

Authors Response to Reviewers Comments

We appreciate the comments from both reviewers. They were both insightful in terms of interpreting our data and helpful with respect to improving the presentation of the manuscript. Below is a list of itemized comments (in italics) and responses. We have also provided additional supplementary material and a separate PDF document with all figures.

Reviewer #1

1. *There are various spelling and grammatical errors throughout*

Sincere apologies. The errors are the responsibility of the first author. The revised manuscript has been checked by internal reviewers for errors. A MS word version of the manuscript with changes is available upon request.

2. *the large amount of detail regarding the accuracy assessment and operations is unnecessary in my opinion as previous work on this topic have established that baseline knowledge*

With respect to operations we have moved Table 1 and Section 2.5 to supplementary material. With respect to accuracy assessment we prefer to retain most of the detail since we feel that it is critical that others can replicate the metrics we have used in our study. Moreover, previous studies (page 27 lines 14-16) have reported metrics that may have not been relevant for our research question (e.g. the compared individual SD measurements rather than transect averages).

3. *The authors need to somehow demonstrate that their in situ SD observational protocol does not bias the point cloud accuracy or density of the SfM solution. Even if stake points are removed from the point cloud the immediately adjacent snow points will also be biased to the more precise stake solution. Are the results of snow depth change valid away from these snow stakes or not?*

This is an important question. We examined maps of Automated Keypoints produced by PIX4D Mapper for each mission. Our response is now given on page 30 lines 20-31 and provided here for convenience:

Validation of ΔSD requires minimally invasive reference estimates using methods that also does not substantially change the performance of UAV estimates. Considering the potential for large variations in SD and ΔSD with microtopography we decided to control the reference locations by using fixed stakes. This strategy could have led to an (artificial) increase in precision if the stakes led to an increase in the D as well as an increase in accuracy if the same keypoints on stakes were detected in multiple images within or between missions. Examination of maps of automated keypoints *a posteriori* indicated that the 10 PIX4D algorithm rarely found a keypoint along a stake (e.g. Supplementary Material Figures S1 to S5). Furthermore, the few cases where a keypoint was identified on a stake corresponded to locations with exposed vegetation around the stake that would potentially exhibit a match in any event. PIX4D Mapper uses a proprietary implementation of a reduced set of features derived from the Scale Invariant Feature Transformation (SIFT) (Strecha, 2011). SIFT features are defined to specifically eliminate keypoints that have poorly determined locations but high edge responses; especially corner features (Lowe, 2004). We hypothesize that, especially for snow covered conditions, the relatively narrow correspond to such features and are subsequently avoided by PIX4D Mapper when identifying keypoints. If so, our results may actually be somewhat pessimistic since there are potentially fewer keypoints in the vicinity of stakes.

4. *Page 2 Line 11-24: This is emblematic of the level of detail concerns I have. Is it necessary to have an explanation of the WMO SD network when the focus on the paper is SD from UAV's?*

The intent was the need to survey current approaches for systematic survey of SD. Specifically, with respect to their spatial coverage and uncertainty. This section has now been shortened to focus on that point (page 2 lines 1-24). Moreover, the discussion of the rationale for using 5 GCPs is now less detailed (page 8 lines 6-10).

5. *Page 3 Line 6-7: If this is not a focus of the paper why mention this?*

These lines have been removed.

6. *Page 3 Line 27-28: Many examples in the literature do this already.*

These lines are a paraphrase of the recommendation of the study of de Michele et al. 2016; a rather recent study. We agree that since 2016 there is a growing body of studies that are evaluating the user of UAV for SD mapping using, for example SfM. Page 3 lines 1-29 survey the literature. We do not feel there is anything wrong in performing additional validation studies for methods as long as they serve as replicate attempts of previous studies that have not been sufficiently replicated and/or include novel elements. The novel elements in our study are discussed on Pages 3 and 4 in terms of issues we aimed to address.

7. *Page 4 Line 6-7: This has been discussed and an example is given in: Schirmer, M. and Pomeroy, J. W.: Factors influencing spring and summer areal snow ablation and snowcover depletion in alpine terrain: detailed measurements from the Canadian Rockies, Hydrol. Earth Syst. Sci. Discuss., <https://doi.org/10.5194/hess-2018-254>, in review, 2018.*

We have added this reference on page 3 line 33.

8. *Page 5 Line 18-19: Why?*

We assume the question "why" refers to our phrase "except for very smooth snow pack conditions". We have added add explanation for this exception on page 5 lines 11-13.

9. *Page 5 Line 28: Are these actually 5 study sites? I was expecting 5 sites with different features and locations based on all the preceding text. This seems like 2 sites with a total of 5 stratified sample areas of analysis.*

As this is a question of nomenclature we have not made changes but confirm that our use of the term "site" is consistent. We use the term "site" since each area had a distinct land surface condition (cover and/or topography) and were surveyed using separate UAV flights. The fact that they are proximal takes nothing away from differences in microtopography and vegetation cover. In contrast we would have used a term "sample area" if we were considering replicates within the same surface and climate conditions. As a further note, we use the term "study regions" to imply areas separated sufficiently to expect different climate conditions.

10. *Table 1 and 2: combine*

Tables combined.

11. *Figure 1 and 2: Google earth citation? Google earth screenshot is not typically publication quality and a better map should be provided prior to any publication.*

Map and citation of map improved. We have combined Figures 1 and 2.

12. *Page 9 Line 21-26: What is the influence of GCP's being located above the surface of interest. Typically GCP's should be located at same height of surface. How were GCP locations measured? dGPS? What is the accuracy of this measurement?*

We did not test the influence of variation of GCP height so we cannot answer the question. Our rationale for GCPs above the surface was to avoid artificially increasing the accuracy of SD estimates by identifying locations on the snow surface as control points. We mention this now on page 8 lines 20-21. The total uncertainty of the GCPs are given on page 8 lines 15-18. The accuracy is less than this amount but is not included since the total uncertainty is very close to the GSD of our data. Measurement of GCPs is given in detail in Prevost 2016a,b. As the focus of the paper is not on GCP measurement we have only added mention of the generic approach for GCP processing and the equipment used on page 8 lines 17-18.

13. Table 3: Is this table necessary as DJI Phantom Pro's are extremely popular (not an obscure UAV)?

It is convenient for reference since the instrument in theory can be modified. The table has been placed in Supplementary Material and referred to on page 11 line 7.

14. Page 13 Line 8-9: imagery was nadir?

Yes. We have noted this now on page 11 line 19.

15. Page 14 Line 17-19: Clarify what was optimized.

We used the wrong term. We should have used the term "model" since the mission parameters were varied to model the sensitivity of height uncertainty to parameter combinations. The change is made on page 12 line 27.

16. Page 18 Line 7-8: What are the implications of this? I would expect that this would add a smoothing artefact.

Removing all points corresponding to dead and live vegetation above the soil would result in smoothing of the index of micro-topography we used. It is for this reason that we only removed points more than the height of the observed maximum transect average snow surface elevation. By doing so we preserve roughness elements that are covered by snow at some point during the season (i.e. that contribute to topographic effects). This is noted on page 15 lines 12-13. Our index of micro-topography was intended to be easy to understand and replicate and relatively robust to between site differences in the summer UAV based elevation model used.

17. Page 19: Line 6-12: These sentences are repetitive. Remove one and merge paragraphs?

The sentences are similar but distinct in that lines 7-9 refer to the median of points identified as snow covered according to the criteria on lines 3-4 while lines 10-12 refer to the median of all points since in this case we are interested in snow free ground. We have not made any change.

18. Table 6. A wind speed of 26 ms⁻¹ is crazy high to fly a UAV safely. Are these correct units? Please explain if/how this wind speed observations are different from actual flight conditions.

Wind speed units were wrong. They should have been km/hr. We have changed the text and the table headers. We also found that we cited the maximum UAV speed in the text but not the speed it was operated at (3.5m/s). We have clarified this in Table 2.

19. Figure 7: y label axe units need to be improved. Xlabels could remove the year from each date. Plot areas are also not consistent. Formatting is not publication ready.

Labels, areas and formatting improved.

20. Figure 8 and 9: combine into a) and b)? what is the meaning of circle size? Add legend.

Combined into new Figure 7. Circle area is proportional to key point match density. The caption has been updated.

21. Figure 13: Putting AC RMSD at 0.1 when it is actually at 0.42 is misleading even if noted.

We have modified the figure to include an x-axis break. The figure now corresponds to Figure 9.

22. Page 34 Line 17: "minimal certification" this is not mentioned elsewhere.

We have removed this phrase since it is not directly relevant to the research goals or issues identified in the introduction. Moreover, certification requirements so to be changing over time and with jurisdiction.

Reviewer #2

23. The information presented in Figure 7 could be used for more detailed analyses and to provide mean and dispersion values for fresh snow, icy conditions and "other days". Perhaps this could be presented in box-plots being complemented with a statistical test to confirm whether the error under the three different conditions belong to a same population. In addition to the density of points I would present the same for the error in snow depth estimation. '

We agree that the accuracy as a function of snow condition is important from both a practical perspective and to explain the cause of low key point matching density conditions. We have modified Figure 7 (new Figure 9) by including icy/fresh snow data; we also removed snow free data from the "other" cases since our goal is to look at key point matching density for conditions with snow. However, we did not include box plots since the sample sizes for icy/fresh snow are both small and differ between regions (6 for Gatineau and 3 for Acadia). Instead, we performed a test for difference of means in point cloud density between icy/fresh snow and "other days" for each site. This test implicitly accounts for sample size and the effect of snow condition considering measurement error and natural variation. We report on this test on page 20 lines 25-26 and in the Figure 9 caption. We also performed the same test for snow depth but found no significant differences due perhaps to a decrease in snow depth variation during icy and fresh snow. Since statistics are not as relevant due to sample size issues, we discuss individual effects on page 30 lines 22-28.

24. I would also consider to compare obtained errors with wind speeds during the missions, as far as I know, this has not been addressed yet in literature in detail and your dataset is nice for this purpose.

A priori we did not consider this factor so we did not perform replicate trials with wind speed changing and other conditions (especially illumination and snow condition). Following the suggestion of the reviewer we evaluated regressions of key point density, geolocation performance and snow depth change performance as a function of wind speed (maximum wind speed for snow depth change). Our findings are briefly discussed on page 24 lines 8-11. We mention this limitation of our experiment in terms of wind speed replicate trials on page 29 lines 10-20 as well as the fact that it may not be important given that PIX4D seems to provide very similar results with or without UAV ephemeris.

25. Why does Figure 13 exclude snow fresh and icy conditions? I think they should be also included or at least to evaluate what happens when they are also included.

We have now included these conditions (new Figure 9).

26. I would give same weight in the results to show errors for snow differences and total snow depth estimation.

We have provided the same detail and annotations in results (new Figure 10) for both quantities and the same statistics (page 25 lines 11-14 and lines 22-26). We acknowledge that our discussion is more detailed for snow depth differences than snow depth estimation. The issue is that, other than a systematic bias noted for snow depth estimation, we did not notice any specific pattern in its errors as a function of snow condition or even as a function of site. Since our results for snow depth estimation were similar to other studies we left our discussion at that rather than trying to tease out patterns that for which we did not have statistical or physical explanations.

27. the figure captions are very difficult to be understood by themselves, I would consider to have a look them and add the text necessary to facilitate its understanding.

We have added text to most figure captions.

28. When the equipment is described, there is indicated the resolution of the camera but not about the size of the sensor and their distortion parameters, I would mention about this as probably it is more important than the resolution itself. Was the distortion of the images corrected?

PIX4D processing includes accounting for camera distortion parameters both as initial conditions for bundle adjustment and as a refinement during bundle adjustment. As Reviewer#1 requested we reduce generic details regarding operations we hesitate to include discussion of how camera distortion is handled in the main body of the manuscript. Rather, we have discussed this in Supplementary material Section 2.

Snow Monitoring snow Depth depth Change change Mapping across a Range range of Landscapes landscapes with ephemeral snow packs Using using Structure from Motion applied to lightweight Quadcopter Unmanned Aerial V-vehicle Videos videos

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10 **Abstract.** Snow depth (SD) can vary by more than an order of magnitude over length scales of metres due to topography, vegetation and microclimate. ~~SD monitoring networks typically rely on in-situ measurements with spatial support less than~~
~~10 m² at a site.~~—Differencing of digital surface models derived from ~~structure~~ Structure from ~~motion~~ Motion (SfM)
processing of airborne imagery has been used to produce SD maps with between ~2 cm to ~15 cm horizontal resolution and
15 accuracies on the order of +/-10 cm over ~~both~~ relatively flat surfaces with little or no vegetation and over alpine regions.
However, these studies have not attempted to relate flight and camera parameters to the expected surface model uncertainty a
priori. Moreover, they indicate that accuracy is lower in the presence of vegetation above or below the snowpack and in
rough topography; suggesting that some biases may be temporally persistent. This study tests two hypotheses: i) the vertical
accuracy of SfM processing of imagery acquired by commercial low-cost UAV systems can be adequately modelled using
20 conventional photogrammetric theory and ii) that SD change can be more accurately estimated by differencing snow covered
elevation surfaces rather than based on differencing a snow covered and snow free surface. ~~Moreover, these~~ These
hypotheses are tested over areas with ephemeral snow pack conditions and across a range of micro-topography and
vegetation cover, and weather and snowpack conditions typical of regions with ephemeral snow packs. The geolocation
performance of derived point clouds agree with photogrammetric theory that predicts uncertainty is proportional to UAV
25 altitude and linearly related to horizontal uncertainty. ~~This study assesses the potential of this approach for weekly SD~~
~~mapping using video imagery from a low cost commercial quad copter ac.~~—Weekly SD maps with <3 cm horizontal
resolution are derived for a period spanning peak snowpack to snow free condition for five sites with differing micro-
topography and vegetation cover. The root mean square difference over the period, Across the sites, the root mean square
difference (RMSD) over the observation period, in-comparisoned to the average of in-situ measurements along ~25–50 m
transects, ranged from was 3.40 cm (2.54|1.58 cm to 8.68|10.56 cm) for SD and from 2.54 cm to 8.68 cm for weekly SD
30 change. RMSD was not related to micro-topography as quantified by the snow free surface roughness. Biases in SD due to

~~vegetation in the snow-covered or snow free image contributed to over 85% of the observed difference at sites where the RMSD of SD exceed 5 cm. In contrast, SD change uncertainty was not un-related to vegetation cover but was dominated by outliers corresponding to rapid in-situ melt or onset. In contrast to the RMSD, the median absolute difference of SD change ranged from 0.65 cm to 2.71 cm. between successive dates and 6.45 cm (1.58 cm to 10.56 cm) for SD; while the accuracy was 0.31 cm (-0.19 cm to 0.80 cm) for SD change between successive dates and 3.33 cm (-10.05 cm to 5.05 cm) for SD. Validation results agree with photogrammetric theory that predicts uncertainty is proportional to UAV altitude. These results indicate that while the accuracy of UAV based estimates of snow depth is similar to other studies in different snow pack and terrain results suggest that UAV based estimates of SD change have an accuracy of UAV based estimates of weekly snow depth change was, excepting conditions with deep fresh snow, substantially better and is comparable to in-situ methods, for low vegetation cover conditions with uncertainty increasing with micro-topographic roughness and vegetation density.~~

1 Introduction

The temporal and spatial pattern of snow depth (SD) is of importance to hydrological, ecological and climate studies (GCOS, 2016). Together with representative estimates of snow density, time series of SD are indicative of changes in snow water equivalent that in turn are of importance to streamflow forecasting and management of hydroelectric resources (Clyde, 1939; Barnett et al., 2005; DeWall and Rango, 2008). In many ecosystems, SD is an important determinant of winter habitat in terms of range and access to forage (Bokhorst et al., 2016). Snow depth also exerts an influence on local climate through insulation of permafrost and ice and global climate through its role in snow albedo feedbacks (IPCC, 2013; IPCC, 2014; Bokhorst et al., 2016).

~~Systematic monitoring of SD is currently performed using in-situ networks (e.g. Worley et al., 2015; Reges et al., 2016; <https://globalcryospherewatch.org/projects/snowreporting.html>) providing daily measurements using automated sensors and less frequent measurements using manual sampling with rulers. The former The World Meteorological Organization (WMO) coordinates a global synoptic in situ SD monitoring network (<https://globalcryospherewatch.org/projects/snowreporting.html>) providing sub-daily measurements using rigorous standards (https://library.wmo.int/pmb_ged/wmo_8_en_2012.pdf). This network is supplemented by public and private sector in situ SD monitoring networks using protocols and instruments similar to the WMO synoptic network (e.g. Worley et al., 2015; Reges et al., 2016). Automated in situ instruments within these networks include acoustic and laser ranging devices that the former are typically fixed in location and that have with spatial sampling footprints from 1 m² to 10 m² (e.g. Ryan et al. 2008; de Haij, 2011) and with the exception of global positioning system (GPS) instruments that can estimate the mean snow~~

depth over a footprint of $\sim 10^4 \text{ m}^2$ (Larson et al. 2014). ~~Manual measurements within in-situ networks are performed using rulers. The WMO protocol for ruler based sampling requires between one and six stakes, each having a spatial footprint of $\sim 10^3 \text{ m}^2$, spaced at intervals between 5 m and 10 m (WMO, 1970). The WMO also specifies supplementary snow courses for occasional measurement with between 50 and 100 locations along a transect where an observer inserts a ruler. Other networks use different ruler sampling protocols with plots or transects covering between 10^{10^4} m^2 and 10^3 m^2 although the total sampled footprint for manual measurements is actually typically under 10^{10^4} m^2 (US Department of Commerce, 1997; Ryan et al., 2008; Meteorological Service of Canada, 2016).~~

While in-situ monitoring networks offer ~~high frequent~~ temporal sampling, with the exception of GPS approaches, their spatial sampling can be imprecise and are often biased in terms of their representativeness of surrounding landscapes (Gelfan et al. 2004; Essery and Pomeroy, 2004; Neumann et al. 2010; Wrzesien et al., 2017). GPS survey may offer a solution for an average SD estimation over open terrain although measurement error is larger than manual methods (e.g. Larson et al. (2014) report bias and precision of -5.7 cm and 10.3 cm respectively when estimating SD of a snowpack typically under 1 m in depth). Irrespective of measurement method, SD monitoring sites usually require road and/or power access; often leading to their co-location with low lying built up areas, airports or weather stations located along mountain tops (Brown et al., 2003). These locations can have vastly different microclimates and topographic conditions than less accessible areas nearby thus increasing the potential for biases in estimated SD.

