The Cryosphere
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Title: Advances in mapping sub-canopy snow depth with unmanned aerial vehicles using
structure from motion and lidar techniques
Authors: Phillip Harder, John W. Pomeroy, and Warren D. Helgason
Paper Summary:
The authors show a comprehensive comparison between snow depth derived from UAV structure from motion and UAV lidar. They compare both datasets in forested areas, shrub areas, and in open/smoother terrain to manual snow depth measurements that are geolocated with GNSS systems. The authors show that UAV lidar can provide information beneath the canopy. This allows the user to look at snow depth variability and snow-vegetation processes with lidar. The authors clearly show issues with UAV SfM. The authors also nicely show a cost comparison stating that lidar is more accurate but costs ~15,000 dollars per additional cm of accuracy. The paper is well written and it discusses many caveats and issues that remain with lidar. The paper is a nice demonstration of the accuracy of UAV lidar, its utility, and remaining limitations.
The authors do not just evaluate the two techniques. The authors show how lidar can capture fine scale variability, such as tree wells, and detect fine scale processes with prairies. This shows originality and significance. I recommend the paper be published pending minor revisions.

General/Major Comments:
No major comments. Mostly, nit-picky comments. Enjoyed the paper, particularly Figure 7 and Figure 10 and their ability to capture tree wells and their changes throughout time.

Thank you for the detailed review. The edits you suggest will make this a much stronger contribution- see the specific responses in red below.

Specific Comments:
Title sounds like a review paper. Perhaps consider something like, UAV lidar improves observations of sub-canopy snow depth variability over UAV SfM.

Good point- this is definitely not supposed to be a review paper. Changed to “Improving sub-canopy snow depth mapping with unmanned aerial vehicles: lidar versus structure from motion techniques “

Line 7: I would disagree that techniques are lacking. You might say something related to that they don’t always exist; satellite remote sensing is difficult. Airborne lidar captures this. So does TLS. This has been shown.

Agreed- changed to “Vegetation has a tremendous influence on snow processes and snowpack dynamics yet remote sensing techniques to resolve the spatial variability of sub-canopy snow depth are not always available and are difficult from space-based platforms”

Line 26: Traditional remote sensing methods is vague. What's traditional to you might to be traditional to someone else.
Traditional = satellite in my mind. Has been changed. "Unfortunately, satellite remote sensing methods…"

Line 35: I would just say test processes
Changed

Line 38: I don't think Painter et al. 2016 initialized or validated a model. Andrew Hedricks recent WRR paper (Hedrick et al., 2018) would be better suited, which uses ASO data to update iSnobal (reinitialize).
Agreed and have changed reference.

Line 66: Leading to variably, I think you mean variability
Corrected

Line 70: It would be great to reference (Currier et al., 2019) here. Table 1 in their paper reviews this and they provide their own evaluation metrics of ALS in a forest and open area. I would also reference (Mazzotti et al., 2019). They showed a comparison of lidar in Switzerland to snow depth transects in forested areas as well.
Have added these references.

Line 75: TLS was used in the forest in (Currier et al., 2019). Yes, the TLS did not go all the way into the entire forest but from an evaluation perspective of airbone lidar or SfM there's little difference from being 300 meters in a forest as long as there are consistent trees overhead that would inhibit returns from the laser. Also, their paper did not explicitly show that TLS couldn't be used further in the forest, it just gets more complicated.
We are seeking a tool that can measure snow-depth below forest canopies to further process understandings at the landscape scale rather than simply evaluating differences in observational technique. TLS will work on forest edges but will always be at a disadvantage further into forests versus mobile airborne platforms due to rapid decrease in point cloud density with distance from sensor, analogous to the lambert cosine law, and attenuation of laser penetration though canopy not to mention with slope aspect/slope/curvature/viewshed constraints. Forest edges, including several 10s of m within the forest canopy from the edge have distinctive snow accumulation and ablation energetics (Pomeroy and Gray, 1995; Musselman et al., 2015; Musselman and Pomeroy, 2016). TLS success is always site context/geometry specific while UAV-lidar will not be. Changed to:
"However, TLS has important limitations to furthering landscape scale understanding of snow processes in forested areas as it is limited by the site specific viewshed and viewing geometry (Deems et al., 2013) and occlusion by forest canopies and low vegetation which decreases point cloud density away from forest edges (Currier et al., 2019). It remains an excellent technique for detailed examination of the forest edge snow environment."

