SPATIAL VARIABILITY OF MECHANICAL AND DIELECTRIC PROPERTIES: GRAND MESA, COLORADO, U.S.A.

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ABSTRACT: In order to accurately map slope to basin-scale snow stability at high resolution, spatial estimates of snow mass changes and snow mechanical properties (e.g., strength, stiffness) are required. New remote sensing tools are providing insight into spatial distributions of snow mass, with the most promising global approach using microwave radar that is sensitive to the dielectric properties of snow. Direct observations of snow mechanical properties are very limited, sparse both spatially and temporally. Using a wide range of tools we acquired spatial measurements of both mechanical and dielectric properties of snow on Grand Mesa, Colorado, at over 3000m elevation in simple low angle terrain, across a 7 km x 14 km area. We measured micromechanical and structural properties with the SnowMicroPen, and imaged decimeter-scale mechanical properties along a 100+ m transect with a new active-source seismic system optimized for seasonal snow. We measured dielectric properties with in situ permittivity probes, and deployed ground-based, UAV, and airborne radar at L-, C-, and Ku-bands. Understanding spatial variability in mechanical properties may improve if we can establish a link between mechanical properties and remote sensing techniques, and we performed a preliminary comparison experiment in a place which contains small-scale topography and wind redistribution, but not a large elevation gradient. While we performed this initial experiment in relatively flat terrain, these preliminary results will be used to plan future experiments in complex terrain and observe changes with time.

Keywords: snow mechanical properties, radar, spatial variability, remote sensing, snow micropenetrometer

1. INTRODUCTION

One of the major limitations towards understanding the distribution of snow across the landscape has been the limited available data, even for bulk properties such as depth, density and SWE. While we can currently estimate where and when snow is covering the landscape, we do not yet have a global remote sensing approach for estimating snow mass in the mountains.
Airborne lidar is now a mature technique that allows measurement of snow depth at high resolution over large areas (Deems et al., 2013). This is changing how water managers forecast in critical reservoir headwaters, however it does not provide information about density nor mechanical properties. Density is an important parameter for converting snow depth observations to estimates of snow water equivalent (SWE), and is needed for estimating overburden stress for avalanche problems. For predicting direct action avalanches, density is often used as a proxy for monitoring changes in storm snow strength (Conway and Raymond, 1993), and it is used in models for military mobility [ref].
While previous work has quantified length scales of variability of snow depth using lidar (Deems et al., 2006; Trujillo et al., 2009), our understanding of spatial variability of snow strength is much more limited; likely correlation lengths are even smaller than for depth (Marshall et al., 2006). Direct in-situ observations of snow mechanical properties are time intensive and destructive, and therefore data is limited in scale and resolution. We are exploring two new sensing approaches to allow estimates over larger scales: active seismic profiling, and UAV-based radar.

2. ACTIVE SEISMIC PROFILING

To advance our understanding of the mechanical properties of snow, we designed, tested and implemented a snow-based seismic land streamer system. This system consists of 24 vertical and 24 horizontal 100 Hz geophones that are spaced 10 cm apart. Combined with a 12-volt three-sensor push-pull solenoid system, we obtain compressional (p-wave) and shear (s-wave) seismic signals that are recorded with the 2.4 m long seismic streamer. We utilize 1) direct first arrival information to measure both p-wave and s-wave velocities within the upper

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0.5 m of snowpack, 2) surface (Rayleigh and Love) wave dispersion information to estimate s-wave velocities to soil depths beneath the snow, and 3) reflection profiles to obtain spatial variations in snow structure and layers.

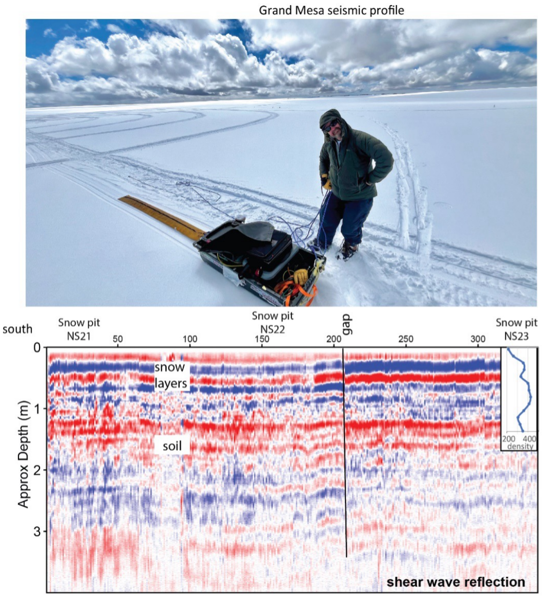

Figure 1: Active seismic reflection profile using a custom snow streamer, with snowpit density shown on the right.

