RETRIEVING SNOW STRATIGRAPHIC INFORMATION USING A FREQUENCY MODULATED CONTINUOUS WAVE (FMCW) KA-BAND RADAR

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ABSTRACT: Considering the Chic Chocs (Québec, Canada) specific climate and the currently observed regional warming, an increased occurrence of rain-on-snow events and winter thaw leading to the creation of ice crusts in the snowpack have been observed. Between these warm periods, arctic air masses bring very cold dry air promoting faceting. Near-surface crust faceting is one of the most common persistent avalanche problem in the Chic Chocs and needs particular attention. As such, the horizontal and vertical identification of crusts is essential for avalanche forecasting. The goal of this research is thus to detect and assess the vertical ice crusts position using a 24 GHz Frequency Modulated Continuous Wave (FMCW) portable radar. This paper focuses on the methodology development, using different in-situ configurations and comparing the radar amplitude signals with in-situ snow geophysical measurements. Comparision with Snow Micro Penetrometer and stratigraphic profiles will be made to help understand the FMCW radar signature.

KEYWORDS: FMCW radar, Ice crust, snow, stratigraphy, avalanche, SNOWPACK

1. INTRODUCTION

According to Stethem *et al.* (2003), snow stratigraphy is considered as the most important factor in snowpack stability and potential slab avalanche triggering studies. However, with the increase of outdoor activities popularity, backcountry frequented territory is expanding while snow geophysical data remain harder to gather all over the covered areas. Slab avalanches occur most of the time when a weak layer is overlying a sliding surface. Having less cohesion than other grain types, faceted crystal and surface hoar are found in most common weak layers (Jamieson and Johnston, 1992), while wind slab and ice crusts represent the most common sliding surfaces (Jamieson et Langevin, 2005). These crusts are common in the Chic Chocs (Québec, Canada), due to the particular climatology that leads to complex stratigraphy (Fortin and Hétu, 2009). As such, the horizontal and vertical identification of ice crusts is essential for avalanche forecasting. However, their monitoring remains quite difficult with current technology, given the rather large avalanche terrain. Traditional methods currently used by forecasters are time consuming so that a very little portion of the avalanche terrain can be monitored in details. Therefore, there is an urgent need for reliable ice crust detection methods for different topoclimatic contexts. As such, the use of a frequency modulated continuous wave radar (FMCW) represent an interesting avenue. Marshall and Koh (2008) provide a nice overview of various studies made on snow using FMCW radar over the past three decades. They highlight the high potential for gathering stratigraphic, depth and snow water equivalent (SWE) data, but also discuss the remaining challenges. In summary, this paper focuses on a methodology development for detecting the ice crusts vertical location using a 24 GHz FMCW portable radar.

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2. METHODOLOGY

2.1 *Data and study sites*

Data were collected during winter 2018 at eight different sites in Canada; two in the Chic-Choc range (eastern Québec), four on the north shore of the Gaspé Peninsula (eastern Québec) and two at Mount Fidelity in Glacier National Park (British Columbia) and others will be made next winter.

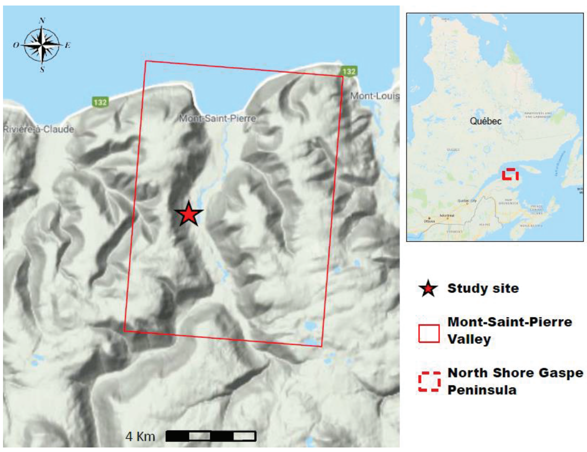

Figure 1. Study site in Mont Saint-Pierre Valley on the north coast of the Gaspe Peninsula

In this paper, we focus on measurements from Febuary 22nd, 2018 at Mont-Saint-Pierre Valley on the north coast of the Gaspe Peninsula (figure 1) where a full deployment of our snow instruments was conducted (figure 2).

