Dear Matt Nolan,

We thank you for your positive feedback and the constructive comments.

"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.

The authors are clearly strong supporters of UAS technology, and I applaud and en- courage their efforts to push the boundaries of this technology towards such an impor- tant scientific subject. However, the paper reaches well beyond the scope of its scien- tific 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, stay- ing 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 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.

We do not at all intend to talk down the value of manned aircraft for snow depth mapping over large areas. We are ourselves strong supporters of this method (e.g. Bühler et al. 2015). However, to cover small areas, I am positive that UAS are more economic than airplanes in most countries around the world. The situation you have in Alaska is very special. I was really jealous to see all the nice airplanes in the gardens outside Anchorage. This is really a dream come true for every remote sensing guy. However, in Switzerland and most European countries, it is quite time-consuming and costly to get an airplane and acquire the necessary flight permissions. This is additionally hampered by very restrictive ATC-regulations for small airplanes in Central European airspace and the use of alpine airports. Repetition flights are nearly impossible to do, we collected some quotations on that. On the other hand, the regulations to fly UAS are different for every country and sometimes even for different states and they are changing quickly. Therefore it is impossible to list all the different regulations. We confine us to give a brief description of the most important regulations for Switzerland in the paper. However, as you suggest, we amended the proposed addition "over several hectare areas" to the sentence in the conclusions to make this clearer. And you are right, compared to North America, the Swiss Alps have a very dense infrastructure (roads, railways and huts that serve spaghetti and fondue), which makes it much easier to deploy UAS, because you can reach most spots of interest quiet easily. On the other hand it is very difficult and expensive to get an airplane with flight permission on short notice.

We will include an assessment of the repeatability by analyzing the snow free road at the Tschuggen test site at all 4 flight dates. Thank you for this valuable suggestion. We add the following paragraph to chapter 4.1: "To assess the repeatability of the UAS HS mapping, we analyze the altitude deviation of the different DSM for 10550 grid cells on the snow-free road. The calculated RMSE values compared to the summer DSM (28 September) are 0.093 m (11 March), 0.052 m (24 April) and 0.045 m (12 May). This indicates that the noise of the method is smaller than 0.1 m."

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.

P1L1: The first sentence intends to give a broad picture why snow depth information is important. We therefore want to keep this sentence.

Line 2: No need for "(HS)" as you don't use it again within the Abstract

P1L2: We use the abbreviation HS for snow depth consequently through the paper, therefore we would like to already include it in the abstract.

Line 3: "Nowadays" is an odd word here

P1L3: We change Nowadays into Currently

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.

P1L6: We change the sentence to "even a dense measurement network like in Switzerland with more than one measurement station per 10 km^2 in average "

Line 10. The implication by saying ‘costly’ is that UAS are cheaper. Remove, or support in the paper.

P1L10: We add „in most countries“ to consider the special situation in Alaska.

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.

P1L15: We change otherwise inaccessible not accessible from the ground. Not all parts of the Brämabühl test site were accessible. The steep north-facing slope is very prone to avalanche danger and cannot be accessed during most days in winter.

Line 21. RMSE of “snow depth values”? Do you mean residuals between the measurement types? Or a mean snow depth? Or?

P1L21: We added “compared to manual snow-depth measurements” to clarify this

Line 24. Again, remove cost effective or justify, and clean up the end of the sentence a bit.

P1L24: We change the sentence as following “This new measurement technology opens the door for efficient, flexible, repeatable and cost-effective snow depth monitoring over areas of several hectares for various applications.”

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).

Introduction:
We put the proposed discussion on UAS capabilities to the discussion section. Are you sure you are able to map avalanche danger as you write? Your impressive results in Nolan and Deslauriers (2015) show the mapping of cornices and the filling of terrain features. However I do not see that you map avalanche danger.

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"

P2L27: We listed three different quotations of airborne LiDAR- and Photogrammetric data acquisition in Bühler et al. (2015). It is clear, if you already have a full system including airplane and pilot, that the costs are considerably reduced. However, we doubt that there are lots of users who have all this equipment available (especially in Europe).

Page 4, Line 2. Again, provide support for "cost-effective"

P4L2: please see answer above

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.

P5L20: We cite two papers demonstrating the advantage of near infrared bands. However, in this study we are not able to investigate this topic in detail. Therefore we just mention the potential by citing. We are right now working on a detailed study to quantify the benefit of near infrared bands.

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

P7L13: We think this is interesting information for readers who want to apply SfM and we would like to keep it in the paper.

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.

P7L25: We usually choose locations for our investigations that are well accessible. We would have a lot of other areas, which are not as well accessible. But the terrain characteristics of the chosen test sites are representative for a lot of areas. We change typical locations into " that represent typical terrain characteristics in high-alpine environment " to clarify.

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.

P8L14: We did several tests with different overlaps. Our experience showed that 70% is a good compromise. We add "from our experience with different overlaps we conclude that" to clarify why we get to this conclusion.

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?

P8L16: We do not use the position of the cameras recorded by the UAS GNSS as the accuracy is estimated to approximately 2.5 m, which is insufficient for snow depth mapping application. We only use the UAS GPS to fly the lines defined in the flight planning software. Unfortunately the producer of our UAS gives no details on the applied GNSS sensor.

Page 8, Line 21. The word 'selected' is repeated.

P8L21: we replace selected with applied

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?

P8L25: This is the orientation accuracy, not the accuracy of the orthoimagery. These values are calculated from the applied RPs. We change orthorectification to "orientation".

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?

P9L17: See answer to P5L20. For this study we do not have simultaneously acquired NIR and RGB data but we work on a secondary study where we will have such data available.

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.

P9L26: We mixed up the correct terms. What we use are reference points RPs not control points GCPs. We use these points to absolutely orientate the photogrammetric products. We change GCPs to reference points RPs throughout the paper. The RPs are used for absolute referencing of the DSM and Orthophotos into the Swiss CH1903 LV03 coordinate system. At Tschuggen, the RPs are the same for all four flight dates and are therefore used also to reference the summer and winter DSMs. At Brämabühl we choose RPs from the absolutely referenced summer orthophoto.

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.

P11L7: We classify the area to snow and no snow. Areas not covered by snow are set to HS = 0. Negative values are not changed but due to the color bar limit, they are depicted red (HS <= 0). We change the sentence to "…. snow-covered areas have been separated from snow free patches using a simple unsupervised classification." to clarify this point.

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.

P13L17: In our opinion the discussion is the right place to discuss this question, as we do. However, we added your suggested changes in the abstract restricting the application of UAS to several hectares areas. As you suggest we move the potential applications from the conclusion to this discussion chapter.

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.

P15L6: In this section we discuss what could potentially improve the results. As stated before we are working on a secondary study quantifying the assumed benefits. We clearly state " However, further studies have to investigate the real benefit of NIR bands for photogrammetric HS mapping in more detail. "

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.

P15L19: Yes this is a mistake. We change GCPs to RPs anyway (see answer P9L26). C is a combination of a and b leading to an absolutely referenced HS map with no offsets in the HS values. As we do not use the UAS GNSS measurements (they are not accurate enough), we must apply RPs, either relative or absolute. We do not understand your proposed approach of matching the HS maps to the probe measurements as we would have a large number different cells with the HS value of the probe (plus minus lets say 5 cm of error). Furthermore we would not be able to assess the achieved accuracy of the HS product if we use the probe measurements for referencing. We add the following sentences to discuss the possibility of very accurate onboard GNSS referencing: "RPs would not be necessary if a very accurate (better than 0.05 m) GNSS system would be available directly on the UAS. First UAS products with such high-accuracy GNSS sensor are already available on the market. However a first investigation by Harder et al. (2016) indicates that the achieved orientation accuracy is not sufficient for snow depth mapping without ground reference measurements."

Page 16, Line 9. Accuracy of what?

P16L9: We add "of the HS maps"

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.

P17L1: Here our experience is different. We are not able to reliably map the ground around and below trees and bushes, mainly because they are moved by wind, which is nearly always present. It is possible that this effect is less distinct within data with lower GSD. Therefore we want to keep this statement. However we change impossible into "difficult"

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

Conclusion:

As suggested we move the list of potential applications to the discussion chapter. In our opinion it is not necessary to map entire catchments for water resource prediction or flood warning, but it may be sufficient to map representative subsections which can be done wit UAS. Therefore we want to keep this application in the list even though this can also be done with manned airplanes, as we showed in (Bühler et al. 2015). However we add “small” to alpine catchments.

Dear Alexander Prokop

Thank you for your fast and constructive review. In our opinion we have already answered a lot of your questions with the answers to the review of Matt Nolan. Therefore we limit here the answers to the questions going beyond the points of Matt Nolan.

First I want to point out that the authors have conducted sound scientific experiments that are well supported and described, and I believe their work deserves to be pub- lished. UAS snow depth measurements will be an useful alternative to measure spatial snow depth distributions in the future and I encourage the authors efforts to push the boundaries of this technology towards such an important scientific subject as well. I also understand and would have had probably the same enthusiasm because of the great data presented, however, when M. Nolan summarizes that the sentence: "UASs enable fast, flexible, repeatable and detailed analysis of the spatial distribution of moun- tain snow cover" describes the essential findings of the work, I have a slight different opinion. UASs enable neither fast nor flexible analysis of the spatial distribution of mountain snow cover as it depends on with what method you compare it to. If you compare it to manual snow probing you are certainly right, but not in comparison to recent technologies such as laser scanning. UASs need a lot of pre-organizing work, if it comes to snow depth measurements many ground control DGPS measurements (to achieve such an accuracy), and significant post processing time. In comparison to laser scanning not that fast. With being flexible I have the biggest issues, in my opinion UASs are everything but flexible. For commercial purposes (and that counts also for scientific applications) the legal limitations in many countries are significant. Usually you need a proper license to fly above populated areas such as ski resorts and you need to get permission for every flight from the air space administration. For example it took us 1 month of paper work to have an UAS flying on Svalbard (same size and weight). And then you are only allowed to fly in line of sight, which means in practice an area about 500 per 500 m wide, which is exactly what you present in your data. Thinking further on about suitable flying weather and illumination conditions you have in harsh mountain climate conditions such as in maritime coastal mountain weather or arctic weather rather more down days than flying days (strong wind and/or snow- fall, very cold and high altitudes (low battery), night, very flat light, etc.)! You present data from 6 measurement days with perfect weather conditions (I assume), therefore it would be interesting what wind, air-temperature as well as air-pressure and cloudi- ness occurred while completing the measurements. I have seen many researchers UAS crashing due to unfavorable conditions in mountainous terrain! So you have to learn flying an UAS first, before starting to make useful measurements. Furthermore you need significant computing time and rather powerful computer equipment to post process the data and create the DEMs. Thinking about the costs, I have the same opinion as Matt, I do not think it is cheaper to ask a company to deliver a DEM of a snow surface 500 x 500m, using a UAS or a laser scanner. In fact I know 2 companies that charge the same, they just use the laser scanner or the UAS depending on the area they have to measure. If the incident angle is sufficient enough and no shaded ar- eas exist they always use the laser scanner. So I would reduce your statement to what you explain in a later step to something like this: "In particular within flat areas, where terrain sections behind convex landforms such as hills or moraines cannot be covered, UAS based digital photogrammetry is a promising option for HS mapping in alpine ter- rain." That hits the application in reality much better in my opinion. That leads me to the applications you have in mind: "precise water resource prediction for hydropower and flood warning in alpine catchments (Jonas et al., 2009)Âz ˙ I have the same opinion as Matt, not enough coverage. Same counts for: "validation of snowpack and snow hydrology models (Bartelt and Lehning, 2002; Mote et al., 2003)" Snow pack models yes, but snow hydrology? I think you did a good job to describe it for small catchments. “Survey of snow distribution in ski resorts to improve the track management (Damm et al., 2014)Âz ˙ I do not see that at all, track management in ski resorts is made by GPS measurements in real time from snow groomers, which is quiet sufficient, the worker knows immediately how much snow is underneath him (his snow groomer), so I do not see ski resort employees additionally flying around with a UAS (above people?) need- ing to post process the data, etc. All other applications have also been satisfactorily completed by alternative methods in the same or better accuracy, which are more flexi- ble than UAS, so why using now an UAS (laser scanners scan up to 5000 m nowadays in very fast operation speed, the measurement is basically done in 30 min. all in all) . For sure you can use an UAS for those applications, but there is no improvement to existing methods except for the already mentioned one.

