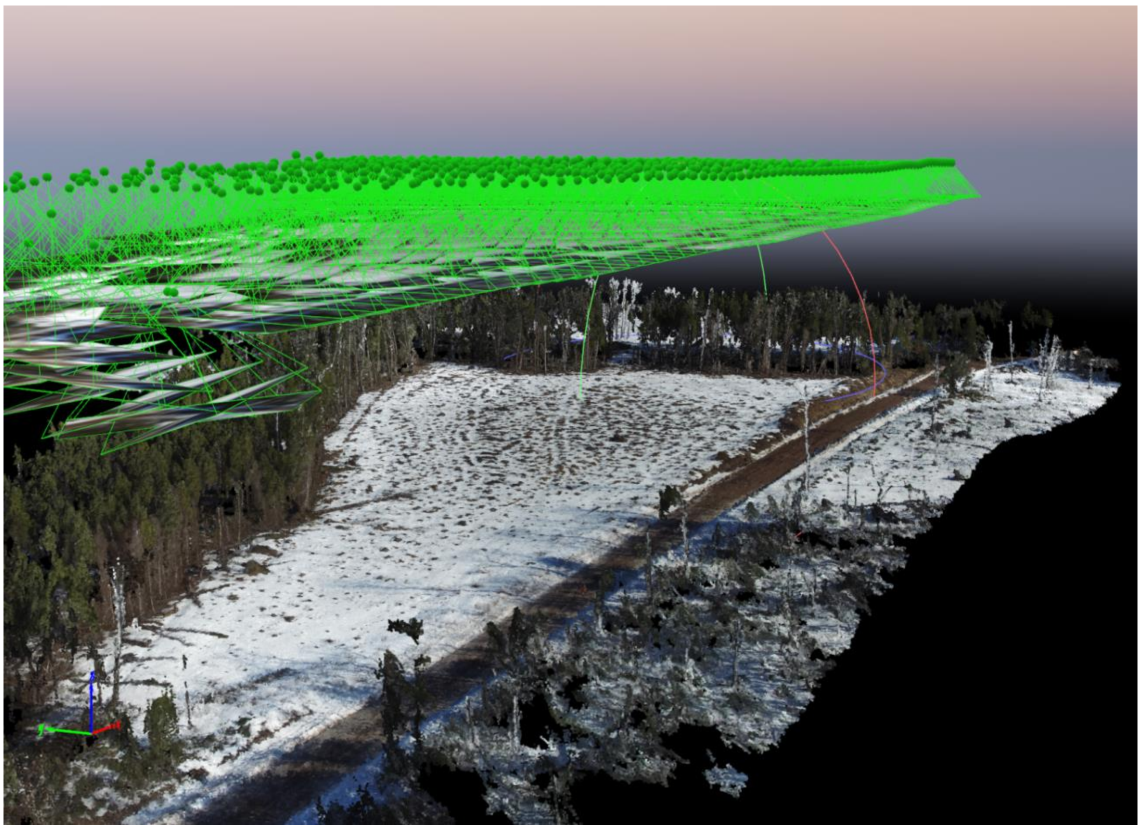

**Figure 16. Acadia A camera positions and UAV image based on ephemeris only (green) shown displaced 25m above the final point cloud. Note poorly located images in the foreground and UAV images showing dark (forested) conditions falling incorrectly in the bright (snow covered) clear cut region.**

Figure 17and 18 shows the density of tie points and the final flight tracks between image pairs Gatineau and Fredericton for two different dates. The flight tracks are very similar between dates indicating that the UAV was able to function with minimum change in velocity under different wind conditions and all images were acquired under similar illumination conditions so spatial patterns or temporal trends in matches are related to surface conditions. The following preliminary observations are noted:

1. PIX4D can find tie points in vegetation, soil, man-made features such as fence posts and snow except where the snow is smooth and crusted. PIX4D cannot find tie points on smooth ice and snow under sunlit conditions.
2. The PIX4D software is able to correct large (>20m) errors in ephemeris through bundle adjustment using automatically located tie points.
3. Edges of flight plans have lower matches in comparison to interior regions with same land cover and shadowing as there are fewer overlapping images.
4. The number of matches decreases by almost an order of magnitude when acquiring data over sunlit snow with a smooth curst of hard snow and water (e.g. Gatineau 18-02-2016) versus fresh snow (e.g. Gatineau 02-02-2016).
5. Forests shaded by terrain or adjacent tall forests result in few matches (e.g. the south portion of Gatineau South and the west portion of Acadia B). This may be due to limitations in the camera dynamic range or simply software algorithms since in most cases point cloud density in forests were reasonable (e.g. Acadia C).
6. Matches increase by at least a factor of two when vegetation features such as trunks emerge from melting snow packs (e.g. Acadia A between 10-02-2016 and 18-02-2016).

These observations indicate that while the current methods and materials are sufficient for generating substantial (100's) of matching points in each image from which surface elevation values can be extracted except under specific conditions of smooth surfaces with specular reflection of heavily shaded vegetation. The former surfaces are not a major issue since they are typically slopes with little internal topography so points around their edges can be interpolated but the latter surfaces may be problematic for snow depth mapping in dense forests or valleys. An analysis of images acquired under different illumination conditions will be performed to further investigate this latter issue,

