

Snow-stratification investigation on an Antarctic ice stream with an X-band radar system

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ABSTRACT. An X-band FM-CW radar was used to determine the feasibility of observing annual snow-accumulation layers in Antarctica with a high-resolution inexpensive radar system. The formation of layering boundaries, their resultant electromagnetic discontinuity and their detection by reflected energy are presented. Large returns from depths corresponding to reasonable positions for annual layers were found. The average accumulation rates calculated from the radar returns agree with those measured in a previous pit study done in the same area. The detection of the annual accumulation layers with this system implies a simple, inexpensive mobile radar could be used to profile large areas allowing the distorting effects of local topography to be removed. This type of system with a concurrent pit study could provide insight into the effect of sub-surface strata on spaceborne or airborne microwave remote sensing.

INTRODUCTION

A visible stratigraphic record was first observed in Antarctic firn by Scott (1905). Sorge (1935) later observed in Greenland that summer and winter firn exhibited different characteristics. The basic model of firn stratification was developed by Schytt (1958), Giovinetto and Schwerdtfeger (1960), Benson (1962) and Gow (1965), and has proven to be a useful glaciological technique for identifying annual layers of accumulation in shallow pits. The model states that coarse-grained, low-density depth-hoar layers are formed in the autumn when the air/surface temperature gradient causes upward vapor transport, and that fine-grained, high-density crusts are formed in the winter by strong winds. Pairs of depth-hoar and wind-crust layers are interpreted as the autumn and winter of 1 year. Shallow-pit studies are done that measure grain-size and snow-density variations, so that annual accumulation rates can be determined. Benson (1962), Gow (1965) and Palais and others (1982) have tested the basic model through comparisons between annual accumulation estimates from pit studies and accumulation stakes. Mosley-Thompson and others (1985) showed that significant horizontal variations in the thickness of the annual accumulation layers can occur over very short distances, making yearly accumulation estimates from a single pit susceptible to error. Bogorodsky and others (1982) detected the presence of accumulation layers using a short-pulse radar system. The system was pulled behind a snow tractor

to obtain horizontal profiles of accumulation layers from Mirnyy to Komosomolskaya stations in Antarctica. The large-scale profiles, spanning tens of kilometers, showed the changing accumulation rates from the coastal to interior regions. In addition, the small-scale profiles, spanning hundreds of meters, produced a more accurate regional representation of the yearly accumulation rates because localized spatial variations in layer thickness were averaged out.

Here, we describe a set of static FM-CW radar measurements made at the Upstream B camp (83° 28' S 138° 53' W) in West Antarctica. The measurements were made to verify whether a high-resolution radar system could detect discontinuities in the electromagnetic properties of the firn that might be caused by the inter-annual accumulation layers. The potential of such a system to detect the annual accumulation layers is demonstrated.

BACKGROUND

The propagation of electromagnetic radiation through firn is governed by the relative dielectric constant. The propagation velocity is given by

$$v = \frac{c}{(\epsilon_{ds})^{\frac{1}{2}}} \quad (1)$$

where ϵ_{ds} is the relative dielectric constant of dry snow and c is the speed of light in air. For frequencies greater than 1 MHz, Glen and Paren (1975) showed that the rel-

ative dielectric constant of dry snow is directly related to snow density by the following empirical formula

$$\epsilon_{ds} = (1 + 0.51\rho_s)^3 \tag{2}$$

where ρ_s is the density of snow in g m^{-3} . Electromagnetic energy incident upon a boundary between two media with different dielectric constants is partially reflected. The magnitude of the reflection coefficient for the boundary is given by

$$\Gamma = \frac{(\epsilon_2)^{\frac{1}{2}} - (\epsilon_1)^{\frac{1}{2}}}{(\epsilon_2)^{\frac{1}{2}} + (\epsilon_1)^{\frac{1}{2}}} \tag{3}$$

Table 1 shows the magnitude of the reflection coefficient for several snow densities typical of stratified firn.

Table 1

Density Medium 1	Density Medium 2	Γ
0.2	0.3	0.03
0.2	0.4	0.07
0.2	0.5	0.10

MEASUREMENT SYSTEM

The block diagram of the FM-CW radar including the digital data-acquisition system is shown in Figure 1. The radar transmits 200 mW at 11 GHz with a 2 GHz bandwidth yielding a 7.5 cm resolution in air. Assuming speed of light in snow of $2.1 \times 10^8 \text{ ms}^{-1}$, the resolution translates to 5.25 cm in snow. Separate transmit and receive horn antennas were mounted on a stationary platform 10–40 cm above the snow surface. The received signal, containing the range information, is demodulated and recorded by a computer-controlled digital oscilloscope. The data are reduced with an FFT and the reflections displayed as a function of snow depth.

The system was range calibrated through the use of two metal plates. The first plate was placed at the snow surface to verify the range location of the initial surface

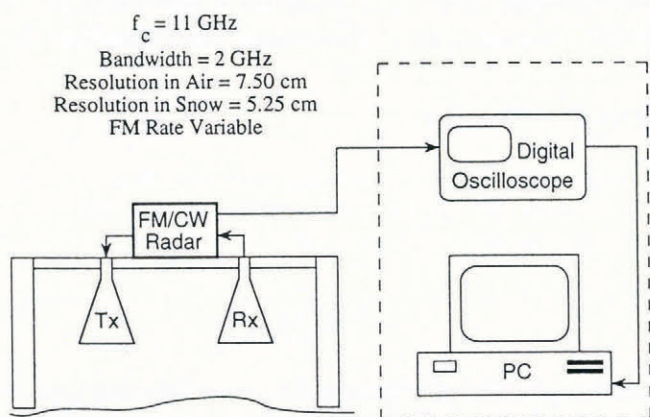


Fig. 1. Experimental configuration.

return. The second metal plate was buried 2 m beneath the snow surface. Using this depth and the known propagation time between the plates, the average speed of light in snow was found to be $2.1 \times 10^8 \text{ ms}^{-1}$. This value was used in determining the approximate depths of the layer reflections observed at the two measurement sites.

