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Abstract

This paper is a review of the radiation emitted from snowpack in the microwave region (1 to 100 GHz). Radiation from dry and wet snowpack are discussed and related to ground observations. Results from theoretical model calculations match the brightness temperatures obtained by truck mounted, airborne and spaceborne microwave sensor systems. Snow wetness and internal layer structure complicate the snow parameter retrieval algorithm. Further understanding of electromagnetic interaction with snowpack may eventually provide us a technique to probe the internal snow properties.

Introduction

The use of remotely-acquired microwave data, in conjunction with essential ground measurements will most likely lead to improved information extraction regarding snowpack properties beyond that available by conventional techniques. Landsat visible and near-infrared data have recently come into near operational use for performing snowcovered area measurements (Rango, 1979). However, Landsat data acquisition is hampered by cloudcover, sometimes at critical times when a snowpack is ripe. Furthermore, information on water equivalent, free water content, and other snowpack properties germane to accurate runoff predictions is not currently obtainable using Landsat data alone because only surface and very near-surface reflectances are detected.

Microwaves are mostly unaffected by clouds and can penetrate through various snow depths depending on the wavelength. Hence, microwave sensors are potentially capable of determining the internal snowpack properties such as snow depth and snow water equivalent (Hall et al., 1978; Rango et al., 1979; Chang et al., 1982). However, operational use of remotely-collected microwave data for snowpack analysis is not imminent because of complexities involved in the data analysis. Snowpack and soil properties are highly variable and their effects on microwave emission are still being explored. Nevertheless much work is being done to develop passive microwave techniques (Edgerton et al., 1973; Schmugge et al., 1974; England, 1975; Chang et al., 1976; Kong et al., 1979; Chang and Shiue, 1980; Matzler et al., 1980; Stiles and Ulaby, 1980; Tiuri et al., 1982; and Tsuchiya and Takeda, 1982) for analysis of snowpack properties. In this paper the characteristics of microwave radiation emerging from snowpack, observational results, theoretical modelings, and future potential applications will be discussed.

Microwave Emissions

The microwave spectrum lies in the higher end of the radio spectrum. No firm definition exists for the microwave region, but a reasonable convention is that it extends through 0.3 to 300 GHz (1 m to 1 mm in wavelength). Letter designation for bands in microwave region is commonly used especially in engineering applications. A set of these schemes is shown in Table 1.1 (Ulaby et al., 1981) for reference.

Table 1.1

Microwave Band Designations (GHz)

P	0.225 - 0.390	K	10.90 - 36.0
L	0.390 - 1.550	Q	36.0 - 46.0
S	1.550 - 4.20	V	46.0 - 56.0
C	4.20 - 5.75	W	56.0 - 100
X	5.75 - 10.90		

All matter radiates electromagnetic energy. This radiation spectrum according to Planck's radiation law can be expressed as:

$$B = \frac{2hf^3}{C^2} \left(\frac{1}{e^{hf/kT} - 1}\right) \tag{1}$$

where B = Blackbody spectral brightness (W/m^2 - sr - Hz)

h = Planck's constant = 6.63×10^{-34} joules

f = frequency (Hz)

K = Boltzmann's constant = 1.38×10^{-23} joule/K

c = velocity of light = 3×10^8 m/s.

In the microwave region the spectrum is relatively flat. Planck's law can be simplified to Rayleigh-Jeans approximation as:

$$B = \frac{2kT}{\lambda^2} \tag{2}$$

The blackbody brightness B can be linearly related to the physical temperature of the matter. The spectral, polarization and angular characteristics of the emitted radiation are also governed by the geometrical configuration of the surface and interior of the medium and by the spatial distributions of its dielectric properties.

The equivalent temperature of the thermal microwave radiation emitted by an object is called its brightness temperature, T_B. It is expressed in units of temperature (K) because for this radiation emitted is proportional to its physical temperature, T. A perfect emitter (blackbody) emits at its physical temperature, while most matters (greybody) emit only a fraction of the radiation of a blackbody. This fraction defines the emissivity, e, of the object. For example, the emissivity is about 0.9 for ice and 0.4 for water in the microwave region.

The emissivity of an object depends very much on its dielectric composition and physical structure. This property gives an opportunity to remotely sense the characteristics and properties of atmosphere and earth surface by microwave technique. Thus, determination of emissivity provides valuable information on the physical properties and conditions of the emitting medium.

The dielectric constant, ε , is a function of wavelength and temperature. It is usually a complex constant. The propagation velocity and wavelength within the media is directly related to the real part of ε . While the energy losses within the media is determined by the imaginary part of ε. Since snow is a heterogeneous mixture of air, ice, and during melting, liquid water, the dielectric properties of ice and water should be examined first in order to understand the effective dielectric properties of snow.

Water and ice, which represent the liquid and solid phases of H_2O molecules, have a dielectric behavior follows closely the Debye dispersion formula:

$$\varepsilon = \varepsilon' - i\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\,\omega\,\tau} \tag{3}$$

or in terms of its real and imaginary parts:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + \omega^2\,\tau^2} \tag{4}$$

and

$$\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\,\omega\,\tau}{1 + \omega^2\,\tau^2} \tag{5}$$

where ε_s = the zero frequency or static relative permittivity,

ε_∞ = the high frequency relative permittivity,

ω = $2\pi f$ angular frequency,

and

τ = relaxation time of the media.

