OBSERVATION OF PASSIVE MICROWAVE EMISSION FROM SNOWPACK

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ABSTRACT

Preliminary results of an experiment to study the microwave emission from snowpacks in northern Vermont are reported. Microwave brightness temperature of snow at frequencies of 10.7, 18.0 and 37.0 GHz were measured by truck-mounted microwave radiometers. The measurement lasted from early December of 1983 to late March of 1984, encompassing a variety of snow depth and stratigraphy conditions. The brightness oscillations found at low frequency are attributed to coherent interference caused by ice layers embedded in the snowpack. For passive microwave remote sensing applications, these oscillations may cause some complications. However, at higher frequencies, the scattering loss is still the dominating one even with the presence of ice layers. And the general characteristics of the snowpack emission are still useful for remote sensing purpose.

INTRODUCTION

Remote sensing of the earth with microwave has witnessed a rapid development during the past decade. Among the land surface features, remote sensing of snowpack is one of the most useful, interesting, and challenging areas[1]. Knowledge of the snowpack conditions is important to hydrologists, because mountain snow represents a significant part of our water resource, e.g. the western part of the U.S. Timely information of the snowpack, such as its depth or water equivalent, permits the society to manage this precious natural resource more wisely. On the other hand, untimely and sudden melting of the mountain snowpack may cause disastrous flash flood, as we have seen too often in the past few years.

Microwave is uniquely suited for the remote sensing of snowpack. Unlike the visible or infrared part of the spectrum, the relatively longer wavelength of microwave energy can penetrate the snowpack and interact with not only the snowpack but also the underlying soil surface. It is because of this considerable penetration depth, the microwave is the only means capable of providing snow depth or water equivalent information.

From the electromagnetic theory point of view, snow on soil can be modelled by a layer (or a multitude of layers, depending on the stratigraphy of the snowpack) of material over the earth. For a dry snowpack, it turns out that the scattering property of the snowpack plays a dominant role in determining how electromagnetic energy propagates through it.

As electromagnetic wave emitted from the underlying earth surface propagates through the snowpack, it is scattered by the randomly spaced snow "particles" into all directions. Consequently, when the wave emerges at the snow/air interface, its amplitude is generally attenuated. The dry snow absorbs very little energy from the wave and therefore, it also contributes very little in the form of self emission. When the snowpack grows

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deeper, the wave suffers more scattering loss, and the "emission from the snowpack" is further reduced. This process, in a nutshell, is the basic reason of the diminishing microwave brightness temperature vs. the increasing snow depth relationship.

Of course there are other factors which also affect the microwave brightness temperature. For example, the scattering property is dependent on the size distribution of the snow particle. And the Fresnel relationship (governing the refraction and reflection across the boundary between two different media) determines the angular dependence of brightness temperature[2,3,4].

In passive microwave remote sensing of snow, microwave radiometers are used to measure the intensity of the emission from the snowpack plus the underlying soil. The Radiative Transfer Theory[5] has been used successfully to relate the observed microwave brightness temperature to the relevant snowpack parameters of interest. Measurements made from simpler type of snowpacks from the Colorado Rockies have been matched with theoretical models[2].

However, when the snowpack is embedded with layers of ice sheets, as frequently is the case of the Northeastern U.S. or the Canadian Priaries, the simple relationship between the depth and the brightness temperature becomes more involved. Internal reflections between two ice layers can cause interference and, depending on constructive or destructive nature, they can lead to increasing or decreasing the brightness temperatures of the snowpack.

The experiment reported here is aimed at establishing a complete data set of microwave emission characteristics of snowpack from different parts of the U.S. Such data set are needed to interprete the spaceborne microwave radiometric data from the existing or future earth sensing satellites.

The microwave radiometers used in this experiment included three frequencies. They are 10.7, 18.0, and 37 GHz. The rationale for selecting these frequencies are: (a) the two adjacent frequencies are separated by about an octove in order to study the frequency dependency of the scattering effect; and (b) the frequencies be identical or very close to the frequencies of some existing or future spaceborne microwave radiometers, so that data obtained from field experiment can be directly related to future works.