You bring up a very important point, the one of legal regulations. It is true that UAS are a hot topic in the press right now and every country, or even every state and community, brings up its own regulations. And it is true, if the regulations are strict, UAS are not flexible anymore, as it seems to be the case for Svalbard. However, to make this point more clear we add the following section at the end of the introduction and move up the part from chapter 2.2:

“The regulations for flying UAS vary a lot from country to country or even between different states or communities. If it is necessary to get a flight certification / permission a long time before data acquisition, this limits the applicability and flexibility of this technology considerably. The regulations in Switzerland are quite user-friendly and are easy to fulfill as long as the UAS is within line of sight, no special permissions are necessary except you want to fly over crowds (more than several dozens of people within short distance of less than 100 m) or close to airports (Swiss regulations: http://www.bazl.admin.ch). However before applying UAS, the local regulations have to be checked carefully.”

Furthermore we add “if the national and regional regulations permit the application of UAS” to the last sentence of the abstract.

We do not understand why UAS should need more pre-organizing work than laser scanning. Also with laser scanning you need reference points and reference measurements. And, if you want to scan areas with different expositions (this is usually interesting for snow depth investigations) you need more than one scanning position, rising the effort in time and costs considerably. Additionally, the entire TLS equipment, plus the power unit required for self-sufficient operation of a TLS in the field, are typically much more bulky and heavy than the UAS-equipment. If we reference the winter DSM onto the summer DSM, as we do at the test site Braemabühl, we do not need reference points at all and are very fast in data acquisition (flight time for Tschuggen ca. 5 minutes, Braemabühl ca. 15 minutes). We will add this information and information on the weather conditions as you suggest.

In our opinion UAS is not “better” than laser scanning but it is a valuable alternative /

complementary technique, as we state at several locations in the paper. From our experience, UAS is definitely cheaper than laser scanning to cover smaller areas with different expositions where you would need more than one scanning position to cover the entire area. Such cases occur very often in alpine terrain if you want to cover more than one mountain flank. So we get more and more requests from our institute to cover areas that have previously been covered by laser scanning. An important problem with long-range laser scanners such as the Riegel VZ 6000 is that they are not eye safe and you have to be sure, that nobody can look directly into the scanner also not with binoculars. This is very hard to ensure at least in the Swiss Alps. Also, the UAS device itself is about a quarter the price compared to the costs of a laser scanner. We were able to acquire TLS data simultaneously to the UAS data for this study at our Austrian test site – a publication of the results is in progress. Additionally, we plan more such simultaneous data acquisition campaigns for this and next winter.

The application in ski resorts is no problem from the regulations point of view in Switzerland. The limitation of existing dGNSS systems on snow groomers is that they only know the snow depth where they drove trough but they do not know what is next to them in particular next to the ski tracks. We have already requests from ski resort to test UAS for this purpose. However, following the suggestions of you and Matt Nolan, we limit our statements (costs, flexibility, data acquisition speed etc.) to "small areas".

In our opinion we focus in this paper on the UAS results we found within this study. The outlook on potential applications, causing critics from the reviewers, is now moved to the discussion part and clearly marked as "potential applications". However, we are convinced that such an outlook is very interesting for the readers and does not reach "beyond the scope of the study ". We discussed this point with different colleagues and they all have the opinion that such an outlook belongs into the paper. Big parts of this outlook are based on discussions and requests from SLF colleagues and we think they are valuable for the readers.

Abstract Line 15: Delete sentence: "Such systems have the ad- vantage that they are comparatively cost-effective and can be applied very flexibly to cover otherwise inaccessible terrain".

P1L15: We add "compared to manual measurements"

Line 24,25: remove flexible and cost effective and investigating the worlds cryosphere Introduction:

P1L24/25: we remove "investigation the worlds cryosphere" as suggested but we want to keep ""flexible and cost-effective" but add "for small areas".

Line 24: the foot print size is not much of an issue with laser scanning anymore, about 25 per 25 cm footprint size in 1000 m distance to the scanner with very low incident angle so I would erase the sentence "TLS-accuracies suffer from acute illumination angles, resulting in unfavorable laser footprints, in particular within flat areas".

P2L24: this is still a big problem for a big part of our applications, as the SLF laser scanning experts report. Therefore we want to keep this sentence.

Page 4 line 19: avalanches Test sites and data acquisition: please include here or in table 2 and 3 the following parameters, air temp., air pressure, wind speed, all at flying altitude, cloudiness, and duration of measurement/flying campaign as well as actual battery durance per flight/time, how many batteries did you use?

We add the requested information on flight time, batteries used and weather conditions within the description of the test sites and data acquisition. We don't list air pressure because we do not hink it is of interest here.

Page 8,9. When you talk about the reference measure- ment using avalanche probes and GNSS please cite here Prokop et al. 2008 (Prokop, A., Schirmer, M., Rub, M., Lehning, M. Stocker, M. (2008): A comparison of mea- surement methods: terrestrial laser scanning, tachymetry and snow probing for the determination of the spatial snow-depth distribution on slopes) and discuss shortly the accuracy to be expected.

We add the suggested citiation Prokop et al. 2008 and discuss quickly the expected errors from manual measurements.

Braemabuehl: mountain top page 12: You do here an anal- ysis of the HS dependent on aspect. I would delete that totally as well as figure 7. It is a known fact that south facing slopes have usually lower HS if there isn't significant snow drifting involved. In my opinion this analysis has nothing to do with the actual topic of the mapping process of HS using an UAS, so I would skip that part totally. Please adapt the discussion and conclusion section to the arguments I pointed out in the general comments section.

Braemabühl: In our opinion such an analysis of snow depth distribution along different expositions is of value for the readers as it is a straightforward application of the UAS datasets. We perform this analysis at the exposed mountain top test-site as we expect a large influence of wind drift. Therefore we want to keep this analysis.

Figure 2. Are you sure the scale bars are correct. It seems that the scale bar is the same even though the size of the images is different.

Figure 2: The scale bars are correct. We covered slightly less area within the first data acquisition that is why the ortho image of March 11 looks a bit different.

Dear Referee

Thank you for your very late but valuable review. In our opinion we have already answered a lot of your questions with the answers to the review of Matt Nolan and Alexander Prokop. Therefore we limit here the answers to the questions going beyond the points of the two other reviewers.

The paper "Mapping snow depth in alpine terrain with unmanned aerial systems (UAS): potential and limitations" by Y. Buhler et al evaluates the ability and accuracy of UASs to estimate snow depth in alpine terrain. This is part of a small, but rapidly growing body, of literature that has begun to test the ability of small UASs to estimate snow depth at high spatial resolutions. This paper contributes a unique perspective by considering the accuracy of a multirotor platform in an alpine setting. The methods employed are solid and the results presented show great promise (RMSE <15 cm over grass surfaces and <30 cm over taller vegetation) as an alternative to laser scanning (airborne or terrestrial) in non-vegetated areas. I would recommend publication of these results in The Cryosphere but the manuscript does overstate the significance of this technique and the implications from this study.

I broadly agree with the comments of the other two reviews by M Nolan and A Prokop. The evaluation of the method to estimate snow depth is solid but the wrapping text needs work. The authors are proponent of using a multirotor for this work and I do not see why this bias is so strong without a direct comparison with a fixed wing platform. The authors clearly pushed their system beyond the manufacturer recommendations (Table 1 max wind speed 12- 15 ms-1 yet they report good results in wind speeds of 20 ms-1) so just comparing manufacturer specs is an insufficient test. It would be sufficient for publication to present the results achieve with this specific platform without overstepping and making broad comments on multirotor vs. fixed wing platforms.

The writing could use some work. Many sentences are awkward or unclear to me and need rewriting (see the specific comments for a non-exhaustive list). There is inconsistent writing tense that, once corrected, will make the manuscript easier to read.

The additional point you bring up in the general comments is that we should not make statements on fixed-wing UAS as we did not use them in this study. That is true but we have quite some experience at our institute with fixed-wing UAS and did fly (and crash) them around Davos (CH) and Innsbruck (AT). We have flight experience with a SensFly eBee, a Trimble UX5 as well as self constructed devices. However, in the paper we will mark all broader statements on fixed-wing UAS with "from our experience". In our opinion, the statements we make are well enough supported by our experience in alpine terrain and are valuable hints for readers, therefore we want to keep these statements.

Specific comments:

Title: while potential and limitations are in the discussion the majority of the paper deals with producing and assessing the accuracy of the snow depth maps. Perhaps the "potential and limitations" could be dropped to simplify the title

In our opinion this investigation reveals a lot on potential and limitations of UAS for snow depth mapping in alpine terrain. We also discuss this point. Therefore we want to keep it in the title, if the editor agrees.

Page 2 Line 1: “spatiotemporal distribution, and variability of snow depth (HS” -> “spatiotemporal snow depth (HS) distribution” . . . may be more clear

P2L1: changed as suggested

Page 2 Line 10: The Nolan review does bring up a fair point regarding making state- ments/ comparing the economics of this system to manned platforms (or even other UASs). Without doing a full economic analysis these statements are merely specula- tive. As well, regulations affecting UAS (which are rapidly changing and vary by nation) and aircraft operations s may play a larger role in determining the application of this method than simply comparing the ticket price of equipment. With all of these compet- ing factors, which are beyond the scope of this paper or journal, perhaps it may be more appropriate and straightforward to limit this paper an assessment of the capabilities of the method.

P2L10: please see answers to M. Nolan and A. Prokop

Page 2 Line 13: “ an unmanned aerial system (UAS)” as you only used one platform- this was not an intercomparison.

P2L13: changed as suggested

Page 2 Line 19-20: “monitor the ablation”-> “monitor the snow ablation”. What about at the second site? I would recommend you mention snow depth was estimated once here to keep the text balanced.

P2L19-20: As we have three DSM acquired during different dates in winter at Tschuggen, we can monitor ablation processes. We cannot do that at Brämabühl as we only have one DSM acquired during one winter date.

Page 2 Line 23-24 and throughout text: “better than” -> “less than”

P2L23-24: changed as suggested

Page 2 Line 24-26: awkward ending to this sentence. Please rewrite.

P224-26: we rewrote the ending

Page 3 Paragraph 1: This paragraph is a list separated by semicolons without any sort of closing to wrap up these points. Rewrite without using semicolons as it is rather awkward.

P3P1: Changed to individual sentences

Page 3 Line 13: Remote sensing is a field of study with many different tools not a tool itself like UAV SfM. Rewrite.

P3L13: Changed to “Remote sensing is useful to monitor”

Page 3 Line 15- 17: perhaps put your definitions of snow depth into a methods section.

P3L15-17: We thought a lot about the best position for this definition. As it is essential for the entire paper, we decided to bring it at this place, early in the paper.

Page 3 Line 21-23: Unnecessary sentence.

P3L21-23: In our opinion this sentence makes sense here as it describes a recent TLS application where snow depth is the key variable.

Page 3 paragraph 2 and 3: After suggested edits merge these two paragraphs.

P3: We think the text is better structured keeping the two paragraphs

Page 4 Line 5-6: "were not feasible to most applications" –awkward

P4L5-6: changed to "were insufficient for most applications "

Page 4 Line 11: "Throughout the last years," -> "Recently,"

P4L11: changed as suggested

Page 4 Line 11-16: replace semicolons with commas.

P4L11-16: changed as suggested

Page 4 Line 20. Replace colon with period.

P4L20: changed as suggested

Page 4 Line 20-21: As you are likely already aware de Michele 2015 in TCD is now de Michele 2016 in TC. Other recent examples can also be found in TCD (Harder et al., 2016 and Marti et al., 2016)

P4L20-21: We update and include the recently published papers

Page 4 Line 23-27: rewrite to avoid faulty parallelism. "implementing sensors capable of measuring at e.g. near infrared wavelengths" is unclear

P4L23-27: rewritten to "De Michele et al. (2016) conclude, that UAS-based HS mapping holds great potential, but that further studies are required especially with regard to multi-temporal mapping, to sensors capable of measuring in near infrared bands or to the mapping of different snow cover conditions (new snow, wet snow, ice crusts etc.)."

Page 5: Why are sections 2.1 and 2.2 distinct from each other?

P5: we merge 2.1 and 2.2 as suggested

Page 5 Line 10: can you define “high positional accuracy”. How accurate is the posi- tioning? Is this standard GPS accuracy ie +- 5m?

P5L10: change to “of better than 2.5 m (personal communication from Ascending Technologies)”

Page 5 Line 17-19: Can you be more explicit on the color bands with and without filters? A table would be valuable to quickly compare the EM spectrum being sampled in the various configurations.

P5L17-19: We list the filter thresholds we have available. As we do not further use the different filters in this study, this information is sufficient in our opinion.

Page 6 Line 1-20: perhaps a new section along the lines of “UAS deployment”

P6L1-20: We do not understand, where you suggest putting the section break.

Page 6 Line 11:” important key” redundant. Pick one

P6L11: changed as suggested

Page 6 Line 12: delete “feasible”. Redundant

P6L12: changed to “good”

Page 6 Line 13-15: the capabilities of camera by themselves do not enable generation of highly accurate DSMs. Other factors such as overlap are critical. Rewrite to clarify what you are trying to say.

