Hydrology and Earth System Sciences Discussions

*Hydrol. Earth Syst. Sci. Discuss., referee comment RC1 https://doi.org/10.5194/hess-2021-281-RC1, 2021* 

***Comment on hess-2021-281***

*Anonymous Referee #1*

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*Referee comment on "Mapping snow depth and volume at the alpine watershed scale from aerial imagery using Structure from Motion" by Joachim Meyer et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-281-RC1, 2021*

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*Meyer et al. present an assessment of Structure from Motion (SfM) to map snow depth at basin scale. They do so by presenting two flights, where phtogrammetric images were captured in the context of the Airborne Snow Observaotry (ASO) lidar scans. This allowed authors to compare SfM to lidar scan. Results show that where snow was mapped by both ASO and SfM, the depths compared well, with a mean difference between -0.02 m and 0.03 m, NMAD of 0.22 m, and close snow volume agreement (+/-5%). Limitations were found in vegetated areas, locations with shallow snow, and steep terrains. Overall, ASO mapped a larger snow area relative to SfM, with SfM missing ~14% of total snow volume as a result.*

*I enjoyed reading this manuscript, which focuses on an important topic: measuring high-resolution snapshots of snow depth at watershed scale using remote sensing.*

*Thank you, we appreciate you taking the time to read the manuscript and provide thoughtful feedback. The comments have improved the manuscript, and specifics about how we made updates in the manuscript to address the concerns are provided below (in blue).*

*Comparatively new techniques have emerged over the course of the most recent decades, including lidar, drones, and in fact photogrammetric flights. From this standpoint, the topic covered by this ms is certainly relevant and in line with the scope of HESS. At the same time, the comparatively large body of literature on these techniques (which the authors present in their ms) means that the novelty provided by this specific study is quite unclear. Some novelty points are highlighted at lines 55ff page 3, but they appear incremental to me. Also, the conclusion that SfM may be biased in areas with vegetation or shallow snow is not new. A more effective case should be made to justify publication.*

*Secondly, results by these surveys look a little unconvincing with regard to SfM applicability, to the extent that the main conclusion of this manuscript (capturing large scale snow depth and volume with airborne images and photogrammetry could be an additional viable resource for understanding and monitoring snow water resources in certain environments) may be not supported by results. SfM missed about 14% of total snow, while snow volume was 86% of ASO volume. Fig 5 also shows clear biases in case of shallow snow cover, which overall leads to SfM underestimating snow depth (line 199).*

*From a presentation standpoint, the ms reads a little like a technical report. According to their aims and scope, "HESS encourages and supports fundamental and applied research that advances the understanding of hydrological systems, their role in providing water for ecosystems and society, and the role of the water cycle in the functioning of the Earth system." What are the specific research questions of the study that could justify publication in an international, broad journal? In other words, how could this survey be used to advance understanding of hydrological systems?*

*To address the reviewer's concerns, we updated the abstract and the introduction, explicitly expanding on the value of this study relative to previous work on photogrammetric snow depth retrieval from piloted aircraft. Additionally, we added a section to the conclusions describing how this work is relevant given NASA's recent focus on incubating measurement methods (including photogrammetry) for Surface Topography and Vegetation (SVT), which includes snow depth, a targeted observable in the most recent Decadal Survey.*

*These updates justify the novelty of this study, better highlight where SfM could add value for expanded mapping of snow depth in the mountains, and support the broader relevance of photogrammetric snow depth mapping. The paper still provides the technical description that has interested many readers, supported by the >400 article views and downloads as a preprint, and added broader context and motivation for the work that makes it suitable for publication in HESS.*

