CONTINUOUS ASSESSMENT OF SNOWPACK PHYSICAL PROPERTIES USING RADAR TECHNOLOGY: INSIGHTS FROM TWO WINTER SEASONS IN GLACIER NATIONAL PARK, CANADA

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ABSTRACT: Consistently assessing the physical properties of the snowpack throughout the winter season is both demanding and indispensable. The ongoing evaluation of the snow's physical properties is crucial for various purposes, including satellite remote sensing applications and avalanche forecasting. A temporal dataset spanning two winter seasons was obtained from a 24 GHz Frequency Modulated Continuous Wave radar positioned at the Fidelity station in Glacier National Park, Canada. The radar continuously evaluated the snowpack at 15-minute intervals throughout the 2019 spring and the 2021-2022 winter. The 2019 spring season was characterized by early melt events followed by refreezing of the snowpack surface before the ablation period in May. Contrasting the lower snow height of the 2018-2019 season (max 295cm), the 2021-2022 winter experienced high snow height (max 431cm). The radar retrieved accurate snow height measurements for both seasons. Evaluation of snow water equivalent (SWE) yielded satisfactory results in both years, with the radar validating a maximum SWE measurement of 1660 mm in the 2021-2022 winter. Within the 2019 spring, melt/freeze events were identified by the radar. Surface refreezing was observed in the signal throughout the spring. The 2021-2022 winter saw a significant rain event in early December that led to an ice crust, triggering a major avalanche cycle and raising concerns throughout the winter. The crust was visible within the radar signal for most of the season. This sensor shows good potential for a variety of applications within mountainous areas for continuous evaluation of the snowpack's vertical and bulk properties.

Keywords: Snowpack assessment, Radar measurements, Snow height, Snow water equivalent (SWE), Remote sensing

1. INTRODUCTION

Avalanche forecasting traditionally hinges on a combination of meteorological observations, instability assessments, and detailed snow stratigraphy analysis (McClung (2002)). The accuracy of these assessments depends on precise data collected in the field. However, acquiring comprehensive stratigraphic data is often constrained by the limitations of time, spatial coverage, and labor-intensive efforts, leading to only localized snapshots of snow conditions. Additionally, accurately capturing and analyzing dynamic processes, such as water percolation within the snowpack, remains problematic due to significant daily variations in liquid water content (LWC) (Mavrovic et al. (2020); Madore et al. (2022)). These variations are crucial because they directly influence snow stability and the potential for persistent weak layers that drive avalanche activity. As such, the traditional reliance on manual profiles and punctual measurements presents clear gaps in data quality, continuity, and representativeness.

In recent years, technological advancements have provided new avenues for addressing these challenges. Among them, remote sensing techniques, particularly using 24 GHz Frequency-Modulated Continuous-Wave (FMCW) radar, have emerged as promising solutions. These radar systems offer the ability to detect snow stratigraphy and key features, such as melt-freeze crusts, with high precision (Pomerleau et al. (2020);Laliberté et al. (2022)). Melt-freeze crusts are especially significant in avalanche forecasting as they can indicate snowpack strengthening after overnight refreezing or become a foundation for persistent weak layers depending on their burial depth and surrounding snow conditions. The capacity of FMCW radar to continuously monitor these crusts and other stratigraphic layers represents a major advancement over traditional field methods.

However, while the potential of these radar systems is well-documented, deploying them effectively in deep snow environments remains an ongoing challenge. Variations in snow depth, density, and water content can influence radar performance, requiring adjustment of the radar signal. This paper focuses on capturing reliable, season-long data on snow properties with a low cost FMCW radar. By doing so, we aim to advance the understanding and mon-

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itoring of critical snowpack characteristics that directly impact avalanche risk assessments. Integrating high-precision radar data with traditional methods could lead to more robust and timely avalanche forecasting practices, reducing risk for backcountry users and communities in avalanche-prone regions.