Due to the movement of the permanent dipole moment of H_2O molecule, the dielectric constant for water is strongly dependent on the temperature and viscosity. The relaxation time for water lies in the microwave region hence provides the rapid change of dielectric constant within these frequencies. In the ice phase of water, the H_2O molecules are more rigidly structural and therefore reduces the relaxation time to the KHz region. For pure ice, the high frequency permittivity was measured by many investigators and believed to have a value about 3.15 (Stiles and Ulaby, 1983). This is not very sensitive to temperature and frequency in the microwave region. While the real part is well-behaved, the imaginary part is dependent on both frequency and temperature. However, due to lack of adequate theoretical expressions and experimental observations, the dependence of ε'' on temperature and frequency in the microwave region is not very well determined. Figures 1 and 2 show the dependence of real and imaginary part of dielectric constants for water and ice with frequency.

The electromagnetic properties of snow vary with its structure and liquid water content. Fresh, dry snow flakes display crystal facets due to rapid growth of crystal in the atmosphere. Once the snow crystals on the ground the metamorphism begin. The temperature of the snow layer determines the rate of metamorphism, and the temperature gradient across the layer determines the types of metamorphism. Equilibrium thermodynamics favorate growth of small, well-rounded grains that dominate a dry snow cover. When there is a steep temperature gradient, large, angular and often hollow crystals of depth hoar grow at the base of the pack (Perla and Martinelli, 1976).

Snowpack temperature usually is quite close to its melting point. When any solid is near its melting point, its molecules have a great amount of mobility and can change quickly in response to changing external conditions.

When snow is melting, its structure and its electromagnetic behavior changes markedly. The effective dielectric constant of the wet snow increases due to high dielectric constant of water in microwave region. In a freely draining snow the grains are arranged in clusters, in which the unit cell is a triangular packing of three grains with a liquid-filled vein at the three-grain boundary (Colbeck, 1982). At higher liquid water content, the grains grow even faster than in freely draining snow. This type of snow is cohesionless, with well rounded grains about 1 mm in radius, and fully surrounded by water.

The dielectric properties of this heterogeneous mixture of air, ice and water can only be described by mixing formula. When the snow is dry, two-component formulations can be applied while it is melting three-component formulation is required. Both theoretical and purely empirical mixing formulas have been reported in the literatures (Stiles and Ulaby, 1983). In the microwave region due to the less sensitivity of the shape factor, linear mixing formula is normally used.

Recently a surface sensor for measuring dielectric constant of snow at about 1 GHz has been reported (Matzler et al., 1984). Based on a coaxial resonator method for the in-situ measurement of the dielectric constant of snow together with a scatterometer (10.4 GHz) and a set of radiometers (4.9, 10.4, 21.0, 35.0 and 94.0 GHz) dielectric information can be obtained for wet snow with flat surfaces over a frequency range from 1 to 100 GHz. The dielectric constant of wet snow obeys a Debye relaxation spectrum with the relaxation frequency of liquid water at 0°C. Hallikainen et al. (1983 and 1984) reported measurements of dielectric of dry and wet snow at 4 to 18 GHz and 3 to 37 GHz range. The Modified Debye formula and the Polder-Van

Santen mixing formula were found to adequately describe the dielectric behavior of snow.

Microwave Observations of Snowpacks

Different experiments using ground based, air-borne and space-borne microwave radiometers have been performed in order to develop the capability of remotely sensing the snowpack properties. Controlled field experiments are used to understand the EM interaction with snow crystals and to develop and verify the theoretical models. Truck mounted or tower mounted system of microwave sensors together with simultaneous detailed conventional snow observations are usually performed at selected test sites. Aircrafts have also been used as a platform to test the remote sensing techniques for a larger area with more spatial variability. Spaceborne microwave sensors, although not dedicated for snow monitoring, have been collecting information about snow since COSMOS 243 launched in 1968.

The first controlled field experiment was conducted at Crater Lake, Oregon (Edgerton et al., 1973) during the winters of 1964-1966. Passive microwave radiometric measurements were made at frequencies of 13.7, 37 and 90 GHz along with meteorological and geophysical support measurements and low frequency dielectric constant measurements. This experiment was continued at Frisco, Colorado and at Truckee, California during the next two winters. The research activities were centered on the effects of melting, layering, surface roughness, density variations on microwave emission, and penetration. Two important characteristics of microwave signatures were observed: (1) brightness temperature decreases as snow water equivalence increases and (2) brightness temperature increases sharply with water content within snowpack. Figure 3 replotted the relationship of brightness temperature and snow water equivalent report by Edgerton et. al. (1973). These results provide the basis for further investigation of snowpack properties using microwave radiometry.

There are many more field experiments that have been performed since Edgerton's measurements in late 1960s. The University of Kansas, Remote Sensing Laboratory has obtained passive microwave data in Steamboat Springs, Colorado during the winter of 1977 with 10.7, 37.0 and 94.0 GHz radiometers (Stiles et al., 1977). The results from this experiment (Stiles and Ulaby, 1980; Ulaby and Stiles, 1980) reconfirmed those results reported by Edgerton's et al. (1973). The slope of decreasing brightness as a function of snow dpeth is somewhat different from Edgerton's due to different snow conditions. Multifrequency sensor techniques was recommended for actually estimating the snow parameters.

A series of field experiments over a period of 5 winters (1979-1984) were taken place in Colorado and Vermont by the NASA/Goddard group. Multifrequency radiometers with frequencies between 5 and 37 GHz were used to measure the brightness temperature. These frequencies were those used by the Nimbus-7 SMMR. The objective of these experiments were: (1) to study the effect of volume scattering by different crystal sizes, (2) to evaluate the interference effect due to layering structure, (3) to understand the angular dependence of microwave interaction with snowpacks, and (4) to define an optimum instrument package for remote determining of snowpack properties. The results from these experiments reconfirm that snowpack parameters such as snow water equivalent, snow wetness can be related to brightness variations (Chang and Shiue, 1980; Chang et al. 1982). The volume scattering dominates the 37 GHz brightness, while interference effect is more pronounced in the 5 GHz observations.

