

DETECTING LIQUID WATER IN SNOW AND RETRIEVING SNOW PROPERTIES WITH HYPERSPECTRAL IMAGING AND UPWARD LOOKING RADAR; A NEW ERA IN SNOWPIT CHARACTERIZATION AND REMOTE SENSING

Kevin Hammonds^{1*}, Christopher Donahue¹, and McKenzie Skiles²

¹ Montana State University, Department of Civil Engineering, Bozeman, MT, USA

² University of Utah, Department of Geography, Salt Lake City, UT, USA

ABSTRACT: Water flow through snow, due to snowmelt or rain-on-snow events, is a heterogeneous process that has implications for snowmelt timing and magnitude, snow metamorphism, albedo evolution, and avalanche hazard prediction. However, there remains no standardized method for the remote retrieval of liquid water content from a snow surface or from within a snowpack, hindering our knowledge of where and how much liquid water is in the snowpack at any given time. To address this limitation, a series of experiments were conducted from within a controlled cold laboratory environment, where snow samples of prescribed microstructures were exposed to simulated melting conditions while being monitored with a near-infrared hyperspectral imaging system and upward-looking polarimetric radar. Following each experiment, the snow samples were characterized using X-ray computed microtomography (micro-CT), a dielectric liquid water content sensor, and serial-section reconstructions via hyperspectral imaging. In addition to these laboratory experiments, hyperspectral imaging snow property retrieval methods were further developed and tested in the field during wet snow conditions at the snowpit scale. The primary outcomes from this work include 1) a new hyperspectral imaging method to map effective snow grain size, 2) the optimal radiative transfer mixing model to simulate wet snow reflectance was determined and used to map liquid water content in snow, and 3) snow melt progression was monitored using continuous upward-looking polarimetric radar, where it was found that when compared to 3-dimensional liquid water content retrievals from hyperspectral imaging, that the cross-polarized radar signal was sensitive to the presence of preferential flow paths.

KEYWORDS: snow, liquid, radar, hyperspectral, micro-CT, mapping

1. INTRODUCTION

Note to reader: In the paper presented herein, the data and methods have already been published in detail in Donahue et al. (2020), Donahue et al. (2022), and Donahue and Hammonds (2022). Therefore, this paper is focused more on the potential applications of this body of work, rather than on the details of the experimentation and results, for which the reader is encouraged to reference these previously published studies.

In recent decades, optical and radar remote sensing technology has advanced our ability to measure key snow parameters through spaceborne, airborne, and ground-based platforms. However, gaps remain in snow remote sensing knowledge and many opportunities exist for better interpretation of these datasets. One important gap is remote sensing of wet snow properties because the presence of liquid water, hereafter referred to as water, changes snow into a three-phase material (i.e., ice, water, and air),

which impacts the physical, optical, and dielectric properties. Additionally, the changes to these properties are spatially and temporally variable due to the infiltration of water into the snowpack being heterogeneous and the liquid water content (LWC) varying over diurnal cycles. To address this knowledge gap, we highlight here our recent work in snow remote sensing from the laboratory and field-based perspectives.

2. BACKGROUND

Understanding wet snow processes and snowmelt timing is of interest to the avalanche and hydrology communities because the presence of water directly impacts snow stability and runoff timing. Using remote sensing to monitor these processes is an active area of research, but challenges remain due to the heterogeneous nature of melt initiation and water infiltration in a snowpack over space and time. Water is first introduced into a snowpack at the surface during melt initiation or rain-on-snow events. Once the surface layer becomes saturated, water percolates vertically into deeper layers of the snowpack, which is generally classified by two mechanisms: (1) matrix flow and (2) preferential flow Colbeck (1979), Schneebeli (1995). Matrix flow describes a semi-uniform vertical melting front, while preferential flow

* Corresponding author address:

Kevin Hammonds, Montana State University,
Bozeman, MT 59718;
tel: +1 406-994-2167;
email: kevin.hammonds@montana.edu

describes concentrated vertical water pathways that extend deep into the snowpack beyond matrix flow Webb et al. (2018). Matrix flow typically has broad horizontal extent that is relatively easy to identify using radar remote sensing Mitterer et al. (2011), whereas preferential flow paths are spatially variable and typically vertically oriented, making them difficult to detect non-destructively using remote sensing techniques