2. METHODOLOGY

2.1 Study site

The study site is located on Mount Fidelity at the Fidelity station, positioned on the western border of Glacier National Park, British Columbia, at an altitude of 1,905 meters. This site serves as the primary reference point for Glacier National Park's Avalanche Control Program, playing a crucial role in monitoring snowpack properties, stability, weather conditions, and conducting explosive tests. Due to its central role in the avalanche control strategy, Mount Fidelity is designated as a research-only zone, off-limits to park users. Preserving snow conditions at this site ensures the accuracy of ongoing evaluations and research.

Mount Fidelity is part of the Selkirk Mountains, one of the snowiest regions in Canada, where the snowpack at the study plot can exceed 4 meters in depth and cumulative snowfall can surpass 15 meters in a single season. This extreme snow accumulation contributes to frequent avalanches, which pose significant risks to public safety, including threats to the TransCanada Highway, railroads, and backcountry users in the Rogers Pass area (Schleiss (1990)). Given the heavy reliance on this route, accurate and timely data from this site are critical for preventing large-scale avalanche events.Access to the study site is maintained via dedicated snowcat tracks, and the area is equipped with a automated weather station and remote sensing instruments operated by the University of Sherbrooke. On-site measurements include air and snow surface temperatures, relative humidity, wind speed and direction, net radiation, and snow depth. Additionally, Parks Canada technicians record storm snow height (HST) and height of new snow (HN24) during their regular visits. The isolated nature of the site, combined with consistent monitoring, ensures that the data collected remains untainted by external influences. The snowpack at Mount Fidelity typically exhibits complex layering, including melt-freeze crusts and weak layers, making it an ideal site for radar measurement experiments.

2.2 FMCW Radar theory

Frequency Modulated Continuous Wave (FMCW) radars differ from synthetic aperture radars by emitting a continuous signal rather than discrete pulses. The modulation of this signal allows for precise distance measurements (Stove (1992)). An FMCW radar emits a continuous wave (constant λ and f) and calculates the phase difference between the transmitted and received signals. Knowing the propagation speed, the distance d can be determined using the equation:

$$d = \frac{1}{2}\left(\frac{v_s \cdot (\Delta f \cdot T_{pl})}{B}\right) = \frac{1}{2}\left(\frac{c}{\sqrt{\epsilon_s}} \cdot \frac{\Delta f \cdot T_{pl}}{B}\right) \quad (1)$$

Where v_s represents the velocity of propagation in snow and T_{2w} is the two-way travel time of the signal. The T_{2w} can be expressed as $\frac{\Delta f \cdot T_{pl}}{B}$, where Δf is the frequency difference, T_{pl} is the duration of the frequency sweep, and B is the bandwidth of the signal. The velocity v_s depends on the mean dielectric constant ϵ_s of snow and c, the speed of light (Marshall et al. (2004)).

FMCW radar signals are influenced by snow density and wetness, which determine the dielectric constant under dry and wet conditions, respectively (Tiuri et al. (1984); Mitterer et al. (2011)). Our study utilized a commercial 24 GHz IMST Sentire™ sR-1200 Series FMCW radar, as described by Pomerleau et al. (2020). This radar has a field of view of 65° in azimuth and 24° longitudinally, with a 2.5 GHz bandwidth. The emitted wave propagates through the snow and reflects back, allowing snow depth estimation based on half the distance traveled by the signal. However, signal speed differs from light speed due to snow's unique properties.

To improve the resolution of radar measurements, we applied zero-padding interpolation, extending the signal with zero-valued samples to increase data points. Previous work (Laliberté et al. (2022); Kramer et al. (2023)) introduced a correction using the refractive index (RI) of snow, which is a function of snow density, following Tiuri et al. (1984):

$$RI = \sqrt{\epsilon_s'} = 1 + 1.7\rho_s + \sqrt{0.7\rho_s^2} \quad (2)$$

where ϵ_s' is the real part of the dielectric constant, dependent on snow density ρ_s under dry conditions. Pomerleau et al. (2020) proposed an algorithm capable of retrieving snow water equivalent (SWE) using the FMCW system employed in this study. In the range of 0 to 500 mm, their work suggested an accuracy of about 30% in estimating SWE. We applied their approach to evaluate SWE using the following equations from Pomerleau et al. (2020):

$$\epsilon_{sd} = \left(\frac{h_{\text{radar raw}} - h_{\text{air}}}{h_s}\right)^2 \quad (3)$$

$$\text{SWE} = h_s \times \rho_s = h_s \times \left(-1.7 + \sqrt{\frac{2.89 + 2.8(\epsilon_{sd} - 1)}{1.4}}\right) \quad (4)$$