The Scanning Multi-channel Microwave Radiometer (SMMR) on board the Nimbus-7 satellite, operates at five frequencies, they are: 6.6, 10.7, 18.0, 21, and 37 GHz. The corresponding footprints on earth surface are: 144 x 92, 88 x 57, 53 x 40, 44 x 28, and 26 x 17 (km) x (km), respectively. SMMR has been providing global data since its launch in 1978. Another multifrequency microwave radiometer, the Special Sensor Microwave/Imager (SSM/I), will soon be flown aboard the Defense Meteorological Satellites Program's (DMSP) satellites. SSM/I will operate at 19, 22, 37, and 85 GHz, and the corresponding footprint sizes are: 70 x 45, 60 x 40, 38 x 30, and 16 x 14 (km) x (km), respectively. The wealth of present and future global satellite data warrants controlled field experiments of passive microwave emission characteristics of snowpacks.

THE EXPERIMENTAL SETUP

The experimental site is located in Danville, Vermont. This area is chosen partly because it is a representative area of the Northeastern U.S. snowpack, and partly due to logistic convenience. Our test site is colocated with the NOAA National Weather Service's Sleepers River Watershed Snow Research Station near Danville, Vermont (elevation 549 m).

The primary instruments used in the experiment were three microwave radiometers. Table 1 lists their essential characteristics. The radiometers are of modulated (Dicke)[6] type. Each radiometer goes through two internal (a "hot" and a "cold") calibrations periodically. The hot calibration reference is a microwave load maintained at a slightly warmer-than-ambient instrument temperature. The cold calibration reference is a noise diode producing a noise power of about 200K warmer than the ambient temperature. With a phase reversal in the detected square wave, the noise diode serves as a virtual cold reference of about 100K. These periodic internal calibrations establish the gain of the electronic system, and from which the amplifier output voltage is interpreted in temperature units. From time to time, the overall radiometer-and-antenna system is also calibrated by pointing the antenna at targets with known temperatures, such as Eccosorb (a specially designed material with emissivity of unity), or water surface.

The antennas used are lens loaded circular horns. Orthomode transducers at the apex of the horns separate the vertical from the horizontal polarizations. The basic (single-sample) temperature sensitivity (precision, or short-term stability) of the radiometers ranges from 1.0 to 4.0 K (corresponding to 0.8 sec integration time). However, we average from 21 to 42 such 0.8 sec samples to generate a datum, therefore, the effective temperature sensitivity ranges from 0.15 to 0.87 K (see Table 1).

The radiometers were mounted in an instrument platform attached to the end of a hydraulically operated aerial boom which, in turn, was mounted on a truck. The radiometer antennas can be pointed at the snowfield by telescoping the boom radially and by moving it in either elevation or azimuthal directions. In addition, the instrument platform can be rotated with respect to the boom in elevation plane by a motor. With the combination of these motions, the radiometers can be pointed at a given spot of the snowpack from different elevation (incidence) angles. This is a convenient feature used to study the incidence angle dependence of microwave brightness temperature. The radiometer raw data (output voltages) were digitized and stored on a magnetic tape recorder. A microcomputer was used to process the raw data and produce a quick-look printout in the field.

PRELIMINARY RESULTS

The truck-based experiment took place from December of 1983 to March of 1984. Some of the preliminary results are discussed here. The test site is a relatively flat area of about 30 feet by 300 feet. It is inside the Town Line Snow Research Station of NOAA's National Weather Service. The test area is subdivided into various "stations", each given a letter name, such as A, B, C, etc., to signify a specific spot.

