AIRBORNE AND SPACEBORNE SNOW REMOTE SENSING WITH OPTICAL AND MICROWAVE SENSORS: A REVIEW OF CURRENT APPROACHES AND FUTURE OUTLOOK FOR AVALANCHE APPLICATIONS

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ABSTRACT: Remote sensing of snow is one of the more challenging targets for many spaceborne sensors, due to the high spatiotemporal resolution required to capture the important dynamics. The regular measurement of snow covered area, or where snow exists, has been operational for many decades, however estimating snow depth or mass at the required resolution in mountain environments remains challenging. Avalanche applications have the most challenging requirements for spatial and temporal resolution (meters, days), which so far has limited application of remote sensing for avalanche forecasting and science. However, during the past decade, new techniques using optical imagery and microwave radar are showing promise for mapping snow depth and avalanches from space, as well as presence of melt, and InSAR approaches show potential for mapping depth and SWE change at weekly intervals. Both optical and SAR approaches have been used with increasing accuracy for mapping avalanche events, and the spatial and temporal resolution of snow products is getting much closer to the requirements for forecasting and management operations. However, the bottleneck is the sound validation of the products. Over the coming decade, resolution will continue to increase, large validation datasets are becoming available, and some exciting new satellites are planned to launch that will provide snow information that is likely to be useful for both, avalanche scientists and practitioners. This presentation will overview progress in snow remote sensing from drone, aircraft, and spaceborne platforms over the past decade, and will highlight future snow data products that are likely to be of interest to the avalanche field.

Keywords: remote sensing, radar, lidar, structure-from-motion

1. INTRODUCTION

Snow remote sensing is a complex but rapidly evolving field, and application to avalanche forecasting and research has been slow. This has in part been due to the resolution and temporal frequency being too low for avalanche applications, compared to the requirements for other fields such as snow hydrology. In recent years new sensors have launched or are near launch which overcome these barriers and are at frequencies more useful for snow. This presentation will help the avalanche community understand what remote sensing tools are available now, with a view toward what will likely be available in the near future.

While previous review papers have focused on avalanche detection (e.g. Eckerstorfer et al., 2016), in contrast this review focuses on recent advances in the more general area of monitoring snow mass. While changes in snow mass can allow avalanche detection, they can also help with understanding of the spatial distribution of snow accumulation and ablation events, aiding practitioners in developing relationships between measurements at study plots and changes in snow mass in avalanche starting zones. Motivated by a need to monitor snow resources, the snow hydrology community has made significant advances in the development of a range of remote sensing techniques to monitor snow mass.

Several major airborne and field campaigns, and satellite mission concepts, have advanced the state of the art, starting with the NASA Cold Lands Processes Experiment (CLPX) in 2002-2003, the European Space Agency (ESA) Cold Regions High-resolution Hydrologic Observatory (CoreH2O), the Canadian Space Agency (CSA) Terrestrial Snow Mass Mission (TSMM), and NASA SnowEx (2017-2023). These efforts have involved snow remote sensing experts from across the globe, and have tested a wide range of sensing approaches, with a goal of a regular global observation of snow mass from space. While these efforts have been motivated more by the snow hydrology application, there is a high likelihood the avalanche community will find these kinds of unique snow mass observations useful for avalanche forecasting.

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2. RADAR REMOTE SENSING OF SNOW MASS

Radar remote sensing of snow can require complex interpretation and is challenging, however it offers the advantages of potentially global coverage, observations at night and during storms, and because microwaves penetrate snow, the signal can interact with the entire snow volume, providing more direct sensitivity to snow mass. There have been two primary approaches to radar measurements of snow: 1) using the time-of-flight through snow, or changes in time-of-flight, and 2) using the amplitude of the signal that is measured.

Both approaches have advantages and disadvantages, and while we do not currently have the optimal sensor in space for either approach, promising results have been shown from airborne campaigns, and under certain conditions, both approaches have been shown to work from the ESA Sentinal-1 C-band radar. Multiple snow satellite mission efforts are currently underway that would provide optimal sensors for each technique, expanding the range of conditions under which snow mass can be monitored from space, at temporal and spatial frequencies relevant to avalanche applications.

