

## Authors' responses to reviewers

13 April 15

We would like to thank the reviewers for their thoughtful responses, which we feel have improved the manuscript. Below are all of their suggestions and concerns followed by our responses [in brackets and bold text].

### Authors' response to Reviewer #1

The manuscript, "Mapping snow-depth from manned-aircraft on landscape scales at centimeter resolution using Structure-from-Motion photogrammetry" From Nolan, Larsen, and Sturm presents a new approach to the collection of snow depth information using photogrammetry techniques from manned aircraft. The presentation of the technique and characterization of the results achieved indicate that the method is quite suitable and in fact could be transformative in the the cryospheric sciences. The authors present a system which is largely made from 'off-the-shelf' components and 'black box' software, and apply the system to three case study test locations. Overall the results are compelling and indicate that the method is more than suitable for most present day requirements of snow-depth change.

Rigorously, portions of the technique are not detailed. As the portions of the system rely on proprietary software there are some details that cannot be accurately assessed. However, the authors do a very good job of presenting a characterization of the accuracy and precision of their results and demonstrate the suitability of the method. Further, the manuscript demonstrates that the method in general will provide users greater information - particularly with regard to spatial extent - than typical snow observation platforms employed today.

However, as this paper's stated goal is that "[Their] chief contribution has been to integrate these components into a simplified and low-cost system." there are a few shortcomings that should and could easily be addressed prior to publication.

First, with regard to the method, this reviewer feels that too little information is provided with regard to any photographic 'preprocessing' or otherwise that may have been required to achieve appropriate images for the determination of the point-clouds. It is stated that a benefit of modern-day DSLRs is the wide dynamic range and ability to use the camera over snow covered surfaces. While images may have been collected without complete distortion or over exposure, the authors do not describe whether they enhance the contrast, or alter the image in any way prior to the Photoscan workflow pipeline. It seems likely that in order for the software to distinguish features, it would be a required pre-processing step. Overall, while the processing by the software is a 'black box' step, but there should be more complete information provided on what is done throughout the workflow.

**[Agreed, we have added a several sentences to address this. In short, the photographs are optimized to highlight local contrast (eg edges of sastrugi, etc) while minimizing global contrast (ie dynamic range), and this is a manual process for us that is unique for each data set.]**

A second place this point arises with with reference to the intervalometer, and ,over

all, the entire hardware description. The system itself needs to be detailed more accurately. As reviewers, we are not able to assess the proprietary components of the system – if so, this manuscript should be submitted to a geomatics or image processing journal. Rather, the authors preport to present a 'system', but in the manuscript, only the results from a system are actually detailed. It is recommended that greater care be taken with regard to the specific hardware used, specifications about any control software, on board computer requirements, etc.. A figure of the system itself would be useful. By way of example, regarding the TTL pulse event marker, this would indicate that the camera and GPS were connected. Is this connection via a microcomputer or is the camera connected directly to the GPS? A complete hardware specification should be provided.

**[Agreed. We have tried to clarify in the text that we are describing a method rather than prescribing the exact hardware required for that method. In the text we identified \*all\* of the components of our system, along with our specific hardware choices, but noted that other choices may offer improvement. We have also made explicit in the abstract and text that no computer is used for acquisition and that the intervalometer directly connects the GPS and camera. ]**

Finally, a few minor editorial comments are provided. Overall, this manuscript is written exceptionally well. The use of English language is very good, and the sections follow clearly. In general, the text could be shortened, and with the addition of point 2 above the text may grow. If there are page limit restrictions or other issues, then it is recommended to reduce some of the results descriptions that are somewhat repetitive in favor of a proper description of the system. Throughout the text the authors use the terms "outstanding", "remarkable", and "excellent" – indeed, the results are impressive and the technique may greatly benefit the cryospheric community, but these judgements should be left to the reader to determine.

**[Agreed. We have toned this down.]**

Rather than making judgemental phrases it would be better to provide a comparison to other comparable types of datasets and indicate whether the errors are within the ranges or better than methods previously employed.

**[Agreed. We have addressed this in the text.]**

p337, l21: Abstract states +-30cm, here +-10cm

**[Agreed. We report two types of accuracy: geolocation accuracy of individual maps at +/- 30 cm and accuracy of snow depth maps at +/- 10 cm. Both are described in the abstract. We have tried to make this clearer in the text.]**

p339, l20: more detail here on image processing workflow is required.

**[Agreed. As described above, we have added more such detail.]**

p340, l18 - p341, more detail here on hardware and system configuration is required.