One solution to address the limitation of sparse and potentially spatially biased in-situ SD monitoring is to estimate the spatiotemporal SD pattern by combining in-situ SD time series and maps of SD change (ΔSD) derived from remote sensing methods (e.g. Liu et al. 2017). ~~Two research questions must be addressed to This solution requires determine if this solution is viable. First, is it possible to provide non-destructive on-demand spatial survey of ΔSD with uncertainty known uncertainty that is, ideally, comparable to that of estimates from in-situ instruments over the same spatial footprint? Second, how well can sparse temporal samples of SD patterns together with dense temporal sampling of ΔSD at a point(s) reconstruct the temporal evolution of ΔSD over a region? This paper addresses the first research question over relatively open areas of varying micro topography and snowpack conditions as a pre-condition for addressing SD mapping over arbitrary surface conditions.~~

Remote ΔSD mapping at a similar or better resolution of automated in-situ measurements (i.e. $< 1 \text{ m}^2$) can be performed using airborne survey with LIDAR (e.g. Deems et al., 2013) or photogrammetric imaging (e.g. Nolan et al., 2015). Here we consider photogrammetric imaging approaches due to both their potential cost effectiveness and the widespread availability of unmanned aerial vehicle (UAV) systems. Nolan et al. (2015) used Structure from Motion (SfM; Westoby et al., 2012) processing of 15 cm ground sampling distance (GSD) digital images from a manned aircraft at an altitude of $\sim 750 \text{ m}$ above

ground level (a.g.l.) to map SD with an accuracy (precision) of ± 10 cm (8 cm ~~at~~ at one standard deviation) in comparison to individual probe measurements over relatively flat surfaces. Similar results were subsequently reported using UAV systems, with GSD ranging from ~ 2 cm to ~ 10 cm and altitude from 60 m a.g.l. to 130 m a.g.l., over prairies (Harder et al. 2016), alpine shrub lands (Buhler et al. 2016; De Michele et al. 2016; Harder et al. 2016; Avanzi et al. 2017) and glaciers (Gindraux et al., 2017). Even greater accuracy (1.5 cm to 3.8 cm) and precision (4.2 cm to 9.8 cm at 1 standard deviation) have been reported for ΔSD mapping over tundra (Cimoli et al. 2015) and alpine terrain (Vander Jagt et al., 2015) when using very low (10 m a.g.l. – 30 m a.g.l.) altitude acquisitions with GSD less than 4 cm.

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While current studies provide increasing evidence of the potential for SD mapping over certain landscapes using multi-date UAV imagery there are a number of issues that must be addressed if this approach is to be applicable for routine seasonal estimation of SD or ΔSD over natural landscapes. A pressing issue is the need to test the performance of this approach over a range of snowpack, vegetation and terrain conditions (de Michele et al., 2016). Studies indicate the presence of large (>10 cm) errors under specific illumination, snowpack, vegetation or terrain conditions. The reduced contrast in imagery of homogenous snowpacks (due to fresh snow covering all vegetation) under overcast conditions results in reduced point cloud density (Nolan et al. 2015; Buhler et al. 2017) and can lead to the failure of commercial SfM algorithms (Harder et al., 2016). While this issue may be partly addressed by using both visible and near-infrared imaging (Buhler et al. 2017; 2017), it may also be less of a factor when there is structure in the snowpack due to emergent vegetation and when GSD is sufficiently high to identify the intersection of snow and vegetation. Dense low vegetation compressed by the snowpack can result in SD underestimates due to a positive elevation bias in the snow free reference image (Nolan et al., 2015; Buhler et al. 2016; Cimoli et al., 2015; Di Michele et al., 2016). Vegetation above the snowpack can result in local overestimates of SD if they are incorrectly interpreted as the snowpack surface (Nolan et al., 2015; Harder et al., 2016). Topographic shadowing can have the same impact as overcast conditions when estimating SD over homogenous snow packs (Buhler et al. 2017). However, the shading from vegetation and micro-topography on SD estimates has not been studied systematically in the sense of considering different terrain roughness under the same snowpack and acquisition conditions.

A second issue that has yet to be addressed is the performance of UAV imaging approaches for estimating ΔSD between two dates with partial or complete snow cover. Current UAV imaging methods may have a practical lower limit of ~ 30 cm SD due to the combined errors in estimating the snow covered and snow free surface elevation (Harder et al., 2016; Shrimmer and Pomeroy, 2018). However, in many circumstances ΔSD may still have relevance (e.g. for temporal monitoring or for estimating SD using a single reference snow covered date where SD is well approximated well-approximated using in-situ methods). Errors due to factors such as vegetation and terrain may be spatially correlated so that estimates of ΔSD between short periods of time periods (e.g. weekly) may be substantially more accurate than estimates of SD itself. There is a need to

compare the relative accuracy and temporal precision of SD and ΔSD estimates, especially for areas with ephemeral snow packs.

A third issue is the need to model the uncertainty of elevation estimates as a function of UAV mission parameters. This is required both to guide mission parameters and to understand the potential limits of current technologies and prospects for improvements as UAV performance and camera systems improve. Nasrullah (2016) demonstrated that photogrammetric theory ~~can~~ could be used for this purpose when estimating the elevation of ~~man-made~~ fabricated targets using UAV imagery and SfM over ~~man-made~~ fabricated targets. A similar modelling approach has yet to be tested over snow covered surfaces.

A fourth issue is the need to have robust low-cost equipment and software for data acquisition and processing (Nolan et al. 2015). ~~Light weight~~ Lightweight systems that require minimal flight certification are especially desirable considering that snow surveys may be episodic ~~both in time and space~~ in both time and space. Nasrullah (2016) found that using commercial SfM software (Pix4D Version 2.1.100) with imagery from off-the-shelf UAV systems weighing less than 2kg and costing under \$US 1000 (Phantom 2 Vision+ provided comparable performance to larger drones. There is a need to evaluate similar systems for ΔSD mapping over a range of environmental and surface conditions.

This study is limited to an assessment of airborne photogrammetric imaging. Nolan et al. (2015) used Structure from Motion (SfM; Westoby et al., 2012) processing of digital images from an aircraft to map SD over bare surfaces at between 6 cm and 20 cm horizontal resolution and 10 cm vertical root mean square difference (RMSD) compared to in situ estimates. Similar results were reported using airborne systems over prairies (Harder et al. 2016), alpine shrub lands (Vander Jagt et al., 2015; De Michele et al. 2016; Harder et al. 2016) and glaciers (Gindraux et al., 2017). Photogrammetric theory suggests that, with all other factors constant, both horizontal and vertical uncertainty in digital surface models is proportional to imaging altitude above ground level (a.g.l.) and inversely proportional to image overlap (Forstner, 1998). Aircraft systems offer wide coverage but are often unable to fly low and slow enough to result in either horizontal or vertical uncertainty of SD comparable to in situ methods. For example, Gindraux et al. (2017) indicated that their final digital surface model (DSM) horizontal resolution of 50 cm based on 6 cm ground sampling distance (GSD) airborne imagery resulted in inconclusive results between observed surface roughness and DSM uncertainty. Bühler, et al. (2016) used an octocopter UAV with a high performance geolocation system flying between 97 m to 113 m a.g.l. to map SD at ~10 cm GSD. They reported a RMSD between 7 cm and 15 cm for flat alpine meadow and exposed rock and up to 30 cm for tall grass. Avanzi et al. (2016) used SfM applied to ~2 cm GSD quadcopter imagery over glaciers to map surface elevation with a root mean square difference (RMSD) under 5 cm averaged over 135 manual measurements within a 1ha region. If some of the uncertainties in UAV are persistent over time then differences in ΔSD between UAV and in situ measurements may be even less than the 5 cm reported by Avanzi et al. (2016). Photogrammetric theory also indicates that vertical uncertainty from SfM should be proportional to the density of matching keypoints between overlapping images (Forstner, 1998). Keypoint density will

~~change with snowpack and surface conditions. Gindraux et al. (2017) reported a two order of magnitude decrease in keypoint density for a fresh snow covered glacier in comparison to one day old snow cover. Current studies have considered only a limited range of snowpack conditions (usually cold snowpacks prior to melt), micro topography and vegetation cover (usually areas without any vegetation above the snowpack).~~

~~The issues that remain to be addressed regarding UAV based mapping of SD require multiple experimental treatments including climate and snow conditions that cannot easily be controlled and land surface conditions that can be controlled. Here we chose to control the survey methodology by using a single low-cost commercially available solution for UAV based mapping of three dimensional point clouds and select mission parameters that should maximize the accuracy of elevation estimation based on photogrammetric theory, even if the solution may not be optimal in the sense of logistical constraints of time or cost. Secondly we select sites with a range of micro-topography and vegetation cover but limit vegetation cover to <50% and only validate SD in openings. This strategy simplifies the approach used to extract surface locations within three dimensional point clouds leaving the issue of UAV based SD mapping under closed canopies for further study. Thirdly we locate the sites within regions of ephemeral snowpack since this should correspond to a worst case assessment of uncertainty, especially with respect to ΔSD . Given these limitations, the initial broad research question regarding snow depth mapping is refined into two specific research questions addressed in this study:~~

~~This study evaluates a baseline solution for mapping ΔSD using one widely used commercial UAV imaging system (the Phantom 3 Professional, P3P https://www.dji.com/phantom_3_pro/info) and one implementation of SfM software (PIX4d Mapper, <https://pix4d.com/product/pix4dmapper-photogrammetry-software/>). Even with this limited scope there are a number of potential experimental treatments including parameters for UAV missions, software parameters, micro-topography and vegetation cover. Here we control the first two treatments by selecting parameters that should maximize the accuracy of elevation estimation based on photogrammetric theory, even if the solution may not be optimal in the sense of logistical constraints of time or cost. Secondly we select sites with a range of micro topography and vegetation cover but limit vegetation cover to <50% and only validate SD in openings. This strategy simplifies the approach used to extract surface locations within three dimensional point clouds. Given these limitations, the initial broad research question regarding ΔSD mapping is refined into two specific research questions addressed in this study:~~

~~What is the accuracy and precision-uncertainty of SD and weekly ΔSD maps derived using small commercial UAV and commercial SfM technology as a function of varying micro-topography and snowpack condition over natural landscapes with sparse vegetation cover in sparsely vegetated regions of with ephemeral snow packs?~~

How well does the ~~measured accuracy and precision~~ uncertainty of ΔSD maps and their corresponding digital surface models correspond to *a priori* estimates based on photogrammetric theory?

~~Our null hypothesis is that the SD accuracy of our approach will perform similarly to previous studies, with greater biases in the presence of vegetation - in terms of SD accuracy to as a function of vegetation and , but the snowpack condition but will show lower bias when considering accuracy of weekly ΔSD will be substantially lower due to correlated errors related to surface conditions. Further, we hypothesize that, except for very smooth snow pack conditions, the accuracy of weekly ΔSD and digital surface models will correspond to the expected accuracy from photogrammetric theory. For very smooth snow pack conditions we hypothesize that there will be a substantial decrease in key point matching density (as observed over glaciers by Gindraux et al. 2017) that in turn will result in accuracy less than expected from theory.~~

In Sect. 2 the study sites and methods used to estimate and validate ΔSD maps are described. A theoretical estimate of the precision of ΔSD as a function of mission parameters is also proposed. Results are presented in Sect. 3. Sect. 4 discusses these results in the context of the experimental conditions and their applicability to the research question. Conclusions with respect to the two research questions are given in Sect. 5.

2 Methods

2.1 Study Sites

Five study sites were located in two study regions: Gatineau and Acadia. To simplify the acquisition of permits for in-situ and UAV surveys, both study regions corresponded to land owned by the Government of Canada. The separation between regions was partly due to the availability of staff to perform surveys but also due to a desire to sample different snowpack and land surface conditions. Climate and weather data were acquired from the based on Environment and Climate Change Canada data (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html).

The Gatineau region (Figure 1) was located at 45°35' N latitude and 75°54' W longitude in Gatineau Park (a 391 km² federal park near Ottawa, Canada). The region consisted of land used for hay production with the meandering Meech Creek flowing across the southern half. Table 1 indicates recorded and climatological monthly rain, snow and temperatures for the nearest climate station (Chelsea, Quebec at 45°31' N, 75°47' W, 112.50 m above sea level (a.s.l.)). During 2016, monthly air temperature was similar to the climate normal but rain (snow) was substantially higher (lower) than normal for March and

lower (higher) for April. Two sites with alternatively flat and hilly macro-topography were established in the Gatineau region.

Gatineau North (GN) was a rectangular site of ~2.0 ha with grass cover less than 5 cm high over a flat surface. Gatineau South (GS) was a rectangular site of ~3.2 ha centred on Meech Creek. The northern portion of GS (Figure 21) shared the same conditions as GN. The centre and southern portion of GS covered the river valley including spur hillslopes. Northern hillslopes where in-situ transects were located, were covered by low shrubs and grasses (<10 cm). Shrubs up to 1 m in height covered southern hillslopes. A small forested area was located at the South West corner of GS.

The Acadia region (Figure 1) was located at 45°58' N latitude and 66°19' W longitude in the Acadian Research Forest (a 91.6km² managed forest near Fredericton, Canada). The region consisted of three parcels of managed forest land, corresponding to sites Acadia A (AA), Acadia B (AB) and Acadia C (AC) respectively, separated by mature forest boundaries on gently undulating terrain. Table 1 indicates recorded and climatological monthly rain, snow and temperatures for the nearest climate station (Fredericton, New Brunswick at 45°52'08" N, 66°32'14" W, 20.70 m a.s.l.). During 2016, air temperature was similar to the climate normal but rain (snow) was substantially lower (higher) than normal from February to April.

AA was a relatively flat trapezoidal site of ~3ha with grass (<5 cm) and stumps (<20 cm). AB was hummocky rectangular site of ~4.5ha with stumps (<20 cm) and substantial brush and shrubs (<1 m) left over from clearing. AC was a rectangular site of ~4.5ha with recently planted Balsam Fir (*Abies balsamea* (L.) Mill.) ranging from 1 m to 5 m in height. AC was also hummocky although shrubs and herbs had covered most stumps. The sites were separated by mature mixed wood stands up to 20 m in height with balsam fir, red maple (*Acer rubrum* L.), and white birch (*Betula papyrifera* Marsh.).

Table 1. Monthly climate data from Chelsea, Quebec (Gatineau region) representative of study sites. Normals correspond to 1981 to 2010.

MONTH	Chelsea, Quebec (Gatineau Region)						Fredericton, New Brunswick (Acadia Region)					
	T (°C)		Rain Fall (mm)		Snow Fall (mm)		T (°C)		Rain Fall (mm)		Snow Fall (mm)	
	2016	Normal	2016	Normal	2016	Normal	2016	Normal	2016	Normal	2016	Normal
JANUARY	-9.2	-11.0	37.2	22.7	29.2	47.9	-6.5	-9.4	25.4	42.4	10.7	59.5
FEBRUARY	-9.8	-8.8	10.0	20.5	41.0	38.7	-5.4	-7.5	12.0	31.7	89.9	38.4
MARCH	1.9	-3.0	106.9	34.6	5.2	26.5	-2.1	-2.2	7.2	45.2	82.0	44.9
APRIL	2.5	5.7	21.4	68.4	27.4	6.0	3.7	4.8	20.4	68.1	23.9	13.5

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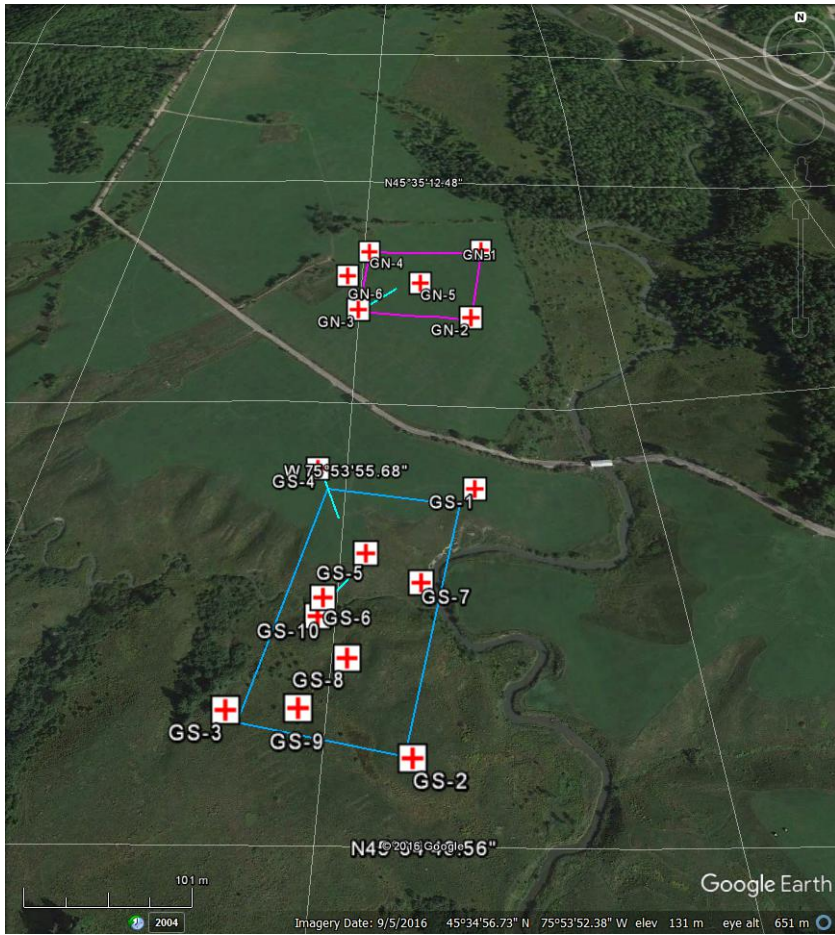
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<u>MAY</u>	<u>12.4</u>	<u>12.6</u>	<u>7.3</u>	<u>89.0</u>	<u>0</u>	<u>0</u>	<u>11.8</u>	<u>11.3</u>	<u>56.7</u>	<u>103.1</u>	<u>0</u>	<u>0.7</u>
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Table 2. Monthly climate data for Fredericton, New Brunswick (Acadia Region). Normals correspond to 1981 to 2010.

