Response to Reviewer 1 regarding: “Accuracy of snow depth estimation in mountain and prairie environments by an unmanned aerial vehicle”

By: Phillip Harder, Michael Schirmer, John Pomeroy, and Warren Helgason

We thank the reviewer for their detailed comments and the points that they raise. Our response will address comments each paragraph at time. Our responses are provided in red text.

Regarding General Comments Paragraph 1:
“More information, context, and discussion regarding the UAV system would help frame the results and conclusions presented in the study. The world of UAVs and their payloads is broad and quickly expanding. Given the diversity of aircraft, cameras, and processing techniques available, the authors should refrain from representing the results from one UAV system (theirs) as indicative of UAV / SfM snow estimation techniques as a whole. Quantitative results may be particular to the UAV system of choice. More discussion of how the choice of aircraft, payload, and processing software may have influenced results is needed.”

We agree that articulating our results more clearly in terms of the platform that we use (fixed wing Ebee RTK) will help us to frame our results in the context of recent work that have used multirotor platforms and differentiate more clearly the results that come from unmanned and manned platforms. The revised manuscript now reflects this context more clearly. More information is also included on the UAV platform and camera.

Regarding General Comments Paragraph 2:
“For example, the Sensefly Ebee Real Time Kinematic aircraft was shown to be sensitive to wind speeds greater than 6 ms-1. While this conclusion may be useful to future surveyors (i.e. it may not be worth their time to collect data on windy days), other platforms, such as rotary aircraft or even delta wings with more sophisticated autopilots, may be able to compensate and collect consistent data at higher wind speeds.”

A minor edit has been made to the wind sensitivity value. Initially a wind speed greater than 6 m s^{-1} was reported to lead to an increase in DSM errors. Re-examination shows that any differences in DSM error with respect to wind speed were not larger for wind speeds up to 10 m s^{-1} and this value is now used in the paper. This value is obviously platform specific.

”Do the authors recommend future surveys use rotary platforms?”

It has been suggested that multirotor UAV’s may be more stable and return better data products in windy conditions (Bühler, et al., 2016). However, there have not been any direct comparison studies that the authors are aware of that validate such assertions. A general statement regarding the use of fixed wing vs. multirotor is challenged by the broad range of UAV designs and capabilities on the market. We see that the only clear benefit of using a multirotor platform is that larger, heavier, potentially more sophisticated, sensors can be carried (which may improve DSM accuracy as our camera's exposure settings were found to generate erroneous points) and landing accuracy is higher. Disadvantages of multirotor UAVs are that flight speeds and areal coverage are more limited than for fixed wing UAVs. We now note in the manuscript that the Ebee RTK returns data at resolutions that are more than sufficient for our purposes (3cm pixel^{-1}), can cover much larger areas and has a higher wind resistance (>14 m/s) than many multirotors – this seems to be a clear overall advantage. Landing accuracy (+/- 5 m) was also sufficient to locate a landing location in the complex topography of the alpine site. The more important issue relative to any comparison between platform types is that all UAVs will have limited flight times and results will be compromised if conditions are windy. A direct comparison between fixed wing and multirotor platforms is necessary to determine exactly how snow depth errors of various platforms may respond to variations in wind speed and lighting conditions. Until then, based on this experience and results of other recent studies (Vander Jagt et al., 2015; Bühler et al., 2016; De Michele et al., 2016), the sufficient image quality, reasonably good high-wind stability, suitable launching and landing procedures for alpine and prairie environments that are noted in the revised manuscript, in conjunction with the clear advantages in fixed wing range, may make fixed wing platforms preferable to the multi-rotor UAVs that have been described in the snow literature to date.

"Or does the decreased flight range / endurance of rotary aircraft compared to fixed wings outweigh the increased stability?"

This is platform specific but comparing this experience and results of other recent studies (Vander Jagt et al., 2015; Bühler et al., 2016; De Michele et al., 2016) would suggest that if the reported errors are similar than the increased range/ endurance of fixed wing platforms hold an advantage. That being said one cannot say anything with certainty without a direct side-by-side comparison. The manuscript has been amended with this discussion as noted above.

"How much of an operational concern is wind sensitivity, given that snow precipitation events and wind events frequently coincide?"

The reviewer does raise the concern that snow precipitation and wind events do sometimes coincide but those events should not be of concern as any UAV should not be flying in a snow event and certainly not in a blowing snow storm because limited visible range (Pomeroy and Male, 1988) would make such operations illegal. Regulatory constraints (in Canada and other regions) restrict operations to visual line of sight, which is significantly hampered by snow in the atmosphere. Practically, airborne snow would significantly obscure surface features as seen from the UAV, reducing its ability to resolve the surface with SfM – there is no point in flying.

The most important consideration when planning to map snow depth with any UAV should be whether the anticipated signal to noise ratio will allow for direct estimates of snow depth or snow depth change. A discussion of platform type and its role in data quality that reflects these points is now in the revised manuscript.

Regarding General Comments Paragraph 3:
"A similar discussion of the camera payload would be useful to readers as well. What is the specific model of the Canon IXUS used in this study? A quick Google search yields at least a dozen different models. What are the specifications of the camera? In particular, what is the bit depth? The point about the camera automatically adjusting exposure based on center-weighted values and overexposing some scenes, causing erroneous points, is important. More discussion of this type is useful – for example, that those planning a UAV snow survey should avoid cameras with automatic light metering. Also, the authors mention their system is not equipped with a stabilizing gimbal, which clearly increased wind sensitivity and decreased vertical accuracy. A 3-axis gimbal capable of maintaining an ideal camera orientation is a common feature of many consumer or "prosumer" level UAVs. A gimbal would certainly increase the quality of the SfM inputs, and therefore perhaps the snow depth resolution. Readers interested in snow, but perhaps UAV/SfM novices, would benefit from a more detailed discussion of the camera system used in the study."