Figure 2. Study Plot in Mont-Saint-Pierre Valley

At each site, radar profiles were completed with a 24 GHz central frequency and 2.5 GHz bandwidth FMCW radar measuring snowpack interferences (dB) with a 12 cm resolution and converting it to amplitude signal (Pomerleau, 2016). The radar used for this research is light (280g) and small (9.8cm x 8.7cm x 4.3cm) making it easily transportable and its high frequency oscillation makes it more sensitive to dielectric contrasts and facilitate ice crust detection (Koh *et al.*, 1996). Stratigraphic analysis and microstructure profiles were also completed following the Observation Guideline and Recording Standards for weather, snowpack and avalanches (OGRS) protocol, along with Snow Micro Penetrometer (SMP) measuring high resolution (0.004mm) snow resistance and density (Schneebeli *et al.*, 1999).

2.2 Data gathering

Two different methods have been used: 1) radar looking down toward the surface (fig.3 A) and 2) looking up from the ground, buried under snow (fig.3 B). The functionality of the radar is to calculate the dielectric change and contrast between the different layers. However, given the difficulty in identifying clearly the snow-ground and snow-air interfaces, both methods have been conducted using a reflective metal plate placed at each interface. Measurements with and without the plate were made in order to see the radar's potential in identifying crust remotely. The snowpack of the chosen study site needs to be free of any disturbance (ski tracks, trees, rocks, snow balling, etc.) and essentially needs to contain crusts. Radar profiles were made in each corner of the snowpit. For every spots where radar profiles are made, in-situ data also needs to be taken so they can be compared. Resistance measurements were made with the SMP at the exact same spot where the radar have been done and the geophysical data (temperature, density, grain form, grain size, humidity and snow resistance) have been gathered manually.

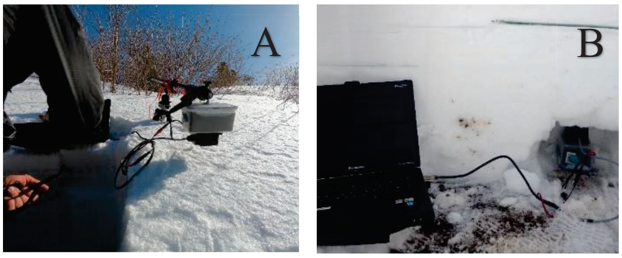

Figure 3. A) Rada looking down, B) Radar looking up

2.3 Data treatment

FMCW radar measure the interference of the dielectric contrast in relation of the depth of the different snow layers by using the following equation:

$$D = \frac{1}{2} V \cdot T_{2w} \qquad (1)$$

where D is the radar-object distance, V the wave propagation speed and T_{2w} the propagation time (Marshall *et al.*, 2005). Originally, the depth is calculated assuming that the radar wave propagates in a vaccum at light speed. However, the snow dielectric constant being different than air, wave propagation speed in the snowpack is slowed down. For this reason, V needs to be replaced by V_{snow} :

$$V_{snow} = \frac{c}{\sqrt{\overline{\varepsilon_s}}} \qquad (2)$$

where C is the speed of light (3x10^8 m/s) and $\overline{\varepsilon_s}$ the snowpack dielectric constant average. According to Tiuri *et al.* (1984) the real part of relative dielectric constant $\varepsilon_s{}'$ depend almost only on the density and can be found with the following equation :

$$\varepsilon_s{}' = 1 + 1.7\rho_s + 0.7{\rho_s}^2 \qquad (3)$$

where ρ_s is the relative density of dry snow (compared to water). Figure 4 shows that it can also be approximated by the linear model $\varepsilon_s{}' = 1 + 2\rho_s$.

