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 intervolometer, 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 addtion 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 repetetive 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]

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 'determinig 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 loos 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]

1
2   **Mapping Snow Depth from Manned Aircraft on Landscape-scales**
3   **at Centimeter-Resolution using Structure-from-Motion Photogrammetry**
4
5
6   Matt Nolan[1], Chris Larsen[2], and Matthew Sturm[2]
7

8   1. Institute of Northern Engineering, University of Alaska Fairbanks, 306 Tanana Loop,
9   Fairbanks, AK 99775, matt2013@drmattnolan.org
10 2. Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Drive, Fairbanks,
11   AK 99775

12 **Abstract**
13 Airborne photogrammetry is undergoing a renaissance: lower-cost equipment, more powerful
14 software, and simplified methods have significantly lowered the barriers-to-entry and now allow
15 repeat-mapping of cryospheric dynamics at spatial resolutions and temporal frequencies that
16 were previously too expensive to consider. Here we apply these advancements to the
17 measurement of snow depth from manned aircraft. Our main airborne hardware consists of a
18 consumer-grade digital camera directly-coupled to a dual-frequency GPS -- no Intertial Motion
19 Unit (IMU) or on-board computer is required, such that system hardware and software costs less
20 than $30,000, exclusive of aircraft,. The photogrammetric processing is done using a
21 commercially-available implementation of the Structure from Motion (SfM) algorithm. The
22 system is simple enough that it can be operated by the pilot without additional assistance and the
23 technique creates directly-georeferenced maps without ground control, further reducing overall
24 costs. To map snow depth, we made digital elevation models (DEMs) during snow-free and
25 snow-covered conditions, then subtracted these to create difference DEMs (dDEMs). We
26 assessed the accuracy (real-world geolocation) and precision (repeatability) of our DEMs
27 through comparisons to ground control points and to time-series of our own DEMs. We validated
28 these assessments through comparisons to DEMs made by airborne lidar and by a similar
29 photogrammetric system. We empirically determined that our DEMs have a geolocation
30 accuracy of ± 30 cm and a repeatability of ± 8 cm (both 95% confidence). We then validated our
31 dDEMs against more than 6000 hand-probed snow depth measurements at 3 separate test areas
32 in Alaska covering a wide-variety of terrain and snow types. These areas ranged from 5 to 40
33 km^2 and had ground sample distances of 6 to 20 cm. We found that depths produced from the
34 dDEMs matched probe depths with a 10 cm standard deviation, and were statistically identical at
35 95% confidence. Due to the precision of this technique, other real changes on the ground such as
36 frost heave, vegetative compaction by snow, and even footprints become sources of error in the
37 measurement of thin snow packs (<20 cm). The ability to directly measure such small changes
38 over entire landscapes eliminates the need to extrapolate limited field measurements. The fact
39 that this mapping can be done at substantially lower costs than current methods may transform
40 the way we approach studying change in the cryosphere.
41
42

Deleted: techniques

Deleted: .

Deleted: T

Deleted: another

Deleted: an absolute

Deleted: relative precision

Deleted: for our methods

Deleted: these

Deleted: depth distributions

Deleted: isolated

1. Introduction

There are many reasons why being able to map snow depth over a landscape is desirable. In the Northern Hemisphere alone over 40 million km², almost half the land surface, becomes covered by snow each winter, making seasonal snow the largest annual topographic change on the planet (Déry and Brown, 2007; Lemke et al., 2007; Robinson et al., 1993). Billions of people rely on snow in some capacity, whether for drinking water, crop irrigation, or electricity (Barnett et al., 2005). Snow can also be a hazard, producing avalanches or floods (Castebrunet et al., 2014; Jamieson and Stethem, 2002). Snow plays a key role in the surface energy balance of the planet, thermally insulating the soil while efficiently reflecting sunlight because of its high albedo (Goodrich, 1982; Warren, 1982). The depth of the snow affects how much work grazing animals such as caribou will need to do in order to feed and it controls the quality of the habitat for sub-nivean animals like voles and weasels (Pauli et al., 2013; Pruitt, 1959; Russell et al., 1993).

Despite its importance, our current abilities to measure snow depth are limited. The simplest and oldest technique is to probe or core the snow by hand, but this technique has severe limitations with respect to areal coverage, and can be risky in avalanche country (Conway and Abrahamson, 1984; McKay, 1968; Sturm, 2009; Sturm and Benson, 2004). Automated point measurements such as snow pillows and sonic rangers have also been employed successfully for many years, but like hand probe measurements, require modeling to move from discrete point data to the landscape-scale (Liston et al., 2007; Liston and Sturm, 2002; Serreze et al., 1999; Slater and Clark, 2006). Remote sensing of snow coverage using optical sensors is fairly routine, but remote sensing of snow depth or snow water equivalent based on the microwave emissivity or radar scattering properties of the snow requires complex and problematic inversions in order to infer the depth and has kilometer-scale resolution (Clifford, 2010; Rittger et al., 2013; Rott et al., 2008). Similarly, it is possible to measure the SWE using an airborne gamma detector, but again the accuracy and spatial resolution of the method is low (Offenbacher and Colbeck, 1991). A technique that has received considerable attention in recent years is to measure the elevation of the snow surface by airborne or ground-based lidar and subtract from this the snow-free surface elevation, with the difference interpreted as snow depth (Deems et al., 2013; Fassnacht and Deems, 2006; Hopkinson et al., 2004; Prokop, 2008). Operating on the similar principles of repeat or overlapping coverage, but pre-dating lidar studies by 30 years, photogrammetry has also been used to produce snow depth maps (Cline, 1994; König and Sturm, 1998; Lee et al., 2008; McKay, 1968; Najibi and Arabsheibani, 2013; Otake, 1980; Rawls et al., 1980; Yan and Cheng, 2008), including using stereo-imagery from opto-electronic linescanners incorporating near-IR wavelengths in addition to RGB (Bühler et al., 2014; Buhler et al., 2015).

Airborne and terrestrial photogrammetry for determining snow depth were seriously investigated starting in the 1960s, though little published information is available (McKay, 1968). At that time, lacking any other method of mapping snow depth at the landscape scale, it was an obvious technique to consider as it was already being used for the study of glaciers (Brandenberger, 1959; Hamilton, 1965; Hitchcock and Miller, 1960; Post, 1995, 1969). However several issues hampered applying classical photogrammetry to snow cover. The low dynamic range of film combined with the difficulties of changing exposures mid-flight often produced over-exposed images of the snowfields, making it impossible for the photogrammetrist to determine elevation. Even when the snow images had suitable contrast, it took an extraordinary amount of time and skill to produce a map of sufficient vertical accuracy to measure snow depth (McCurdy et al., 1944), as the errors incurred produced uncertainty beyond the thickness of typical snowpacks

---

Deleted: about 30

Deleted:

Deleted: 10 to 400 cm

Deleted: is

Deleted: and

Deleted: same

Deleted: .

91   These maps required identifying control points on the ground and establishing their elevation and
92   position, and the process of subtracting one elevation field from another using paper or mylar
93   maps was challenging. The overall complication and expense of this method in the pre-digital
94   era was enough to cause the technique to largely be abandoned in the study of seasonal snow,
95   though it has continued to be used for glacier volume change detection and for other large-scale
96   deformation processes such as landslides (Bauder et al., 2007; Bitelli et al., 2004; Cox and
97   March, 2003; Krimmel, 1989; Miller et al., 2009).

99   As we report here, recent advances in digital photogrammetric technology have now made it
100   possible to not only produce accurate snow depth maps through airborne photogrammetry, but to
101   do so at larger spatial-scales, at lower cost, and without loss of accuracy compared to most other
102   techniques. These advances include improvements in consumer camera sensors, GPS processing
103   techniques, desktop computational power, and especially, photogrammetric software. This
104   software largely eliminates the need for purpose-built photogrammetric cameras and inertial
105   motion units (IMUs), saving hundreds of thousands of dollars. These techniques are gaining
106   popularity across all of earth sciences, being primarily deployed on low-cost unmanned aerial
107   vehicles (UAVs). These systems are being used to map glaciers, river beds, coastlines,
108   archeological sites, forest canopies, urban development, and more (d'Oleire-Oltmanns et al.,
109   2012; Eisenbeiß, 2009; Fonstad et al., 2013; Gauthier et al., 2014; Hugenholtz et al., 2013;
110   Irschara et al., 2010; Lucieer et al., 2013; Nex and Remondino, 2014; Rinaudo et al., 2012; Ryan
111   et al., 2014; Vanderjagt et al., 2013; Westoby et al., 2012; Whitehead et al., 2013; Woodget et al.,
112   2014). Our techniques were designed for manned aircraft, which can measure larger spatial
113   scales with better accuracy and without the regulatory restrictions currently imposed on UAVs.
114   Using an airborne equipment package costing less than $30,000 (excluding the aircraft), we
115   demonstrate here that we can produce maps of snow depth accurate to ±10 cm with ground
116   sampling distances (GSD) as low as 6 cm. We present results from 3 field sites in Alaska to
117   show that the results produced using this technique (Figure 1) reveal details of snow depth
118   distribution heretofore rarely available for study. The technique takes advantage of many of the
119   technological developments of the past ten years, but in principle builds on the pioneering efforts
120   of photogrammetrists and snow scientists beginning in the 1940s.

123   **2. Recent Enhancements to Airborne Photogrammetric Methods**

125   In this section we address the question "Why wasn't this method possible until now?" Our
126   approach relies on three components that have undergone much improvement in recent years.
127   These are the photogrammetric software used to create the maps, the digital cameras used to take
128   the aerial photographs, and the airborne GPS techniques that geolocate the maps within the real
129   world. We were not involved with these developments, our chief contribution here has been to
130   integrate these components into a simplified and low-cost system. Below we describe the
131   improvements to these components, as well as our choices for specific hardware/software.
132   Evaluating whether our choices were optimal, and how other components might improve or
133   degrade the results is beyond the scope of this paper, but it is likely to be an active topic of future
134   research.

