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The Cryosphere Discussions

Interactive comment on "Monitoring snow depth change across a range of landscapes with ephemeral snow packs using Structure from Motion applied to lightweight unmanned aerial vehicle videos" *by* Richard Fernandes et al.

Richard Fernandes et al.

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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. Please note that The Cryosphere requests that the revised manuscript be uploaded after this response is accepted. We hope that our responses have sufficient detail but would be happy to provide the revised manuscript if required.

Regards

Richard Fernandes on behalf of the Authors

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 ΔðİŚĘðİŘů requires minimally invasive reference estimates using meth-

ods that also does not substantially change the performance of UAV estimates. Considering the potential for large variations in ðİŚĘðİŘů and △ðİŚĘðİŘů 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 ðİŘů as well as an increase if 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). 15 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" in 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 rational 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 whiles 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 an 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 confiirm 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 misions, 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 issues 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 facilitaty 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.

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2018-82/tc-2018-82-AC1-supplement.pdf

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-82, 2018.

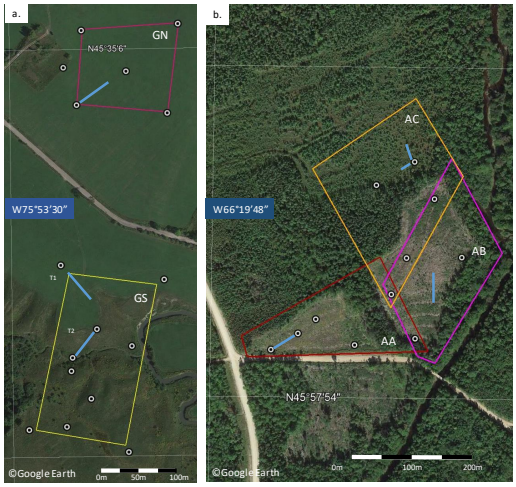

Figure 1. Gatineau region (a) showing GN (pink) and GS (yellow) sites and Acadia Region (b) showing AA (red), AB (magenta) and AC (gold) sites. Also indicated are ground control points (hollow circles) and in -situ transects (blue lines). Map data: Google, Digital Globe.

Fig. 1.

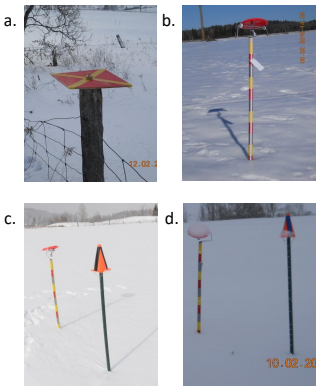

Figure 2. GCP Targets: a) square plywood b) disk on pole and c) disk on pole and cone on pole snow free d) disk on pole and cone on pole with snow.

Fig. 2.

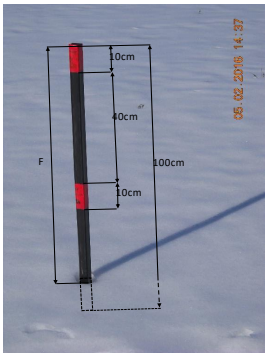

Figure 3. In-situ snow stake dimensions. Dashed lines correspond to locations below the snow surface.

Fig. 3.

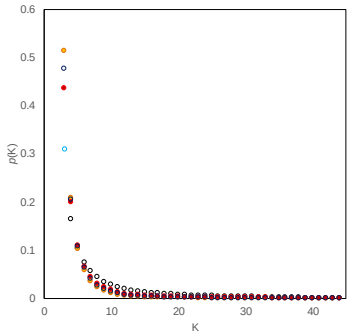

Figure 4. Empirical probability *p* of observing *K* matches for key points acquired during four trial missions (filled symbols are for overcast dates)

Fig. 4.

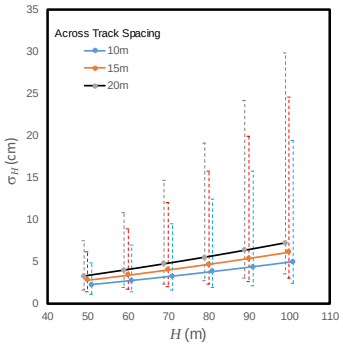

Figure 5. Theoretical relationship between vertical uncertainty σ_H and UAV height H. Solid lines correspond to five matching images per key point. Upper (lower) bars correspond to three (eight) matching images key per point.

Fig. 5.

