TOWER-BASED SNOW REMOTE SENSING FOR IMPROVED UNDERSTANDING OF RETRIEVAL ALGORITHMS

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ABSTRACT: Microwave snow remote sensing has been challenged by a lack of the ideal frequencies, polarizations, spatial resolution, and temporal resolution, in order to test retrieval algorithms over a wide range of well-characterized snow conditions. Large efforts using combined airborne and field campaigns, such as CLPX, CoreH2O, and SnowEx, have resulted in snapshots of snow conditions with both low and high frequency radar. However aligning independent observations for calibration and validation, and addressing scale mismatches, can be difficult. While time-series campaigns have been the most valuable, they are costly. We present a time series of observations from tower platforms, combining scanning lidar, P-band signals of opportunity, radar, and standard meteorological and snowpack measurements. These tower-based remote sensing experiments provide an opportunity to observe a large dynamic range in well-characterized conditions.

KEYWORDS: snow remote sensing, radar, lidar, SWE, tower-based observations, retrieval algorithms

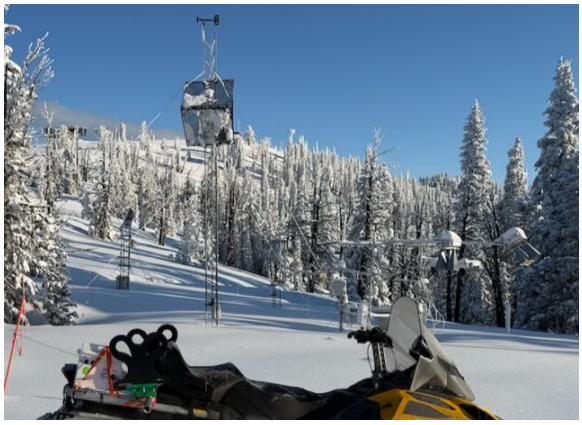


Figure 1: BSU Snow Study Plot at Brundage Ski Area.

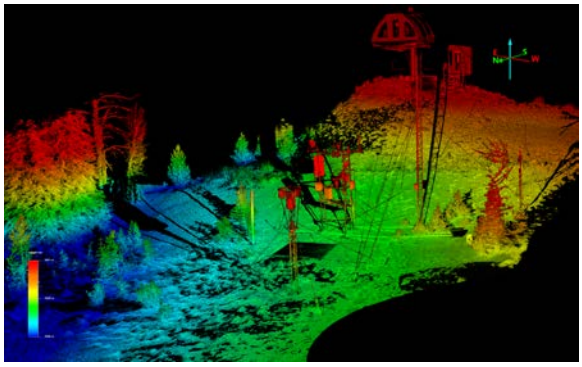


Figure 2: TLS survey in November during near snow-free conditions, where SWE scale is still visible.

1. INTRODUCTION

Compared to other earth observables, measuring changes in snow mass at 100m-scale spatial resolutions at weekly-scale temporal resolution remains one of the most important challenges in earth science remote sensing. Spatial estimates of snow mass changes are required for forecasting avalanches, water resources, hydropower, and floods. Current operational approaches often rely on historical statistical relationships between snow measured at study plots or SNOTEL sites, and the snow in a starting zone of interest or at high elevations in a watershed.

While the use of these index sites can be quite effective when the current year is well represented in the historical record, this approach can break down in unusual conditions. Remote sensing and modeling can provide spatial estimates, but must be accurately calibrated and validated. Errors in spatial snowfall estimates are one of the most significant sources of uncertainty in snowpack modeling, and therefore remote sensing approaches

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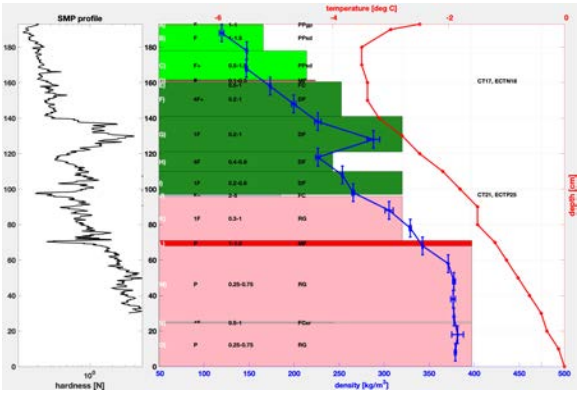


Figure 3: Example snowpit observations at site with SnowMicroPenetrometer profile.

to measuring snow accumulation are desperately needed.