At the ground-based scale, radars are commonly pulled on a sled to collect transects McGrath et al. (2019) or mounted to a tower for continuous monitoring Marshall & Robertson (2016), both of which collect data in a downward-looking nadir configuration relative to the top of the snow surface. When snowmelt initiates, radars in this configuration get large magnitude returns at the snow surface and microwave penetration into the snowpack is reduced, making it difficult to track snowmelt progression. To mitigate this problem, some studies Gubler & Hiller (1984), Mitterer et al. (2011) have buried radars in the ground in an upward-looking configuration to monitor the snowpack from below. This configuration is advantageous in wet snow conditions because the radar can track homogenous matrix flow as it moves towards the radar Mitterer et al. (2011), however, preferential flow paths have yet to be detected using upward- or downward-looking radar systems.

Previous studies using upward-looking radar to monitor wet snow have used single co-polarized radar systems, which are generally limited to detecting planar single-scattered features in the snowpack, like the horizontal extent of matrix flow. Prior to the research presented here, a polarimetric radar (i.e. co-pol and cross-pol) had yet to be used in an upward-looking configuration to monitor snowmelt processes, but it could provide additional information about the orientation and structure of melt pathways, like vertical preferential flow paths. The primary goal of this body of work was to use a polarimetric radar in an upward-looking configuration to determine if cross-polarized radar returns could be leveraged to help classify wet snow process (i.e., matrix vs preferential flow). To achieve this goal, experiments were conducted in a controlled laboratory environment where snow layer structure and snow melt timing could be controlled, and the final state of the wet snow sample could be precisely characterized.

However, to achieve the primary goal, a new methodology was needed to characterize laboratory snow samples at the scale ($\sim 0.5 \text{ m}^3$) of radar experiments in terms of LWC and grain size distribution. Previous to this work, in situ

instruments were limited to discrete point measurements for LWC Denoth (1994), A2 Photonic Sensors (2019) and grain size Painter et al., (2007), Gergely et al. (2014), which do not adequately capture the spatial variability of snow microstructure. Similarly, X-ray computed microtomography (micro-CT) is frequently used in laboratory experiments to measure snow grain size and other microstructural properties, but the sample size used for analysis is relatively small (cm scale) compared to the scale at which patterns in water infiltration manifest. The need for these new methods led to the development of new optical remote sensing methods that could quantify snow properties in high spatial resolution maps, rather than discrete point measurements, via near infrared hyperspectral imaging.

With the hyperspectral imager, obtained from Reonon Inc., the first objective was to develop an effective snow grain size mapping method using hyperspectral imaging, which could be used to characterize grain growth due to the presence of water (i.e., wet snow metamorphism) Donahue et al. (2020). Building upon the first objective, the second objective was to develop a hyperspectral imaging method to map the LWC across the vertical profile of a wet snow sample. Although these two retrieval methods were developed in a laboratory, they were subsequently tested in the field by imaging a snowpit sidewall Donahue et al. (2022). Using the results from objectives one and two, the third objective was to reconstruct the retrieved snow properties in 3-dimensions using a serial-sectioning approach, which could be used for comparison to the polarimetric radar measurements Donahue and Hammonds (2022).

3. RESULTS

The work presented here led to a number of novel results and methods, however, presented below are only those most relevant for avalanche practitioners.

First and foremost, we present a novel methodology and retrieval algorithm for retrieving LWC and the snow specific surface area (SSA) using hyperspectral imaging. This technology and retrieval algorithm make possible a vastly new approach to more standardized snowpit characterizations, given that the LWC and SSA can be retrieved on the pixel scale of the camera ($\sim 0.5 \text{ -} 2 \text{ mm}$). As shown in Figure (1), adapted from an image of a wet snowpack at the Bridger Bowl Ski Area, this capability allows the practitioner to not only see in more detail the stratigraphy of the snowpit, but to also quantify the regions of higher/lower values of LWC and SSA. This is thought to be of particular relevance to avalanche practitioners, given 1) the limited

time they have available to characterize a snowpit, 2) the dramatic spatial variability in LWC and SSA that can exist across a snowpit wall, and 3) the SSA of the individual grains of a dry snowpack can also be characterized, which have been shown to have direct correlations to the snow grain morphology.



Figure 1: Overlay of hyperspectral image on snowpit wall excavated in wet snow conditions at Bridger Bowl. Dark blue regions represent regions of high LWC.

