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FMCW Radar Investigation of Snow Pack Evolution

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ABSTRACT

Numerous snow pack evolution models have been developed to predict the physical properties of a snow pack as a function of past and present weather conditions. In order to evaluate the effectiveness of these models, continuous and noninvasive techniques are required to monitor the properties of a snow pack over an extended time period. The temporal resolution of these techniques must be adequate enough to respond to the changes in snow pack properties under rapidly varying weather conditions. The most promising noninvasive technique for monitoring snow pack properties may be the frequency modulated continuous wave (FMCW) radar. Time series radar backscatter measurements obtained with an FMCW radar (26.5 to 40 GHz) are presented and compared with the environmental conditions and the snow properties. The capabilities and limitations of an FMCW radar for snow pack studies are highlighted.

INTRODUCTION

The use of radar remote sensing techniques to characterize the physical properties of a snow pack has great appeal since radar techniques are noninvasive and have the potential to monitor large areas of a snow-covered terrain. However, the ability to infer the basic snow pack parameters based on radar measurements still remains a challenge due to the complex properties of a snow pack and the equally complex radar-snow pack interaction. At present, the most promising radar technique for snow pack studies is the frequency modulated continuous wave (FMCW) radar. FMCW radars have the characteristic of detecting reflections from interfaces within a snow pack which makes them particularly suited for investigating the internal structure of a snow pack. In addition, radar frequencies are extremely sensitive to the presence of water which make them ideal for monitoring melting and freezing cycles.

The use of FMCW radars to characterize the structure of a snow pack has been reported by numerous investigators (Ellerbruch and Boyne 1980; Gubler and Hiller 1984; Fujino et al. 1985; Koh 1992). Although these studies suggest that FMCW radars have the potential to be a valuable tool for snow scientists, more field studies are required to document both the capabilities and limitations of radar remote sensing techniques for monitoring the physical properties of a snow pack. In particular, it is necessary to identify the optimal radar frequencies and radar configurations for use in snow pack studies.

This paper discusses the use of an FMCW radar operating at 26.5 to 40 GHz to investigate the changes in the snow pack properties. Extensive time series radar backscatter measurements from a snow pack under varying environmental conditions have been obtained. These time series measurements are analyzed to detect both the gradual and sudden changes in the radar responses. These changes are correlated with the environmental conditions as well as the snow pack properties. The dynamics of snow properties observed with an FMCW radar are presented and some potential

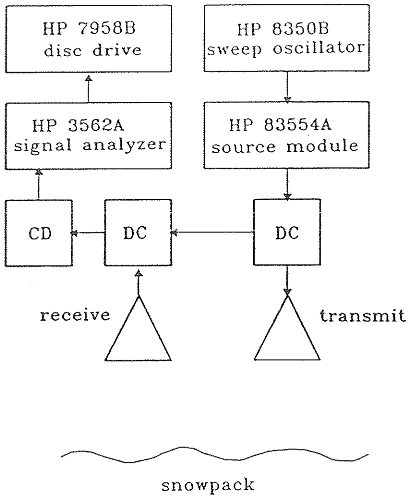

Figure 1. Schematic of FMCW radar used to measure radar backscatter from a snow pack.. DC and CD are directional couplerand crystal detector.

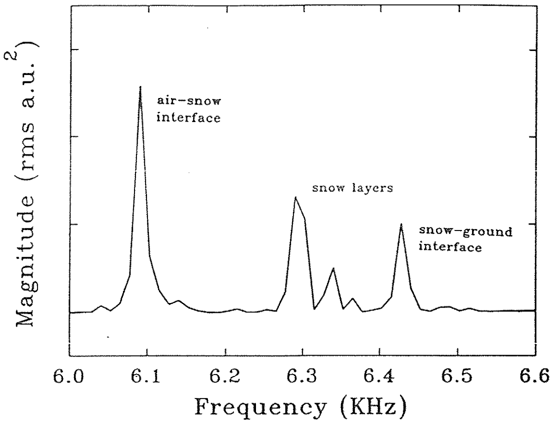

Figure 2. FMCW radar output. The frequency of the power spectrum is proportional to the electromagnetic distance and the magnitude is proportional to the target reflectivity.

applications are highlighted.

