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A Comparative Study of Microwave Radiometer Observations Over Snowfields With Radiative Transfer Model Calculations

A. T. C. Chang and J. C. Shiue

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A. T. C. Chang and J. C. Shiue

Laboratory for Atmospheric Sciences (GLAS)
NASA, Goddard Space Flight Center

ABSTRACT

The increase demand for water throughout the world imposes a challenging problem for water resources managers. Since the water stored in snowpacks represents an important source of the water supply, a system which monitors and inventories the water equivalent of snow should clearly improve the water resources estimate.

Recent results indicate that spaceborne microwave radiometry has the potential for inferring the snow depth and water equivalent information over large snow-covered areas. In order to assess this potential for determining the water equivalent of a snowpack, it is necessary to understand the microwave emission and scatter behavior of the snow at various wavelengths. The emitted microwave radiation is dependent on the physical temperature, crystal size, and density. The basic relationship between the properties of the snowpack and the emitted radiation can be derived by using the radiative transfer approach.

Truck-mounted microwave instrumentation was used to study the microwave characteristics of the snowpack in the Colorado Rocky Mountain region in the vicinity of Fraser, Colorado during the winter of 1978. The spectral signatures of 5.0, 10.7, 18, and 37 GHz radiometers with dual polarization were used. These data compared favorably with calculated results based on recent microscopic scattering models.

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INTRODUCTION

The increase demand for water throughout the world imposes a challenging problem for the water resources managers. A conservative estimate of future needs indicates an increase of three to five times the present demand by the year 2000. In order to meet this demand, effective management of the water resources is required to distribute the available water supply effectively. Since precipitation deposited as snow represents an important source of the water supply, a system which could monitor and inventory the water equivalent of snow over large regions should improve the water resources manager's estimate of eventual runoff.

To model the snow pack runoff, the measurement of the snow depth, density, free water content, and snow cover are required. Runoff estimates are typically derived from in situ measurements of these parameters along snow survey courses. These observations are collected by skiers, by use of snowmobiles, and from a few unattended isolated stations instrumented with pressure-pillow and other sensors. These data collection methods are time consuming and only a limited number of data points are measured. Consequently, the calculated model outputs may differ significantly from the actual runoff data because of the sparsity of the observation inputs in space and time. The use of satellite remote sensing techniques may offer a way to augment or complement conventional observations by providing observations with a high spatial density and repetivity over an entire watershed.

Snowcovered area estimates from spaceborne visible and infrared images for several test watersheds have correlated well with the actual runoff yields, Rango, et al. (1975). Recent results by Rango, et al. (1978) also indicate that microwave radiometry can be utilized to determine the snowcover. To deduce the snow depth and water equivalent, it appears advantageous to study the applicability of the microwave radiometer data from the NASA, Nimbus 5 and 6 satellite's electrically scanning microwave radiometer experiments. The advantages of using microwave sensors are: they are largely unaffected by cloud cover, have the capability of penetrating the snowpack and, thereby, being able to estimate snowpack characteristics.

In order to quantitatively determine the water equivalent of the snowpack, it is necessary to understand the microwave emission and scattering behavior of snow at various wavelengths. This paper reports on a truck mounted microwave system experiment that has been conducted to study the microwave emission characteristics of snowpacks in the Colorado Rocky Mountain region during the winter of 1977-78. The spectral signatures of 5.0, 10.7, 18, and 37 GHz radiometers with dual-polarization were used to measure the snowpack density and temperature profiles, rain profile, and free water content. These data have been compared with calculated results based on a microscopic scattering model developed by Chang, et al. (1976) for dry, surface melting, and very wet snowpacks. The experimental data compare favorably with calculated results based on the microscopic scattering models.

TRUCK MOUNTED RADIOMETER EXPERIMENTAL RESULTS

A microwave test measurement experiment was conducted with truck-mounted radiometers at three test sites covering both shallow, uniform snowpacks in a valley and deeper snowpacks in a high elevated mountain pass. One of the valley test sites was located in the vicinity of Fraser, Colorado adjacent to state highway 40 between the towns of Hideaway Park and Fraser. The Fraser site in February 1978 had a uniform snow depth of 60 to 70 cm. The high elevation site (3658 meters) was located near Pass Lake of Loveland Pass where the snow depths measured 2.4 to 3 m. The third test site was located in a valley south of the town of Steamboat Springs, Colorado which had approximately 70 cm of wet snow at the end of March 1978. In this paper, only the test data taken near the Fraser, Colorado test site are discussed.

Four radiometers monitoring emitted radiation at 5, 10.7, 18, and 37 GHz were mounted on the framed, metal enclosure of a truck-mounted crane lift. The detailed description of the instrumentation, the test sites, and the measurement procedures were reported by Chang, et al. (1979). The brightness temperature data were obtained by scanning the instrument at different incidence angles. Two types of scanning procedures were used in measuring the brightness temperature as a function of the incidence angle. In the "swath scan," Figure 1, the radiometer antennas scanned in a vertical plane from nadir (normal incidence) until it was almost perpendicular (90°) to the nadir. The antennas were directed at different spots along a radial "swath" as the incidence angle changed. Under this condition, any inhomogeneity of the snowfield may modify the characteristics of the angular dependence. In order to remove the potential field inhomogeneity effect, the radiometer antennas were maneuvered so that they viewed the same snow spot "spot scan," Figure 2, as the incidence angle changed. The instrument package was usually located about 5 meters above the snow surface so the reflection of the instrument package had virtually no effect on the measured brightness temperature. The influence of the reflected atmospheric brightness due to water vapor and cloud liquid water on the measured brightness temperature was very small due to the high altitude of the test sites (about 2700 meters above mean sea level) and low air temperatures.

The physical characterization of the snowpack, "ground truth," was also documented with the microwave measurements of snow density and temperature, Chang, et al. (1979). The relative hardness and strength for each layer of snow was measured by a ram penetrometer, with visual inspections made on the average grain size at various depths. The liquid water content was measured by centrifuge separation and freezing calorimetry.

Figure 3 shows the measured brightness temperatures T_B versus incidence angle for both horizontal and vertical polarization for a set of spot scan data taken on February 16, 1978. Due to the leakage of liquid nitrogen from the calibration load dewar, measurements were made for incidence angles greater than 30 degrees. The air temperature was approximately -10°C when the test data were taken, hence, no free water was present in the snowpack. The snow depth was 70 cm which consisted of about 30 cm of new powdered snow and 40 cm of depth hoar which has a slightly larger crystalline structure. The metamorphasis for the bottom 10 cm was more advanced and the ram-hardness measurement increased from approximately 0 to 10 kg. No noticeable ice layer was observed within the snowpack. The underlying ground surface was frozen soil sparsely covered with driedup stalk cover. Under these conditions, the brightness temperature contribution from the ground surface was closely related to each of the four test frequencies. The 5, 10.7, and 18 GHz measured brightness readings were closely related, and these readings strongly suggest that the scattering effect of snow is relatively small for these frequencies. The brightness temperature of 37 GHz was about 40 K lower than the other frequencies. This difference showed that the scattering effect is a dominant factor affecting the measured brightness temperature at this frequency.