We concur that more details on the camera system would be beneficial. The camera a Canon PowerShot ELPH 110 HS, (which is the same as a Canon IXUS 125 HS) is used to capture red, green and blue band imagery and is modified to be triggered by the autopilot. Exposure settings are automatically adjusted based on a centre-weighted light metering and results may be improved in the future if one could manually adjust exposure settings (not possible with Canon ELPH). Most small fixed wing UAV's do not employ a gimbal due to the space and weight requirements for such arrangements and in the case of the Ebee RTK the camera is fixed in the UAV body. To stabilize the camera when taking photos the UAV cuts power to the motor to minimize vibrations and levels the entire UAV resulting in consistent nadir image orientation. The camera has a 16.1 Mp 1/2.3-inch CMOS sensor and stores images as JPEGs, resulting in images with 8-bit depth for the three color channels. These details are now in the revised manuscript and addressed in the discussion of errors.

Regarding General Comments Paragraph 5:
"Whether or not the erroneous points caused by overexposure are included in the authors' results is unclear upon first reading. For example, section 3.1 (256 - 257) reads "These results exclude areas affected by erroneous points, as described in section 3.3.2, which was small compared to the total snow-covered area." Which results are the authors referencing? Are the authors speaking generally about every single treatment? Or just the alpine-bare? For example, the authors should consider replacing "These results" with "The alpine-bare results" or "All results." In general, an instance of the word "this" or "these" which lacks a referent can be confusing to the reader because they are unsure as to what precisely the writer is referring. After reading section 3.1 it seems the authors did not include the erroneous points for some or all of the results - but upon referencing section 3.3.2 (322 - 324) the reader finds conflicting information: "Erroneous points could be eliminated with the removal of overexposed images. However, reducing the number of images in such a large amount caused a larger bias and gaps in the point cloud, which made this method inappropriate." Are the overexposed erroneous points included in the results or not? If the erroneous points are included, specify which results are impacted."

We appreciate the reviewer's identification of a confusing discussion on the identification and removal (or not) of erroneous points. This discussion has been simplified and limited to section 3.3.2. Some of the erroneous points encountered in early processing, only on alpine snow, coincide with snow surface measurement locations. On certain days, these errors limited the number of useful surface measurements. Incidentally, the erroneous points are located several metres above the surrounding surface, and thus are obvious and simple to exclude and so it does not make sense to include these in the error statistics.

The areas removed for each flight (as a percentage of the total snow covered area (SCA)) varied between 2% at the beginning of melt when the surface was predominantly snow-covered and 22% near the end of melt when a small number of snow patches persisted. The values of the removed SCA are now noted in the revised manuscript. The point of this discussion was to note how we approached the errors in the hope of helping others who may encounter this issue in the future.

Regarding General Comments Paragraph 6:
"Although the literature is sparse regarding SfM estimates of snow, the authors must be wary of comparing results derived from much different methods. For example, in the discussion section (286 - 292) the results are contrasted against the findings of Nolan et al. 2015, despite their methods using a manned aircraft. Similarly, Buhler et al. 2015 is a reference to a manned aircraft experiment. Given the topic sentence of this section begins "Differencing of *UAV* derived DSMs…" (emphasis mine) some readers may find the contrast of the authors' results with that of a manned aircraft campaign misleading. Also, the 30 cm mean error reported by Nolan et al. is a geolocation error rather than a snow depth error. Snow depth errors were reported as 10 cm, and rigorously documented. Mean snow depths are not reported by Nolan et al. and thus as readers we cannot calculate or assess the SNR of his results, but it does seem like this study is suggesting a higher snow depth threshold for measurements than Nolan et al. That needs to be addressed."

We agree it is important to differentiate that the imagery in this study was collected with a small fixed wing UAV rather than a multirotor or manned aircraft. The main difference between these studies is the collection platform, as application of SfM is fundamentally the same. Different processing software: Agisoft versus Pix4D Mapper versus Postflight Terra (and even between versions of Postflight Terra as we noticed) will give different results but the SfM principles are all the same. The differences in platform will lead to differences in the accuracy of image geotags and orientation, image resolution, bit depth and image overlaps. Regardless, very similar errors are being reported from the many recent studies applying SfM to snow despite the range of platforms and software being employed- this suggests to us that the greatest sources of uncertainty is the SfM procedure, followed by the differences in platform characteristics. The revised manuscript differentiates more clearly between the sources of uncertainty and the platforms used in the referenced studies. The 30cm mean error that we attribute to snow depth error from Nolan et al. (2015) was an error and are grateful that the reviewer brought it to our attention. It is corrected in the revised manuscript.

Regarding Technical Corrections:
Both errors were typos, we thank the reviewer for noticing them, and they are corrected in the revised manuscript.

Regarding Overall recommendation:
"I recommend the authors make revisions to the paper based on the comments above. In general, the authors need to discuss the results appropriately with respect to the referenced work and use more precise language. Also, given the limited scope of this study, readers will prefer a considerably shorter paper. Striving for concision may improve the clarity of the paper as well. The paper could easily be shortened by up about 30%."

We thank the reviewer for these detailed comments. More precise language will be implemented in the revised manuscript and we will adjust how we reference similar studies to more appropriately reflect their results and the platforms they used in contrast to this study. Efforts were made to be more concise and the revised manuscript is shorter than before and includes recommended details on the UAV platform, camera and more explicit discussion of this work with respect to platform type.