Second, we present the findings from our polarimetric and co-pol upward-looking radar experiments. Shown in Figure (2), is an example of the polarimetric radar data (left) and 3-D reconstruction of LWC (right) from our hyperspectral camera. Also shown in Figure (3), is an example of water pooling at a capillary barrier from a laboratory experiment, where only the co-pol radar data is shown, highlighting the utility of co-pol data for observing the location of water pooling in a snowpack in real time, which is also perhaps easier to interpret than the cross-pol data.

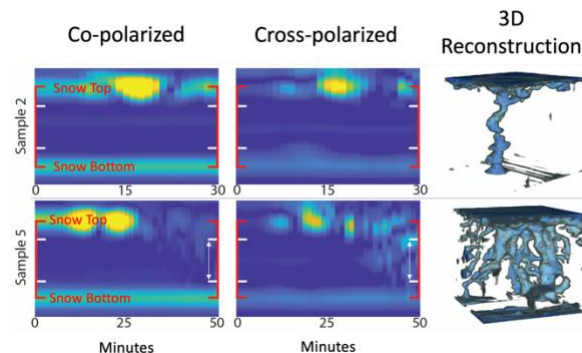


Figure 2: Radar data (left) and hyperspectral camera LWC reconstruction (right) of two wet snow laboratory experiments, as adapted from

Donahue and Hammonds (2022). These two samples were chosen to show the disparity in the cross-pol data between a single liquid water path and multiple liquid water paths through the snow sample. Notice that this cannot be discerned from the co-pol data alone. The snow volume used was approximately 40x40x40 cm. In the radar data, yellow represents high radar reflectivities, while dark blue represents no reflectivity. In the hyperspectral data, the LWC threshold chosen for these images was that greater than 5% LWC.

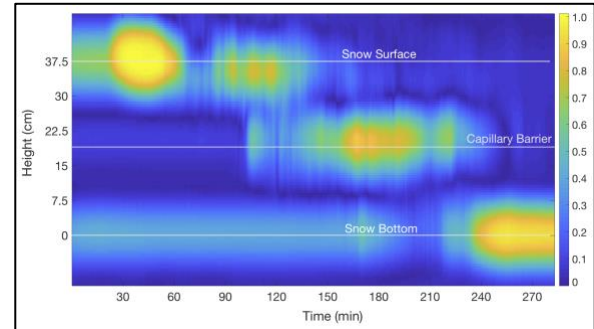


Figure 3. Upward-looking co-pol radar data from a laboratory experiment of liquid water percolation through snow where a capillary barrier had been created at mid-height. Similar to Figure 2, yellow shows high radar reflectivity, while dark blue shows no reflectivity. Notice that liquid water pooling can be easily observed at the surface, at the capillary barrier, and at the bottom of the artificial snowpack. Snowpack dimensions were 40x40x40 cm and the melt was due to simulated solar heating at the surface from within a -5°C cold room.

4. DISCUSSION & CONCLUSIONS

In its totality, this work highlights the potential advantages of using hyperspectral cameras in the field for snowpit characterizations, as well as the benefits of upward-looking radar for liquid water observations in snow. Furthermore, with the deployment of unmanned aerial vehicles (UAV's) becoming common in many remote sensing applications, it seems plausible to also extend these retrieval algorithms to downward-looking hyperspectral camera units, which if used in tandem with other instruments like lidar, could be used to successfully map snow grain habits over wide areas, as well as obtaining snow depth, slope, and aspect data. This work has yet to be done, but with the ubiquity of UAV's and the increasing affordability of lidar, radar, and hyperspectral cameras, it would seem as though it is only a matter of time before the deployment of these instruments for avalanche forecasting purposes also becomes common-place.

In summary, we show in Tables 1 and 2 what the future of snowpit characterizations and snow surface mapping may look like with the implementation of these more advanced remote sensing instruments. Although some snowpit measurements will likely remain manual measurements by necessity (e.g. snow hardness, stability tests, etc.), the potential for a more automated and efficient means of snowpit characterization seems to be upon us.

Snowpit Characteristic	Capable Instrument
Depth	Manual
Hardness	Manual
Temperature	Manual
Density	Manual
Stratigraphy	Hyperspectral
Grain Type (Replace w/ SSA)	Hyperspectral
Grain Size (Replace w/ SSA)	Hyperspectral
Liquid Water Content	Hyperspectral

Table 1: Display of typical measurements made manually in a snowpit (left column) and what instrument they may be replaced or augmented with (right column).

