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# MICROWAVE SCATTERING PROPERTIES OF SNOW FIELDS

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## ABSTRACT

A review is presented of the results obtained in the research program of microwave scattering properties of snow fields. The program is a cooperative effort between a group at the University of California, Berkeley (D. J. Angelakos, F. D. Clapp, K. K. Mei, and S. Coen) and NASA-Ames (W. I. Linlor). A goodly portion of the research was undertaken at the Central Sierra Snow Lab and with the active cooperation of the U.S. Forest Service (J. L. Smith).

Experimental results are presented showing backscatter dependence on a) frequency (5.8-8.0 GHz), b) angle of incidence (0-60 degrees), c) snow wetness (time of day), and d) frequency modulation (0-500 MHz). Theoretical studies are being made of the inverse scattering problem yielding some preliminary results concerning the determination of the dielectric constant of the snow layer.

The experimental results lead to the following conclusions: a) Snow layering affects backscatter, b) Layer response is significant up to 45 degrees of incidence, c) Wetness modifies snow layer effects, and d) Frequency modulation "masks" the layer response.

## Introduction

At the Electronics Research Laboratory, University of California, Berkeley, the research program of microwave scattering properties of snow fields along two directions. One is the experimental determination of the microwave properties of snow fields and the other is a theoretical program of mathematical modeling and the inverse scattering problem. The ultimate goal of the project is the coalescence of the two into a useful diagnostic technique for the determination of water content in snow.

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Experimental Portion of the Project - D. J. Angelakos, F. D. Clapp, W. I. Linlor and J. L. Smith: The primary objective of the experimental program was to determine the effect of snow conditions on the amount of backscattered electromagnetic energy. In addition the investigation was to seek out any effects on the backscatter due to snow layering and to determine the dependence on frequency and frequency deviation.

In proceeding towards the objective several additional phenomenological effects appeared which added insight to backscatter signal response. What follows is a sampling of results which indicates the partial attainment of our goal.

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Equipment: Most of the data were taken for swept-frequency ranging from 5.8 to 8.0 GHz. The sweepers were the "Alfred" and the "Hewlett-Packard" sources. These were connected with coax cable to horns having nominally 20-dB gain. The receiver horns were coupled to crystal detectors and HP SWR meters, whose output was plotted on XY plotters, on a logarithmic scale. For some measurements a converter unit was employed (Wiltron manufacturer) that permitted a uniform dB scale for the Y-axis.

For the 13.5 GHz measurements a fixed-frequency solid state oscillator was used (Varian manufacturer). Time was not available to take measurements at other frequencies, either fixed or swept.

Sites: Two sites were used: one is called the "tower site" which is on the roof of the snow hut, for which only two fixed angles (39° and 45°) could be used; the other is called the "ladder site" where all desired angles could be obtained.

The limited available time — dictated by the snow depth — for measurements and also the limited manpower made a choice necessary between taking data or ground truth (i.e., snow electrical characteristics). Under the circumstances the ground truth had to be limited to:

a. Density profile of the snow

b. Visual inspection of layers in the snow and granularity

c. Dielectric constant measurement of a few samples, near the top and middle of the snowpack

d. Wetness measurement of these samples

Discussion of Experimental Results: The solid line of Fig. 1 shows the backscatter in dB versus frequency in the range of 5.8 to 8.0 GHz, at the fixed angle of 39° from the vertical, and a snow depth of 70 cm. The electric field vector of the horns (20 dB gain each for transmitter and receiver) was parallel to the earth surface.

The various peaks are produced by layering effects in the snow. The peak values are about 25 dB greater than the minima.

To then determine what effect frequency deviation (more specifically, frequency modulation) had on the measurement the signal source was reset to the frequency for each maximum and minimum, but a modulation of ±100 MHz was superimposed for the + points; and a modulation of ±200 MHz was superimposed for the 0 points. Evidently the effect of frequency modulation is merely the averaging of the unmodulated response over the bandwidth represented by the modulation.

