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Snow Cover Characterization Using Multiband FMCW Radars

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ABSTRACT

The use of radars to characterize the physical properties of a snow cover offers an attractive alternative to manual snow pit measurements. Radar techniques are noninvasive and have the potential to characterize large areas of a snow-covered terrain. A promising radar technique for snow cover studies is the frequency modulated continuous wave (FMCW) radar. The use of a multiband radar approach for snow cover studies was investigated in order to fully exploit the capabilities of FMCW radars. FMCW radars operating at and near the *C*-, *X*-, and K_a-bands were used to obtain radar profiles over a wide range of snow cover conditions. These frequency-dependent radar signatures were used to identify important snow cover features such as ice and depth hoar layers. Snow grain size information was also obtained from the frequency-dependent scattering losses that were observed in the snow cover. Several case studies of FMCW radar profiles are presented in order to demonstrate the advantages of a multiband radar approach for monitoring the spatial and temporal variability of snow cover properties and/or processes over an extended area.

Key words: Snow cover, FMCW radar

INTRODUCTION

Vast differences in the physical properties of a snow cover can be observed over relatively short distances due to varying terrain and land cover features. Under these varying snow cover conditions, point measurements such as a snow pit are often inadequate for distributing snow cover properties over an extended area. Accurate spatial distribution of snow cover properties are needed to improve ground truth measurements for remote sensing applications and to improve the present capability of modeling and predicting snow cover processes such as snowmelt runoff. To obtain a more realistic representation of the spatially varying snow cover conditions, alternative techniques are needed to efficiently measure the snow cover properties. The use of radars to characterize the physical properties of a snow cover is an attractive alternative to snow pit measurements since radar techniques are noninvasive and have the potential to cover large areas of a snow covered terrain. At present, the most promising radar technique for snow cover studies is the frequency modulated continuous wave (FMCW) radar (Ellerbruch and Boyne 1980; Gubler and Hiller 1984, Fujino et al. 1985, Koh 1992, and Koh and Jordan 1995). These studies have shown that FMCW radars can detect physical changes within a snow cover that make them ideal for profiling the snow cover stratigraphy and depth, for measuring the snow water equivalence (SWE), and for monitoring the presence of liquid water in a snow cover. However, due to the complexity of radar–snow cover interaction, the interpretation of the radar data to infer basic snow cover properties still remains a challenge. This is particularly true when one tries to interpret radar signature using a single-band radar. Multiband characterization of snow cover properties are needed to fully exploit the capabilities of FMCW radars.

This paper investigates the use of a multiband FMCW radar approach for snow cover studies. FMCW radars operating at and near the *C*-, *X*-, and K_a-bands were used to obtain radar signatures from a

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wide range of snow cover conditions. The frequency-dependent radar signatures were used to identify important snow cover features such as ice and depth hoar layers. Snow grain size information was also obtained from the frequency-dependent scattering losses that were observed in the snow cover. Several case studies of the frequency-dependent radar signatures are presented to demonstrate the advantages and the potential of a multiband FMCW radar approach for monitoring the spatial and temporal variability of snow cover properties and/or processes over an extended area. These results suggest that multiband FMCW radars mounted on a platform such as a snowmobile or a helicopter can be used to measure the snow cover properties with detailed spatial resolution that is not obtainable using other techniques.