This need has motivated large community airborne and field campaigns to test different sensing technologies (SnowEx, CoreH2O, CLPX), however these are costly and have typically focused on intensive 2-3 week efforts. Airborne campaigns that have been performed as a time series (e.g. UAVSAR with SnowEx, lidar with ASO) have captured a much larger dynamic range in snow conditions but are confined to highly mature sensing techniques.

Here we propose that the most cost-effective approach to developing a new remote sensing approach is to perform tower-based experiments. This allows observation of a very large range of snow conditions, but removes the costly step of aircraft integration. Multiple sensors can be compared, and regular in-situ destructive observations can be performed. We present example results from multiple tower-mounted sensors at the Brundage Snow Site: a Terrestrial Lidar Scanner (TLS), a C-band SFCW radar, an ultra-wideband (0.5-6 GHz) FMCW radar, and a P-band Signals of Opportunity receiver. We also show example in-situ observations and mention the use of the site as a teaching tool.

Our research team visits the site two times per month to complete full snow profiles, measuring snow density, temperature, stratigraphy, grain size/type, hardness, liquid water content, and permittivity. In addition we use multiple snow penetrometers (RAM, SnowScope, SMP, Lyte), which support both remote sensing and snow strength projects. Fig. 3 and 4 show typical in-situ observations. Snow water equivalent, density, temperature and permittivity are important for understanding the lower frequency radar remote sensing



Figure 4: Photo of completed snowpit, showing observations of density, temperature, stratigraphy, grain size/shape, and permittivity.

approaches, and the higher frequency radar (> 4 GHz) requires microstructural characterization in addition. The Brundage site has internet and line power, along with year-round site access, facilitating tests of prototype instruments that have large power requirements.

2. TERRESTRIAL LIDAR SCANNER (TLS)

Repeat lidar observations have been used to track snow depth since the early 2000s when it was first tested during the NASA Cold Land Processes Experiment (CLPX) (Deems et al., 2013; Deems et al., 2006; Trujillo et al., 2007). Here we use repeat lidar from a fixed tower to scan the 100m x 100m site, every 6 hours, to document the spatiotemporal variability in depth, and map surface roughness for radar retrievals. This provides both a way to correct snowpit observations for the snow conditions under any of the microwave sensors, and provides a surface and estimate of layer roughness for electromagnetic scattering models.

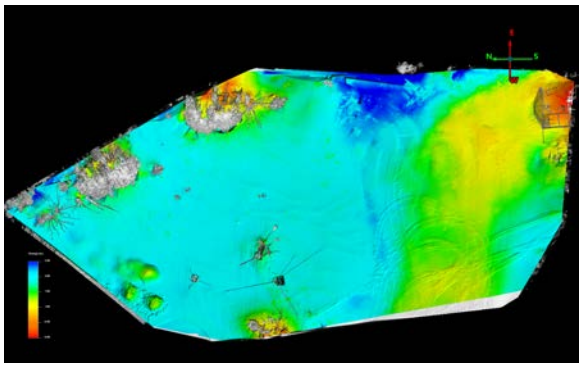


Figure 5: TLS survey on April 22, 2026 showing snow depth distribution at site. Area near ski lift that is groomed is visible on the right side, and disturbance from previous snowpit observations is visible on the left.

3. ULTRA-WIDEBAND FMCW RADAR FOR MONITORING SNOW

FMCW radar has been used for snow for more than 40 years (Gubler and Hiller, 1984); for a review see Marshall and Koh (2008). The majority of ultra-wideband FMCW radar studies have been done at frequencies above 2 GHz, with a focus on dry snow conditions. Here we show results from last winter from a new 500 MHz-6 GHz FMCW system, which penetrates the entire snowpack throughout the spring melt. While frequencies above 2 GHz are mostly responding to the near surface of the snowpack due to attenuation by liquid water, the lower end of the spectrum penetrates to the snow-ground interface in over 2m of wet snow.