EXPERIMENTAL RESULTS

Measurements were made in January 1990 at the upstream field camp on Ice Stream B located on the Siple Coast of West Antarctica. Two locations spaced 1 km apart were chosen for the measurement sites. At each site, numerous radar depth profiles were obtained. Five independent measurements were combined to average out fading effects in the radar return. An averaged return power vs depth profile is shown in Figure 2a. Reflections were observed to depths of 6 m with the strongest returns contained in the top 3 m. The strong attenuation in the first 3 m greatly reduced the energy so that reflections from comparable dielectric discontinuities at greater depths are substantially reduced. The initial surface return is weaker than the rest of the reflections due to the very low density of the snow in the top 15 cm. The peaks of the returned signal correspond to discontinuities of the dielectric constant created by the varying density profile. The valleys between the peaks do not return to zero because of volume scatter from the homogeneous density regions.

Looking at the top 2 m, the average distance between the amplitude peaks is 24.7 cm for the profile in Figure 2a. The depth of each peak amplitude and the peak-to-peak Δ s are shown in the adjacent chart in Figure 2b. This assumes a constant speed of light instead of one that varies with density and could cause an error on the order of $\pm 3 \text{ cm}$. These distances are very close to the accumulation-layer thicknesses reported by Alley

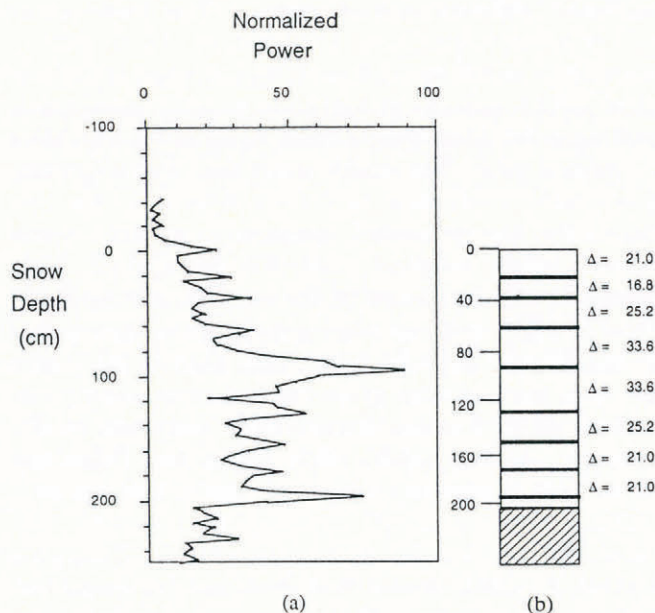


Fig. 2. (a) Radar return from accumulation layers. Average of five independent samples assuming a constant speed of light. (b) Depth of peak amplitude and corresponding layer thickness, Δ .

and Bentley (1988) from their pit study at Upstream B. The average distance between depth-hoar layers, corresponding to the years 1978–85 (0–2 m), was 22.9 cm. Assuming the distance between each reflection peak represents 1 year of accumulation, the radar profile contains 8 years (0–2 m), the same number as the first 2 m in the Alley and Bentley pit study. The difference in accumulation rates for the 5 years between the pit study and the radar measurements makes a direct comparison of layer depths impossible. However, we believe that the average distances between the radar measurements and the pit study are close enough to associate the reflections with the dielectric discontinuities created by the annual accumulation layers. The electromagnetic theory of reflections at a boundary between two different dielectric media is well developed, and this seems the only plausible explanation for the observed amplitude variations with depth.

In addition to the normal configuration of the radar antennas (like polarization), several profiles were obtained in which the receive antenna was rotated 90° to observe the cross-polarization returns. All of the profiles showed reflections at the same depths as that of the normal configuration: however, the spike amplitudes and the background returns were significantly reduced.

At each measurement site, the spatial (horizontal) variation of the reflection depths remained correlated. However, a comparison of the reflection depths from the two different sites, 1 km apart, showed that over greater distances the correlation was lost. The differences in the depths of the reflections are probably caused by surface-topography variations at the time of deposition. Thus, a single radar depth profile, just as a single pit study, could produce an erroneous estimate of the accumulation rate.

CONCLUSIONS

The experimental results indicate that a high-resolution radar system is capable of detecting reflections that, based upon electromagnetic theory, are caused by dielectric discontinuities associated with the density variations between inter-annual accumulation layers. An inexpensive mobile radar system could be developed with the ability to obtain a continuous horizontal profile of the layered reflections. Such a system could be used in conjunction with a pit study to correlate each reflection with the corresponding stratum in the pit. Then, the spatial variation of the accumulation-layer thicknesses could be determined, thereby obtaining a more accurate estimate of the true accumulation rate for that region. Bogorodsky and others (1982) used a short-pulse radar system to measure accumulation rates; however, a simpler and cheaper FM–CW radar system could produce comparable results with a finer depth resolution.

Static measurements made directly alongside a pit study would be useful for determining the scattering and extinction coefficients of snow. This is important for determining the effect of sub-surface strata on satellite remote sensors such as synthetic-aperture radar imagers, radar altimeters and passive microwave radiometers.

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