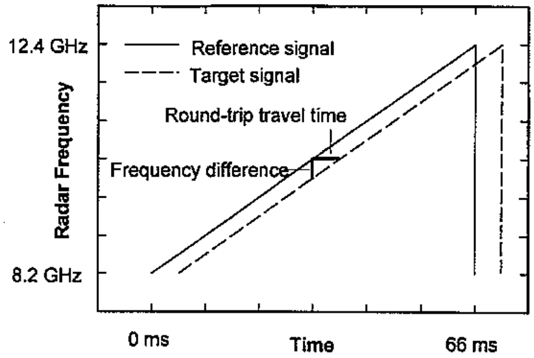
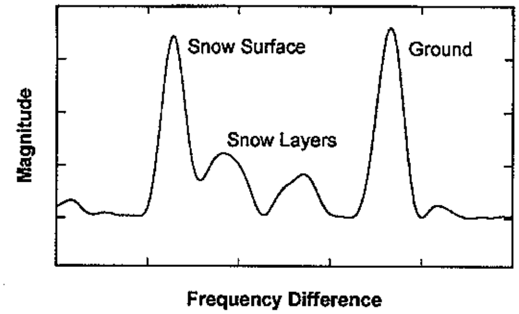
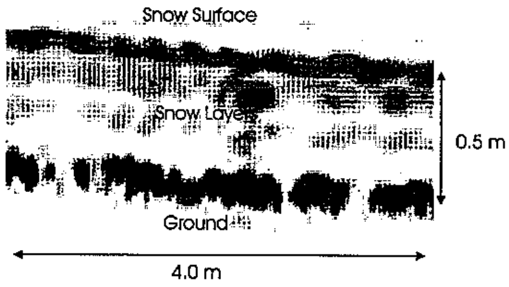


Figure 1. Relationship between time and radar frequency for an X-band FMCW radar system with a sweep time of 66 ms. The instantaneous frequency difference between the reference signal and the target signal is proportional to the round-trip travel time of the target signal.



a. Power spectrum of a typical FMCW radar trace illustrating various transitions in a snow cover.



b. Two-dimensional FMCW radar profile of a snow cover (4-m horizontal scan).

Figure 2. FMCW radar displays.

EXPERIMENT

FMCW radar

The salient feature of an FMCW radar is that it measures the distance to a target (i.e., snow surface, snow layers and snow/ground interface) from the instantaneous frequency difference between a reference signal and a target signal. The equation governing the operation of an FMCW radar is given by

$$F_d = \frac{2 B_w d \sqrt{\varepsilon}}{c T_s} \tag{1}$$

where F_d = the frequency difference
d = the distance to a target
T_s = the sweep time of the modulated signal
B_w = the radar bandwidth
ε = the dielectric constant of the medium between the radar and the target.

Figure 1 illustrates the relationship between time and radar frequency for a typical FMCW radar system (an X-band radar operating with a sweep time of 66 ms is shown). The instantaneous frequency difference between the reference signal and the target signals is proportional to the round-trip travel time of the target signal. This frequency difference is obtained by mixing the reference and target signals and by performing a fast Fourier transform on the mixer output. Therefore, the output of an FMCW radar is a power spectrum where the frequency differences represent various targets (electromagnetic discontinuity) encountered by the radar signal. Figure 2a is a power spectrum representative of a typical FMCW radar return that shows the frequency differences corresponding to discontinuities at the snow surface, within the snow cover and at the snow/ground interface. The magnitude of the frequency difference is proportional to the target reflectivity (attenuation due to scattering and absorption must be factored in). A two-dimensional radar profile of a snow cover can be obtained by scanning the radar and displaying the resulting power spectra as a contour plot. This is illustrated in Figure 2b.

Figure 2 clearly illustrates the potential of FMCW radars for snow cover studies. The snow water equivalent (SWE) of a snow cover can be determined from the travel time of radar signal in the snow (Ellerbruch and Boyne 1980). If the density of the snow is known or can be estimated, then the depth profile of a snow cover can also be obtained using FMCW radars. The physical properties of snow corresponding to the reflections within the snow cover are more difficult to determine. To obtain information about the internal structure of a snow cover, multiband radar profiles of a snow cover are required.

Measurements

The multiband radar profiles of various snow cover types were obtained at test sites in Hanover, New Hampshire, and Danville, Vermont, between January and April 1996. The radars were initially operated at the C (3.9 –5.9 GHz), X (8.2–12.4 GHz), and K_a (26.5–40 GHz) bands. In addition to these standard radar bands, the radars were also operated at 2- to 5-GHz, 9- to 12-GHz and 32- to 35-GHz bandwidths. By operating at the identical 3-GHz bandwidth, we were better able to isolate the frequency-dependent radar responses from a snow cover.