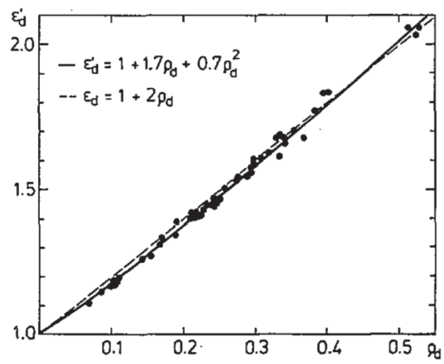

Figure 4. Real part of the dielectric constant of dry snow as a function of the density of dry snow relative to water (Tiuri et al., 1984)

Once the real radar wave propagation speed (V_{snow}) is known for this parcel of snowpack, the conversion factor allowing radar depth to real depth conversion can be found by dividing V_{snow} by the speed of light.

We then simply multiply radar depth by this factor to find estimated real depth.

The amplitudes of observed echoes are then calculated from the different layers. The larger the dielectric change/contrast, the stronger the amplitude, which allows ice crust detection. By knowing the ice crust amplitude threshold and the signal propagation speed through the different snow layers, it becomes possible to identify which peak represents an ice crust and its vertical location. The threshold used to identify significant ice crust peaks is the whole profile amplitude mean.

2.4 Radar and in-situ data comparison

In order to develop a remote ice crust detection method, we have compared FMCW radar profiles with in-situ data to be able to understand the signal-snow interaction. To do so, comparison of radar, SMP and snow profiles have been conducted. Only visual profile and depth values matching comparison have been made for the moment.

3. RESULTS

Downward and upward profiles with and without the reflective metal plate have been made at this site. Although the results are conclusive, for the purpose of conciseness only the downward profile without any metal plate will be analyzed here.

When plotting the radar data for this site, we obtain the profile shown in figure 5. But as mentioned above, the radar signal is slowed down by snow so we need to convert the radar depth to real depth with the conversion factor and subtract the snowpack surface (air-snow interface) to the dataset. This allows the localization of the real amplitude depths. Here, the air-snow interface is the first amplitude peak, which is at 31.19 cm.

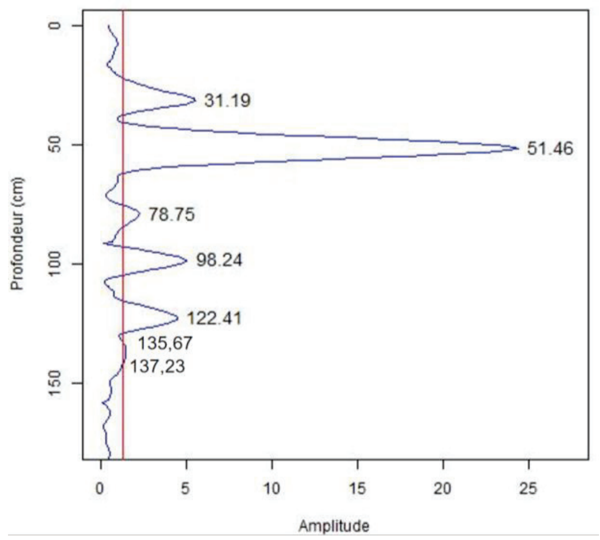

Figure 5. Profile of radar looking down without reflective plate at Mont-Saint-Pierre showing the relation between the amplitude and the radar depth.

The average snow density of this study site was 249 kg/m^3, so using 1000 kg/m^3 as water density, ρ_s=0.249. If we put this value in equation 3, we obtain $\varepsilon_s = 1.467$ and with equation 2, we find V_s = 247 713 973.1 m/s. Finally, when dividing V_s by the speed of light, we obtain the conversion factor (0.8257) we need to convert radar depth to real snowpack depth shown in figure 6.

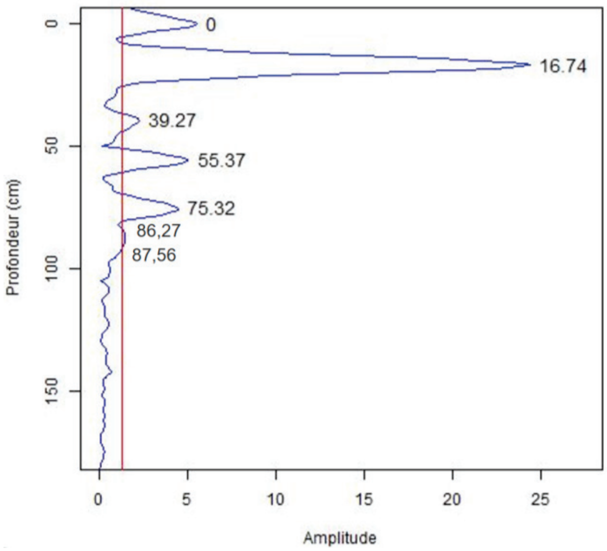

Figure 6. Profile of radar looking down without reflective plate at Mont-Saint-Pierre showing the relation between the amplitude and the real depth (corrected by the conversion factor).