One of the major features of interest is the relationship between snow depth and its brightness temperature. Fig. 1 shows such features at 37 GHz. The plots in Fig. 1 are in the form of brightness temperature (T_B) as a function of incidence angle (θ_I). In order to creat natural snowpacks of different depths within a small area, we maintained the snowpack at station C undisturbed since the first snowfall but cleared the snow off station F in mid-December of 1983. It is seen from Fig. 1 that the shallower snowpack of station F has a warmer T_B than the deeper snowpack at station C, even though both contain an ice layer labeled "A" in the profile sketch. The general trend of decreasing T_B versus θ_I is expected for horizontal polarization.

To illustrate the dependency of brightness temperature on frequency, we plot corresponding measurements obtained at 10.7 GHz in Fig. 2. The data were taken from the same stations F and C, and at about the same snow depths as Fig. 1.

The salient features of Fig. 2 are: (a) the expected "decreasing T_B vs. θ_I" is still evident; (b) there appears to be many "oscillations"; (c) the difference in T_B from different depths is smaller compared to the 37 GHz case in Fig. 1 (except for $\theta_I >$ 35 degrees); and (d) the T_B's are some 15 to 40 K warmer than those of corresponding curves at 37 GHz in Fig. 1 (again, except for $\theta_I > 35$ degrees).

The fact that 10.7 GHz has warmer T_B compared to 37 GHz is because the longer wavelength suffers less scattering losses. Furthermore, because it has less scattering loss, the longer wavelength is more coherent and hence is more sensitive to ice layers interferences. This may be the reason why there are as many oscillations. Also, because of the relatively smaller scattering loss in passing through the snowpack, the 10.7 GHz frequency is relatively insensitive to snow depth variation.

Table 1

CHARACTERISTICS OF MICROWAVE RADIOMETERS USED IN SNOWPACK EXPERIMENT

Frequency (GHz)	37.0	18.0	10.7
Bandwidth (MHz)	200	200	200
Polarization	V, H	V, H	V, H
Beam Width (degree)	6	6	6
Integration Time (sec)	0.8	0.8	0.8
Temperature Sensitivity (K) (Single Sample, Nominal)	1.5	1.0	4.0
Number of Samples Averaged	42	42	21
Effective Temperature Sensitivity (K)	0.23	0.15	0.87
Calibration Accuracy (K)	3	3	3