P6L13-15: changed to: “The radiometric and spatial resolution of the Sony NEX-7 camera enable the generation of highly accurate digital surface model (DSM).”

Page 6 Line 19: not simply limited by weight. Also limited by space and power. In case of Ebee specifically, cameras are primarily limited by what the manufacturer offers as only Sensefly sensors can be used in the ebee.

P6L19: changed to “due to limited carrying capacity, space and battery power.”

Page 6 Line 19-22: I disagree with this simplification. The octocopter may be easily transportable but with an effective flight time of <10 minutes the operator needs to be in or directly adjacent to the area of interest. While a larger system may not be able to be transported as near to the area of interest as a multirotor it can travel further to overcome such a disadvantage. It may necessary to emphasize that the best platform for the job will be site specific.

P6L19-22: We add “from our experience” and change not appropriate for high mountain areas into “difficult to fly in high mountain areas”

Page 6 Line 23: Speculation. Will be site specific.

P6L23: This is not a speculation but a feedback we get from nearly all colleagues flying fixed-wing UAS in mountains. This is clearly the point causing most trouble applying fixed-wing UAS in alpine terrain. And should therefore stay in our opinion.

Page 6 Line 9-11: Tense is inconsistent

P6L9-11: we do not find an inconsistent tense here

Page 6 Line 13-20: What parameters were used in this study? Was the accuracy of the estimated snow depths sensitive to these parameters? Was this tested?

P6L13-20: We describe the data acquisition parameters in the chapters 3.1 and 3.2. We did not perform a sensitivity study of the DSM quality to the parameters yet but we are planning such a study for this winter.

Page 6: Point cloud generation is discussed but how are the DSMs and orthomosaics generated. This needs to be added.

P6: We add "using dense point cloud generation with the PhotoScan default parameters"

Page 6 line 23 and elsewhere: change "well-accessible" to "easily accessible" or some- thing less awkward.

P6L23: changed as suggested

Page 7 line 5: delete "quite"

P7L5: changed as suggested

Page 7 line 9: "usually not exposed" -> "not usually exposed"

P7L9: changed as suggested

Page 7 Line 9-11: how were slope angles estimated? From the DSM?

P7L9-11: yes from the summer DSM resampled to 1 m

Page 7 Line 13-15: How was this overlap determined to be optimal? Was this deter- mined through trial and error? Was this a recommendation? How do you determined DSM quality? Did you test quality versus time? Justify the selection of this overlap more clearly.

P7L13-15: This overlap was chosen based on discussions with different colleagues and is based on our own experience. We are planning to investigate this question in more detail in a follow on study. To make this clear we write "From our experience".

Page 7 Line 18-20: Were multiple batteries switched out during each image acquisi- tion period or was acquisition limited to what could be acquired off a single battery. Switching out batteries greatly extends the duration of any proposed missions and this information will help potential users evaluate your experience.

P7L18-20: we add: "The Tschuggen test site can now be covered with one battery." And "To cover the Brämabühl test site we need four batteries".

Sect. 3.1 and 3.2: please include the size of the areas mapped at each site.

Sect 3.1 & 3.2: we already list the areas in the tables 2 & 3.

Page 9 Line 17: Why was NIR selected at this site and not at Tschuggen? Does this change the accuracy results? Was there a test of the different wavelengths at a common site and time to see if this would influence the accuracy results?

P9L17: We are currently investigating the benefit of NIR compared to RGB. This was not yet investigated for this study.

Page 10 Line 3: delete "e.g."

P10L3: there could be other causes why a slope is not accessible. Therefore we want to keep the e.g.

Page 10 Line 5: spelling "referene"

P10L5: changed as suggested

Page 10 Line 6: "are resulting" -> "results"

P10L6: changed as suggested

Page 11 Line 4: Do you have confidence that you were actually able estimate a mean snow depth of 1cm? Granted that this is an areal average of variable snow depth but this is a lot less than any of your estimated geolocation or snow depth errors.

P11L4: This is the mean snow depth averaged over the entire test site. There are only a few spots with remaining snow cover (Fig. 4)

Page 11 Line 18: "is an average systematic underestimation of HS by 0.2 m" is this the same as bias? Perhaps it would be good to use terms common to other papers on this topic (ie Harder et al 2016)

P11L18: changed to "average underestimation of HS by 0.2m". In our opinion this formulation is more precise as bias.

Page 11 Line 26-29: Are these values an average of the errors for all respective snow depth in each class for all flights? This is unclear. What is mean shift? Same as bias? Clarify/keep your terminology consistent.

P11L26-29: This are the RMSE values per class (as it is written). We change mean shift to bias as suggested and add “for all three flight dates”.

Page 12 Line 3: “RMSE of σ is 0.04 m” based on all flights? Clarify please.

We add „based on all reference measurements“

Page 12 Line 13: Would it be possible to add a legend/color bar to the animation to

more easily interpret the snow depths.

We will try to add a legend tot he animation

Page 12 Line 28: I fail to see the value of including the correlation coefficient. The RMSE is sufficient while the R2 (due to the small RMSE and large range in snow depths) will give a deceptively good value.

P12L28: The correlation between the reference HS measurements and the photogrammetrically measured HS is in our opinion a useful estimation of the mapping quality, as many readers will be used to correlation as a measure of quality. As the investigated test sites are typical for alpine catchments, want to keep these values. They depict that no drift of error occurs at very high or low HS values.

Page 13 Line 1: can make text more concise if you refer to this as bias (if that is what it is).

P13L1: In our opinion our description here is easier to understand and more precise

Page 13 Line 3-4: This sentence is unclear to me as to what you are comparing.

P13L3-4: we change mean deviation to bias. We compare to the standard deviation within a reference plot as we write.

Page 13 Line 20-21: delete “which is the appropriate starting/landing procedure we apply in alpine terrain”. Redundant.

P13L20-21: We want to keep this information as we think it is important for the readers.

Page 13 Line 21-23: Perhaps. But this is platform and site specific so such a strong universal statement is rather speculative.

P13L21-23: we add “Based on our experience” to make this clear

Page 13 Line23-24: Did you actually fly in -30C or is this also speculative?

P13L23-24: We did flights were we had air temperatures of -25 ° C, -30° can occur in the early mornings in Davos. We faced problems with cold batteries several times.

Page 14 Line 6-9: Without an actual comparison this is also speculation. Flying conditions will be site specific and fixed wing platforms have vastly different capabilities negating any universal conclusions.

P14L6-9: we add “Our experience shows that”

Page 14 Line 13: delete “However,”.

P14L13: changed as suggested

Page 14 Line 18: DSM instead of “DEM”?

P14L18: changed to “DSM” as suggested

Page 14 Line 23: delete “However,”.

P14L23: changed as suggested

Page 15 Line 6-12: You used NIR and no-NIR imagery in this study already. Can you make any comments on this topic already?

P15L6-12: We are investigating the difference between NIR and RGB this and next winter. We do not have reliable quantitative results yet to publish them in this paper.

Section 5.3: Coregistration is important but this section could be removed as the differ- ent methods were not compared as far as I can see and doesn’t directly contribute to the results of the paper.

S5.3: Coregistration is an absolutely crucial point for photogrammetric HS mapping. Therefore we want to keep this part.

Page 17 Line 13: add recent papers as previously mentioned.

P17L13: changed as suggested

Page 17 Line 15-16: Maximum altitudes of UAV’s is generally quite low due to regula- tions (which will of course vary by country) so this is likely unfeasible.

P17L15-16: In Switzerland you are allowed to fly at an altitude of 500 m above ground, so it is feasible. We cannot mention all the different regulations around the world here.

Page 18 Line 9-26: I agree with the M Nolan review that this should be moved to the discussion.

P18L9-26: Moved to the discussion as suggested

Page 19 Line 1-3: Rewrite final sentence as it is unclear.

P19L1-3: rewritten to “We expect that UAS will get more and more important for mapping applications also high alpine terrain and that this methodology will change the frequency and quality of geodata acquisition fundamentally.”

Figure 5: in caption, do the R2 values refer to HS measurements? Clarify. Remove shading from points on plots

Fig5: we add “for the HS values” to clarify.

Figure 7: If you do keep this section (re: Prokop review) clarify what the bars and line represent (unclear which is mean snow depth and which is standard deviation). Also make bars a solid color.

Fig7: we add “(bars) and (line) to clarify”

Figure 8: what is the line in the HS measurement plot below the 1:1 line? Remove or explain. Rearrange order of figures to reflect the order they are referred to in the text.

Fig8: We remove this trend line as it is too close to the 1:1 line

Any mention of “significance” should be removed unless backed up with statistical tests.

Removed as suggested

Mapping snow depth in alpine terrain with unmanned aerial systems (UAS): potential and limitations

Y. Bühler[1], M. S. Adams[2], R. Bösch[3], and A. Stoffel[1]

[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[2]Austrian Research Centre for Forests (BFW), Innsbruck, Austria
[3]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

Correspondence to: Y. Bühler (buehler@slf.ch)

Abstract. Detailed information on the spatiotemporal ~~distribution, and variability of~~ snow depth (HS) distribution is a crucial input for numerous applications in hydrology, climatology, ecology and avalanche research. ~~Nowadays~~Today, snow depth distribution is usually estimated by combining point measurements from weather stations or observers in the field with spatial interpolation algorithms. However, even a dense measurement network like in Switzerland with more than one measurement station per 10 km^2 in average, is not able to capture the large spatial variability of snow depth present in alpine terrain.

Remote sensing methods, such as laser scanning or digital photogrammetry, have recently been successfully applied to map snow depth variability at local and regional scales. However, such data acquisition is costly if manned airplanes are involved in most countries. The effectiveness of ground-based measurements on the other hand is often hindered by occlusions, due to the complex terrain or acute viewing angles. In this paper, we investigate the application of unmanned aerial ~~systems~~ system (UAS), in combination with structure-from-motion photogrammetry, to map snow depth distribution. Such systems have the advantage, compared to manual measurements, that they are comparatively cost-effective and can be applied very flexibly to cover ~~otherwise inaccessible terrain~~ terrain not accessible from the ground. In this study, we map snow depth at two different locations: (a) a sheltered location at the bottom of the Flüela valley (1900 m a.s.l.) and (b) an exposed location on a peak (2500 m a.s.l.) in the ski resort Jakobshorn, both in the vicinity of Davos, Switzerland. At the first test site, we monitor the ablation on three different dates. We validate the photogrammetric snow depth maps using simultaneously acquired manual snow depth measurements. The resulting snow depth values have a root mean square error (RMSE) ~~better~~ of less than 0.07 to 0.15 m on meadows and rocks and a RMSE ~~better~~ of less than 0.30 m on sections covered by bushes or tall grass, compared to manual probe measurements. This new measurement technology opens the door for efficient, flexible, repeatable and cost effective snow depth monitoring over areas of several hectares for various applications, ~~investigating the worlds cryosphere~~if the national and regional regulations permit the application of UAS.

1 Introduction

Information on the spatiotemporal distribution of snow depth (HS) is important for numerous applications: As it is a robust indicator for the amount of water stored as snow (snow water equivalent – SWE) (Jonas et al., 2009)~~, it~~. It has a substantial impact on water supply and hydropower~~; the~~. The quality of hazard forecasting for floods and snow avalanches depends substantially on snow depth information (Bavay et al., 2009; McClung and Schaerer, 2006)~~; the~~. The growth and habitat patterns of alpine flora and fauna is linked to the seasonal snow depth distribution (Bilodeau et al., 2013; Mysterud et al., 2001; Wipf et al., 2009)~~; annual~~. Annual changes in snow depth over the winter season have strong impact on alpine tourism as more and more ski resorts depend on technical snow production.

Numerous studies report a very high spatial variability of snow depth within small distances, in particular in alpine terrain (Egli et al., 2011; Elder et al., 1998; Grünewald et al., 2010; Schweizer et al., 2008). Remote sensing is ~~a promising tool~~ useful to monitor this spatial variability, because it can provide spatially continuous measurements at a high spatial resolution of otherwise inaccessible areas. We define snow depth (HS) according to Fierz et al. (2009) as the vertical distance from the base to the snow pack surface at a specific location.

Terrestrial laser scanning (TLS) has been successfully applied in many case studies to measure HS distribution in small catchments with high vertical accuracies in the range of 0.10 m (Deems et al., 2013; Grünewald et al., 2010; Melvold and Skaugen, 2013; Mott et al., 2010; Prokop, 2008; Schaffhauser et al., 2008). A recent study by Deems et al. (2015) uses TLS to visualize the HS distribution in avalanche release zones for the education of ski resort staff and assesses the different error sources. However, TLS-accuracies suffer from acute illumination angles, resulting in unfavorable laser footprints, in particular within flat areas. Furthermore, terrain sections behind convex landforms such as hills or moraines cannot be covered. Airborne laser scanning (ALS) on the other hand is still very costly (e.g. Bühler et al., 2015a). Therefore, digital photogrammetry is a promising and economic option for HS mapping in alpine terrain, in particular if it can be performed with cost-effective UAS.