The FMCW radars were mounted at the end of a 2-m-long boom approximately 2 m above the ground. The boom was attached to a motorized tripod that allowed us to scan the radar over an undisturbed snow plot at a constant speed. For this investigation the length of the radar scan was limited to approximately 6 m. The sampling rate of the data acquisition system and the scanning speed were such that a 6-m snow profile consisted of approximately 280–300 equally spaced power spectra. The details of the radar data acquisition system are described elsewhere (Arcone et al. in press). After each radar scan, the frequency and/or the bandwidths of radars were changed to investigate the effects of various radar parameters for snow cover studies.

In conjunction with the radar measurements, a detailed snow pit measurement was obtained. The snow pit was located as close to the radar scan line as possible (approximately 1 to 2 m from the end or radar scan line) in order to correlate the radar profiles with the snow pit results. The density profile of the snow cover was obtained by measuring the snow density at 3-cm intervals. Photographs of snow grains were also taken at 3-cm intervals to determine the snow grain types and sizes. The snow type was classified using the ICSI guidelines (Colbeck et al. 1990).

RESULTS AND DISCUSSION

Several case studies of the frequency-dependent radar profiles of a snow cover are presented. In addition, case studies of the temporal changes in snow cover properties monitored using a radar operating at a single bandwidth are also presented. The relationship between radar responses and snow cover properties are not always obvious. This is particularly true at the higher frequencies where the radar becomes sensitive to subtle changes in snow microstructure, which are easily disturbed during the course of a snow pit measurement. As more frequency-dependent radar profiles over a wider range of snow cover types become available in conjunction with more refined snow characterization procedures (such as snow stereology), the ability to infer snow cover properties using a multiband FMCW radar technique will improve.

Case study 1

A multiband FMCW radar profile of a snow cover obtained at the C-, X-, and K_a-bands is illustrated in Figure 3. The corresponding snow cover information

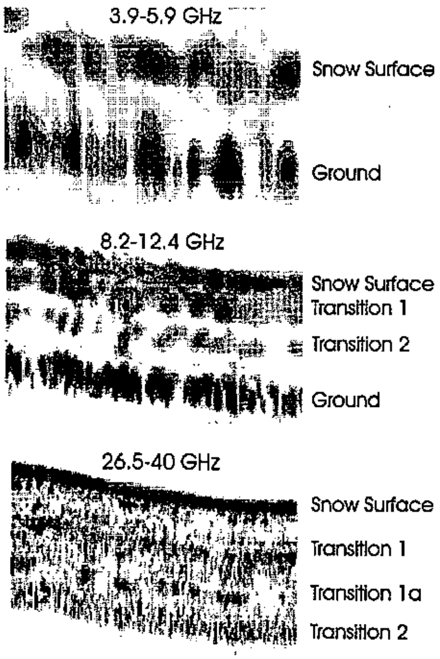


Figure 3. Multiband FMCW radar profile (6-m horizontal scan) of a 50-cm-deep snow cover.

Table 1. Snow cover information for radar profiles illustrated in Figure 3.

Snow level (cm)	*Density (kg/m)*	*Temperature (°C)*	*Crystal classification*	*Max crystal size (mm)*	*Radar transitions*
48–45	110	−12.5	4b,4a	0.5	
44–41	107		1a,4a,4b	1.5	
40–37	140	−10	4b	0.5	transition 1
38–35	150			0.5	
35–32	160	−10	4b	0.5	
32–29	170	−8	4b	0.5	
29–26	180	−7	4a,4b	1	
25–22	210			1	
23–20	210	−3.5	4a,4b	1	transition 1a
20–17	220	−4	4a,4b	1	
17–14	250		4a,4b	1	transition 2
14–11	240	−3		1	
11–8	220	−2	4a	2	
8–5	200	−0.5	4a, 5a	3	