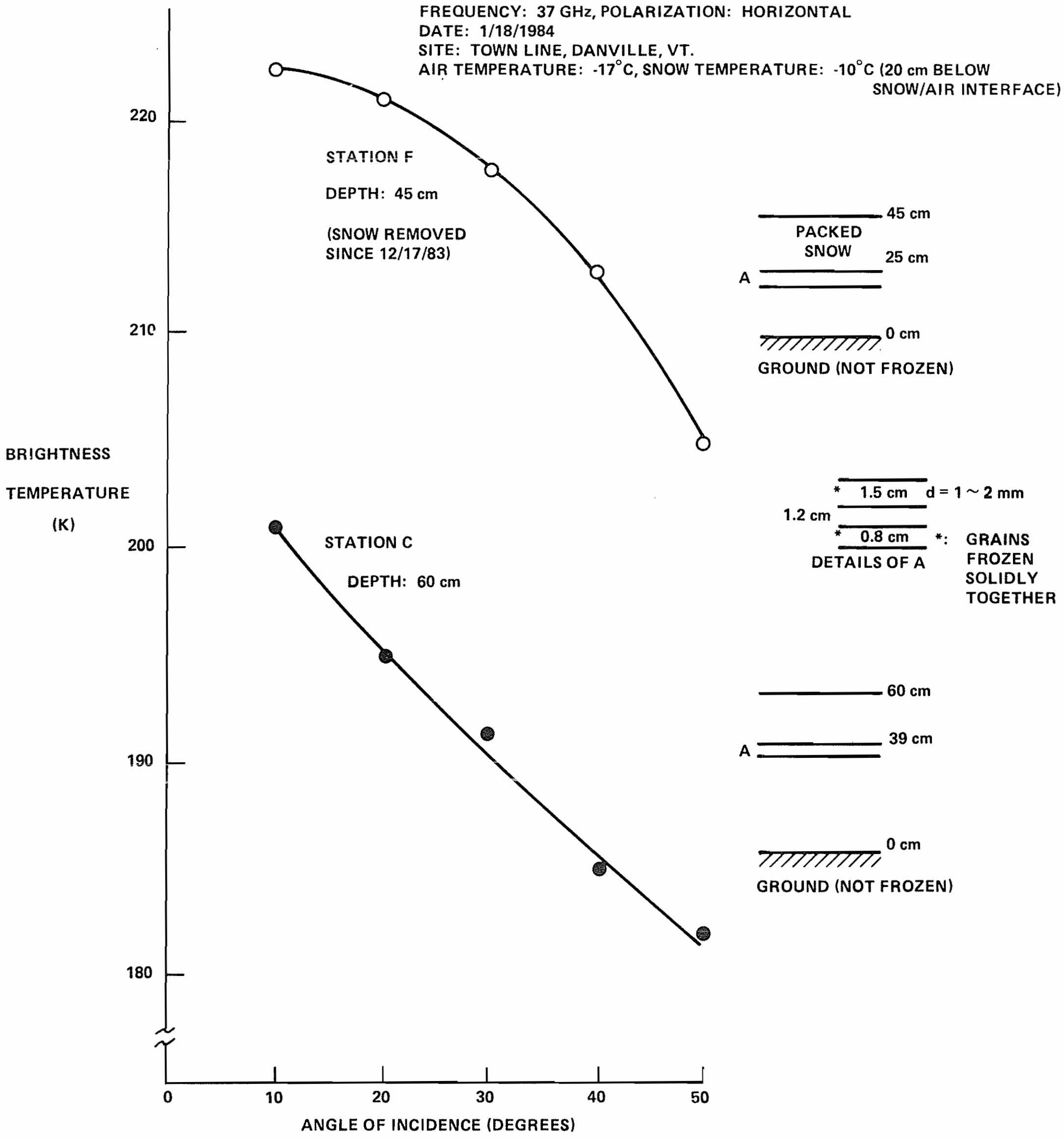

Figure 1. Microwave Brightness Temperature of Snowpacks With Two Different Depths