*Included below are relevant updates to the text:*

*(Abstract)*

*Time series mapping of snow volume in the mountains at global scales and at resolutions needed for water resource management is an unsolved challenge to date. Snow depth mapping by differencing surface elevations from airborne lidar is a mature measurement approach filling the observation gap operationally in a few regions, primarily in mountain headwaters in the Western United States. The same concept for snow depth retrieval from stereo- or multi-view photogrammetry has been demonstrated, but these previous studies had limited ability to determine the uncertainties of photogrammetric snow depth at the basin scale. For example, assessments used non-coincident or discrete points for reference, masked out vegetation, or compared a subset of the fully snow-covered study domain. Here, using a unique data set with simultaneously collected airborne data, we compare snow depth mapped from multi-view Structure from Motion (SfM) photogrammetry to that mapped by lidar at multiple resolutions over an entire mountain basin (300 km2). After excluding reconstruction errors (negative depths), SfM had lower snow extent (~15%) and snow volume (~14%) compared to lidar. The reconstruction errors were primarily in areas with vegetation, shallow snow (< 1 m), and steep slopes (> 50o). Across the remaining snow extent, snow depths compared well to lidar with similar mean values (< 0.03 m difference) and snow volume (+/- 5%) across output* *resolutions of 1 m, 3 m, and 50 m, and with a normalized median absolute deviation (NMAD) of 0.22 m. Our results indicate that photogrammetry from aerial images can be applied in the mountains but would perform best for deeper snowpacks above tree line.*

*(Introduction)*

*Previous studies have demonstrated photogrammetric snow depth retrievals from piloted aircraft (Bühler et al., 2015; Nolan et al., 2015; Eberhard et al., 2020), but gaps remain for understanding uncertainties at the mountain basin scale. For example, Nolan et al., 2015 had a relatively flat terrain and small study typically not found in watersheds. Bühler et al., 2015 and Eberhard et al., 2021 used larger areas with representative alpine terrain, but only a smaller subset was compared to reference data. Additionally, both of these studies did not record the reference data simultaneously with images used for photogrammetry. This has important implications as the snowpack undergoes constant changes, and depth is unlikely to remain constant. From a methodology perspective, Bühler et al., 2015 also excluded all areas with visible vegetation in the snow scenes and did not analyze the characteristics of negative snow depths in the results. Additionally, the approach was different; the images were from a multispectral line scanner, and the snow depth map was produced in chunks. In contrast, Eberhard et al., 2021 had imagery from an RGB camera and reconstructed the study area as a whole. However, the processing step required manual placement of ground control points (GCP) for the scene to be geo-referenced accurately. The use of GCP makes it challenging to follow this approach in vast, remote, snow-covered areas. Their approach also aligned the snow depth via cubic-convolution resampling and left no understanding of the individual scenes' geo-location accuracy (snow-free and snow-on).*

*This work evaluates the ability of SfM to map snow depth distributions over a watershed with high-resolution RGB imagery captured by a piloted aircraft and its accuracy relative to a simultaneously collected lidar-based retrieval. The comparison is spatially complete, across different output product resolutions, with identical snowpack conditions, sensor viewing geometry, and environmental influences, such as the weather. The same data processing for snow-free and snow-on scenes reduces potential errors that could arise from combining different methods and datasets. The data sets are from an operational snow water resource mapping company, which could readily adapt this presented workflow. Meyer & Skiles (2019) showed that SfM can generate accurate snow surface DEMs from imagery collected from piloted aircraft over bright, freshly fallen snow. The compared snow-on surfaces from SfM and lidar had a relative accuracy of 0.17 m at 1m resolution. Building upon this work, we show in this paper that two SfM DEMs (snow-on and snow-free) can be used to calculate snow depths and corresponding snow volume over a larger alpine watershed (300 km2) across different output resolutions. The broader application of SfM will expand our understanding of the strengths and weaknesses of photogrammetric-based snow depth in the mountains, and ideally support broader use of aerial snow observations in terrain where these observations are suitable.*

*(Methods)*

*For consistency, the SWE calculation used the mean snow density calculated from the ASO SWE product distributed through NSIDC at the 50 m resolution (Painter, 2018c). SWE is a highly desired quantity for water resource forecasting and is commonly expressed in meters. In this study, we aggregated SWE as a sum of all pixels of measured snow depths and showed how depth differences propagate.*