The measurement set of March 2, 1978 was carried out on a day with air temperatures at 2°C, Figure 4. The uppermost snow layer had started to melt and the free water content for the surface layer of snow varied from 0 to 3 percent as measured by the freezing calorimeter technique. Figure 5 shows the measured brightness temperature T_D versus incidence angle for the 5 and

37 GHz data. By comparing this data with Figure 3, the brightness temperature for 37 GHz increased by 40 K due to changing wetness of the surface snow layer, which is quite consistent with the results of Hofer and Schanda (1978); and Stiles, Hanson and Ulaby (1977). The wavy behavior of the curves may be attributed to the interference between the various snow layers. At 5 GHz the small amount of snow wetness on the surface layer did not seem to have a strong effect on the brightness temperature, probably due to its larger penetration depth.

The data set of March 23 1978 represented a measurement for a very wet snow case as it was melting within the isothermal snowpack, Figure 5. The free water content was about 15 to 20 percent by volume. Figure 5 shows the measured brightness temperatures at 5, 10.7, and 37 GHz. The brightness temperatures of 37 GHz show a slight angular variation for vertical polarization and horizontal polarization for an incidence angle between 0° and 50°. The brightness temperature of the snow was nearly identical to its physical temperature.

RADIATIVE TRANSFER EQUATION ANALYSIS

The microwave radiation emitted from a snowpack is dependent on the physical temperature, crystal size, and density of the snow pack. The basic relationship between the properties of the snowpack and the emitted radiation can be derived by using the radiative transfer approach.

An insight into the microwave emission from snow fields has been provided by a macroscopic volume scattering model by England (1974). This model specifically involves a parameter called the volume scattering albedo, ω_0, which is the ratio of the volume scattering coefficient to the total extinction coefficient. The extinction coefficient includes both the resistive and scattering losses. The analysis involves a value for ω_0 which is used to compute the brightness temperature or emissivity based on the ω_0 parameter. The model may be used to calculate the emissivity or the brightness temperature of finite slabs of snow and ice with varying compositions.

A snow particle scattering model was developed by Chang, et al. (1976) using the microscopic approach. This model assumed that the snow field or snow cover consisted of randomly spaced scattering spheres which did not scatter coherently. Since the snow fields of interest generally consisted of nonspherical particles which were not well separated, two assumptions were required to apply the theory. Firstly, it was assumed that the scattering particles were spherical; secondly, that the particles scattered incoherently and independently of the path length between scatters. These assumptions, however, were not expected to influence the quantitative nature of the test results. The Mie theory was then used to calculate the extinction and scattering cross sections of the individual particles as a function of particle radius and the complex index of refraction for given wavelengths. Subsequently, these quantities were used to solve the radiative transfer equation within the snow medium and to calculate the radiative emission from the model snowfield surface.

For the case of the melting ice sphere, it was assumed that the sphere consisted of a central core of ice and a surrounding shell of water. The solution of scattering of electromagnetic waves from these concentric spheres were solved by Aden and Kerker (1951). In this study, the thickness of the water layer is set according to the measured free water content. The index of refraction for water is calculated according to the results of Lane and Saxton (1952). The reflective index of ice is also taken to be 1.78 + i 0.0024 for this study.

The radiative transfer equation for an axially symmetric inhomogeneous medium in which all interactions are linear can be written in the form of an integro-differential equation as stipulated by Grant and Hunt (1969).

$$\mu \frac{dI(\tau,\mu)}{d\tau} = -I(\tau,\mu) + [1 - \omega(x)]\ B(x)$$

$$+\frac{1}{2}\omega(\tau) \int_{-1}^{1} p(\tau,\mu,\mu')\, d\mu\ I(\tau,\mu') \tag{1}$$

where the radiation intensity $I(x,\mu)$ is at depth x traveling in the direction making an angle whose cosine is μ with the normal toward the direction of increasing x, Figure 6.

The functions $\sigma(x)$, $\omega(x)$, $B(x)$, and $p(x,\mu,\mu')$ are prescribed functions of their arguments. They are referred to as the extinction per unit length, the single scattering albedo, the source, and the phase function, respectively. For a nonuniform medium these functions are generally piecewise continuous functions of depth subject to the conditions.

$$B(x) \geqslant 0,\ \sigma(x) \geqslant 0,\ 0 \leqslant \omega(x) \leqslant 1,\ p(x,\mu,\mu') \geqslant 0. \tag{2}$$

In the present work, the following normalization for the phase function will be used

$$\frac{1}{2}\int_{-1}^{1} p(x,\mu,\mu')\, d\mu' = 1 \tag{3}$$

for all values of x. Instead of working with depth x, one generally works with a dimensionless depth variable called optical depth τ, defined in differential form as

$$d\tau = \sigma(x)\, dx. \tag{4}$$

In terms of optical depth, equation (1) reduces to

$$\mu \frac{dI(\tau,\mu)}{d\tau} = -I(\tau,\mu) + [1 - \omega(x)]\ B(x)$$

$$+ \frac{1}{2}\ \omega(\tau) \int_{-1}^{1} p(\tau,\mu,\mu')\ d\mu\ I(\tau,\mu'). \qquad (5)$$

The equation of radiative transfer was solved numerically by the invariant imbedding technique by Chang and Choudhury (1978). By using the proper scattering phase function and the boundary conditions, the brightness temperatue emerging from the snowfield can be calculated. To calculate the microwave radiation emitted from the snowpack, it is necessary to know its physical temperature, snow density, and mean crystal radius within the snowpack. In order to perform the model calculation, snow profiles were taken on February 16, 1978, March 2, 1978, and March 23, 1978. The characteristics for each profile are listed as follows.

FEBRUARY 16, 1978 TEST PROFILE

On this date, the snowpack consisted of 70 cm of dry snow with a mean crystal radius of 0.3 mm. The physical temperature of the snowpack was assumed to be -5°C. The snow density was 0.3 g/cm^3, and the underlying surface was assumed to be frozen soil with a dielectric constant of 3.0 + i 0.0002, Figure 7.

MARCH 2, 1978 TEST PROFILE

The snowpack on this date consisted of two different snow layers, a 1.5 cm melting snow layer with 2 percent free water on top of a 50 cm dry snow layer. The mean crystal radius for both layers was 0.3 mm with a snowpack temperature of 0°C. The snow density was 0.3 g/cm^3 with the ground dielectric constant assumed to be 6.0 + i 1.0, Figure 8.

MARCH 23, 1978 TEST PROFILE

The snowpack on this data was isothermal and melting within the entire snowpack. The melt consisted of a layer of melting snow 60 cm in thickness with 20 percent free water. The mean crystal radius was assumed to be 0.3 mm, the temperature of the snow pack 0°C, and the snow density 0.3 g/cm^3. The underlying soil was not frozen and contained 20 percent soil moisture by weight, Figure 9. The dialectic constants used were those reported by Wang, et. al. (1978).

The calculated brightness temperatue for all four frequencies, based on these snow parameters, are shown in Figures 10, 11, and 12.