137   2.1. Photogrammetric Software. We used Agisoft's Photoscan software for processing, which
138   uses a Structure from Motion (SfM) algorithm at its core (Koenderink and Van Doorn, 1991;

Deleted: .

139 Westoby et al., 2012); at least 7 other software packages are currently available utilizing this
140 algorithm. Both SfM and traditional photogrammetric-processing software triangulate the
141 positions of points on the ground that have been imaged multiple times in overlapping
142 photographs to create a 'point cloud' – a collection of X,Y,Z values defining the measured
143 surface. This point cloud can then be gridded into a digital elevation model (DEM) or an
144 orthometrically-corrected image mosaic (Maune, 2001); here we use the term *map*
145 interchangeably with DEM. As part of this process, two types of unknowns must be determined
146 before the maps can be made. Exterior orientations refer to the position and tilt of the photos and
147 include 6 unknowns: X, Y, Z, yaw, pitch, and roll (that is, position and tilt of the camera).
148 Interior orientations refer to the specifics of the camera and lens: focal length, sensor dimensions,
149 pixel pitch of the sensor, lens distortions, and principle point. These result in about 10 unknowns,
150 depending on the lens distortion model. Where the modern software has an advantage is that it
151 requires no ground control points, no tilt information, and no a priori lens calibrations, as these
152 can be calculated if the remaining variables are provided with adequate accuracy. Because tilts
153 are not required as input, there is no need for an inertial measurement unit (IMU) on the aircraft.
154 Because the software performs a camera/lens calibration on the fly, the need for a purpose-built
155 aerial photography camera with strong camera-lens stability is also removed, allowing use of
156 consumer-grade cameras. To create the point cloud, the software is able to access the full
157 computational resources available, including the GPU of the graphics card.
158
159 2.2. Camera and Image Procesing. For this work we used a digital single lens reflex camera
160 (DSLR), the Nikon D800E, which was the highest ranking DSLR (www.dxomark.com) when it
161 was released. It costs about $3300 USD; in contrast, a modern, high-end photogrammetric-
162 camera such as the Vexcel Ultracam might cost between $300,000 and $1,000,000. A primary
163 attribute of photogrammetric cameras is their stable lens mount, but as we show, the SfM
164 software adequately accounts for the less stable mounts on DSLRs. Photogrammetric cameras
165 also have a greater number of pixels in the cross-track direction in comparison with a DSLR.
166 For example, the D800E sensor has 7,360 x 4,912 pixels (36Mpix), compared to the Vexcel
167 Ultracam with 11,704 x 7,920 (92 Mpix), resulting in flight lines that need to be about 60%
168 closer for the same amount of overlap. In our applications the increased cost of extra flight time
169 due to using a DSLR is more than offset by the reduced purchase price, high image quality, and
170 ease of use of the consumer camera, driven by relatively enormous consumer demand and
171 competition. Similar advantages exist in consumer lens selection. The wide dynamic range and
172 low noise of the D800E are largely responsible for our ability to capture texture in both bright
173 snow and shadowed rock in the same image, problems that plagued film-based photogrammetry
174 of snow in the past. Similar improvements in image processing now allow us to easily maximize
175 local contrast (eg., sastrugi or suncups) while constraining global contrast to ensure the entire
176 dynamic range is persevered. We used Adobe Camera Raw for this, though there are literally
177 dozens of software packages with similar features. While the specifics for each data set varied,
178 in general our approach consists of shooting in raw mode (with separate R, G, B channels),
179 pushing the exposure as far as possible to the bright side of the histogram during acquisition
180 where more bits are available for recording, then pulling the exposure down in post-processing
181 (essentially turning the snow greyer) to enhance its visible contrast, while keeping the shadows
182 from clipping. Despite these improvements in hardware and software, the quality of the
183 photogrammetric results still depends on the skill of the photographer, especially in challenging
184 lighting conditions, thus there is no simple prescription for camera settings or post-processing
185 that can ensure success. However, as our results demonstrate it is possible to achieve accurate
186 results, even in flat light.

Deleted: .

Deleted:

Deleted: There are

Deleted:)

Deleted: .

Deleted: I

Deleted: . DSLRs are

Deleted: by

Deleted: , and the D800E image quality specifications were the highest ranked when it was released (www.dxomark.com).

Deleted:

187

188 2.3. GPS. While the GPS techniques we used have been available for some time, advances in
189 processing software and hardware integration have streamlined the user-experience substantially.
190 When maps are directly georeferenced (that is, without using ground control), the accuracy of the
191 georeferencing is dependent on the accuracy of photo positions. To achieve our results, a
192 modern multi-frequency GPS system must be used that can track aircraft position to within
193 centimeters. We used a Trimble 5700 receiver, a discontinued model which measures only 12
194 GPS satellites at a time; modern receivers are capable of recording hundreds of channels from a
195 variety of international constellations, which would likely improve position accuracy. The three
196 dimensional offsets of the GPS antenna relative to the camera image plane, often referred to as
197 "lever arms", must also be determined for each aircraft installation. In processing the GPS data,
198 the lever arms are used in a coordinate transformation from the antenna position to the camera
199 position. Without an IMU, this transformation relies upon the assumption that the aircraft frame
200 of reference is aligned with the tangent of its trajectory. This assumption is often violated in the
201 presence of crosswinds, but such errors associated with aircraft yaw can be mitigated by placing
202 the GPS antenna directly above the camera. Finally, the exact time that the photo was taken must
203 be used to determine its position within the post-processed GPS record. An aircraft traveling at
204 50 m s^{-1} (about 100 knots) will travel 5 cm in a millisecond. Thus to achieve a 5 cm accuracy in
205 camera position requires a timing connection between camera and GPS with signal latencies
206 reduced to below the millisecond level. There are a variety of ways this can be done; our method
207 converts the flash output from the camera into a TTL pulse for the event marker in the GPS; the
208 camera and GPS receiver are thus directly coupled through this device without use of a computer.

209
210
211 **3. Methods**

212
213 3.1. Photo Acquisition and Processing. We pre-planned flight lines and shutter intervals to
214 provide 60% sidelap and 80% endlap, such that most of the ground coverage within the map was
215 imaged more than 9 times. Flight lines were uploaded into a Garmin aircraft-GPS for pilot
216 display and navigation. The survey-GPS was set to record at 5 Hz. The Nikon D800E with
217 Nikkor 24 mm lens was mounted vertically in the aircraft's camera port. The shooting interval
218 rate (typically 2 to 5 s) was controlled by an intervalometer (contact www.fairbanksfodar.com
219 for details), which also provided precise shutter-timing to the survey GPS as described in Section
220 2.3. Photos were acquired as raw NEF files, post-processed to maximize available contrast, and
221 saved as JPGs for photogrammetric processing. A Cessna 170 flown by the first author was used
222 to acquire the photos.

223
224 3.2. Airborne GPS Processing. GPS data were processed with GrafNav GNSS Post-Processing
225 Software using their Differential GNSS method for projects near a CORS base station and using
226 the PPP (Precise Point Positioning) method in remote areas (Gao and Shen, 2002; Snay and Soler,
227 2008). Positions were automatically interpolated within GrafNav from the 5 Hz GPS solution
228 using the event markers created by the camera flash port to TTL pulse converter. Each photo
229 position was exported and manually associated with image filenames to create an exterior
230 orientation file that was imported into Photoscan Pro along with the photos themselves. The true
231 accuracy of photo positions is difficult to assess, but most of the software's metrics (such as
232 comparison of a forward and reverse solution) indicate that 95% of the points are within ±10 cm
233 on most projects.
234

Deleted: ¶

Deleted: a

Deleted:

Deleted:

Deleted: ; oO

Deleted:

Deleted: above

Deleted: Typically p

235 3.3. Photogrammetric Processing. We used Photoscan running on a dual Xeon eight-core
236 computer with 192 GB Ram and a high end GPU for map construction. To make individual maps,
237 a batch file was typically initiated within Photoscan to align the photos, optimize the bundle
238 adjustment, construct the geometry, build a mesh, and export a DEM and orthophoto product.
239 Total processing times ranged from 2-24 hours, depending on size of the project and processing
240 resolution. As described in Section 2.1, processing time is dependent strongly on processing
241 power, as well as having adequate RAM to prevent disk caching. Thus nearly any computer
242 would work in this application, but processing times are dependent on computer resources.
243
244 3.4. DEM Differencing. To measure snow depth, we created a difference DEM (dDEM) by
245 subtracting a snow-free DEM from a snow-covered DEM to determine the vertical change
246 between them for each pixel (James et al., 2012; Maune, 2001; Nuth and Kääb, 2011; Wheaton
247 et al., 2010). To optimize the differencing, the two maps were first co-registered horizontally to
248 minimize errors in geolocation using simple 2D offsets determined with standard sub-pixel
249 image correlation techniques using Matlab.   Vertical alignment was done at snow-free locations
250 in both maps (e.g., a wind-blown outcrop or a plowed runway). As described later, we found
251 that we did not need to employ sophisticated techniques to determine misfits or non-affine co-
252 registrations (Nuth and Kääb, 2011).
253
254 3.5. Snow probing. We tested the resulting snow depth maps by collecting about 6000 hand-
255 probed depth measurements. We used several GPS-enabled depth probes to do this (Sturm and
256 Holmgren, 1999). In most cases these depth data were collected along traverse lines that cut
257 through obvious snow features (drifts, shallow areas, etc.), but in some cases we probed on a grid
258 or on a spiral in a way that would allow the production of a snow depth map. Probe spacing
259 varied depending on the length of the traverse line and the time available for the work, but was
260 typically about 1 m. The GPS used on the probes is not a differential GPS and has a nominal
261 accuracy of about 5 m. The probes have an inherent error due to penetration of the probe tip into
262 the snow substrate of about ± 2 cm. In our remote field areas the substrate of tussocks and ice
263 wedges usually had a surface roughness on a wavelength shorter than the probe spacing, which
264 can introduce spatial aliasing when compared to airborne maps that have 6-20 cm resolution.
265
266 3.6. Validation DEMs. On the same day we acquired a photogrammetric DEM at the Minto
267 Flats study area (3 April 14, described below), we also acquired a lidar DEM and a
268 photogrammetric DEM from a system of slightly different design to validate our accuracy and
269 precision assessments. This lidar and second photogrammetric system were carried in a Cessna
270 180 flown by the second author and acquired simultaneously. This lidar system is based upon a
271 Riegl Q240i and is the principal system used for NASA's Operation IceBridge flights in Alaska.
272 The system has been in extensive use since 2009 and is particularly well characterized with
273 dozens of calibration flights and a careful program of boresight angle determination and
274 monitoring (Johnson et al., 2013). At 95% confidence it has an accuracy of ±30 cm and precision
275 of ±16 cm. The photogrammetric system differs from the one described above in that it used a 28
276 mm lens and routed its photo event markers through the IMU associated with the lidar system.
277 With the GPS/IMU data, the software is able to directly calculate the full lever arm solution
278 between the GPS antenna and camera. Thus image positions from this aircraft were derived
279 from the fully coupled GPS/IMU processing, and there were other minor differences in
280 processing workflow as well. This photogrammetric DEM was processed to a 12 cm ground
281 sample distance (GSD).
282

283   3.7. Ground Control Points. We acquired ground control points for this project using the same
284   Trimble 5700 receiver and Grafnav software used in airborne processing. Here we placed the
285   antenna on a rod over photo-identifiable targets, as described later. We processed these
286   measurements using the same Differential GNSS methods, which indicated a resulting accuracy
287   of better than 3 cm in vertical and horizontal direction.

288
289
290   **4. Study Areas and Measurements**
291
292   We collected data from three study areas in Alaska: the Fairbanks International Airport, Minto
293   Flats, and the Hulahula River watershed (location map in Supplemental Materials). As this was
294   a technique-development project, these sites were chosen opportunistically to minimize our
295   development costs, as described below.
296
297   The Fairbanks International Airport was selected due to its convenience and snow characteristics.
298   It is located only a few miles from the University of Alaska Fairbanks and the plane we used for
299   this work is located there. During the winter of 2013-14, about 43 cm of snow fell and remained
300   undisturbed in the infields between runways. Near the runways and taxiways the snow gets
301   extensively reworked to accommodate aircraft operations. The runways are kept clear of snow,
302   which requires snow blowing, grading, and removal, all of which create berms adjacent to the
303   runways of different thickness, and which change shape and depth frequently. Due to security
304   and other issues, snow probing at the airport was limited to collection of a few hundred points
305   and we do not statistically analyze these data. We made six airborne acquisitions over the airport
306   (Table 1) mostly for assessments of accuracy and precision, using the snow-free runway as
307   control. The maps made were roughly 5 km x 1 km and processed to 6 or 12 cm GSD. We used
308   a GPS to measure 29 taxiway markings as ground control points (GCPs); all GCPs used in this
309   paper have an accuracy of about ±3 cm. The airborne imagery was acquired in a variety of
310   lighting conditions, including low-angle mid-winter sun and beneath a thick overcast.
311
312   The Minto Flats site was selected because of its undisturbed snow cover and heterogeneous
313   terrain. It is located about 50 km from Fairbanks and can be accessed using a ski-plane to land on
314   its many frozen lakes. The area is characterized by tundra, swamps, areas of shrubs, spruce and
315   birch forests, and taiga snow cover (Sturm et al., 1995). The airborne study area was about 2 km
316   x 5 km and encompasses the full range of these terrain elements. Our snow-probe measurements
317   were made at the edge of the largest lake in the area and cover about 9 hectares (about 1% of the
318   area mapped by air). Using three separate GPS-enabled probes, 2,432 snow depth measurements
319   were made on 2 April 2014, largely in a grid pattern with along-track separation of about 1 m
320   and cross-track separation of about 6 m. Measured snow depths largely ranged from 0.1 – 0.6 m.
321   We made six airborne maps of this area processed to about 15 cm GSD (Table 2); we also made
322   two other maps on April 3rd using lidar and a 2nd photogrammetric system for validation, as
323   described above. We also measured 21 GCPs on April 2nd using spray paint to create markers;
324   these remained visible in the April 3rd orthoimagery as there was no intervening snow fall or melt.
325
326   The Hulahula River valley was selected for our snow research due to its history of hydrological
327   studies, its relationship to the nearby, long-term McCall Glacier research project, its relevance to
328   ecological research in the Arctic National Wildlife Refuge (Nolan et al., 2005; Nolan et al.,
329   2011; Weller et al., 2007), and the availability of snow-probing conducted to support related
330   snow research there (Sturm et al., in prep; Sturm et al., 1995). Located 330 miles north-east of

Deleted: which was placed

Deleted: , and

Deleted: e

Deleted: and

Deleted: .

331   Fairbanks, the valley extends from the continental divide of the Brooks Range to the Arctic
332   Ocean, with a watershed of about 1800 km^2, about 6% of which is covered by glaciers (Nolan et
333   al., 2011). Unlike most watersheds in the Alaskan Arctic, the snowmelt pulse is not the major
334   hydrological event of the year due to the influence of glaciers and to a lesser extent aufeis. As
335   the climate warms, however, these ice reservoirs are likely to disappear and allow snowmelt to
336   dominate the run-off. A longer term project seeks to understand current rates and volumes of
337   snowmelt, glacier melt, and aufeis melt through the photogrammetric techniques we describe
338   here; these environmental questions will be addressed in subsequent papers. The probe data in
339   the Hulahula River valley were collected in three terrain types on 18 March 2014: 1) a flat river
340   terrace with a thin (15 - 20 cm), uniform snow cover, 2) a set of islands in the river with snow
341   depths varying from 0.2 – 0.6 m, and 3) a series of drifted-in gullies cutting into a 40 m bluff
342   with snow depth from 0 – 3 m. Airborne mapping was done on 20 April 14 (snow-covered) and
343   15 June 14 (mostly snow-free except in drifts). Though the snow-covered map was made 31 days
344   after the probing, our results indicate that little change had occurred in snow depths over this
345   period. The DEMs were processed to about 20 cm GSD and covered an area 14 km x 2.5 km.
346   No GCPs were acquired.
347
348
349   **5. Assessment and Validation of Map Accuracy and Precision**
350
351   Our goal in this section is to answer two questions "How well do our airborne maps align with
352   the real-world without using ground control?" and "After correcting for geolocation errors, how
353   identical are our maps assuming no changes to the surface have occurred?" These questions
354   address map *accuracy* and *precision*, respectively. Because both the photogrammetric and GPS
355   software we used to make our maps is proprietary and essentially black-box, we could not
356   conduct a first-principle error analysis so we empirically assessed map errors, largely following
357   Maune (2001). In all of our assessments we use the ± range to indicate the level of accuracy or
358   precision at the 95% confidence interval for normal distributions (following Maune, 2001) and
359   we simply cite the values of points ±47.5% about the mean for non-normal distributions; with 5
360   or less data points, we use +/- 50% of the full range.
361
362   We used two methods to assess accuracy. In the first, we assessed the difference between the
363   maps and GCPs, calling the results *geolocation offsets*. The GCPs are accurate to about 3 cm,
364   but the most we have for any one site is 29 and they are not well-distributed throughout the study
365   area, making this a weak test spatially. In the second method, we applied these geolocation
366   offsets to one of our maps, which we defined as a *reference map,* and then compared this map to
367   the other maps (Maune, 2001); we term these map differences *co-registration offsets*. Using this
368   method, the millions of pixels of the entire reference map become pseudo-GCPs, with their
369   accuracy largely controlled by the precision of reference map itself (about ±8 cm, as we
370   described below) rather than the GPS-GCPs (± 3 cm). We determined horizontal co-registration
371   offsets using standard image correlation. We calculated vertical co-registration offsets at snow-
372   free areas. The plowed runway in the airport data was the only location where we could do this
373   statistically; at other sites we used the orthoimages to locate snow-free pixels for spot
374   measurements only.
375
376   We report our precision as ±95% of the RMSE elevation difference between two DEMs after
377   they have been optimally co-registered. Using this method, the magnitude of spatially correlated
378   and uncorrelated errors are captured in the same precision metric. Given that our precision is on

Deleted:

Deleted:

379 the centimeter-level and that we later show that this was sufficient to produce maps with
380 excellent agreement to our snow probing data, we did not distinguish the amount of spatial-
381 correlation within this ±95% RMSE further. Technically this RMSE measures the precision of a
382 dDEM, not an individual DEM, but when computed from two maps where no changes in the
383 surface have occurred and no gridding artifacts are present (both described later), the metric
384 defines how identical the maps are and therefore the level of change-detection possible in the
385 dDEMs.
386
387 Our overall assessment is that our maps (at 6 to 15 cm GSD) have accuracy better than ± 30 cm
388 and precision better than ±8 cm, as described in sections 5.1-5.3. In this paper we do not address
389 whether accuracy or precision vary with larger GSDs, but note that this remains to be explored.
390 To validate these accuracy and precision assessments, in section 5.4 we compared one of our
391 reference DEMs to two DEMs made on the same day using different systems and found that they
392 confirmed our results.
393
394
395 5.1 Accuracy based on geolocation offsets from GCPs
396
397 We measured 29 GCPs at the airport. These were made at taxiway markings, all located within
398 300 m of each other. We compared these to the October snow-free acquisition and found a mean
399 horizontal geolocation offset of 30 cm and a vertical offset of 13 cm (Table 1). Applying the
400 offsets in Table 1, we define this October map as the reference map to determine co-registration
401 offsets of the other maps made at the airport.
402
403 We measured 21 GCPs at the Minto Flats site. These targets were circles on the snow surface
404 made with orange spray paint. They were too small for sub-pixel alignment within the
405 orthomosaic, but they were suitable for determining that the horizontal geolocation offset was
406 less than 15 cm (one pixel). The mean vertical offset was 23 cm (Table 2). This vertical offset
407 was applied to our April 3rd photogrammetric DEM to create the reference map; no horizontal
408 offset was applied given that a subpixel offset could not be reliably determined.
409
410 The results of these two GCP tests indicate a geolocation accuracy of ±30 cm.
411
412
413 5.2 Accuracy from co-registration offsets
414
415 We assessed the co-registration offsets of the other 5 maps from the airport time-series relative to
416 October reference map. We calculated the horizontal offsets through image correlation of the
417 snow-free runway markings, rounding to the nearest centimeter (Table 1, Columns 1-2). We
418 calculated mean vertical offsets (Table 1, Column 3) using a block of pixels (roughly 20 m x
419 2000 m) surrounding the centerline of the runway, which was largely snow-free throughout the
420 winter (Figure 2). The range of offset (highest minus lowest, last row Table 1) about the mean
421 (2nd to last row, Table 1) is a better indicator of accuracy than the mean itself, as the mean could
422 be due to a systematic issue with the reference DEM. As discussed in more depth in Section 5.3,
423 this "snow-free" area was not completely snow-free, so the range of vertical error has been
424 impacted by real changes to the surface. Nonetheless, both the mean and the range indicate ±30
425 cm as a reasonable co-registration accuracy.
426

Deleted: the

Deleted: below

427   We repeated this same analysis for the Minto Flats time-series (Table 2). As shown in Table 2,
428   the full range of horizontal co-registration offset is about ±0.05 m. Because there was no large
429   snow-free surface like the runway, we determined vertical offsets by making spot measurements
430   of the dDEMs in snow-free areas located using the orthoimage. These show a scatter of only
431   ±0.07 m, with 5 of the 7 maps clustered within half that.

433   Overall the Minto Flats data showed better co-registration accuracy than the airport data, about
434   ±15 cm compared to ±30 cm. The difference may relate to differences in relief of the terrain –
435   the airport is nearly flat and thus perhaps making the solution geometry weaker due to fewer
436   differences in scale. In any case, overall we conclude that our accuracy was ±30 cm, noting that
437   is likely conservative. The underlying causes for why map geolocation accuracy is ±30 cm when
438   photo position accuracy is ±10 cm remains unclear.

440   5.3 Precision

442   The primary challenge in determining map precision is that many real changes occur on the
443   ground at the centimeter level that confound the precision assessment. For example, surface
444   change at this level or higher can be caused by frost heave and thaw consolidation of the ground,
445   or by compression of vegetation under the weight of snow (Esch, 1995; Ménard et al., 2014;
446   Sturm et al., 2005; Taber, 1929). Thus the design of our tests are largely about controlling for
447   such confounding influences and we assessed the precision at the airport differently than we did
448   at Minto Flats. At the airport, we used the same time-series of the snow-free runway sections
449   that we used for accuracy assessments. At Minto Flats, we compared the November 6th and 8th
450   maps as intervening changes were negligible.

452   5.3.1 Airport precision assessment

454   We tried to assess vertical precision in several ways using the runway time-series. Real changes
455   in the surface elevation were present in these tests (but of unknown magnitude), yet the precision
456   was still excellent.

458   First, we examined the data graphically as is shown in Figure 2A-C. This demonstrated that in
459   the absence of confounding changes, our DEMs had a precision of about ± 3 cm. Figure 2A
460   shows an example of a difference DEM, with Figure 2B showing the corresponding snow-
461   covered scene for reference. Figure 2C shows transects from all 6 maps that extend across the
462   snow-free runway. Over the crest of the centerline where plowing is best, we found that the
463   elevations compared to within ± 3 cm (95% confidence).

465   Next we examined the scatter about the mean co-registration offsets described in Section 5.2. We
466   did this over a block of the runway that was kept largely snow-free through winter. Column 4 of
467   Table 1 indicates that once co-registered using the offsets in Table 1 (Columns 1-3), 95% of the
468   vertical difference between the runway blocks were less than ±10 cm (about twice the standard
469   deviation shown in Column 4). Visual inspection of the orthophotos (e.g., Figure 2B) shows that
470   this block of pixels was not completely clear of snow and changed between maps. Further, our
471   inspection of the difference maps indicates that spatially-correlated variations of 5-10 cm in
472   elevation occur over segments separated by expansion joints across all of the tarmac, suggesting
473   differential frost heave and settling. Despite these confounding influences (real changes in
474   surface elevation), we still found only a range of ±10 cm, which is excellent.

475
476 Finally, we extracted elevation profiles down the centerline of that block where plowing is best
477 to further eliminate the influence of snow (green line in Figure 2A). Figure 2D shows that each
478 of these transects captured the same decimeter variations in runway topography, though each
479 differs slightly. We measured the scatter of these centerline transects as function of distance
480 along the runway. Here the maximum range between transect points was 21 cm, the mean range
481 was 9 cm, and over 95% of the transect length these differences had a range less than 12 cm (±6
482 cm). Whether these differences are due to frost heave or spatially-coherent noise (perhaps
483 caused by photo misalignments) is not known, but the fact that 95% of the variation is within ±6
484 cm is an outstanding result and, as we describe in Section 6, more than sufficient to measure
485 snow depth variations at centimeter resolution.
486
487 To assess the horizontal precision, we used custom feature tracking software (Mark Fahnestock,
488 pers. comm.., 2014) using a python version of the feature-tracking software Imcorr (Scambos et
489 al., 1992). Such software is commonly used to measure velocity fields of glaciers from optical
490 and radar satellite imagery (Berthier et al., 2005; Huang and Li, 2011). In our case, because we
491 know that the position of runway markings and many other surface features are not moving, any
492 relative motion between them detected by this software indicates a lack of horizontal precision
493 within the maps. Using the two snow-free orthoimages (6 Oct 13 and 30 Sept 13) and search
494 chips of 100 x 100 pixels (6 m x 6 m), we found that 95% of the RMSE pixel displacement about
495 the mean was within ±6 cm (all subpixel). The mean value of displacement was also within a
496 few centimeters of the co-registration offset we found through whole-image correlation (Table 1),
497 as expected.
498
499 Thus our overall assessment of the airport time-series is that is that both vertical and horizontal
500 map precision is ±6 cm or better when the confounding influence of real surface changes is
501 removed.
502
503 5.3.2 Minto Flats precision assessment
504
505 Here we compare two DEMs of the Minto Flats area made two days apart with no intervening
506 snow fall or snow melt (November 6th and 8th). Once co-registered we created the dDEM of the
507 entire area at 15 cm GSD (~15 km^2, n>6x10^8) and found 95% of the vertical variation to be
508 within ±44 cm. This distribution was non-gaussian, with tails extending to +/- 15 m. We
509 cropped the dDEM to include only a large lake (n>10^6) and found the variation dropped to ±8 cm.
510 These distributions are shown graphically in Figure 3A. The difference in scatter between the
511 lake and entire area is largely caused by spatial aliasing of trees. Minto Flat trees are tall and
512 skinny spruce and leaf-free birch, up to 20 m tall, typically separated from each other by a tree
513 length or more like a forest of widely scattered flag poles. Even at 15 cm GSD, our DEMs are
514 not able to resolve these spike-shape targets adequately and thus most trees are represented by
515 several pixels that each average some fraction of tree height with surrounding ground height.
516 The result is that trees appear as cones in the DEM, with cone height dependent on how the
517 DEM mesh happened to lie over that tree. Because these cones are so narrow, slight errors in
518 horizontal co-registration or origin coordinates can cause dDEM errors approaching the heights
519 of the trees; one of these maps was made when winds at ground level were over 15 m s-1, which
520 could also cause similar aliasing at this resolution. Visual inspection of the dDEM confirms that
521 within clearings between the trees that precision is the same as on the lakes. Thus any mapping
522 system creating a DEM at this GSD would have these same spatial aliasing issues, and our

Deleted: 10 to 50 cm

Deleted:

523 precision is therefore represented better where gridding artifacts such as the spatial aliasing of
524 trees are not present.
525
526
527 Based on our results at the airport and Minto Flats, we believe ± 8 cm is a reasonable value for
528 the precision of our method. If any warps, tilts, or other spatially-correlated errors exist in our
529 data, they are largely confined to within this level. Thus our DEMs should be repeatable to ±8
530 cm, exclusive of any spatial aliasing or other gridding artifacts.
531
532 5.4 Comparison to Validation DEMs
533 Here we seek to validate our accuracy and precision numbers by answering the question "How
534 well do our DEMs compare to those made by other systems?" We do this by comparing our
535 reference DEM for Minto Flats (April 3rd) to DEMs on the same day using lidar and a 2nd
536 photogrammetric system (Section 3.5).
537
538 We co-registered the validation photogrammetry with our reference DEM using the same
539 methods previously described and found a vertical co-registration offset of 21 cm, with variation
540 of ±8 cm (95%) over the largest lake in the area. While we don't have any formal accuracy or
541 precision specifications for the validation system, given its similarity to the system that created
542 the reference DEM it seems reasonable that they should have similar specs.
543
544 Comparisons with the lidar DEM similarly validated our results, We created a 100 cm GSD
545 DEM from the lidar point cloud, which had a point density of 2 points m^{-2} and a footprint of
546 about 100 cm. We then resampled the reference DEM to this GSD. Because we have no
547 orthoimage for the lidar, we created shaded relief images of the DEMs and then used these for
548 sub-pixel image correlation to calculate horizontal offsets. Once co-registered, over the entire
549 domain the vertical offset from our reference DEM was only 2 cm. Visual inspection of the
550 dDEM showed no spatially-correlated errors, such as warps or tilts, greater than the lidar's
551 precision level of 16 cm. Nearly all differences observed above that precision level were due to
552 trees, likely caused by the different imaging physics between lidar and photogrammetry and by
553 aliasing artifacts caused by the 100 cm GSD, as described in Section 5.3.2. Over the entire
554 domain we found a variation of ±51 cm (95%), but over just the largest lake in the area the
555 variation was only ±10 cm, with the latter being a better test in terms of validation; these
556 distributions look nearly identical to those in Figure 3A. Statistically the lidar DEM is
557 essentially identical to our reference DEM. We performed a Kolmogorov–Smirnov test and
558 determined that statistically the two samples are from the same continuous distribution at the
559 95% confidence level. That is, our photogrammetric maps are essentially identical to the
560 validation data. This is shown graphically in Figure 3B, which shows the similarity between the
561 hypsometries of the lidar and the reference DEM.
562
563
564 **6. Snow Depth Mapping Accuracy**
565
566 Here we address the question "How well do our photogrammetric techniques measure snow
567 depths?" To do this we compared our maps to over 6000 snow probe measurements. The mean
568 of these differences is directly related to how well we can co-register the two DEMs used to
569 produce the dDEM. This co-registration error, in turn, is related to finding snow-free areas that
570 are not confounded by real changes to the surface such as vegetative compression, frost heave,

Deleted: such

Deleted: the

571   aufeis melt, or erosion. Without suitable snow-free ground control points, the accuracy of our
572   snow depth maps is limited to our geolocation accuracy, or about ± 30 cm. But when suitable
573   ground control points can be found, this accuracy is effectively improved to the level of the
574   precision of our maps, or about ±8 cm. Here we describe the accuracy our photogrammetric
575   snow depth measurements by the standard deviation of the difference between probe and map
576   values, as the mean is a function of ground control and co-registration, which have accuracies
577   independent of system precision. As before, our assessment is confounded by real changes
578   occurring on the ground, as we describe below. We conducted this map-probe analysis at three
579   sites: the Fairbanks International Airport, Minto Flats near Fairbanks, and the Hulahula River
580   valley, as described in Section 4.
581
582   6.1 Airport Snow Depth Analysis
583   Due to security and other issues we were only able to collect a few spot measurements of snow
584   depth. We found the undisturbed snow depth to be about 43 cm, the packed and groomed ramp
585   area snow depth to be 10-15 cm, and the plowed drifts to be greater than 1 m. Comparison of
586   these values to Figure 2A shows close agreement, as described in the caption of Figure 2.
587
588   6.2 Minto Flats Snow Depth Analysis
589   Before statistically comparing our probe measurements to the dDEM (03 April 14 minus 28 Sept
590   13), we assessed whether the probe measurements were optimally co-registered to the maps
591   using our footprints in the snow. These were clearly resolved in the DEM and orthophoto (Figure
592   4A-B). We each wore different footwear (ski, snowshoe, or boots), and the resolution of the map
593   was such that we could differentiate these individual tracks based on their indentations (Figure
594   4C), which ranged from 6 cm to 10 cm deep and about 10 times as wide. The GPS units
595   embedded into the probes each have an independent nominal accuracy of about 5 meters, thus
596   the ground data has better vertical precision than the maps but a coarser horizontal precision.
597   Analysis of all of the probe measurements together suggested there was no single shift that
598   aligned them properly relative to the footprints, likely because each probe's GPS accuracy was
599   independently varying. Short of manually shifting each of the 2432 measurements independently
600   to the corresponding footprints, there was no simple spatial alignment possible. This meant that
601   footprints' disturbance to the snow depth was included in the aerial mapping of snow depth, but
602   not in the ground probe data. Nevertheless, even without exact co-registration the depth
603   comparisons were 10-26 cm (on the order of footprints) and thus our results conservative, as we   **Deleted:** satisfactory
604   show next.
605
606   Figure 4D presents a comparison of about 500 probe measurements typical of the data set. The
607   standard deviation of offset for those measurements was 10 cm. For the full 2432 measurements,
608   including those made within the forests (with aliasing errors), the standard deviation was 26 cm,
609   but careful visual examination of imagery reveals that nearly all of the offsets greater than 15 cm
610   were located in areas where the vegetation was compressible, such as in the tall grasses near the
611   edge of the lake or shrubs at the edge of the forest. The mapped summer surface in these areas is
612   the top of the vegetative canopy. In winter, this canopy becomes compressed to the point where
613   it can even produce 'negative' snow depths in the difference maps. Here we found such snow-
614   vegetation dynamics were causing up to 30 cm of error. That is, the maps we produced here
615   were no less precise than described in Section 5 (±8 cm), but the fundamental assumption that
616   the differences between maps were caused only by snow accumulation has been violated where
617   there is compressible vegetation.
618

619   6.3 Hulahula River Snow Depths
620
621   Similar to the other sites, we began this analysis by co-registering the DEMs. Using the same
622   image correlation technique we used in Minto Flats, we found no horizontal offset. Using
623   several snow free areas identified using the orthoimages, we determined there was a vertical
624   offset of 55 cm. Subsequent analysis of the probe data indicated that 20 cm of that vertical offset
625   needed to be removed to reduce the map-probe mean offset to zero over the snow-covered points
626   that had the least likelihood of there being vegetation compression. Considering the surface
627   amplitude of the tussock tundra here is about 15 cm, these shifts are small and within the noise of
628   other confounding factors. Nevertheless, this process highlights that the primary errors in snow
629   depth accuracy are co-registration in the absence of ground control points. Once the maps were
630   co-registered, we created a dDEM and compared it to the probe values in the gullies, on the
631   islands, and on a large river terrace (Figure 5).
632
633   Figure 6 highlights some results from the gullies. Here a series of ice wedges have thermally
634   eroded to form a connected drainage system. In winter, this drainage network is completely
635   drifted over by snow, as can be seen by comparison of Figures 6A-C with 6D, with snow depths
636   of 100 to 200 cm. To the right of the gully a polygonal network can be seen in both the summer
637   image and difference map with snow depths of only 10 to 20 cm.   Figure 6D reveals a snow
638   depth of near zero to the right of the gully and about 20 cm to the left of it. These values can be
639   qualitatively confirmed by the winter image in Figure 6B, where exposed tussocks can be seen to
640   the right but not to the left. Comparison of about 200 probe points in Figure 6E reveals that the
641   maps match the probe depths and the features delineated by probing, including those parts of the
642   gully that exceed the 120 cm range of the probes. The standard deviation of offset here was 20
643   cm, not including points where the probes did not reach the bottom. The bulk of this offset
644   beyond 10 cm is likely attributed to 1) uncorrected probe positions resulting in misalignment
645   between probes and maps, which matters more in steeper terrain where spatial depth
646   heterogeneity is larger, 2) a spatial sample bias caused by the tussock terrain's surface roughness
647   of 15 cm on spatial wavelengths below GSD and below probe spacing, and 3) real surface
648   changes such as vegetative compressibility or frost heave. Considering these potential sources of
649   error, the agreement makes clear that we are measuring snow depth at the centimeter to
650   decimeter level.
651
652   The island transects (Figure 7) revealed a similarly strong correspondence between map and
653   probe data as well as new sources of confounding error in interpreting the difference map as a
654   change in snow depth. In winter, the river bed surrounding the island was completely snow
655   covered and the transects extended over the edge of the island's summer boundaries (Figure 7A).
656   In most of these edge locations, the map indicates changes up to a meter larger than revealed by
657   the probe (Figure 7B). Interpretation of our difference maps in the active river bed is
658   complicated by the fact that our photogrammetric technique does not work as accurately over
659   water, for a variety of reasons outside the scope of this paper. Further, our stream gaging
660   measurements (Nolan, unpub. data) show that the water height in spring can be over a meter
661   higher than in fall here. Thus extra care in interpretation needs to be taken of differences over
662   liquid water bodies. Given our map precision, it is therefore likely that remaining edge-offsets
663   were caused by either the probe being stopped by river ice obscured by the snow or that the
664   edges of the island were eroded, or both. On the island itself, numerous shrubs also influenced
665   the correspondence, yet the agreement remains in the 10 – 20 cm range.
666

Deleted: , and that determining co-registration below the 30 cm level can be overcome using

Deleted: remarkable

Deleted: Nevertheless, the agreement between the map depths and the probe values is still excellent.