is listed in Table 1. The radar profile at the C-band was characterized by a transition (electromagnetic discontinuity) at the air/snow interface and at the snow/ground interface. Based on the C-band information alone, one could falsely conclude that this snow cover was relatively uniform without any internal structure. However, the X -band radar profile of the same snow showed that, in addition to the snow surface and the ground reflections, two distinct transitions were observed at approximately 10 and 30 cm below the snow surface. These are labeled transitions 1 and 2, respectively. The K_a -band radar profile revealed the presence of another transition approximately 25 cm below the snow surface (labeled transition 1a) that was not detectable using the X -band radar. These transitions correspond to various changes in snow grain sizes and shapes. The shorter wavelength and broader bandwidth of the X-band radar made it more sensitive to the subtle changes in the snow cover properties than the K_a- and the X-band radars.

The most interesting feature of the radar profiles shown in Figure 3 was the inability of the K_a-band radar to detect the ground reflection. Both the X- and the K_a-band radars were able to detect transition 2 in the snow cover. However, the snow property between transition 2 and the ground was such that the K_a-band radar was not able to penetrate this layer. Photographs of the snow indicated that this layer was composed of depth hoar. The sizes of these depth hoar grains (2–3 mm) were such that they were efficient scatterers at the K_a-band frequency but not at the X -band. Frequency-dependent scattering losses observed at the bottom layer of a snow cover, such as those demonstrated in this case study, are good indicators that a depth hoar layer is present. As the size of the depth hoar increases, the ability of the X-band to penetrate this layer would be reduced.

Case study 2

For this set of experiments, the FMCW radars were reconfigured and operated at 2–5, 9–12, and 32–35 GHz in order to better isolate frequency-dependent responses from a snow cover. An example of snow cover profiles obtained at these frequencies are illustrated in Figure 4. The corresponding snow

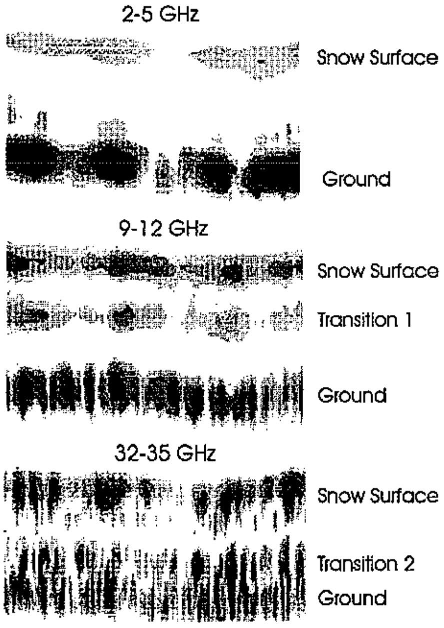


Figure 4. Multiband FMCW radar profile (6-m horizontal scan) of a 35-cm-deep snow cover.

Table 2. Snow cover information for radar profiles illustrated in Figure 4.

Snow level (cm)	*Density (kg/m)*	*Temperature (°C)*	*Crystal classification*	*Max crystal size (mm)*	*Radar transitions*
33–30	30	−1.5	1a,1c,1e	2	
30–27	55		1c	3	
28–25	60	−3	1f,1c		
25–22	55	−2.5		2	transition 1
22–19	60		1e	3	
19–16	80	−3	1e		
16–13	110	−2.5		2	
13–10	140	−2	1f		transition 2
10–7	135	−3		2	
7–4	140		2a	2	
4–1	150	−1	2a,2b	1	

cover information is listed in Table 2. As was observed in the previous case study, the lowest frequency (2–5 GHz) radar was not sensitive to any internal variations in the snow cover properties (the radar profile consisted of surface and ground reflections). However, a distinct transiton approximately 15 cm below the snow surface (labeled transition 1) was detected by the 9- to12-GHz radar. The 32- to 35-GHz radar profile failed to detect transition 1, but it was able to detect another transition approximately 25 cm below the surface (labeled transition 2). Snow pit data indicated that a layer of rimed snow grains was responsible for transition 2.