<u>MONTH</u>	<u>T (°C)</u>		<u>Rain-Fall (mm)</u>		<u>Snow-Fall (mm)</u>	
	<u>2016</u>	<u>Normal</u>	<u>2016</u>	<u>Normal</u>	<u>2016</u>	<u>Normal</u>
<u>JANUARY</u>	<u>-6.5</u>	<u>-9.4</u>	<u>25.4</u>	<u>42.4</u>	<u>10.7</u>	<u>59.5</u>
<u>FEBRUARY</u>	<u>-5.4</u>	<u>-7.5</u>	<u>12.0</u>	<u>31.7</u>	<u>89.9</u>	<u>38.4</u>
<u>MARCH</u>	<u>-2.1</u>	<u>-2.2</u>	<u>7.2</u>	<u>45.2</u>	<u>82.0</u>	<u>44.9</u>
<u>APRIL</u>	<u>3.7</u>	<u>4.8</u>	<u>20.4</u>	<u>68.1</u>	<u>22.0</u>	<u>13.5</u>
<u>MAY</u>	<u>11.8</u>	<u>11.3</u>	<u>56.7</u>	<u>103.1</u>	<u>0</u>	<u>0.7</u>

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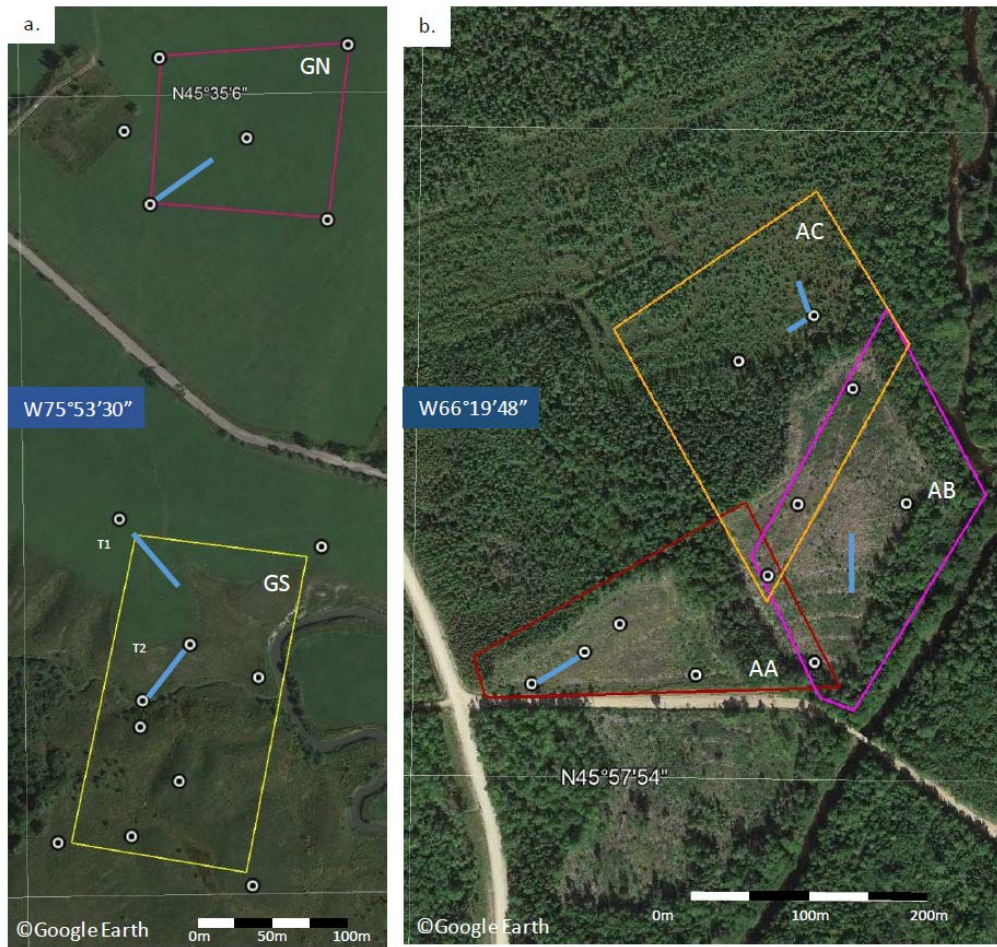


Figure 1. (a) Gatineau region showing GN (pink) and GS (yellow) sites and (b) Acadia Region showing AA (red), AB (magenta) and AC (gold) sites. Also indicated are ground control points (hollow circles) and in-situ transects (blue lines). Map data: Google, Digital Globe.

5 **Figure 1.** Gatineau region showing Gatineau-North (pink) and Gatineau-South (blue) sites and ground control points (crosses) and in-situ transects (cyan lines).

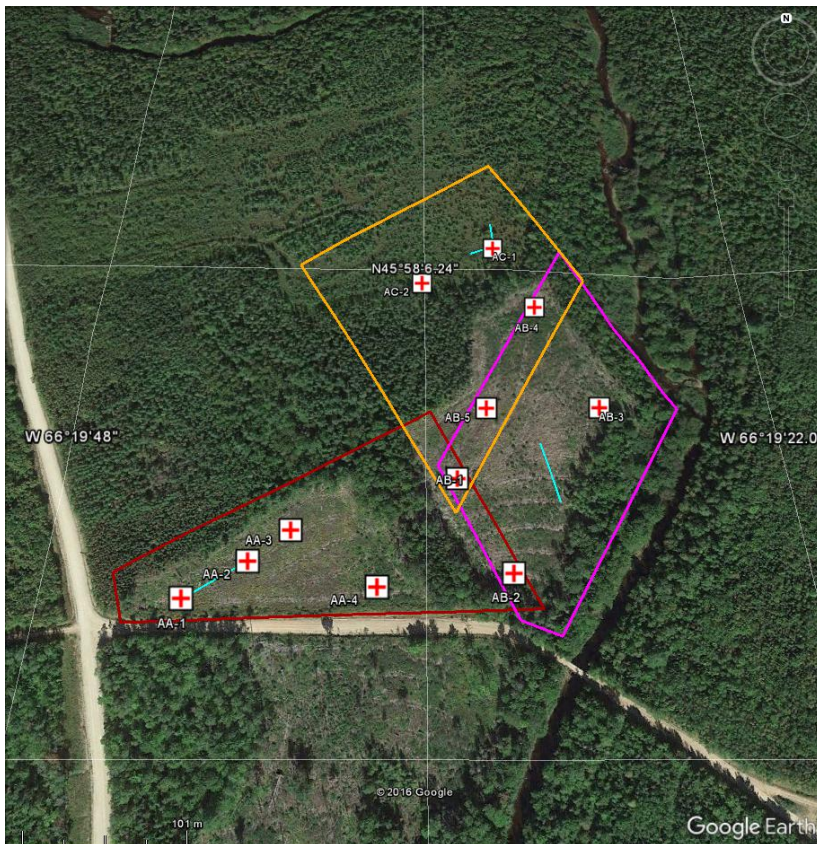
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The Acadia region (Figure 2) was located at 45°58' N latitude and 66°19' W longitude in the Acadian Research Forest (a 91.6km² managed forest near Fredericton, Canada). The region consisted of three parcels of managed forest land, corresponding to sites Acadia A (AA), Acadia B (AB) and Acadia C (AC) respectively, separated by mature forest boundaries on gently undulating terrain. Table 2 indicates recorded and climatological monthly rain, snow and temperatures for the nearest climate station (Fredericton, New Brunswick at 45°52'08" N, 66°32'14" W, 20.70 m a.s.l.). During 2016, monthly air temperature was similar to the climate normal but rain (snow) was substantially lower (higher) than normal from February to April.

AA was a relatively flat trapezoidal site of 3ha with grass (<5 cm) and stumps (<20 cm). AB was hummocky rectangular site of 4.5ha with stumps (<20 cm) and substantial brush and shrubs (<1 m) left over from clearing. AC was a rectangular site of 4.5ha with recently planted Balsam Fir (*Abies balsamea* (L.) Mill.) ranging from 1 m to 5 m in height. AC was also hummocky although shrubs and herbs had covered most stumps. The sites were separated by mature mixed wood stands up to 20 m in height with balsam fir, red maple (*Acer rubrum* L.), and white birch (*Betula papyrifera* Marsh.).



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Figure 2. Acadia region showing Acadia A (red), Acadia B (pink) and Acadia C (gold) sites with

Table 1. Monthly climate data from Chelsea, Quebec (Gatineau region). Normals correspond to 1981 to 2010.

MONTH	T (°C)		Rain-Fall (mm)		Snow-Fall (mm)	
	2016	Normal	2016	Normal	2016	Normal
JANUARY	-9.2	-11.0	97.2	92.7	29.2	47.9
FEBRUARY	-9.8	-8.8	10.0	20.5	41.0	38.7
MARCH	1.0	-2.0	106.0	24.6	5.2	26.5
APRIL	2.5	5.7	21.4	68.4	27.4	6.0
MAY	12.4	12.6	7.2	89.0	0	0

Table 2. Monthly climate data for Fredericton, New Brunswick (Acadia Region). Normals correspond to 1981 to 2010.

MONTH	T (°C)		Rain-Fall (mm)		Snow-Fall (mm)	
	2016	Normal	2016	Normal	2016	Normal
JANUARY	-6.5	0.1	25.4	42.4	10.7	59.5
FEBRUARY	-5.4	7.5	12.0	24.7	89.9	38.4
MARCH	-2.1	2.2	7.2	45.2	82.0	44.0
APRIL	2.7	4.8	20.4	68.1	22.0	12.5
MAY	11.8	11.2	56.7	102.1	0	0.7

5 | Figure 2. Acadia region showing Acadia A (red), Acadia B (pink) and Acadia C (gold) sites with ground control points (crosses) and in situ transects (cyan lines);

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2.2 Ground Control Points

10 | Ground Control Points (GCPs) were established for each site for geolocation of UAV imagery and derived maps. The number and location of GCPs were determined based on Tonkin and Midgley (2016) who assessed the ~~accuracy performance~~ of a digital surface model (DSM) ~~derived from SfM processing of UAV imagery acquired at 100m a.g.l. over a 14.5ha hummocky-grassy landscape derived by applying SfM (Agisoft PhotoScan V1.1.5) to imagery acquired using a Canon EOS M 18 megapixel camera mounted on a hexacopter (altitude 100 m, forward speed 2 ms⁻¹, 95% along track overlap, 75% across track overlap, 2 cm GSD).~~ They observed ~~an average precision of 2.0 cm (83% circular error probably or c.e.p.) in comparison to 530 check points. Moreover, the~~ average (extreme) vertical difference of the DSM was not statistically different when the number of GCPs ranged from 4 (5) to 101. They also observed a statistically significant relationship between the vertical difference and the distance to the nearest GCP leading to their recommendation that GCPs be ideally located within 100 m of mapped DSM locations.

20 | Following the recommendations of Tonkin and Midgley (2016), at least 5 GCPs were positioned within the UAV coverage at each site and at least one GCP near the corner of each site. AC was ~~an exception~~ as GCPs could not be located at the northern edge due to access constraints. Six GCPs were located in GN and 10 GCPs in GS with 95% circular error probably of less than 2.05 cm (Prevost, 2016a). For Acadia, four GCPs were located in AA, five GCPs in AB and two GCPs in AC with a 95% circular error probable of less than 2.46 cm (Prevost, 2016b). GCPs were located using ASHTECT Zextreme dual frequency instruments using precise point positioning.

25 | GCP targets at Gatineau consisted of both 30 cm square plywood (Figure ~~3a2a~~) and 15 cm diameter plastic disks (Figure ~~3b2b~~) suspended between 1 m and 1.3 m above ground level on fence posts or poles to avoid artificially increasing the accuracy of SD estimates by placing control points on the snowpack surface. The targets had a red background with a yellow cross (for boards) or black centre (for disks) marked with tape. Targets were cleaned prior to flights. Based on
30 | experience at Gatineau, GCP targets corresponding to plastic pylons, suspended on fence posts at ~1.3 m height (Figure ~~3e2c~~) were used at Acadia to reduce the need to clear snow from targets (e.g. Figure 2d) and to assist in identifying the centre of the GCP target within UAV imagery. Black tape was used to mark vertical stripes on the cones to increase their visibility.

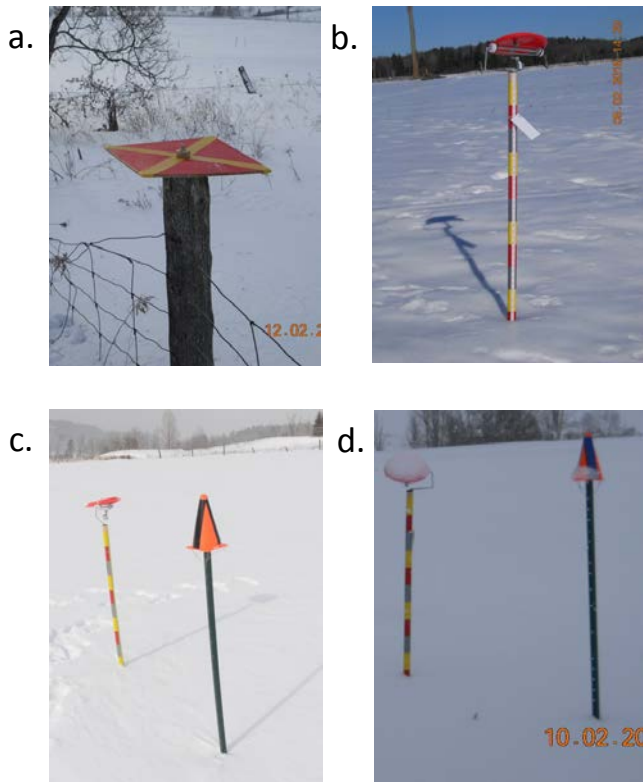


Figure 2. GCP Targets: a) square plywood b) disk on pole and c) snow free disk on pole and cone on pole d) snow covered disk on pole and cone on pole.

Figure 3. GCP Targets: a) square plywood b) disk on pole and c) disk on pole and cone on pole snow free d) disk on pole and cone on pole with snow.

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2.3 In-Situ ΔSD Measurement

Transects of ~50 m length (see Figures 1 and 2) were positioned at each site within 5 m of a GCP. Each site had one transect except for GS where two transects were located (GS-1 in the flat northern portion and GS-2 along and across a spur hillslope leading into the floodplain). Along each transect, twelve 48" x 2" x 1" wooden stakes were placed equally spaced apart ~10 cm deep and approximately vertical and equally spaced apart. Stakes were covered with black all weather tape in

addition to two red bands each 10 cm wide separated by 50 cm (Figure 43). The attitude of the stakes was measured at the start and end of the field season using a digital level to a precision of 0.1°. The elevation of the stakes above the soil layer was measured at the end of the field season using a plumb line and tape measure to a precision of better than +/-0.5 cm (95% confidence interval).

5

In-situ ΔSD was estimated at each stake using the protocol described in Oakes et al. (2016). For snow free conditions, the freeboard (F), defined as the stake height above the current surface, was determined from the plum-bob measurement. Otherwise, F was determined using an in-situ high resolution digital image. For each stake, a 14 Mpixel photograph (Nikon D7000 camera and 70-300 mm / f4.5 Nikon lens) was taken ~5 m parallel to the transect using manual focus and automatic exposure. To reduce precision errors due to localized snow melt or drifting at the stake, the point of intersection of the snow pack and the stake was visually determined by interpolating the snow pack horizon closest to the front of the stake (e.g. Figure 43) rather than within the well (or mound) of snow adjacent to the stake. The distance from the top of the stake to the edge of each visible red-tape band and to the midpoint of the snow pack intersection with the stake was measured in pixel units using Adobe Photoshop. Freeboard was then estimated using the ratio of distances in pixel units and the known distance between bands and converted to a vertical distance using measurements of the stake angle. The difference in F between two dates was used to estimate ΔSD at each stake. When comparing snow covered conditions, the uncertainty for measuring the ΔSD assuming independent errors in determining F is ~2.06 cm (95% confidence interval) for typical uncertainties in delineating F and the stake angle (Oakes et al. 2016). As both sources of uncertainty are spatially random the uncertainty in estimating the average snow depth using all 12 stakes in a transect is ~0.60 cm (95% confidence interval).

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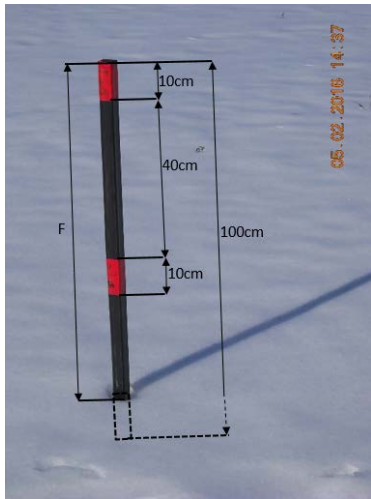


Figure 3. In-situ snow stake measurements. Dashed lines correspond to locations below the snow surface.

Figure 4. In-situ snow stake measurements. Dashed lines correspond to locations below the snow surface.

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2.4 UAV Missions

Missions were performed weekly at Gatineau (26/01/2016 to 19/04/2016) and Acadia (10/02/2016 to 14/04/2016) during periods without precipitation at the start of the mission, using a Phantom Pro 3 Plus UAV (<https://www.dji.com/phantom-3-pro: P3P>). The same P3P-UAV was used for all missions in a given region. Imagery was acquired using the provided gimbal mounted 12.4 Mpixel rolling-shutter camera with a f2.8 fixed aperture in auto-exposure mode recording in 4K MPEG-4 AVC/H.264 format (MP4) (Table 3 see Supplementary Material Table S1). MP4 was used in preference to full resolution photographs since i) the system firmware limited the maximum photograph sampling rate to 1 frames/2s and ii) the 4K video frames have almost identical resolution to the full resolution photographs (Leblanc 2018). Auto-exposure mode was used since the flights encountered rapid variations between sunlit and shaded snow and vegetation areas making it challenging to adjust exposure manually during the flight.

Table 3. UAV Specifications

PARAMETER	VALUE	ABBREVIATION
MASS	1280g	=
OPERATING TEMPERATURE	0 ^o C to 40 ^o C	T
FLIGHT TIME PER BATTERY	23 minutes	t_{max}
MAXIMUM CRUISING SPEED	16 m/s	v
VERTICAL PRECISION	0.5 m	δ_z
HORIZONTAL PRECISION	1.5 m	δ_x
LENS FOCAL LENGTH	3.66624 mm	e
CAMERA APERTURE	f2.8	F
DIAGONAL FIELD OF VIEW	94 ^o	θ
CAMERA SENSOR	Sony Exmor IMX377	-
DETECTOR SIZE	1.55 cm	l
#VERTICAL PIXELS	3044 pixels	-
#HORIZONTAL PIXELS	4072 pixels	-
VIDEO FRAME RATE	24 frames/s	f_{max}
VIDEO VERTICAL RESOLUTION	2160 pixels	n_y
VIDEO HORIZONTAL RESOLUTION	4096 pixels	n_x
VIDEO EFFECTIVE DETECTOR SIZE	1.57937 cm	l_e

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5 Lichee V3.0.4 (<https://flylitchi.com/new>) flight planning software was used to create flight plans. The same flight plan was used for all missions at a given site. Flight plans were defined using equally spaced parallel linear tracks flying oriented North to ensure consistent locations of shadows between dates. The exception was AC where tracks were oriented parallel to the GPS targets at AB to maximize overlap over these targets. Cross tracks were not used since this would increase flight time and since [NasurallahNasrullah](#) (2016) found that they did not significantly improve point cloud accuracy or density when using data acquired using a similar consumer grade UAV and SfM software. Flight plans, using nadir view geometry, were defined to cover rectangular (triangular in the case of [Acadia AAA](#)) regions with a buffer of 100 m to ensure adequate side views at the edges of each study area and to include GCPs from adjacent sites. Flights were planned such that the UAV was always flying along the vertical axis of the camera to minimize post processing complexity. Turns were limited to 90° with smoothing of arcs to provide adequate side overlap during the turn.