Where ϵ_{sd} is the mean effective permittivity, h_s is the radar-derived snow depth, $h_{\text{radar raw}}$ is the raw radar-measured distance, and h_{air} is the snow surface distance at an angle of 23°, uncorrected for the refractive index.

2.3 Radar installations

Two different setups were implemented to record the radar datasets. The first setup collected data during the winter and spring of 2019, with the radar mounted at a height of 3.67 meters on a wooden tower. After the site renovation and the installation of new, taller steel towers, the setup was reinstalled in autumn 2021, with the radar positioned at a height of 5.20 meters (Figure 1). Both setups were angled downward at 23°, pointing towards an aluminum plate positioned at the same angle to clearly identify the snow-soil interface. This setup allows snow depth derivation without prior RI quantification by using the contrast in signal amplitude between the air and the snow surface. The snow depth h_{snow} can be calculated from the radar height h_{radar} and the optical distance d_{snow} using the following equation:

$$h_{\text{snow}} = h_{\text{radar}} - (\cos(\angle_{\text{snow}}) \cdot d_{\text{snow}}) \qquad (5)$$

This data is filtered on a 6-hour basis to ensure accuracy and consistency in snow depth measurements.

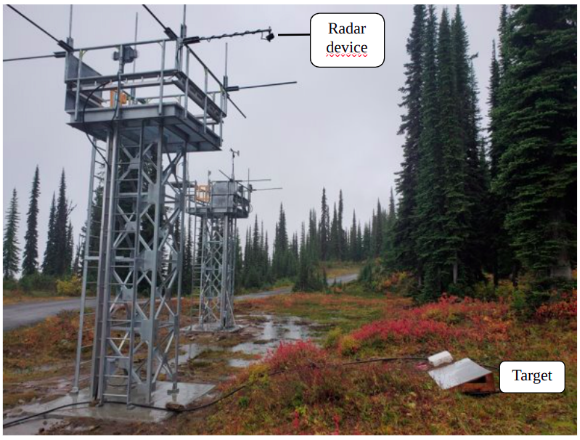

Figure 1: 2021-2022 winter radar installation at the Fidelity station.

3. RESULTS

3.1 Winter 2018-2019 vs Winter 2021-2022

The two winters evaluated exhibited significantly different characteristics. The 2018-2019 season experienced higher monthly average air temperatures from January to June compared to the 2021-2022 season, which had an unusually cool spring. Precipitation during the 2018-2019 winter was below average, resulting in a maximum snow accumulation of 3 meters. In contrast, the 2021-2022 season saw above-average precipitation, leading to a maximum snow height of 4.3 meters, compared to the typical 3.5 meters. Notably, the 2021-2022 winter was impacted by a significant amount of liquid precipitation due to an atmospheric phenomenon in early December. The crust that formed during this event persisted throughout the season and evolved into a critical weak layer, particularly by mid-January, when a major avalanche cycle occurred. In contrast, the spring of 2018-2019 saw multiple wet avalanche cycles driven by diurnal melt-freeze patterns starting in mid-March. These contrasting years underscore the variability in snowpack conditions in Glacier National Park.