2.1. Radar time-of-flight

The most straight forward approach to measuring snow mass using radar is to measure the time-of-flight of a radar signal through snow. This was first demonstrated using a ground-based radar system by Boyne and Ellerbruch (1979) and Gubler and Hiller (1984), using an ultra-wideband (UWB) Frequency Modulated Continuous Wave (FMCW) radar system. Over the next several decades, these ground-based FMCW systems were miniaturised and advanced for research, as measurements of snow depth, snow water equivalent (SWE) and stratigraphy can be made rapidly (see review by Marshall and Koh (2008)). However, these systems require very large bandwidths, which are not possible from space, and therefore global coverage with such a system is not possible, limiting their application to research.

However, the change in the time-of-flight can be measured by a narrow-band radar, through a measurement of phase with interferometry. This type of measurement is routinely made from space for measuring changes in the elevation of the earth's surface at centimeter-scale vertical resolutions, for earthquake and volcano research. Very high horizontal resolution (meters) can also be achieved from space, through Synthetic Aperture Radar (SAR), a sophisticated processing approach that uses the satellite's motion, knowledge of the antenna pattern, and time-of-flight.

Combining both phase measurements and SAR is called Interferometric Synthetic Aperture Radar (InSAR), and Guneriussen et al. (2001) first showed that this could be used to measure changes in SWE. Fig. 1 shows the conceptual approach. We assume that the ground surface did not move, and snow accumulation causes both a change in path length and a change in radar wave speed, resulting in a phase change that can be related to the change in SWE. During the NASA SnowEx Time Series campaign (2020-2021), this approach has recently been shown to provide snow depth change estimates accurate to less than 5 cm (Marshall et al., 2021) over flat terrain, and has shown a high correlation with modeled SWE and depth estimates at the regional scale in complex topography (Hoppinen et al., 2023). During the spring, with observations early in the morning, after the snowpack has refrozen and drained, SWE losses can also be estimated (Tarricone et al., 2023).

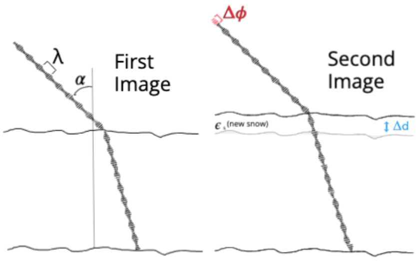

Figure 1: Conceptual approach to measuring change in snow mass from radar phase. From Hoppinen et al. (2023).

The upcoming NASA/ISRO NISAR mission will provide changes in phase at 10m resolution, everywhere on the globe, every 12 days. While this isn't optimal for avalanche forecasting, this mission will likely provide data that can give forecasters insight into patterns of accumulation across mountain ranges. While forecasters often develop relationships between measurements at study plots or automatic weather stations, and starting zones, these relationships are likely to change in a changing climate, and InSAR may provide a tool for monitoring spatial patterns in snow accumulation.

2.2. Radar backscatter

Microwave radar penetrates dry snow, and depending on the wavelength, may scatter significantly from the individual snow grains. At wavelengths close to the grain size, this volume scattering can be significant and can provide a mechanism for measuring changes in SWE. Fig. 2 shows the conceptual model for how microwave energy can be scattered from snow. As the snowpack develops, more scatterers are present, and therefore there is a relationship between radar backscatter and SWE.

However, changes in snow grain size and bonding

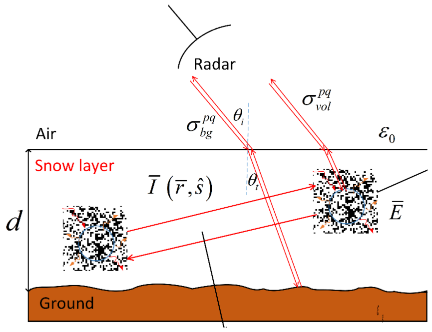

Figure 2: Conceptual approach to measuring snow mass from radar backscatter. From Tsang et al. (2022).

between grains can also significantly impact radar backscatter. Tsang et al. (2022) presents a detailed review of high-frequency radar approaches to measuring snow mass. While this approach is complex and requires some knowledge of the snow microstructure, great progress has been made in coupling physically based snowpack models with radar observations, and this has been the leading approach for measuring snow mass from space for more than 2 decades.