First attempts to map snow depth with photogrammetry from manned aircrafts were already made decades ago (Cline, 1994, 1993; Smith et al., 1967). However the reported efficiency and the achieved accuracies of more than one meter were ~~not feasible to~~ insufficient for most applications. With the advent of digital photogrammetry, this changed fundamentally. Recent investigations report accuracies in the range of centimeters to decimeters, which allow a detailed analysis of the spatial variability of the mountain snow cover (Bühler et al., 2015a; Lee et al., 2008; Nolan et al., 2015) but still require a fully equipped manned aircraft and corresponding maintenance logistics.

~~Throughout the last years~~Recently, UAS have been used for a wide range of mapping and monitoring studies in mountainous regions, especially with a focus on natural hazards~~:~~. Fernández et al. (2015) provide an extensive overview of recent surveys of landslides; Ryan et al. (2015) and Whitehead et al. (2013) reported on UAS applications on glaciers; Danzi et al. (2013) for rockfall, Dall'Asta et al. (2015) for rock glacier and Tampubolon and Reinhardt (2015) on volcano mapping. Enßle et al. (2015) successfully tested UAS-data acquisition in elevations up to 4200 m a.s.l., proving that UAS are capable of operating even at very high altitudes. However, to this date, the number of studies dealing with UAS-based photogrammetry to map snow and avalanche are very limited: First results have recently been published by De Michele et al. (2015), Eckerstorfer et al. (2016) and Vander Jagt et al. (2015). Additionally, Basnet et al. (2015), Prokop et al. (2015) and Thibert et al. (2015) reported on using ground-based photogrammetry for snow and avalanche detection. De Michele et al. ~~(2015~~(2016) conclude, that UAS-based HS mapping holds great potential, but that further studies are required especially with regard to multi-temporal mapping, implementing to sensors capable of measuring at e.g. near infrared wavelengths, or mapping in near infrared bands or to the mapping of different snow cover conditions or topographic areas.(new snow, wet snow, ice crusts etc.).

2 Methods: UAS and data processing

2.1 UAS AscTec Falcon 8

The UAS missions have been performed with an Ascending Technologies (AscTec) Falcon 8 octocopter equipped with a customized Sony NEX-7 camera. The Falcon 8 has been in serial production since 2009 and can be customized with different sensor systems. The system weighs 2.3 kg (incl. camera) and can be transported to remote locations fully assembled in a special backpack, a prerequisite for most alpine applications. A combination of onboard navigation sensors (Global Navigation Satellite System GNSS, Inertial Measurement Unit IMU, barometer and compass) and an adaptive control unit, permit high positional accuracy of better than 2.5 m (personal communication from Ascending Technologies) and stable flight characteristics even in challenging, alpine environmental conditions. The specifications of the Falcon 8 are listed in Table 1.

2.2 Technical specifications of the Falcon 8 UAS

The Sony NEX-7 system camera features a 24 MP APS-C CMOS sensor and is equipped with a small and lightweight Sony NEX 20 mm F/2.8 optical lens (81 g). By removing the built-in near infrared filter, the camera sensor is also sensitive above the red spectrum. This allows us to mount the lens with different filters such as visible colors (RGB) and near infrared (NIR) bands ($\lambda > 550$ nm, $\lambda > 770$ nm and $\lambda > 830$ nm) and without filter the camera sensor operates in a combined visual and NIR range. The near infrared sensitivity has advantages for snow (Bühler et al., 2015b) and vegetation (Tucker, 1979) analysis. The camera is connected to the Falcon 8 by a gimbal with active stabilization and vibration damping and is powered by the UAS battery. The viewfinder of the camera is transmitted to the ground control station as video signal and the basic camera functions such as the exposure time can be controlled from the ground.

The UAS missions are planned using the AscTec Navigator software on a tablet computer. Topographic maps are imported and the waypoint navigation is calculated based on camera specifications, desired ground sampling distance (GSD) and image overlap. At the location of a planned mission the tablet computer is connected to the ground control station and last corrections to the flight plan, e.g. due to unexpected terrain variations, can be applied. During the flight mission, the UAS automatically moves from waypoint to waypoint, only the launch and final landing phase require manual interaction. UAS must be operated within visual line of sight and the pilot has to be ready to interrupt the flight at any time, as requested by Swiss regulations ().

Portability From our experience, portability of the UAS, a high image resolution and the ability to take off and land from an exposed site are important key features for photogrammetric UAS missions within alpine, snow-covered terrain. The Falcon 8 offers a feasible good compromise between flight endurance, payload and stability in most conditions. The spectral and spatial capabilities radiometric and spatial resolution of the Sony NEX-7 camera enable the generation of highly accurate digital surface model (DSM). The portability is excellent as UAS, radio modem and controlling computer fit to a daypack. The short flight time per battery on the other hand, is a critical disadvantage of the octocopter technology. ~~Longer~~ From our experience, longer flight times are the major advantage of fixed-wing UAS like the eBee (sensefly). However, their available cameras have only limited image resolution due to ~~strict weight limits~~limited carrying capacity, space and battery power. Larger fixed-wing drones like Sirius Pro from MAVinci, the UX5 from Trimble or the Q-200 from Quest UAS suffer from quite bulky overall equipment and are therefore ~~not appropriate for~~ difficult to fly in high mountain areas. Feasible terrain (large flat areas) to safely land them does ~~usually~~ often not exist. For an extensive overview of currently available UAS systems the reader is referred to Colomina and Molina (2014).

The regulations for flying UAS vary a lot from country to country or even between different states or communities. If it is necessary to get flying licenses long time before data acquisition, this limits the applicability and flexibility of this technology considerably. The regulations in Switzerland are quite user-friendly and are easy to fulfill as long as the UAS is within line of sight and the pilot is able to interrupt the flight at any time, no special permissions are necessary except you want to fly over crowds (more than 24 people within short distance) or close to airports (Swiss regulations: http://www.bazl.admin.ch). However before applying UAS the local regulations have to be checked carefully.

2.2 Data processing

The images are processed with Agisoft PhotoScan Pro v1.1.6, to generate georeferenced DSMs and orthophotos using dense point cloud generation with the default parameters. PhotoScan is based on a structure-from-motion (SfM) algorithm (Koenderink and van Doorn, 1991; Verhoeven, 2011) and implements a complete photogrammetric workflow with special emphasis on multi-view reconstruction with UAS-based images. The tie point matching of PhotoScan allows the estimation of the internal and external camera orientation parameters and is followed by adding georeference information (coordinate system and ~~ground control~~ reference points). The resulting model is linearly converted using the Helmert-Transform with 7 parameters and therefore compensates only for linear misalignment. Non-linear deformations from the model are removed by optimizing the estimated point cloud and camera parameters using 4 radial and 4 tangential distortion coefficients (Agisoft PhotoScan User Manual, http://www.agisoft.com/downloads/user-manuals/). During creation of the dense point cloud the estimated camera positions are used to calculate depth information for each camera and will be combined into a single dense point cloud. Two parameters of the dense cloud processing step have the strongest impact on the resulting point cloud:

1. “Quality” defines the desired reconstruction detail level. Higher quality settings can be used to obtain more detailed and more accurate geometry, but can results in ~~significantly~~ much longer time for processing.

2. “Depth filtering” allows removing outliers from the point cloud, which are caused by poor texture of the scene, noisy or blurry images. Depending on the complexity of the scene geometry, different depth filtering modes can be applied. The accuracy of the exported product needs to be analyzed to estimate the complexity in the model and thus select an appropriate depth-filtering mode.

3 Test sites and data acquisition

To test the feasibility of UAS-based HS change mapping, two ~~well-accessible~~ easily accessible test sites in the region of Davos, Switzerland have been chosen ~~and represent typical locations for HS studies~~ that represent typical terrain characteristics in high alpine environment (Fig. 1).

3.1 Tschuggen: sheltered valley bottom

The test site Tschuggen is at the bottom of the Flüela valley at an elevation of 1940 m a.s.l. very close to the timberline. This spot is well accessible even during the winter season, because the Flüela pass road is regularly cleared until this point. The high alpine valley bottom features both, ~~quite~~ flat alpine meadows and hilly alpine terrain. The main land cover is a mixture of bushes (mainly alpine rose, juniper and erica) containing steep rocky outcrops and sparse larch and pine trees (Fig. 10). Only moderate HS variability can be expected at this site in an average winter season because it is ~~usually not~~ not usually exposed to high winds. The mean slope angle of the test site is 19° ranging from 0 to 80°. The reference measurement plots have been acquired in areas between 4 and 36° slope angle with an average slope angle of 20°.

A total of 252 images at 4 different dates have been acquired at this test site between March and September 2015 (Table 2; Fig. 2). ~~An~~ From our experience with different overlaps we conclude that an image overlap of 70 % along-track and across-track is a good compromise between the time required for data acquisition and quality of the resulting DSM. The first three flights were done with an old version of the AscTec flight control hardware, which required the UAS to stop and stabilize for every image acquisition, consuming considerably more time and energy to cover a specific area. The last data acquisition was performed with an updated software version where the UAS does not stop, enabling the acquisition of up to five times more images with one battery. The Tschuggen test site can now be covered within 5 minutes and one battery. The air temperature at the flight dates, measured at an automated weather station (AWS) located 4 km south-east and from the test site and 450 m higher, were between -5 and + 0.5° C. The mean wind speeds ranged from 4 to 22 $\mathrm{km\,h^{-1}}$, the maximum wind speeds from 18 to 45 $\mathrm{km\,h^{-1}}$.

For the absolute orientation, selected ~~ground control~~ reference points (~~GCPs~~RPs) have been ~~selected~~applied, which were required to be clearly visible in the base imagery of all four acquisition dates. The ~~GCPs~~RPs, bright quartz marks on rocks and center lines of the road, have been measured with a Leica TPS 1200 differential GNSS with an expected accuracy of better than 0.03 m. The achieved average accuracy of the ~~orthorectification~~ orientation process is 0.038 m ($x = 0.029$ m, $y = 0.021$ m, $z = 0.012$ m).

Simultaneously to the UAS data acquisition, HS reference measurements were acquired with a marked avalanche probe (Fig. 2). ~~Five~~ An investigation by Prokop et al. (2008) as well as our own experience show that such measurements are also affected by errors in the range of 0.05 - 0.10 m. At every reference plot, five manual, plumb vertical measurements within one square meter (at all corners and the center) have been carried out and the center point have been recorded with a Trimble GeoXH differential GNSS device with an expected accuracy better than 0.10 m.

3.2 Brämabühl: exposed mountain top

The test site Brämabühl is located at the top of the ski area Jakobshorn in Davos, Switzerland at an elevation of 2500 m a.s.l. and is approximately 5.5 km linear distance from the test site Tschuggen (Fig. 1). At this test site we expect a much higher variability of HS and in particular higher maximum HS values compared to the test site Tschuggen. The high wind exposure around the top of a crest at high elevation is expected to lead to a large amount of windblown snow. Additionally, the ski runs present within the area are typically areas for snow grooming and artificial snow production. The top of Brämabühl is covered mainly by high alpine meadow and small bushes (Fig. 10). No trees or larger bushes grow at this elevation and local climate. The mean slope angle of the test site is 30° ranging from 0° up to 90° in the small rock faces. The reference measurement plots have ben acquired at slope angles between 5 and 41° with a mean slope angle of 20°. The air temperature at the flight date, measured at an AWS located 5.5 km north-west of the test site at the same elevation, was -2° C. The mean wind speed was 14 $\mathrm{km\,h^{-1}}$, the maximum wind speed 28 $\mathrm{km\,h^{-1}}$.

For this test site near infrared imagery has been selected, which is expected to have higher contrast and lower reflection on snow-covered areas (Bühler et al., 2015b). Table 3 shows the data acquisition information and Fig. 3 the resulting orthophotos, with a spatial resolution of 0.025 m. The same image overlap of 70 % along-track and cross-track, like at the Tschuggen test site, has been used. For the second field campaign, data acquisition was performed with the updated Falcon 8, explaining the much higher number of images and ground coverage in Table 3. To cover the Brämabühl test site we need approximately 20 minutes and four batteries.