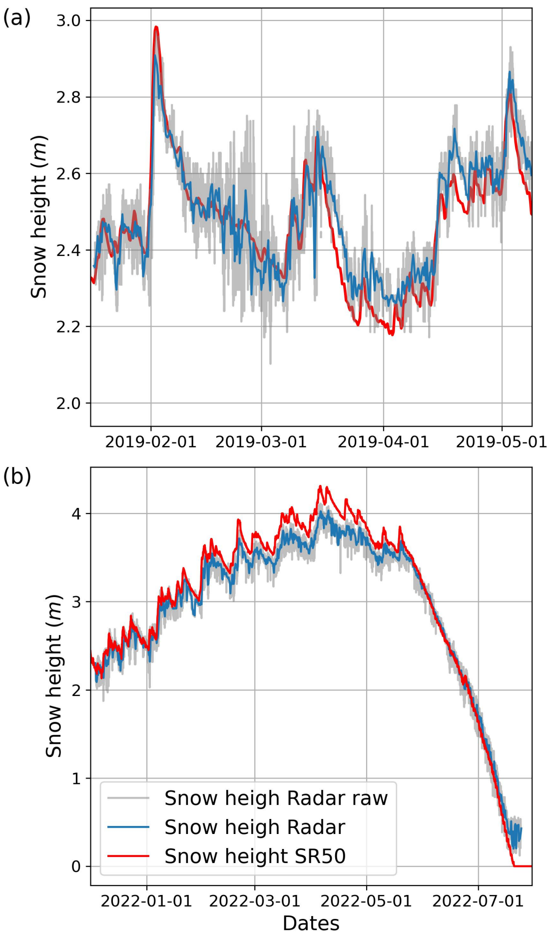

Figure 2: Snow height measurement with the FMCW radar and the SR50 device at the Fidelity station for a) 2018-2019 and b) 2021-2022 winter.

3.2 Radar snow height retrieval

The equation (5) was used to determine snow height with the radars, adapting to varying snow conditions. Both years produced promising results; however, the winter of 2021-2022 exhibited more stable distance surface readings (Figure 2). It should be noted that with the replacement of the towers,