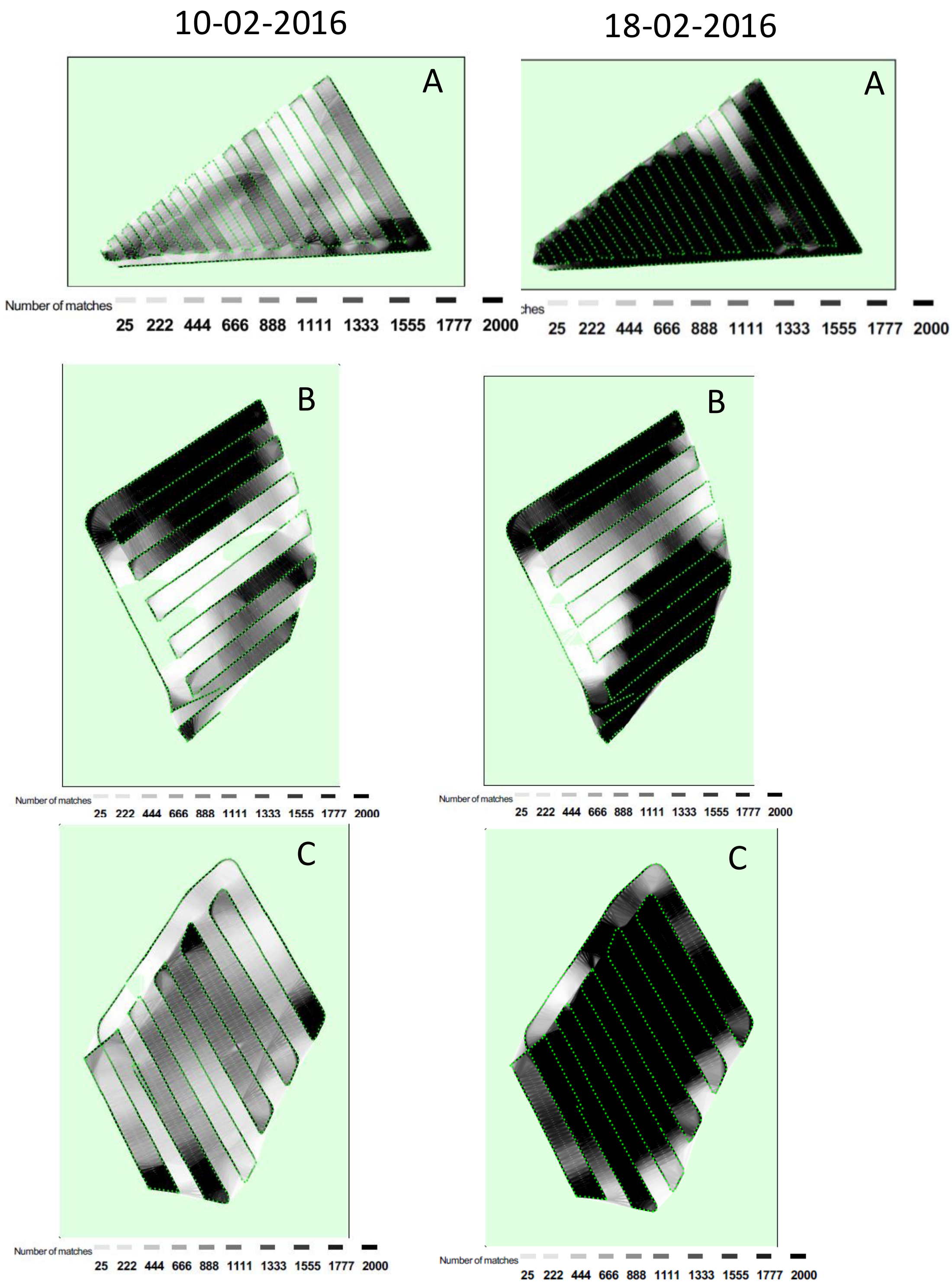


**Figure 17. Actual flight tracks and tie point density maps for Acadia for two dates corresponding to high (left) and low (right) SD with 100% snow cover.**

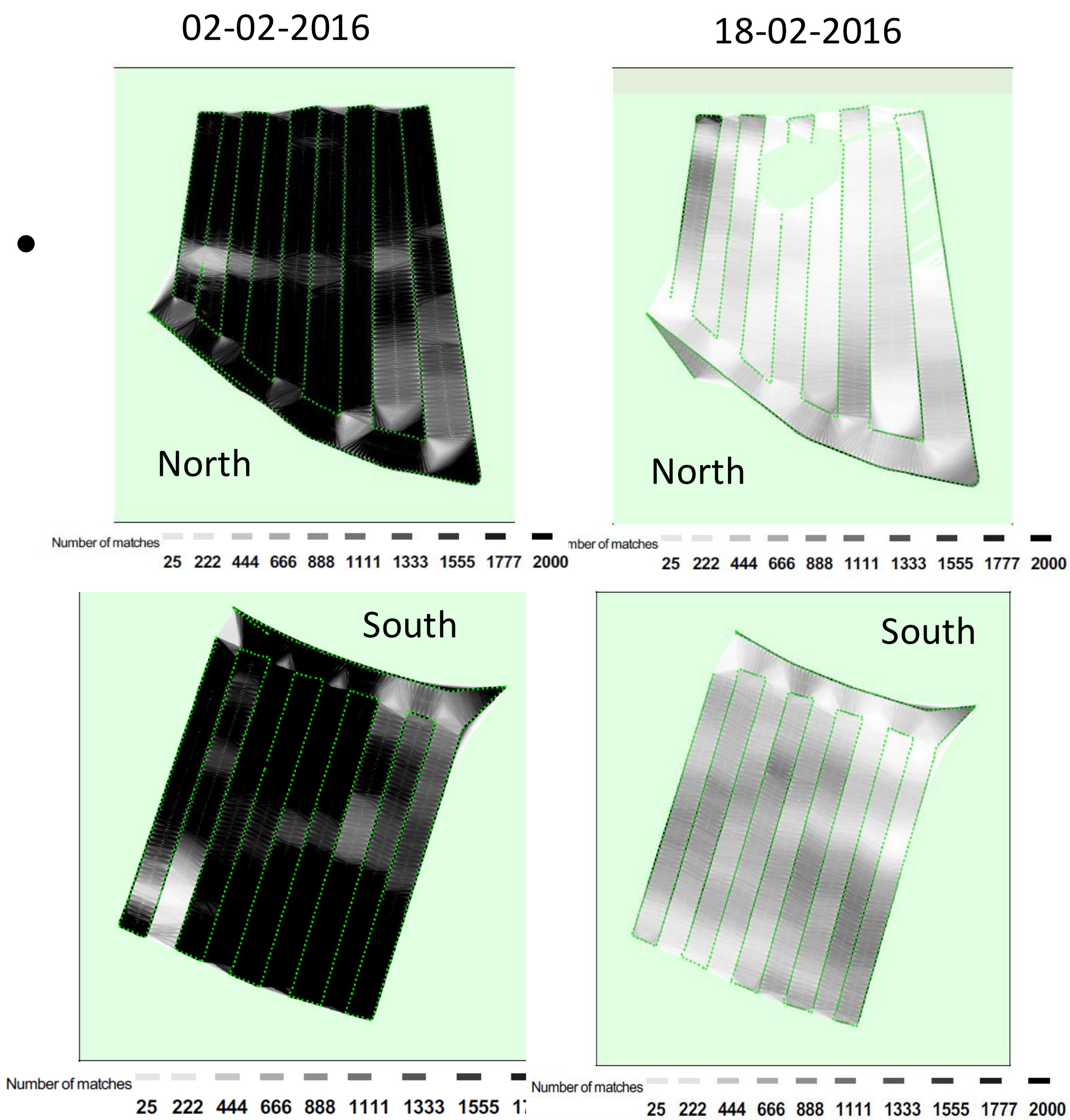


**Figure 18. Flight tracks and tie point maps for Gatineau for two dates corresponding to fresh rough snow (left) and frozen crusted snow (right).**

### 3.4.2 Point Clouds

Point clouds are formed using image correlation algorithms to find features in multiple images and then solve for their location using the estimated camera locations. The correlation algorithm assumes images are co-located and the camera position and attitude are known although PIX4D does not report the maximum error.

The point cloud is the critical output of our project since other derived outputs such as orthoimages and DSMs in PIX4D currently only use the point clouds for interpolation. Point clouds for each site are not shown here as they tend to look similar to the final orthomosaic when seen at coarse scale. Rather, selected sub-areas in certain scenes are shown to show the differences between point clouds and other outputs over different land cover conditions and to compare clouds between dates.

Figure 19 shows point clouds for Acadia A for two dates corresponding to deep snow covering the surface debris and tree stumps and shallow snow where stumps are exposed. In both cases the tie point and point cloud images look rather similar in open areas with perhaps more detail with the point cloud. However, the tie point images over forests show many missing areas (black shadows) that are later identified in the point cloud matching algorithm.

Figure 20 shows all PIX4D outputs for Gateinau North during sunny conditions with ice covered snowpack. The software is unable to navigate the images over the icy region due to a complete absence of tie points. The photos are susequently not used for point cloud derivation resulting a missing data area. The missing area edges are interpolated during surface mesh creation. The final orthoimage include the overlapping images around the issing area that were geolocated but the DSM shows clear evidence of interpolation over this region. This artifact is not a major issue in this case where the snow surface is actually flat but may be an issue for ice covered surfaces that exhibit elevation changes (snow banks after freezing rain). More analysis is required with recent images to determine software performance under such conditions.