**[Agreed. As described above, we have added more such detail.]**

p341, l18: what are 'most metrics'?

**[Here we mean metrics offered by the gps processing software. We have added more detail on this.]**

p341, l20: Suggestion, change MAP Construction to DEM Construction for title heading.  
**[Agreed. We have changed this to “photogrammetric processing”.]**

p349, l27: Where is the 50cm difference? On figure max is 40, and even there it seems closer to +-30.

**[Generally speaking agreed. However, the green line (28 Sept) shows a range of 50 cm, so we thought it most conservative to use that and have left it.]**

p351, l4: "This difference in scatter" is unreferenced. To what exactly is the author referring. Also, showing a point-cloud example of conic tree features could be of interest.

**[ Corrected. There was an unintentional paragraph break at that sentence; we have corrected this. We did not add any new figures, but the reviewer could check out [www.fairbanksfodar.com](http://www.fairbanksfodar.com)]**

p351, l17: such gridding artifacts → the trees?

**[Yes. We have modified the text to make this clearer.]**

fig4b, surprising that snowshoes sink the deepest – more than boots?

**[Agreed, it is surprising.]**

p355, l14: "and that determining co-registration below the 30 cm level can be overcome using ground control points." seems awkward, perhaps: "can be achieved" "overcome" refers to to 'determining co-registration' not 'primary errors'. Suggest rewriting sentence.

**[Agreed. We have modified the text to improve clarity here.]**

Sec6.3, Fig 5 not referenced before Fig 6 or Fig 7. In fact, it seems Fig 5 is not mentioned at all until later in the text (p356, l24). Also the inset boxes in Fig 5 are not so clear, some small text could aid in labeling the boxes.

**[Agreed. We have modified the text to introduce Figure 5 first. We have modified Figure 5 to make the inset boxes more clear.]**

General Figure Comment: Probe Transects – it is unclear how these are shown as lines. Shouldn't the probe be point locations (and given as a bar with +- of location accuracy)? For example, the variation shown in the probe transect in Fig 6e indicates a continuous measurement, but aren't these point measurements? Was interpolation used?

**[Agreed. The reviewer makes an excellent point here which we had not addressed. The point measurements have been presented as lines for clarity, but they are still fundamentally point measurements. We have made an unstated assumption that snow depth likely varies linearly between the point measurements, which were closely spaced in nature. We modified the figure caption to make this assumption explicit.]**

Fig 7a refers to (see island inset in Fig. 1), but this is not present (or not clear). Perhaps it should be ('see island inset in Fig. 5')

**[Yes, this was a typo which has been corrected.]**

Legend in Fig 7b needs to indicate both colors of probe

**[Agreed. This exists already. Hopefully in the final typeset version it will be more clear.]**

p358, l19: can be ignored – maybe better to say 'can be accepted'?

**[Agreed. We have modified the text.]**

p358, l20-...: This issue of contrast adjustment should be better addressed in the methods section. Examples, of images used, and if any contrast enhancement

**[Agreed. As described previously, we have modified the text to address this.]**

## Response to Reviewer #2

The paper entitled “Mapping snow-depth from manned-aircraft on landscape scales at centimeter resolution using Structure-from-Motion photogrammetry” by Mat Nolin et al. describes the application of airborne photogrammetry to accurately map the depth of shallow snowpack in three test sites in Alaska. This work demonstrates the big potential of digital photogrammetry for spatially continuous snow depth mapping, which is of great value for numerous applications. Even though in most parts of the world it is not as easy as in Alaska to get suitable airplanes, it is still a very interesting option.

The paper is well written and interesting to read, however I see the following major issues that should be resolved before publishing this paper:

1. The whole assessment of the product quality is based on the terms “accuracy” and “precision”. The essential terms should get carefully defined in the beginning of the paper and be illustrated by examples and/or figures. These essential terms should then be used consequently through the entire paper and no new or changed terms should appear. This would help the readers to better follow the large descriptions of quality assessment.

**[Agreed. In the beginning of Section 5 when we first use these terms, we define what we mean by accuracy and precision and later illustrate these with examples and figures. ]**

2. The structure-from-motion technology is the base for the presented methodology. The description in section 2.1 Software is too short and incomplete. A section should be added under chapter 3 Methods describing the applied structure-from-motion technology in detail and including figures and examples. Central questions are: What are the parameters, which have to be set? What is the influence of these parameters on the results? Where do the authors find problems? Would a near infrared band result in more matching points on homogenous snow surfaces or is there enough contrast in the RGB? How would it be on fresh snow surfaces? What software packages are available today? Do they have specific strength and weaknesses? I do understand that not all software packages can be tested but it would be nice to have at least a comparison between two different solutions or to cite references, investigation different products.