*(Conclusion)*

*We would like to see photogrammetry, including SfM, applied to larger areas and more frequent image acquisition to improve our understanding of this technology at scale. Our results show that it can provide spatially complete data sets with sub-meter accuracy across multiple output resolutions in the mountains and is best applied above the tree line and for deeper snowpack. This capability, possibly as a complement to lidar, can further improve our ability to monitor and understand snow-driven hydrological processes and environments. The importance of monitoring the mountain snow water reservoir is well recognized, with seasonal snow depth and snow water equivalent both being identified as 'targeted observables' in the most recent Earth Science Decadal Survey (National Academies of Sciences, Engineering, and Medicine, 2018). This United States National Academy of Sciences survey guides upcoming scientific missions and goals for earth observations from space. Targeted observables are priority observations that may not yet have mature measurement techniques but could within the next 10+ years. This recognition brings attention to emerging technologies and incubation funding to mature their approaches and application. Surface Topography and Vegetation (STV) is one such incubation effort, which focuses on high-resolution global topography mapping and topography change. Photogrammetry, along with lidar and radar, was specifically targeted as a measurement technology with potential for maturation (Donnellan et al., 2021). Although the focus is on stereo-photogrammetry, for which satellite capability is well established, the potential for spaceborne multi-view photogrammetry is also promising and equally suitable. Comparisons and data like those in this work contribute to the STV effort with methods undergoing active development. Ultimately, the goal is for global satellite-based time-series mapping of snow volume in the mountains and at resolutions needed for water resource management.*

*National Academies of Sciences, Engineering, and Medicine: Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space, The National Academies Press, Washington, DC, 716 pp., https://doi.org/10.17226/24938, 2018.*

*Donnellan, A., D. Harding, P. Lundgren, K. Wessels, A. Gardner, M. Simard, C. Parrish, C. Jones, Y. Lou, J. Stoker, K.J. Ranson, B. Osmanoglu, M. Lavalle, S. Luthcke, S. Saatchi, R. Treuhaft, Observing Earth's Changing Surface Topography and Vegetation Structure: A Framework for the Decade, NASA Surface Topography and Vegetation Incubation Study, 210 pp., 2021*

*I encourage authors to work on the above points, since obtaining snapshots of snow depth at basin scale is indeed a clear and important open issue in snow hydrology. I am looking forward to reading a revised version.*

*SPECIFIC COMMENTS*

*Line 47: various regulations exist at national and international level, which may limit the use of RPAS (e.g., over populated areas). This fact may be worth mentioning here.*

*We added this aspect to the paper.*

*RPAS have additionally limited areal coverage due to battery life, cannot be operated safely outside the line of sight, or face strong regulations in public areas*

*Line 134: why was the 1 m raster down sampled from the 3 m one, instead of being directly derived from the point cloud? What is the associated uncertainty?*

*It is indeed technically possible to export the point clouds from lidar at the higher resolution. However, the ASO workflow involves more steps than gridding the point cloud to produce the distributed snow depth map. This study focuses on the possibilities with SfM compared to the publicly available products at 3 m and 50 m. Downsampling to the higher resolution was done to demonstrate additional capabilities. The section that describes the creation of the 1 m ASO snow depth map has been revised:*

*This iteration resampled the 3 m ASO snow depths, kept the identical bounding box, and used the nearest-neighbor algorithm.*

*Line 196: 3770 m is unclear to me. Do you mean 3770m^3 (likely to small for watershed SWE) or 3770 mm on average?*

*This is the total amount of SWE when adding all the pixel values. We also added a description in the method section that explains why this number is presented as a 'm' value:*

*SWE is the desired quantity for water resource forecasting and is commonly expressed in meters. In this study, we aggregated SWE as a sum of all pixels of measured snow depths and showed how depth differences propagate*

*Line 285: despite being supported by some references, this threshold on 25 m for hydrologic models looks a little arbitrary. Hyper-resolution models are on the rise, also supported by satellite products that now exceed that threshold (e.g., Sentinel-2 images at 20 m).*

*We reworded the sentence to:*

*Inputs for hydrologic models, for instance, currently do not require or have been assessed against image resolutions of less than 25 m (Behrangi et al., 2018; Hedrick et al., 2020; Pflug and Lundquist, 2020)*