The group of the University of Bern, Institute of Applied Physics performed a series of experiments during the winters of 1977 and early 1980 at Davos, Switzerland. Radiometers at 1.8, 4.9, 10.5, 21.0, 36.0 and 94.0 GHz were mounted on a tower to study the seasonal variation of snowpack with depth up to several meters (Hofer and Matzler, 1980). In this deep snowpack, different signatures have been reported. Instead of negative correlation of snow depth and brightness temperatures for wavelengths at approximately 1 cm, the brightness increases with snow depth when the snowpack reaches more than 2 meters in depth. The decrease of brightness with increasing depth is explained by increasing volume scattering of snow crystals. The depth hoar, which contributes greatly to the volume scattering, is usually located at the bottom of the snowpack. If the microwave only penetrates portions of the snowpack, than the brightness will be higher due to less volume scattering from the top portions of the pack. The penetration depth reported by Hofer and Matzler (1980) is about 1 meter for 36 GHz radiation.

Two other tower experiments were performed during the last several years. From 1978 the Radio Laboratory, Helsinki University of Technology started the measurements at 5, 12 and 37 GHz at Finland (Tiuri and Schultz, 1980). From 1981, National Institute of Resources of Japan using 23.8 and 31.4 GHz radiometers to measure the snowpack properties at Hokkaido University test site (Tsuchiya et al., 1982). Both of these groups are aiming toward using microwave techniques to monitoring snowpacks as a valuable resources in the future.

Airborne missions with multifrequency microwave radiometers on-board the NASA CV-990, C-130 and P-3 aircrafts have been flown over snow-covered areas in the Colorado Rocky mountains, Sierra Nevada of California and northern Great Plains. From airplane the sensors view a larger area with terrain variations than the truck experiments. Yet researchers can still concentrate on a small study area collecting ground truth simultaneously with the overflights. A summary list of aircraft snow experiments was compiled by Foster et al. (1984). This data set generally supports the conclusions that the relationship between microwave emissions and snowpack properties (Chang et al., 1982). Figure 4 shows a typical brightness/snow depth relationship for 18 and 37 GHz radiation.

Passive microwave imagery from space have been available since December 1972, when Nimbus-5 was launched with the Electrically Scanning Microwave Radiometer (ESMR) using 19.35 GHz (Wilheit, 1972). Further data became available in June 1975 with the launch of Nimbus-6 with a dual polarization radiometer at 37 GHz (Wilheit, 1975). A five-frequency dual-polarization Scanning Multichannel Microwave Radiometer (SMMR) was flown on board of Nimbus-7 since November of 1978. The five frequencies are 6.6, 10.7, 18, 21 and 37 GHz (Gloersen and Barath, 1977). Studies have been and are currently being conducted to study the utilities of microwave sensors on snowpack properties determination. The major drawback of these sensors for snow hydrology applications is the poor spatial resolution of about 25 km. However, results from various studies indicate that qualitative monitoring of snowpack buildup and disappearance during the winter appears feasible (Rango et al., 1979; Patil et al., 1981). In a relative homogeneous, flat area such as Canadian high plains and the Russian steppes, a significant regression relationship between snow depth and microwave brightness temperature can be developed (Figure 5). The estimation of snow depth under optimum conditions can be achieved using microwave data in certain study areas (Rango et al., 1979; Foster et al., 1980; Kunzi et al., 1982).

Modeling Snow Emission in Microwave Region

Shortly after the launch of the Nimbus-5 satellite in November 1972, the Electrically Scanned Microwave Radiometer (ESMR) images showed brightness temperatures as low as 160K covered large areas of Greenland and Antarctica. The cause of these low brightness temperatures was attributed to layering effect or scattering by snow crystals. In order to understand more quantitatively the electromagnetic wave interaction with snowpack, theoretical models are needed to explain these brightness variations. Historically, radiative transfer models have been used to understand and describe the electromagnetic response of materials in all wavelength bands suitable for remote sensing. The radiative transfer equation (Chandrasekhar, 1960) generally serves as the starting point for model calculations. It can be written in the form of a differential-integral equation:

$$\mu \frac{dI}{dX} = - \sigma \cdot I + \sigma \{(1 - \omega) B + 1/2 \, \omega \int P(\mu,\mu') \, I \, d\mu'\} \tag{6}$$

where the radiation intensity I is the instantenous intensity along the propagation direction X, μ is the cosine of the angle between x direction and normal direction. The functions σ , ω , B and $P(\mu,\mu')$ are referred to as the extinction per unit length, the single scattering albedo, the source, and the phase function respectively. This equation of radiative transfer normally can be solved by numerical techniques, except in few special cases where analytical solutions are available.

Since snow crystals usually become rounded shape in a short time period after it is on the ground, it is reasonable to assume that each snow crystal is a scattering particle. England (1975) assumed that arbitrary scattering centers imbedded within a snowpack contributed to the brightness temperature variations using radiative transfer technique. Chang et al. (1976) extended the calculation by assuming a spherical shape snow crystal and using measured snow crystal sizes and density to match the observed brightness. Results of these models are subject to the assumptions that diffraction and interference are neglectable and the radiation intensity is additive in the calculations. In a densely packed snow with large crystal size, these assumptions may contribute some uncertainty in the calculations. Melting snow was modelled as water coated ice spheres by Chang and Gloersen (1975). The calculated brightness increases rapidly by introducing several percents of liquid water content in the snowpack as observed.