In the course of taking measurements, whether at normal incidence or otherwise it was observed that the backscattering data depended on the observation time and temperature. Figures 2, 3 and 4 show the backscatter response at normal incidence. The experimental conditions for the three sets of data were identical except for the time taken and accompanying ambient temperature. Variation of backscatter with snow conditions, at 13.5 GHz and incidence angle of 39° is shown in Fig. 5.

The decrease in backscatter shortly before noon was initially observed by us in March 1976 for a snowpack 150 cm deep, and has been confirmed at other frequencies by several groups (Currie et al., 1976, Ulaby et al., 1977). Evidently the increase in surface snow wetness by solar heating is the reason for the backscatter decrease, totaling about 15 dB. The air temperature variation included is useful in correlation the phenomenological effects.

Snow wetness produced during a few hours of sunlight can significantly affect the frequency response. March 5, 1977, when the measurements were taken, was a clear, warm day with a temperature of about 10° C between noon and 16:00, so the snow was essentially saturated with water in the upper surface.

Figure 6 shows typical data demonstrating that variation in backscatter as a function of frequency can be observed even for other than normal incidence (39°). Significant backscatter data has been obtained for incidence angles approaching 45°.

A continuous variation of incidence angle from the vertical is shown in Figure 7, giving the backscatter in relative dB for the fixed frequency of 11.8 GHz (no modulation, with snow depth of 53 cm. The backscatter is down about 20 dB at the angle of 40° from the vertical.

Theoretical Portion of the Project – K. K. Mei and S. Coen: It is suggested that certain useful properties of the snow-pack may be approximately determined by using inverse scattering theory; the inverse problem is that of determining the properties of inaccessible snow pack from the back-scattered electric field due to normally incident plane waves at varies discrete frequencies.

Let the back-scattered frequency response of the snow-pack be taken as the reflection coefficient amplitude $|\rho(\omega_i)|$, $i = 1,2,\ldots,N$. Neglecting for the moment the experimental errors, the question is: how can we learn as much as possible about the characteristics of the snow-pack from a set of numbers $|\rho(\omega_i)|$, $i = 1,2,\ldots,N$? Alternatively what do the numbers $|\rho(\omega_i)|$, $i = 1,2,\ldots,N$ tell us about the dielectric constant and conductivity of the snow-pack? The density and wetness of the snow may be then approximately determined by using Weiner's theory of dielectric mixtures or other available experimental relations.

In what follows, we show that there is enough information in the numbers $|\rho(\omega_i)|$, $i = 1,2,\dots,N$, to construct local averages of the snow profile.

Here the experimental errors are neglected and a mathematical model that describes the physical behavior of the snow-pack is chosen. The simplest model that we choose, is that of a plane stratified snow-pack, whose properties are characterized by a linear, isotropic and nonhomogeneous dielectric medium, as shown in Fig. 8a. Maxwell's equations now show that, for time harmonic dependence $e^{j\omega t}$, the electric field E, satisfies the one dimensional wave equation

$$\left\{\frac{\partial^2}{\partial x^2} + k^2 q(x,k)\right\} E(x,k) = 0 \qquad (1)$$

where $k = \omega(\mu_o \varepsilon_o)^{1/2}$ is the free space wave number and $q(x,k) = \varepsilon(x) - j\,\frac{\sigma(x)}{\omega\varepsilon_o}$ is the profile function. Here $\varepsilon(x)$ is the dielectric constant of the snow and $\sigma(x)$ its conductivity.

