The Cryosphere Discuss.,
https://doi.org/10.5194/tc-2019-284-RC2, 2020

The Cryosphere
Discussions

Interactive comment on "Advances in mapping sub-canopy snow depth with unmanned aerial vehicles using structure from motion and lidar techniques" *by* Phillip Harder et al.

Anonymous Referee #2

Received and published: 30 March 2020

Paper Summary:

The authors compare two relatively new methodologies for using UAVs for mapping snow depths in forested and open prairie environments with in situ ground validation GNSS surveys. They present a very thorough analysis involving an impressive collection of data from 19 unique survey dates from two distinct environments over the course of a single winter season. The time and effort taken to plan, collect, and process such a comprehensive dataset cannot be overstated! The results of the comparison on the ability of both the UAV-lidar and UAV-SfM to estimate snow depths are not necessarily new, but to my knowledge, they have not been compared as extensively with both the successes and failures of both methodologies clearly presented. In open environments, the UAV-lidar and UAV-SfM snow depth mapping capabilities are similar, but in vegetated areas, the UAV-lidar methods excel by having the ability to penetrate through vegetation and measure sub-canopy snow depth. However, in densely vegetated, tight canopy environments, even the UAV-lidar mapping method cannot penetrate the canopy and therefore cannot produce reliable snow depth estimates. An added benefit of using the UAV-lidar over UAV-SfM for snow depth mapping is the insensitivity of the lidar to homogeneous surface conditions and variable/poor solar illumination, both of which contribute to substantial errors in UAV-SfM mapping. In-addition, the increased vertical accuracy of the UAV-lidar sensors can be used to better detect patterns in snow distribution and depth previously not obtainable over basin-wide study sites in complex landscapes. The authors do a nice job at presenting their findings in a well-written manner using suitable figures. As an added bonus, the authors also discuss the cost difference between the UAV measuring methodologies, and calculate a metric that assigns a dollar value to each centimeter of improved RMSE between methods. This cost analysis is of interest, but probably has less relevance for the future, as the price for the type of equipment used in this study continues to decrease dramatically year-by-year. I recommend the publication of this paper pending minor revisions addressing the suggested comments and technical edits.

A PDF supplement has also been uploaded that contains all the suggested edits/comments. In the technical edits section, this PDF supplement has all changes highlighted in BOLD.

An example of the suggested changes to Figure 7a has also been uploaded as Figure 1 – Slide 1.JPG. This example figure provides a visualization of the changes being suggested for Figures 7a, 8a, 9a (applies to General Comment at Line 270/295/300).

General Comments:

Line 59 – 'differencing snow-covered (hereafter snow) and snow-free (hereafter ground)…’ Double check terminology throughout paper for consistency. The following different term are used: bare-ground, bare ground, ground, surface, bare surface. Personally – I like the use of the term bare-ground.

Line 59 – ‘Digital Surface Models (DSMs)’ I think you are actually referring to the Digital Terrain Models (DTMs). Change this reference throughout the paper.

Line 134 – ‘flight parameters to maximise mapping efficiency were set to…’ What about limiting the scan angle? The Riegl lidar can scan 360 degrees, what level of off nadir scan angle did you limit the data collection/processing to and why?

Line 135 – ‘100 m flight altitude above the surface…’ Did the mission planning software make use of terrain following mode to ensure consistent flight altitude above ground? If so, what source of terrain information did you use?

Line 148 – I deleted the term differential: differential GNSS corrections (code-based) are significantly less, accurate than RTK/PPK/PPP (carrier phase methods) – I suspect even though the Leica GS16 unit is DGPS capable, you used the more accurate carrier phase correction methods.

Line 150 - suggest removing the term ‘random within the survey areas and’ if the transects were also selected to most efficiently survey the greatest variety of vegetation types.

Line 152 – ‘provided a real-time-kinematic (RTK) survey solution …’ While conducting your manual surveys did you make use of the RTK capabilities – or did you post-process the rover data as indicated at line 153?

Line 152 – ‘accuracy of $< \pm 2.5$cm.’ Can you provide a reference for this?

Line 154 – ‘(https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php)’ Add this website to the references section

Line 154 – ‘absolute base station location.’ How long did you collect your raw GNSS

data for and what were the PPP computed standard deviations for the base station locations? Did you always use the same base station location for every flight?

Line 174 – ‘<2.5 cm.’ Do you mean +/- 2.5 cm as mentioned earlier in the text? Is this value based on the specs of the Leica GS16 GNSS survey equipment or was it based on the PPP online standard deviations? How did you obtain this value?