FRASER, COLORADO TEST RESULTS

No obvious ice layer was detected within the snowpack during the test period in the vicinity of Fraser, Colorado. The measured brightness data corresponded with the smooth curves for the vertical and horizontal polarized data. These curves correspond to the Fresnel reflection characteristics for a dielectric media interface. The volume scattering effect became a dominant factor affecting the brightness temperature when higher frequencies were used which decreased the penetration depth. At 37 GHz (0.8 cm), the scattering effect caused a decrease of 50 K in the emerging brightness temperature over the entire measuring angular range for a dry snowpack. The comprehensive change in the brightness temperature provides an opportunity to deduce the mean crystal radius within a snowpack by microwave measurement.

By comparing Figures 3 through 8, the calculated brightness temperatures generally agreed with the measured values. The rms deviations, $\text{rms} = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2 / n}$, of the measured brightness for each channel away from the calculated results are tabulated in Table 1. By reviewing these results, it was obvious that the scattering model simulates the real scattering behavior of the snow cover for the test site near Fraser, Colorado. The fine structure variation within the snowpack, which was not included in the scattering model calculation, would have contributed to the deviation between the measurements and the calculated brightness temperatures. The input to the scattering model may be improved by collecting more information on the snowpack properties. When the snowpack starts melting, it is difficult to characterize the surface snow dielectric constant accurately. Due to changing snow conditions, it is necessary to develop techniques which monitor the surface complex dielectric constant of the snowpack for better modeling results. The mean crystal rough estimate radius used was 0.3 mm for newly fallen snow. This element tends to be smaller than the typical depth hoar observed during the experiment. For estimating the size of the snow crystal, it is necessary to measure the three dimensional size of the snow crystal. In future studies, a photographic technique will be used to record the size and shape of the snow crystals.

Table 1

RMS Deviation of measured brightness away from the calculated brightness temperature

Frequency GHz	Polarization	February 16	March 2	March 23
5	V	4.3	6.2	4.4
	H	6.3	12.6	9.6
10.7	V	7.2	–	9.1
	H	5.5	–	13.5
18	V	5.0	–	–
	H	11.9	–	–
37	V	5.9	7.0	5.3
	H	6.8	10.4	16.2

The snow depth for the Fraser test site was generally less than one meter, which is typical for the high plains in the central and western United States. Snow depths, however, could be greater in the mountain valleys. Under a dry snow condition, the high frequency (37 GHz) is most sensitive to the mean crystal size of the snowpack, whereas the lower frequencies (5 and 10.7 GHz) are more sensitive to the conditions of the underlying surface. Using these spectral characteristics Chang (1978), it appears possible to retrieve relevant snow parameters using the multispectral technique.

CONCLUSIONS

Variations in the snow accumulation and snow metamorphosis at the Colorado test sites are reflected in related variations in a passive microwave brightness temperatures observed in the truck mounted radiometer, snow monitoring experiment conducted during February and March 1978. In a relatively homogeneous snowpack, such as the Fraser test site, the microwave brightness temperatures for various microwave frequencies may be calculated by a simple scattering model with an accuracy of 5 to 10 K. The accuracy of the experiment could be improved by having better quantitative snowpack parameter information. By calculating the microwave radiative transfer in snowpacks, a multispectral retrieval algorithm could be developed to retrieve the interested snow parameters.

The presence of melt water in the snowpack drastically changes the microwave emission characteristics resulting in as much as 50 K increase in the brightness temperature over a dry cross section snow condition because the extinction cross section for melting snow is an order of magnitude larger than that for dry snow. For a detailed quantitative analysis of snow wetness, new in situ techniques should be developed for measuring the snow parameters quickly and simultaneously with the microwave measurements.

Both vertically and horizontally polarized brightness temperatures showed a distinct signature for dry, surface melting, and very wet snowpacks, Figures 10, 11, and 12. These differences may be utilized to monitor the ripeness of the snowpack for the snow runoff predictions.

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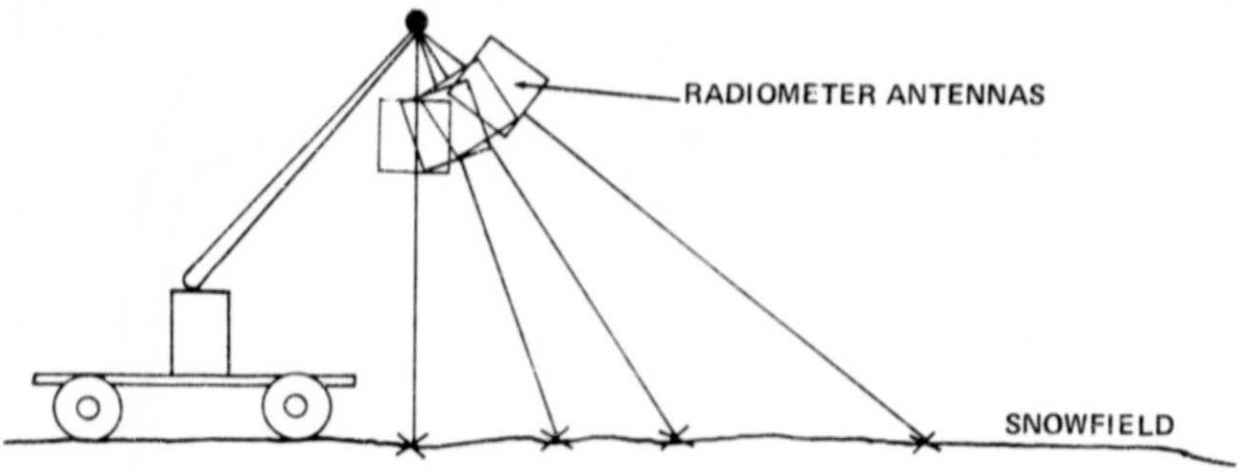

Figure 1. Swath Scan – The instrument package is directed to new test spots as the incidence angle is changed.