667 Map values along the terrace (orthogonal transects in Figure 5) showed even better
668 correspondence with probe values than they did at gully and island sites. Here, the offset of *all*
669 1111 sample points spanning a transect of 1.6 km had a standard deviation of only 10 cm. This
670 low variance could be explained by the relatively homogenous terrain of wide, shallow slopes
671 characterized by a low shrub cover where sprigs and branches poked through the consistently 18
672 cm deep snow. However, despite the better standard deviation, the mean offset was 10 cm, as
673 opposed to zero at the other sites. This mean offset could be eliminated using a different co-
674 registration offset for the terrace points than used at the islands or gullies, but compression of the
675 relatively uniform vegetative canopy, differential ablation or drifting of the prober's snow
676 machine track over the intervening month, or the imprecise geolocation of the snow probe data
677 could easily explain the offset as being real.
678
679 The offset between map and probe for all 3382 points measure at the Hulahula site had a
680 standard deviation of 16 cm, without filtering for any of the sources of error noted above. We
681 briefly explored the influence of different GSDs on results by using a 40 cm GSD compared to a
682 20 cm GSD; this did not appreciably change the standard deviation of offset, but it did change
683 the individual pointwise comparisons. That is, comparing map data to map data (20 cm to 40 cm
684 GSD) at the probe locations led to a 7 cm standard deviation, which is on the order of the
685 precision we found in Section 4. Thus perhaps half of the 16 cm variation we found between
686 map and probe may be attributable to real change on the ground. The similarity between map
687 and probe data sets is further confirmed by a Kolmogorov–Smirnov test, which gives a value of
688 0.06; this is well below the critical D-value of 0.35, indicating that the two sample distributions
689 are the same at the 95% confidence level. That is, to the best of our ability to determine, the
690 photogrammetric maps are just as accurate as the probe data for characterizing snow depth,
691 despite the many confounding influences besides depth that are incorporated into the maps.
692
693 **7. Discussion**
694
695 The photogrammetric method described here is sufficiently accurate to measure snow packs of
696 nearly any thickness, and future software and hardware improvements are likely. The primary
697 technological challenge for the future is improving geolocation accuracy, which relates to GPS
698 data and how it is used within the photogrammetric bundle adjustment. Given the wealth of
699 airborne-GPS research from lidar studies, it is likely that a map accuracy of 10 cm is currently a
700 hard limit and one that will be difficult to overcome in the future. However, as we have
701 demonstrated, geolocation (accuracy) is not as important as repeatability (precision). As long as
702 stable, snow-free points within the mapped domain can be found such that the map differences
703 there can be reduced to zero, a single affine translation appears to be enough to co-register an
704 entire map and create excellent difference maps. A key lesson learned here is that it is not
705 enough that these points are snow-free, but also that they be free of confounding real changes
706 such as frost heave (as at the airport) or vegetative compression (as at Minto Flats). Similarly,
707 the primary non-photogrammetric challenge for mapping of thin snow packs relates to the
708 interpretation that changes in the difference map are being caused by snow depth. Because our
709 technique can measure change at the centimeter to decimeter level, any real change at that level
710 becomes noise when interpreting the results as purely changes in snow depth. These
711 confounding changes in surface elevation are all site dependent and often a function of snow
712 cover itself, such as the amount of vegetative compression or the rate of thermally-driven frost
713 heave. However, given that our map-probe comparisons were still in the 10 – 20 cm range

Deleted: Indeed, it is again remarkable that the offset is only 10 cm despite these confounding influences.

Deleted: though

Deleted: possible

Deleted: good

714 without accounting for these errors, it seems our technique is sufficient for many types of
715 studies without further modification.
716
717 The issues of contrast and lighting that plagued the early pioneers of film photogrammetry to
718 map snow depth can largely be overcome using modern technology applied with skill. With the
719 advent of digital cameras and in-flight exposure evaluation, flat lighting conditions are still
720 challenging but they do not prevent measurement. Such flat lighting conditions are typically
721 caused by a thick overcast over fresh snow. Two types of map errors are produced by lack of
722 contrast in deep shadows or flat lighting. In the worst of these cases, the spatial density of
723 contrast features are reduced, resulting in the point cloud density also being reduced. In this case,
724 either the resolution of the DEM must be reduced or a void of no data will result. This does
725 occur, but rarely. Depending on camera settings (and camera) in such areas, the sensor noise
726 itself can be misinterpreted by the photogrammetric software as real contrast features. Because
727 the location of this sensor noise changes from image to image, topographic noise results. This
728 noise is typically on the 1-2 m level, but in steep mountainous terrain can reach 10-20 m. We
729 did not formally address such errors in this paper because none of the study areas used in this
730 paper suffered from them due to suitable photographic technique. The most challenging contrast
731 issues can also be avoided completely by waiting for better lighting. In any case, when these
732 noise errors do occur they are easily identifiable in the DEM and confirmed by the orthoimage.
733
734 While there is currently a lot interest in using low-cost UAVs as platforms for SfM
735 photogrammetry (also known as small Umanned Aerial Systems, or sUASs), our research
736 requires manned aircraft for several reasons. Though it may be possible in the future to adapt
737 our methods onto a UAV platform, we could not achieve the precision our needs required
738 without use of multi-frequency GPS and high-quality optics, which both increase cost and
739 payload outside the limits a low-cost sUAS. Our goal is also to measure snow depth of entire
740 watersheds, covering hundreds to thousands of square kilometers, and this simply is not feasible
741 with sUASs. Fundamentally, an sUAS is a field tool requiring the same logistics as ground-
742 based measurements. For example, we flew our Hulahula missions as day trips from Fairbanks,
743 over 500 kilometers away – to do similar work with an sUAS would require a multi-day field
744 expedition with attendant logistical support and costs; even our work at Minto Flats, 30 miles
745 from Fairbanks, would require overcoming similar challenges. Thus for use off the road system,
746 an expeditionary field effort cannot be avoided without using a UAV that can truly replace a
747 manned-aircraft, such as a Predator, Global Hawk, or Sierra (Fladeland et al., 2011; Schreiber et
748 al., 2002; Whitlock, 2014). Such UAVs are considerably more expensive than the manned
749 aircraft we used, are considerably more complicated to fly than small UAVs, and have a
750 regulatory component that is currently undefined in the US. Thus manned-aircraft are the only
751 choice throughout most of Alaska, where our research is based, when other ground-based field
752 work is not required.
753
754 While lidar is also typically flown from manned-aircraft, photogrammetry offers several
755 advantages for mapping snow depth. Both offer the advantage of mapping large spatial-scales,
756 but the photogrammetric method allows creation of a color orthoimage that is perfectly co-
757 registered with the DEM. For snow studies, this image allows us to unambiguously identify
758 what is snow and what is not, especially useful in thin snow-packs or those covering aufeis, as
759 well as useful for recognizing structures in the snow like barchans and sastrugi. When
760 interpreting the difference maps, these summer and winter images allow us to investigate
761 changes that seem suspect, such as those we described related to vegetation or sediment erosion.

Deleted: it is clear that for many purposes such errors can be ignored

Deleted: have

Deleted: en

Deleted: they occur rarely, and

Deleted: se

Deleted: ,

Deleted: and

762 We found that our photogrammetric system had about twice the precision as the lidar system we
763 compared to (8 vs. 16 cm respectively) and about the same accuracy, and thus the
764 photogrammetric system can measure thinner snowpacks more accurately. The photogrammetric
765 system is also substantially less expensive than most lidar units, reducing the cost of ownership
766 for research groups wanting to operate their own systems.
767
768 Photogrammetry from manned-aircraft thus fills an important gap between ground-based and
769 satellite methods, not just for snow depth but for measuring nearly any change in topography.
770 No satellite methods can produce DEMs of our resolution and quality, though they operate on
771 larger spatial-scales where such resolution and quality may not be required, such as ice sheets
772 dynamics. Those satellite techniques that can detect change at the centimeter level, such as
773 InSAR and its Persistent Scatter techniques, require substantial expertise to implement, have a
774 variety of limitations (look-angles, shadowing/layover, phase decorrelation, scatterer
775 permanence, etc), and have high data costs (Delacourt et al., 2007; Ferretti et al., 2001; Nolan
776 and Fatland, 2003). Given the cost of repeat lidar from manned aircraft, most cryospheric
777 scientists studying landscape change resort to extrapolation of ground-based measurements using
778 GPS and increasingly sUASs, with the essentially unverifiable assumption that their
779 measurements are representative of the broader area. Our study of snow-depths has
780 demonstrated that using photogrammetry from manned-aircraft fills a niche that approaches the
781 spatial-scales of satellites with the accuracy of ground-based measurements, for about the price
782 of either. Glacier melt, coastal erosion, thermokarst, aufeis dynamics, and landslides are all
783 examples of topographic changes in the cryosphere that we have also measured without resorting
784 to extrapolation, and done so at lower cost than field measurements that generate only point
785 measurements. Given that nearly all experimental field designs are attempts to minimize errors
786 due to extrapolation of point measurements, this method has the potential to transform our study
787 designs and thereby remove many of the impediments to understanding the current changes to
788 the cryosphere.
789
790

791 **8. Conclusions**

792

793 This paper presents a method for measuring topographic change from manned aircraft that is
794 accurate enough to measure the snow depth of most of the snow packs found worldwide. It can
795 be used to map snow-depth of entire watersheds, with system costs that are much lower than
796 lidar and operational costs on par with ground measurements that only yield transect
797 measurements within those watersheds.   This airborne method allowed us to measure
798 topography with a geolocation accuracy of ± 30 cm and a precision of ±8 cm at a spatial
799 resolution of centimeters to decimeters. We used these maps to measure snow depth by
800 subtracting a snow-free map from a snow-covered map, and found these difference maps have a
801 snow depth accuracy of ± 10 cm when confounding influences of other real changes could be
802 minimized. The mapping technique is based on digital photogrammetry that uses consumer-
803 grade cameras, multi-frequency GPS, and Structure from Motion algorithms, but requires no
804 IMU, on-board computer, or ground control. The airborne methods are straightforward and the
805 processing is done by off-the-shelf software that is reasonably user-friendly. All of the
806 components of our system are under intense consumer pressure to improve, thus future
807 improvements to our results are likely. The main conclusion of this paper is that centimeter-
808 scale change-detection is now within reach of many earth scientists who previously could not

Deleted: n

Deleted:

Deleted: and dual

809   afford it, and that this technology is already being used to measure snow depth as well as other
810   cryospheric changes at unprecedented accuracy and cost.
811
812
813
824
825

826
827
828   **References**
829

830
831   Barnett, T. P., Adam, J. C., and Lettenmaier, D. P.: Potential impacts of a warming climate on
832   water availability in snow-dominated regions, Nature, 438, 303-309, 2005.
833   Bauder, A., Funk, M., and Huss, M.: Ice-volume changes of selected glaciers in the Swiss Alps
834   since the end of the 19th century, Annals of Glaciology, 46, 145-149, 2007.
835   Berthier, E., Vadon, H., Baratoux, D., Arnaud, Y., Vincent, C., Feigl, K., Remy, F., and Legresy,
836   B.: Surface motion of mountain glaciers derived from satellite optical imagery, Remote Sensing
837   of Environment, 95, 14-28, 2005.
838   Bitelli, G., Dubbini, M., and Zanutta, A.: Terrestrial laser scanning and digital photogrammetry
839   techniques to monitor landslide bodies, International Archives of Photogrammetry, Remote
840   Sensing and Spatial Information Sciences, 35, 246-251, 2004.
841   Brandenberger, A. J.: Map of the McCall Glacier, Brooks Range, Alaska, American
842   Geographical Society, New York, AGS Report 11 pp., 1959.
843   Bühler, Y., Marty, M., Egli, L., Veitinger, J., Jonas, T., Thee, P., and Ginzler, C.: Spatially
844   continuous mapping of snow depth in high alpine catchments using digital photogrammetry, The
845   Cryosphere Discussions, 8, 3297-3333, 2014.
846   Buhler, Y., Meier, L., and Ginzler, C.: Potential of Operational High Spatial Resolution Near-
847   Infrared Remote Sensing Instruments for Snow Surface Type Mapping, 2015. 2015.
848   Castebrunet, H., Eckert, N., Giraud, G., Durand, Y., and Morin, S.: Projected changes of snow
849   conditions and avalanche activity in a warming climate: the French Alps over the 2020–2050 and
850   2070–2100 periods, The Cryosphere, 8, 1673-1697, 2014.
851   Clifford, D.: Global estimates of snow water equivalent from passive microwave instruments:
852   history, challenges and future developments, International Journal of Remote Sensing, 31, 3707-
853   3726, 2010.
854   Cline, D. W.: Digital photogrammetric determination of alpine snowpack distribution for
855   hydrological modeling, Proceedings of the Western Snow Conference, 1994. 115, 1994.
856   Conway, H. and Abrahamson, J.: Snow stability index, J. Glaciology, 30 (106): 321, 327, 1984.
857   Cox, L. and March, R.: Comparison of geodetic and glaciological mass balance techniques,
858   Gulkana Glacier, Alaska, draft, 2003. 2003.
859   d'Oleire-Oltmanns, S., Marzolff, I., Peter, K. D., and Ries, J. B.: Unmanned aerial vehicle (UAV)
860   for monitoring soil erosion in Morocco, Remote Sensing, 4, 3390-3416, 2012.
861   Deems, J. S., Painter, T. H., and Finnegan, D. C.: Lidar measurement of snow depth: a review,
862   Journal of Glaciology, 59, 467-479, 2013.
863   Delacourt, C., Allemand, P., Berthier, E., Raucoules, D., Casson, B., Grandjean, P., Pambrun, C.,
864   and Varel, E.: Remote-sensing techniques for analysing landslide kinematics: a review, Bulletin
865   de la Societe Geologique de France, 178, 89-100, 2007.
866   Déry, S. J. and Brown, R. D.: Recent Northern Hemisphere snow cover extent trends and
867   implications for the snow‐albedo feedback, Geophysical Research Letters, 34, 2007.
868   Eisenbeiß, H.: UAV photogrammetry, 2009.Dipl.-Ing., University of Technology Dresden,
869   Zürich, Eidgenössischen Technischen Hochschule, ETH, Zürich, 237 pp., 2009.
870   Esch, D. C.: Long-term evaluations of insulated roads and airfields in Alaska, Transportation
871   research record, 1995. 56-62, 1995.
872   Fassnacht, S. and Deems, J.: Measurement sampling and scaling for deep montane snow depth
873   data, Hydrological processes, 20, 829-838, 2006.

874 Ferretti, A., Prati, C., and Rocca, F.: Permanent scatterers in SAR interferometry, Geoscience
875 and Remote Sensing, IEEE Transactions on, 39, 8-20, 2001.
876 Fonstad, M. A., Dietrich, J. T., Courville, B. C., Jensen, J. L., and Carbonneau, P. E.:
877 Topographic structure from motion: a new development in photogrammetric measurement, Earth
878 Surface Processes and Landforms, 38, 421-430, 2013.
879 Gao, Y. and Shen, X.: A new method for carrier-phase-based precise point positioning,
880 Navigation, 49, 109-116, 2002.
881 Gauthier, D., Conlan, M., and Jamieson, B.: Photogrammetry of fracture lines and avalanche
882 terrain: Potential applications to research and hazard mitigation projects, International Snow
883 Science Workshop, Banff, Canada, 109-115, 2014.
884 Goodrich, L.: The influence of snow cover on the ground thermal regime, Canadian
885 Geotechnical Journal, 19, 421-432, 1982.
886 Hamilton, T. D.: Comparative glacier photographs from northern Alaska, Journal of Glaciology,
887 5, 479-487, 1965.
888 Hitchcock, C. B. and Miller, O. M.: Nine glacier maps, northwestern North America, American
889 Geographical Society, New York, AGS Special Publication 34 pp., 1960.
890 Hopkinson, C., Sitar, M., Chasmer, L., and Treitz, P.: Mapping snowpack depth beneath forest
891 canopies using airborne lidar, Photogrammetric Engineering & Remote Sensing, 70, 323-330,
892 2004.
893 Huang, L. and Li, Z.: Comparison of SAR and optical data in deriving glacier velocity with
894 feature tracking, International Journal of Remote Sensing, 32, 2681-2698, 2011.
895 Hugenholtz, C. H., Whitehead, K., Brown, O. W., Barchyn, T. E., Moorman, B. J., LeClair, A.,
896 Riddell, K., and Hamilton, T.: Geomorphological mapping with a small unmanned aircraft
897 system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived
898 digital terrain model, Geomorphology, 194, 16-24, 2013.
899 Irschara, A., Kaufmann, V., Klopschitz, M., Bischof, H., and Leberl, F.: Towards fully automatic
900 photogrammetric reconstruction using digital images taken from UAVs, na, 2010.
901 James, L. A., Hodgson, M. E., Ghoshal, S., and Latiolais, M. M.: Geomorphic change detection
902 using historic maps and DEM differencing: The temporal dimension of geospatial analysis,
903 Geomorphology, 137, 181-198, 2012.
904 Jamieson, B. and Stethem, C.: Snow avalanche hazards and management in Canada: challenges
905 and progress, Natural hazards, 26, 35-53, 2002.
906 Johnson, A. J., Larsen, C. F., Murphy, N., Arendt, A. A., and Zirnheld, S. L.: Mass balance in the
907 Glacier Bay area of Alaska, USA, and British Columbia, Canada, 1995–2011, using airborne
908 laser altimetry, Journal of Glaciology, 59, 632-648, 2013.
909 Koenderink, J. J. and Van Doorn, A. J.: Affine structure from motion, JOSA A, 8, 377-385, 1991.
910 König, M. and Sturm, M.: Mapping snow distribution in the Alaskan Arctic using aerial
911 photography and topographic relationships, Water Resources Research, 34, 3471-3483, 1998.
912 Krimmel, R. M.: Mass balance and volume of South Cascade Glacier, Washington 1958–1985.
913 In: Glacier fluctuations and climatic change, Springer, 1989.
914 Lee, C., Jones, S., Bellman, C., and Buxton, L.: DEM creation of a snow covered surface using
915 digital aerial photography, Remote Sensing and Spatial Information Sciences., Beijing 831-836,
916 2008.
917 Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P.,
918 and Thomas, R. H.: Observations: Changes in snow, ice and frozen ground, Part of the Working
919 Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate
920 Change
921 Cambridge University Press, 337-383 pp., 2007.

Liston, G. E., Haehnel, R. B., Sturm, M., Hiemstra, C. A., Berezovskaya, S., and Tabler, R. D.: Instruments and methods simulating complex snow distributions in windy environments using SnowTran-3D, Journal of Glaciology, 53, 241-256, 2007.

Liston, G. E. and Sturm, M.: Winter precipitation patterns in arctic Alaska determined from a blowing-snow model and snow-depth observations, Journal of hydrometeorology, 3, 646-659, 2002.

Lucieer, A., de Jong, S., and Turner, D.: Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography, Progress in Physical Geography, doi: 10.1177/0309133313515293, 2013. 97-116, 2013.

Maune, D.: Digital elevation model technologies and applications: the DEM users manual, Asprs Publications, 2001.

McCurdy, P., Woodward, L., Davidson, J., Wilson, R., and Ask, R.: Manual of photogrammetry. American Society of Photogrammetry. Pitman Publishing Corporation, 1944.

McKay, G.: Problems of measuring and evaluating snow cover, 1968, 49-62.

Ménard, C. B., Essery, R., Pomeroy, J., Marsh, P., and Clark, D. B.: A shrub bending model to calculate the albedo of shrub‐tundra, Hydrological Processes, 28, 341-351, 2014.

Miller, P. E., Kunz, M., Mills, J. P., King, M. A., Murray, T., James, T. D., and Marsh, S. H.: Assessment of glacier volume change using ASTER-based surface matching of historical photography, Geoscience and Remote Sensing, IEEE Transactions on, 47, 1971-1979, 2009.