Line 181 – ‘$< \pm 2.5$ cm’ Same comment as above? Is this value based on the specs of the Leica GS16 GNSS survey equipment or was it based on the PPP online standard deviations? How did you obtain this value?

Line 205 – ‘vegetation height (open <0.1 m, shrub <0.5 m, and trees >0.5 m)…’ These values differ from what is in the Figure 4 caption. Which vegetation height classes did you use, and how did you choose the class heights?

Line 223 – I deleted reference to RTK - In line 55 you indicate the rover survey points were post-processed, therefore I am assuming you used a PPK GNSS solution here?

Line 230 – ‘points extracted from the point clouds or interpolated surfaces…’ This sentence is confusing. It is unclear whether you extracted the UAV snow depth values from the point clouds or the interpolated DSMs? Which one was it?

Line 256 – Figure 6 - Please add to the caption a description of which metrics are visualized by the whiskers of the boxplots.

Line 266 – ‘The noisy UAV-SFM points in the middle of the slope challenge the snow surface extraction even without the presence of vegetation leading to an underestimation of the snow surface.’ Do you have any idea on why the SfM product detected something in the open areas on the slope? Why does it lead to an underestimation of snow in this area? Based on the Figure 7a cross-section it looks like the UAV-SfM red points are equal to or above the green lidar points. Why did the interpolation go so low? Did the interpolation treat missing points as 0 or bare ground values?

Line 270/295/300 – Figure 7-8-9 - Suggest using shaded/transparent colour bars on plot a) to indicate the extent of the tree features. This will help highlight the tree well extent and how the UAV-SfM interpolation result in deeper snow values across these features (I have uploaded an example Figure of 7a. that illustrates what I am trying to describe – Slide 1.JPG). Suggest using a more obvious colour in Figure b) for highlighting the SfM only classes. Suggest trying to match the tone of colours in Figure c) to more closely match that used in Figure b). Making the open areas a little bluer, and again highlighting the SfM only points in a more obvious colour. Figure 7b It sort of looks like the SfM only class occur near the edges of the study area in a just a couple areas. Is this related to steeper scan angles at the edge of the study site, perhaps coupled with steep terrain? Figure 9c) I suggest mentioning in the figure caption that the large dark areas of no lidar points represent the extent of the melt water ponds.

Line 288 – the negative UAV-SfM snow depth estimates discussed here are explained at lines 443-450. Perhaps also providing further explanation here might be helpful.

Line 316 – In the example of 7a, the interpolation resulted in erroneously deep snow depth estimates. This will not always be the case and in some instances can result in underestimations depending on the season, elevation, forest type, etc. Many studies have highlighted the differences in snow depths/characteristics between open/forested sites that will influence these interpolation errors. I think providing some further explanation on the type/magnitude of interpolation errors that may occur when using UAV-SfM techniques would help strengthen your findings/statement here.

Line 318 – 'major improvement on previous attempts.' Can you provide some context on what is considered a major improvement, including references to previous studies/RMSEs?

Line 318 – 'previous efforts. . .' Can you provide some references?

Line 321 – '0.14 m RMSE (Deems et al., 2013).' Can you provide the actual magnitude of errors previously reported for comparison in the Deem et al., 2013? What is the significance of this 0.14 m RMSE?

Line 342 – 'intermittent precipitation totaling approximately 100 mm' How was this determined/measured? What kind of uncertainties are associated with this reported precipitation value. I also want to confirm that you mean 10 cm of snow? This seems low for mountain snow.

Line 350 – 'and development of a tree well in the middle of the transect. The Figure 10b transect demonstrates the lack of wind redistribution in the canopies relative to the Figure 10c transect on the ridgeline.' It is unclear where the development of the tree well is highlighted/visible in Figure 10b. It also unclear how Figure 10b demonstrates the lack of wind re-distribution in the canopies. Please provide more detail here.

Line 366 – 'In contrast UAV-SfM struggled with sensing snow depths in the short shrubs on the edges of wetlands.' This sentence contradicts the results displayed in Figure 5, which illustrated that the UAV-SfM had lower RMSE in the shrub class compared to the UAV-lidar. It also does not support the discussion starting at Line 286 and expanded at Lines 443-450, which discusses the challenges that BOTH lidar and SfM face in trying to measure below the canopy in dense shrub vegetation.