The most interesting feature of the radar profiles shown in Figure 4 was transition 1. This transition was detected at the 9–12 GHz band but not at the 32–35 GHz band. This was a rare case where a transition in a snow cover was more sensitive at the longer wavelengths. Unfortunately, this unusual scattering behavior could not be correlated to the snow pit data; the snow photographs did not reveal noticeable changes in the snow properties. It is likely that the snow cover structure responsible for the such a trend was disturbed during the course of the snow pit measurement. This case study reflects a situation where a radar technique can detect transitions within a snow cover that otherwise might go undetected using a standard snow pit procedure. The detection of these subtle transitions using FMCW radar are of interest since these transitions affect not only the electromagnetic properties of a snow cover, but may also influence the mechanical and thermal properties of a snow cover.

Case study 3

In the previous case studies the radars operating at or near the *C*-band were not sensitive to the internal variations in the snow cover properties. A case study of a snow cover type where these low frequency radar can provide valuable information is now presented. Figure 5 illustrates radar profiles at 2–5, 9–12, and 32–35 GHz from a snow cover that experienced several melt-freeze cycles. The 2–5 GHz radar detected two transitions located approximately 10 and 20 cm below the snow surface. The snow pit data indicated that ice layers were responsible for these two transitions. These results suggest that the low frequency radars can be used to locate well-defined physical transitions in a snow cover such as ice and crust layers.

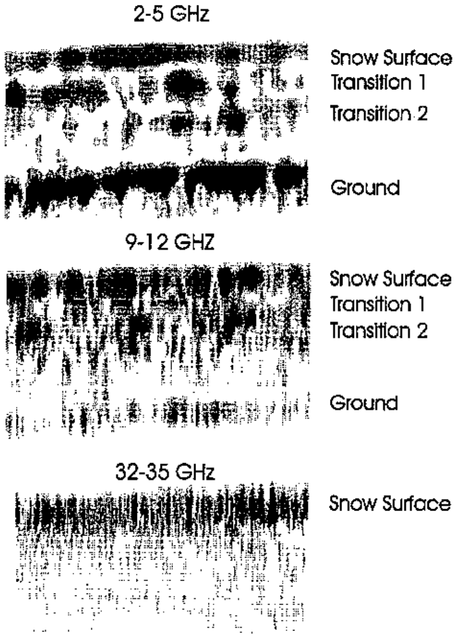


Figure 5. Multiband FMCW radar profile (6-m horizontal scan) of a 45-cm-deep snow cover.

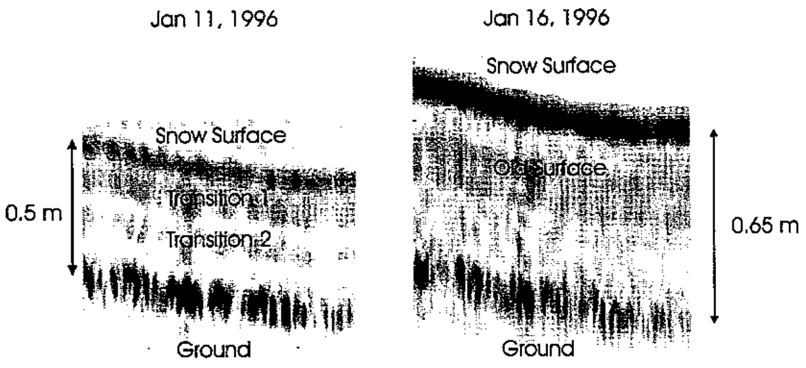


Figure 6. The temporal changes in snow cover properties measured with an X-band FMCW radar. Accumulation of new snow and metamorphism of old snow can be seen.