EXPERIMENTAL METHOD

The FMCW radar system used in this study is illustrated in Figure 1. An HP8350B sweep oscillator and an HP83554A millimeter-wave source module generate signals whose frequency varies linearly with time from 26.5 to 40 GHz with a sweep time of 80 ms. A directional coupler divides the frequency-modulated signals into two paths; a reference signal is fed directly into a mixer (directional coupler and crystal detector) and a target signal is directed toward to the snow pack via the transmitting antenna. The reflected signal from the snow pack is fed into the mixer input via the receiving antenna. An HP3562A signal analyzer is used to obtain the fast Fourier transform (FFT) of the mixer output and an HP7968B disc drive is used to store the FFT's. The FFT of the mixer output yields a power spectrum whose frequency is proportional to the electromagnetic distance of the target and whose magnitude is proportional to the target reflectivity. A power spectrum illustrating the output of an FMCW radar is shown in Figure 2. For the FMCW radar system used in this study, the relationship between the distance within the snow, $\Delta Z\,(cm)$, and the frequency difference in the power spectrum, $\Delta f\,(Hz)$, is expressed as

$$\Delta Z = 0.085 \times \Delta f \div \sqrt{\varepsilon'}\ ,$$

where ε' is the effective dielectric constant of snow that depends largely on its density.

The radar backscatter measurements were conducted between January 1993 and March 1993 at Hanover, New Hamsphire. The FMCW radar was mounted on a gantry approximately 6 m above the ground and positioned so that the transmitted signal was directed toward the snow pack at a 4^o incident angle. The radar was kept stationary so that the backscatter from the same location on the snow pack was measured. (The gantry was moved during snowfall and repositioned after the snowfall). The backscatter measurements were made once every 10 to 30 minutes depending on the ambient conditions. An instrumented tower located approximately 25 m from the radar recorded the meteorological parameters. When a significant change in radar basckscatter response was observed, a snow pit near the radar footprint (approximately 5 to 10 m away) was investigated so that the change in snow properties could be correlated with the radar response. It was assumed that the snow pit was representative of the snow near the radar footprint (some judgement was required since spatial variations in snow properties can occur).

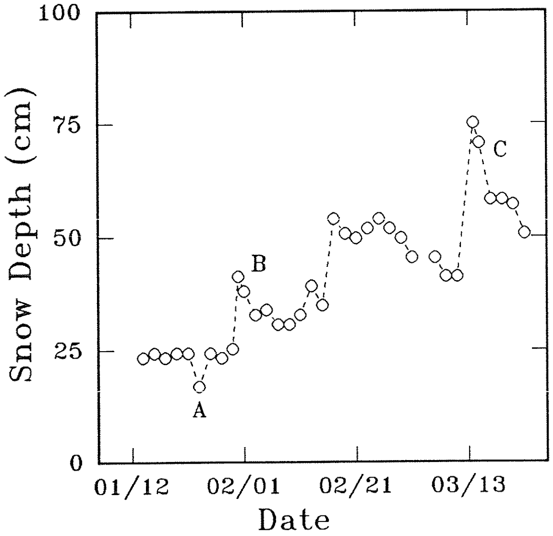

Figure 3. Snow depth history obtained with the FMCW radar.

RESULTS AND DISCUSSIONS

The radar responses from a variety of snow pack conditions are investigated in order to highlight some of the capabilities and multiple uses of an FMCW radar for snow pack studies.

Snow Depth

The FMCW radar output is a power spectrum whose frequency is proportional to the electromagnetic distance of a target. Therefore, if the distance between the antenna and ground is known, the snow depth can be obtained from the frequency difference between the reflections at the air-snow and air-ground (measured with no snow on the ground) boundaries. The use of an FMCW radar to monitor the changes in snow depth is illustrated in Figure 3. The figure illustrates the changes in snow depth that were observed during the measurement period at approximately 2 day intervals. Some of the notable features of the snow depth history are the rapid decrease in snow depth due to a rain event (point A), to settling of freshly fallen snow (point B), and to a melting event (C). It is possible to increase the time resolution of the snow depth measurement to better monitor such effects as the snow accumulation rate, erosion rate due to wind action and ablation rate due to melt. By recording the frequency differences between reflections from layers within the snow pack, it may be possible to infer the settlement rates of different snow layers.