The image processing scheme from the Tschuggen experiment was repeated, but due to the smoother terrain with only a few clearly identifiable reference points, 10 artificial GCPs RPs (white plastic sheets with a symmetric black cross in the middle) have been distributed and were measured with a Trimble GeoXH differential GNSS with an expected accuracy of better than 0.10 m. This approach allows a very accurate identification of the GCPs RPs in the imagery. However, the distribution of the artificial GCPs RPs is time consuming and a meaningful distribution over the test site is often not possible due to e.g. avalanche danger. In addition the applied Trimble GeoXH has a lower positioning accuracy than the Leica TPS 1200 GNSS used at Tschuggen. Using 10 GCPsRPs, the achieved referene reference accuracies of 0.019 m in x, 0.030 m in y and 0.032 m in z direction, are resulting results in a combined error of 0.048 m.

The snow-covered imagery has been referenced by taking natural GCPsRPs, which are clearly visible in the snow-free and snow-covered imagery (Fig. 3). The corresponding x, y and z coordinates of the snow-free imagery have been used to reference the snow-covered imagery. This approach ensures an accurate coregistration of the two DSMs. However, it is only possible if snow free areas contain enough well visible features that are sufficiently distributed over the test site. The achieved georeferencing accuracy with 10 control reference points is 0.155 m ($x = 0.079$ m, $y = 0.102$ m, $z = 0.086$ m), the result is worse than for the artificial GCPsRPs, as the natural GCPs RPs are harder to locate exactly.

Simultaneously to the winter UAS data acquisition, HS has been measured with a marked avalanche probe at 22 plots as reference data, locating the center points of the plots using the Trimble Geo XH GNSS.

4 Results and validation

4.1 Tschuggen: valley bottom

To produce the high spatial resolution (0.10 m) HS maps, the snow-free DSM (29 September 2015) has been subtracted from the snow-covered DSMs (11 March, 24 April and 12 May). These maps reveal the high spatial variability of HS already present at sheltered locations in alpine terrain (Fig. 4, top panels). Particularly in the southeastern part of the test site, areas with complex topography exist. Patches with nearly no snow in wind facing areas (luv) and pockets filled by windblown snow with HS up to 2 m in the wind sheltered areas (lee) are connected within less than a meter distance. For the area depicted in Fig. 4, the mean HS $\overline{x}$ and the standard deviation σ decrease from $\overline{x} = 0.66$ m and $\sigma = 0.36$ on 11 March to $\overline{x} = 0.31$ m and $\sigma = 0.31$ on 24 April and to $\overline{x} = 0.01$ m and $\sigma = 0.09$ on 12 May. Because of the produced HS maps from different dates, including approximately the peak of winter HS accumulation (11 March 2015), the spatial distribution of HS change as the percentage of remaining snow compared to the maximum HS can be calculated and visualized. Prior to the generation of the relative HS change maps the snow-covered areas have been ~~classified~~ separated from snow free patches using a simple unsupervised classification, based on the three spectral bands of the orthophoto. All areas not covered by snow have been set to zero HS. Isolated negative snow depth values, mainly caused by summer vegetation (Sect. 5.4), are not masked out but depicted as 0 HS in the maps.

The locations of the probe measurements are depicted in Fig. 2. We compare the mean $\overline{x}$ and the standard deviation σ of the five manual measurements per plot with the $\overline{x}$ and σ of all pixels ($10 \times 10 = 100$) within the 1 m^2 box around the center localized with differential GNSS. The results of this comparison are depicted in Fig. 5.

The HS root mean square error (RMSE) over all 50 reference plots is 0.25 m and there is an average ~~systematic~~ underestimation of HS by 0.2 m. For a more detailed analysis we divide the reference measurements in two classes based on the manual analysis of the 0.025 m spatial resolution snow-free orthophoto acquired on 28 September 2015: (a) *short grass/rocks* where no high vegetation is present and (b) *bushes/high grass*, where the surface of the dense vegetation is more than 0.10 m higher than the bare ground. In the second class the snow-free DSM is ~~significantly~~ higher than the terrain without vegetation. Because the snow presses the grass and bushes down to the ground in winter, the difference between the snow-covered and snow-free DSM results in a systematic underestimation of HS. For the class *short grass/rocks* the RMSE is 0.07 m and there is a mean shift of only 0.05 m for all three flight dates. For the class *bushes/high grass* on the other hand the RMSE is 0.30 m and there is a ~~mean shift~~ bias of 0.29 m, corresponding to the mean height of bushes and tall grass within the investigation area. For snow hydrological applications it is also important to gain information on the standard deviation σ of HS within a specific plot. Even though the reference plots are only 1 m^2 we find σ values up to 0.2 m. The RMSE of σ is 0.04 m, based on all reference measurements, and there is no ~~significant~~ clear difference between the two investigated classes at all three flight dates.

To assess the repeatability of the UAS HS mapping we analyze the altitude deviation of the different DSM at 10550 grid cells on the snow-free road. The calculated RMSE values compared to the summer DSM (28 September) are 0.093 m (11 March), 0.052 m (24 April) and 0.045 m (12 May). This indicates that the noise of the method is smaller than 0.1 m.

4.2 Brämabühl: mountain top

The HS map with a spatial resolution of 0.1 m shows different characteristics compared to the Tschuggen test site. The expected higher HS values of up to 5 m are clearly visible in Fig. 6. The close-up of the central part reveals interesting details such as the linear feature of buried hiking paths in the northwest or the snow grooming on the ski tracks. Over the entire area we calculate a mean HS $\overline{x} = 1.41$ m and $\sigma = 0.78$. Both $\overline{x}$ and σ are more than twice as high as at the Tschuggen test site. The high spatial variability gets even more obvious in the 3-D view. We provide an animation of this 3-D visualization as Supplement to the paper (mp4 3-D movie). Snow filled bowls lay directly next to ridges where nearly all snow has been blown off. HS differences reach up to 5 m within only a few meters in horizontal distance. Artificial terrain features such as hiking paths and the edges of the ski track can easily be identified in the HS map. The gray features on the top and on the left side are the station building of the chairlift Brämajet and its masts. This visualization highlights the role of wind in combination with small terrain features for the spatial variability of HS.

The mean HS distribution classified by the terrain expositions confirms the visual impression that the south facing slopes have much lower HS values than the north facing slopes (Fig. 7). Also the standard deviation of the mean HS shows a tendency to be smaller at southern expositions (SE, S, and SW). This slope aspect analysis was performed on the snow-free DSM, which was resampled to 1 m to filter out small exposition changes. Such statistical evaluation enables a more detailed analysis of mountain HS distribution on local to regional scale.

The comparison of the photogrammetric HS with manual HS measurements results in a RMSE of 0.15 m and a very high correlation coefficient of $R^2 = 0.99$ (Fig. 8). The photogrammetric HS values are, on average, 0.11 m lower than the manual measurements. The summer vegetation can at least partly explain difference, as dense grass and small bushes cover the peak of Brämabühl. The comparison of the standard deviations within a reference plot results in a ~~mean deviation~~ bias of 0.03 m; the RMSE is 0.06 cm. These results confirm the high accuracy of the photogrammetric HS measurements we found at the Tschuggen test site.

5 Discussion

Based on the experience gained at the two presented test sites, the following key points require a more detailed discussion because they are crucial for the application of UASs in high alpine terrain.

5.1 UAS applied in high alpine terrain

Steep terrain, high altitudes, low temperatures and often wind speeds of more than 10 m s^{-1} are typical for high alpine regions. To successfully apply UASs, platform and sensor must be able to handle such conditions and have to be easily transportable in a backpack on foot or on skis. The key limitation of the applied Falcon 8 UAS is the comparably short flight time of 6 to 10 min with one battery at elevations above 2000 m a.s.l. This also limits the range of the UAS. As a consequence, the pilot position has to be close to the area of interest, which is often difficult or even impossible for example if snow avalanche release zones have to be mapped. A big advantage of a multicopter UAS is that they can be started and landed by hand, which is the appropriate starting/landing procedure we apply in alpine terrain. This Based on our experience, this is in contrast to the application of winged UASs, which require large flat areas to safely land but such areas are typically missing in high alpine regions. Cold temperatures of down to $-30\,^{\circ}\mathrm{C}$ are a major problem for battery transportation. As soon as the battery is deployed and running in the UAS there is self-heating. Therefore it is critical that the batteries are transported in a heated environment for example close to the body, otherwise they will lose a big part of their performance before taking off significantly again reducing the already short flight time. On the other hand, our experiences with the UAS regarding high wind speeds were surprising. Even under foehn conditions with gusty wind speeds up to $20\,\mathrm{m\,s^{-1}}$ the acquired imagery was of high quality and the flight plan and its specific overlap could be accomplished. Fixed-wing UAS achieve significantly Our experience shows that fixed-wing UAS achieve longer flight times per battery (20–60 min), but are less stable in windy conditions, are less easy to transport and to fly and they need gentle terrain to land. In our opinion, this limits their successful application in alpine terrain considerably in particular on missions in alpine terrain.

We identify the following potential applications where UAS have not yet been applied and further investigations are required:

- precise water resource prediction for hydropower and flood warning in small alpine catchments (Jonas et al., 2009);
- validation of snowpack and snow hydrology models (Bartelt and Lehning, 2002; Mote et al., 2003);
- survey of snow distribution in ski resorts to improve the track management (Damm et al., 2014);
- precise documentation of specific avalanche release and deposition to validate and calibrate numerical avalanche simulations (Christen et al., 2010) and to generate precise, up-to-date DSMs e.g. after an avalanche event blocks a channel, as base for such simulations (Bühler et al., 2011);
- identification of representative locations for automated weather stations (Grünewald and Lehning, 2015);
- survey of avalanche defense structures to prevent ineffectiveness due to potential overfill (Margreth and Romang, 2010);
- ideal positioning of artificial avalanche release trigger points (Stoffel and Margreth, 2009);
- identification of wind blown snow packets prone to snow avalanche release (Schweizer et al., 2008).

5.2 Photogrammetry on snow covered terrain

For a long time, photogrammetry on snow-covered terrain was considered unfeasible, due to low contrast, a limitation only recently overcome as highlighted in current studies (Bühler et al., 2015a; Lee et al., 2008; Nolan et al., 2015). However, the The smoother the snow surface is, the harder it gets for the structure-from-motion software to identify meaningful matching points. This gets obvious if we look at homogenous areas within the hillshade DSM at shadowed and at well-illuminated snow covered locations (Fig. 9). In shadowed areas (e.g. shadow of the chapel tower) the clearly visible noise introduced into the ~~DEM~~ DSM gets amplitudes of up to 0.40 m. In the bright, very homogenous areas the noise shows amplitudes of up to 0.15 m. This indicates that a fresh snow surface is less suitable than an older, weathered surface. But due to strong winds and large differences in radiation, alpine snow surfaces develop detectable features such as sastrugis or wind ripples already during or very quickly after fresh snowfall. ~~However, very~~ Very homogenous snow surfaces occur only within very small parts of our test sites.

Additional problems occur if reflections of the sun on the snow saturate the camera sensor. Therefore it is recommended that the camera exposure time is properly set and the imagery is stored in raw format using the full bit depth of the sensor, typically 10 to 14 bits. Standard JPEG image compression, which is the default storage setting for most cameras, is limited to 8 bits storing only 256 gray scale values per band. To acquire an optimal contrast on homogenous snow surface we recommend using RAW image storage format with 12 bit. However, further investigations have to quantify the benefit of 12 bit image storage over the 8 bit JPEG compression on snow covered areas.

As snow absorbs more energy in the near infrared NIR part ($\lambda \approx 760$–2500 nm) of the electromagnetic spectrum than in the visible part ($\lambda \approx 400$–700 nm) and the reflection is sensitive to snow grain size (Warren, 1982) at the snow surface, additional features are expected to be discriminated if NIR data can be used (Bühler et al., 2015b). However, further studies have to investigate the real benefit of NIR bands for photogrammetric HS mapping in more detail. This might only be significant if multi-imager cameras with narrow NIR bands and simultaneous band acquisition are applied.

5.3 Orthorectification

Exact relative georeferencing (coregistration) between the two DSMs is essential for correct HS calculation (snow-covered DSM minus snow-free DSM). Even small shifts in x and y can lead to large differences in z direction on steep terrain. The following referencing approaches exist:

a. absolute referencing with artificial ~~GCPs~~ RPs measured with differential GNSS;

b. relative referencing with natural ~~GPSs~~ RPs that are well visible in the snow-free and the snow-covered imagery;

c. absolute referencing of one DSM with differential GNSS and then relative referencing of the second DSM by identifying well visible points in the second DSM.