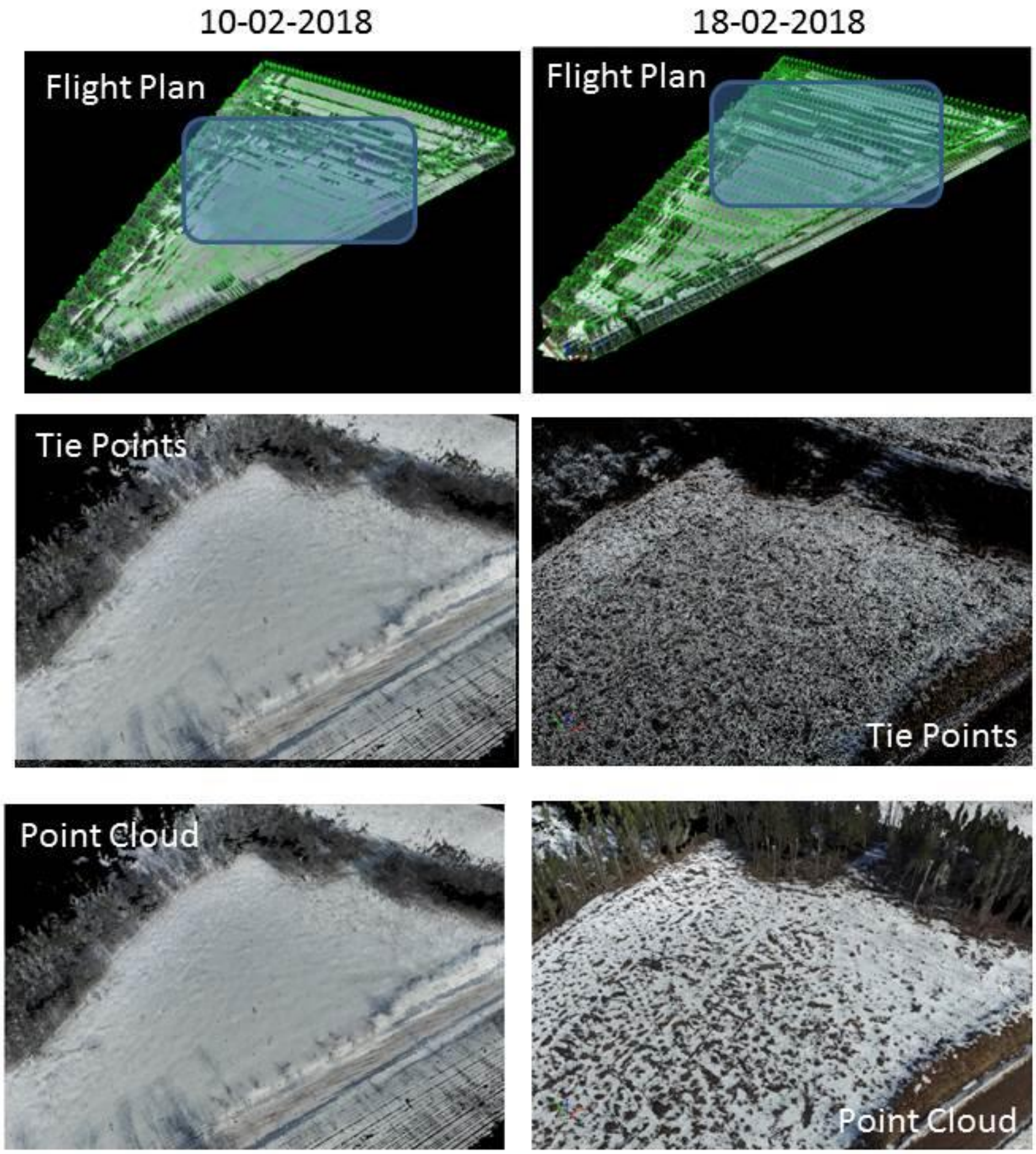


**Figure 19. Deep snow (left) and shallow snow (right) acquisition over Acadia A.**

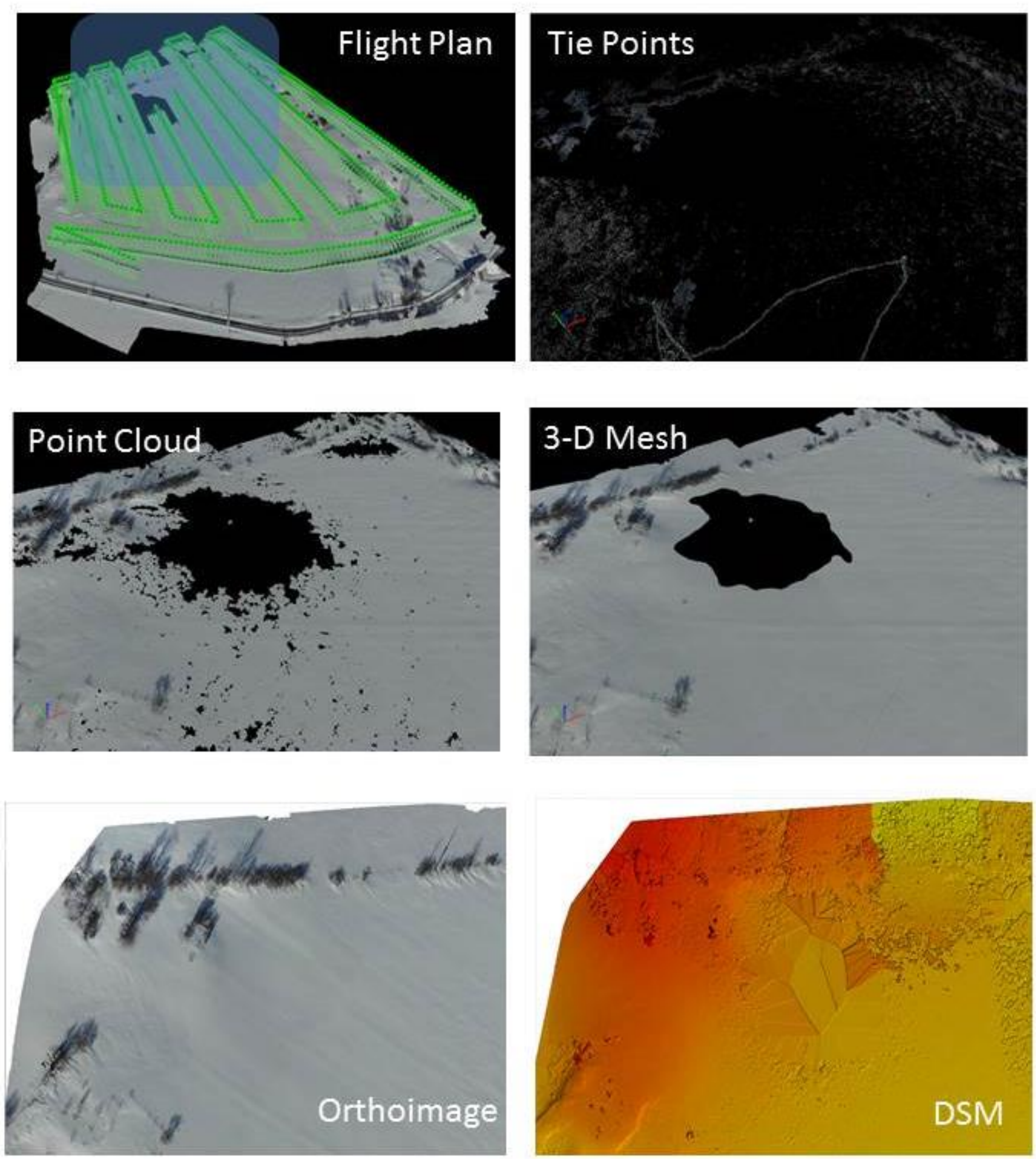


**Figure 20. Limitations of PIX4D over flat specular surfaces.**

Figure 21 shows the remarkable ability of PIX4D to idenify very small features (15cm x 30cm x 2cm deep) in snow such as footprint tracks, snow stakes and GCP posts. The tie points related to these features allow for a dense point cloud to be built up since the features allow for camera navigation even with ice covered snow. For example, there are small areas north of the footprints where the point cloud is not mapped. The final DSM shows these features but does interpolate them incorrectly suggesting there is room for improvement when interpolating the DSM from the point cloud.