4. C-BAND RADAR FOR SIMULATING SENTINEL-1

Previous work has shown strong correlations between C-band backscatter from Sentinel-1 and snow depth (Lievens et al., 2019; Lievens et al., 2022), while physical mechanisms to explain these observations are still being explored. Isolating the radar signal from snow can be done much easier with a tower based system, which has a much smaller footprint, and by using a wideband radar system with a radar range resolution much finer than the snow depth. Season-long observations show scattering from both layer interfaces and from volume scattering. New experiments this winter will be made at a range of incidence angles, to quantify the mangitude of energy coming from layer interfaces compared to volume scattering from within the layers.

5. P-BAND SIGNALS OF OPPORTUNITY RECEIVER

Another idea for a spaceborne SWE imager is to launch many P-band (300 MHz) receivers, which record the signals from geostationary military communications satellites. This allows a much smaller, lower cost satellite to be launched with only a receiver, which records both the direct signal from the satellite and the reflection from the snow-ground interface. Similar to InSAR, the phase difference can be used to track SWE (Shah et al., 2017). During WY2026, we measured P-band signals from MUOS-5, and Figure 9 shows the relationship between unwrapped phase and SWE, as measured on a digital SOMMERS SWE scale.

6. EDUCATIONAL OPPORTUNITIES

The Brundage research site is accessible by ski lift and less than a 3 hour drive from Boise State University, providing opportunities to bring students during the winter. The data is used in GEOPH 566: Snow and Ice Physics course, and students in GEOPH 567: Snow Science Field Methods visit the site, dig snowpits and compare data to the observations from all of the automated meteorological and snowpack instruments.

ACKNOWLEDGEMENTS

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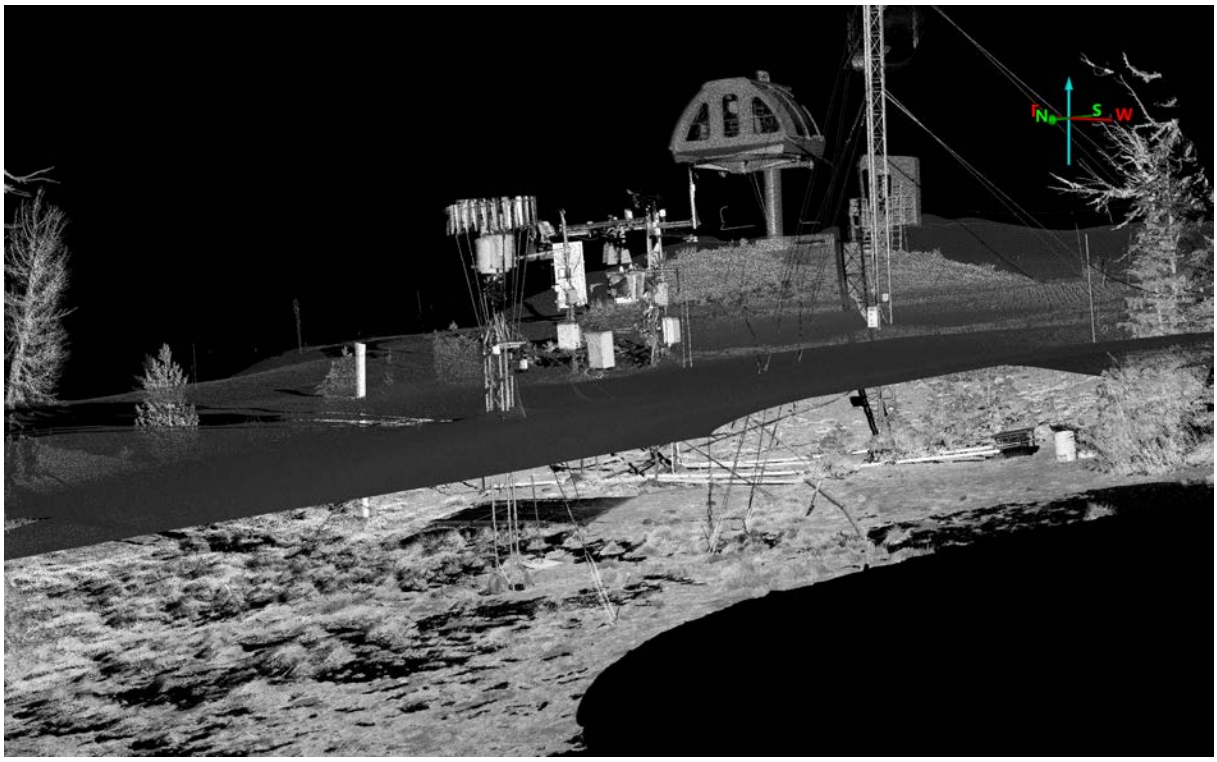