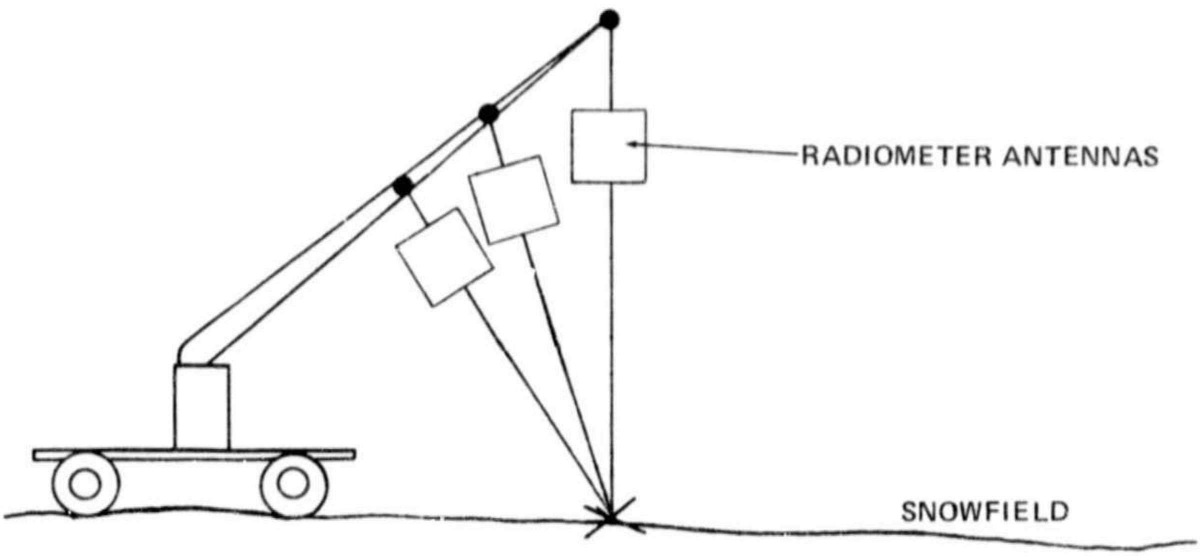

Figure 2. Spot Scan – The instrument package is always directed to the same test spot while the boom's height is changed.

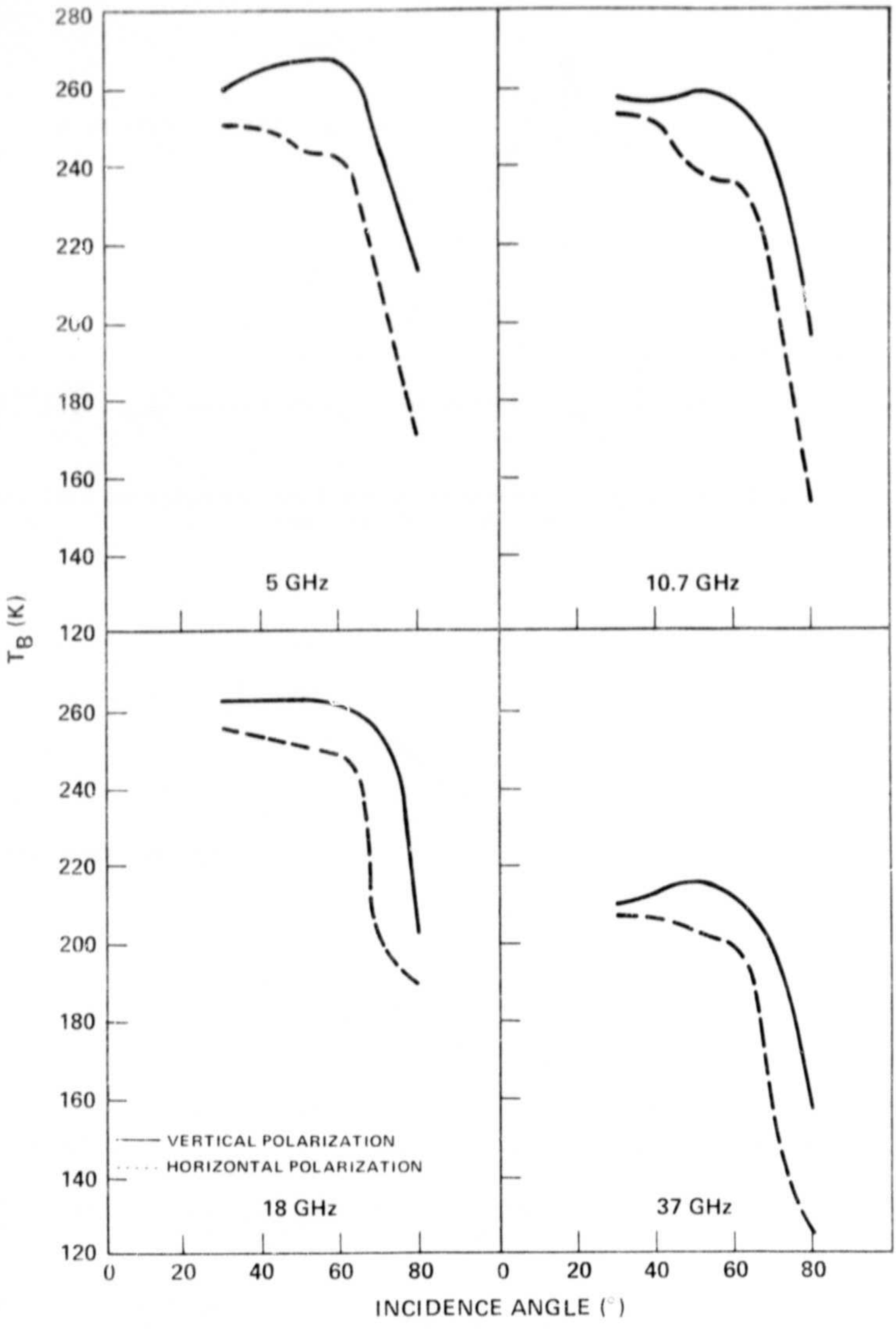

Figure 3. February 16, 1978 – Brightness Temperature T_B Versus Incidence Angle (Fraser, Colorado).