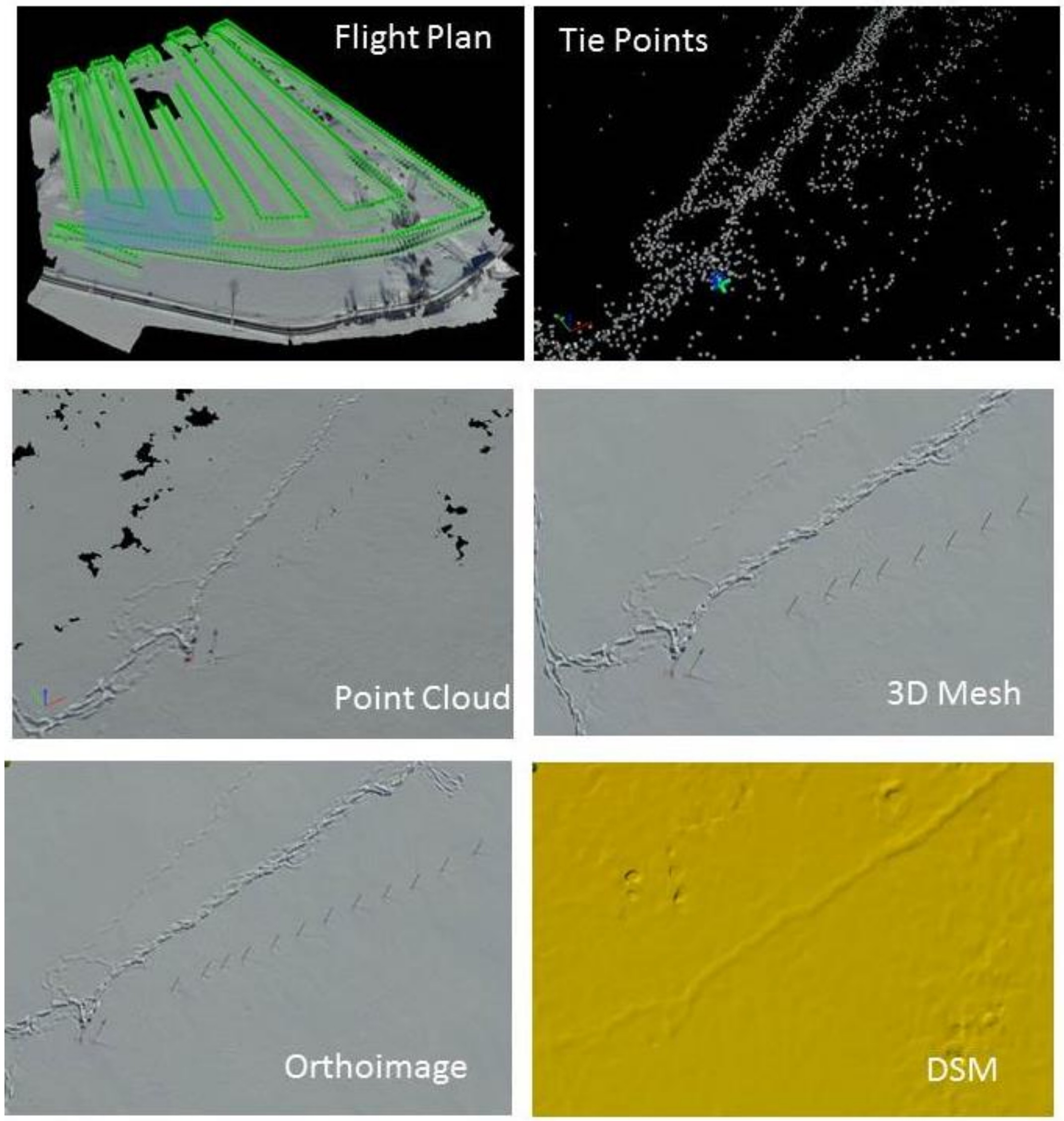


**Figure 21. Subarea of Gatineau N during icy snow conditions showing snowshoe features approximately 15cm x 30xm x 2cm deep. The features result in a ridge in the DSM.**

Figure 22 shows that PIX4D retrieves discontinuous point clouds under forests. The oblique view under the Acadia C forests shows that while there are dense points under the open conifers there are gaps in the point cloud under the taller mixedwood forest. This suggests that there may be a benefit of merging point clouds from multiple acquisitions at different view angles if continuous SD mapping under forests is required.