Figure 6: Example scan on March 16, 2026 showing both the snow surface and the underlying ground surface.

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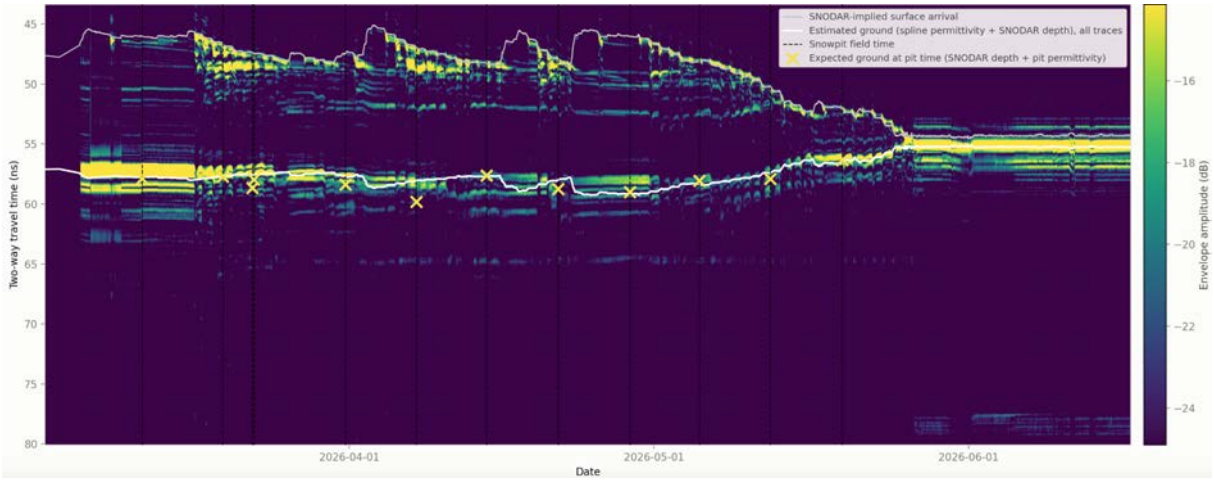


Figure 7: Time series data from a 500MHz–6 GHz FMCW radar system, showing penetration during melting conditions.