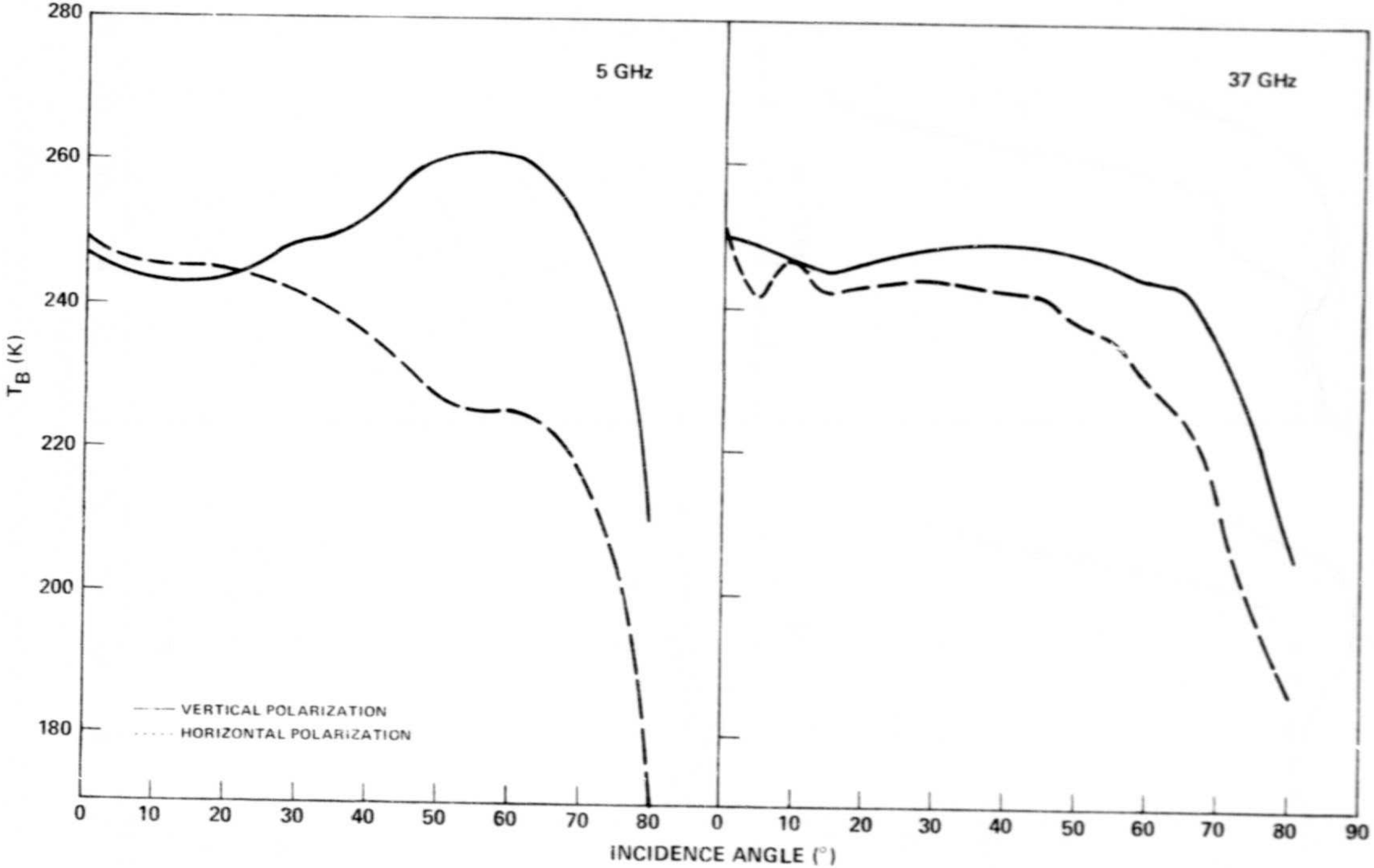

Figure 4. March 2, 1978 – Brightness Temperature T_B Versus Incidence Angle (Fraser, Colorado).

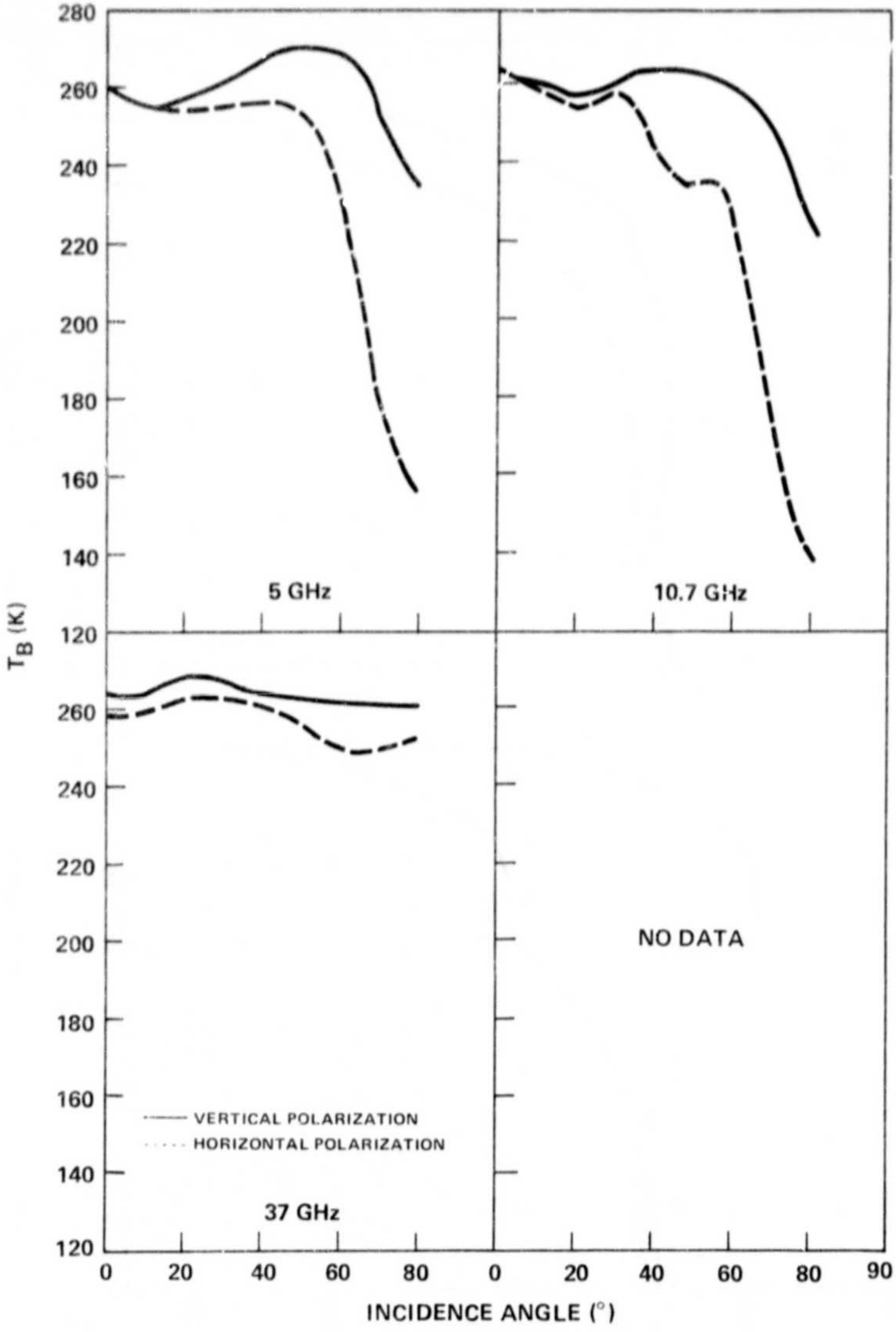

Figure 5. March 23, 1978 – Brightness Temperature T_B Versus Incidence Angle (Fraser, Colorado).