According to the radar amplitude profile, ice crusts are expected at 17 cm, 39 cm, 55 cm and 75 cm. If we compare these results to SMP (fig. 7) and the manual stratigraphic profile (fig. 8), we can see a good agreement between the three methods for the first (17 cm) and second (39 cm) crust. As for the crust seen at 55 cm with the radar, it is not recorded by the SMP, but a layer of hard facets (knife) is present on the stratigraphic profile. Finally, as for the fourth crust (75cm), it is not present in the stratigraphic profile, but we can see a small peak around 78 cm on the resistance and density profile of the SMP that could correspond. Finally, there are two very small, but still significant (over threshold) peaks at 86.27 cm and 87.56 cm. Because they are very close one from each other (less than 12cm), they are merged together (rounded average of 86.27 and 87.56). So according to the radar profile, the ground would be at 87 cm, which is not so bad in the resolution limit of the method, considering that the manually measured height of snow (HS) taken exactly on the radar profile area on the field was 90 cm and the HS general stratigraphic profile was 89 cm.

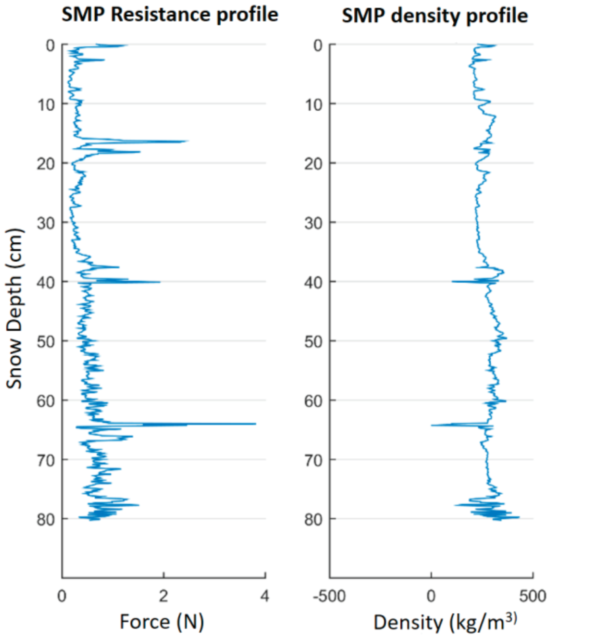

Figure 7. SMP profile for Mont-Saint-Pierre. Resistance profile on the left and density profile on the right.

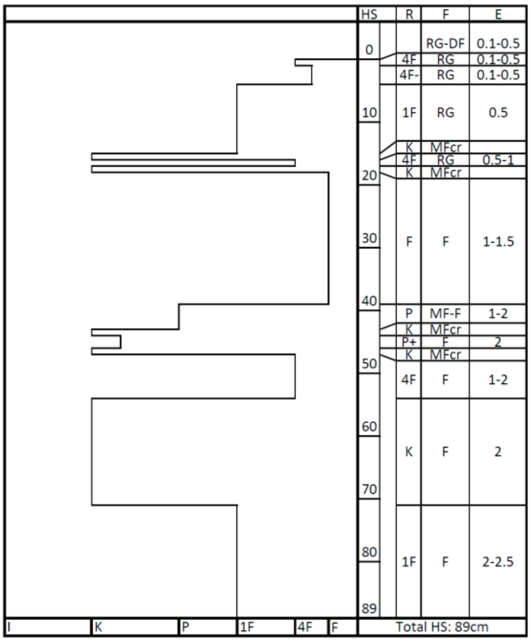

Figure 8. Mont-Saint-Pierre snowpit stratigraphic profile

4. DISCUSSION

In general, for this site, we can see a good agreement between all the different instruments. Except for the third and the fourth crust layers where only one compared instrument (SMP or snow profile) was matching the radar observation, all three methods used provided similar results for the surface, the first and the second crust and for the ground at +/- 3 cm. However, the radar did not notice any interference around 40-45 cm as shown on the stratigraphic and the SMP profiles, neither at 64 cm like the SMP showed. Analyzing more study sites will help understanding why the radar missed these interfaces transitions.