15

For convenience, missions were constrained to a single P3P battery. Since surveys were to be conducted in cold and windy conditions a maximum flight time (~~t_{max}~~) of 17.25 minutes was used for flight planning. The effective time for image acquisition (~~t_{eff}~~) was further reduced to 15 minutes to accommodate travel time to and from the launch location and to execute turns between flight tracks. Mission parameters were optimized to minimize the vertical precision error in altitude H (σ_H) derived from the block triangulation of images at matching key points covering a nominal mapped extent of 10ha. For a matching key point found in K images each acquired at a lateral distance of d_k from the key point (Forstner, 1998):

$$\sigma_H = \frac{H^2}{c} \frac{\sigma_x \sqrt{12}}{\sqrt{\sum_{k=1}^K d_k^2}} \quad \text{_____ (1)}$$

10 where σ_x is the average horizontal uncertainty when matching the location in each image pair on the camera focal plane and c is the lens focal length. Ignoring edges of flight tracks, $\{d_k\}$ and therefore σ_H will be a function of the along track image spacing (b_y), the across track image spacing (b_x) and H . With 4K video it is generally possible to chose a frame sampling rate f such that $b_y \leq b_x$.

15 Eq. 1 assumes that matches are found in all overlapping images. Based strictly on geometric considerations, for the P3P with $H \leq 100m$ and $b_x < 40m$ we ~~have expect~~ $K > 20$ matches. In practice, K is much less than 20 due to the difficulty in matching the same feature in multiple images (Nasrullah, 2016). Adopting the worst case assumption that the matched images are closest to the key point location and assuming similar along and across track spacing, from Forstner (1998):

$$20 \quad \sigma_H \leq \frac{H^2}{cb_x} \frac{\sigma_x \sqrt{12}}{\sqrt{K(K^2-1)}} \quad \text{_____ (2)}$$

Here, σ_x was estimated as the Euclidean sum of the mean reprojection error after block adjustment σ_{re} , the uncorrected motion blur during integration of the detector ~~signal~~ (~~signal~~ (σ_m), and the uncorrected rolling shutter motion (σ_{rs}).

$$25 \quad \sigma_x^2 = \sigma_{re}^2 + \sigma_m^2 + \sigma_{rs}^2 \quad \text{_____ (3)}$$

Mean reprojection error is computed during block adjustment by the PIX4D Mapper Pro. Motion blur is given by

$$30 \quad \sigma_m = \frac{v_y c \tau_e}{Hl} \quad \text{_____ (4)}$$

where v_y is the along track velocity, c is the lens focal length, τ_e is the exposure time and l is the detector size along track. Rolling shutter correction error is determined by the uncertainty in v and the sensor readout time τ_s :

$$\sigma_{rs} = \sigma_v \frac{c\tau_s}{Hl} \quad \text{-----}(5)$$

Estimates of K , σ_{re} , σ_m and σ_{rs} were required to ~~model optimize σ_H with respect to flight parameters.~~ Trial flights using parameters given in Table 4.2 were performed at both GN and GS on one sunny ~~day~~ (January 26, 2016) and one overcast ~~day~~ (February 2, 2017) ~~day~~ with complete snow cover and processed using Pix4D Version 3.0. The lowest feasible H of 50 m (to ensure clearance of terrain and cover a 10 ha site using one battery) was selected to provide a best case estimate of K corresponding to the smallest feasible GSD.

Table 4.2. ~~Mission parameters for all flights.~~ The nominal 10ha study area assumes a rectangular region with 300 m transects.

Parameter	Value	Abbreviation
Height	50 m	H
Speed	15-3.5 m/s	v
Ground Sampling Distance	0.021 m	GSD
Effective Shutter Speed	<0.02 s	τ_e
Motion Blur	0.039 pixels	None
Track spacing	15 m	b_{ac}
Frame sampling interval	1 s	None
Across Track Overlap	82%	None
Along Track Overlap	93%	None
Minimum study area	10 ha	A

Figure 5.4 indicates that K followed an exponential distribution that was relatively consistent over the four flights. Key points with $K = 2$ matches ~~are were~~ discarded as insufficiently accurate to include in the σ_x estimation. In this case, the average K over the four missions was 5.5 matches with a range of 4.3 matches to 7.4 matches. The two overcast dates had lower than average K while the sunny dates were above average. These values of K are substantially lower than the maximum possible K based only on geometric considerations but are similar to values reported in Nasrullah (2016).

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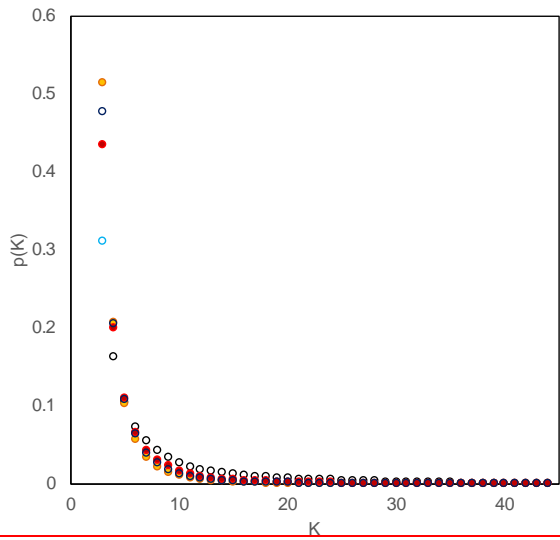


Figure 4. Empirical probability of observing K matches for key points acquired during four trial missions (filled symbols are for overcast dates)

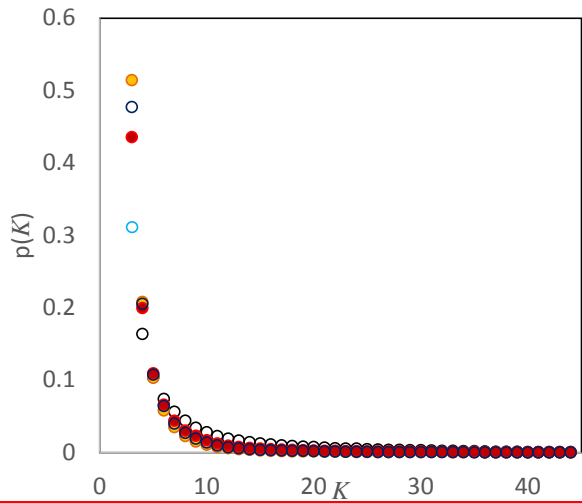


Figure 5. Empirical probability of observing K matches for points acquired during four trial missions (filled symbols are for overcast dates)

For the four test flights σ_{re} ranged of 0.179 pixels to 0.209 pixels, and τ_e ranged from 0.017 s to 0.005 s. Worst case values of $\sigma_{re} = 0.25$ pixels and $\tau_e = 0.02$ s were used for selecting flight parameters. We did not have sufficiently accurate on-board sensors to provide reference values of σ_v . Instead, we relied on a published comparison of v based on imagery from a PIX4D block adjustment and on-board measurement (Vautherin et al., 2016) indicating $\sigma_v \approx 0.05 v$.

5

Using measurements from the training flights the relationship between σ_H and H was modelled for the average and extreme values of K using the 10ha minimum area constraint to relate v_y to b_x . Figure 6-5 indicates ~~shows~~ that σ_H increases almost linearly with H for any given K although the rate of increase is steeper for low K . This result indicates it is critical to select the lowest feasible H . At $H = 50 m$ the sensitivity of σ_H to b_x is negligible ($<10\% \sigma_H$) for $15 m \leq b_x \leq 30 m$. Here we selected $b_x = 15 m$ to maximize across track overlap since we were able to increase f to achieve a constant along track overlap irrespective of b_x . This was important since ~~the density of key point matches per square metre mapped the density of keypoints(D)~~ increases with overlap with all other parameters fixed (Nasrullah 2016). The selected flight parameters predict a $\sigma_H = 1.44 cm$ for $K = 5$ matches (ranging from $\sigma_H = 0.92 cm$ for $K = 8$ matches to $\sigma_H = 3.73 cm$ for $K = 3$) matches. As ~~ΔSD_{ASD}~~ was ~~later~~ estimated by computing the temporal difference of DSM (Sect. 2.7) the precision error ~~in~~ ΔSD , assuming uncorrelated errors in H between two dates, corresponds to the Euclidean sum of σ_H for each date. Ignoring uncertainty due to surface roughness for snow free conditions, $\sigma_{\Delta SD} = 1.2 cm$ where both dates have $K = 8 m$ matches, $\sigma_{\Delta SD} = 2.14 cm$ where both dates have $K = 5 m$ matches and a worst case $\sigma_{\Delta SD} = 5.25 cm$ where both dates have $K = 3$ matches.

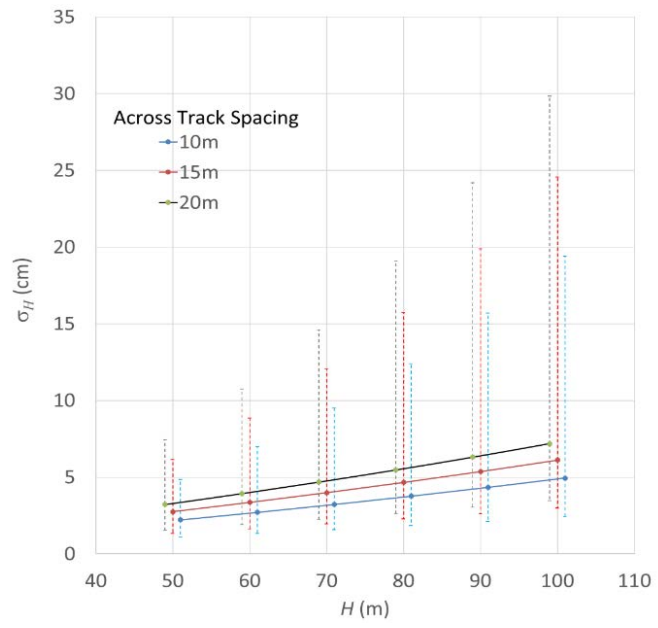
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Each UAV mission resulted in two consecutive MP4 videos (due to a limitation of 3.91Gbytes for a single MP4 file) and an ephemeris file providing the P3P position and attitude with a temporal resolution of about 0.1s. Data from each mission was processed in Pix4D Mapper PRO Version 3.2 (<https://pix4d.com/product/pix4dmapper-photogrammetry-software/>) as described in the Supplementary Material.

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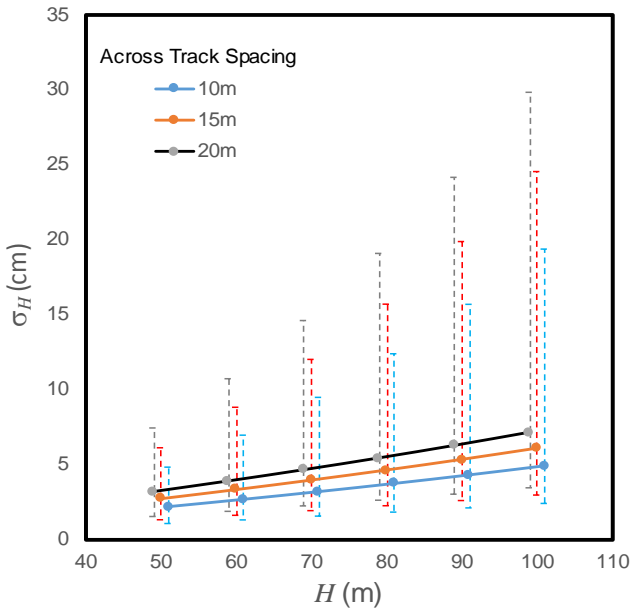


Figure 5. Theoretical relationship between vertical uncertainty and UAV height. Solid lines correspond to five matching images per key point. Upper (lower) bars correspond to three (eight) matching images per key point.

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Figure 6. Theoretical relationship between vertical uncertainty and UAV height. Solid lines correspond to 5 matching images per point. Upper (lower) bars correspond to 3(8) matching images per point.

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2.5 UAV Video Processing

Each UAV mission resulted in two consecutive MP4 videos (due to a limitation of 3.91Gbytes for a single MP4 file) and an ephemeris file providing the P3P position and attitude with a temporal resolution of about 0.1s. Data from each mission was processed in Pix4D Mapper PRO, Version 3.2 (<https://pix4d.com/product/pix4dmapper-photogrammetry-software/>) as follows:

- I. ~~The two videos were subsampled with a 1s interval and extracted as JPEG images together with ephemeris data to provide an initial location for each image. The 1s interval ensured the desired minimal along track overlap while minimizing computation.~~
- II. ~~Nominal geolocation uncertainty was specified as 5 m horizontal and 10 m vertical considering that the P3P was always operating within Wide Area Augmentation System coverage.~~
- III. ~~Camera parameters were initialized using the P3P Video specification with rolling shutter.~~
- IV. ~~An initial camera calibration and point cloud was produced using the Pix4D algorithm for feature matching and bundle adjustment with rolling shutter correction.~~
- V. ~~Each GCP was manually geolocated in as many (at least 10) JPEG images as feasible.~~
- VI. ~~Feature matching was repeated and internal and external camera parameters refined using bundle adjustment with rolling shutter correction at the highest quality setting.~~
- VII. ~~If the GCPs were not fit within 5 cm root mean square difference (RMSD) steps V. and VI. were repeated once.~~
- VIII. ~~The point cloud was densified using the Pix4D default two pixel sub sampling of images.~~
- IX. ~~The resulting dense point cloud (PC) was exported to MATLAB in XYZ format.~~
- X. ~~To quantify the geolocation uncertainty of the point cloud the internal and external camera parameters were refined while holding out individual GCPs.~~

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20 2.6 Assessment of Micro-topography

Micro-topography was assessed for each transect within each site using a snow free PC acquired within one week of complete snowmelt. ~~Since compressed~~ ~~Compressed~~ ~~vegetation was included within micro-topography since it~~ ~~vegetation~~ ~~also acts to bias estimates of $SASD$ (Harding et al. 2016) from our UAV approach.~~ ~~Micro-topography was quantified as~~ ~~the deviation from a local robust linear slope trend (MATLAB function 'lmfit' with robust option,~~ ~~<https://www.mathworks.com/help/stats/fitlm.html>) with a 15 m moving window oriented along the transect. Deviations~~ ~~greater than the maximum snowpack elevation at each transect during the season were removed when computing the~~ ~~root~~ ~~mean square deviation RMSD~~ over a transect to eliminate overstory vegetation that normally would be above the snowpack.

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30 2.7 Elevation and Overstory Cover Extraction

Surface elevations were extracted from each PC in a sampling region around each stake. The sampling region was held constant for all missions over a given site. The sampling region corresponded to a 2 m tall vertical elliptic cylinder centred on the nominal horizontal location of a stake and extended 50 cm below the nominal vertical location of a stake. The horizontal (vertical) centre of the sampling region was specified as the average (average less 50 cm) of the visually determined location of the base of the stake from the colorized PCs for two missions acquired during sunny conditions with less than 5 cm snow depth. The 50 cm vertical offset was required to account for both PC geolocation uncertainty and local topography (including snow pits due to melt at the base of the stake) close to the stake. The horizontal major and minor axes of the cylinder were specified to approximate twice the Euclidean sum of geolocation uncertainty of the PC and the typical geolocation uncertainty of the stake corresponding to the difference between both reference image locations. These considerations typically resulted in horizontal axes lengths ranging from 10 cm to 24 cm depending on the precision of the stake geolocation between reference images.

The average overstory vegetation cover in the vicinity of transect sampling locations was estimated for each UAV mission. Overstory vegetation cover near each stake was estimated for a 1 m radius cylinder centred horizontally at each nominal stake location as the fraction of grid cells where at least one other point was found vertically above a surface point. A 1 m radius was used as an approximation of points within the field of view of images used to map the elevation in the smaller region used around each stake.

2.8 ΔSD Estimation from Point Clouds

ΔSD was estimated for each transect using geolocated PCs. For each PC, snow cover points were identified in each sampling window-region using points exceeding the 50th percentile of the blue band in a sampling region. The blue band was used as a simple indication of snow considering that vegetation and shadows should both have substantially lower blue intensity in a region with similar view geometry and similar top of canopy illumination conditions (Miller et al., 1997). To minimize bias due to the presence of melt depressions at the base of each stake and due to snow on vegetation, the median elevation of snow cover points within the sampling region was used to represent-estimate the snow surface elevation at each-stake-the corresponding stake.

~~The snow free surface elevation from a PC produced using a UAV flight over snow-free conditions within one week after complete snowmelt. For each sampling region, the snow free elevation~~ was estimated as the median elevation of all points falling in the sampling window, that were unobstructed by points vertically below them, ~~for a PC produced using a UAV flight over snow free conditions within one week after complete snow melt.~~ For each UAV flight, the average ΔSD across all sampling windows for the transect was used to estimate the transect ΔSD . The precision of ΔSD was estimated using the central 67.5%ile interval of sampled ΔSD within the transect to include both measurement error and natural variability.

2.9 Performance Assessments

The performance of geolocated DSMs ~~and~~ ΔSD , in comparison to reference values from GCPs and in-situ transects respectively, was ~~reported~~ quantified in terms of accuracy, precision and uncertainty statistics following ~~(ANSI/NCSL7 (1997).~~ Here accuracy is defined as the mean difference between sampled validated and reference data (i.e. the bias), precision is the RMSD after subtracting the accuracy from the validated data, and uncertainty is the RMSD between the validated and reference data. For convenience, we use the term 'bias' for accuracy and 'RMSD' for uncertainty when discussing DSMs and ΔSD performance. In contrast to previous studies that report RMSD in comparison to individual in-situ sample locations, assessments were performed using transect averages since addressing the broader research goal of combining in-situ and UAV based ΔSD requires an assessment of UAV estimates of ΔSD over a sampling footprint comparable to the reported in-situ measurement (i.e. transect average at ruler locations).