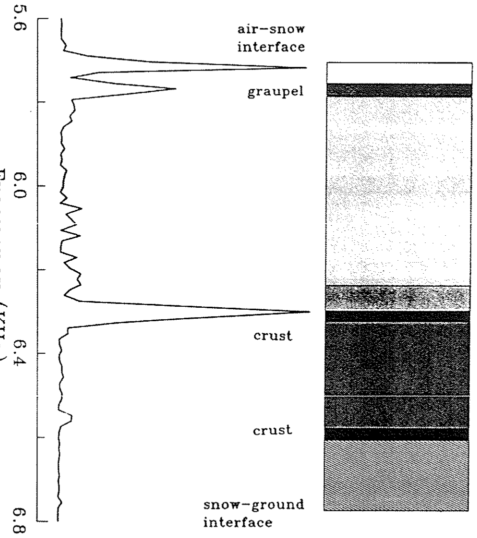

Figure 4. Comparison of radar backscatter and snow pack structure. Graupel and crust layers are clearly distinguished. Reflection from the ground is barely detectable.

Snow Stratigraphy

The strength of an FMCW radar for snow pack studies is its ability to detect internal structure. A comparison of an FMCW radar return and the internal structure of a snow pack is illustrated in Figure 4. The radar return represents the deepest snow pack that was observed during the measurement period. The snow depth was approximately 75 cm and occurred after 35 cm of new snow fell over an existing snow pack.

The radar return is characterized by three large reflections and several small ones. The first return represents the reflection from the air-snow boundary. The second return represents a layer of graupel that fell during the latter part of the snowstorm. The strongest return is from a dense crust that formed on the surface of previous snow. A small return from a second crust is also seen. The reflection from snow-ground interface is extremely weak. A series of small reflections from the snow just above the crust layer suggest the presence of several weak discontinuities. However, visual examination of the snow layer did not reveal noticeable differences in the snow structure at this depth..

The figure illustrates that an FMCW radar operating at 26.5 to 40 GHz may have limited penetration depth for snow pack studies. The maximum depth that a radar can penetrate into a snow pack depends on the extent of scattering and

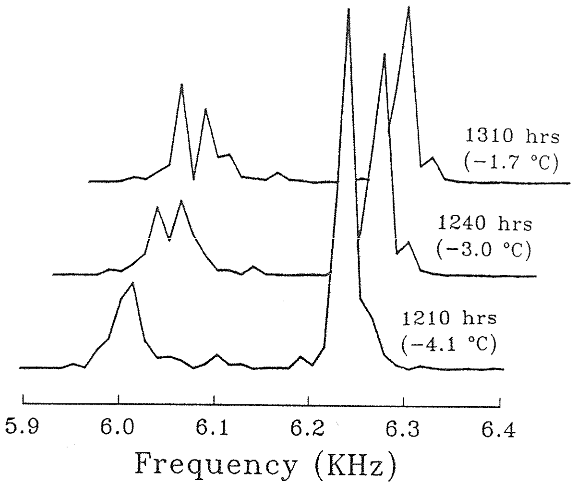

Figure 5. Sequence of FMCW radar response illustrating sub-surface melt due to solar heating. The time and air temperature are also shown.

and absorption losses within a snow pack. The penetration depth of a radar in wet snow is limited due to the high absorption loss in water. For dry snow, scattering by individual snow particles and reflection from layer boundaries will limit the effectiveness of a radar. In order to penetrate deeper into a snow pack, an FMCW radar operating at lower frequencies is required (the penetration depth can vary from 10 to 100 times the wavelength in dry snow). However at the lower frequencies, the resolution decreases. In order to overcome these deficiencies, a multi-frequency FMCW radar is required for snow pack studies.

Sub-Surface Melting

The possibility of sub-surface melting in a snow pack due to solar radiation penetration on days when the surface temperature remains sub-freezing has been discussed by several investigators (Fukami etal.1985; Colbeck 1989). The onset of sub-surface melting can be easily detected using an FMCW radar since a layer of wet snow with high dielectric contrast forms below the snow surface. The analyses of FMCW radar returns from a snow pack on calm clear days when the surface temperature remains below freezing indicate that sub-surface melting is not an uncommon event.

A sequence of FMCW radar returns illustrating the onset of sub-surface melting is shown in Figure 5. The radar return which was obtained from a dry snow pack around 1210 hrs shows reflections from the air-snow boundary and crust below the surface. Around 1240 hrs, a layer beneath the snow surface begins to emerge until a distinct layer is detected around 1310 hrs. During this period the air temperature remained below freezing (the temperature increased from -4.1 to -1.7$^{\circ}C$). The reflection from the crust gradually decreased during this period due to water absorption and due to the additional reflection loss at the wet snow boundary. The snow temperature measurement and the application of water sensitive dye to the snow below the surface confirmed the occurrence of sub-surface melt.

