The Cryosphere Discuss.,
doi:10.5194/tc-2015-220-RC1, 2016

The Cryosphere Discussions
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EGU

Interactive comment on "Mapping snow depth in alpine terrain with unmanned aerial systems (UAS): potential and limitations" *by* Y. Bühler et al.

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Received and published: 9 March 2016

"UASs enable fast, flexible, repeatable and detailed analysis of the spatial distribution of mountain snow cover". This sentence from the paper describes the essential findings of the work, though I would add "over several hectare areas" to improve the accuracy of that description. Towards these ends, the authors have conducted sound scientific experiments that are well supported and described, and I believe their work deserves to be published. The only scientific analysis I found lacking was an analysis of the repeatability of their system – measuring the same location twice on the same day (or a snow-free road on two different days) and seeing how close the measurements are to each other; that is, determining the noise level of their system, and it seems they have data in hand to do this.

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The authors are clearly strong supporters of UAS technology, and I applaud and encourage their efforts to push the boundaries of this technology towards such an important scientific subject. However, the paper reaches well beyond the scope of its scientific findings to make claims about the implications or justifications of this work without support for those claims. I found two categories of such claims. First are claims that UAS are somehow more cost effective to use than manned aircraft. Though I readily admit my bias, as a scientist on a budget I would not be using a manned aircraft to measure snow pack photogrammetrically if I believed this to be true. These claims need to either be removed or validated through an actual economic analysis, and this analysis needs to at least encompass variables such as region of the world, full costs for manpower, and areal coverage. For example, I can map 100 km2 at 10 cm GSD in an hour in my manned aircraft and I can do so over steep, dangerous terrain without risk being caught in an avalanche, for a total of perhaps 4-5 man-hours of field effort. By comparison, the UAS work in this paper failed to demonstrated that it could map more than 1 km2 in a day's work for several people – though its direct costs may be much less, how much salary time would it take a 2-3 man team to map 100 km2? Perhaps there are economics that I don't understand and I am happy to be educated, but in any case these statements require justification before manned aircraft can be summarily dismissed in favor of UAS due to cost. This leads to the second category of unsupported claims regarding future use of UAS for the purpose of wide-area mapping. The conclusions, for example, list 8 future uses of UASs, only one of which the authors have shown any support for within the paper. For example, claims that a UAS can make "precise water resource predictions for hydropower and flood warning in alpine catchments" – that is, that they can map 100s of km2 – have no support in the paper, and indeed the paper admits several times that the limited flight times of 10-20 minutes are a major hindrance to their research in even small areas. As another example, staying in line of sight of the UAS means that the pilots must travel essentially through the dangerous avalanche terrain they claim their UAS can measure. If the authors want to assert these uses, then more validation and description is required that their system is

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capable of it. I'm enthusiastic about the potential uses for this technology, but I don't see that the actual uses are highlighted here.

Thus overall I think the paper would be substantially improved by changing the wrapper placed around their work and rewriting it to focus on the useful results they found and their true significance – they have shown that they can measure several hectare areas in a variety of terrain types at very high spatial resolution and very good accuracy and this will benefit many types of studies that are currently hampered by the lack of such measurements. There are plenty of such applications, no need for touting these as a replacement for manned aircraft in those many applications where manned aircraft are much more cost effective (like large area mapping) and much safer. The text could use a bit of cleanup but is overall well written and the science seems well done, supported, and verifiable, though as stated earlier a repeatability spec would improve it further.

Specific Comments Abstract Line 1: Not really a topic sentence. Best to get as much of the who, what, where, why, and when out in the first sentence, but this is personal preference. Line 2: No need for "(HS)" as you don't use it again within the Abstract Line 3: "Nowadays" is an odd word here Line 6: This sentence is not quite accurate or meaningful, as 'dense' is not defined well enough to evaluate it. A dense enough network could be devised for any locale, the question is really whether it is feasible to implement. Line 10. The implication by saying 'costly' is that UAS are cheaper. Remove, or support in the paper. Line 15. Again, either provide an analysis in the paper that UAS are "comparatively cost effective" or remove the statement. Similarly about the next part of the sentence for use in "otherwise inaccessible terrain" as this was not supported in the paper as all the sites used were easily accessible, and the paper actually recognizes this as a limitation. Line 21. RMSE of "snow depth values"? Do you mean residuals between the measurement types? Or a mean snow depth? Or? Line 24. Again, remove cost effective or justify, and clean up the end of the sentence a bit.

Introduction I believe in this section some clear mention should be made of the true

roles that UAS can play today in terms of areal coverage and contrast this with what manned aircraft can do. I use both, but I only use a UAV when I'm already on the ground somewhere. This is the place for an economic justification for the use of UAVs over manned aircraft, if there is one. Flying a manned aircraft to a remote location to drop off a team to use a UAV in a tiny area makes little scientific sense for most applications and costs more. But if you have a road or trail system through a mountain range with huts that serve spaghetti every 5 miles and you have no budget at all then using a UAV to map small areas nearby may make some sense economically. Or however you think about it, just be explicit about your claims. Please also see Nolan and Deslauriers 2015 currently in Cryosphere Discussions, where we map snow depth over the tallest and most remote peaks in the US Arctic using a manned aircraft. Here we show that we can truly map avalanche danger, cornice development, gully filling, etc, not as some future possibility but as true examples of our current capabilities. While we did not discuss economics much there, the ability to map snow depth on a big chunk of a mountain range located 350 miles away in a single flight is something that UAS will never be able to do at any cost, and this is worth bearing in mind in this paper, especially since UAS are banned in most US federal lands. Here also some mention should be made of what sorts of projects that a UAS can actually do better than can be done from a manned aircraft; if there are none, this should be stated (I think there are).