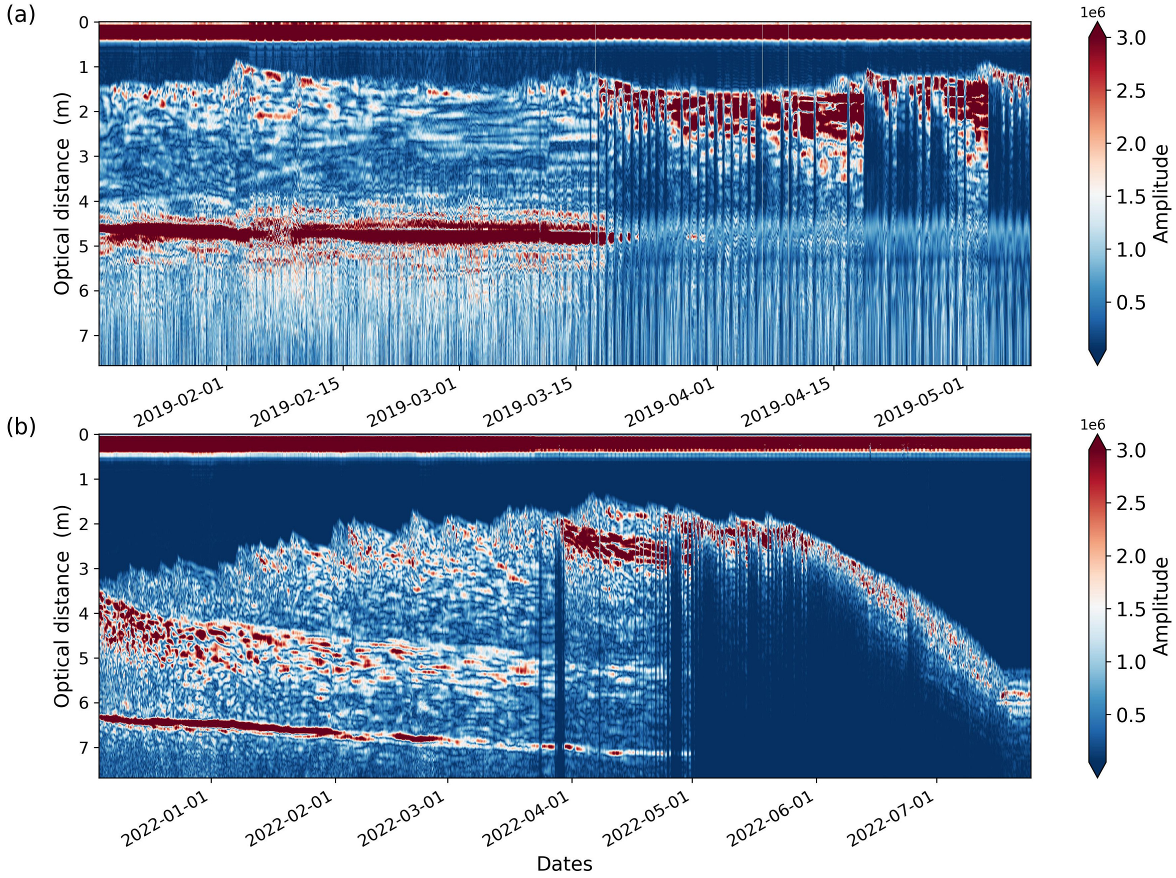

Figure 3: Temporal radar amplitude for the a) 2018-2019 and b) 2021-2022 winter.

the snow height reference instrument (SR50) was also reinstalled, which affected the reference data due to its placement at a higher elevation in 2021-2022. The radar's snow height measurements for 2021-2022 showed strong correlation with the reference data up to a snowpack depth of 3.5 meters. Beyond this point, the radar consistently underestimated snow height, with a maximum discrepancy of 40 cm in mid-April when snow height peaked. The offset in measured snow height gradually diminished to approximately 0 cm by the end of May as the snowpack returned to around 3.5 meters.

3.3 Radar amplitude evaluation

The internal reflection of the radar can be observed in both winters within the first 30 cm (Figure 3). The radar installed during the winter of 2018-2019 was active from mid-December to mid-May. The reference plate remained visible until the onset of melt/freeze events in March. Although the influence of the reference plate can still be detected afterward, it lacks precision due to the reduced return amplitude following the melt events. The diurnal melt/freeze cycles in spring are primarily identified by surface refreezing and the formation of denser crusts. Refreezing at the top of the snowpack from mid-March to mid-April is visible until April 17th, when increasing moisture in the snowpack prevented the signal from penetrating further.

The 2021-2022 radar was active from December to July. The profile showed greater interaction with the snow structure during the dry state of the snowpack. Notably, the reference plate remains discernible in the profile even at considerable snow depths. Although the plate returned lower amplitude signals when the snowpack reached 4 meters, it still reflected more than the surrounding snow. Additionally, the melt/freeze crust recorded in early December is clearly visible throughout the winter. Another crust, formed at the end of March, is also evident until the onset of spring melt. The increased refractive index is well illustrated by the position of both the plate and the December crust.

3.4 SWE measurments

The SWE measurements were calculated using the radar and compared to the monthly measurements made by the Park's technicians with a Federal sampler. During the winter of 2018-2019, only two data points fell within the measurement range. In contrast, the winter of 2021-2022 had more data available, with four measurements made by the Park's technicians. Although the limited data prevents a precise analysis of the accuracy of the SWE retrieval, it provides enough information to confirm that the method is functioning as intended. Variations in the radar-derived values are influenced by the radar's ability to detect the signal from the plate. The anomalies, which are primarily due to the moistening of the snowpack surface, can be observed in Figure 3, where the plate's signal disappears.