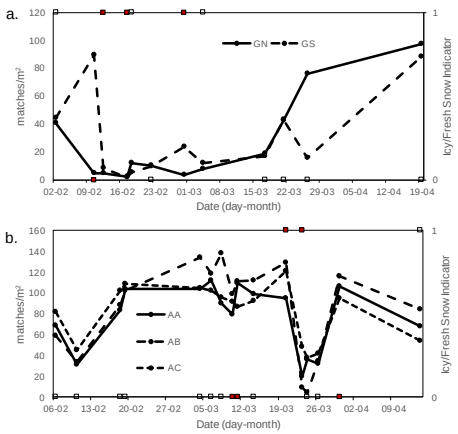

Figure 6. Pix4D automated key point match density for Gatineau (a) and Acadia (b) together with indicator of fresh snow (squares symbols). Missions (solid circular symbols) for the same site are connected by lines. Red squares indicated overcast conditions.

Fig. 6.

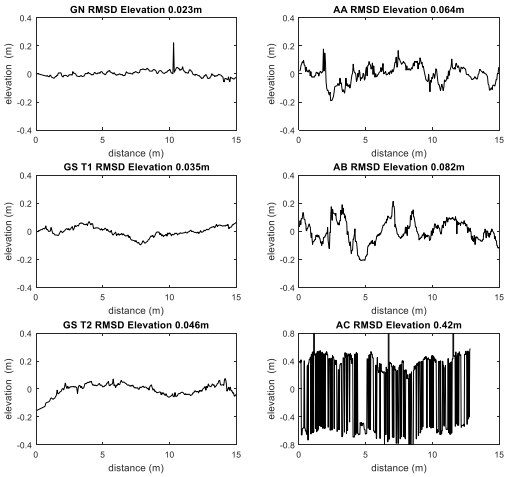

Figure 8. Deviations from local robust linear trend (based on 15 m moving window) of densified point cloud elevations along each transect. Only the first 15 m of each transect are shown for clarity. The root mean square deviation (RMSD) for elevations over the entire transect is also indicated. AC is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

Fig. 7.

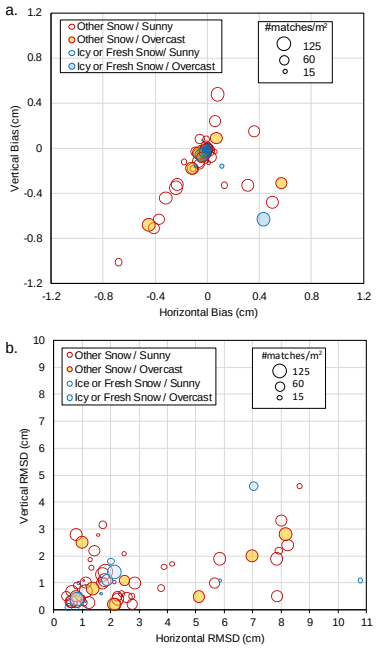

Figure 7. Accuracy (a) and uncertainty (b) of absolute geolocation for digital surface models based on cross-validation with GCPs. Symbol area proportional to mission average key point match density.

Fig. 8.

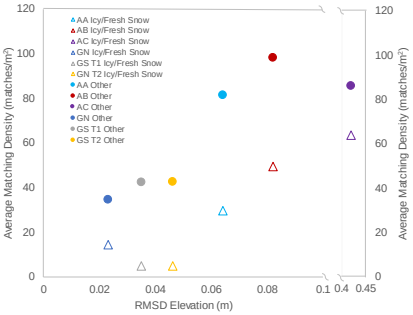

Figure 9. Season average key point matching density versus root mean square deviation (RMSD) of elevation deviation along transect for icy and fresh snow missions (hollow triangles) and "other" missions with snow cover (solid circles) during snow covered periods. The difference in season average matching 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).

Fig. 9.

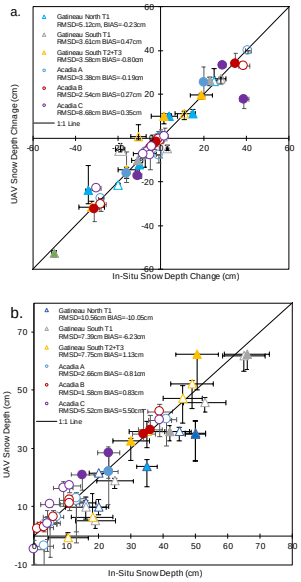

Figure 10. Validation of (a) snow depth change for successive (~weekly) measurements and (b) corresponding snow depth over transects. Shaded symbols correspond to icy or fresh snow conditions. Horizontal (vertical) bars correspond to +/-34%ile interval of within transect in-situ (UAV) snow depth estimates.

Fig. 10.