**[Following the reviewers suggestion, we have tried to clarify the text to address these comments. Our goal here was to describe which improvements in technology are responsible for allowing our methods to work. We did not conduct a comprehensive review of alternatives of other options and so have stated this in the text, but such a paper would indeed be interesting and useful. We have also added a statement about fresh snow to address comments by both reviewers. ]**

3. The application of references seems rather occasionally in some parts of the introduction. E. g. at page 337 line 14, the authors list 15 publications but it gets not clear which reference belongs to which application. I suggest checking the cited references carefully throughout the paper and skipping papers, which are not really necessary.

**[We agree that the sentence highlighted by the reviewer does have a lot of references, but it was not our point to discuss any of these other applications in**

**particular, only to alert the reader that UAV use with similar techniques has wide and recent application.]**

4. The results are described over many pages and it is very hard for the reader to follow all the numbers and names. I think the structure of this part should be reorganized. One option would be to present the test sites in a separate section including the reference data. There is no figure depicting the applied ground control points even though this would be interesting to see. Also the effect of a high and low distribution quality of the GCP's would be interesting. In a results section the outcome of the accuracy and precision investigation can be presented with the help of tables and figures.

**[At the reviewer's suggestion we have we have added several such figures to the supplemental materials including a location map and ones showing ground control points. We have also modified the text and subheadings to make some of the transitions and roadmaps clearer, and hopefully Tables 1 and 2 will appear more prominently in the final paper. ]**

5. The authors use only term GPS. I do not know if they really just used GPS satellites, but I would suggest changing it to GNSS throughout the paper because GLONAS and in the future GALILEO would substantially improve the positioning accuracy in particular within difficult terrain such as the Alps.

**[At the reviewer's suggestion have modified the text to indicate that we used only GPS satellites, as that is all the Trimble 5700 can measure, and that more modern receivers may improve on our results. ]**

6. The conclusions are rather short and weak. What are the major issues of SfM technology? The authors test in mainly quite gentle terrain. What would be the implications for rough terrain (e.g. minimal flight elevation possible, differences in GSD, steep slopes etc.). Are there some plans to apply this technology for further studies?

**[We have expanded the conclusions and discussion to address this comment. ]**

Specific comments:

Title "landscape scale" is not very precise, is there a better term? The title is rather long and filled with technical jargon

**[Yes, the title is a mouthful, but our intent was to capture the essence of the paper at a glance. ]**

P334 L17 "another photogrammetric system", what is different?

**[We have modified the abstract text. Please also see section 3.6.]**

P335 L6 How do you get to the limit of 400 cm, in the Alps we have spots with much more snow!

**[Agreed. We did not intend 400 cm to sound like a limit and agree this is unnecessarily confusing and have eliminated it.]**

P335 L27 Why do you lose now word at all on spatial resolution here? This is the major drawback of microwave emissivity!

**[Agreed. We have added this.]**

P336 L 9 In my opinion my paper is cited here at the wrong place. In our study we investigated quite similar topics but in different terrain, so it would be helpful to set

your results in context with our previously achieved results (the overworked paper is published now in TC). Again here, the citation of papers seems quite randomly and the reader cannot follow why these references are there.

**[At the reviewer's suggestion we have addressed his new approach separately. The purpose of this sentence and the following paragraph was simply to alert the reader that we were not the first to consider or attempt photogrammetric measurement of snow, and give readers unfamiliar with such studies a place to start learning more.]**

P336 L22 What is a "sufficient accuracy"? Please specify.

**[Here we simply meant that the errors were too large to be useful, and have updated the text.]**

P339 L6 It would be nice to have a table with other devices, which could be used for this approach. It gets not clear why the authors choose the Nikon D800E.

**[At the reviewer's suggestion, we have modified the text to make clear that we selected the D800E simply because it was ranked the best DSLR camera at the time and that we evaluated no other cameras as part of this research.]**

P339 L 23 Here the near infrared option is not mentioned. From our experience, the near infrared bands enable much more contrast over snow-covered areas (e. g. Bühler et al. 2015). This option should at least be mentioned.

Bühler, Y., et al. (2015). "Potential of operational, high spatial resolution near infrared remote sensing instruments for snow surface type mapping." *Geoscience and Remote Sensing Letters*, IEEE 12(4): 821 - 825.