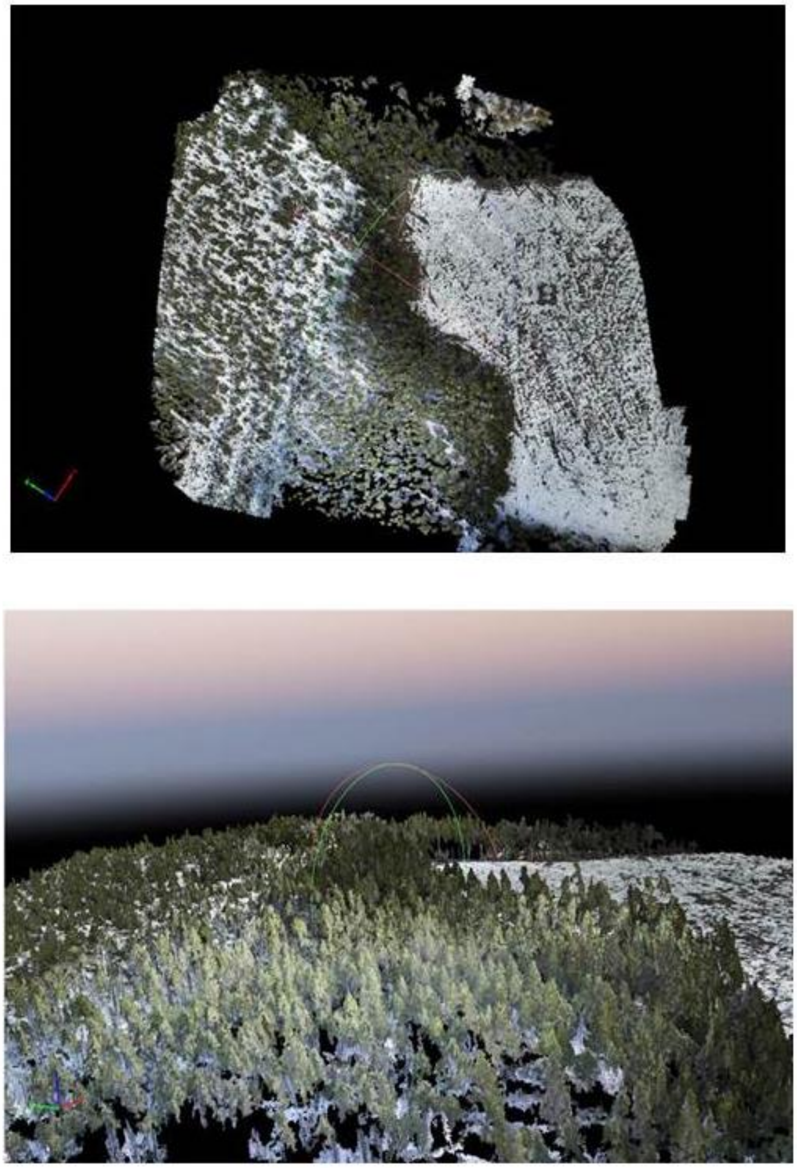

**Figure 22. Acadia C point cloud seen from above and oblique view under low snow depth conditions. Oblique view indicates missing points under dense forests in foreground in comparison to snow free coloured points in open field and retrieved points in open forest in background.**

### 3.4.3 Orthoimages and DSM

Orthoimages and DSMs were successfully derived for each acquisition but have not been assessed for temporal consistency in terms of SD over time or consistency of targets other than GCPs (e.g. tree trunks, roads, bridges, stumps). In this section, qualitative comparisons of both outputs for two dates are provided at each site. For Gatineau sites these dates correspond to 02-02-2016 with ~10cm snow depth and fresh snow and 18-02-2016 with ~48cm snow depth and ice covered snow.

For Acadia sites these dates correspond to 10-02-2016 with ~46cm snow depth in Acadia A and 18-02-2016 with ~8cm snow depth in Acadia A and fresh snow conditions at all sites. DSMs are displayed using the same colour scale at each site but shading was used resulting in black areas that cannot be directly compared.

Figure 23 shows outputs for Gatineau N. There is clear evidence of artifacts in the north half of the DSM in 18-02-2016 that indicates the importance of multi-date acquisitions for filtering these effects from SD time series. The south half of the DSMs show the same within date pattern as expected for a flat field accumulating snow. There is evidence of microtophraphic shading (black spots) in the south region and also, for 02-02-2016, what seems to be rectangular region in the centre that may be related to image frames. More analysis of this artifact is ongoing.

Figure 24 shows orthoimages and DSMs Gatineau S. The terrain relief masks that actual SD changes but there is evidence of snow accumulation in valleys along hillslopes between dates (e.g. less black shaded area in 18-02-2016 as the snowpack has filled valleys). The DSM is unrealistically rough around the shaded forests in the south east. An analysis of the point cloud density in shaded versus sunlit forest understory is being conducted to determine if this artifact is due to illumination conditions – if so changing view angle may reduce the effect.

Figure 25 shows orthoimages and DSMs for Acadia A. The consistency of DSMs around the sunlit forests in the east of the image indicates that PIX4D can consistently map within gaps in forests if they are on the order of 1m or larger. An analysis of the minimum mappable gap is being conducted. The DSMs have similar spatial patterns between dates although 10-02-2016 has a lot more microtopographic shading. Initial assessment of both dates indicates that PIX4D retrieves significantly more point cloud locations around emergent tree stumps so that, when the DSM is interpolated from snow to stump to snow it is smoother that the original snow surface as the stump surface is relatively flat. Analysis of this effect is ongoing. If it is valid then alternative DSM algorithms may have to be applied to point cloud data.

Figure 26 shows orthoimages and DSMs for Acadia B. As with Acadia A there is significant topographic shading for10-02-2016 that we hypothesize corresponds to snow drifts. There is also evidence of loss of snow on forest crowns between dates. The orthoimages clearly show the emergence of stumps on the second date related to the absence of covering snow drifts. A quantitative assessment along SD stake transects is underway currently.

Figure 27 shows orthoimages and DSMs for Acadia C. This is the most complex site with different tree heights and densities as well as hummocky open areas. DSMs with consistent broad patterns were produced for both dates. The largest change is the evident loss of snow around the forests in the centre of the image. However, there are forests at the eastern edge that seem to have increased in elevation. It is not clear if this was due to insufficient points in the initial acquisition date resulting in interpolation using snow surface points. Once again a point cloud analysis is being performed in this area.