A major drawback of method (a) is that all reference points have to be manually deployed and measured with differential GNSS devices to achieve accuracy in the range of centimeters to a decimeter. They should be distributed equally over the entire area of interest and all elevation bands. In high alpine terrain this is often not possible for example due to avalanche danger. The methods (b) and (c) exclude the possibility of a potential GNSS shift but are only applicable if areas with distinct terrain features exist that are not covered by snow. This was the case at our test sites but might not be feasible in winters with exceptionally high amounts of snow. The referencing strategy has to be evaluated carefully prior to a UAS HS mapping campaign. A direct matching of the snow-covered to the snow-free point cloud (Gruen and Akca, 2005) is not feasible as the terrain shows large differences over most parts due to the snow cover.

RPs would not be necessary if a very accurate (better than 0.05 m) GNSS system would be available directly on the UAS. First UAS products with such high-accuracy GNSS sensor are already available on the market. However a first investigation by Harder et al. (2016) indicates that the achieved orientation accuracy is not sufficient for snow depth mapping without ground reference measurements.

5.4 Underlying vegetation

Within the accuracy range of the HS maps of 0.05–0.15 m, the vegetation at the base of the snow cover has a ~~significant~~ strong influence on the results. At the test site Tschuggen small bushes, mainly alpine rose, juniper and erica, rise up to 0.50 m above ground in summer (Fig. 10a). In winter they are pressed down to the ground by the snowpack but form a snow-free layer at the bottom of the snowpack which can have a depth of a few centimeters to decimeters (Feistl et al., 2014). This leads to a systematic underestimation of HS mapped with photogrammetry (snow-free DSM is too high) as well as a systematic overestimation of HS measured manually with the avalanche probe because the probe penetrates the snow-free bottom layer and sometimes even the first layers of the ground. The “real” HS is most probably a value between the manual probe and the photogrammetric measurements. High grass on the other hand is usually pressed down to the ground completely only leaving a snow-free layer of less than some centimeters (Fig. 10b). This makes the probe measurements more reliable but can falsify the photogrammetric measurements ~~significantly~~ if the grass is high during the snow-free data acquisition. Alpine meadows should therefore be surveyed right after mowing or late in autumn while the grass is low. From our experience it is very difficult to correct the photogrammetric HS based on underlying vegetation because the elevation differences vary very much within short distances. A possibility might be to apply a vegetation classification based on the orthophotos to correct the underestimation of HS in areas with many bushes. But there is a high risk to introduce new errors and this possibility has to be investigated in more detail in the future. Photogrammetric HS mapping is ~~impossible above~~difficult above, below and around trees as trees are nearly always moved by wind and the resulting ambiguous tree top positions interfere with image matching. Additionally areas below trees are not visible in the nadir imagery. Therefore laser scanning, measuring first and last returns or even full wave form signals, is still the best choice for investigations where trees play a major role (Moeser et al., 2015).

6 Conclusions

UAS-based digital photogrammetry is able to map the spatial variability of alpine HS with accuracies of 0.07 to 0.15 m RMSE compared to traditional manual measurements with avalanche probes. These accuracies are in the same range as HS measurements acquired by terrestrial laser scanning (Deems et al. 2013) and reported in the manned airplane based study by Nolan et al. (2015) and the UAS based ~~study by~~ studies by Vander Jagt et al. (2015)~~. It is significantly~~ , de Michele et al. (2016) and Harder et al. (2016). It is clearly better than the RMSE of 0.30 m reported by Bühler et al. (2015a), using an ADS80 survey camera mounted on a manned airplane, but can only cover considerably smaller areas. Fixed-wing UAS, flying at high altitudes above ground, would be able to cover larger areas of several square kilometers. Future investigations have to clarify how accurate the results from such platforms can get as the spatial resolution of the input imagery is worse and the results might get much more affected by wind.

UASs enable fast, flexible, repeatable and detailed analysis of the spatial distribution of the mountain snow cover over several hectare areas. We successfully applied a complete photogrammetric workflow at a sheltered test site at the valley bottom (Tschuggen) and at an exposed test site at a mountain top (Brämabühl) mapping extreme HS variability of up to 5 m within less than 3 m distance, confirming the important role of wind and terrain features on HS distribution in alpine regions (Mott et al., 2010).

A key to robust photogrammetric HS measurements is the accurate co-registration of the snow-free and the snow-covered digital surface models (DSM). Even small shifts in x and/or y direction can lead to large shifts in z in particular within steep terrain. To avoid shifts introduced by global navigation satellite system measurements (GNSS) we propose to reference the snow-covered DSM directly on the snow-free DSM. But this is only possible if snow-free areas exist, that contain well visible point- or linear features. Another important point is that alpine vegetation, such as bushes and tall grass, lead to a significant an overestimation of snow-free DSM elevations, resulting in underestimated HS values. This can introduce errors in HS values of up to 0.50 m.

We identify numerous promising applications where UAS have not yet been applied: precise water resource prediction for hydropower and flood warning in alpine catchments (Jonas et al., 2009); validation of snowpack and snow hydrology models (Bartelt and Lehning, 2002; Mote et al., 2003); survey of snow distribution in ski resorts to improve the track management (Damm et al., 2014); precise documentation of specific avalanche release and deposition to validate and calibrate numerical avalanche simulations (Christen et al., 2010) and to generate precise, up-to-date DSMs e.g. after an avalanche event blocks a channel, as base for such simulations (Bühler et al., 2011); identification of representative locations for automated weather stations (Grünewald and Lehning, 2015); survey of avalanche defense structures to prevent ineffectiveness due to potential overfill (Margreth and Romang, 2010); ideal positioning of artificial avalanche release trigger points (Stoffel and Margreth, 2009); identification of wind blown snow packets prone to snow avalanche release (Schweizer et al., 2008). In our opinion the number of investigations applying UAS based digital photogrammetry will rise quickly within the next years and change the way of collecting spatial information within alpine terrain sustainablyexpect that UAS will get more and more important for mapping applications also high alpine terrain and that this methodology will change the frequency and quality of geo-data acquisition fundamentally.

The Supplement related to this article is available online at doi:10.5194/tc-0-1-2016-supplement.

Acknowledgements. Parts of this work was supported by the Austrian Academy of Sciences (ÖAW) under the project RPAS4SNOW.

References

Bartelt, P. and Lehning, M.: A physical SNOWPACK model for the Swiss avalanche warning Part I: numerical model, Cold Reg. Sci. Technol., 35, 123–145, 2002.

Basnet, K., Muste, M., Constantinescu, G., Ho, H., and Xu, H.: Close range photogrammetry for dynamically tracking drifted snow deposition, Cold Reg. Sci. Technol., 121, 141–153, doi:10.1016/j.coldregions.2015.08.013, 2015.

Bavay, M., Lehning, M., Jonas, T., and Löwe, H.: Simulations of future snow cover and discharge in Alpine headwater catchments, Hydrol. Process., 23, 95–108, 2009.

Bilodeau, F., Gauthier, G., and Berteaux, D.: The effect of snow cover on lemming population cycles in the Canadian High Arctic, Oecologia, 172, 1007–1016, 2013.

Bühler, Y., Christen, M., Kowalski, J., and Bartelt, P.: Sensitivity of snow avalanche simulations to digital elevation model quality and resolution, Ann. Glaciol., 52, 72–80, 2011.

Bühler, Y., Marty, M., Egli, L., Veitinger, J., Jonas, T., Thee, P., and Ginzler, C.: Snow depth mapping in high-alpine catchments using digital photogrammetry, The Cryosphere, 9, 229–243, doi:10.5194/tc-9-229-2015, 2015a.

Bühler, Y., Meier, L., and Ginzler, C.: Potential of operational, high spatial resolution near infrared remote sensing instruments for snow surface type mapping, IEEE Geosci. Remote Sens. Lett., 12, 821–825, 2015b.

Christen, M., Kowalski, J., and Bartelt, P.: RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain, Cold Reg. Sci. Technol., 63, 1–14, 2010.

Cline, D. W.: Measuring alpine snow depths by digital pho-togrammetry: Part 1. conjugate point identification, Proceedings of the Eastern Snow Conference, Quebec City, 1993.

Cline, D. W.: Digital Photogrammetric Determination Of Alpine Snowpack Distribution For Hydrologic Modeling, Colorado State University, CO, USA, 1994.

Colomina, I. and Molina, P.: Unmanned aerial systems for photogrammetry and remote sensing: A review, ISPRS J. Photogram. Remote Sens., 92, 79–97, 2014.

Dall'Asta, E., Delaloye, R., Diotri, F., Forlani, G., Fornari, M., Morra di Cella, U., Pogliotti, P., Roncella, R., and Santise, M.: Use of Uas in a High Mountain Landscape: The Case of Gran Sommetta Rock Glacier (Ao), ISPRS International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-3/W3, 391–397, 2015.

Damm, A., Köberl, J., and Prettenthaler, F.: Does artificial snow production pay under future climate conditions? – A case study for a vulnerable ski area in Austria, Tourism Manage., 43, 8–21, 2014.

Danzi, M., Di Crescenzo, G., Ramondini, M., and Santo, A.: Use of unmanned aerial vehicles (UAVs) for photogrammetric surveys in rockfall instability studies, Rend. Online Soc. Geol. It., 24, 82–85, 2013.

Deems, J. S., Painter, T. H., and Finnegan, D. C.: Lidar measurement of snow depth: A review, J. Glaciol., 59, 467–479, 2013.

Deems, J. S., Gadomski, P. J., Vellone, D., Evanczyk, R., LeWinter, A. L., Birkeland, K. W., and Finnegan, D. C.: Mapping starting zone snow depth with a ground-based lidar to assist avalanche control and forecasting, Cold Reg. Sci. Technol., 120, 197–204, doi:10.1016/j.coldregions.2015.09.002, 2015.

De Michele, C.,Avanzi, F., Passoni, D., Barzaghi, R., Pinto, L., Dosso, P., Ghezzi, A., Gianatti, R. ~~,~~ and Della Vedova, G.: ~~Microscale variability of snow depth using U.A.S. technology~~Using a fixed-wing UAS to map snow depth distribution: anevaluation at peak accumulation, The Cryosphere~~Discuss., 9, 1047–1075, , 2015.~~ , 10(2), 511-522, doi:doi:10.5194/tc-10-511-2016., 2016.

Eckerstorfer, M., Bühler, Y., Frauenfelder, R., and Malnes, E.: Remote sensing of snow avalanches: Recent advances, potential, and limitations, Cold Reg. Sci. Technol., 121, 126–140, 2016.

Egli, L., Jonas, T., Grünewald, T., Schirmer, M., and Burlando, P.: Dynamics of snow ablation in a small Alpine catchment observed by repeated terrestrial laser scans, Hydrol. Process., 26, 1574–1585, 2011.

Elder, K., Rosenthal, W., and Davis, R. E.: Estimating the spatial distribution of snow water equivalence in a montane watershed, Hydrol. Process., 12, 1793–1808, 1998.

Enßle, F., Fritz, A., and Koch, B.: Comparing Icesat/Glas Based Elevation Heights with Photogrammetric Terrain Heights from Uav-Imagery on the East Tibetan Plateau, ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-3/W3, 385–390, 2015.

Feistl, T., Bebi, P., Dreier, L., Hanewinkel, M., and Bartelt, P.: Quantification of basal friction for technical and silvicultural glide-snow avalanche mitigation measures, Nat. Hazards Earth Syst. Sci., 14, 2921–2931, doi:10.5194/nhess-14-2921-2014, 2014.

Fernández, T., Pérez, J. L., Cardenal, F. J., López, A., Gómez, J. M., Colomo, C., Delgado, J., and Sánchez, M.: Use of a light UAV and photogrammetric techniques to study the evolution of a landslide in Jaén (southern spain), Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XL-3/W3, 241–248, 2015.

Fierz, C., Armstrong, R. L., Durand, Y., Etchevers, P., Greene, E., McClung, D. M., Nishimura, K., Satyawali, P. K., and Sokratov, S. A.: The International classification for seasonal snow on the ground, IACS, UNESCO, Paris, France, 2009.

Gruen, A. and Akca, D.: Least squares 3D surface and curve matching, ISPRS J. Photogram. Remote Sens., 59, 151–174, 2005.

Grünewald, T. and Lehning, M.: Are flat-field snow depth measurements representative? A comparison of selected index sites with areal snow depth measurements at the small catchment scale, Hydrol. Process., 29, 1717–1728, 2015.

Grünewald, T., Schirmer, M., Mott, R., and Lehning, M.: Spatial and temporal variability of snow depth and ablation rates in a small mountain catchment, The Cryosphere, 4, 215–225, doi:10.5194/tc-4-215-2010, 2010.

~~Jagt, B., Lucieer, A., Wallace, L., Turner, D., and Durand, M.: Snow Depth Retrieval with UAS Using Photogrammetric Techniques, Geosciences, 5, 264–285~~Harder, P., Schirmer, M., Pomeroy, J., and Helgason, W.: Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle, The Cryosphere Discuss., ~~2015.~~ 2016, 1-22, 2016.