Line 467 – 'Observational approaches are also a challenge as typical in situ measurements are destructive, limited in extent, and often too limited to develop robust relationships of depth versus density at the small scales needed (Kinar and Pomeroy, 2015a; Pomeroy and Gray, 1995).' The methods developed by Proksch et al., 2015 do provide a method for measuring snow density at a much smaller scale applicable for these process-scale studies. The Proksch et al., 2015 methods have been recently rigorously applied to a set of snow on sea ice measurements by King et al., 2020, highlighting the ability to document the local-scale variations in snow density relatively quickly over larger spatial extents.

Proksch, M., Löwe, H. and Schneebeli, M., 2015. Density, specific surface area, and correlation length of snow measured by highâĂŘresolution penetrometry. Journal of Geophysical Research: Earth Surface, 120(2), pp.346-362.

King, J., Howell, S., Brady, M., Toose, P., Derksen, C., Haas, C., and Beckers, J.: Local-scale variability of snow density on Arctic sea ice, The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-305, in review, 2020.

Line 474 – 'necessary spatial scales' – Please be more specific on what scales you are referring to.

Technical Comments:

Line 13 – suggest changing to 'measure returns from a wide range of scan angles, increasing the likelihood of successfully. . .'

Line 51 – suggest changing to 'are valuable automated data sources, but are spatially limited in extent and can often suffer from location/elevation bias. . .'

Line 53 – suggest changing to 'and so may not be suitable for snow hydrology calculations or model validations in forested regions even though they are often. . .'

Line 60 – spelling correction: quality

Line 62 – suggest changing to 'pulse can be observed with returns possible from within the canopy and from the sub-canopy ground surface. In contrast UAV-SfM. . .'

Line 64 – spelling correction: variability

Line 80 – spelling correction: focused

Line 87 – punctuation: 'In dense forests, vegetation. . .'

Line 90 – suggest changing to 'increase in snow accumulation over aerodynamically rough surfaces or in sheltered areas where the wind speeds decrease and snow is deposited – this includes forest edges. . .'

Line 98 – suggest changing to 'varies across complex vegetated landscapes. . .'

Line 105 – suggest changing to 'ability of the UAV-lidar and UAV-SfM techniques for measuring snow depth in open

Line 106 - (50.833 N, 115.220 W)

Line 108 – spelling correction: focused

Line 109 – suggest changing to '(Figure 1a – background center). . .'

Line 111 – suggest changing to 'alpine ski resort in the 1960's, but is currently a limited-use. . .'

Line 114 – suggest changing to 'Canadian Prairies were examined in this study.'

Line 117 – correction: remove negative sign if using 'W' to indicate west (51.941 N, 106.379 W) & (52.694 N, 106.461 W)

Line 125 – Figure 1 caption: suggest changing to 'Figure 1: a) Fortress Mountain Snow Observatory in Kananaskis, Alberta Canada, b) Rosthern and c) Clavet prairie study locations in Saskatchewan Canada. Data collection was on Fortress Ridge (background center) an area of high topographic variability and a mix of dense forests and clearings. The Clavet photo highlights the transition zone between the open upland terrain and the lower elevation vegetated wetland. The Rosthern scene highlights the low vertical relief of upland areas and isolated woodlands amongst cultivated fields.

Line 155 – suggest changing to 'GS16 rover points to correct for the PPP updated base station locations were completed using the Leica Infinity software. . .'

Line 158 – 'suggest changing to 'To assess the accuracy of the UAV snow depth measuring methods, as well as provide insight into the seasonally evolving snow depth/distribution, a total of 19 flight/manual surveys were conducted between all three study sites between September 2018 to April 2019. These are summarised by date, surveyed surface, UAV data collected, and corresponding number of manually surveyed surface elevation points in Table 1.

Line 165 – suggest changing to 'difference between a bare ground DSM and a snow surface DSM.'

Line 176 – suggest changing to ‘Finally, overlapping scan data from adjacent flight lines are used to optimise the IMU trajectory, to align the scan lines and reduce the noise of the final point cloud within the RiPrecision tool. This final step in noise reduction can improve the final product because the 1.5 cm laser data precision is greater than the post processed IMU trajectory accuracy. (I used the 15mm stated precision of the Reigl sensor presented earlier in the text to get the 1.5cm value here)

Line 193 – suggest changing to ‘For the bare-ground lidar scans, the height of vegetation. . .’