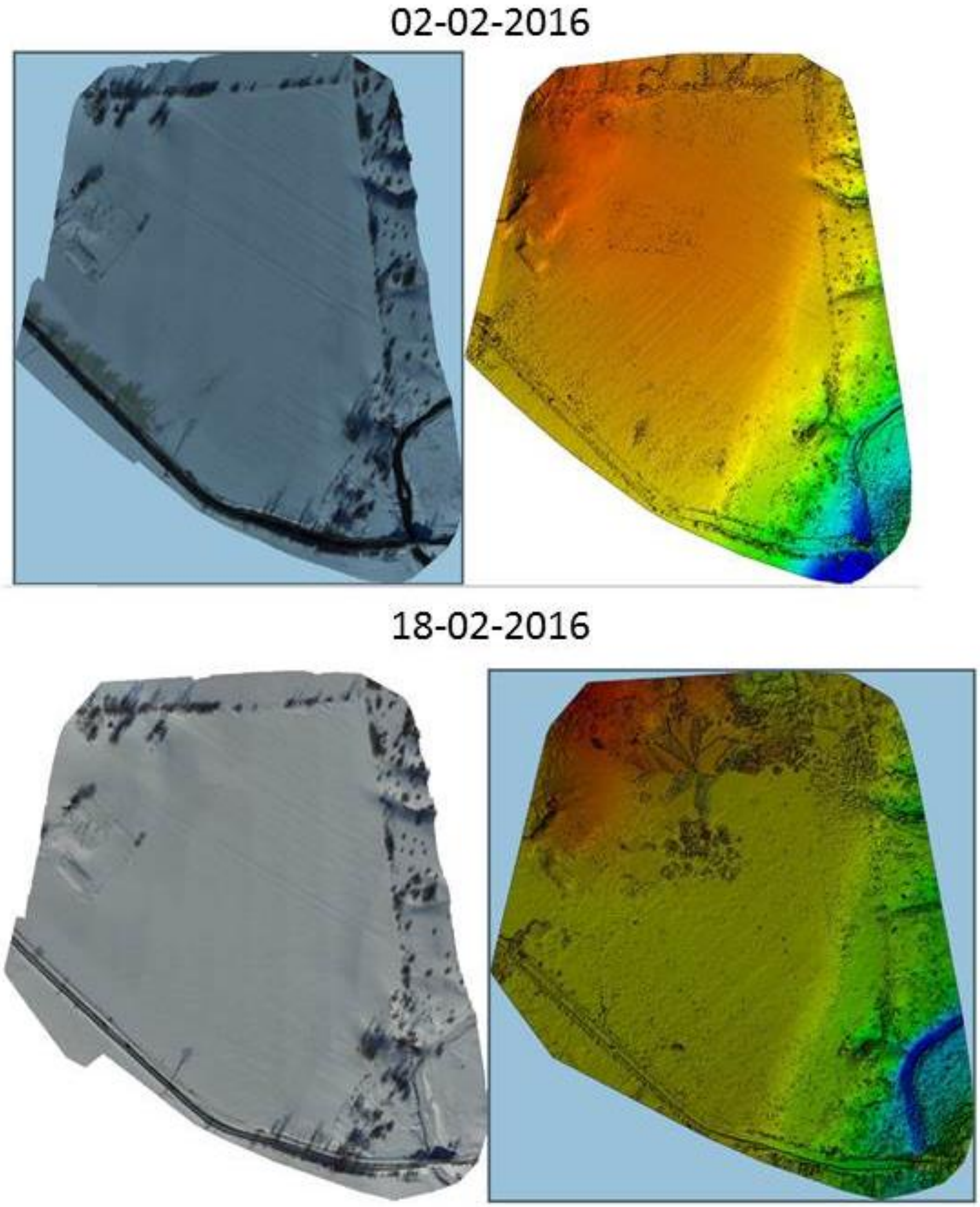


**Figure 23. Gatineau N orthoimages (left) and DSMs (right).**

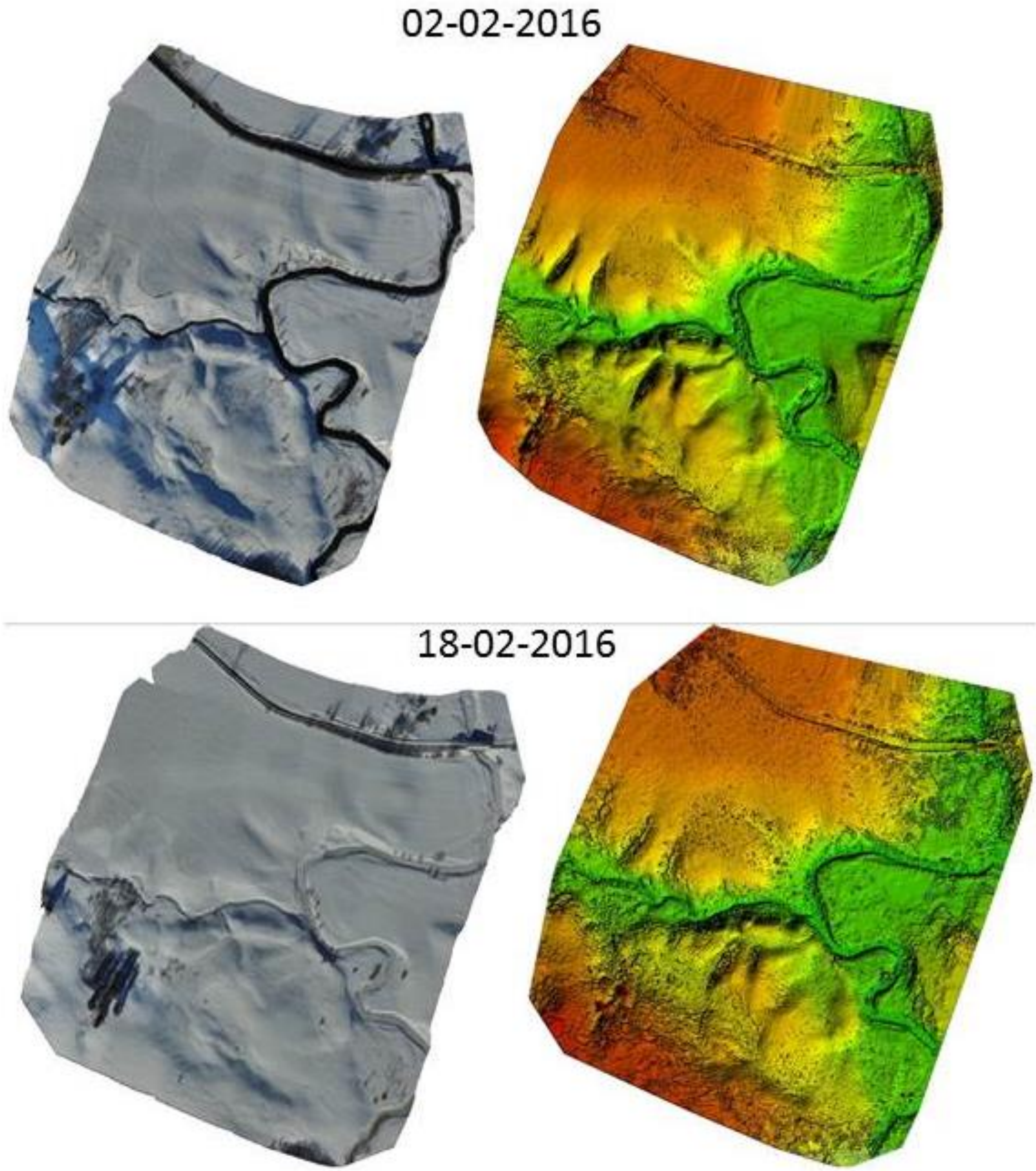


**Figure 24. Gatineau S orthoimages (left) and DSMs (right).**

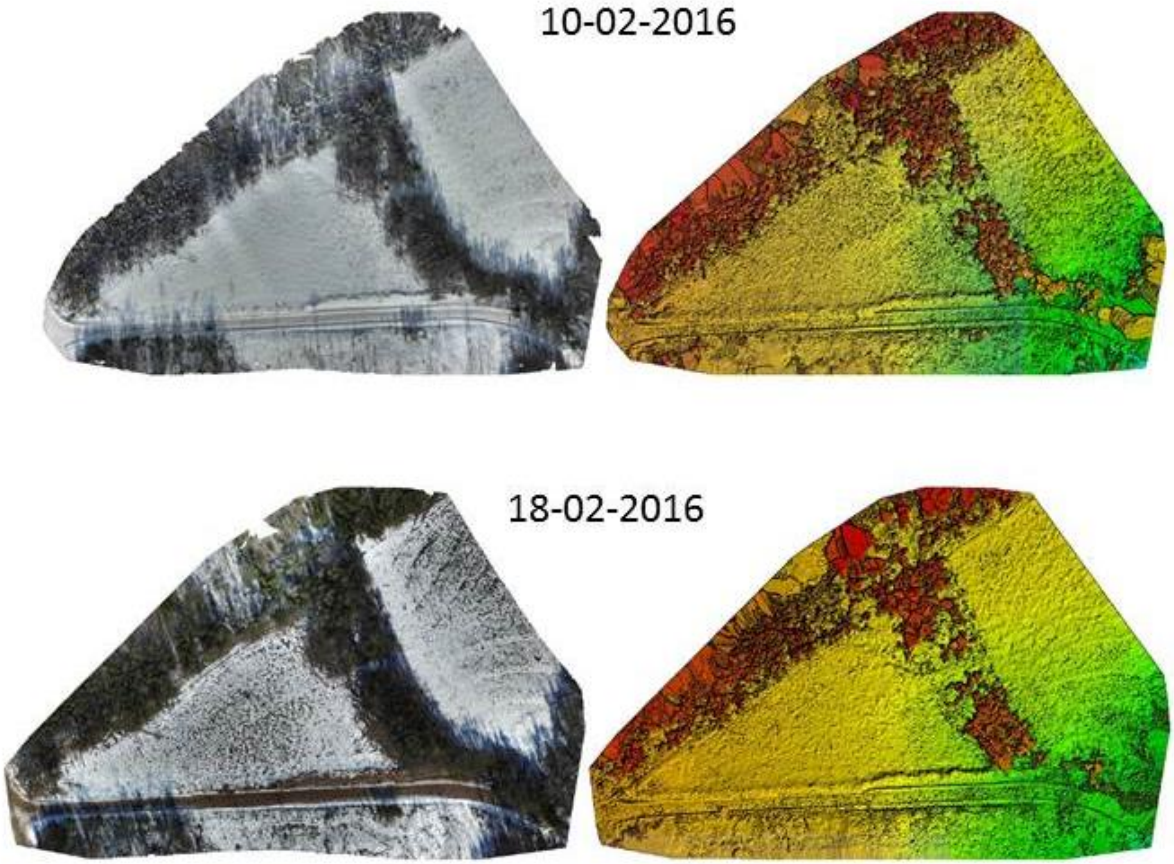


**Figure 25. Acadia A orthoimages (left) and DSMs (right).**

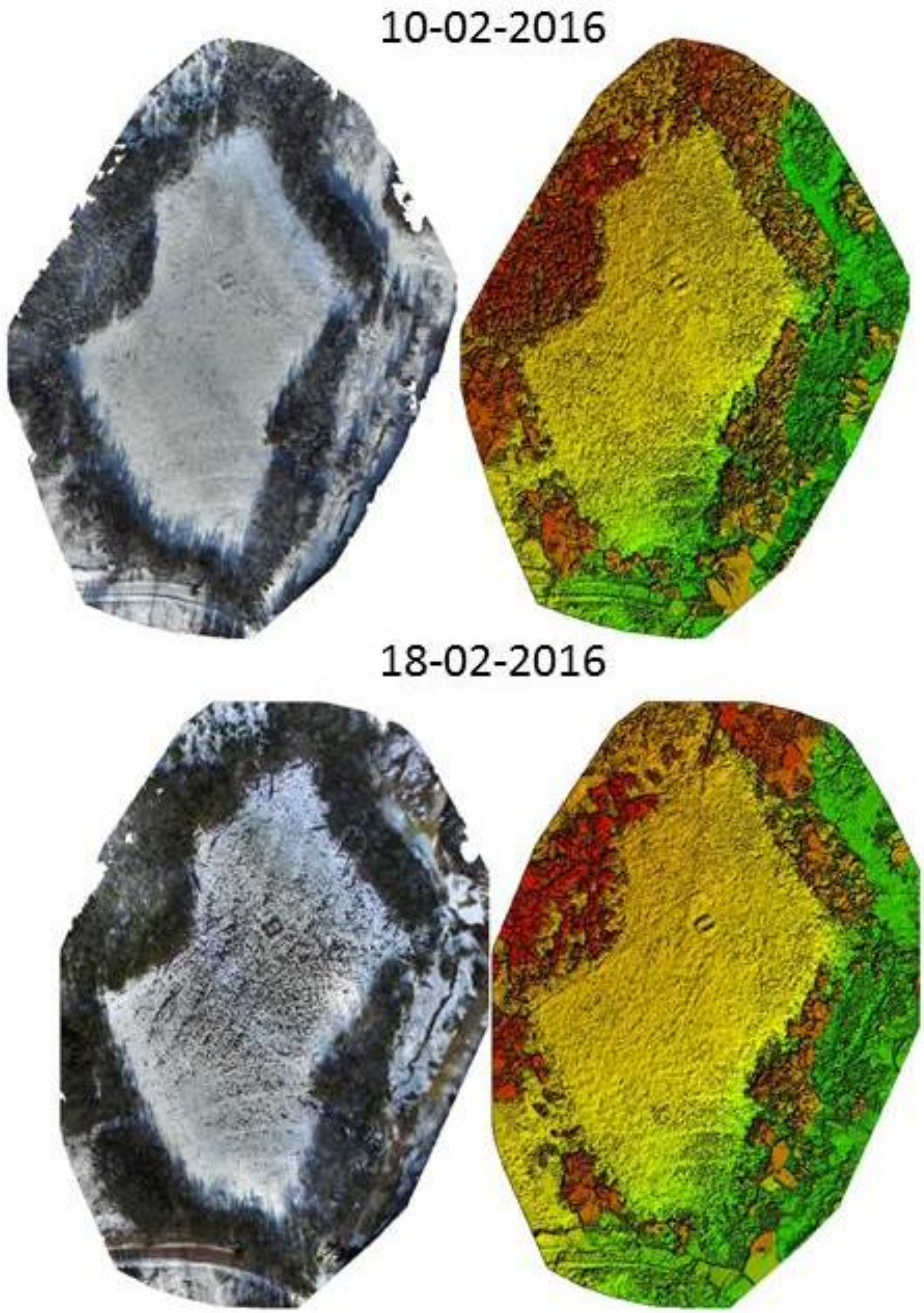


**Figure 26. Acadia B orthoimages (left) and DSMs (right).**

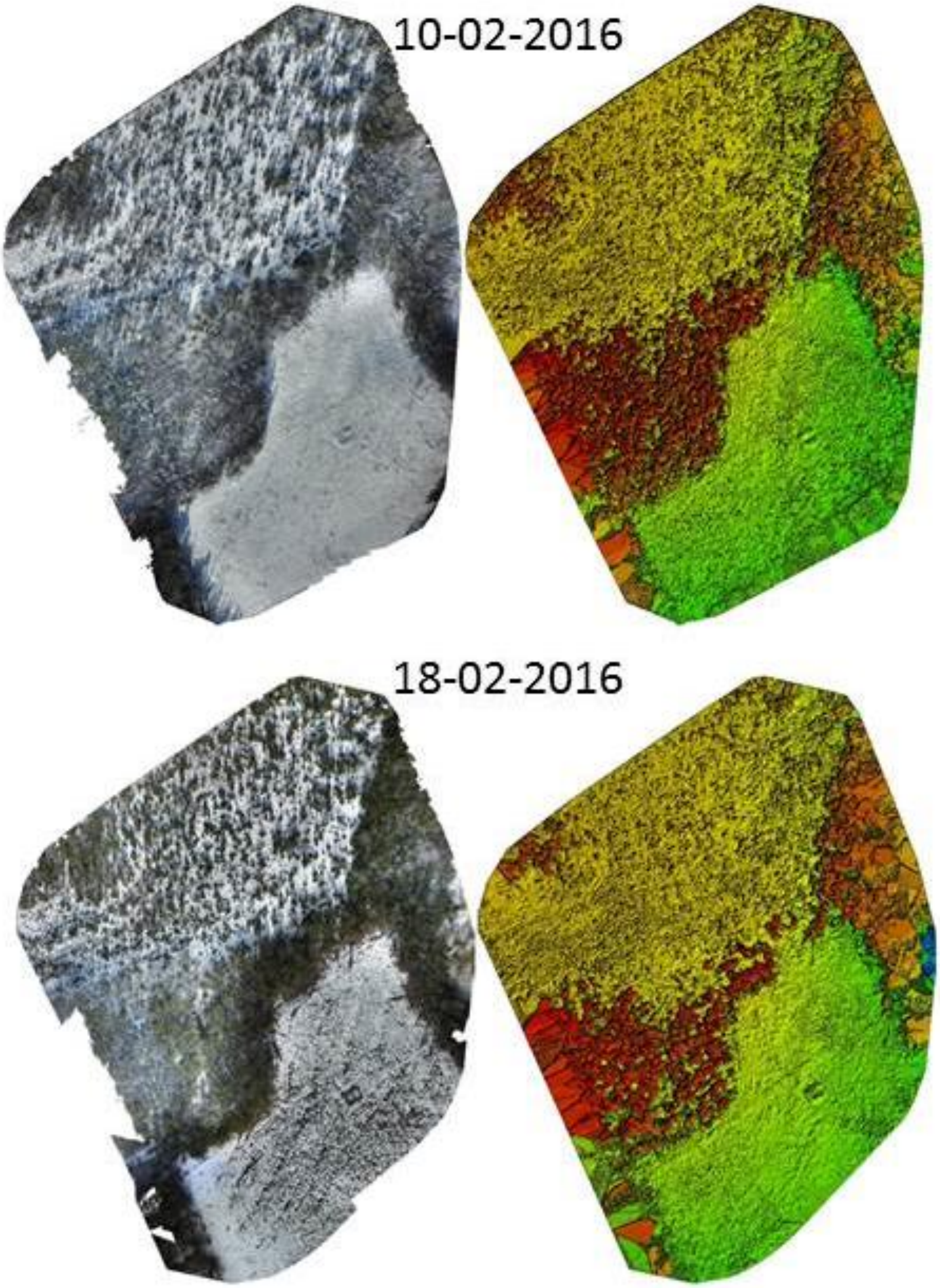


**Figure 27. Acadia C orthoimages (left) and DSMs (right).**

# 4 Conclusions and Recommendations

This report summarized the planning, acquisition and initial assessment of a complex multi-date and location field campaign targeted at mapping of snow depth using low cost UAV systems. Measurements are still being performed and processed as the snowpack melts in winter 2016. At this point the following conclusions apply:

1. The UAV technology is robust in winter conditions, easy to use, and flew consistently and safely. This is surprising – it was rated to 0dC and significantly more sophisticated UAVs dis not function in trials.
2. Care must be taken to place at least 6 GCP targets to provide sufficient information on absolute geolocation accuracy and as a redundancy for snow covered targets.
3. Simple cone on pole GCPs are robust, un-obtrusive, and easy to identify in imagery.
4. With commercial grade cameras, 4K video recording is preferred to still frames as the additional overlap is preferable to slight benefits in resolution (14Mpixel vs 12MPixel).
5. A 60% or greater across track overlap and 90% along track overlap was sufficient for navigating cameras and point cloud mapping in sunny conditions.
6. Tie points cannot be identified over flat ice or water.
7. Fewer tie points were identified under forest canopies than in open areas. The potential to improve tie point density by using oblique and nadir images should be explored.
8. The PIX4D software workflow allows for consistent processing, good workflow management and detailed diagnostics and reports.
9. PIX4D DSM algorithms tend to produce artifacts around vegetation when mapping snow covered surfaces.