**[At the reviewer's suggestion we have included this reference in the introduction. We did not use near infrared to produce our results and have no basis ourselves for determining whether it would be an improvement or not so it is somewhat outside the scope here, but obviously worthy of investigation. ]**

P341 L15 "manually associated with image filenames" This is an important step in the processing. How time-consuming is it? Do you face some problems there? Would there be other options?

**[We have modified the text to address this comment.]**

P341 L 21The computer described is extremely well equipped with RAM and cores, can you say something about the processing time needed if you take a standard desktop computer?

**[At the reviewer's suggestion, we have added more information on this. ]**

P342 L 11 In this chapter you should mention the problems arising, if you compare point measurements to spatial continuous data. Which problems can occur if you localize the probe measurements with a GPS with an accuracy of 5 m?

**[Agreed. We discuss these errors later in the paper.]**

P344 L5 Why did you not analyze the probe measurements statistically? It would be interesting to compare the statistics to the ones derived from the photogrammetric maps.

**[This was done and presented in Section 6.3 using the Kolmogorov–Smirnov test using the Hulahula river data. To streamline the paper we limited such analysis to on one location, as the results were similar.]**

P346 L6 How were the GCP's measured? Why did you not measure GCP's which have a better distribution?

**[At the reviewer's suggestion, we have added a new section on GCP measurement to the text, Section 3.8. Regarding GCP distribution, this was not funded research and we did the best we could given the constraints we had. Our main ground control was the snow depth probing, which is of more value to our change-detection methods.]**

P347 L1 Why do you have different GSD's? Different flight heights above ground?

**[The flights were all done at the same height, we just processed the DEMs to different final resolutions, partly to save time, partly to assess whether this affected the results.]**

P352 L18 It would be interesting to get more information on these artifacts. When do they occur? What are the reasons for them? Do you have some strategies to limit artifacts? The 100cm GSD should reduce artifacts because it smoothens the terrain. This point is not clear to me.

**[We have modified the text to make it more clear that the only way to mitigate these errors is to map at a higher resolution, and that this bias is an inherent issue of any gridding process and thus independent of the airborne technology used. ]**

P354 L26 There is no clear statement in the paper how well the method works in forested terrain or in areas covered by bushes. Could you specify this?

**[We have tried to clarify the text that we have no reason to believe it should not work well in forests with open canopies, dependent only on the spatial biasing described previously, but we did not test this specifically and it remains to be verified statistically.]**

P357 L26 please describe the possible improvements in more detail.

**[Agreed and modified.]**

P358 L4 Geolocation is very important in steep terrain! A small shift in x or y results in a very large error in z. Please discuss this point.

**[We have tried to make it clearer in the text that we distinguish between geolocation and co-registration. The accuracy of our snow depth maps is independent of geolocation (the real world location), only co-registration between maps matters (how well aligned they are). That is, each map could be a kilometer in error in terms of geolocation, yet produce accurate snow maps, because we do not subtract them until they are optimally co-registered.]**

P360 L14 I do not know any satellite application that can map snow depth accurately!

**[Agreed.]**

P371 Fig1 You map very deep snow in the very steep slopes of the bluff. Are you sure the snow is that deep in the steep areas. The geolocation is very important here, could

it also be error? In the Alps we usually find only small snow deposits on very steep slopes. There might be cornice but I would expect the major snow mass at the toe of the slope. Please check that.

**[Yes, we are certain this is correct. If what the reviewer suggests would have been true, we would see an error of similar magnitude but opposite sign on the other side of the valley, which we do not see, as can be verified in Figure 5 of the same site. We are very sensitive to this sort of co-registration error in our analyses.]**

P375 Fig 3b: Where are these errors located? Why do they occur? This information would be interesting.

**[Please see sections 5.3.2 and 5.4]**

P374 This caption is very long, can't you take some information to the text? This applies for all long figure captions.

**[We have tried to eliminate duplication between captions and text. However, by including more information in the caption, it allows readers to more quickly skim the text and decide what sections to read in more detail.]**

P376 Fig 4a: a scale bar would be helpful Fig 4d: Where are the big differences around probe 120, 380 and 450 coming from?

**[4a: As described in the caption, the graticule has 50 m spacing to provide scale. 4d.: We have expanded this caption to clarify the reviewer's question. In short, we believe it to be largely caused by vegetative compression of the grass and shrubs near the woods on the left of Figure 4a]**