Line 207 – spelling correction: include

Line 214 – suggest changing to ‘2.3.6 Point Cloud Density’

Line 221 – suggest changing to ‘3.1 Accuracy of UAV-lidar versus UAV-SfM snow depth estimates

Line 231 – suggest changing to ‘Plots are segmented for points extracted from the point clouds or interpolated surfaces within each vegetation class (rows), sites (columns) and observation method (colours).’ – See general comments above about clearing up the confusion concerning which product the points were extract from.

Line 232 – suggest changing to ‘The influence of vegetation on estimating snow depths from UAVs can be directly assessed by. . .’

Line 234 – suggest changing to ‘Open Prairie and open Fortress RMSE values are similar (0.09 m and 0.1 m RMSE respectively). . .’

Line 235 – suggest changing to ‘equally successful at penetrating the open leaf-off deciduous tree canopy at the prairie sites as the closed needleleaf canopy at the Fortress site based on the similar RMSE values within each site’s tree vegetation class.’

Line 238 – suggest changing to ‘The Open vegetation has a large RMSE range between sites (0.1 m in Prairie and 0.3 m in Fortress respectively) while vegetation class

RMSEs range from. . .’

Line 240 – suggest changing to ‘UAV-lidar in the prairie Shrub case, the difference between these techniques is only 0.04 m, which is within the +/- 2.5 cm observational uncertainty of the GNSS survey equipment used in this project.

Line 247 - suggest changing to ‘manual GNSS surveys using boxplots (Figure 6). The boxplots in Figure 6 illustrate that the UAV-SfM snow surface elevations. . .’

Line 257 – suggest changing to ‘3.2 Point cloud density’

Line 263 – suggest changing to ‘could not reliably return surface points with a density > 1 pt 0.25 m-2 whilst. . .’

Line 263 – punctuation: ‘At Fortress, UAV-lidar. . .’

Line 265 – suggest changing to ‘lack of UAV-SfM sub-canopy points identified within the treed vegetation class results in an interpolated snow surface that is erroneously deep under trees, completely missing the detection of the reduced snow depths which are clearly detected (green line) around the base of the trees by the UAV-lidar.’

Line 274 – suggest changing to ‘c) with the same overlain transparent point type classification colour scheme as shown in b).’

Line 276 – suggest changing to ‘The predominantly open nature of the Prairie sites demonstrates a minimal difference in point density between UAV-lidar and UAV SfM measurement techniques. The average extent of the study domain covered with a point density of > 1 pt 0.25 m2 for 5 coincident flights at the Prairie sites was computed, resulting in the mean coverage of 92% versus 83% of the study area for the UAV-lidar and UAV-SfM respectively.

Line 281 – suggest changing to ‘These gaps in the UAV-SfM point clouds are interpolated and therefore will represent. . .’

Line 287 – suggest changing to ‘both lidar pulses and SfM solutions interpret the vegetation surface as the top of the bare-ground or snow surface and therefore little difference exists between these two DSMs during all measurement periods. An additional challenge of using the UAV-SfM techniques is that large gaps in points appear beneath the tall wetland edge vegetation due to the inability to penetrate the sub-canopy, as visualized in the cross-sections of Figure 8a and 9a, where the estimated UAV-SfM snow surface is below the UAV-lidar ground surface.'

Line 316 – suggest changing to 'Sub-canopy snow depth mapping with UAV-SfM therefore becomes an exercise in interpolating snow depth values observed in open areas without vegetation to areas with dense vegetation, rather than sensing the actual snow depth under the canopy.'

Line 322 – suggest changing to '4.2 Bare-ground point cloud density is critical'

Line 323 – suggest changing to 'The increased point density of UAV-lidar. . .'

Line 325 – suggest changing to 'The point cloud cross-sections illustrated in Figure 7 emphasize these findings, highlighting the wider gaps in the UAV-SfM point cloud beneath individual trees that require interpolation over longer distances resulting in greater potential for error.' (The lidar data also requires interpolation)

Line 332 – suggest changing to 'In contrast, mountainous regions have much more complex topography. . .'

Line 337 – suggest changing to 'continuous bare-ground point cloud coverage.'

Line 338 – suggest difference word choice for: foreshadow

Line 340 – suggest changing to 'Differences between open and forest snow cover processes can be explored by examining the difference in snow depth. . .'

Line 342 – suggesting changing to 'UAV-lidar measured change in snow depth visualizes. . .'

Line 343 – suggest deleting line: 'The upper, open terrain clearly demonstrates the

influence of blowing snow redistribution' because this sentence is ambiguous.

Line 343 – suggest changing to 'In the Figure 10c transect cross-section there was accumulation of up to 2 m over the September-April time period on lee slopes, whilst the upper windswept portions of the ridge demonstrate snow erosion between February and April."