10. The orthoimages are valuable for qualitative assessment of floodplains during snowpack accumulation and melt and can resolve small features consistently (footprints in snow, measurement stakes) at ~2cm resolution.
11. The dataset sampled sufficient snow, vegetation and sky conditions to provide a rigorous quantitative assessment of UAV mapping of snow depth.

The following recommendations arise from the current work although we expect more will be provided at the end of the study:

1. The snow depth stake approach for in-situ monitoring may itself serve as a cost effective means of in-situ survey in floodplains and should be tested using other targets (fences, trees, buildings) with high resolution cameras with telephoto lens.
2. The UAV acquisitions should continue until snow free conditions and absolute SD surfaces derived from multi-date differences. These should be compared to in-situ SD change data.
3. The sensitivity of PIX4D outputs to different overlap densities, image resolution, and illumination should be quantified.
4. Different DSM algorithms should be applied to PIX4D point cloud outputs. Quality indicators relating SD accuracy to point cloud density should be developed.
5. A protocol for UAV acquisition, processing and data analysis should be published and piloted with an interested partner.

## 5 Acknowledgements

The authors acknowledge the support of the CCMEO Floodplain Mapping Project and Public Safety Canada, field data acquisition by the University of New Brunswick and St. Lawrence Trust, and advice from Dr. Robert Fraser.

## 6 References

GCOS, 2010, Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update), GCOS-138, available at https://www.wmo.int/pages/prog/gcos/index.php?name=Publication.

WMO, 2008, WMO Guide to Meteorological Instruments and Methods of Observation, 7th edn.,WMO No. 8, Geneva.

Lee, J.-E., Lee, G. W., Earle, M., and Nitu, R.: Uncertainty analysis for evaluating the accuracy of snow depth measurements, Hydrol. Earth Syst. Sci. Discuss., 12, 4157-4190, doi:10.5194/hessd-12-4157-2015, 2015.

Prokop, A., Schirmer., M., Rub, M., Lehning, M., and Stocker, M., 2008, A comparison of measurement methods: terrestrial laser scanning, tachymetry and snow probing for the determination of the spatial snow-depth distribution on slopes, Ann. Glaciol., 49, 210–216.