Najibi, N. and Arabsheibani, R.: Snow-covered surface variability and DEM generation using aerial photogrammetry in Mount Odin, Canada, Geodesy and Cartography, 39, 113-120, 2013.

Nex, F. and Remondino, F.: UAV for 3D mapping applications: a review, Applied Geomatics, 6, 1-15, 2014.

Nolan, M., Arendt, A., and Rabus, B.: Volume change of McCall Glacier, Arctic Alaska, from 1956 to 2003, Annals of Glaciology, 42, 409-416, 2005.

Nolan, M., Churchwell, R., Adams, J., McClellands, J., Tape, K., Kendall, S., Powell, A., Dunton, K., Payer, D., and Martin, P.: Predicting the impact of glacier loss on fish, birds, floodplains, and estuaries in the Arctic National Wildlife Refuge, Fairbanks, AK2011, 49-54.

Nolan, M. and Fatland, D. R.: Penetration depth as a DInSAR observable and proxy for soil moisture, Geoscience and Remote Sensing, IEEE Transactions on, 41, 532-537, 2003.

Nuth, C. and Kääb, A.: Co-registration and bias corrections of satellite elevation data sets for quantifying glacier thickness change, The Cryosphere, 5, 271-290, 2011.

Offenbacher, E. L. and Colbeck, S. C.: Remote Sensing of Snow Covers Using the Gamma-Ray Technique, DTIC Document, 1991.

Otake, K.: Snow survey by aerial photographs, GeoJournal, 4, 367-369, 1980.

Pauli, J. N., Zuckerberg, B., Whiteman, J. P., and Porter, W.: The subnivium: a deteriorating seasonal refugium, Frontiers in Ecology and the Environment, 11, 260-267, 2013.

Post, A.: Annual aerial photography of glaciers in northwest North America: How it all began and its golden age, Physical Geography, 16, 15-26, 1995.

Post, A.: Distribution of surging glaciers in western North America, Journal of Glaciology, 8, 229-240, 1969.

Prokop, A.: Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements, Cold Regions Science and Technology, 54, 155-163, 2008.

Pruitt, W. O.: Snow as a factor in the winter ecology of the barren ground caribou (Rangifer arcticus), Arctic, 1959. 158-179, 1959.

Rawls, W., Jackson, T., and Zuzel, J.: Comparison of areal snow storage sampling procedures for rangeland watersheds, Nordic Hydrology, 11, 71-82, 1980.

969   Rinaudo, F., Chiabrando, F., Lingua, A. M., and Spanò, A. T.: Archaeological site monitoring:
970   UAV photogrammetry can be an answer, The International archives of the photogrammetry,
971   Remote sensing and spatial information sciences, 39, 583-588, 2012.
972   Rittger, K., Painter, T. H., and Dozier, J.: Assessment of methods for mapping snow cover from
973   MODIS, Advances in Water Resources, 51, 367-380, 2013.
974   Robinson, D. A., Dewey, K. F., and Heim Jr, R. R.: Global snow cover monitoring: An update,
975   Bulletin of the American Meteorological Society, 74, 1689-1696, 1993.
976   Rott, H., Cline, D., Duguay, C., Essery, R., Haas, C., Macelloni, G., Malnes, E., Pulliainen, J.,
977   Rebhan, H., and Yueh, S.: CoReH2O Â¿ A Ku-and X-Band SAR Mission for Snow and Ice
978   Monitoring, 2008, 1-4.
979   Russell, D. E., Martell, A. M., and Nixon, W. A.: Range ecology of the Porcupine caribou herd
980   in Canada, Rangifer, 13, 1-168, 1993.
981   Ryan, J., Hubbard, A., Todd, J., Carr, J., Box, J., Christoffersen, P., Holt, T., and Snooke, N.:
982   Repeat UAV photogrammetry to assess calving front dynamics at a large outlet glacier draining
983   the Greenland Ice Sheet, The Cryosphere Discussions, 8, 2243-2275, 2014.
984   Serreze, M. C., Clark, M. P., Armstrong, R. L., McGinnis, D. A., and Pulwarty, R. S.:
985   Characteristics of the western United States snowpack from snowpack telemetry (SNOTEL) data,
986   Water Resources Research, 35, 2145-2160, 1999.
987   Slater, A. G. and Clark, M. P.: Snow data assimilation via an ensemble Kalman filter, Journal of
988   Hydrometeorology, 7, 478-493, 2006.
989   Snay, R. A. and Soler, T.: Continuously operating reference station (CORS): history,
990   applications, and future enhancements, Journal of Surveying Engineering, 134, 95-104, 2008.
991   Sturm, M.: Field techniques for snow observations on sea ice, Field Techniques for Sea Ice
992   Research, 2009. 25-47, 2009.
993   Sturm, M. and Benson, C.: Scales of spatial heterogeneity for perennial and seasonal snow layers,
994   Annals of Glaciology, 38, 253-260, 2004.
995   Sturm, M., Douglas, T., Racine, C., and Liston, G. E.: Changing snow and shrub conditions
996   affect albedo with global implications, Journal of Geophysical Research: Biogeosciences (2005–
997   2012), 110, 2005.
998   Sturm, M., Hellig, H., Urban, F., and Liston, G.: The snow cover of the Arctic National Wildlife
999   Refuge, Arctic, in prep. in prep.
1000   Sturm, M. and Holmgren, J.: Self recording snow depth probe. Office, U. P. (Ed.), US Army
1001   Corps of Engineers, 1999.
1002   Sturm, M., Holmgren, J., and Liston, G. E.: A seasonal snow cover classification system for local
1003   to global applications, Journal of Climate, 8, 1261-1283, 1995.
1004   Taber, S.: Frost heaving, The Journal of Geology, 1929. 428-461, 1929.
1005   Vanderjagt, B., Turner, D., Lucieer, A., and Durand, M.: Retrieval of Snow Depth Using Low
1006   Cost UAV-Based Lidar and Photogrammetry, 2013, 0593.
1007   Warren, S. G.: Optical properties of snow, Reviews of Geophysics, 20, 67-89, 1982.
1008   Weller, G., Nolan, M., Wendler, G., Benson, C., Echelmeyer, K., and Untersteiner, N.: Fifty
1009   years of McCall Glacier research: from the International Geophysical Year, 1957-1958, to the
1010   International Polar Year, 2007-2008, Arctic, 60, 101-110, 2007.
1011   Westoby, M., Brasington, J., Glasser, N., Hambrey, M., and Reynolds, J.: 'Structure-from-
1012   Motion'photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology,
1013   179, 300-314, 2012.
1014   Wheaton, J. M., Brasington, J., Darby, S. E., and Sear, D. A.: Accounting for uncertainty in
1015   DEMs from repeat topographic surveys: improved sediment budgets, Earth Surface Processes
1016   and Landforms, 35, 136-156, 2010.

1017   Whitehead, K., Moorman, B., and Hugenholtz, C.: Brief Communication: Low-cost, on-demand
1018   aerial photogrammetry for glaciological measurement, The Cryosphere, 7, 1879-1884, 2013.
1019   Woodget, A., Carbonneau, P., Visser, F., and Maddock, I.: Quantifying submerged fluvial
1020   topography using hyperspatial resolution UAS imagery and structure from motion
1021   photogrammetry, Earth Surface Processes and Landforms, 2014. 2014.
1022   Yan, K. and Cheng, T.: Close Shot Photogrammetry for Measuring Wind-Drifted Snow
1023   Distribution on Stepped Flat Roofs, 2008, 332-335.

1024

1025   **Tables**

1026

1027   **Table 1. Fairbanks International Airport accuracy and precision assessment**. Values for the
1028   reference DEM (6 Oct 13) are geolocation offsets to 29 GCPs. All other offset are co-
1029   registration offsets of that DEM minus the reference DEM for the snow-free area of the runway.
1030   The group statistics at bottom do not include the reference DEM. The first 3 columns of
1031   numbers represent accuracy while the 4th represents precision.

Date	Easting offset (m)	Northing offset (m)	Elevation offset (m)	Elev. St. Dev (cm)	GSD (cm)	Notes
06 Oct 13	0	0.30	0.13	1.7	6	Reference, snow free
30 Sept 13	-0.15	-0.51	0.45	5.3	6	Snow free
21 Jan 14	-0.11	-0.48	0.24	5.8	6	Snow covered
18 Feb 14	0.02	-0.18	-0.29	5.2	6	Peak snow
03 April 14	-0.18	-0.09	-0.04	4.2	12	Snow covered
20 April 14	-0.25	-0.46	0.31	5.0	14	Mostly melted
Means:	**-0.13**	**-0.34**	**0.13**	**5.1**		
±(Range/2):	**±0.13**	**±0.21**	**±0.37**	**±0.08**		

1032

1033

1034   **Table 2. Minto Flats accuracy assessment**. Values for the reference DEM are geolocation
1035   offsets to 21 GCPs. All other values are co-registration offsets of that DEM minus the reference
1036   DEM. Statistics at bottom do not include the reference DEM.

Date	Easting offset (m)	Northing offset (m)	Elevation offset (m)	GSD (m)	Notes
03 April 14	0	0	0.23	0.15	Reference Map
28 Sept 13	-0.01	0.25	0.03	0.15	snow free
27 Jan 14	0.02	0.26	0.03	0.15	snow covered
19 April 14	-0.07	0.23	-0.02	0.14	snow melting
06 Nov 14	0.01	0.15	0.02	0.15	Frozen, snow dusting
08 Nov 14	-0.06	0.22	0.30	0.15	Frozen, snow dusting
Means:	**-0.02**	**0.22**	**0.07**		
±(Range/2):	**±0.05**	**±0.05**	**±0.16**		

1037
1038