Line 90: Could add that (Zheng et al., 2016) lidar to understand vegetation processes effect on snow. They particularly note bias that might occur due to tree wells. (Currier & Lundquist, 2018) used lidar to understand the snow-vegetation interactions in multiple climates. (Mazzotti et al., 2019) also used airborne lidar data to improve the understanding of snow depth related to the forest in Colorado and Switzerland.
Have added these references.

Line 190: I would mention here that the code is provided on your github page. Great job with providing this.
Have added a reference to github at start of data processing section.

Line 205: Trees typically are taller than 50 cm. Most people consider a tree to be at least 2 m tall. Why did you choose 50 cm? This is inconsistent with what the caption shows in Figure 4.
This was a typo and has been corrected. Classes for vegetation height bins are open <0.5m, shrub 0.5 – 2m, and tree >2m.

Line 230: What is estimated and what is observed? I'd say UAV-derived Snow Depth and Snow Depth Probe Manual Observations, or something more specific.
Caption text for Figure 5 has been update to be clearer on what is observed and what is estimated.

Line 235: Yes, the reported error metrics are inflated when moving into the forest. It'd be worthwhile mentioning that the sample size is much less.
Have added a sentence to express this.
"The sample size of snow depth probe observations is smaller for vegetation sites than open sites has implications for error metrics –outliers will have greater weight."

Some lidar points do great. In the methods the GNSS mentions a ±2.5 cm accuracy, how was that determined. Is it possible that this is inflated when in the forest? If not, mention that. Are these errors from how the point cloud was processed and points were classified? Is ±2.5 cm true for both horizontal and vertical accuracy?
The accuracy is reported by the Leica GS16 for each point at time of observation. It is computed from signal quality on the controller as the 3D uncertainty between the base and rover. Only points in the forest that were able to resolve the RTK solution were collected – there is no decrease in accuracy for the forest/non forest data analyzed. Have added the following to section 2.2.3 in methods: ". The 3D uncertainty of the relative position between the base and rover was computed in real-time to be < ±2.5cm accounting for errors in signal strength, satellite coverage, and instrument precision. RTK signal quality can degrade in forests but only points with fixed RTK solutions were used in this analysis so all survey points are of equal quality irrespective of vegetation cover."

Line 238: I'd start a new paragraph when introducing the error metrics with SfM.
Separated

Line 245: The authors should be using Digital Terrain Models instead of Digital Surface Models throughout.
I agree that DSM may not be appropriate here as its definition implies that it is the top of the surface whether that be the soil surface in open areas or the top of the canopy in forested areas. A DEM is closer to our meaning in that it is a bare-surface raster grid, with trees and vegetation excluded, referenced to a vertical datum. A DTM on the other hand has various definitions, some of which are incompatible with what we are describing in this paper:

1) DEM can be synonymous with DTM in some countries https://gisgeography.com/dem-dsm-dtm-differences/
2) In the US and other countries, a DTM is not a DEM, but is a vector data set composed of regularly spaced points and natural features such as ridges and breaklines. A DTM augments a DEM by including linear features of the bare-earth terrain. https://gisgeography.com/dem-dsm-dtm-differences/
3) DTM: bare-earth representation with irregular spaces between points (non-raster). Behrendt, R. Introduction to LiDAR and forestry, part 1: a powerful new 3D tool for resource managers. The Forestry Source, p. 14-15, set. 2012.

DTM is an acronym with various definitions that may complicate its application here as we are considering both bare ground and snow surfaces beneath a forest canopy. We feel that it is more appropriate to call these “snow DEM” and “ground DEM” as I am filtering out vegetation points and focusing on the extracted “bare surface” points. Deems et al. 2013 uses DEM to describe snow and bare ground surfaces.

Figure 6: Cool analysis. I would consider adding a black dashed line for 2.5 cm. This plot supports the results of Currier et al. 2019, that the airborne lidar is more likely to penetrate the shrubs than the TLS observations. What’s the scientific name for the shrubs found at these locations?