While this ideally requires a wavelength on the order of 1 cm, recently Lievens et al. (2019, 2022) showed that the ESA Sentinel-1 C-band radar can be used to measure snow depth from space, especially in deep snow (greater than 1m). The physical basis for this retrieval has still not been developed, however, the statistical comparisons with ground-based observations of snow depth are compelling.

Both the Canadian Space Agency and NASA have current satellite mission concepts that could result in high-frequency microwave radar observations in the near future, which would allow a radar backscatter-based SWE retrieval, with global coverage, 5-day repeat intervals, and resolutions on the order of 100m. While the spatial resolution is too coarse to detect smaller avalanches, this kind of observation will greatly improve understanding of snow accumulation patterns over mountain regions, at a resolution much finer than current weather models or in-situ observations.

3. LIDAR OBSERVATIONS OF SNOW DEPTH

For more than a decade, LiDAR, either mounted on airplanes or ground-based, was the preferred methodology to measure snow depth (HS) and its distribution spatially continuous in complex terrain. The main advantages are its high accuracy and independence of illumination conditions (Deems et al., 2013). It demonstrated its ability to capture snow depth distribution in various studies from the ground (e.g. Grünewald et al., 2010; López-Moreno et al., 2013; Deems et al., 2015; Prokop, 2008) and on a larger scale from aircraft platforms (e.g. Painter et al., 2016; Hopkinson et al., 2004). Fig. 3 shows the conceptual approach (from (Deems et al., 2013)).

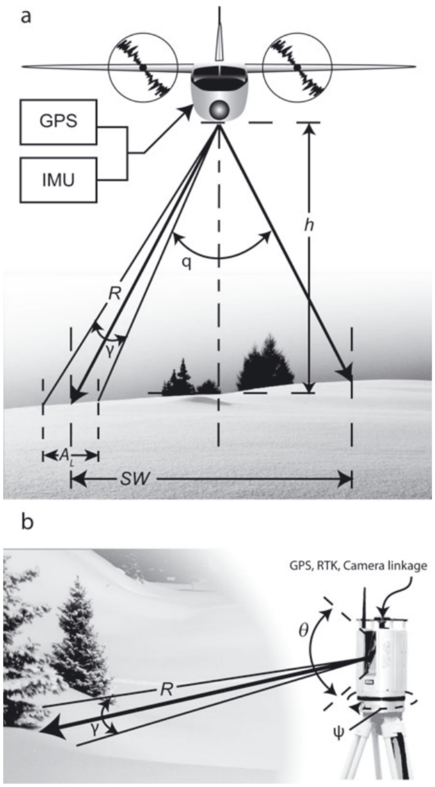

Figure 3: Conceptual approach to measuring snow depth from lidar, using an airborne platform (a) and from a ground-based system (b). Observations are performed during snow-on and snow-free conditions, and the difference between the two surface topographies, after vegetation filtering and co-registration, provides snow depth. From Deems et al. (2013).

Recently more focus is given to the performance of LiDAR mapping of snow depth within forested terrain applying drone-based LiDAR systems (e.g. Mazzotti et al., 2019; Harder et al., 2020; Jacobs et al., 2021). The enhanced penetration of the LiDAR through the vegetation is clearly an advantage, compared to photogrammetry. However, if the density of the vegetation is too high, LiDAR will also not record many points from the snow surface. Nevertheless, LiDAR remains a key tool for snow depth mapping and holds great value for the generation of very accurate reference measurements to test novel approaches. Spaceborne LiDAR is not yet able to provide spatially continuous snow depth measurements with sufficient accuracy as it is limited to laser altimetry along widely spaced satellite orbits (e.g. Enderlin et al., 2022) but can provide high-resolution snow depth information along-track (Deschamps-Berger et al., 2023).