Camera calibration performance was assessed in terms of the percentage of images (P) successfully calibrated using a single block adjustment, the number of key point matches per image, ~~and~~ D ~~the density of keypoint matches per square metre mapped (D).~~

3.0 Results

3.1 Data Acquisition

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UAV flights were conducted on 13 days at Gatineau and 16 days at Acadia resulting in ~~64~~74 missions. For brevity, results for a mission are referenced using the site acronym followed by the date (e.g. GS 26/01/2016 is the Gatineau ~~south~~South mission for 26/01/2016). Flights were performed between 10:00 and 14:00 local time. Environmental conditions for each date are provided in Tables ~~5-3~~ and ~~6-4~~ based on the nearest climate station. Maximum daily temperatures at Gatineau (Acadia) ranged from -7.6 °C (-9.0 °C) to 14.5 °C (11.5 °C) and can be considered representative of typical temperature variability during late winter and spring melt periods. Hourly average wind speed at 10m a.g.l. ranged from 3 ~~m/s~~km/hr to 26 ~~m/s~~km/hr although the higher value may not be representative of local conditions since flights were not conducted if there was strong evidence of surface gusts or swaying conifer trunks. Sky conditions included both cloudy and overcast with one instance (GN 10/02/2016) where snow was falling. Snowpack conditions included fresh snow, icy snow, wet snow, patchy snow (incomplete cover) and snow free. Ephemeral melt, preceded by over 10 mm of rain, occurred at both Gatineau (02/02/2016) and Acadia (18/02/2019).

Three missions were not processed due to issues with the recorded data. In one case (GS 26/01/2016) the camera was pointed horizontally rather than nadir looking down. In the other two cases (AA 23/02/2016 and AC 10/03/2016) the mission was aborted due to a communication error between the flight controller and the UAV. It was later determined this error was due to a conflict between automatic updates of the Lichee software and manual updates of the P3P control software.

~~Three missions were not processed due to issues with the recorded data. In one case (GS 26/01/2016) the camera was pointed horizontally rather than nadir looking down. In the other two cases (AA 23/02/2016 and AC 10/03/2016) the mission was aborted due to a communication error between the flight controller and the UAV. It was later determined this error was due to a conflict between automatic updates of the Lichee software and manual updates of the P3P control software.~~

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Table 53. Environmental conditions during P3P missions over Gatineau. Rain and snow correspond to cumulated totals since previous mission. Melt periods are in bold font.

DATE	T _{MAX} °C	CUM. RAIN MM	CUM. SNOW CM	WIND SPEED <u>KM.HR⁻¹MS⁻¹</u> +	SKY CONDITIONS	SNOW CONDITIONS
2016-01-26	-5.5	No data	No data	12	Clear	Icy
2016-02-02	0.5	10.8	1.6	3	Clear	Wet
2016-02-10	-3.5	0	6.4	4	Snowing	Dry
2016-02-12	-5.5	0	2.0	10	Overcast	Fresh Snow
2016-02-17	0.5	0	23.6	3	Overcast	Icy
2016-02-18	-6.5	0	0.6	7	Clear	Dry
2016-02-22	-7.6	10.0	5.4	11	Clear	Icy
2016-02-29	0.1	27.4	9.2	9	Overcast	Dry
2016-03-04	-6.0	0	9.1	10	Clear	Icy
2016-03-17	7	33.4	0	6	Clear	Wet
2016-03-21	4	0	0	18	Clear	Wet
2016-03-26	3.8	11.0	5.2	11	Clear	Wet
2016-04-19	14.5	72.4	0	22	Clear	Bare

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Table 64. Environmental conditions during P3P missions over Acadia. Rain and snow correspond to cumulated totals since previous mission. Melt periods are in bold font.

DATE	T _{MAX} °C	CUM. RAIN MM	CUM. SNOW CM	WIND SPEED MSKM·HR ⁻¹	SKY CONDITIONS	SNOW CONDITIONS
2106-02-10	-3.0	0	22.8	9	Clear	Dry
2016-02-18	0	26.1	1.6	11	Clear	Wet
2016-02-19	-1.0	22.0	6.0	26	Clear	Wet
2016-02-23	-8.0	5.4	0	10	Clear	Wet, Patchy
2016-03-04	-3.5	50.0	0	21	Clear	Wet, Patchy
2016-03-06	-2.0	0	0	25	Clear	Wet, Patchy
2016-03-08	4.0	0	2.0	24	Clear	Wet, Patchy
2016-03-10	4.0	5.5	0	18	Overcast	Wet, Patchy
2016-03-11	0	0	4.3	11	Overcast	Dry
2016-03-14	0	0	0	13	Clear	Dry, Patchy
2016-03-20	-9.0	0	0	13	Clear	Dry
2016-03-23	-1.0	19.0	0	18	Overcast	Icy
2016-03-24	-8.0	0.5	12.2	5	Overcast	Fresh Snow
2016-03-26	-2.0	11.2	4.0	4	Clear	Dry
2016-03-30	3.0	39.3	0	13	Clear	Fresh Snow
2016-04-14	11.1	65.8	0	15	Overcast	Bare

5

3.2 UAV Data Processing

~~SixtySeven~~one missions were processed with Pix4D (~~details in details provided in Appendix 4~~Supplementary Material). ~~Of these, (~~Three missions over GN, ~~corresponded corresponding~~ to either snowing or icy snow conditions, resulted in <500 matches/image and subsequently $P < 50\%$. Two other missions (GN 29/02/2016) and (AB 08/03/2016) also resulted in $P < 50\%$ ~~less than 50% images with successfully calibrated virtual cameras~~. During both of these missions, there was spatially uniform fresh snow that possibly reduced the number of spatial features suitable for matching. The remainder of the missions were each processed using a single block adjustment with a median $P = 97\%$ (minimum = 80%).

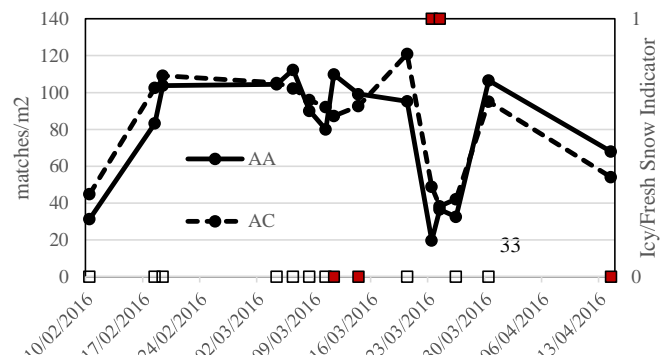
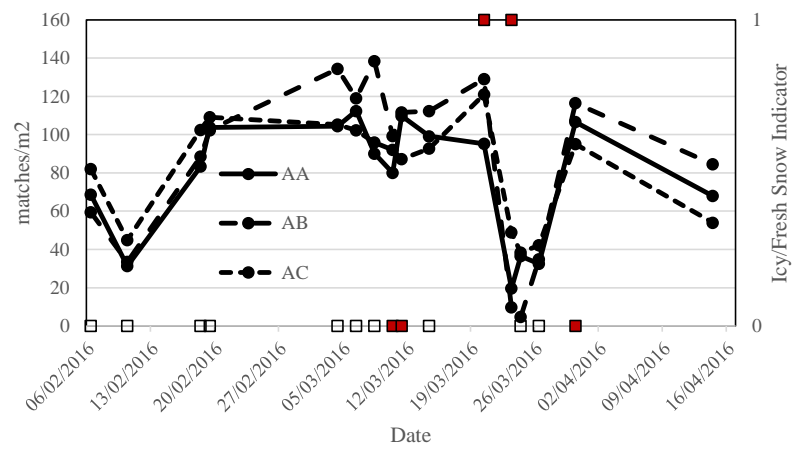
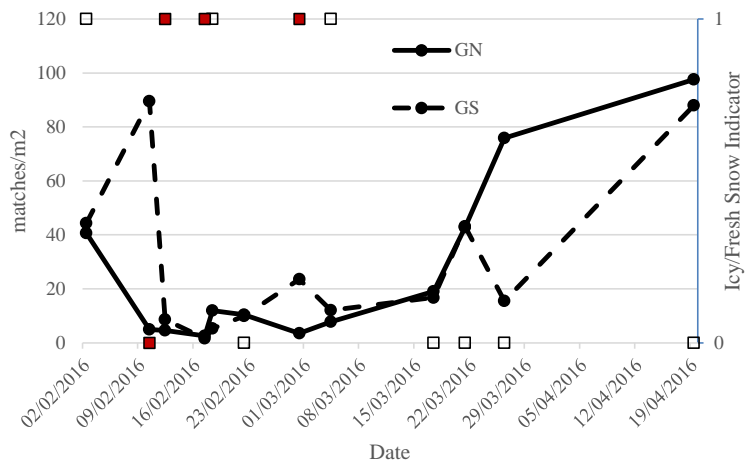
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The key ~~_~~point match density varied ~~significantly-substantially~~ between missions and sites (Figure 76). Fresh snow or ice conditions resulted in $D < 10$ ~~ma~~matches/m² irrespective of the site. Season average D was higher over Acadia (83 matches/m²) than Gatineau (28 ~~ma~~matches/m²) even considering only dates without icy or fresh snow (91 matches/m² for Acadia versus 42 matches/m² for Gatineau). For dates at or exceeding the median D , K ranged from 4 to 8 (not shown). Pix4D does not provide a similar statistic over sub-areas. Missions with differing sky conditions but constant snowpack conditions only occurred at AA for one pair of dates (08/03/2016 and 10/03/2016) when missions were repeated due to instrument failure on the first date at AB. For these two missions, D was higher under clear versus overcast conditions but there was insufficient replication to determine if this impacted ΔSD estimation.

~~Horizontal uncertainty ranged from 0.44 cm to 11 cm with a median of 1.87 cm while the vertical uncertainty ranged from 0.045 cm to 4.6 cm with a median of 1.02 cm (Figure 8). Over 75% of missions resulted in a geolocation uncertainty under 4 cm in both horizontal and vertical. Uncertainty less than 0.5 cm RMSD were only observed for missions with $D > 50$ matches/m² but uncertainty was unrelated to D past this matching density. Horizontal accuracy ranged from -0.68 cm to 0.57 cm (median -0.01 cm) and vertical accuracy ranged from -1.10 cm to 0.48 cm (median -0.04 cm) (Figure 97a). There was evidence of a linear relationship between vertical and horizontal accuracy after accounting for outliers. Horizontal uncertainty ranged from 0.44 cm to 11 cm with a median of 1.87 cm while the vertical uncertainty ranged from 0.045 cm to 4.6 cm with a median of 1.02 cm (Figure 7b). Over 75% of missions resulted in a geolocation uncertainty under 4 cm in both horizontal and vertical. Uncertainty less than 0.5 cm RMSD was only observed for missions with $D > 50$ matches/m² but uncertainty was unrelated to D past this matching density. Horizontal precision ranged from 0.04 cm to 10.7 cm (median 1.76 cm) and vertical precision ranged from 0.04 cm to 4.5 cm (median 0.99 cm) (not shown). A least absolute residual regression of vertical versus horizontal precision gave an adjusted r^2 of 0.97 with a slope of 1.11 (95% confidence interval [1.04,1.18]). Precision error was closely related to uncertainty due to the low bias relative to uncertainty (not shown). Similar to accuracy, a least absolute residual regression of vertical versus horizontal precision gave an adjusted r^2 of 0.95 with a slope of 0.58 (95% confidence interval [0.54, 0.62]). The effect of sky condition on geolocation performance was not systematic across the entire dataset. There were insufficient replicates having the same surface conditions but different sky conditions to perform a quantitative analysis of this effect on geolocation performance.~~

~~As expected, micro-topographic roughness increased from qualitatively smooth to rough sites with average RMSD values under 5 cm at Gatineau, between 5 cm and 10 cm at Acadia-AA and AB and 42 cm at Acadia-CAC (Figure 408). AC indicated the presence of high spatial frequency variation (length scales < 10 cm) that were due to low vegetation rather than variation-s in ground surface elevation *per se*. Figure 9 indicates that for conditions other than icy/fresh snow, except for the forested AC site, D increased with micro-topographic roughness. Key point density was lower for icy/fresh snow conditions versus other conditions at all sites; decreases ranged from ~35% at AC to ~1000% at GS. The season average~~

decrease was only different from zero at a significance level of 0.05 when the RMSD related to topographic roughness was less than 0.08 (i.e. GN, GS and AA).



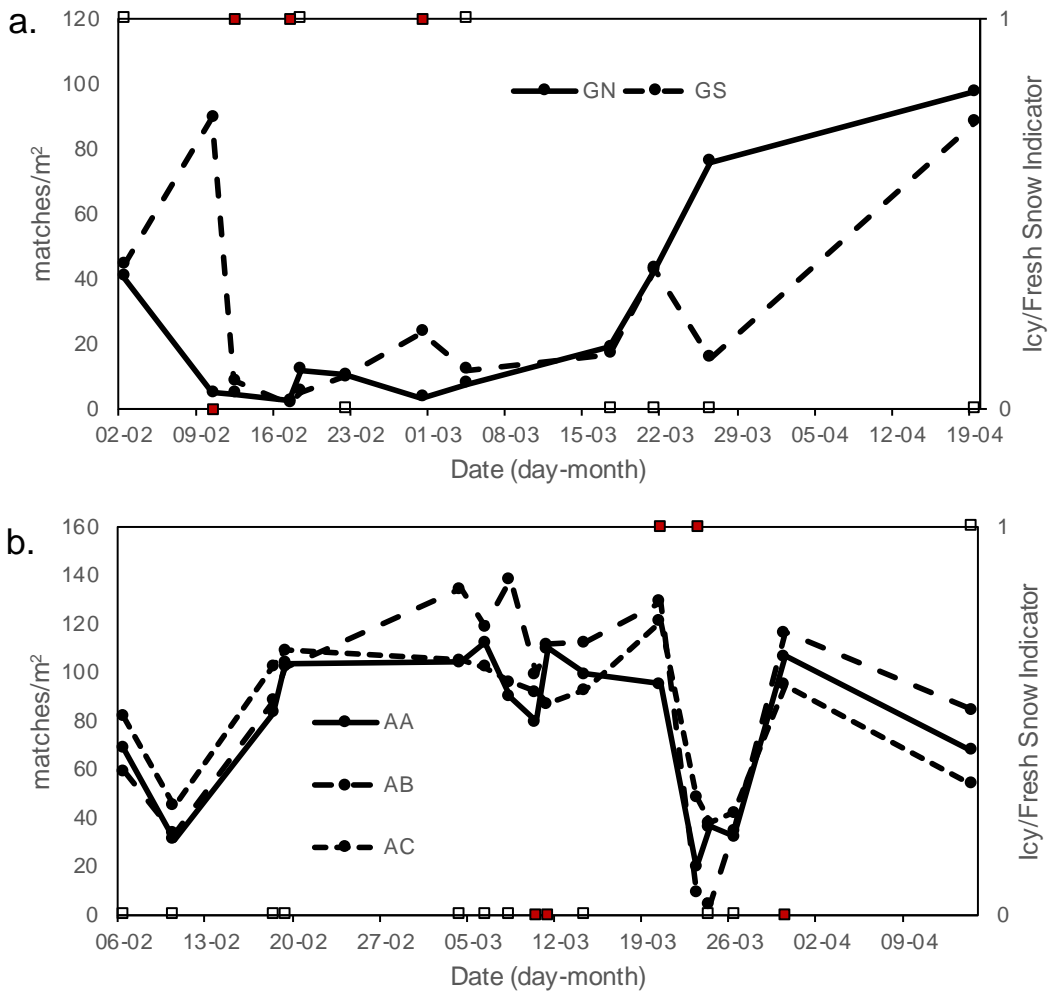


Figure 6. Pix4D automated key point match density for (a) Gatineau and (b) Acadia together with an indicator of fresh snow (square symbols). Missions (solid circular symbols) for the same site are connected by lines. Red squares indicated overcast conditions.

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Figure 7. Pix4D automated tie point match density for Gatineau (upper panel) and Acadia (lower panel) together with indicator of fresh snow (square symbols). Missions (solid circular symbols) for the same site are connected by lines. Red squares indicated overcast conditions.

Horizontal uncertainty ranged from 0.44 cm to 11 cm with a median of 1.87 cm while the vertical uncertainty ranged from 0.045 cm to 4.6 cm with a median of 1.02 cm (Figure 8). Over 75% of missions resulted in a geolocation uncertainty under 4 cm in both horizontal and vertical. Uncertainty less than 0.5 cm RMSD were only observed for missions with $D > 50$ matches/m³ but uncertainty was unrelated to D past this matching density. Horizontal accuracy ranged from -0.68 cm to 0.57 cm (median -0.01 cm) and vertical accuracy ranged from -1.10 cm to 0.48 cm (median -0.04 cm) (Figure 9). There was evidence of a linear relationship between vertical and horizontal accuracy after accounting for outliers. Horizontal precision ranged from 0.04 cm to 10.7 cm (median 1.76 cm) and vertical precision ranged from 0.04 cm to 4.5 cm (median 0.99 cm) (not shown). A least absolute residual regression of vertical versus horizontal precision gave an adjusted r^2 of 0.97 with a slope of 1.11 (95% confidence interval [1.04, 1.18]). Precision error was closely related to uncertainty due to the low bias relative to uncertainty (not shown). Similar to accuracy, a least absolute residual regression of vertical versus horizontal precision gave an adjusted r^2 of 0.95 with a slope of 0.58 (95% confidence interval [0.54, 0.62]).

As expected, micro topographic roughness increased from qualitatively smooth to rough sites with values under 5 cm at Gatineau, between 5 cm and 10 cm at Acadia A and B and 42 cm at Acadia C (Figure 10). AC indicated the presence of high spatial frequency variation (length scales <10cm) that were due to low vegetation rather than variation in ground surface elevation per se.