Instead of treating snow crystal as a scattering particle, the snowpack was modeled as a half space random medium by Gurvich et al. (1973) and Tsang and Kong (1975). The permittivity of snow is assumed composed of a constant part and a slow varying fluctuating part. Scattering of electromagnetic wave is caused by the randomly fluctuating part of the permittivity. Radiative transfer technique is then applied to derive the emerging brightness temperature. Subsequently, layers and multi-dimensional fluctuations have been added to models to match different sets of observations (Tsang and Kong, 1976a, 1976b, 1979, and 1980).

A more exact approach to this problem is to solve the basic wave equations together with the scattering and absorption characteristics of the medium. Equations are derived for the average fields and correlation functions of the fields. This is a mathematically rigorous approach in which all the multiple scattering, diffraction and interference are included. However, due to the generality and complexity of these equations, it is rather difficult to solve them even numerically. Simplifying assumptions are needed in obtaining solutions for actual problems.

The field approach of dealing the wave interaction in a random medium may be categorized into two types. The first type is the Neumann series approach where the first term of the series is the well known Born approximation. Modified Born approximation using a method of smooth pertubation allows a less restrictive range of validity in dielectric fluctuations. The second type is the renormalized Neumann series approach (Tatuskii, 1964; Bassanini et al., 1967; Fung, 1978; Fung and Fung, 1977; Tseng and Kong, 1979). This method allows an infinite sub-series converge and take on a closed form solution. This approach leads to the Dyson equation for the mean field in the random medium and the Bethe-Salpeter equation for the mean intensity. Multiple scattering effects are included in the higher order Neumann series.

The spatial distribution of the permittivity of snow varies from 1.0 to 3.2 dependent on whether the space is occupied by snow crystal or not. Most of the theory is only valid for cases of weak fluctuation of permittivity, because the singular nature of dyadic Green's function has not been taken into account. A strong fluctuation theory was formulated by Tseng and Kong (1981 and 1982) to resolve this problem. This theory is pertinent when the snow crystal is large (1-2 mm in radius) and closely packed with each other. Preliminary model calculations shown considerable differences as compared with weak fluctuation theory.

Potential Applications

Recent advances of remote sensing systems provide new information needed for retrieval of important snowpack parameters. The most definite feature can be extracted from spacecraft or aircraft is the area of a drainage basin covered by snow. Because of the promising aspects of satellite snow-cover mapping, a cooperative demonstration project was conducted to deal with the operational application of satellite snow-cover observations. The study employed hydrological modeling, regression analysis, low altitude aircraft flights, calculation of melting snow areas in addition to basic photo interpretation. These snow-covered area data have been used in numerical snowmelt runoff models with success. In order to permit remote sensing technique to be more fully utilized, the capability for sensing snow-cover extent must be extended to all weather situations and coupled with a complementary capability for measurement of areal snow water equivalent.

Based on experimental observations and theoretical model calculations, microwave radiation emitted by snowpack can be used to retrieve snow-covered area and snow water equivalent information under almost all weather conditions. The brightness temperatures are mainly infuenced by the crystal size, depth and wetness of the snowpack. Variations in snow accumulation and depletion at specific locations result in related variation in passive microwave brightness temperature observations. Qualitative monitoring of snow-covered area appears feasible in the open area (Rango et al., 1979). Due to the effet of surface roughness, underlying soil condition and vegetation distribution within a resolution cell, the depth of shallow snowpack may not be very accurately determined. Based on the brightness gradient technique, three snow depth categories: (1) thin and patchy snow (5-25 cm), (2) less deep snow (25-50 cm) and (3) deep snow (> 50 cm) have been reported by Kunzi et al. (1982). Better determination of snow depth may be achieved by adopting regional retrieval algorithm utilizing the land use classification and surface terrain information.

In the last two winters, due to excessive snowpack buildup in the Colorado river basin spring flooding in several western states have been resulted by snow melting. Although the threat to human life is not critical, damage to the properties are substantial. A joint research project betwen USGS, USDA and NASA is now being formed to improve the snowmelt runoff prediction using existing remote sensing data especially the SMMR data. The most pertinent information for hydrologists to improve the prediction on the amount of spring runoff is the amount of water storages in the snowpacks. At present the snow water equivalent for selected sites is routinely monitored by Snowtel network in the Western United States and snow surveyors. These point measurements of snow water equivalent may not directly represent the snow storage for a given watershed. Area estimates of snow water equivalent are preferred quantity for better estimating the spring runoff. Results from aircraft and field experiments shown the snow water equivalent retrieved for selected Colorado Rocky test sites based on model prediction compared favorable with ground truth observation (Figure 6). However, for the mountainous region additional attentions are required in extracting the snowpack information.

The onset of snowpack melting is another important parameter for better estimating the snowmelt runoff and understanding the snow processes. Liquid water content can be measured in the field by calorimetry. The measurement is sufficiently awkward and inconvenient that the measurement is rarely made. Recently dye solution methods have been developed and successfully tested in the field. To monitor large area snow wetness, microwave signatures are the most ideal tool due to the large dielectric differences of water and ice.

When the snowpack starts melting due to solar irradiation, it will create a thin surface layer of wet snow. The sharp increase of brightness could be readily detected by the 37 GHz observations. When the snowpack refreezes at night, the brightness will return to normal. While the snowpack is isothermal (0°C) and ripe, then melting will continue throughout the entire night. The high brightness will be measured for both day- and night-time observations. Due to different penetration depth for radiation with different frequency, multifrequency technique may be developed to infer the wetness profile information.