Line 346 – suggest changing to 'The dynamics and extents of blowing snow sources (grey/red) and sinks (blue) are clearly visualized in 10a, which closely match the findings of Schirmer and Pomeroy (2019) using SfM for this same study region.

Line 347 – suggest deleting line: 'Considering the forest slope brings out features that UAV-SfM cannot observe.' Because this sentence appears as a fragment

Line 349 – suggest changing to 'there is a general decline in snow depth from February to April (due to melt on the south facing slope).'

Line 360 – suggest changing to 'wind-blown snow from open upwind sources and are typically associated with. . .'

Line 366 – suggest changing to 'Areas that the UAV-lidar was able to measure correspond to areas. . .'

Line 390 – suggest changing to 'This gradient in dust and albedo is likely associated with the increases in snowmelt rates observed downwind of the grid road.'

Line 405 – suggest changing to 'UAV-lidar, relative to UAV-SfM, provides the ability to measure snow depth below vegetation. . .'

Line 408 – suggest changing to 'and cheaper equipment, subscriptions to virtual reference station networks if available in the study area (requires only a rover and not a base station), or equipment rentals are all viable alternatives to lower costs.'

Line 410 – suggest changing to 'The main cost difference between UAV-lidar and UAV-SfM platforms is therefore in terms of the UAV sensor payload.'

Line 412 – suggest changing to ‘like consumer grade UAVs (DJI Phantom 3 < $2,000 CAD), to more expensive options like…’

Line 413 – suggest changing to ‘Current integrated lidar systems suited to UAV snow mapping’

Line 423 – suggest changing to ‘In contrast, most current UAV-lidar configurations need larger platforms that require more cycles of large battery sets to cover similar areas, which represents a logistical challenge in keeping the batteries warm and charged in cold and remote areas.’

Line 428 – suggest changing to ‘Despite the lower initial purchase cost and longer flight endurance, the errors and artefacts that UAV-SfM measuring techniques introduce in sub-canopy snow depth measurements, as detailed in sections 4.3.1 and 4.3.2, suggest that UAV-SfM is not able to directly measure snow depth in densely vegetated environments.’

Line 434 – suggest changing to ‘Precise classification of surface points from snow and ground scans are needed to resolve…’

Line 435 – suggest changing to ‘The accuracy and resolution demands are such that bare-ground surface classification techniques developed for airborne platforms to resolve topography and hydrography at watershed scales from lidar last returns may be unsuitable for resolving snow depths.’

Line 438 – suggest changing to ‘filtering tools and associated parameters to be able to reliably detect the sub-canopy bare-ground surface and achieve desired quality…’

Line 441 – spelling correction: ‘large-scale’

Line 448 – suggest changing to ‘the areas of negative snow are limited to areas where snow depth is relatively shallow in comparison to the deep snow in the wetland edges.’

Line 452 – suggest changing to ‘snow depth estimation in these hydrologically significant snow accumulation areas.’

Line 453 – suggest changing to ‘ground surface, but current sensors with these characteristics may exceed the payload capacities of most UAV platforms. Advances in bare surface classification/filtering software…’

Please also note the supplement to this comment:
https://www.the-cryosphere-discuss.net/tc-2019-284/tc-2019-284-RC2-supplement.pdf

---

Interactive comment on The Cryosphere Discuss., https://doi.org/10.5194/tc-2019-284, 2019.

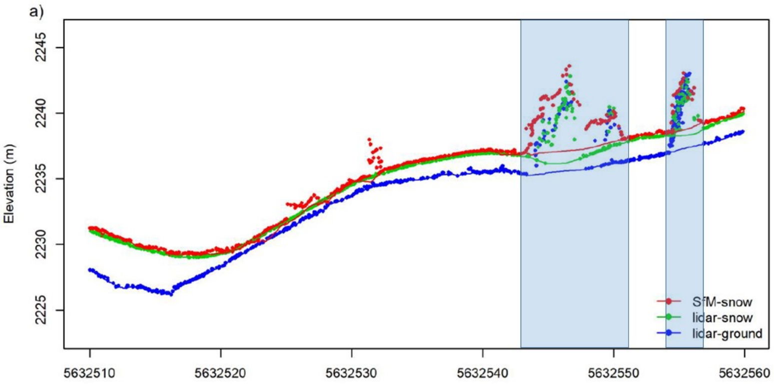

Fig. 1. Example of suggested change to Figure 7a.