Remote Mapping & Detection	Capable Instruments (UAV or Stationary Sites)
Snow Depth	Lidar, Radar
Snow Surface Density	Lidar
Surface Hoar Detection	Hyperspectral
Surface Grain Type (Replace w/ SSA)	Lidar, Hyperspectral
Surface Grain Size (Replace w/ SSA)	Lidar, Hyperspectral
Liquid Water on Surface	Lidar, Hyperspectral, Radar
Liquid Water Location in Snowpack	Upward Radar
Slope Angle	Lidar
Slope Aspect	Lidar

Table 2: Display of remote mapping and detection measurements that could be useful for avalanche forecasting applications (left) and the current instruments that may be used for their quantification and mapping (right). It should be noted that further information on current snow lidar research is given in ISSW 2023 abstracts 304 and 306.

ACKNOWLEDGEMENT

This research was supported by NASA New Investigator Program Award 80NSSC18K0822. Additionally Skiles, was supported by the University of Utah GCSC, SWC, and Nexus. We acknowledge Resonon Inc. for supplying the hyperspectral imager used in this study. We also acknowledge the use of the Subzero Research Laboratory in the Department of Civil Engineering at Montana State University.

REFERENCES

- A2 Photonic Sensors 2019. WISE - Snow liquid water content sensor - User Manual.
- Colbeck, S. 1972. A theory of water percolation in snow. *Journal of glaciology*, 11(63): 369-385.
- Denoth, A. 1994. An electronic device for long-term snow wetness recording. *Annals of Glaciology*, 19: 104-106.
- Donahue, C., S.M. Skiles and K. Hammonds 2020. In situ effective snow grain size mapping using a compact hyperspectral imager. *Journal of Glaciology*, 67(261): 49-57.
- Donahue, C., S.M. Skiles and K. Hammonds 2022. Mapping liquid water content in snow at the millimeter scale: an intercomparison of mixed-phase optical property models using hyperspectral imaging and in situ measurements. *The Cryosphere*, 16(1): 43-59.
- Donahue, C., K. Hammonds, 2022. Laboratory Observations of Preferential Flow Paths in Snow Using Upward-Looking Polarimetric Radar and Hyperspectral Imaging. *Remote Sensing*, 14, 2297.
- Gergely, M., F. Wolfsperger and M. Schneebeli 2014. Simulation and Validation of the InfraSnow: An Instrument to Measure Snow Optically Equivalent Grain Size. *Geoscience and Remote Sensing, IEEE Transactions on*, 52: 4236-4247.
- Gubler, H. and M. Hiller 1984. The use of microwave FMCW radar in snow and avalanche research. *Cold Regions Science and Technology*, 9(2): 109-119.
- Marshall, H.-P. and M. Robertson 2016. Continuous Real-time Snow Properties with Ground Penetrating Radar. *Proceedings of the 2016 ISSW, Breckenridge, CO*.
- McGrath, D., R. Webb, D. Shean, R. Bonnell, H.P. Marshall, T.H. Painter, N.P. Molotch, K. Elder, C. Hiemstra and L. Brucker 2019. Spatially extensive ground-penetrating radar snow depth observations during NASA's 2017 SnowEx campaign: Comparison with In situ, airborne, and satellite observations. *Water Resources Research*, 55(11): 10026-10036.
- Mitterer, C., A. Heilig, J. Schweizer and O. Eisen 2011. Upward-looking ground-penetrating radar for measuring wet-snow properties. *Cold Regions Science and Technology*, 69(2-3): 129-138.
- Painter, T.H., N.P. Molotch, M. Cassidy, M. Flanner and K. Steffen 2007. Contact spectroscopy for

determination of stratigraphy of snow optical grain size. *Journal of Glaciology*, **53**(180): 121-127.

Schneebeli, M. 1995. Development and stability of preferential flow paths in a layered snowpack. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences*, **228**: 89-96.

Webb, R., M.W. Williams and T. Erickson 2018a. The spatial and temporal variability of meltwater flow paths: Insights from a grid of over 100 snow lysimeters. *Water Resources Research*, **54**(2): 1146-1160.