This case study also demonstrates how the snow grain sizes can be inferred from the frequency dependent scattering losses. The 2–5 GHz radar easily penetrated the snow cover so that the reflected signal from the ground was easily detected. However, the ground reflection was barely detectable at 9–12 GHz. The 32–35 GHz radar signal was such that even the ice layers were barely detectable. The increased attenuation observed at the 9–12 GHz and 32–35 GHz suggested that the snow grain sizes were much larger than those observed in previous case studies. The snow pit data confirmed these results. The snow cover consisted of large spherical ice grains whose size exceeded 3 mm in diameter.

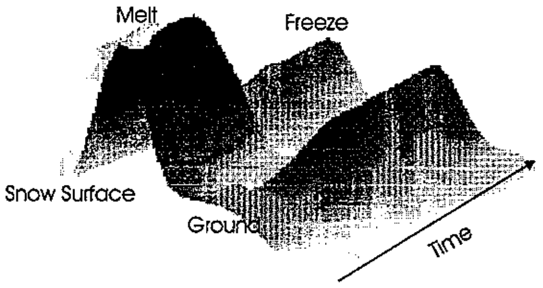


Figure 7. Melt-freeze cycle of snow cover detected using a C-band FMCW radar. The sharp decrease in reflected signal from the snow surface just prior to the freeze cycle has yet to be explained.

Case study 4

The case studies presented above clearly demonstrate the potential of multiband FMCW radars for characterizing the spatial variability of snow cover. Since the FMCW radar techniques are noninvasive, they can also be used to investigate the temporal changes in snow cover properties. Figure 6 shows FMCW radar (*X*-band) profiles of a snow cover which were obtained 5 days apart. The latter radar profile shows the accumulation of new snow over the 5-day period. Temporal snow profiles such as these can be used to update the distribution of SWE over a test site. In addition, the metamorphism of a snow cover can also be monitored using temporal radar data. During the 5-day period, the snow cover properties has changed so that transition 2 (caused by density and grain size discontinuity) is no longer clearly defined as before. In addition, there are suggestions that the transition between the old snow surface and transition 1 may be gradually disappearing.

Case study 5

Due to the large difference in the dielectric properties of ice and water at the microwave frequencies, the presence of liquid water can be easily detected using FMCW radars. Therefore, the FMCW radars can be used to monitor processes such as the melt–freeze cycle of a snow cover. The temporal changes in the FMCW radar signature (*C*-band) from a snow cover as it went through a melt-freeze cycle are illustrated in Figure 7. This temporal signature was obtained by directing a radar at the given spot on a snow cover and recording the radar signature once every 15 minutes. During melt, when the liquid water was present, the FMCW radar signature was characterized by increased reflection at the snow surface. In addition, the radar signal that penetrated into the snow cover was rapidly attenuated due to water absorption so that the ground reflection was barely detectable. However, as the snow gradually froze, the surface reflection decreased while the ground reflection increased. The time-dependent changes in snow cover properties such as those illustrated in this case study are valuable data set that can be used to evaluate various mass- and energy-balance models for a snow cover.

CONCLUSIONS

Improved snow characterization techniques are needed to supplement or to replace snow pit measurements in order to accurately distribute the spatially varying snow cover properties over a large area. A promising technique for distributing snow cover properties is the FMCW radar. In order to fully exploit the capabilities of FMCW radars for snow cover studies, a multiband radar approach is required. The frequency-dependent radar signatures can be used to detect and to identify important snow cover features such as ice and depth hoar layers. The sizes of the snow grains can also be inferred from the frequency-dependent scattering losses observed in a snow cover. Since the radar techniques are noninvasive, the temporal changes in snow cover properties at a particular location can also be monitored using FMCW radars. The preliminary results presented in this paper suggest that a multiband FMCW radars mounted on a snowmobile or a helicopter could be used to monitor the temporal and spatial variability of snow cover properties over an extended area.

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