MEASURING SNOW DEPTH USING RPAS PHOTOGRAMMETRY IN A SUBALPINE COASTAL REGION OF BRITISH COLUMBIA

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EXTENDED ABSTRACT

Mountain snow in British Columbia is primarily monitored using automated remote weather stations, which measure snow depth (SD), snow water equivalent (SWE), and multiple weather parameters, and a manual snow survey program, with records dating back to the 1930's The network provides excellent information to track change through time and data are effectively used to provide regional forecasts for both flooding and drought, however there is still high uncertainty when scaling these measurements to the watershed level. In addition, there is potential for the current network of stations and snow courses to have more frequent snow free years due to climate change, and gaining a better understanding of how they represent snow that occurs above them is needed. Advances in remote sensing technologies present important opportunities to accurately measure the high degree of spatial variation in SD, and use existing methods (Hill et. al., 2019; Strum et. al., 2010) or develop new approaches to improve estimates of snow density and SWE at finer spatial resolutions. To help address the limitations of relying on discrete, in-situ SD sampling and reduce the uncertainties in overall snowpack measurements, small remotely piloted aircraft systems (RPAS) based structure-from-motion photogrammetry (SFM) has emerged as an effective technology. While they are not capable of measuring areas at the same scale as full-size aircraft or satellites, certain RPAS can be used to capture data across several square kilometres, are much less cost prohibitive and their potential to produce 3D models at high accuracies and very fine spatial resolutions is becoming increasingly well established.

The fundamental approach to calculating SD via remote sensing involves measuring the difference in elevation recorded between snow-off and snow-on surveys. The resulting differenced digital elevation model (dDEM) represents SD across the survey area. With relatively low-cost RPAS, this approach can be applied by using automated flight and photogrammetric image processing software to create digital elevation models (DEMs) which are used to generate dDEMs.

To minimize the systematic error associated with co-registration of the DEMs, real-time kinematic global navigation satellite system (RTK GNSS) equipment is used to survey a network of ground control points (GCPs) within the study area to georeference each dataset. The resulting range of potential absolute geolocation accuracy of the final DEMs can be 2 to 8 times the ground sampling distance (GSD or pixel dimension) of the original images collected during flight (Sanz-Ablanedo et al., 2018). In addition to georeferencing and GSD, numerous survey design, environmental and site-specific factors present challenges in creating optimal SFM derived DEMs. Specific to SFM based SD mapping, two important challenges are at play. First, images of highly homogeneous surfaces, i.e. undisturbed fresh snow, are computationally difficult for SFM image matching algorithms, resulting in noise and missing data, especially when low contrast or over-exposure are difficult to avoid (Bash et al., 2020; Gindraux et al., 2017; Nolan et al., 2015). Second, the presence of vegetation or any object that limits the camera's line of sight to the surface leads to an increased level of uncertainty regarding the true surface elevation (Anders et al.,2019; Fernandes et al., 2018; Vander Jagt et al., 2015).

A common method used to assess the accuracy of modelled SD is through comparison to manual snow probe measurements. Previous studies report root mean square error (RMSE) values of SD measured using RPAS SFM relative to snow probe depths ranging from approximately 6cm to 30cm (Adams et al., 2018; Avanzi et al., 2018; Buhler et al., 2016; Cimoli et al., 2017; De Michele et al., 2016; Eberhard et al., 2021; Goetz & Brenning, 2019; Harder et al., 2016; Redpath et al., 2018; Vander Jagt, et al., 2015). These studies focused mainly on alpine areas, meadows and prairies. When any notable vegetation was present, it contributed to an important source of SD

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error (Avanzi et al., 2018; Buhler et al., 2016; Harder et al., 2016; Redpath et al. 2018). In the case of Vander Jagt et al. (2015), probe measurements that aligned with vegetation were removed altogether. This highlights the need to further investigate the potential accuracies than can be achieved in more densely vegetated areas where deep snowpacks often form. In this study, we evaluate the accuracy of SD measurements derived from RPAS-SFM against manual probing at four sites in a subalpine, coastal region of British Columbia, characterized by considerable shrub and low vegetation cover.

The four sites examined in this study are located just beyond the northern boundary (50.226° -126.353°) of the Mt. Cain Alpine Ski Area, situated in a mountainous region of northern Vancouver Island. Mean annual precipitation is 2512mm, with peak snow depth ranging from 200 to 450cm. Snow generally starts to accumulate in December and can be present at all locations into May and June. The sites range from 3 to 9 hectares in size, spanning 1150m to 1350m in elevation ASL on mostly gentle slopes. The study area falls within the Mountain Hemlock moist maritime (MHmm1) biogeoclimatic subzone where oval-leaved blueberry, Alaskan blueberry, false azalea and copperbush are the dominant shrub species which grow to heights ranging from 0.5m to 3m (Green & Klinka, 1994; Douglas, Meidinger & Pojar, 1999). Dominant tree species are Mountain Hemlock and Yellow Cedar.