Line 27. Qualify this claim further. Do you mean the equipment is very expensive? Or commercial acquisitions? If a University or lab already owned own, ts not very expensive to operate. Page 4, Line 2. Again, provide support for "cost-effective"

Methods Page 5, Line 20. Near infrared is mentioned several times throughout the paper as having advantages on snow, but I found no results of this UAS work that supported this. Perhaps I missed it, so this should either be emphasized further or this discussion toned down.

Page 7, Line 13. The quality setting is directly related to resolution used in the calcu-

lations: ultra high uses each pixel individually, High uses 2x2 pixels, Medium 3x3, etc. The filtering is mostly necessitated by parallax caused by motion and match point errors I believe. This doesn't need to be mentioned in the paper, just commenting. Page 7, Line 25. This sentence is confusing. It says two "well accessible" sites that are "typical locations" – does this mean most sites in these mountains are easily accessible? This relates directly back to claims earlier of being able to work in inaccessible locations. Page 8, Line 14. Do you have support for this claim of being a good compromise? I think its true, but it should be supported when stated like this. Page 8, Line 16. I don't see anywhere in the paper or tables specs on the GPS accuracy of the UAV position? It strikes me that the 'older' version may actually be better than the newer one, because if the UAV stabilization on a location, its positional accuracy may be improved simply because there the timing error is reducing (if the position uses the camera's exif data in integer seconds). Have you explored whether the old and new methods give the same results? Page 8, Line 21. The word 'selected' is repeated. Page 8, Line 25. How was orthoimage accuracy measured? By eye in comparison to photo-identifiable GCPs? What does the Z value mean in terms of an orthophoto? Page 9, Line 17. I'm confused about the use of the NIR imagery. From figure 3, it looks to me that the NIR shows less detail than the other. The text says NIR is 'expected' to be better – well, was it? Page 9, Line 26. I'm confused about the use and necessity of GCPs in this study. Are these being used in the bundle adjustment at all, or just for validating the results? A clear statement needs to be made about this. Page 11, Line 7. I'm confused as to what this classification is doing? Also, why set negative snow depths to zero? There is clearly snow there, so its not zero.

Page 13, Line 17. Here range and pilot positioning are discussed as being limitations. There's nothing wrong with this, it is what it is. UAVs have a place, but that place is not wide area mapping as can be done from manned aircraft. As stated earlier, I think these limitations need to be discussed in the abstract and introduction, so as not to give the reader false expectations about what UAVs are capable of, but I also don't feel that limitations are something to be ashamed of, different tools for different jobs.

Page 15, Line 6. Again, its not clear whether the research of this paper demonstrated anything regarding NIR superiority, so its not clear to me what this paragraph's purpose is. Page 15, Line 19. "GPSs" is used when I think "GCPs" are meant. I found these 3 options confusing and I'm not sure what any of them mean. What's the difference between "a" and "c"? Why are GCPs needed at all – why not just co-register them and ignore the realworld coordinates? There is also a better option – just use the manual probe depths for co-registrations. This is a great advantage for UAVs – you are going to be standing in your field area anyway, so you have opportunity to probe, and then just match the UAV snow depths to those manual probe measurements, at locations where vegetation is minimal. Further, this sort of registration is only required in the first place because the on-board GPS is not accurate enough to directly georeferenced the data accurately enough for this application; this should be discussed and mentioned for future development. That is, if your photo positions had < 1cm accuracy, your maps would too, and this is a possibility for slow moving UAVs even today.

Page 16, Line 9. Accuracy of what? Page 17, Line1. This is far overstated. UAVs have particular trouble with tree motion because they are such high resolution GSD (or TSD in this case. . .). From a manned aircraft, tree motion has a negligible effect on results in the 30-50 cm GSD range, and I have tons of data at 5-10 cm GSD within forests. Whether the area beneath the tree is visible depends on the tree – our black spruce are quite skinny, and our birch tree lose their leaves in winter allowing us to map the ground beneath clearly.

Conclusions This section needs a rewrite, as there is a lot of Discussion mixed in with actual review of results and findings. For example, the fixed wing UAS discussion. See also my earlier comments regarding using the manual probe depths for co-registration and to eliminate the last paragraph/list describing uses that UAVs are not capable of currently (and probably never will be) or justify these claims more fully, but in any case move to Discussion. I believe a list of true potential uses for the system that the authors used to measure snow depth (that is, snow depth with tiny GSD over small areas) would

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be a great idea, but this should placed in the Discussion.

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