Jonas, T., Marty, C., and Magnusson, J.: Estimating the snow water equivalent from snow depth measurements in the Swiss Alps, J. Hydrol., 378, 161–167, 2009.

Koenderink, J. J. and van Doorn, A. J.: Affine structure from motion, J. Opt. Soc. Am. A 8, 377–385, 1991.

Lee, C. Y., Jones, S. D., Bellman, C. J., and Buxton, L.: DEM creation of a snow covered surface using digital aerial photography, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Part B8, Beijing, China, 831–835, 2008.

Margreth, S. and Romang, H.: Effectiveness of mitigation measures against natural hazards, Cold Reg. Sci. Technol., 64, 199–207, 2010.

McClung, D. M. and Schaerer, P.: The Avalanche Handbook, The Mountaineers Books, Seattle, 2006.

Melvold, K. and Skaugen, T.: Multiscale spatial variability of lidar-derived and modeled snow depth on Hardangervidda, Norway, Ann. Glaciol., 54, 273–281, 2013.

Moeser, D., Morsdorf, F., and Jonas, T.: Novel forest structure metrics from airborne LiDAR data for improved snow interception estimation, Agr. Forest Meteorol., 208, 40–49, 2015.

Mote, T. L., Grandstein, A. J., Leathers, D. J., and Robinson, D. A.: A comparison of modeled, remotely sensed, and measured snow water equivalent in the northern Great Plains, Water Resour. Res., 39, SWC41–SWC412, 2003.

Mott, R., Schirmer, M., Bavay, M., Grünewald, T., and Lehning, M.: Understanding snow-transport processes shaping the mountain snow-cover, The Cryosphere, 4, 545–559, doi:10.5194/tc-4-545-2010, 2010.

Mysterud, A., Stenseth, N. C., Yoccoz, N. G., Langvatn, R., and Steinheim, G.: Nonlinear effects of large-scale climatic variability on wild and domestic herbivores, Nature, 410, 1096–1099, 2001.

Nolan, M., Larsen, C., and Sturm, M.: Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry, The Cryosphere, 9, 1445–1463, doi:10.5194/tc-9-1445-2015, 2015.

Prokop, A.: Assessing the applicability of terrestrial laser scanning for spatial snow depth measurements, Cold Reg. Sci. Technol., 54, 155–163, 2008.

Prokop, A., Schirmer, M., Rub, M., Lehning, M., and Stocker, M.: A comparison of measurement methods: Terrestrial laser scanning, tachymetry and snow probing for the determination of the spatial snow-depth distribution on slopes, Annals of Glaciology, 49, 210-216, 2008.

Prokop, A., Schön, P., Singer, F., Pulfer, G., Naaim, M., Thibert, E., and Soruco, A.: Merging terrestrial laser scanning technology with photogrammetric and total station data for the determination of avalanche modeling parameters, Cold Reg. Sci. Technol., 110, 223–230, 2015.

Ryan, J. C., Hubbard, A. L., Box, J. E., Todd, J., Christoffersen, P., Carr, J. R., Holt, T. O., and Snooke, N.: UAV photogrammetry and structure from motion to assess calving dynamics at Store Glacier, a large outlet draining the Greenland ice sheet, The Cryosphere, 9, 1–11, doi:10.5194/tc-9-1-2015, 2015.

Schaffhauser, A., Adams, M., Fromm, R., Jörg, P., Luzi, G., Noferini, L., and Sailer, R.: Remote sensing based retrieval of snow cover properties, Cold Reg. Sci. Technol., 54, 164–175, 2008.

Schweizer, J., Kronholm, K., Jamieson, J. B., and Birkeland, K. W.: Review of spatial variability of snowpack properties and its importance for avalanche formation, Cold Reg. Sci. Technol., 51, 253–272, 2008.

Smith, F., Cooper, C., and Chapman, E.: Measuring Snow Depths by Aerial Photography, Proceedings of the Western Snow Conference, April 1967, Boise, Idaho, USA, 1967.

Stoffel, L. and Margreth, S.: Artificial avalanche release above settlements, edited by: Schweizer, J. and van Herwijnen, A., Davos, GR, Switzerland, 572–576, 2009.

Tampubolon, W. and Reinhardt, W.: Uav Data Processing for Rapid Mapping Activities, ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XL-3/W3, 371–377, 2015.

Thibert, E., Bellot, H., Ravanat, X., Ousset, F., Pulfer, G., Naaim, M., Hagenmuller, P., Naaim-Bouvet, F., Faug, T., Nishimura, K., Ito, Y., Baroudi, D., Prokop, A., Schön, P., Soruco, A., Vincent, C., Limam, A., and Héno, R.: The full-scale avalanche test-site at Lautaret Pass (French Alps), Cold Reg. Sci. Technol., 115, 30–41, 2015.

Tucker, C. J.: Red and photographic infrared linear combinations for monitoring vegetation, Remote Sens. Environ., 8, 127–150, 1979.

Vander Jagt, B., Lucieer, A., Wallace, L., Turner, D., and Durand, M.: Snow Depth Retrieval with UAS Using Photogrammetric Techniques, Geosciences, 5, 264–285, 2015.

Verhoeven, G.: Taking computer vision aloft – archaeological three-dimensional reconstructions from aerial photographs with photoscan, Archaeol. Prospect., 18, 67–73, 2011.

Warren, S.: Optical Properties of Snow, Rev. Geophys. Space Phys., 20, 67–89, 1982.

Whitehead, K., Moorman, B. J., and Hugenholtz, C. H.: Brief Communication: Low-cost, on-demand aerial photogrammetry for glaciological measurement, The Cryosphere, 7, 1879–1884, doi:10.5194/tc-7-1879-2013, 2013.

Wipf, S., Stoeckli, V., and Bebi, P.: Winter climate change in alpine tundra: Plant responses to changes in snow depth and snowmelt timing, Climatic Change, 94, 105–121, 2009.

Table 1. Technical specifications of the Falcon 8 UAS.

UAS type	V-form octocopter
Dimensions	$770 \times 820 \times 125$ mm
Engines	8 electrical, brushless (sensor less) motors
Rotor diameter	$8''$ ($\sim$ 0.20 m)
Number of rotors	8
Rotor weight	6 g
Empty weight	1.1 kg
Max. take off weight	2.3 kg
Max. payload weight	0.8 kg
Max. flight time per Battery	12–22 min
Max. range	1 km
Tolerable wind speed	12–15 m s^{-1}
Navigation sensors	AscTec Trinity (IMU, barometer and compass)
	AscTec High-Performance GPS (GNSS)
Max. airspeed	Manual mode 15 m s^{-1}
	Height mode 15 m s^{-1}
	GPS mode 4.5–10 m s^{-1}
	Data acquisition 10 m s^{-1}
Max. climb/sink rate:	Manual mode 6–10 m s^{-1}
	Height mode 3 m s^{-1}
	GPS mode 3 m s^{-1}
Wireless communication	2 independent (diversity) control/data links 2.4 GHz FHSS link (10 to 63 mW)
	1 analogue diversity video receiver 5.8 GHz (25 or 100 mW)
LiPo battery	PP 6250, 3 Cells 6250 mAh ($\sim$ 426 g)

Table 2. Data acquisition parameters for Tschuggen.

Acquisition date	Images	Covered area	Mean flight height above ground	Average points per m^2	Reference measurements
11 March 2015 close to peak of winter	43	57 000 m^2	97 m	772	12 plots (60 single points)
24 April 2015 snow melt ongoing	55	87 000 m^2	126 m	469	19 plots (95 single points)
12 March 2015 snowmelt nearly completed	55	91 000 m^2	130 m	439	19 plots (95 single points)
28 September 2015 completely snow free	99	128 000 m^2	113 m	563	–

Table 3. Data acquisition parameters for the Brämabühl test site.

Acquisition date	No. of images	Covered area	Mean flight height above ground level	Average points per m^2	No. of reference measurements
14 April 2015 close to peak of winter HS accumulation	85	285 000 m^2	157 m	274	22 plots (110 single points)
21 September 2015 completely snow free	274	363 000 m^2	133 m	386	–

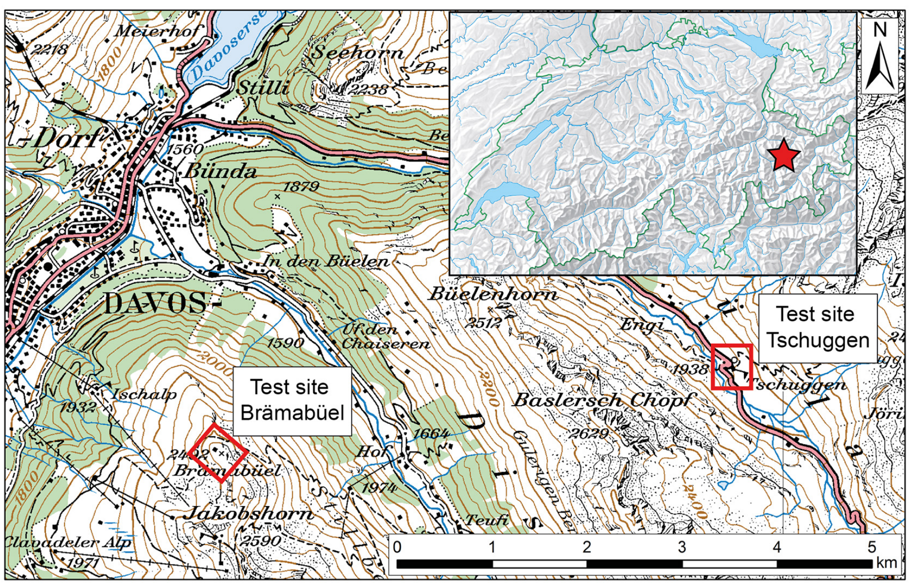

Figure 1. Location of test sites Tschuggen and Brämabüel close to Davos, Switzerland, Pixmap© 2015 swisstopo (5 704 000 000), reproduced by permission of swisstopo (JA100118).

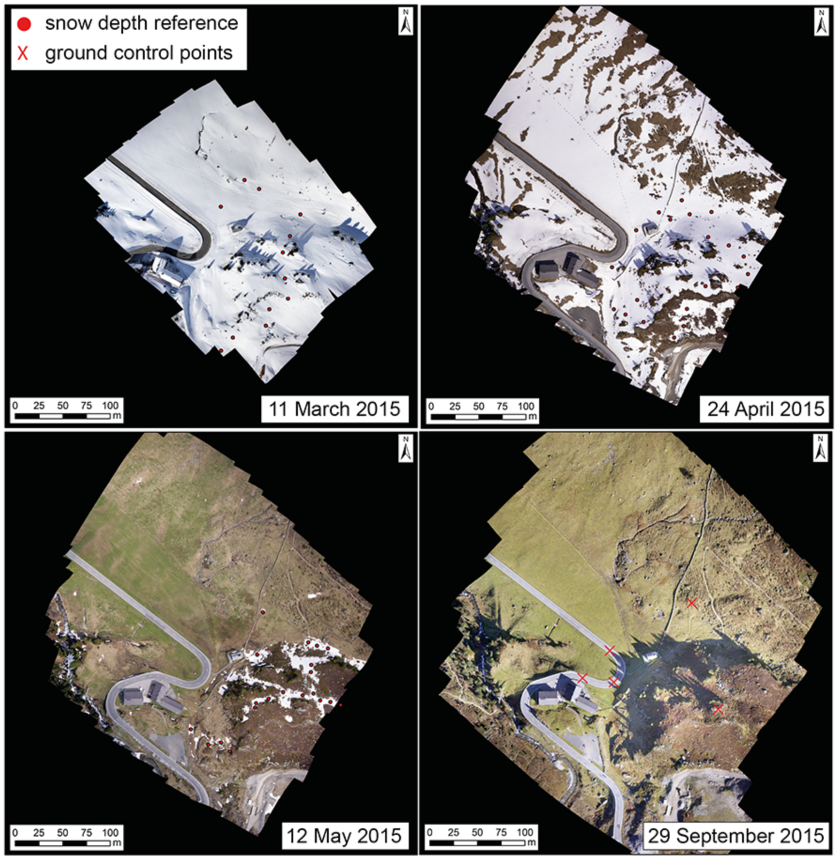

Figure 2. Orthophotos of the four different data acquisitions at Tschuggen depicting the change in snow coverage overlaid by the locations of the manual HS measurements and the applied ~~ground control~~ reference points.