Pix4D Capture automated mission planning software was used to collect imagery three times at each of the four sites. The first series of flights took place early March (winter) of 2018, to capture the approximate height of the season's snowpack. The second series was completed in late May (spring), to test the approach with shallower snowpacks and the final flights, done in early September (summer), served to create the snow-free DEMs. Using DJI Phantom 3 Pro and Phantom 4 Pro RPAS, images were captured at a height ranging from 50m to 80m AGL, flying in a grid pattern with high image overlap (≥80%) and a camera angle of 10 to 20 degrees from nadir. RTK GNSS surveying equipment was used to record the coordinates at the centre point of GCPs that were dispersed throughout each site prior to RPAS flight. During the winter and spring surveys, manual snow probe depth measurements were taken and their coordinates were recorded along transects throughout each site. Pix4D Mapper software (V4.2.26) was used to process and georeference the 12 datasets to their corresponding GCPs, generating dense point clouds and orthomosaics.

The filtering methods used to extract ground points for the creation of DEMs from SFM point clouds can affect their final quality, especially when vegetation is present. The evaluation of multiple filtering methods performed by Anders et al. (2019) suggests that the algorithms available through the LAStools software package achieved the most effective filtering of noise and vegetation across a wide range of landscape types. A workflow proposed by the software developer of LAStools for filtering SFM point clouds was adapted for use in this study (Isenburg, 2017). The sequence of noise and ground point filtering algorithms was applied to each raw point cloud dataset, generating raster DEMs at a spatial resolution of 20cm. A total of 8 dDEMs were then generated by subtracting elevation values of the summer DEMs from their respective winter and spring snow surface DEMs. The resulting dDEM pixel values representing modelled SD were sampled at corresponding manual snow probe measurement locations for comparison and error analysis.

Table 1. Summary of Absolute Depth Error by Season

Season	Count	Min	Max	Mean	Median	Std. Deviation	IQR[1]	RMSE[2]	MAD[3]	MAPE[4]
Winter	309	0.1	149.5	20.7	15.2	19.7	21.1	23.9	9.7	10.1%
Spring	160	0	56.5	10.5	6.7	10.7	10.3	11.5	4.4	36.9%

[1] Inter Quartile Range [2]Root Mean Square Error [3]Median Absolute Deviation [4]Mean Absolute Percent Error

The root mean square error (RMSE) for winter and spring was 23.9cm and 11.5cm respectively and the median absolute deviation (MAD) was 9.7cm and 4.4cm (Table 1). Mean absolute Error (MAE), by site, ranged from 6.3cm to 15.6cm for spring measurements and 17.5cm to 27.6cm for winter. By season MAE, was similar to RMSE at 20.7cm and 10.5cm for winter and spring models respectively (Table 1). Mean absolute percent error (MAPE), or relative error, revealed the high error value of 36.9% for spring and 10.1% for winter (Table 1). On the site level, MAPE values ranged from 17.7% to 48.5% for spring and 9.0% to 14.6% for winter. This aligns with values reported by Vander Jagt et al. (2015) who found a relative error of 27.6% in shallower snowpacks and 8% where SD was deeper.

In line with previous research, modelled SD was found to be within a similar margin of systematic underestimation when compared to probed depths (Adams et al., 2018; Buhler et al., 2016; Eberhard et al., 2021;

Fernandes et al., 2018; Goetz & Brenning, 2019). Mean difference between probed and modelled SD was -9.2cm for spring and -13.4cm for winter. As proposed in past studies, this is likely due to low vegetation increasing the elevation of the snow-off DEMs and limitations of the point cloud filtering algorithm used (Adams et al., 2018; Anders et al., 2019; Avanzi et al., 2018; Buhler et al., 2016; Redpath et al., 2018). Figures 1 & 2 illustrate the difference in distribution between modelled and probed SD for spring and winter measurements at the site level.