Consider two media as shown in Fig. 8b.c. The electric field in the respective medium satisfies

$$\left\{\frac{\partial^2}{\partial x^2} + k^2 q_n(x,k)\right\} E_n(x,k) = 0 \qquad n = 1,2 \qquad (2)$$

and the scattered fields are outgoing. Equation (2) can be reformulated into an integral equation form suitable for iterative solutions,

$$\delta\rho(k) = \frac{k}{2j}\int_0^h \delta q(x,k)\; E_1^2(x,k)dx + \alpha(k) \qquad (3)$$

where we have used the relation $E_2 = E_1 + \delta E$ and $\delta\rho = \rho_2 - \rho_1$ and $\rho_2(k)$ were given from measurement without error. It may be shown that the term $\alpha(h)$ goes to zero as $\|\delta q\|^2$, where $\|\cdot\|$ is the $L^2$ norm. Thus, if $\delta q$ is small enough, this term may be dropped, and we obtain a linear approximation

$$\delta\rho(k) = \frac{k}{2j}\int_0^h \delta q(x,k)\; E_1^2(x,k)\; dx \qquad (4)$$

which is a linear Fredholm integral equation, for the determination of $\delta q$ from the given functions $\delta\rho$ and $E_1$. Once $\delta q$ is found, the profile $q_2$ is given by $q_2 = q_1+\delta q$. However, equation (4) is not exact, so the profile $q_2$ will not in general, satisfy the equation (2). To overcome this, we solve the equation by iterations, until convergence occurs. In practice few iterations will suffice.

In practice, the amplitude of the reflection coefficient is much to be preferred than its phase, and equation (4) can be rewritten into the form

$$g_i = \int_0^h \delta\varepsilon(x)\ F_i(x)\,dx \qquad i = 1,2,\ldots,N \tag{5}$$

where $g_i = \log\left|\dfrac{\rho_2(k_i)}{\rho_1(k_i)}\right|$, $\delta\varepsilon = \varepsilon_2-\varepsilon_1$ and $F_i(x) = \mathrm{Re}\{\dfrac{k_i}{2j\rho_1(k_i)}\ E_1^2(k_i,x)\}$; here the frequency k is discretized and the medium is assumed lossless. The approach to be discussed is however applicable to lossy medium as well.

We now show how to solve Eq. (5) by the Backus and Gilbert approach. Multiply the equation by $\mathcal{a}_i(\xi)$ and sum over i; this results in

$$\langle\delta\varepsilon\rangle_\xi = \int_0^h \delta\varepsilon(x)\ A(\xi,x)\,dx \tag{6}$$

where

$$\langle\delta\varepsilon\rangle_\xi = \sum_{i=1}^{N} \mathcal{a}_i(\xi)\ g_i \tag{7}$$

is the local average of $\delta\varepsilon$, and

$$A(\xi,x) = \sum_{i=1}^{N} \mathcal{a}_i(\xi)\ F_i(x) \tag{8}$$

is the averaging kernel.

The coefficients $\mathcal{a}_i(\xi)$, $i = 1,2,\ldots,N$ are determined, such that the averaging kernel resembles the Dirac-Delta function most closely. One way of doing this is by minimizing the quadratic form

$$\int_0^h (\xi-x)^2 A^2(\xi,x)\,dx \tag{9}$$

subject to

$$\int_0^h A(\xi,x)\,dx = 1 \tag{10}$$

for each $\xi$; this minimization problem may be reduced to the linear equation upon introducing a Lagrange multiplier.

Once the coefficients $\mathcal{a}_i(\xi)$ are determined, the local average $\langle \delta\varepsilon \rangle_\xi$ is computed via equation (7).

In Figs. 9 and 10 we present results for 3 different snow profiles; the results shown in Figs 9a and 9b have been obtained with data at 3 frequencies only, whereas, the results shown in Fig. 10 have been obtained with data at 7 frequencies. The approximate results obtained from our analysis are in good agreement with the exact results for smooth profiles, as is evident from Figs. 9a and 9b. The poor resolution near the edges of the ice layer (Fig. 10) may be improved by using more data. It will be noted that the computation cost is about 5 dollars per profile on CDC 7600.

We are currently investigating the influence of experimental errors on the resulting snow profiles.

We find that there is a tradeoff between resolution and uncertainty, which is in agreement with the Backus and Gilbert theory.

References

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