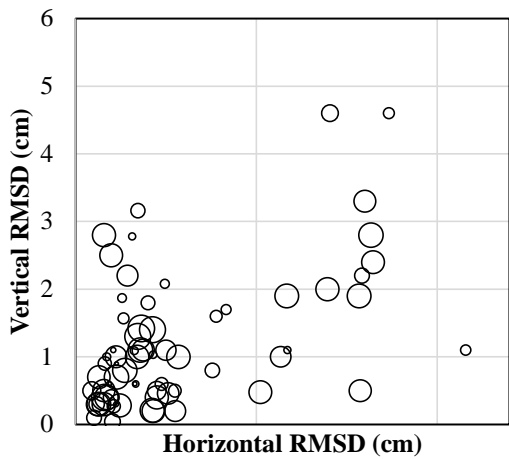
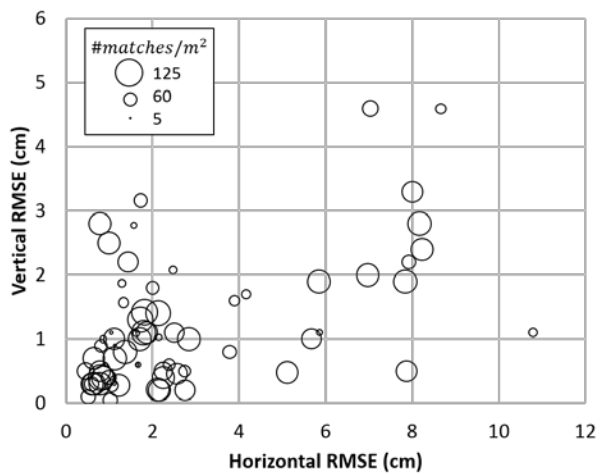


Figure 8. Uncertainty of absolute geolocation for digital surface models based on cross-validation with GCPs.

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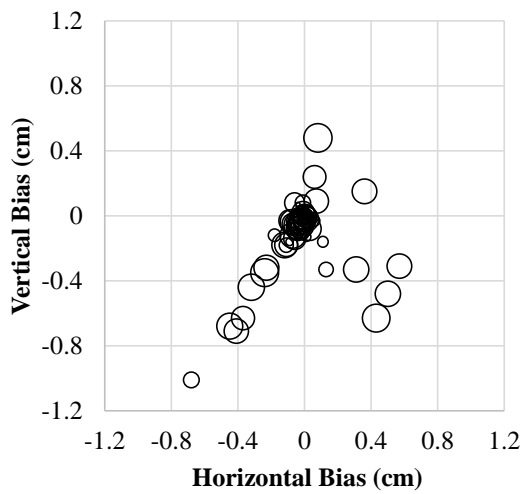


Figure 9. Accuracy of absolute geolocation for digital surface models based on cross validation with GCPs.

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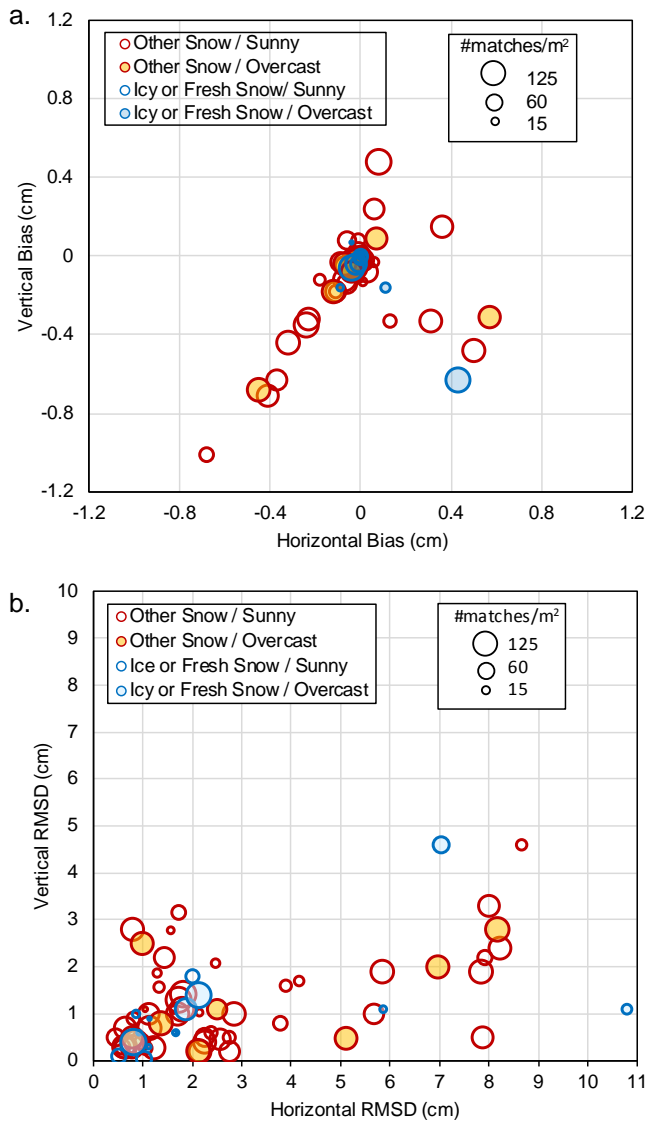
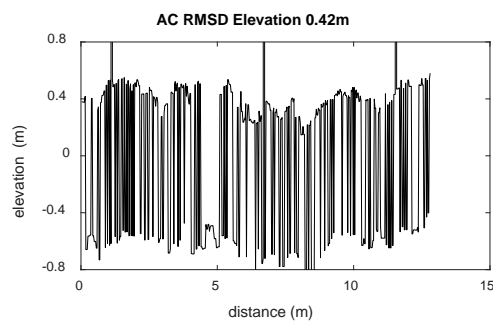
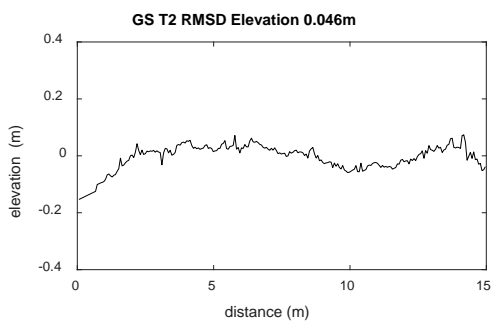
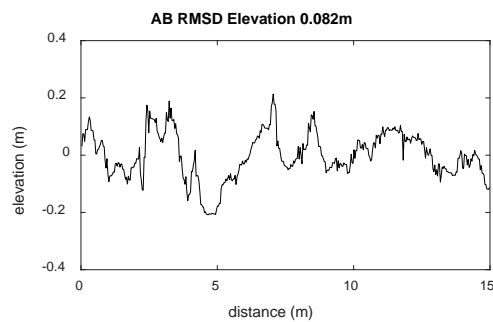
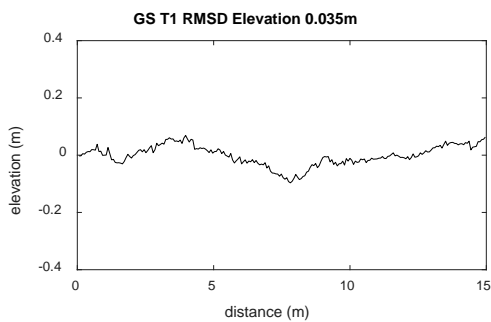
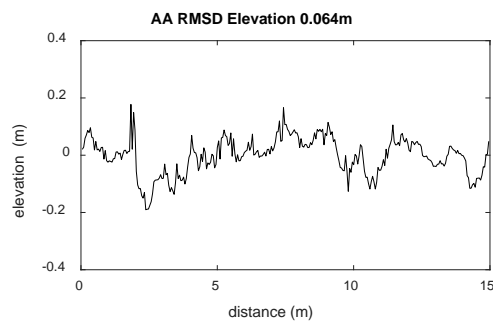
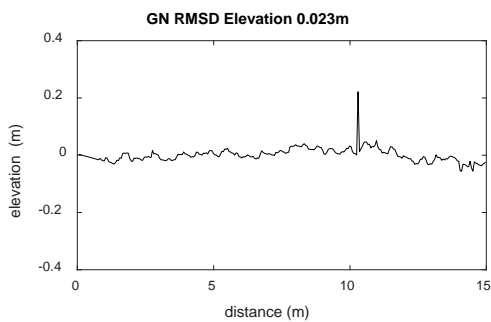


Figure 7. (a) Accuracy and (b) uncertainty of absolute geolocation for digital surface models based on cross-validation with GCPs. Symbol area proportional to mission average key point match density.

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Figure 8. Deviations from local robust linear trend (based on 15 m moving window) of densified point cloud elevations along each transect. Only the first 15 m of each transect are shown for clarity. The root mean square deviation (RMSD) for elevations over the entire transect is also indicated. AC is truncated as the transect consisted of shorter line segments.

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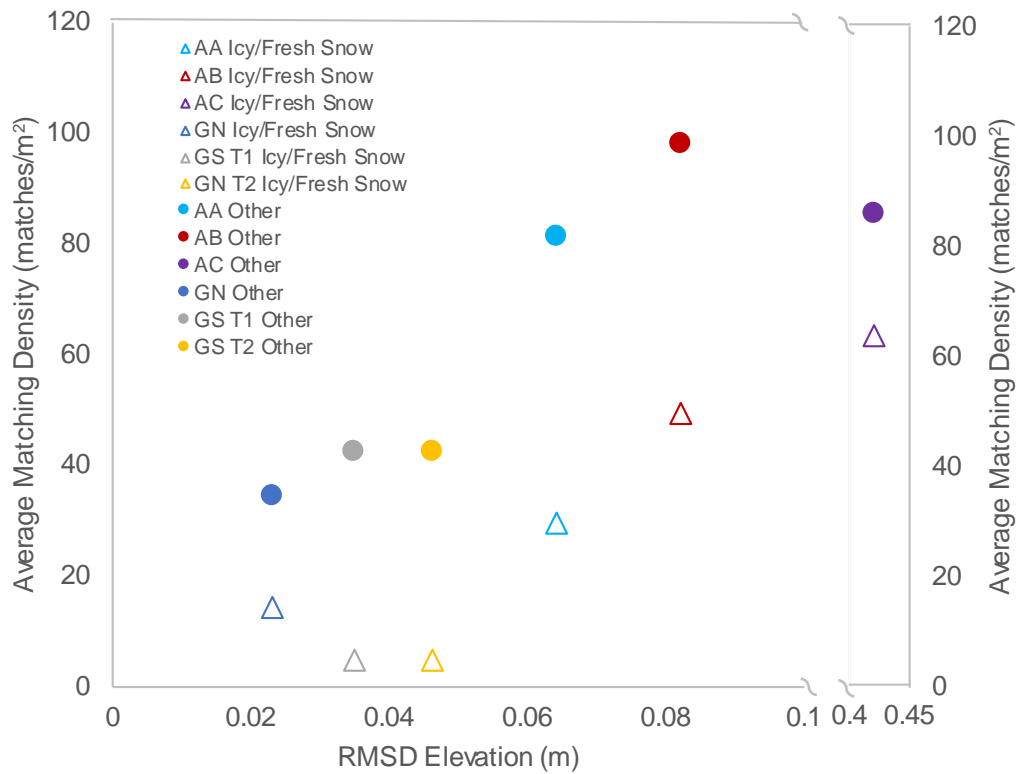


Figure 9. Season average key point matching density versus root mean square deviation (RMSD) of elevation deviation along transect for icy and fresh snow missions (hollow triangles) and “other” missions with snow cover (solid circles) during snow covered periods. The difference in season average matching density between icy/fresh snow and “other” was statistically significant at $p=0.05$ for $RMSD < 0.8$ (plots GN, GS, AA) but not statistically different at $p=0.15$ for $RMSD < 0.8$ plots AB, AC).

The effect of hourly average wind speed on either D_{geo} , geolocation accuracy or geolocation uncertainty was also evaluated at each site using ordinary least squares regression. For each site, the r^2 was below 0.5 and the slope was not significantly different from 0 at $p=0.05$. As with sky condition there were insufficient trials to control for snow surface condition when evaluating the effect of wind speed.

Figure 8. Uncertainty of absolute geolocation for digital surface models based on cross-validation with GCPs.

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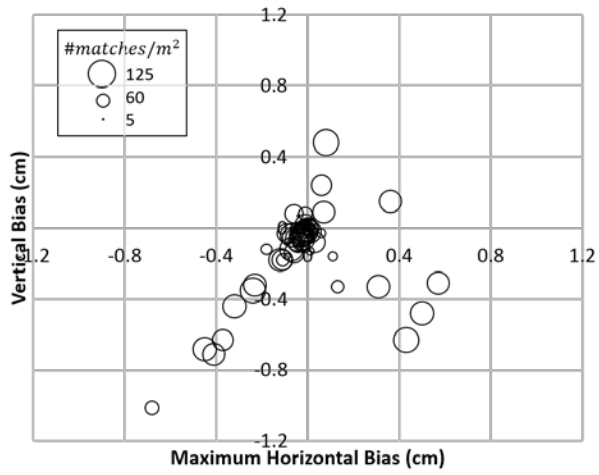
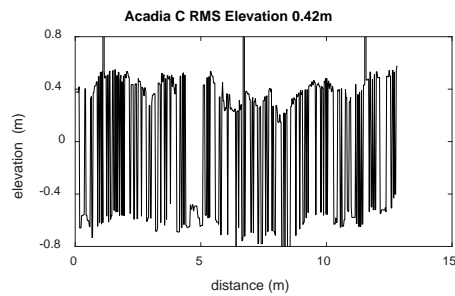
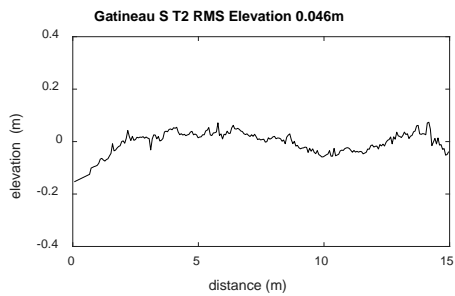
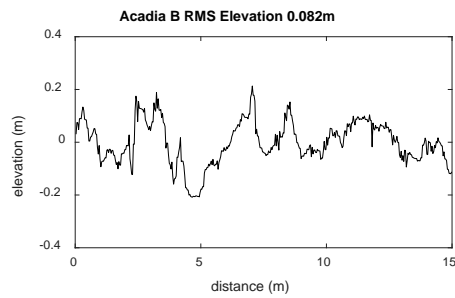
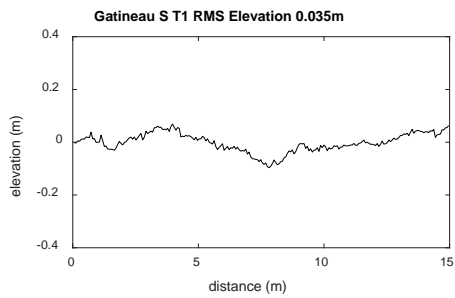
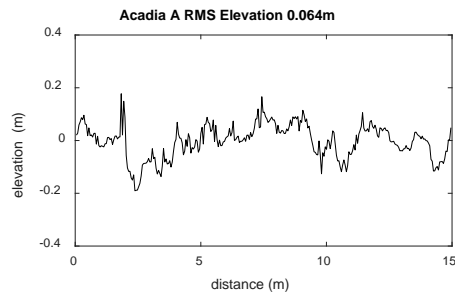
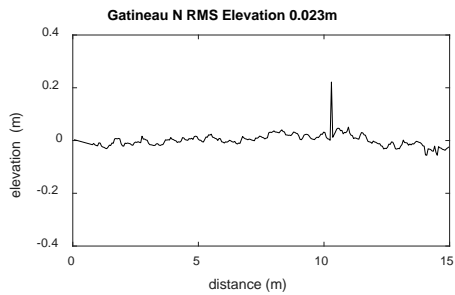


Figure 9. Accuracy of absolute geolocation for digital surface models based on cross-validation with GCPs.



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Figure 10. Deviations from local robust linear trend (based on 15 m moving window) of PC elevations along each transect. Only the first 15 m of each transect are shown for clarity. Acadia C is truncated as the transect consisted of shorter line segments.

3.2 ΔSD Mapping Performance

The performance of ΔSD mapping was evaluated in terms of both changes between successive dates and changes between a given date and snow free conditions. ~~Figures 11~~Figure 10a shows the ΔSD between successive dates for each transect.

5 Vertical (horizontal) bars indicating their one standard deviation confidence interval due to within transect variation in ΔSD from the image data (in-situ data). The bars indicate that spatial variability in ΔSD within a transect was often larger than the ~~0.32~~6 cm (1 standard deviation) uncertainty for in-situ ΔSD estimation for a transect assuming no spatial variability. As such, the in-situ measurement method was considered sufficiently precise for reference estimates. Nevertheless, due to within transect variation in ΔSD , the precision of both in-situ and image based methods was often similar in magnitude to
10 observed ΔSD so that statistically significant comparisons could not be conducted for individual dates. Rather, in-situ and image based ΔSD were compared using statistics based on differences observed for all dates for each transect. In this case, uncertainty ranged from 2.54 cm to 5.12 cm for the non-forested sites to 8.68 cm at AC. ~~Accuracy error, corresponding to the~~The temporal bias ~~over all the temporal samples~~, was substantially smaller than uncertainty, ranging from between -0.80 cm at GS to 0.35 cm at AC. As such the precision error was only slightly less than the uncertainty (not shown). ~~There were seven instances where the observed difference exceeded 5cm. Four were overestimates ranging from 5cm to 10cm at Gatineau and the other three were all at AC including the largest residual corresponding to an underestimate of 20cm. Four of these instances, including the 20cm error, involved at least one date with either extremely icy snow and another with deep fresh snow. In such cases the D can be low (Figure 7) while the snowpack itself has changed substantially between dates. Two other cases involved rapid melt leading to exposed ground surfaces on the latter date. We also noted that at AC, the identified key points were often at snow-vegetation intersections (not shown), that may differ systematically in ΔSD when compared to the stakes that were placed within openings.~~

25 Figure ~~12-10b~~ compares ΔSD between snow covered and snow free conditions (*i.e. estimated SD*). In this case, the confidence interval of ΔSD for a transect ~~is~~was on average +5.2 cm/-6.3 cm for in-situ and +4.1 cm/-7.8 cm for image based estimates. Uncertainty ranged from 1.58 cm at AB to 10.56 cm at GN. -Accuracy varied between sites. Bias was below 1.2cm for GS T1, AA and AB. In contrast, bias at the other sites exceed +/-5cm (-10.05cm at GN T1, -6.23cm at GS T1 and 5.5CM at AC). Moreover, the bias was consistent over time with the exception of large (>5cm) under estimates for the date just prior to snowmelt for all sites except AB.