4. STRUCTURE FROM MOTION

Despite the long-standing paradigm that photogrammetry does not work for snow surfaces because they are too homogenous, recent studies established photogrammetry as an efficient and accurate approach for snow depth distribution mapping in unforested terrain. A conceptual model is shown in Fig. 4. Due to its long tradition and relatively low costs, photogrammetry from the ground (e.g. Basnet et al., 2016; Eberhard et al., 2021), drones (e.g. Bühler et al., 2016; Redpath et al., 2018; Harder et al., 2016; Vander Jagt et al., 2015; De Michele et al., 2016), airplanes (e.g. Bühler et al., 2015; Nolan et al., 2015; Meyer and Skiles, 2019; Meyer et al., 2022; Bührle et al., 2023) and high-spatial resolution satellites (e.g. Marti et al., 2016; Deschamps-Berger et al., 2020; Shaw et al., 2020) demonstrated its value for snow depth mapping. The achieved accuracies (Eberhard et al., 2021) are in the range of LiDAR studies for drones (RMSE ~0.1 m) and only slightly worse for airplanes (RMSE ~0.15 m). For satellites however the achieved accuracy is still limited (RMSE ~0.5 m) reducing its applicability for shallow snowpacks. Ground-based applications are limited by the visibility of the terrain and strongly reduced accuracies with longer distances from the sensors. However, for steep slopes, ground-based photogrammetry might still produce good results.

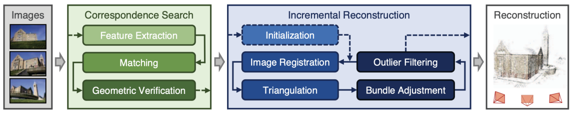

Figure 4: Conceptual approach to measuring topography from Structure-from-motion (SfM) From Schönberger and Frahm (2016). To measure snow depth, similar to lidar, surface topography is measured during snow-on and snow-free conditions.

The largest value of photogrammetry is its flexibility. It can be applied from very different platforms covering very small areas (a few km2) at low costs with high accuracies (drones), medium-sized areas (a few 100 km2) with still high accuracies (airplanes), and very large areas (>1000 km2) with intermediate accuracies (satellites) at higher costs. This makes it a very valuable tool for generating meaningful reference datasets to evaluate the performance of novel approaches including, for example, modeling or radar (e.g. Revuelto et al., 2020; Helbig et al., 2021; Lievens et al., 2022; Daudt et al., 2023). This is urgently needed because the validation of spatially continuous snow depth (HS) and snow water equivalent (SWE) products with spatially isolated point measurements, for example from automated weather stations, is not meaningful because the spatial variability is so large in complex terrain.

5. CONCLUSION

Snow varies over length scales less than a few hundred meters, and therefore high-resolution snow measurements are required to understand the distribution of snow depth, SWE, and changes in these properties throughout the winter. Avalanche practitioners often develop relationships between their study plots and the starting zones that they forecast for, however these take decades to develop and are likely to change with changing climate.

Remote sensing of snow depth and SWE has been an active area of research, but mainly from a snow hydrology perspective. In the past, this approach has had temporal and spatial resolutions, and spatial extents, that have been too low for avalanche applications, and therefore it has been used primarily for research. However, recent advances in both optical and microwave radar remote sensing have led to drastic increases in spatiotemporal resolutions, and large extents are now covered regularly. While avalanche applications require much higher spatiotemporal resolutions than snow hydrology, these techniques are nearing the requirements for the avalanche field.

The different sensor technologies presented here (radar, LiDAR, photogrammetry) each have their specific strengths and weaknesses, and a combination of the different approaches holds great potential to further improve snow measurements. As with any new promising tool, accurate validation observations are required, and to push these techniques into regular practice, collaboration between avalanche practioners and remote sensing experts is required.

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