Stratigraphy of snowpack such as layering and depth hoar growth could affect its mechanical properties greatly. This is measured by inspecting and sampling snow from snow pit. Depth hoar generated by thermal gradient metamorphoses of snow grains usually are weakly bounded to other crystals. Ice layer, which blocks the water vapor movement, usually intensified the metamorphism immediately about or beneath it. Avalanche researcher usually monitors this phenomenon with great care. The electromagnetic properties also can be changed by the internal structures. Layers in the snowpack will enhance the absorption of the incoming shortwave radiation. For microwave radiation, interference by ice layer could noticeably vary the brightness. This effect usually is more distinguished for longer wavelength (3-10 cm). For shorter wavelength (1 cm) the volume scattering effect masks out the influence by layer interference. This information could be utilized to study the stratigraphy of snowpack without digging a snow pit. A swept frequency radiometer system with frequency between 3 and 10 GHz would provide greater detail information on snowpack structures.

Since microwave radiation can penetrate snow depth 10 to 100 times of the wavelength, it provides an opportunity to study the snow-soil boundary condition. The state (frozen or thawed) and moisture content of the soil underlying the snow plays a major role in many processes such as winter kill prediction and runoff estimate. Frozen soil with water molecules tightly bounded emits microwave radiation like dry soil. It is quite different from those emitted by wet soil. The low brightness and large polarization could be used to reveal the underlying soil condition.

Concluding Remarks

Microwave radiation emitted by snow crystals contains valuable information on the characteristics and internal stratigraphy of snowpacks. This provides us an opportunity to remotely sense the important snow parameters such as snow covered area, water equivalent and wetness content. Recent researches have advanced our knowledge on the radiation emitted by snow. Many models have been developed to explain the observed microwave responses. Promising results could be achieved in the near future. Yet this problem, at present, is still largely treated as a forward calculation problem. That is, model calculations can explain the brightness from different snow conditions. The techniques to accurately retrieve and extract the snow parameters based on observed brightness still require extensive refinement. Algorithms for extracting the snow parameters have to be tested, refined and evaluated with data in the near future.

Presently and for the next few years, passive microwave resolution from space will be no better than 20 km. The use of microwave observations for snow parameters is restricted to large, homogeneous regions such as high plains. Even this could be valuable for runoff prediction during rapid spring melting in these areas once enough representative data sets are collected. When large antenna structures in space become feasible on the future space station, the resolution might improve to 1 km at the short wavelength ($\sim$ 1 cm). However, more researches are needed to improve the retrieval techniques in order to extend the applications for global snow monitoring.

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Figure Captions

Figure 1: Real Part of Dielectric Constant for Fresh Water and Ice vs. Frequency (from Stiles and Ulaby, 1981).

Figure 2: Imaginary Part of Dielectric Constant for Fresh Water and Ice vs. Frequency (from Stiles and Ulaby, 1981).

Figure 3: Snow Water Equivalent vs. Microwave Brightness Temperature (from Edgerton et al., 1973).

Figure 4: Snow Depth vs. Microwave Brightness at 18 and 37 GHz from Airborne Sensors (from Hall et al., 1978).

Figure 5: Snow Depth vs. Microwave Brightness at 37 GHz from Satellite for (a) Canadian High Plain and (b) Central Russia (from Rango et al., 1979 and Chang et al., 1982).

Figure 6: Measured Snow Water Equivalent from Colorado Test Sites vs. Predicted Snow Water Equivalent.