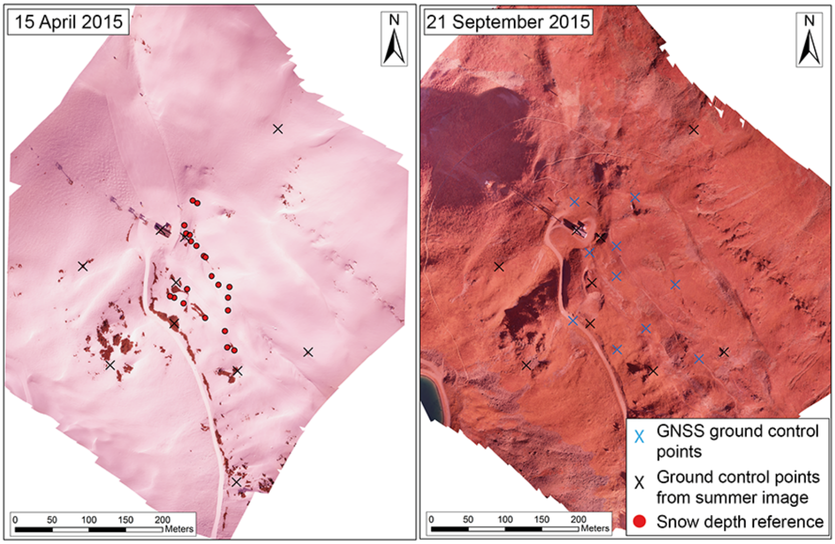

Figure 3. Near infrared orthophotos snow-covered (left panel) and snow-free (right panel), acquired over the Brämabühl test site including the applied ~~ground control~~ reference points and reference HS measurements.

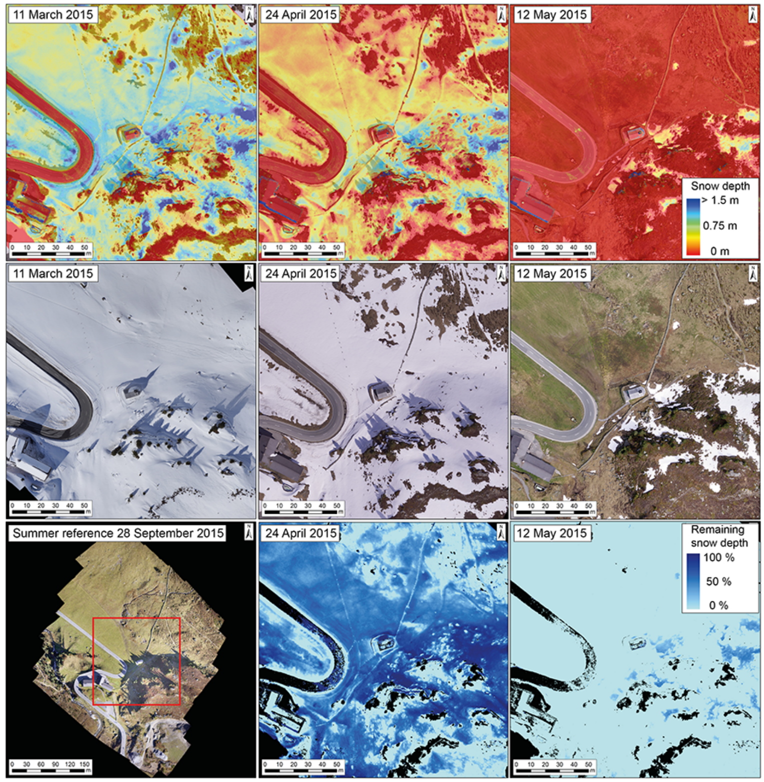

Figure 4. HS maps (top panels) and corresponding orthophotos (middle panels) of the area around the chapel in the center of the test site. At the bottom the orthophoto of the snow-free reference (bottom left panel) and the spatial distribution of melt rates as percentage of remaining snow compared to the peak of winter (11 March 2015) are depicted. Black areas are no data values.

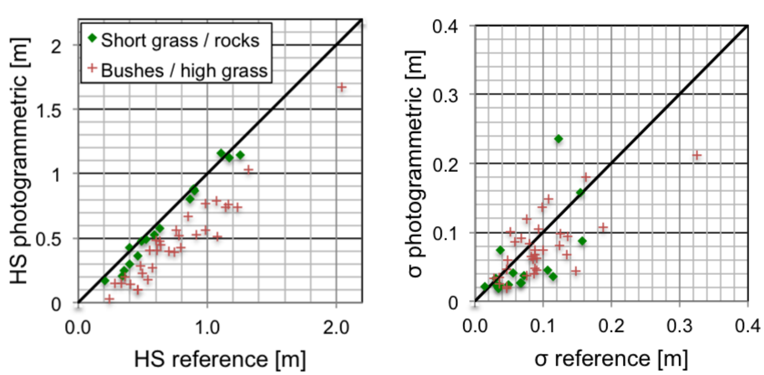

Figure 5. Statistical evaluation of the HS measurements (left panel) and the standard deviations σ of HS within a specific reference plot (right panel). The overall correlation coefficients R^2 for the HS values is 0.84 ($R^2 = 0.98$ for the class *short grass/rocks* and $R^2 = 0.92$ for the class *bushes/high grass*).

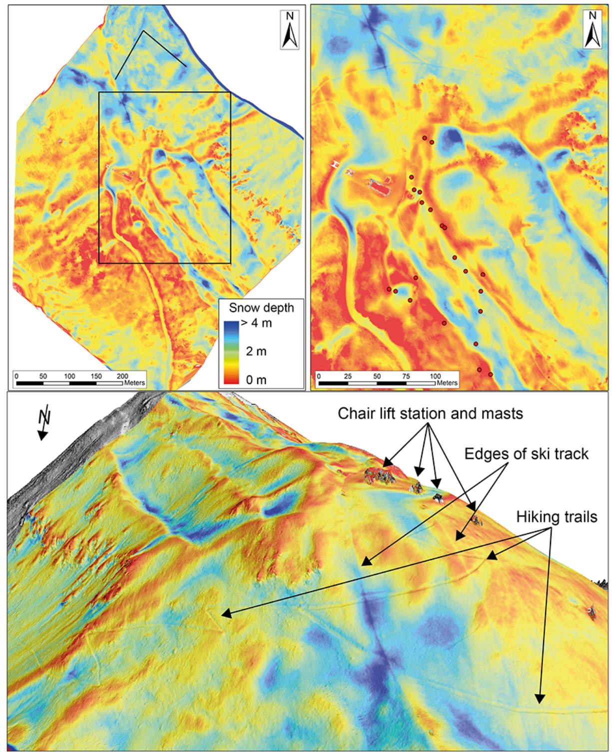

Figure 6. Overall HS map of the Brämabühl test site (top left panel) and close-up of the central part (top right panel). The locations of the reference plots are displayed as red circles. 3-D view of the HS draped over the hillshade of the snow-free DSM looking from north to south (bottom panel).

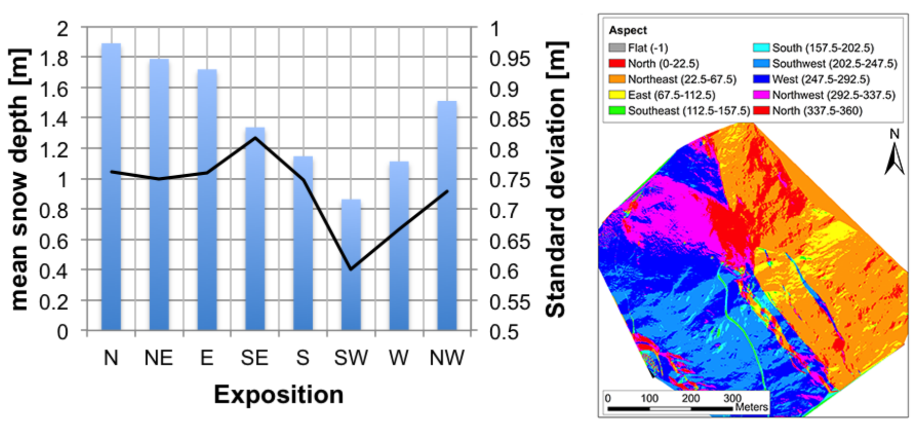

Figure 7. Statistical evaluation of the mean HS (bars) and its standard deviation (line), classified by the exposition (left panel) and exposition map (right panel).

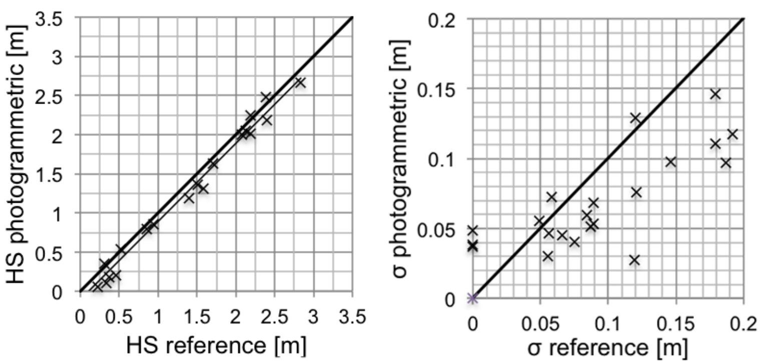

Figure 8. Statistical evaluation of the HS measurements (left panel) and the standard deviations σ of HS within a reference plots (right panel).

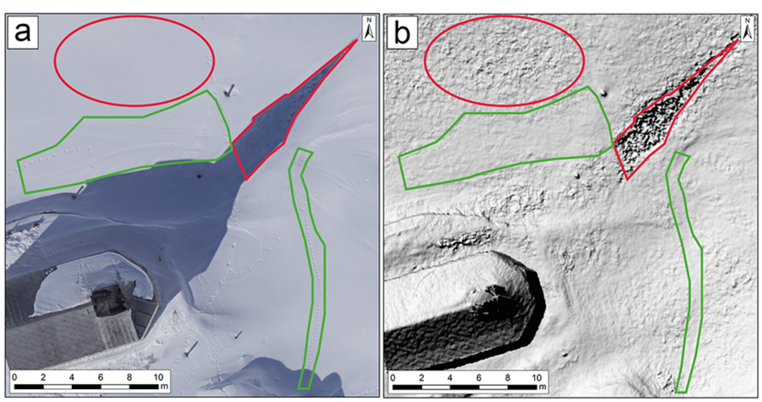

Figure 9. Winter orthophoto of the area close to the chapel within the test site Tschuggen **(a)** and hillshade of the derived DSM **(b)**. Areas in red show very homogeneous snow surfaces either in cast shadow or nearly saturated areas. Areas marked in green are areas with better contrast at the snow surface due to tracks of animals or wind features.

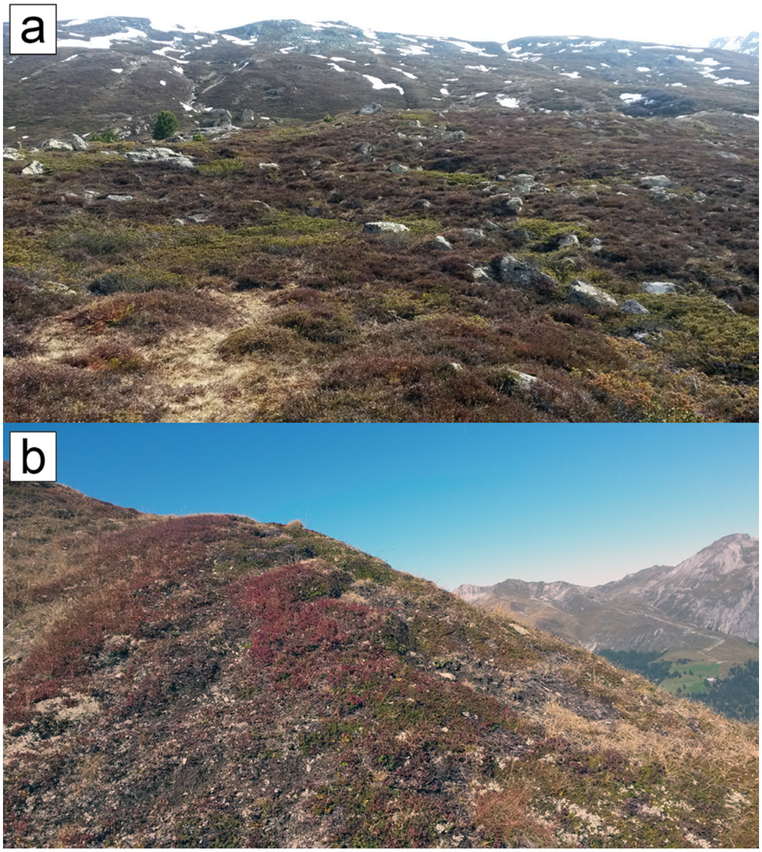

Figure 10. (a) Photograph of the bushes that rise up to 0.50 m above ground and patches of low grass at the test site Tschuggen. **(b)** Photograph of the shallow vegetation at the test site Brämabühl with maximum elevation of approximately 0.15 m.