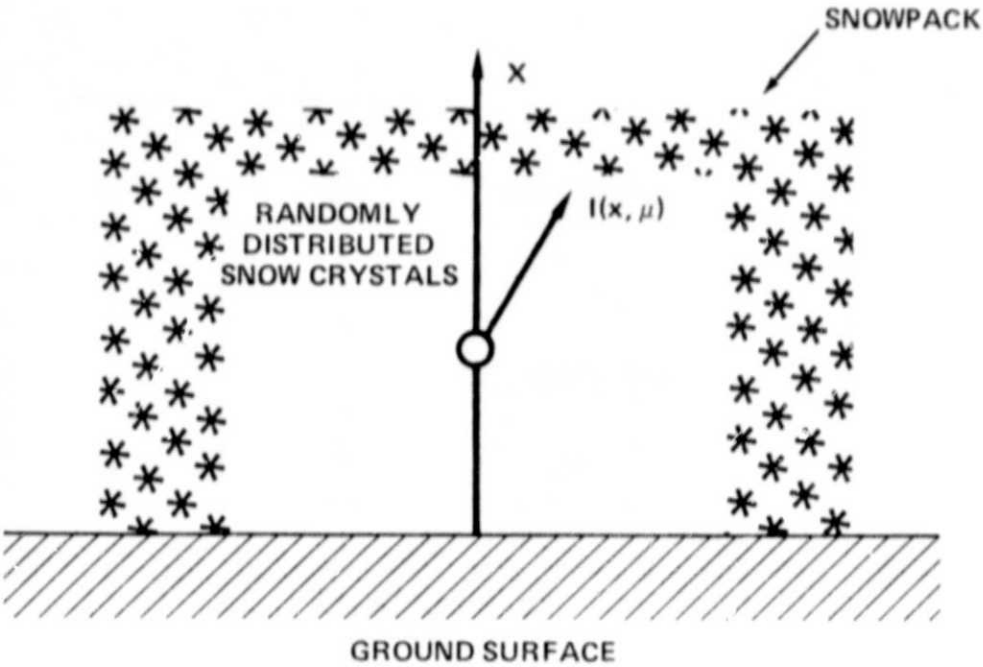

Figure 6. Radiation Intensity of I (x, μ).

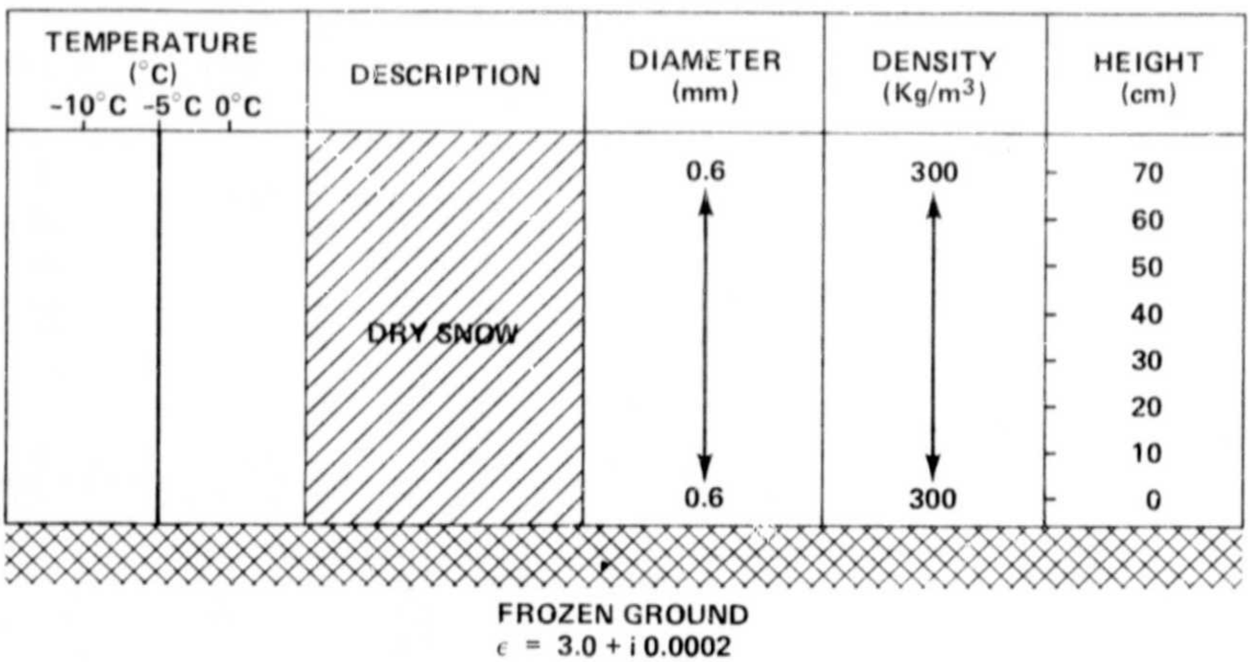

Figure 7. February 16, 1978 – Test Data.

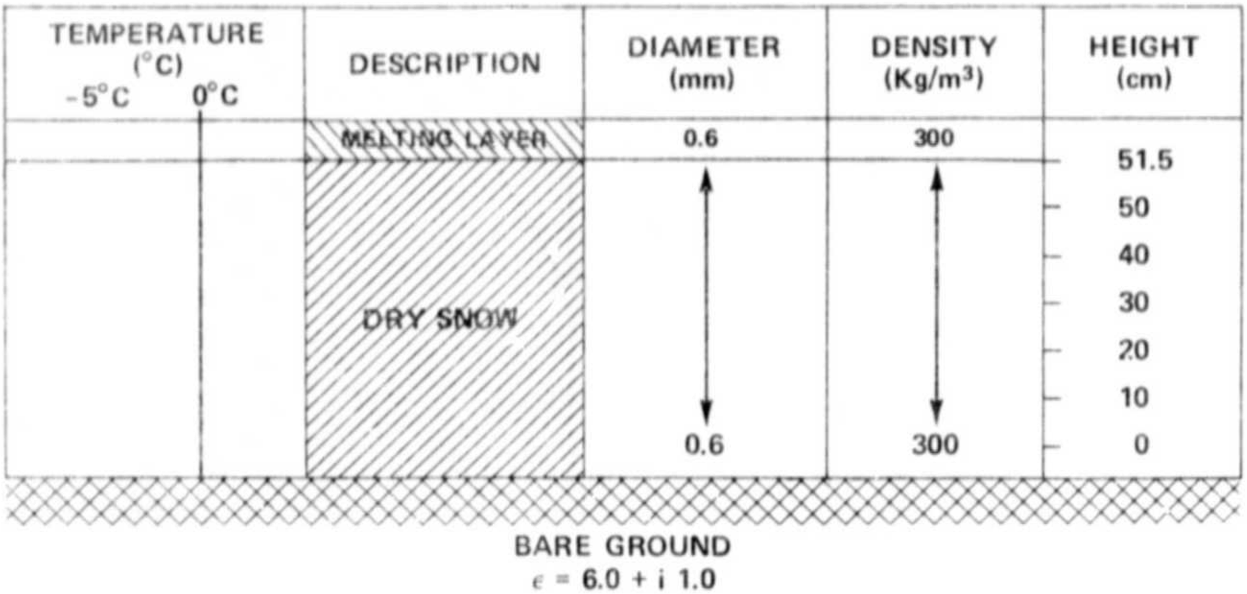

Figure 8. March 2, 1978 – Test Data.