The presented method here is based on the fact that the first peak represents the snow surface. This assumption can be made since the signal should always be minimal in air before crossing the air-snow surface. However, if the snow at the surface is very sparse, the dielectric contrast between these two interfaces could be very small and the amplitude peak could be under the threshold. For this reason, for the moment we always validate this first peak value considered as vertical snow surface location with the radar height measurement taken on the field. If it does not match, we can look if a smaller peak (bellow threshold) could fit the surface. If not, we can subtract the measured snow-radar height to the depth value of the whole dataset. However, according to the previous observations made using this method, it is less accurate than the one explained in this paper. We need to understand as well that this situation can occur with any other snowpack layer transition. If the dielectric constant of two overlying snow layers are too similar, the radar might not see the contrast and the peak might be considered as non-representative.

With the snow density changing considerably across the whole snowpack, we also tried to modulate the conversion factor as a function of depth along the snowpack for the same dataset. Results showed that the difference between using the average density for the whole dataset and using adjustable densities for the different layers was not considerable.

Finally, it is really important to specify that the FMCW radar antenna opening used for this research is 24° per 65°, meaning that it see's a 1.22 m^2 ground surface at a height of 1.5 m and it makes an average amplitude profile of the crusts depths for this conic field of view (figure 9). This suggests a spatial coverage much larger than the 5 mm SMP measuring tip (Schneebeli et Johnson, 1998) and the few centimeters wide stratigraphic profile. For this reason, it is possible that the average depth given by the radar be different from the one taken by the probe or the SMP.

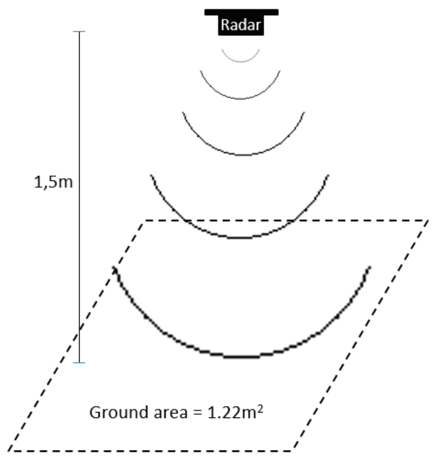

Figure 9. Conic field of view of the radar at a height of 1.5m (graphic made by Jacob Laliberté)

Also, the equation used to find ε_s' comes from Tiuri *et al.* (1984), but Schneebeli *et al.* (1998), Gubler and Hiller (1984) and Matzler (1996) also found relations between snow density and effective permittivity that could be used to find the right conversion factor to convert radar depth to real depth. All these relations will be compared in further works.

5. CONCLUSION

After a year of working with the 24 GHz FMCW radar, we can point out that it is efficient for at least three reasons: 1) its compactness makes it easily transportable, 2) it allows in-depth snow data gathering without disturbing the snow and 3) it is very sensitive to dielectric contrasts, facilitating ice crust detection.

However, according to the fact that the method is in development, we still need to validate the robustness with more study sites. Many different methods have been investigated. Although the results presented here are quite promising, the same field setup needs to be repeated in different sites and times of year. However, for the moment, a few sites have been analysed and the method seems to work for the majority of them.

This paper highlights a first winter analysis of FMCW radar data collected by the *Groupe de Recherche Interdisciplinaire sur les Milieux Polaires (GRIMP).* More work is required to better understand the different snow mechanisms controlling the radar signatures. This paper present a great first step in that direction and future work will investigate the possibility of creating artificial ice crusts at the study site in order to help developing the detection threshold.

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