FIRST RESULTS FROM A FMCW RADAR FOR SNOWPACK MONITORING

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ABSTRACT: We are presenting a frequency modulated continuous wave radar (FMCW) connected to four antennas for investigating water transport through the snowpack. The Hubra FMCW sweeps from 0.5GHz to 3GHz within 4 ms. The radar was developed by the Norwegian Defence Research Establishment (FFI). The radar was installed at Brunkollen to monitor a 0.7 m thick snowpack in a maritime climate setting, (located about 30 km northwest of Oslo). Two Vivaldi antennas were mounted under the snowpack and two above the snowpack for the entire melt season, enabling alternating measurements of wave reflection and transmission, both from above and from below the snowpack. We analyze the data in three different combinations: transmitting and receiving above the snowpack, transmitting and receiving below the snowpack and transmitting a signal across the snowpack. The sets of measurements can be used for monitoring snow height and changes of the dielectric properties of the snow. Liquid water content is derived from permittivity of the snowpack using an empirical equation. The first season was mainly for testing the system to explore its capabilities.

KEYWORDS: Ground penetrating radar, FMCW, wet snow, snow hydrology, permittivity

1. INTRODUCTION

There are many complex processes that happen when liquid water is present in a snowpack, such as water flow via matrix and finger flow, lateral water transport, energy flows, latent heat release and accelerated crystal morphology (Kettelmann, 1984, Wakahama, 1975). Because the snowpack is such a complicated system, state of the art snowpack models such as SNOWPACK or CROCUS use the tipping bucket method to describe vertical water transport (Vionnet et al. 2012, Bartelt and Lehning, 2002). Wever et al. (2013) have shown that Richard’s equation for the snowpack predicts successfully the timing of melt water arrival at the ground-snow interface. However, uncertainty remains about water transport through individual snow layers since most studies employed lysimeter data that only provide information on the bulk of the snowpack.

Dye tracer tests highlight how complicated some of the flow patterns between individual snow layers can be (Marsh and Woo, 1984, Williams et al. 2010). By creating a three dimensional representation with 1cm resolution of water flow in the snowpack, the snow guillotine is one such experiment that shows how complex water transport between snow layers is. It was found that the number of preferential flow paths decreased in the lower snow layers (Williams et al. 2010).

Not only is liquid water in the snowpack challenging to model it is also a challenge to measure partly because there is high spatial variation in the snowpack. Liquid water detected on the surface of the snowpack has a correlation length of 5 to 7 m (Williams et al. 1999). The snow layers which makeup the snowpack have their own set of physical properties that affect their interaction with water (Denoth, 1989). The boundaries between snow layers influence water transport, in particular ice lenses and small over large grain boundaries (Marsh & Woo, 1984, Kettelmann, 1984, Colbeck, 1979). Time domain reflectometry (TDR) sensors (Topp et al. 1980, Stein et al. 1997), capacitance type probes such as the Denoth fork (Denoth,1989) and ground penetrating radar systems (Alumbaugh et al. 2002) take advantage of the difference in electrical properties that wet and dry snow have. The permittivity of ice and liquid water differ drastically, thereby offering a possibility to monitor the distribution and evolution of water content by means of measuring electromagnetic properties.

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2. EXPERIMENTAL SETUP

The Hubra radar is a frequency modulated continuous wave (FMCW) radar, developed by FFI. The radar has two transmitting and two receiving channels, that were all connected to Vivaldi antennas. An electromagnetic wave is broadcasted over the transmitting antennas. The signal starts at a frequency of 500 MHz and is ramped up to 3 GHz in 4 ms. The signal is then collected by the receiving antenna after the electromagnetic wave is transmitted or reflected through the media that separate the antenna, in this case snow and air. A PC connected via USB cable controls the radar.

Figure 1: The FMCW and antenna setup.

Two of the antennas (one transmitter and one receiver) were mounted facing upwards in waterproof plastic cases and buried in the ground. The antennas were placed approximately 30 cm from each other. Two more antennas were mounted facing downwards on a wooden frame about 2 m above the ground as shown in figure 1. A plastic box protected the upper antennas from the elements. The antennas connect to the FMCW control unit via 10 m long N type cables. The FMCW and PC are stored in a waterproof case that is buried in the snowpack near the measurement area.

Fig. 2: The different measurements the antenna setup can perform (each arrow represents two antenna one transmitter and one receiver). 1) Transmit and receive from the top, 2) transmit and receive from the bottom, 3 & 4) transmit from bottom and receive at top, and vice versa.

This setup allows for four measurements to be made as seen in figure 2, transmit and receive the signal above the snowpack (1), transmit and receive below the snowpack (2) and transmit the signal through the snowpack (3 & 4) (transmitting both from the bottom and top).