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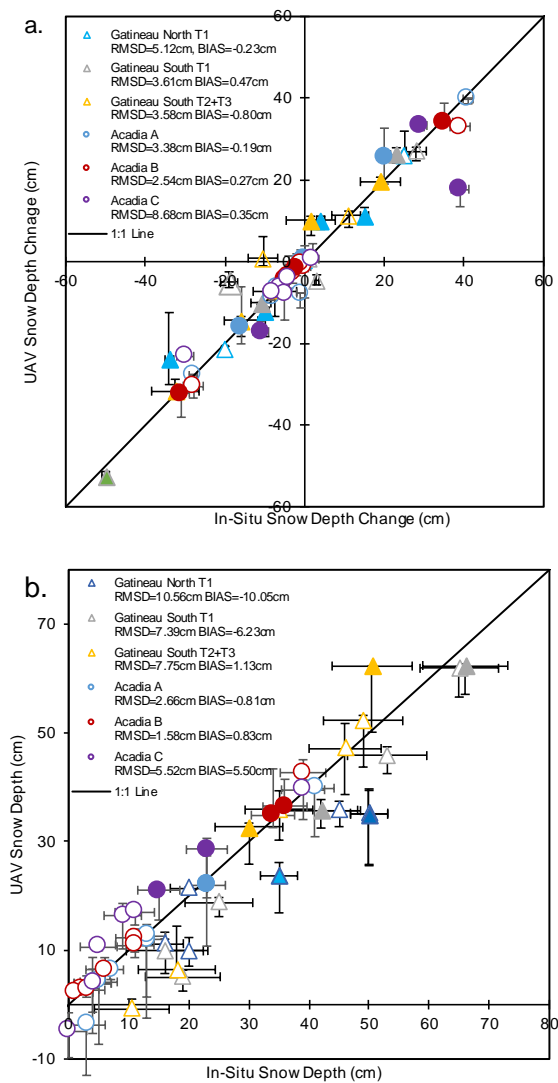
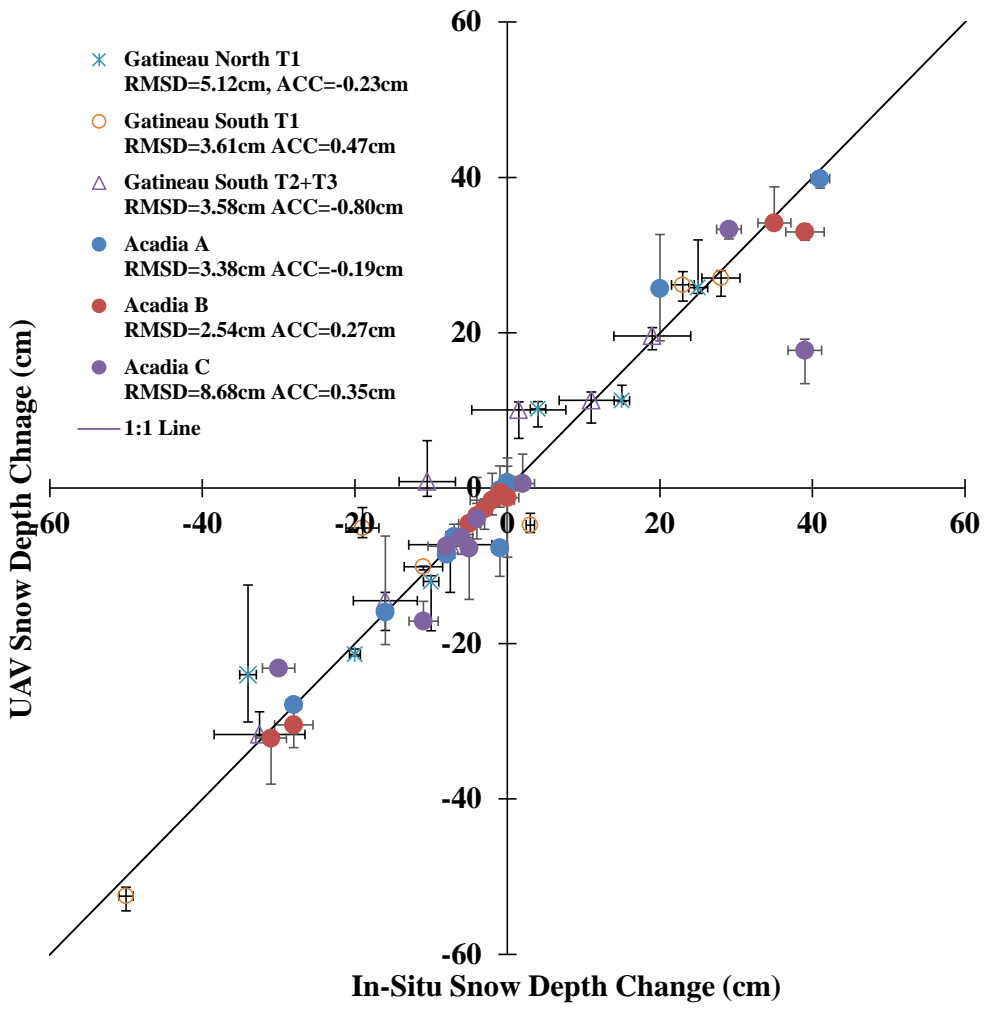


Figure 10. Validation of (a) snow depth change for successive (~weekly) measurements and (b) corresponding snow depth over transects. Shaded symbols correspond to icy or fresh snow conditions. Horizontal (vertical) bars correspond to +/-34%ile interval of within transect in-situ (UAV) snow depth estimates.

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~~ranged between from between 10.05 cm at GN to 5.50 cm at AC indicating temporal bias. Snow depth was systematically underestimated by between 4 cm and 8 cm at GN and GS T1.~~



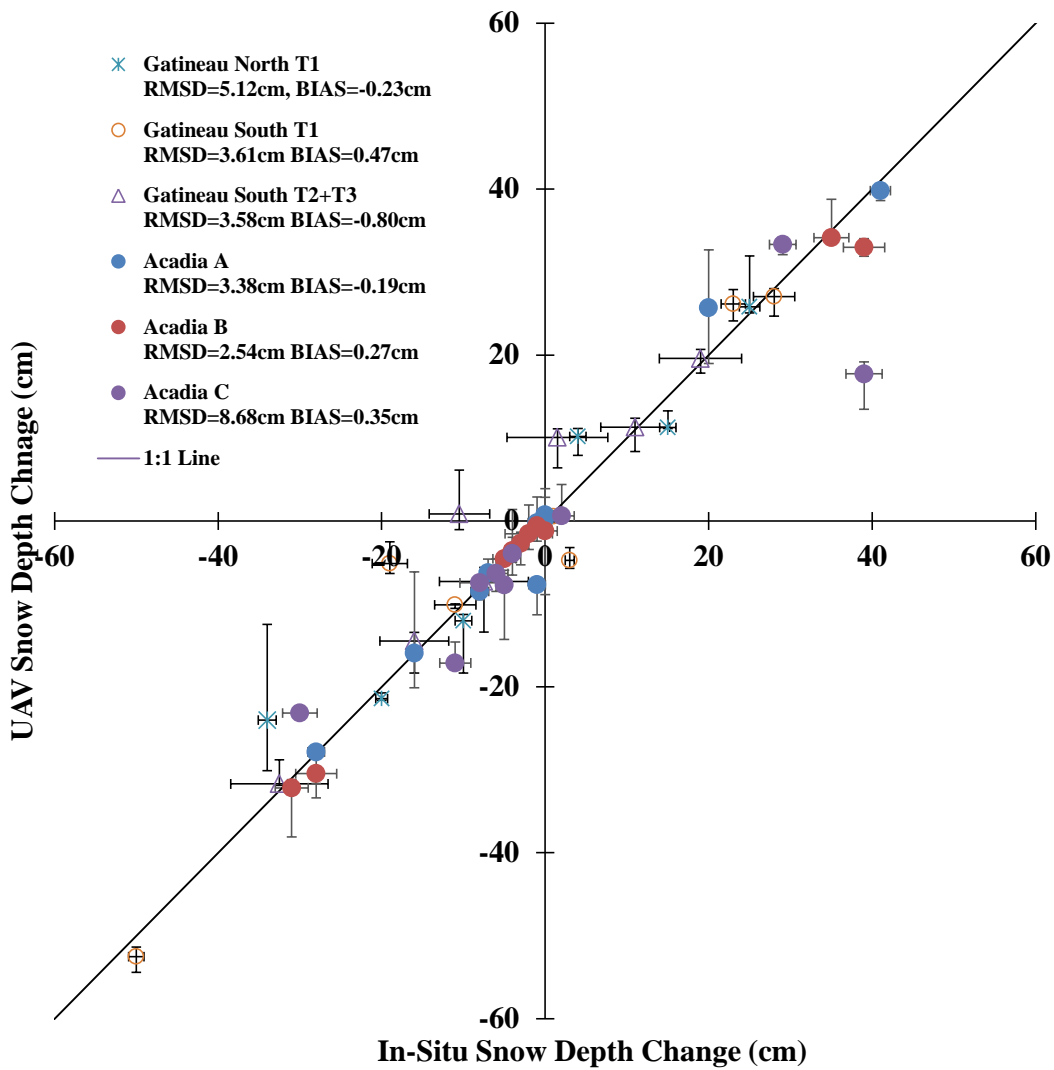
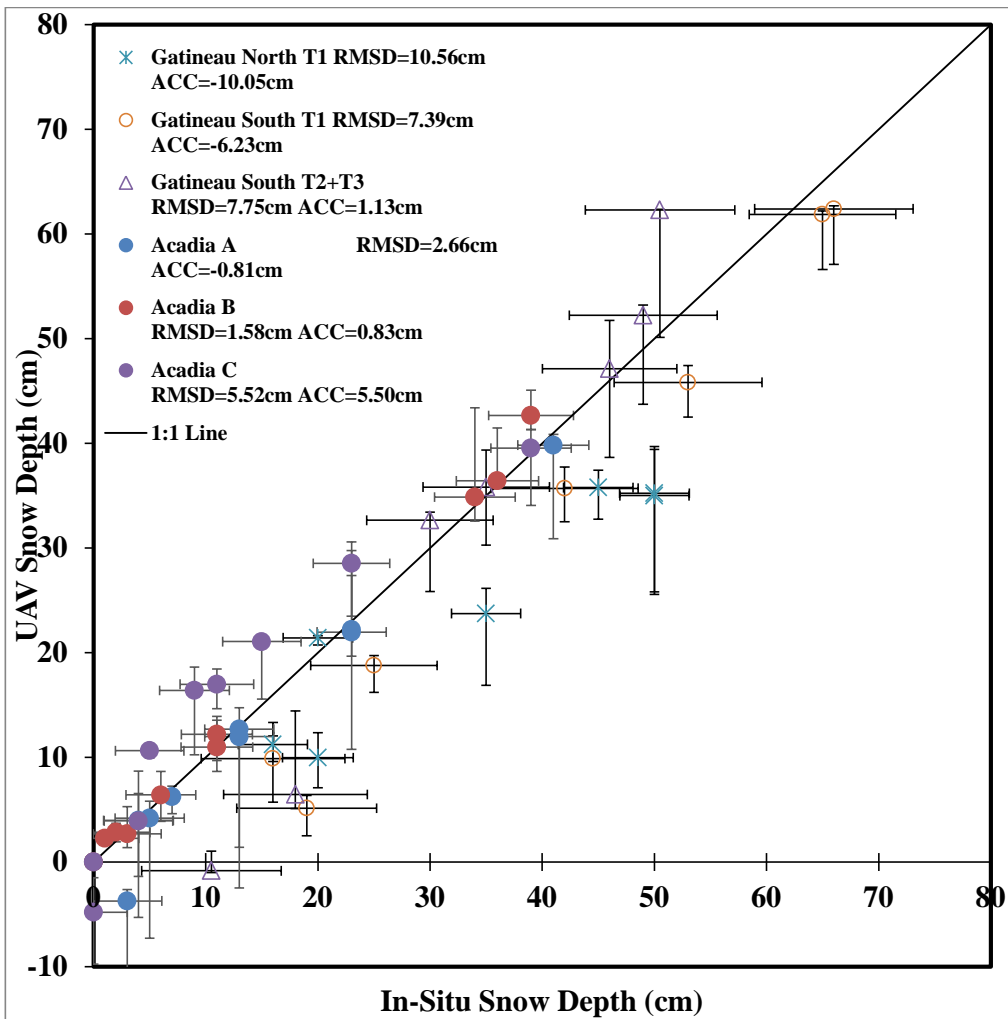


Figure 11. Validation of average snow depth change over transects for successive (~ weekly) measurements.

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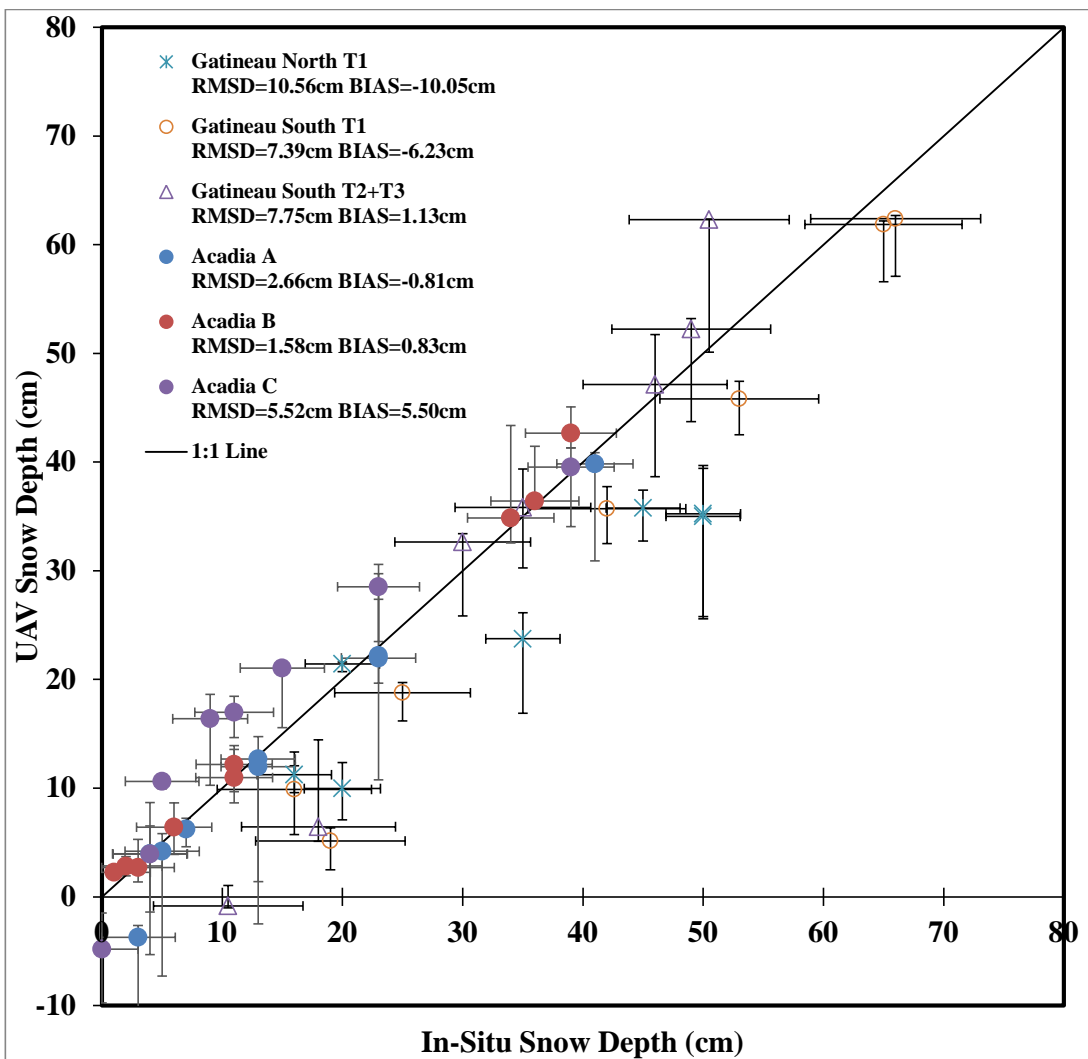


Figure 12. Validation of average snow depth over transects for successive (~ weekly) measurements.

~~Season average key point matching density (excluding fresh and icy snow) versus RMSD elevation deviation along transect. AC had an RMSD of 0.42m but is depicted at RMSD 0.1m for display purposes.~~

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~~Figure 13. Season average key point matching density (excluding fresh and icy snow) versus RMSD elevation deviation along transect. AC had an RMSD of 0.42m but is depicted at RMSD 0.1m for display purposes.~~

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4.0 Discussion

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4.1 Temporal and Spatial Variation of Snowpack Conditions

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~~Missions were conducted over a range of snowpack conditions including peak snowpack with both fresh and aged snow, ice covered snow, partial snow cover during melt and snow free just after melt. In this sense, the experiment offers a realistic sampling of ephemeral snowpacks for the temperate climate regions of our study sites. In contrast to studies reviewed in Section 1, snow pack conditions were often icy (5 of 29 dates) and patchy (6 of 29 dates) due to frequent rain on snow events. Ideally, the temporal sampling could have been enhanced by adding additional missions during the same day or adjacent days to assess the impact of sky and weather conditions on estimates of ΔSD .~~

20

~~The uncertainty of in-situ ΔSD was primarily due to precision error from spatial variability rather than measurement error. This aspect is important when evaluating image based estimates of ΔSD since the difference between a single in-situ and remote measurement will include some element of spatial uncertainty due to differences in the compared area. A number of previous studies have directly reported the RMSD between image based ΔSD and point measurements (e.g. Nolan et al. 2014; Harder et al. 2016; Vander Jagt et al., 2016). One may argue that single measurement comparisons includes the horizontal uncertainty of the image based map but practically speaking many users ΔSD maps are likely interested in the transect average in the same manner that users of current in-situ networks require transect averages rather than the spatial~~

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distribution of ΔSD at cm resolution. Nevertheless, the within transect range of ΔSD from both in-situ and image based approaches is important for understanding the representativeness of the measurements as well as potential biases. In this regard, the within transect variation for image based ΔSD was approximately the same magnitude as for in-situ ΔSD but skewed towards lower ΔSD when considering snow depth due to local positive biases in the snow free DSM in the presence of vegetation. Similar biases have been reported in previous studies (Vander Jagt et al., 2016; Gindraux et al., 2017).

4.2 SfM Performance with Snowpack Condition, Micro-topography and Wind Speed

The mission performance of the consumer-grade UAV was encouraging given that it was often operated at the edge of its performance envelope in terms of wind speed and air temperature and under varying illumination conditions. The percentage of calibrated images and D decreased substantially in the presence of precipitation or very smooth surface conditions such as fresh snow or ice. The decrease was greatest over sites with low micro-topographic roughness (GN, GS and AA) although the lack of statistical significance for the decrease at AB and AC may be due to the limited number of icy/fresh snow dates (three). Qualitative assessment of imagery during snow covered conditions indicated that, in contrast to AB and AC that had substantial exposed vegetation and rough topography, key points at the other sites were chiefly found along ridges and shadows cast by snowdrifts. Bühler et al. (2017) and Gindraux et al. (2017) reported similar findings with other UAV systems for fresh snow but not for glacier ice. In our study, ice was typically in the form of a flat surface pond or smoothed snow pack while in these studies ice was the surface of a glacier that included topographic roughness. In any case, the lower key point density in both their study and ours was due to smooth surfaces. In principle one could interpolate ΔSD across smooth regions using the ΔSD at their perimeter. Otherwise, the percentage of calibrated images did not vary substantially across sites and was consistently not a limiting factor in terms of performance (i.e. >97%).