Preliminary results from Mores Creek summit, Idaho show clear velocity differences when comparing fresh snowfall (March 8, 2024) and older snow (March 22, 2024) conditions. A 350 m long reflection profile from Grand Mesa, Colorado shows lateral variations in reflection strength and depth to key seasonal snow layers. Coupled with snow pit and snow micropenetrometer measurements where snow density is inferred, our snow streamer system shows great promise in capturing decimeter-scale snow structure for the full range of snow conditions. Additional data analysis and field tests are planned to incorporate autonomous operations and advanced signal processing approaches. Future work will involve quantitative comparisons with SMP profiles.

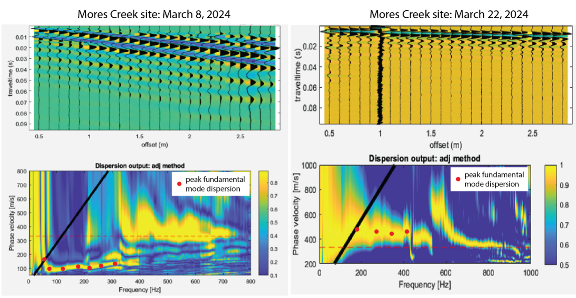

Figure 2: Results from March 8 (left) and March 22 (right), showing clear velocity differences.

3. UAV RADAR

Active seismic profiling provides an opportunity to measure mechanical properties at larger scales than previous studies in snow. However it requires moving over the terrain you are measuring, and therefore doesn't allow large scale observations like remote sensing. Using coincident observations from airborne high frequency (14-15.5 GHz) radar, we profiled the snowpack from an altitude of 30-50m from a UAV platform.

Figure 3: Photo of radar in flight on the Vulcan UAV.

An example radar profile is shown in Fig. 4. We convert radar two-way travel time to snow depth using the measured bulk density. The profile shows some response to internal structure, although the information is limited due to the smaller bandwidth (1.5 GHz) compared to our snowmobile-based radar systems. We had to make some compromises with the radar design to fit within the payload. Future efforts will explore larger bandwidths to provide more stratigraphic information.

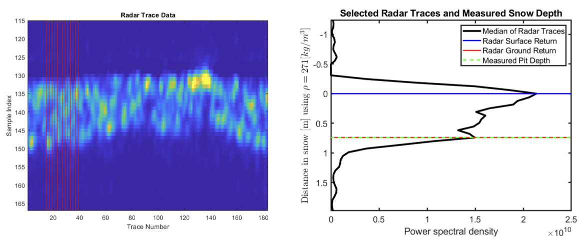

Figure 4:

We measured snow depth and snow water equivalent through the radar two-way travel time through snow Marshall and Koh (2008) at 29 different snowpits. Results comparing radar-estimated depth to snowpit depth are shown on the left of Fig. 5. We also convert travel time directly to SWE, and compare to the measured SWE in the snowpits (right).

Both comparisons show agreement to the accuracy limits expected from the radar resolution (∼10cm) and geolocation errors.

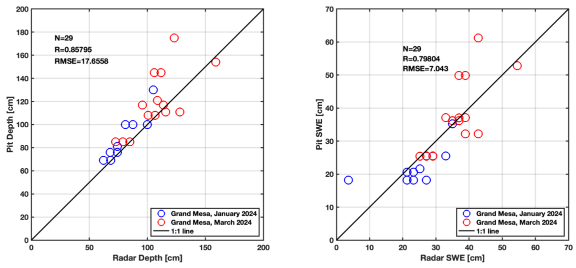

Figure 5: Comparison of radar estimates of depth (left) and SWE (right) to snowpit observations at 29 locations.

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