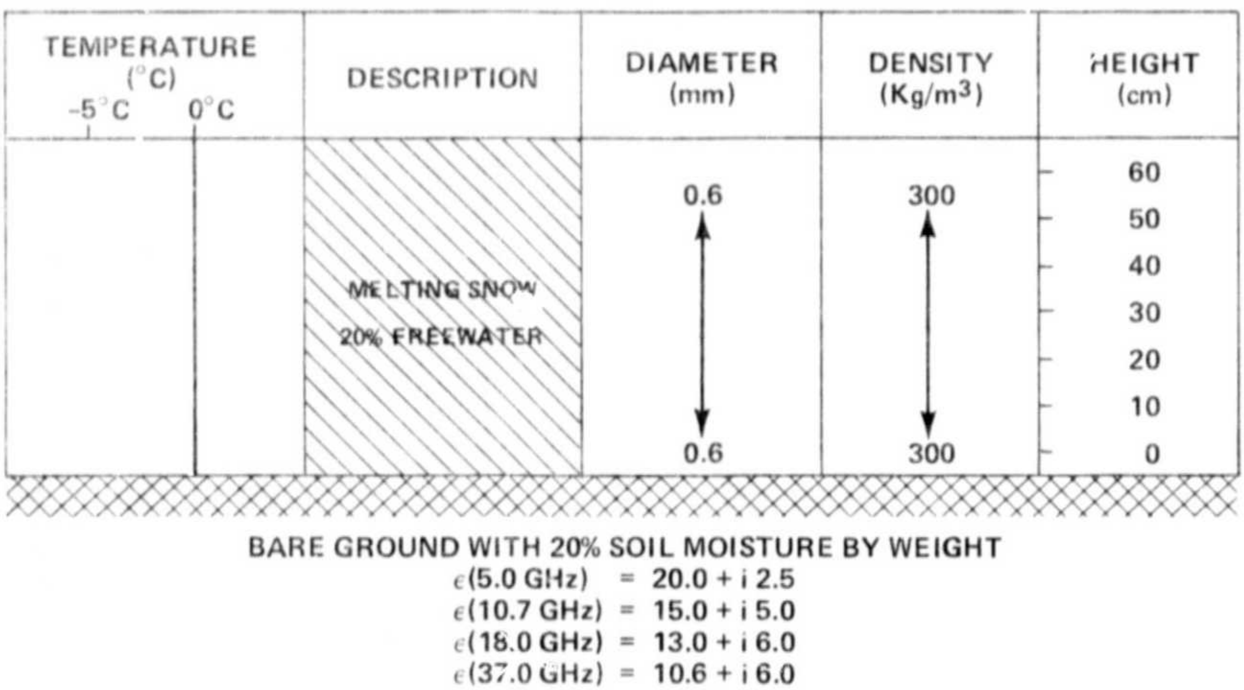

Figure 9. March 23, 1978 – Test Data.

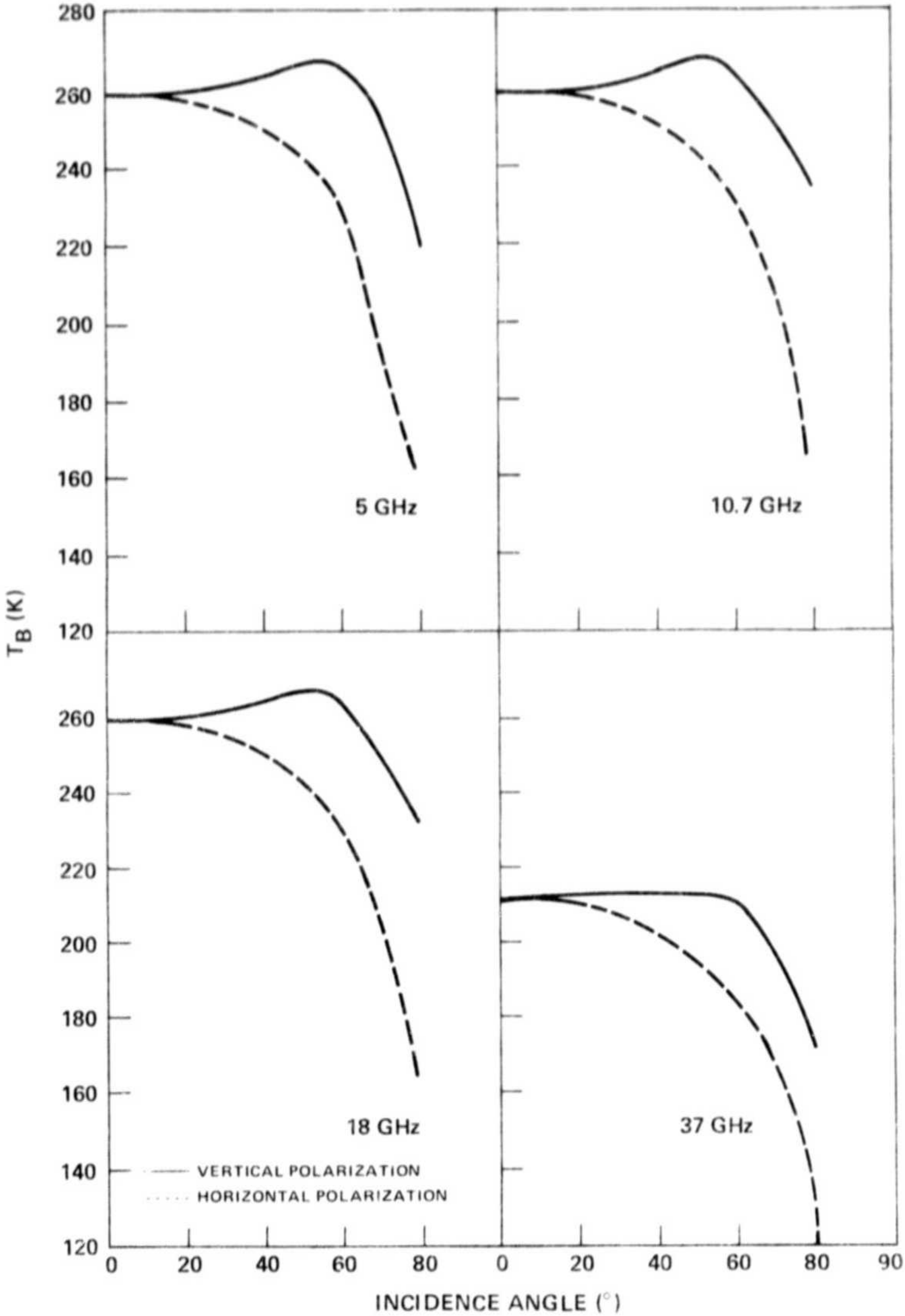

Figure 10. Dry Snow – Calculated Brightness Temperature T_B Versus Incidence Angle.