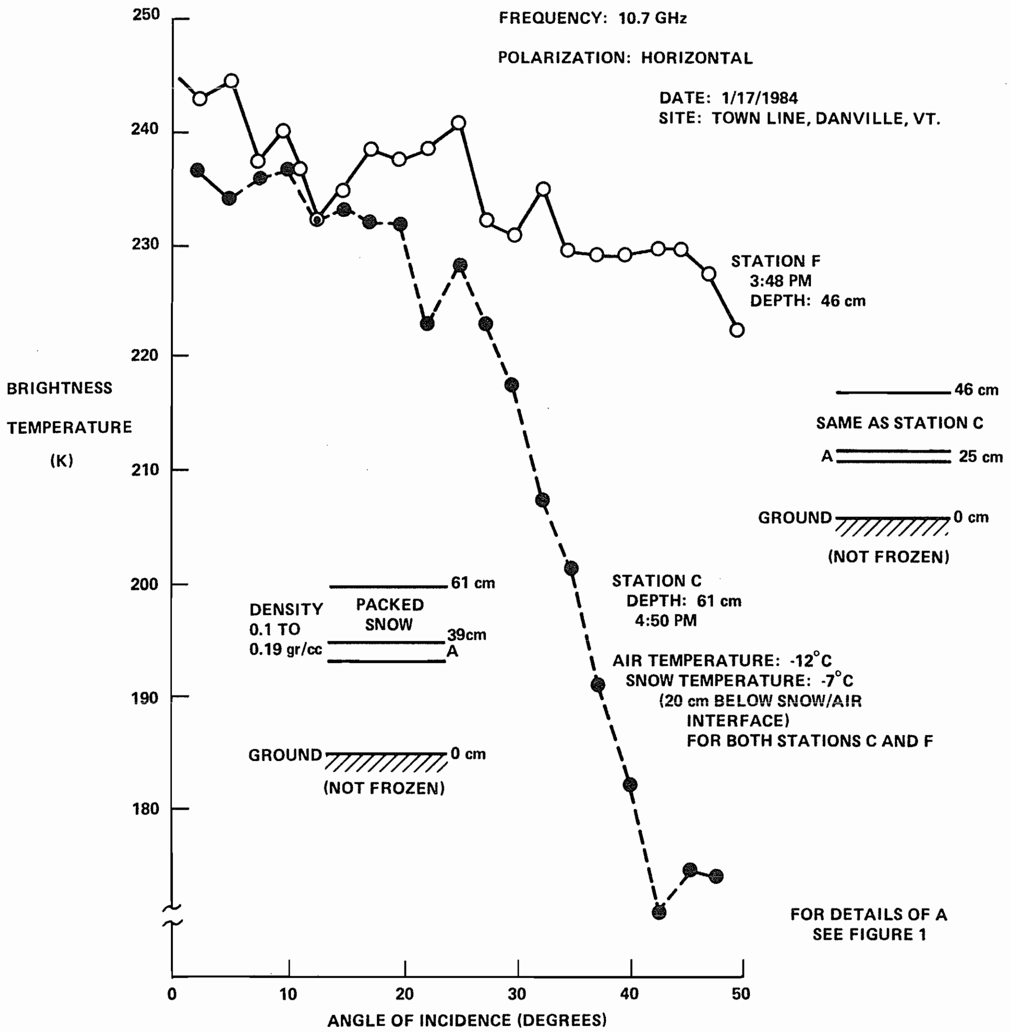

Figure 2. Brightness Temperature at Low Frequency

Fig. 3 shows the microwave brightness temperatures (at 10.7 and 37 GHz) of the snowpack after a major storm when the snow depth was nearly 100 cm. Comparing the 37 GHz curve in Fig. 3 to that of Fig. 1, when the snow depth was 60 cm, we see that for the 37 GHz, the rate of brightness temperature reduction (with depth) has begun to saturate at this depth.

As the snow becomes wet, the absorption loss (due to liquid water) increases drastically and the absorption overtakes the scattering effect to become the dominant energy loss mechanism for the waves.

Fig. 4 shows the microwave brightness temperatures of a wet snowpack after a recent rain. Because of the dominant absorption loss mechanism[7], the snowpack's self-emission at its own thermal temperature now constitutes a major portion of the brightness temperature. This is the reason why the T_B's in Fig. 4 are quite warmer than those of Fig. 3. At 37 GHz the absorption due to liquid water is the highest among the three frequencies, and the T_B is almost reaching the snowpack's themal temperature[8].

The most interesting feature of microwave emission from snowpacks with embedded ice layers is the oscillatory nature of the T_B vs. θ_I curve. Since lower frequencies are relatively more sensitive to the ice layers, we make a careful angular dependence study with the 10.7 GHz horizontal polarization. (The horizontal polarization is more sensitive to ice layers because its electric field vector is parallel to the ice surface.)

The distinct oscillations are clearly displayed in Fig. 5. Assuming the interference between two plane ice surfaces is the underlying cause of the brightness temperature oscillations, then when the brightness temperature changes from a minimum to a next maximum, the electromagnetic wave, in a return path between the planes, must have changed its phase by an additional 180 degrees (or odd integer multiple of 180 degrees). From this, the relationship expressing the separation distance d between the ice layers and other relevant snow parameters is given by

$$d = \frac{\lambda_0}{4\sqrt{\varepsilon}\,\Delta\sec\theta_I} \qquad (1)$$

where λ_0 = free space wavelength

ε = dielectric constant of snow

and $\Delta\sec\theta_I = \sec\theta_{I,min} - \sec\theta_{I,Max}$

In our case, $\lambda_0 = 2.8$ cm, and $\theta_{I,min} = 7.5°$, $\theta_{I,Max} = 17°$; if $\varepsilon = 1.8$, then d = 14 cm from equation (1).