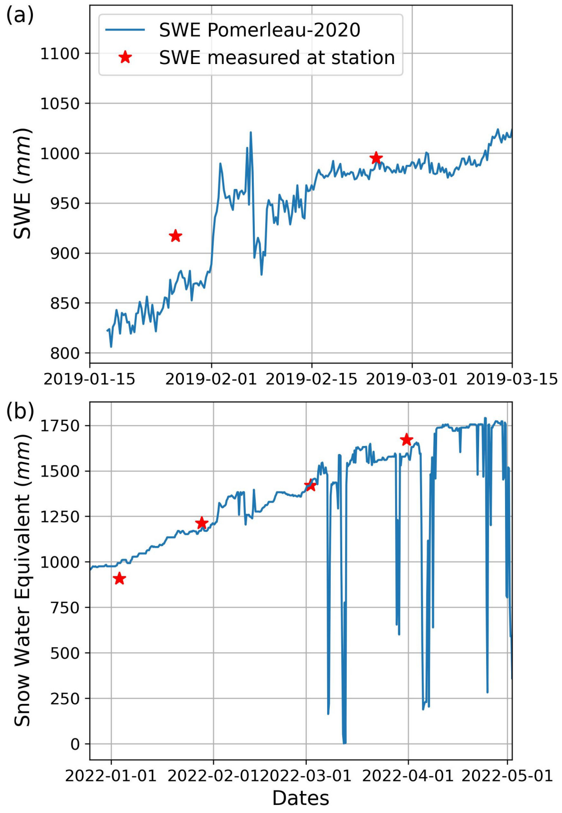

Figure 4: SWE retrieval from the radar data for the a) 2018-2019 and b) 2021-2022 winter.

4. DISCUSSION

The main challenge in recording data during both winters was due to the harsh conditions and limited accessibility in the mountainous areas. In both years, the recording of autumn snowfall was missed due to logistical issues. This prevented the collection of valuable data that could have helped to understand how the signal behaves with shallow snow, especially in evaluating the refractive index and retrieving the reference plate. We hypothesize that much of the noise in the first dataset (2018-2019) could be linked to the instrument and the setup. First, more noise was recorded within the air portion of the signal in the first winter, which could be directly related to the device itself. Second, in the 2021-2022 setup, the radar was positioned higher, allowing more snow to be evaluated and keeping the snow further from the radar at all times. Although the height of the radar could have been a problem in the first year, it fortunately coincided with a low-snow year. Thirdly, the initial setup was installed in September, without realizing that the reference plate was placed in an area where water accumulates during snowmelt.

Snow height was retrieved for both winters. The retrieval of the snow surface could be noisy partly due to the type of snow at the surface and, as previously mentioned, due to device noise. The systematic underestimation in the second winter could be linked to the fixed angle of 23° used in the equation. The radar's viewing angle is large (24° in elevation) and affects the conversion of the ranging signal to vertical snow height. This angle should be adjusted as snow height increases. In both years, interesting snow structures were identified by analyzing the amplitude. The identified structures are mainly ice crusts formed after melt/rain events. This aspect is crucial and could be used as a tool for avalanche forecasting purposes. The December 2021 event is of particular significance, as the crust depth is well identified throughout the season. More work is needed to distinguish the portion of the crust depth related to settlement from the portion influenced by additional snow and an increased refractive index. Another noteworthy observation is the crust's decomposition, which appears to have started in March. The impact of the snow accumulation on top of the crust and its effect on the signal amplitude need further study to draw definitive conclusions. Additionally, the successful retrieval of 1750 mm of SWE with the radar during the 2021-2022 season is a promising result. The radar's ability to detect the reference plate at this depth using a 24 GHz antenna exceeded expectations. This underscores the relevance of this device for use in deep snowpacks for snow characterization.

5. CONCLUSION

This study demonstrated the potential of FMCW radar for snowpack characterization in alpine environments, with a focus on retrieving snow height, snow structure, and SWE. Despite challenges related to data collection under difficult conditions, the radar setups in both winters provided valuable insights into snowpack dynamics. The systematic underestimation observed in the 2021-2022 season highlights the importance of considering variable radar viewing angles, especially as snow height increases. Additionally, the ability to detect key snow structures such as melt-freeze crusts underscores the utility of radar data for avalanche forecasting.

The retrieval of 1750 mm of SWE in the 2021-2022 season, despite challenging conditions and high snow depth, demonstrates the effectiveness of the radar system used in this study. The successful identification of the reference plate at this depth, using a 24 GHz antenna, suggests that this approach is suitable for monitoring deep snowpacks. Future work should focus on refining the algorithms for snow height and SWE estimation, particularly under conditions where snow density and moisture content vary significantly.

In conclusion, while some limitations and noise were encountered, the results affirm the potential of FMCW radar as a reliable tool for continuous snowpack monitoring and snow structure analysis in remote and challenging environments.

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