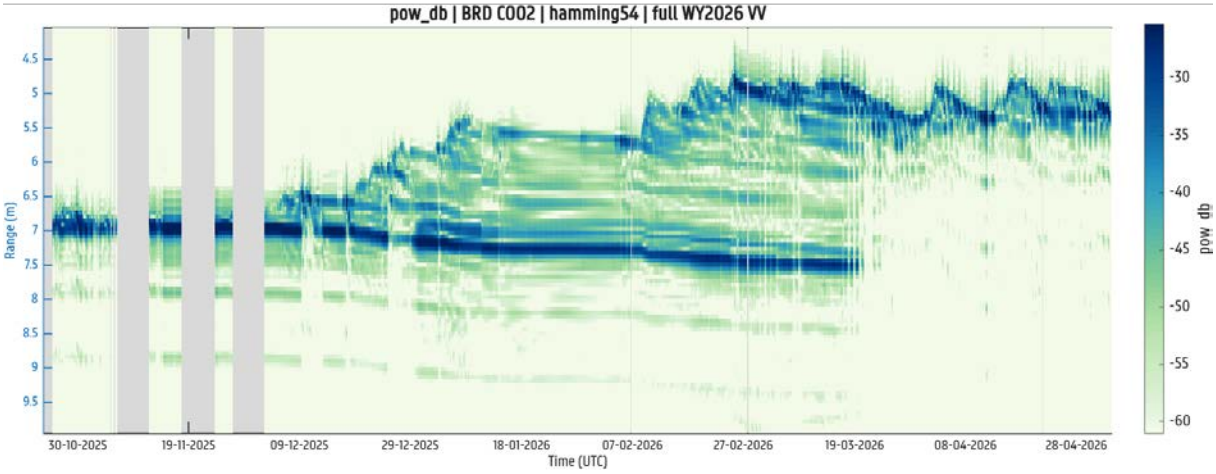


Figure 8: Broadband (5–6 GHz) backscatter at C-band at 0 degrees incidence and VV polarization.

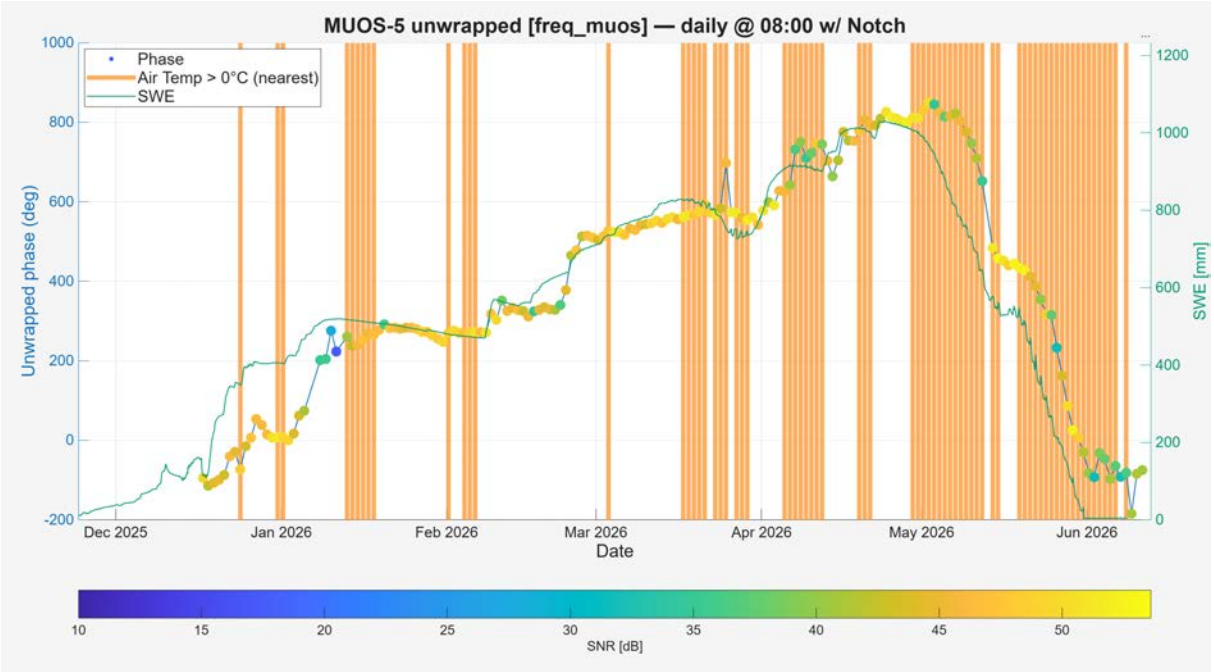


Figure 9: Pband unwrapped phase compared to SWE from a scale at the Brundage site, WY2026.



Figure 10: Boise State University GEOPH 567: Snow Science Field Methods class at Brundage Site.