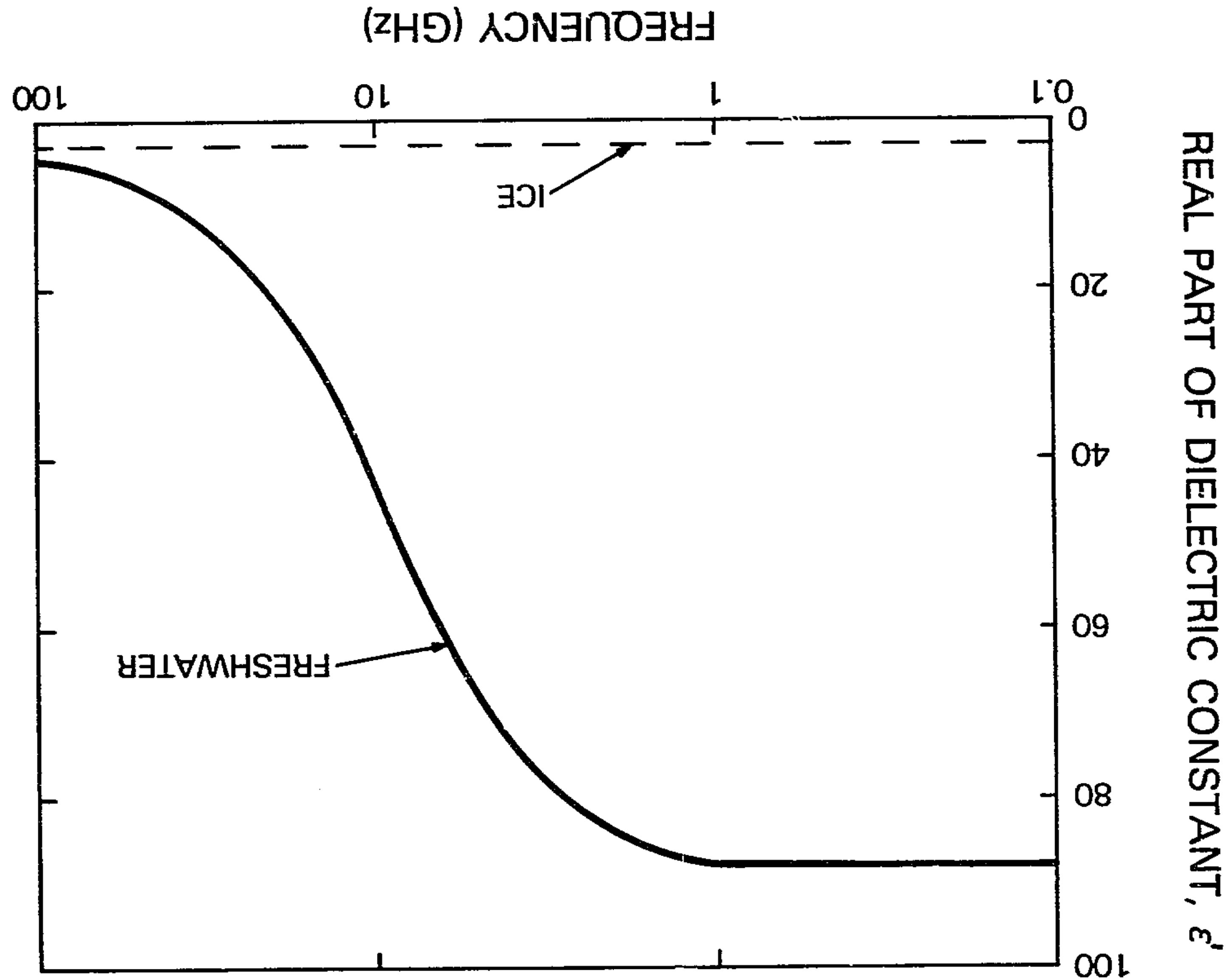


Figure 1. Real Part of Dielectric Constant for Fresh Water and Ice vs. Frequency (from Stiles and Ulaby, 1981).

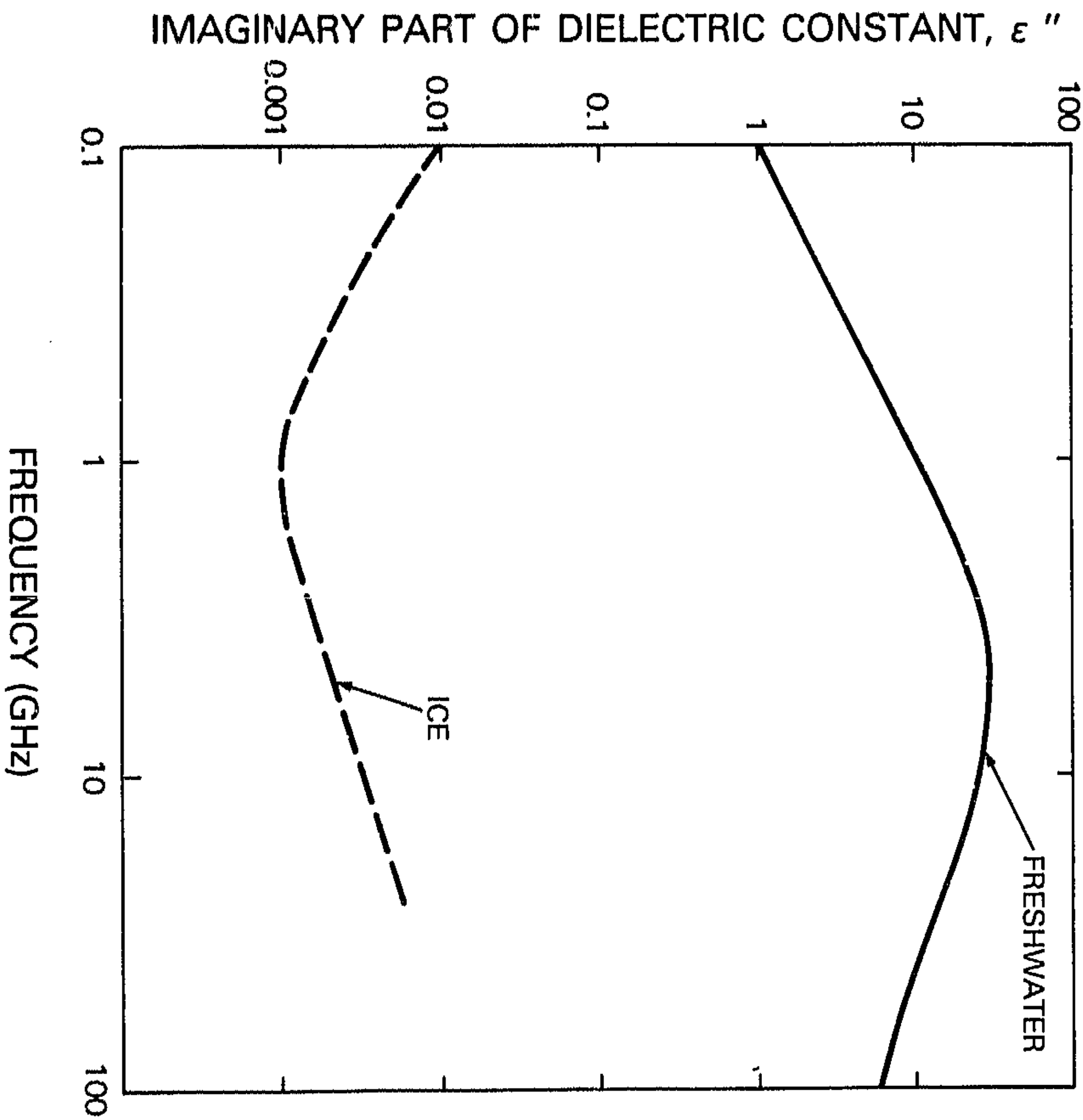


Figure 2. Imaginary Part of Dielectric Constant for Fresh Water and Ice vs. Frequency (from Stiles and Ulaby, 1981).

