RADAR REMOTE SENSING OF MOUNTAIN SNOW: A REVIEW OF CURRENT GROUND-BASED, AIRBORNE AND SATELLITE-BASED APPROACHES TO MONITORING SNOW PROPERTIES

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ABSTRACT: Satellite remote sensing products are used on a daily basis by avalanche forecasters, as a crucial aid in prediction of storms during the winter and spring. While these remote sensing products provide valuable information about approaching storms, and have been part of an avalanche forecaster's daily routine for decades, we still do not have remote sensing products which provide information about snowfall amounts, nor total snow on the ground. Although research over the past decade has demonstrated the potential for monitoring snow using remote sensing, current operational snow remote sensing products are limited to snow covered area, which is of little direct use to avalanche forecasters. Snow radar remote sensing is just now reaching a maturity level where sensors and data are becoming available at the necessary spatial and temporal resolutions, and at the appropriate frequencies, that are relevant for avalanche forecasting. Satellite radar with spatial resolutions on the order of meters, and repeat intervals on the order of days, have just recently removed some of the major limitations for radar remote sensing in the mountains. Microwave radar is highly sensitive to liquid water, providing both a challenge to estimating snow mass, as well as an opportunity for monitoring the spatial extent of melt and rain-on-snow events. Changes in snowpack mass cause changes in microwave radar amplitude and phase, and radar is also being used to monitor snowfall rates. Ground-based radar systems can track snow water equivalent, estimate snow density and liquid water content, are used to measure falling snow, and for avalanche detection. Recent airborne snow radar missions, and preliminary results from recently launched satellite-based radar sensors, have indicated that operational monitoring of changes in snow water equivalent and depth, as well as recent avalanche activity, will likely be possible at high resolution in the near future from space. Recent results from our network of tower-based radar systems, as well as results from the recent intensive NASA SnowEx airborne snow remote sensing campaign will be presented. This presentation will review the current state-of-the-art of radar remote sensing of snow from ground-based, airborne, and satellite-based platforms, in the context of snow products that will be available and useful to avalanche forecasters in the near future.

KEYWORDS: radar, snow water equivalent, wet snow, snow remote sensing

1. INTRODUCTION

While satellite based products have been used operationally for decades by weather and avalanche forecasters, the satellite products for snow on the ground are currently of limited use for the avalanche forecasting application. Due to the large variability in seasonal snow, with correlation lengths on the order of 50-100 meters (Deems et al., 2007), relatively high resolution is required to capture the patterns of snowfall across the landscape, in particular in the mountains. Temporal resolution also provides a challenge, as avalanche forecasters need information during and immediately following storms.

Current and future satellite sensors are rapidly closing the resolution gap, and although avalanche forecasters have the highest spatial and temporal resolution requirements for snow products, estimates of snow properties from spaceborne sensors are likely to become useful to the snow avalanche community in the near future. Optical sensors only give information about the snow surface and the fractional snow covered area, which is of limited use for avalanche forecasting. Radar, in contrast, is sensitive to the properties of the entire snowpack, and can achieve the required spatial and temporal resolutions for avalanche applications.

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Ground-based radar experiments have shown that microwave radar can be used to estimate snow water equivalent, snow depth, and map stratigraphy (Ellerbruch and Boyne, 1980; Gubler and Hiller, 1984; Marshall and Koh, 2008). There are complications when snow is wet (Lundberg and Thunehed, 2000), but recent work has leveraged this sensitivity to directly estimate liquid water content (e.g. Bradford et al., 2009; Heilig et al, 2015), providing the first non-destructive approach to monitoring liquid water dynamics. Tower-mounted radars now provide continuous real-time estimates of snow water equivalent (Marshall and Robertson, 2016). While individual radar observations can be difficult to interpret, after spatial averaging, the amplitude of the reflections from stratigraphic layers can be directly related to the density contrast (Rutter et al., 2016). Ground-based radars have been used to study creep and to detect avalanches (e.g. Gubler and Hiller, 29184; Lucas et al., 2016). Ground-based radar has also been used to study glacier mass balance (e.g. McGrath et al., 2018).

Airborne radar has been used for decades to map snow accumulation rate patterns in the polar regions (e.g. Gogineni et al., 2007; Kanagaratnam et al., 2001), and to estimate snow water equivalent (SWE) in the mountains (e.g. Yueh et al., 2009; Rott et al., 2013). The SWE retrievals from Ku-band radar are sensitive to microstructure, which has challenged this approach, but has lead to the use of the SnowMicroPenetrometer in these snow hydrology remote sensing efforts (e.g. Proksch et al., 2015). Satellite radar has been used to monitor changes in the surface of ice sheets, for detection of melt events, and recently has been applied to avalanche detection (Eckerstorfer et al., 2017)

This coming winter, the NASA SnowEx mission will perform biweekly radar observations in the Western U.S. with a lower frequency L-band InSAR, which is not sensitive to microstructure and can be used to estimate SWE in some conditions. This experiment will help determine the potential for operational use of the NISAR L-band radar, which launches in early 2022 and will have a 10 meter resolution, and a 12-day repeat, with near global coverage.

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