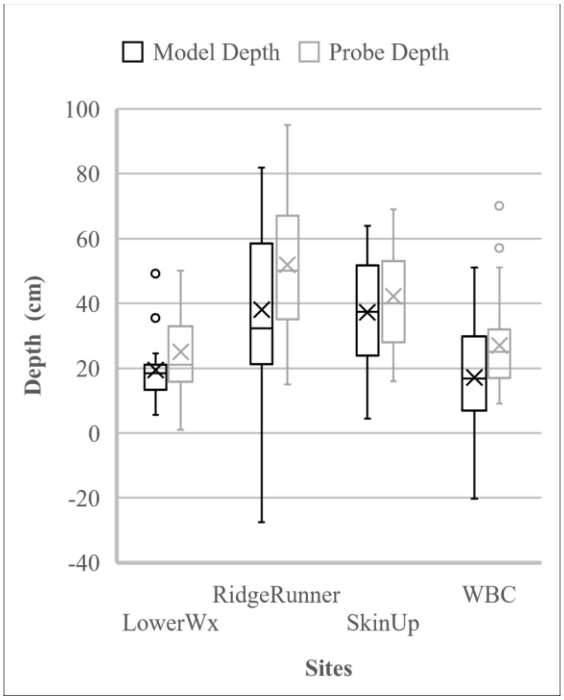

Figure 1. Probe and model depths by site - *Spring*

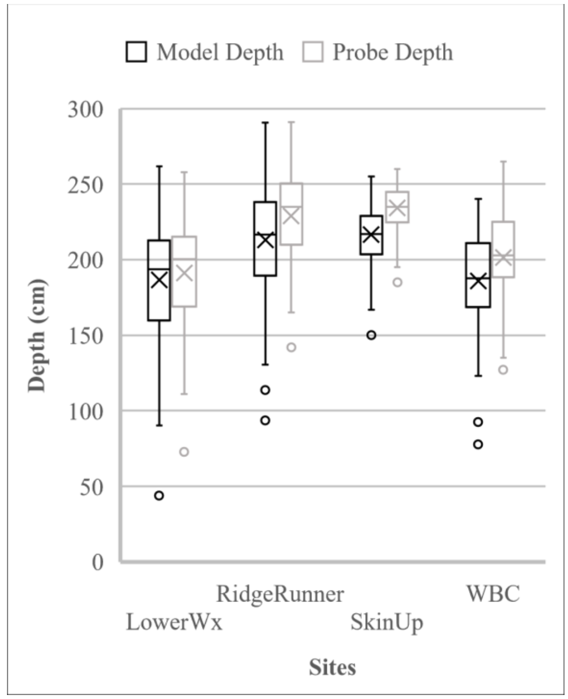

Figure 1. Probe and model depths by site - *Winter*

Buhler et al. (2016) found RMSE to range from less than 7cm to 15cm in rocky meadows, and less than 30cm in areas characterized by tall grasses and shrubbery. Harder et al. (2016) reported a RMSE of 8.8cm for areas with short prairie grain stubble, 13.7cm for tall prairie grain stubble and 8.5cm for an alpine site. When Avanzi et al. (2018) excluded areas where vegetation was likely causing outliers, RMSE values dropped from 20cm-30cm to 6cm-17cm. In the current study, vegetation height and ground cover characteristics were not analysed and no outliers were removed. Relative to findings from similar research, RMSE of 23.9cm to 11.5cm places this study's results within the range of error values reported in areas associated with taller vegetation.

Results from this work suggest that these methods are suitable for measuring snow depth over larger areas, with the relative error increasing as snow depths become shallower. As discussed by Nolan et al. (2015), minor changes to the surface due to vegetation compaction or even footprints can become notable sources of relative error when examining shallow snowpacks at a fine spatial resolution. For instance, with an average probed depth of 37cm in spring, despite the rather low MAE value of 10.5cm, the corresponding relative error of 36.9% indicates that higher accuracies would be required to characterize a meaningful proportion of these shallower snowpacks. However, when applied to deeper snowpacks, it can be suggested that in spite of the cumulative sources of potential error, more useful measurements of SD can be achieved as supported by the 10.1% relative error found in this study for snowpacks averaging just over 2 metres.

This study presents a straightforward comparative analysis of SD measurements derived from RPAS SFM against manual snow probing at four coastal subalpine sites with substantial shrub and low vegetation cover. Results fall within the range of error reported in previous research despite the aforementioned presence of vegetation and provides an additional example of the systematic underestimation of SFM based SD measurements relative to manual probing. The greater suitability of this technology for measurements of deeper snowpacks is supported, as well as the importance of point cloud filtering methods used for optimizing DEM quality. This study also highlights the importance of taking manual SD measurements to validate SFM derived SD. The number and location of validation measurements will vary by site, vegetation type and snowpack characteristics, however once initial SD maps are created, sampling can be stratified based on these characteristics for future surveys. This will be especially useful if done at existing manual snow survey locations, automated weather stations or at research plots/watersheds.

This extended abstract summarizes the initial component of larger study which will include an analysis of SWE and snow density data collected during the field campaigns. This research is being conducted as part of a collaboration between Vancouver Island University, the Hakai Institute, the University of Northern British Columbia and the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development. (KEYWORDS: snow depth, structure from motion photogrammetry, remote sensing, RPAS, vegetation, point cloud filtering).

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