The sites selected for this experiment were nominally flat at length scales of tens of metres, except in the vicinity of GS T3. However, micro topography varied between sites. All of the Gatineau sites had little or no micro topographic variation while the Acadia sites progressed from tree stumps (AA) to mounds covered with shrubs (AB) to mounds covered with shrubs and a regenerating canopy (AC). Overstory vegetation cover was less than 10% along transects except at AC where cover within a 1 m radius vertical cylinder centred at each stake was estimated to average 38% ([0%, 52%]). In this sense, the validation results from this study are representative of either sparse vegetation or areas with open canopies.

Missions were conducted over a range of snowpack conditions including peak snowpack with both fresh and aged snow, ice covered snow, partial snow cover during melt and snow free just after melt. In this sense, the experiment offers a realistic sampling of snowpack except for snow onset for the climate regions of our study sites. Key point density decreased by almost one order of magnitude when comparing missions flown with snow more than 1 day old and missions with either

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deep fresh snow or smooth icy snow packs. Previous studies have identified the drop in both elevation and SD accuracy due to deep fresh snow (Nolan et al. 2014; Avanzi et al. 2017) and icy conditions (Gindraux et al., 2017). Here we demonstrate that D may be a useful indicator of such conditions and hence an indicator of the quality of ΔSD estimates. The experiment did not control for sky conditions ~~although the~~. The one pair of missions with similar snow conditions but different sky conditions did not show substantial changes in either the percentage of calibrated images or D ~~keypoint matching density~~. Nevertheless, the lack of dense canopy conditions and controlled sky conditions means that this study does not address the issue of large cast shadows (or lack thereof) on estimating snow depth changes using a low flying UAV. Bühler et al. (2017) reported that digital surface models from UAV images acquired in cast shadows appeared to be qualitatively noisier than those without shadows and resulted in unrealistic (both negative and very high) estimates of SD after differencing from accuracy bare earth models. They suggested that a combination of visible and near-infrared imagery might reduce uncertainty in areas of cast shadow. Alternatively, measurements during overcast conditions may be sufficient to map ΔSD with sufficient accuracy in areas of persistent shadows.

Previous studies have not systematically evaluated the sensitivity of ΔSD estimation to micro-topography or vegetation density. The sites selected for this experiment were nominally flat at length scales of tens of metres, except in the vicinity of GS T3. However, micro-topography varied between sites. All of the Gatineau sites had little or no micro-topographic variation while the Acadia sites progressed from tree stumps (AA) to mounds covered with shrubs (AB) to mounds covered with shrubs and a regenerating canopy (AC). Overstory vegetation cover was less than 10% along transects except at AC where cover within a 1 m radius vertical cylinder centred at each stake was estimated to average 38% (range [0%, 52%]). However, GN and GS T1 has substantial thatch exceeding 5cm in height under the snow that was present during the snow free mission while AC had cover of understory herbs low shrubs ranging from 5cm to 10cm in height. As such, this experiment provides new results for a range of micro-topography and understory/low vegetation but is limited in terms of over story cover. As previously indicated, this was a conscious decision due to the difficulty of adequate non-destructive in-situ sampling in forested areas and our desire not to further complicate the point cloud processing when having to deal with snow on vegetation. Excluding fresh and icy snow, that varied in frequency between Gatineau and Acadia, D was generally proportional to micro-topographic roughness for sites without overstory. The behaviour with overstory (AC) may have been due more to our inclusion of vegetation PC points within our micro-topography index since the matching density at AC was similar to AB where the understory and surface topography was subjectively similar. Assuming this is the case, these results suggest a compensating effect between increasing variability in ΔSD due to micro-topographic complexity and increasing D that may explain why, outside of icy and fresh snow, RMSD and accuracy was similar across sites when estimating ΔSD change.

5 The absence of a statistically significant linear relationship between hourly average wind speed and either D or geolocation performance was not surprising. Firstly, we did not perform missions where all other factors but wind speed were controlled. In addition, our wind speed data may not have been representative of actual conditions. Daily maximum gusts, corresponding to instantaneous recordings, were often twice the magnitude of hourly average wind speed suggesting that the UAV may have experienced higher wind speeds during its mission on calmer days. Additionally, missions were delayed if extreme local gusts were observed. We also did not control for snow and illumination conditions when considering the effect of wind speed (e.g. by performing missions on subsequent days with different wind speed by same illumination). We hypothesize that, except for very large gusts, the PIX4D block adjustment procedure is capable of accounting for uncertainty in camera attitude and location since we observed little or no sensitivity of either D or geolocation performance when using imagery with our without ephemeris (not shown). Rather, the major difference was the decrease in time for key point matching and block adjustment when providing accurate ephemeris in comparison to no ephemeris information except for the time of acquisition.

4.2 Geolocation and ΔSD Validation

20 The uncertainty of in-situ ΔSD was primarily due to precision error from spatial variability rather than measurement error. This aspect is important when evaluating image based estimates of ΔSD since the difference between a single in-situ and remote measurement will include some element of spatial uncertainty due to differences in the compared area. One may argue that single measurement comparisons reflects the horizontal uncertainty of the image based map but practically speaking users of a map of ΔSD are interested in the transect average in the same manner that users of current in-situ networks require transect averages. Nevertheless, the within transect range of ΔSD from both in-situ and image based approaches is important for understanding the representativeness of the measurements as well as potential biases. In this regard, the within transect variation for image based ΔSD was approximately the same magnitude as for in-situ ΔSD but skewed towards lower ΔSD when considering snow depth due to local positive biases in the snow-free DSM in the presence of vegetation. Similar biases have been reported in previous studies (Vander Jagt et al., 2016; Gindraux et al., 2017).

30 The mission performance of the consumer grade UAV was encouraging given that it was often operated at the edge of its performance envelope in terms of wind speed and air temperature and under varying illumination conditions. The percentage of calibrated images and matching density decreased substantially (~by a factor of 10) in the presence of precipitation or very smooth surface conditions such as fresh snow or ice. Bühler et al. (2017) and Gindraux et al. (2017) reported similar findings for fresh snow but not for ice. However, in our study ice was typically in the form of a flat surface

pond while in Gindraux et al. (2017) ice was the often rough surface of a glacier. In any case, the lower matching density in both their study and ours was due to smooth surfaces. In principle one could interpolate ΔSD across smooth regions using the ΔSD at their perimeter. Otherwise, the percentage of calibrated images did not vary substantially across sites and was consistently not a factor in terms of performance (i.e. >97%). Matching density were consistent within Acadia and 70% higher than Gatineau for conditions without fresh snow or ice. Examination of match points suggests that the higher matching density over Acadia was due to a combination of increased microtopographic features and increased vegetation in comparison to Gatineau. This result suggests a potential compensating effect for the image based approach whereby more matches are found in landscapes where DSM variation, and possible SD variation, is greater. However, we have not considered closed canopies where occlusion due to other canopy elements may result in a saturation of matches as vegetation density or cover increases.

The number of images matches per point (K) was not rigorously addressed since there is no means of extracting this information for a sub-image within Pix4D other than by manual examination of individual images (there are 1000 images per mission). Average values of K for each mission (4-10) fell within or above the range observed in our trial missions (4.3-7.4). The higher values of K were observed over Acadia where some vegetation and stumps were matched in almost all overlapping images. In contrast, for Gatineau the average values of K ranged from 4-5. The similarity between our initial estimates of K from four trial flights and actual values for K suggests that the theoretical prediction of accuracy should also be in general agreement with observed accuracy for ΔSD .

The geolocation performance of derived DSMs was exceptional considering that the UAV was a consumer grade device. Bias errors were smaller than the precision of the GCPs themselves suggesting that spatial variation in DSM errors may have a large random component. We could not test this hypothesis as we had limited control points that were all in relatively open areas. The DSM accuracy over GCPs was higher than reported in other studies over natural landscapes (e.g. Nolan, 2015; Harder, 2016; Gindraux 2017) but similar to performance over man-made/fabricated targets (Nasrullah et al., 2016). This is partly explained by the high spatial resolution of the imagery in our study but we hypothesize it was also due to use of easily visible elevated GCP targets that were identified in many images. For example, the number of image matches at GCPs ranged from 10 to 30. Assuming independent errors at each GCP this number image matches corresponds corresponds to a theoretical ratio of vertical to horizontal accuracy of between 0.9 to 5 between vertical and horizontal accuracy at a single point or 0.42 to 2.2 over five GCPs. The assuming independent errors at each GCP while the observed ratio based on a robust line fit was 1.1 indicating agreement with theory. The strong correlation observed between horizontal and vertical accuracy error was also in line with expected given the theoretical error model. We did not have sufficient spatial sampling of surface elevations over snow covered areas to test the model in terms of snow surface

elevation. This should be performed in future studies using reference measurements from surface instruments (e.g. Avanzi et al., 2017).

5 Validation of ΔSD requires minimally invasive reference estimates using methods that also does not substantially change the performance of UAV estimates. Considering the potential for large variations in SD and ΔSD with microtopography we decided to control the reference locations by using fixed stakes. This strategy could have led to an (artificial) increase in precision if the stakes led to an increase in the D as well as an increase in accuracy if the same key points on stakes were
10 detected in multiple images within or between missions. Examination of maps of automated key points *a posteriori* indicated that the PIX4D algorithm rarely found a key point along a stake (e.g. Supplementary Material Figures S1 to S5). Furthermore, the few cases where a key point was identified on a stake corresponded to locations with exposed vegetation around the stake that would potentially exhibit a match in any event. PIX4D Mapper uses a proprietary implementation of a reduced set of features derived from the Scale Invariant Feature Transformation (SIFT) (Strecha, 2011). SIFT features are defined to specifically eliminate key points that have poorly determined locations but high edge responses: especially corner
15 features (Lowe, 2004). We hypothesize that, especially for snow covered conditions, the relatively narrow stakes correspond to such features and are subsequently avoided by PIX4D Mapper when identifying key points. If so, our results may actually be somewhat pessimistic since there are potentially fewer key points near stakes.

20 Validation of weekly ΔSD indicates that bias across all sites and dates was smaller than the typical uncertainty for a given transect both from in-situ or image based methods and of the same order of magnitude of conventional automated or manual measurements at point locations. There was evidence of two larger (>5 cm) over and underestimates at the forested AC site that may be due to snow present on vegetation near the ground (overestimates) or under sampling of the PC due to fresh snow (underestimates). There were also ~~two instances~~ instances of underestimates exceeding 5 cm during melt over the
25 Gatineau sites. Both of these cases corresponded to icy anterior conditions that may have favoured point cloud matches in areas with rougher snow that had not yet melted. In each of these cases, one of the compared elevation surfaces had far lower D than typical for the site suggesting that D may be a useful indicator of confidence in estimated ΔSD . Notwithstanding these issues, the
30 typical uncertainty of ΔSD was close to the theoretical error of ~ 2.44 cm for a single estimate. This suggests that sources of error within a transect are likely correlated since one would expect substantial reduction in the ΔSD for the transect considering that 100s of PC samples are averaged. The correlation is potentially explained by the fact that the stakes in each transect share the same images for the most part and therefore potentially suffer the same lateral displacement errors.

~~Validation of ΔSD (comparing snow and snow free conditions) indicated that the range of RMSD (from ~1.5cm to ~10.5cm) falls within the +/-10 cm uncertainty reported in previous studies (see Section 1). Validation of ΔSD when comparing snow and snow free conditions indicates a linear relationship with a tendency for underestimation of in situ estimates of ΔSD in areas with substantial ground thatch layer. The underestimate in these conditions was approximately the same magnitude of the thatch height leading us to hypothesize that they are related to an overestimate in the local DSM height as previously suggested (Nolan et al., 2014; Avanzi et al., 2017). GCPs should be placed along the snow stake transects to test this hypothesis. This hypothesis could be directly validated using supplementary in-situ elevation measurements (e.g. Avanzi et al., 2017) although it is also consistent with the relatively unbiased estimate of ΔSD changes between snow covered dates. We also hypothesize that the overestimate at AC may be due to snow covered vegetation being included in the sampled PC around each stake when estimating the DSM for snow covered areas. Harder et al. (2016) noted a similar bias due to stubble protruding from shallow snow packs. Here, we used the median snow surface elevation based on PC colour processing that seemed to avoid this effect for other sites. The use of a median snow surface elevation may not have been sufficient to remove bias at this site. More sophisticated algorithms for separating snow covered surfaces from over story vegetation should be evaluated.~~

~~Validation of ΔSD indicates that bias across all sites and dates was smaller than the typical uncertainty for a given transect both from in situ or image based methods and of the same order of magnitude of conventional automated or manual measurements at point locations. There was evidence of two larger (> 5 cm) over and underestimates at the forested AC site that may be due to snow present on vegetation near the ground (overestimates) or under sampling of the PC due to fresh snow (underestimates). There were also two instances of underestimates exceeding 5 cm during melt over the Gatineau sites. Both of these cases corresponded to icy anterior conditions that may have favoured point cloud matches in areas with rougher snow that had not yet melted. The typical uncertainty of ΔSD was close to the theoretical error of 2.44 cm for a single estimate. This suggests that sources of error within a transect are likely correlated since one would expect substantial reduction in the ΔSD for the transect considering that 100s of PC samples are averaged. The correlation is potentially explained by the fact that the stakes in each transect share the same images for the most part and therefore potentially suffer the same lateral displacement errors.~~

~~Validation of ΔSD when comparing snow and snow free conditions indicates a linear relationship with a tendency for underestimation of in situ estimates of ΔSD in areas with substantial ground thatch layer. The underestimate in these conditions was approximately the same magnitude of the thatch height leading us to hypothesize that they are related to an overestimate in the local DSM height. GCPs should be placed along the snow stake transects to test this hypothesis. We also hypothesize that the overestimate at AC may be due to snow covered vegetation being included in the sampled PC~~

~~around each stake when estimating the DSM for snow covered areas. The use of a median snow surface elevation may not have been sufficient to remove bias at this site. More sophisticated algorithms for separating snow covered surfaces from overstorey vegetation should be evaluated.~~

54.0 Conclusions

Snow depth is an important geophysical quantity that exhibits substantial variation in space over distances of metres and in time over daily intervals. Systematic snow depth monitoring to date has emphasized temporal resolution. This study evaluated the potential for ~~light-weight consumer grade~~-UAV imagery, processed using off-the-shelf SfM software, for mapping the change in snow depth over natural vegetated landscapes. The primary goal of this study was to ~~validate~~ compare this approach when mapping changes in snow depth between successive snow covered dates versus between a snow covered and snow free date over land cover with varying vegetation density and micro-topography and with ephemeral snow packs. The sampled sites exhibited only modest variation in overstorey vegetation cover (from 0% to 38% averaged over a transect) but substantial variability in micro-topography including tree stumps, hummocky terrain and mowed pasture. The study also addressed a second goal of comparing observed accuracy and precision of snow depth change and associated surface elevations with estimates based on photogrammetric theory.

A total of ~~64-71~~ UAV missions were flown in a range of conditions with ~~56 successful~~ surface elevation maps derived at between 2 cm and 3 cm horizontal ground sampling distance and with median (range) of horizontal and vertical uncertainty of 1.87 cm (0.44 cm to 11 cm) and 1.02 cm (0.045 cm to 4.6 cm) respectively in comparison to man-made ground control points. Validation over five different study sites from mid-winter to snow free conditions indicated an uncertainty of 6.45 cm (1.58 cm to 10.56 cm) and accuracy of 3.33 cm (-10.05 to 5.05 cm) for the average snow depth over a ~50m long transect. Snow depth was systematically underestimated over sites with dense low vegetation by ~5 cm. As the underestimate was the same magnitude as the vegetation height during snow free conditions we hypothesize the underestimate is related to an overestimate of the snow free ground elevation. Validation for the average change of snow depth over a transect between successive (~weekly) missions indicated uncertainty of 3.40 cm (2.54 cm to 8.68 cm) and accuracy of 0.31 cm (-0.19 cm to 0.80 cm).

Observed uncertainty for snow depth change agreed with the theoretical uncertainty (mean value of 2.44 cm and range of 1.2 cm to 5.25 cm depending on the number of matches at a key_point) when considering the difference between two snow covered dates. In general, uncertainty in associated surface elevations agreed with theoretical estimates both in magnitude

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and in terms of the expected correlation between horizontal and vertical errors. The observed uncertainty in absolute snow depth was larger than theoretical uncertainty chiefly due to bias in estimates of the bare ground elevation in the presence of vegetation within the snow free reference image. In this case the bias is likely to be specific to local conditions and it may be possible to use in-situ measurements to calibrating for this bias if UAV based estimates of snow depth are combined with in-situ measurements. Even so, the uncertainty of UAV based weekly snow depth change is comparable to typical in-situ measurements approaches suggesting that a combination of both measurements should be considered for producing high spatiotemporal resolution maps of snow depth change in complex terrain. We recommend that future studies consider the potential of using UAV information on snow depth change rather than absolute snow depth.

Further studies are required to investigate the performance of snow depth change mapping using similar UAV data in terms of sensitivity to changes in key_point sampling density due to changing illumination and wind speed, in terms of the precision of snow depth change estimates under denser canopies where the non-vegetated surface is substantially obscured, and to quantify performance as a function of UAV mission and SfM software parameters. Nevertheless, the results from our multi-site/multi-operator study suggest that UAV based estimates of snow depth and snow depth change over areas corresponding to a typical in-situ transect have comparable uncertainty to current manual in-situ estimates while offering substantially greater coverage. Moreover, the technology can be applied with widely available off the shelf equipment and software with minimal certification. While our study had a ~10ha limit due to using a single mission, spatial coverage can be extended to line of site using multiple missions or multiple cameras on the same UAV or even past line of sight given adequate certification. Moreover in-situ GPS targets may not be required if baseline networks can be processed using post processed kinematic methods. —Assuming these results are representative of wider landscapes and snow conditions we recommend that subsequent studies address the problem of combining airborne UAV survey based information on snow depth change with high temporal sampling satellite and in-situ information to improve snowpack characterization and reduce uncertainty in estimates of streamflow.

Author Contribution

RF designed the experiment, performed observations, analysis, and prepared the manuscript. CP, FC and SL designed the experiment and performed observations. MM and SO performed observations and analysis. , KH and AK performed analysis.

Competing Interests

The authors declare that they have no conflict of interest.

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