3. STUDY AREA

The radar has been tested during the winter of 2013 to 2014 at Brunkollen located about 30 km outside of Oslo, Norway. A snow measurement station is located at Brunkollen which consists of a snow pillow, ultra sonic depth sensors and air temperature measurements. The weather station is located about 5 m away from the radar installation. Plots made from the weather station data can be seen in figure 3. The antennas were installed in December before the seasonal snowpack built up. Due to technical issues there was only a section of 21 hours (from 18/3 to 19/3) where the radar continuously measured every 30 minutes. During the measurement period the snowpack was isothermal due to a warm winter in southern Norway for the 2013/2014 season. The snowpack height was about 70 cm at the weather station for the measurement period. The snow depth at the radar could be as much as 30 cm different than the weather station due to the ground topography.
4. RESULTS AND DISCUSSION

Due to the limited temporal coverage, the first results of this radar experiment do not provide insight into snowpack dynamics. The results are more of a calibration of the FMCW and antenna setup and a validation that the Hubra FMCW can detect the snow surface and ground.

The FMCW's records a mix (the beat frequency) of the transmitted and received electromagnetic wave (Marshall and Koh, 2008). The raw data is in the frequency domain and hence, not intuitive to picture. Using a fast Fourier transform the frequency signal can be transformed to the time domain. The time domain transformed signal can be seen in figure 4 left. Figure 4 right shows radar data for 21 hours measuring every 30 minutes transmitting and receiving from the top of the snowpack. It can be seen that the snowpack did not change much over this period even when the temperature dropped to -3°C during the night. Figure 4 shows there are three strong signals from the top down measurements, the direct wave, snow surface reflection and the reflection from the ground/bottom antenna. The direct wave travels from the transmitter to the receiver without reflecting off anything. In this case the direct wave travels about 30 cm.

The 21 hour data set for transmitting and receiving antenna pair from the bottom of the snowpack (not shown) is less clear because the snow was moist. Wet snow strongly attenuates with some strong internal reflections. Yet there were still distinguishable reflections from the snow surface and the upper antenna, which can be seen in the single trace data (figure 5 Left).

Relative permittivity ($\varepsilon_R$) is a dimensionless complex number as seen in equation 1, where $\varepsilon'_R$ is the real part and $\varepsilon''_R$ is the imaginary part.

$$\varepsilon_R = \varepsilon'_R + i\varepsilon''_R$$  \hspace{1cm} (1)

Assuming the imaginary part of the permittivity is small and can be neglected in the frequency range used, the velocities of the electromagnetic wave in the snowpack ($v$) and the speed of light in a vacuum ($c$) the permittivity of the snow ($\varepsilon_R$) can be calculated (equation 2). This assumption is justified because it has been shown that the imaginary part of the permittivity for ice, water and air is small compared to the real part for frequencies above 1 MHz (Frolov and Macheret, 1999).

One trace of both upward and downward looking antenna can be seen in figure 5 with a simple diagram of air, snow and the ground for help interpreting the radar traces. The upward and downward traces complement each other well; the snow surface can be distinguished in both traces. The antenna mount about the snowpack can be detected by the upward looking radar. The time it takes the wave to travel between the snow surface and upper antenna match well in both traces.
The velocity in the snowpack can be calculated from snow depth on figure 3 (≈0.7 m) and half the time difference from the snow surface reflection and ground reflection in figure 4 (2.5 ns). The real part of the permittivity is 1.15 across the whole snowpack using the numbers above. The permittivity of dry snow ($\varepsilon'_{dry}$) is density dependent and ranges from 1 with low density snow to about 2.5 with compact high density snow. Equation 3 describes the effect that liquid water has on the permittivity of the snow. $\Delta\varepsilon'_{wet}$ is the permittivity added to the snowpack by the presence of liquid water, and can be as large as 2 for snow with about 10% liquid water content (Frolov and Macheret, 1999).

$$\varepsilon'_{total} = \varepsilon'_{dry} + \Delta\varepsilon'_{wet}$$  \hspace{1cm} (3)

The permittivity of wet snow should fall in the range of 2 to 4 assuming that the density of wet seasonal snow falls within 400 to 600 kg m$^{-3}$. The snow packs permittivity was not within the reasonable range stated above. This could be due to the uncertainty in the snow depth that was measured 5 m away from the radar installation. The uncertainty could be as large as 30 cm due to the uneven ground at the field site.

There are many empirical equations that relate permittivity of the snow pack to its liquid water content (Stein et al. 1997) however this is not shown because the permittivity of the snowpack has such a large uncertainty. This result allows for the snow packs permittivity to be monitored and indirectly liquid water content of the snowpack. However longer datasets are needed to see how well the radar system tracks the wetting front or drying front in the snowpack. The measurements transmitting the wave across the snowpack also need a longer dataset and some control or reference points to be useful.

5. CONCLUSION

The Hubra radar shows some promising signs that it could be used as a tool to monitor snowpack development particularly snow height and snow wetness. The snow surface had a clear reflection in the radiogram. The upward and downward scans allow for reflections to be crosschecked for an easier interpretation of the radar data. The winter of 2013/2014 was used for testing out the equipment and overcome technical challenges. More validation is needed to fully understand the capabilities of this FMCW and antenna system. Next season the radar will be setup on the west coast of Norway in a maritime climate where wet snow avalanches occur often.

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$$\varepsilon_R = \left(\frac{\varepsilon}{n}\right)^2$$  \hspace{1cm} (2)
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