Diurnal Variations

Due to the differences in the complex dielectric constants of ice and water at radar frequencies, the presence of even a small amount of water can affect the radar response from a snow pack. For this reason diurnal variations in radar backscatter as a snow pack undergoes melting and freezing cyles are often observed. An example of the diurnal variations and the corresponding air temperature measurement is illustrated in Figure 6. It is seen that during the night when the air temperature remains sub-freezing, the radar reflection from the air-snow interface (surface scattering) remains stable. The radar responses during the day are characterized by rapid fluctuations due to the melting effect.

The radar fluctuations from the air-snow interface observed during the melt period may be attributed to the movement of water and/or changes in the surface roughness. A portion of the fluctuations may be attributed to a rough surface scattering effect and its associated Rayleigh statistics. Fujino et al. (1985) also observed fluctuations during melting cycles using a lower frequency FMCW radar (2-8 GHz) where the effect of surface roughness is expected to be mimimal. They attributed their fluctuations to the accumulation and release of meltwater. More studies are required before the radar fluctuations due to snow melt can be satisfactorily explained.

Spatial Variations

A snow pack is characterized by both spatial and temporal inhomogeneities. Although the primary focus of this study was to investigate the temporal changes in a snow pack, Figure 7 is presented to illustrate that spatial variations can occur. The figure shows two FMCW radar spectra that were obtained from two different locations separated by

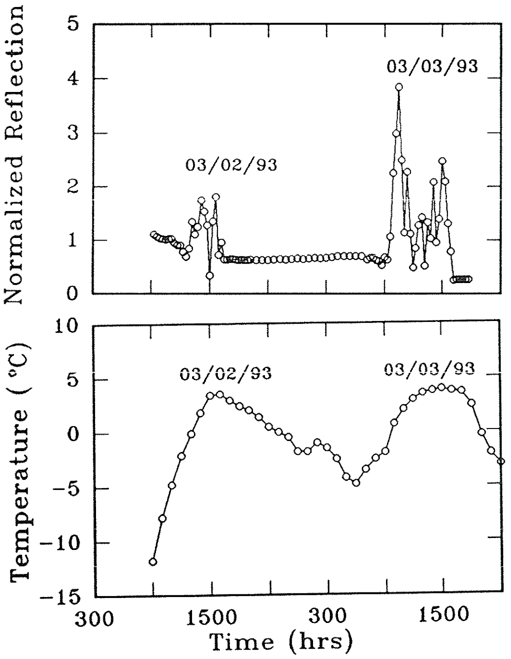

Figure 6. Diurnal variations in radar response and corresponding air temperature.

a distance of approximately 5 m. The return from location A indicates structure near the snow surface which was not present at location B. It is speculated that the difference may be due to a melt-freeze event; complex water flow in a snow pack can result in spatial variations. The spatial variations illustrate the problems that one can encounter when one tries to infer the areal properties of a snow pack based on point measurements of snow properties. In order to accurately study the snow pack dynamics, the integration of temporal and spatial characterizations of a snow pack is necessary.

CONCLUSIONS

An FMCW radar operating at 26.5 to 40 GHz has been used to monitor the changes in snow pack properties under varying weather conditions. The potential use of an FMCW radar for investigating the temporal and spatial properties of a snow pack is demonstrated. Due to the complex properties of snow pack and radar-snow snowpack interactions, more studies are required before one can fully evaluate the impact that FMCW radars can have in advancing our knowledge of snow pack dynamics. Multifrequency FMCW radars should always be used in order to evaluate the utility of FMCW radars for snow studies

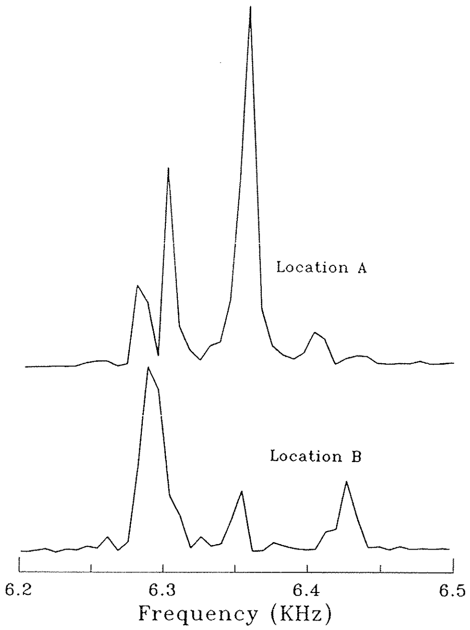

Figure 7. Two FMCW radar spectra illustrating spatial variability in a snow pack. The traces were obtained approximately 5 m apart.

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