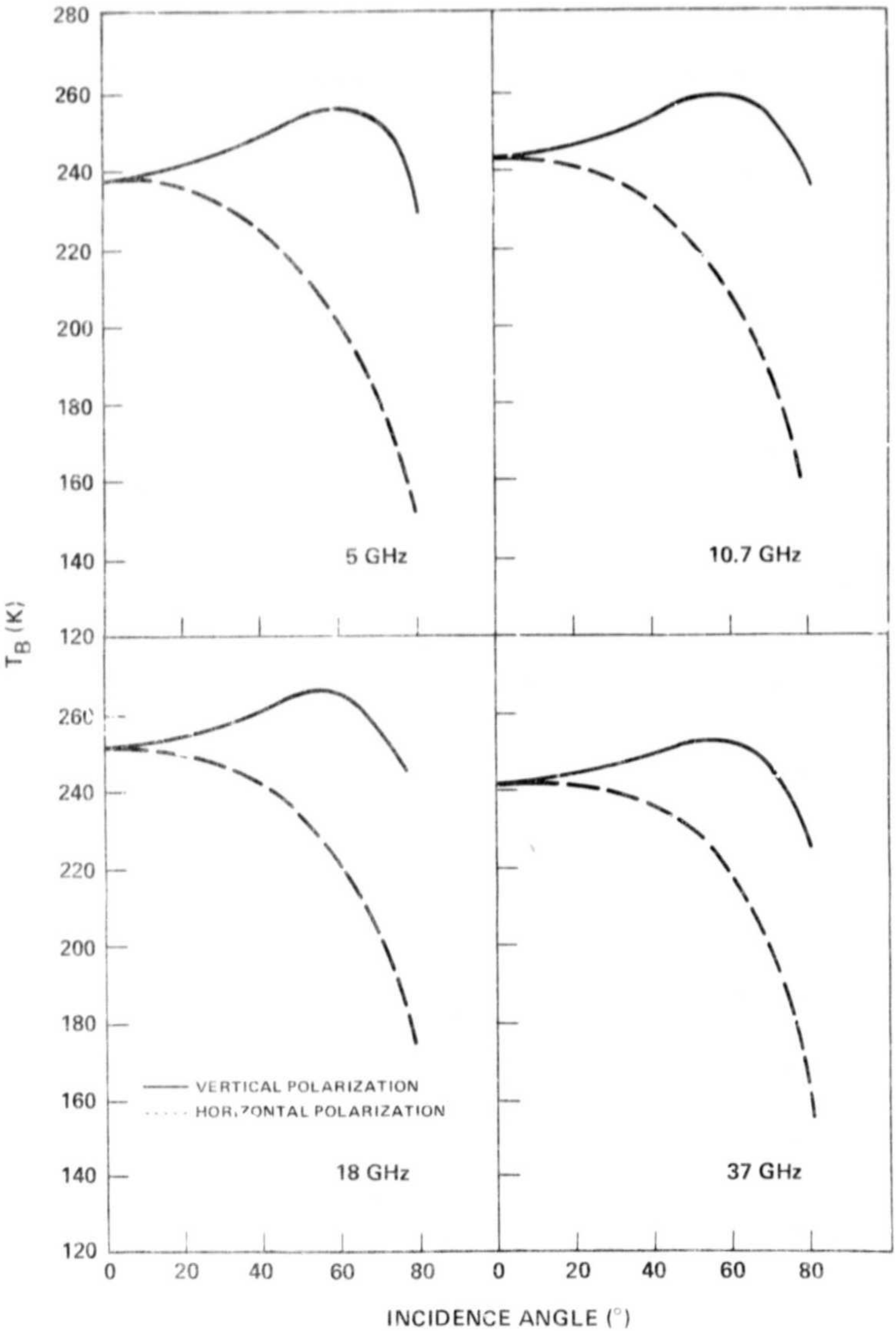

Figure 11. Surface Melting – Calculated Brightness Temperature T_B Versus Incidence Angle.

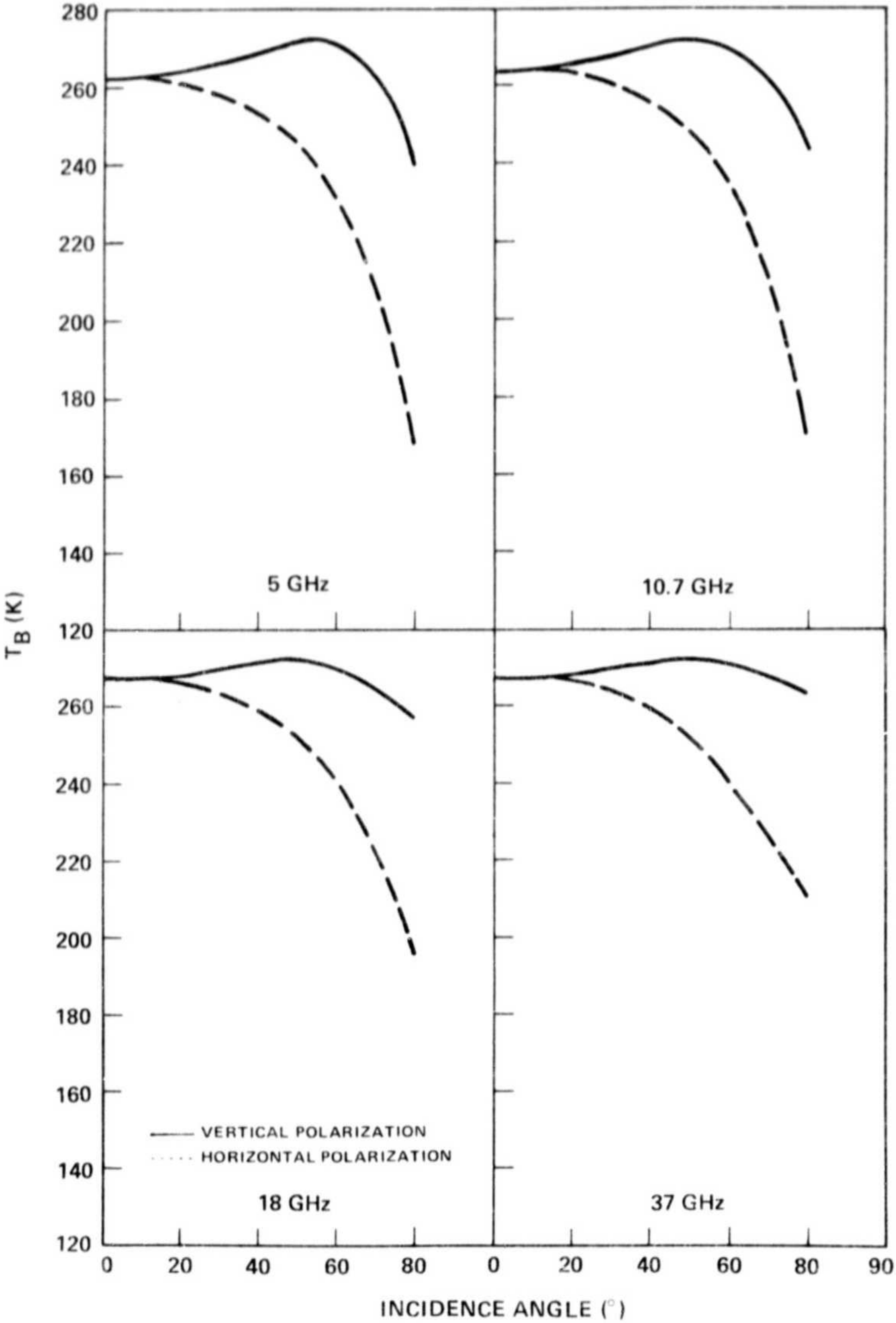

Figure 12. Wet Snow – Calculated Brightness Temperature T_B Versus Incidence Angle.

BIBLIOGRAPHIC DATA SHEET

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16. Abstract

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