From our ground truth, the value of d is 12 cm, or 14 percent smaller than the expected value based on equation (1). It is quite possible that the errors in angle determination or in the values of snow dielectric constant could account for the discrepancy.

CONCLUDING REMARKS

The ice layers embedded in snowpacks can modify the emission characteristics of the snow. The interference effect is more prominant at lower frequencies (e.g. 10 GHz or lower) than at higher frequencies (e.g. 37 GHz or higher). From the passive remote sensing point of view, the higher frequencies are therefore better suited for the areas where the weather cycles are likely to produce such ice layers. The observed oscillations (in amplitude) of microwave brightness temperature seems to be attribut to the interference caused by ice layers embedded in the snowpack. However, in order to prove this point more conclusively, it would be interesting to repeat the same experiment while: (a) artificially adding an ice layer, or (b) removing an ice layer from the snowpack, to see if the oscillatory behaviors in brightness temperature change accordingly. Another

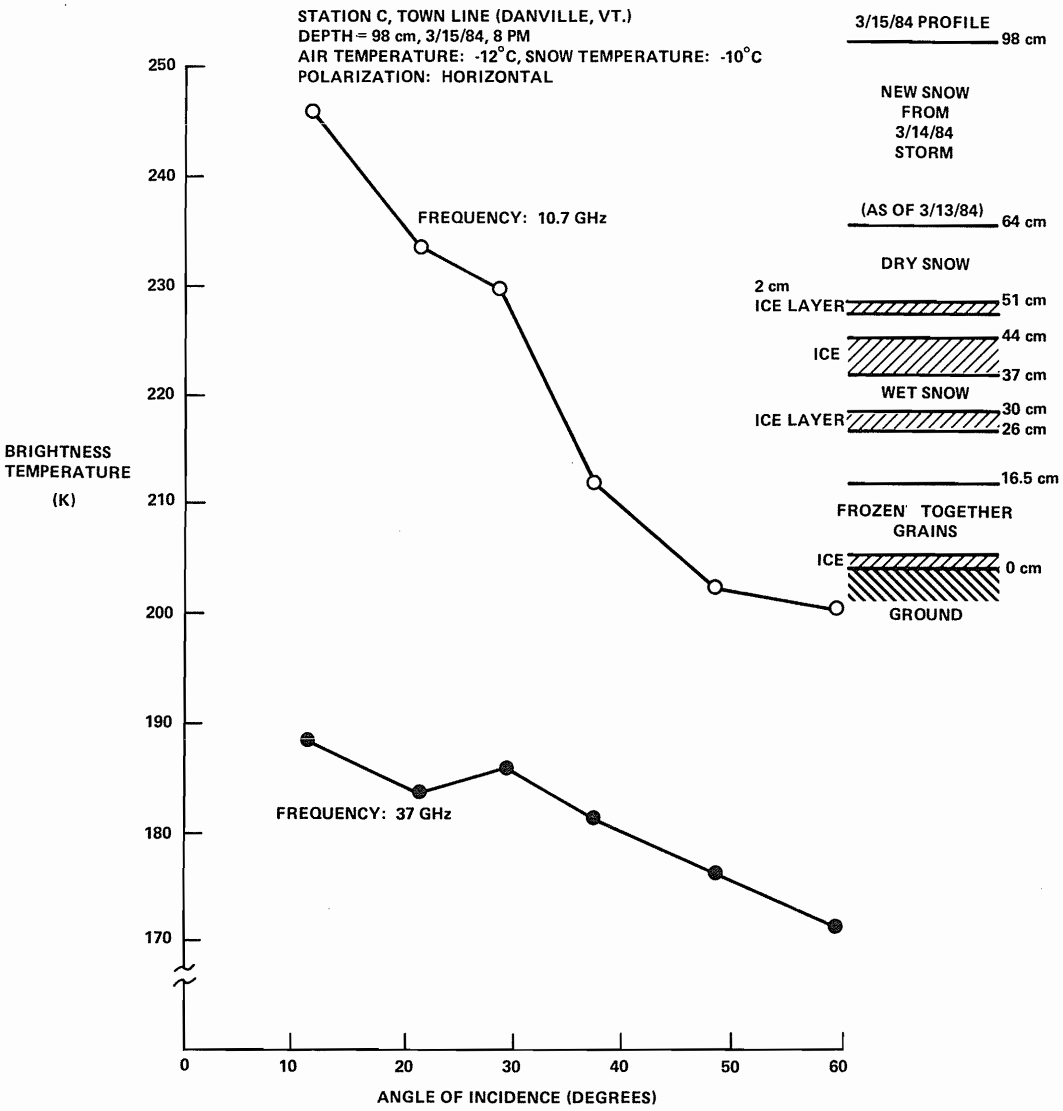

Figure 3. Microwave Brightness Temperature of Snowpack at Different Frequency

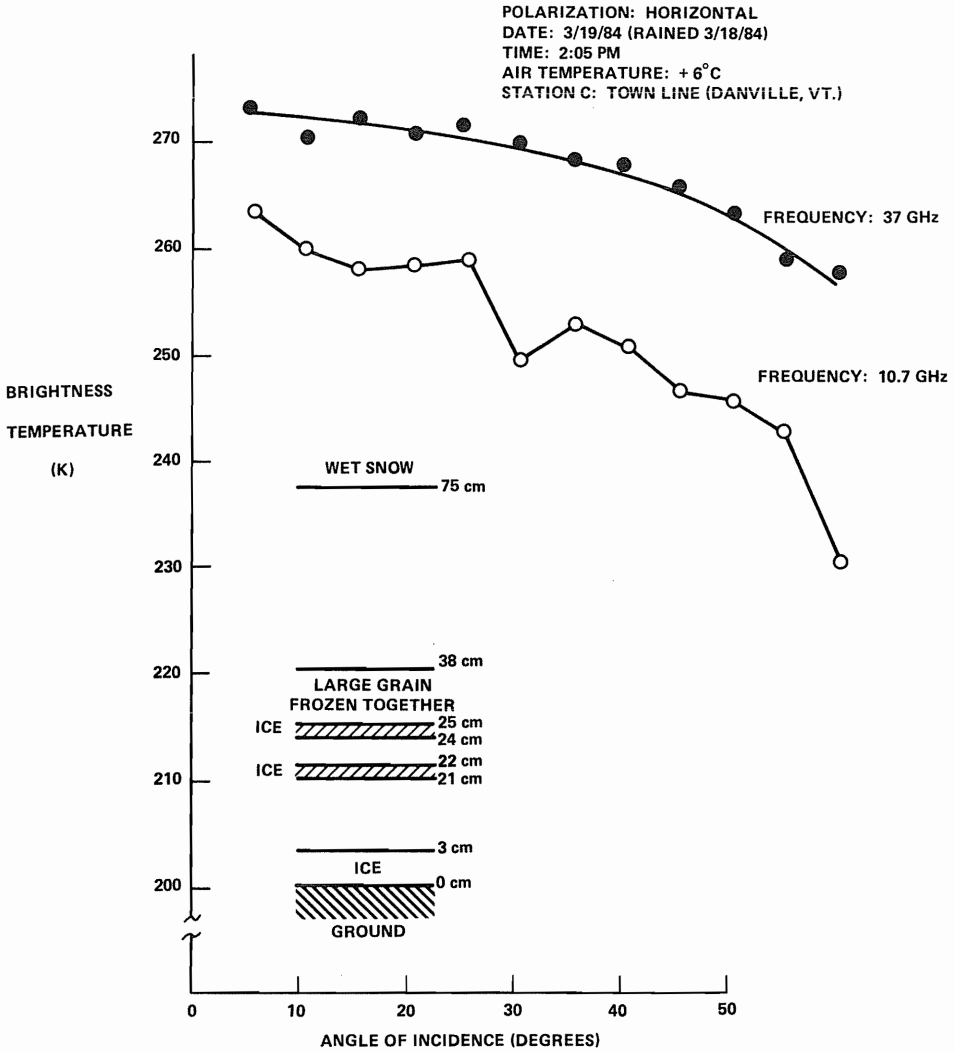

Figure 4. Characteristic Microwave Brightness Temperature of a Wet Snowpack

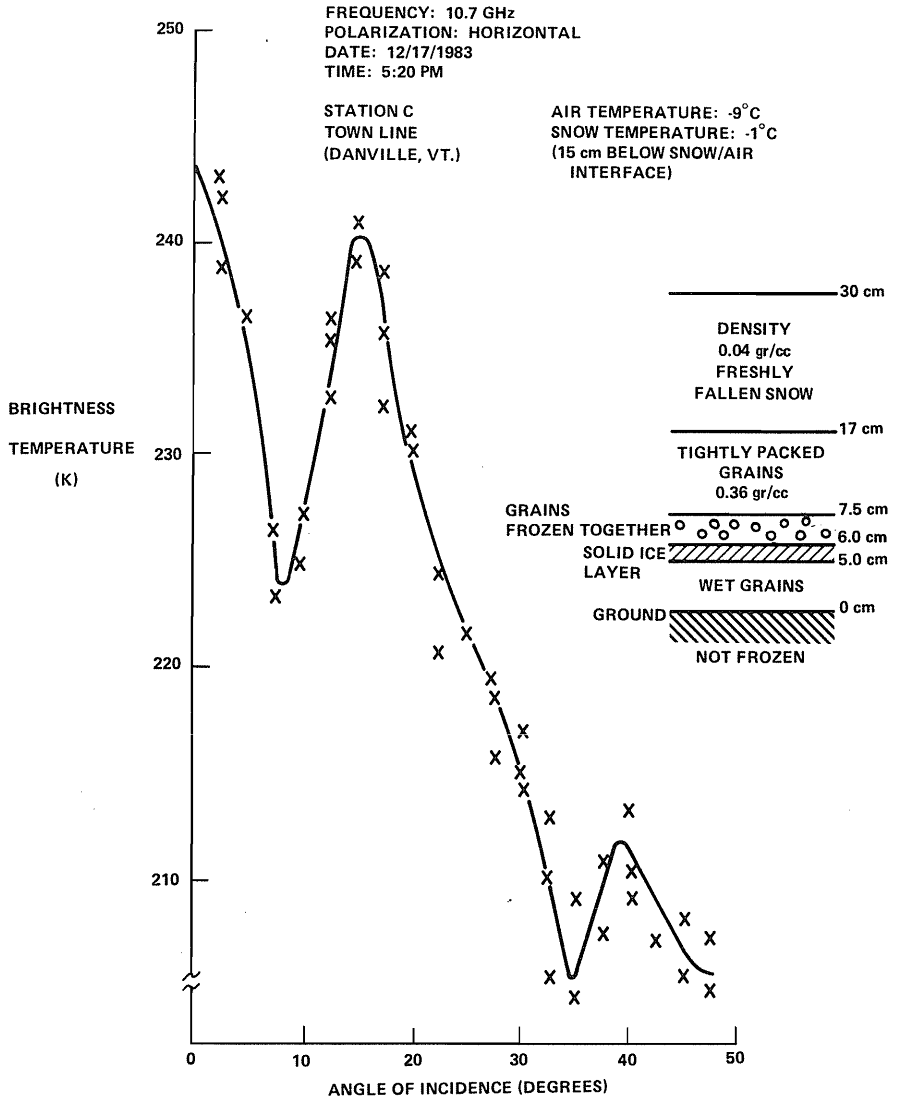

Figure 5. Oscillations in Brightness Temperature of an Ice-Layers-Embedded Snowpack

interesting area regarding the ice embedding would be to use the coherent type theoretical treatment rather than the radiative transfer theory.

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