Horizontal black line added at 2.5 cm as a reference in Figure 6. There are many shrub or similar low vegetation species at these locations. The Prairie sites have a lot of tall prairie grasses and reeds in the wetland areas along with willow and dogwood shrubs and poplar trees. In the cropland around it will be crop residues/standing stubble of wheat or barley. In the Fortress mountain site, shrubs are primarily willow but there are others too. The site descriptions have been updated to reflect these vegetation details.

Figures: I would change the easting northing to the total number of meters within the domain, or start at 0 and show ticks from 0 m. I don’t know the projection information, and if I did the numbers aren’t that meaningful. If the location is important, please provide the UTM zone. But still it’s a bit annoying to do the subtraction each time to get a sense of scale. I would just make it easier for the readers, if possible. Otherwise the figures are great.

Have changed all the figures to have 0,0 UTM origins consistent to each scene.

Line 317: This seems like an appropriate time to re-mention UAV lidars ability to capture tree wells.
Have re-mentioned this here.

Line 321: Confusing sentence. Deems reported errors in the forest larger than 14 cm? Why is 14 cm mentioned. Figure 5 reports RMSE of 0.15 and 0.16. Also, in the previous sentence. Studies have masked out the forest? Studies have looked at airborne lidar accuracy in the forest.
These results report error metrics for forest situation that are comparable to airborne lidar for open areas. Some lidar snow depth errors in the forest are comparable to metrics reported here but it's always hard to have apples- to apples comparisons as "forest" is not a uniform landscape class in terms of structure/density and species with respect to how lidar interacts with it. The advantage of UAV-lidar is that we can get a much broader range in scan angle so we can improve probability of reaching surface points below the tree crown from "oblique" angles. Have changed text to be:

"This RMSE is comparable to previous efforts with UAV or airborne-SfM and airborne-lidar that have been focussed on mapping the snow depth of open snow surfaces. Applications of airborne-lidar to forested areas report similar errors (Currier et al., 2019; Mazzotti et al., 2019) but the higher flight altitude of airborne platforms and their near nadir perspective limit point densities near tree centres that are necessary to capture tree wells."

Line 355: Really cool figure and analysis
Thanks!

Line 375: Green polygons look cyan when zoomed out, might choose a different color. Furthermore, the near infrared data seemingly comes out of nowhere – maybe provide some more context within the section for it and why it needs to be mentioned. Provide a citation for NIR serving as a proxy for albedo.

I have removed the NIR figure and discussion of its data as it is beyond the scope of the paper and needlessly complicates the story.

Line 435: "The accuracy and resolution demands mean that bare surface classification techniques suitable for airborne platforms that efficiently resolve topography and hydrography at watershed scales from last returns will be unsuitable for resolving the snow depth around a particular shrub from a dense point cloud for example" The paper did not show that using the last returns was unsuitable. The classification technique used something similar to last returns. Previous studies have showed using the last returns resulted in a generally unbiased snow depth estimate, and provided a reasonable approximation of the variability. I am not sure what this sentence is attempting to say.

A long winded way to say that where there are dense shrubs the last returns will not necessarily be the snow or ground surface and therefore last-return methods will not be appropriate. This is clarified as "Where there are dense shrubs, the last returns will not necessarily be the snow or ground surface and therefore last-return methods common to airborne applications will not be appropriate"

Line 465: A discussion referencing the difficulties with modeling in Mark Raleigh's paper seems appropriate and a better citation then Tom Painters 2016 paper. Furthermore, when mentioning snow pack density variability, mentioning Karl Wetlaufer's paper seems appropriate (Raleigh & Small, 2017; Wetlaufer et al., 2016).

These are much more appropriate references- thanks.

Line 479: "The UAV-lidar metrics consistently exceed the UAV-SfM metrics and are better than previously reported results in the airborne-lidar and UAV-SfM literature." This isn't true. Metrics are similar but not better than. Please note line 69.
Have rewritten this sentence. To be "The UAV-lidar performance consistently exceeded the UAV-SfM performance and was better than previously reported results in the airborne-lidar and UAV-SfM literature"

References Currier, W. R., & Lundquist, J. D. (2018). Snow Depth Variability at the Forest Edge in Multiple Climates in the Western United States. *Water Resources Research, 54,* 1–18. https://doi.org/10.1029/2018WR022553
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