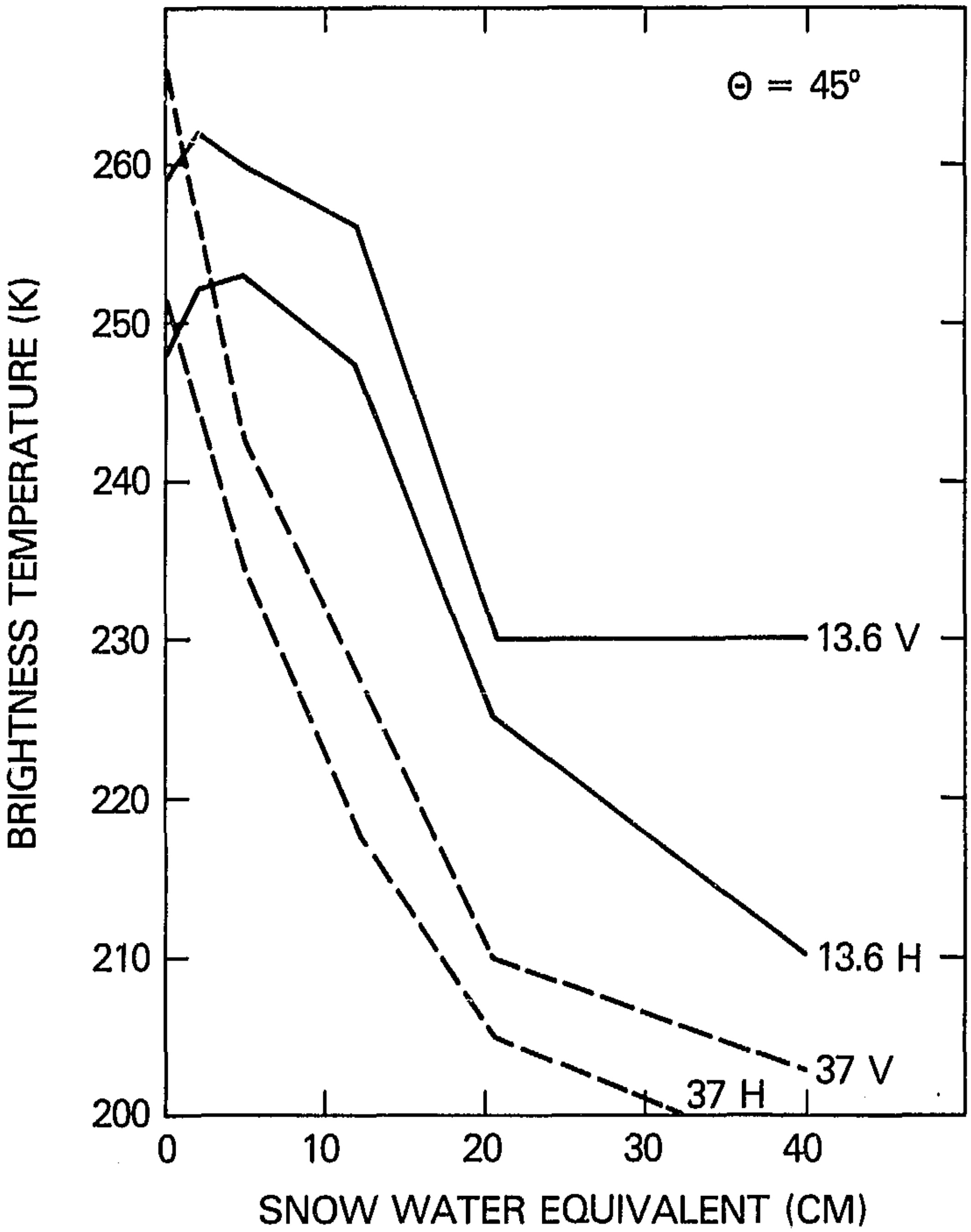


Figure 3. Snow Water Equivalent vs. Microwave Brightness Temperature (from Edgerton et al., 1973).