NOAA, 2013, Snow Measurement Guidelines for National Weather Service Surface Observing Programs, National Weather Service, available at http://www.nws.noaa.gov/om/coop/reference/Snow_Measurement_Guidelines.pdf.

Gruenewald, T. and Lehning, M., 2015, Are flat-field snow depth measurements representative? A comparison of selected index sites with areal snow depth measurements at the small catchment scale, in Hydrological Processes, vol. 29, num. 7, p. 1717-1728.

*Dellaert, F., Seitz, S., Thorpe, C. and S. Thrun, S. , 2000, Structure from Motion without Correspondence . IEEE Computer Society Conference on Computer Vision and Pattern Recognition.*

Nolan, M. Larsen, C. and Sturm, M. , 2014. Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry, The Cryosphere, 9, 1445-1463.

De Michele, C., AvanziF., Passoni, D., Barzaghi,R., Pint,o L., Dosso, P., Ghezzi, A., Gianatti, R., and Della Vedova, G., , 2015, Microscale variability of snow depth using U.A.S. technology, The Cryosphere Discussions, 9 , 1047-1075.

Harder, P., Schirmer, M., Pomeroy, J., and Helgason, W.: ACCURACY OF SNOW DEPTH ESTIMATION IN MOUNTAIN AND PRAIRIE ENVIRONMENTS BY AN UNMANNED AERIAL VEHICLE, The Cryosphere Discuss., doi:10.5194/tc-2016-9, in review, 2016.

Prevost, C., Fernandes, R., Canisius, F., 2016a, Ground Control Point Acquisition for Gatineau, Quebec during winter 2016, in Support of CCMEO Snow Depth from UAV Activities, CCRS Open File, in review.

Prevost, C., Fernandes, R., Canisius, F., 2016b, Ground Control Point Acquisition for Acadia, New Brunswick, during winter 2016, in Support of CCMEO Snow Depth from UAV Activities, CCRS Open File, in review.

Maloley, M., Leblanc, S., Canisius, F., Fernandes, R., 2016. Operations manual for Phantom 3 Profiessional UAV surveys of Gatineau and Acadiai in Support of CCMEO Snow Depth from UAV Activities, CCRS Open File, in review.

Oakes, S., Fernandes, R.A., Canisius, F., 2016. Protocol for photographic survey of snow depth stakes in Support of CCMEO Snow Depth from UAV Activities, CCRS Open File, in review.