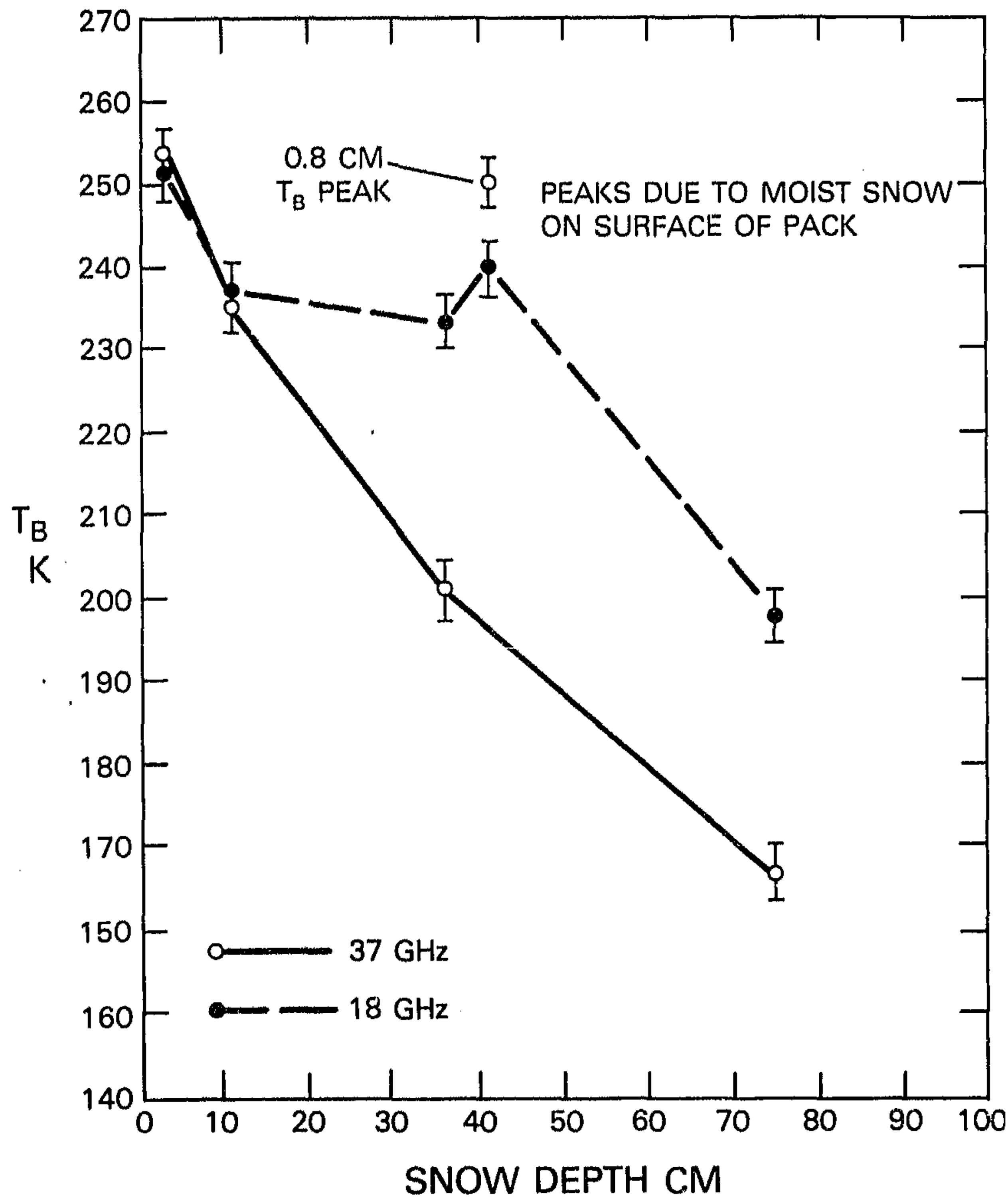
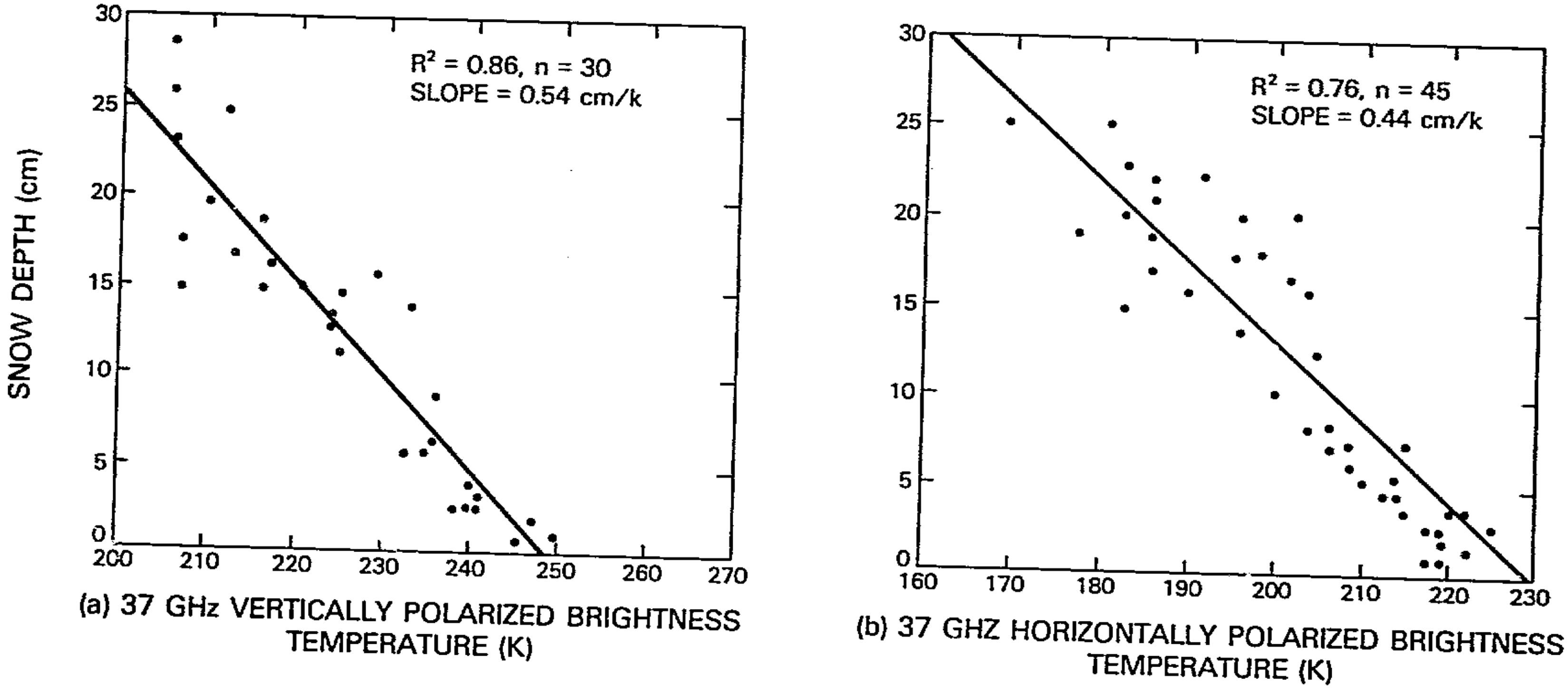


Figure 4. Snow Depth vs. Microwave Brightness at 18 and 37 GHz from Airborne Sensors (from Hall et al., 1978).



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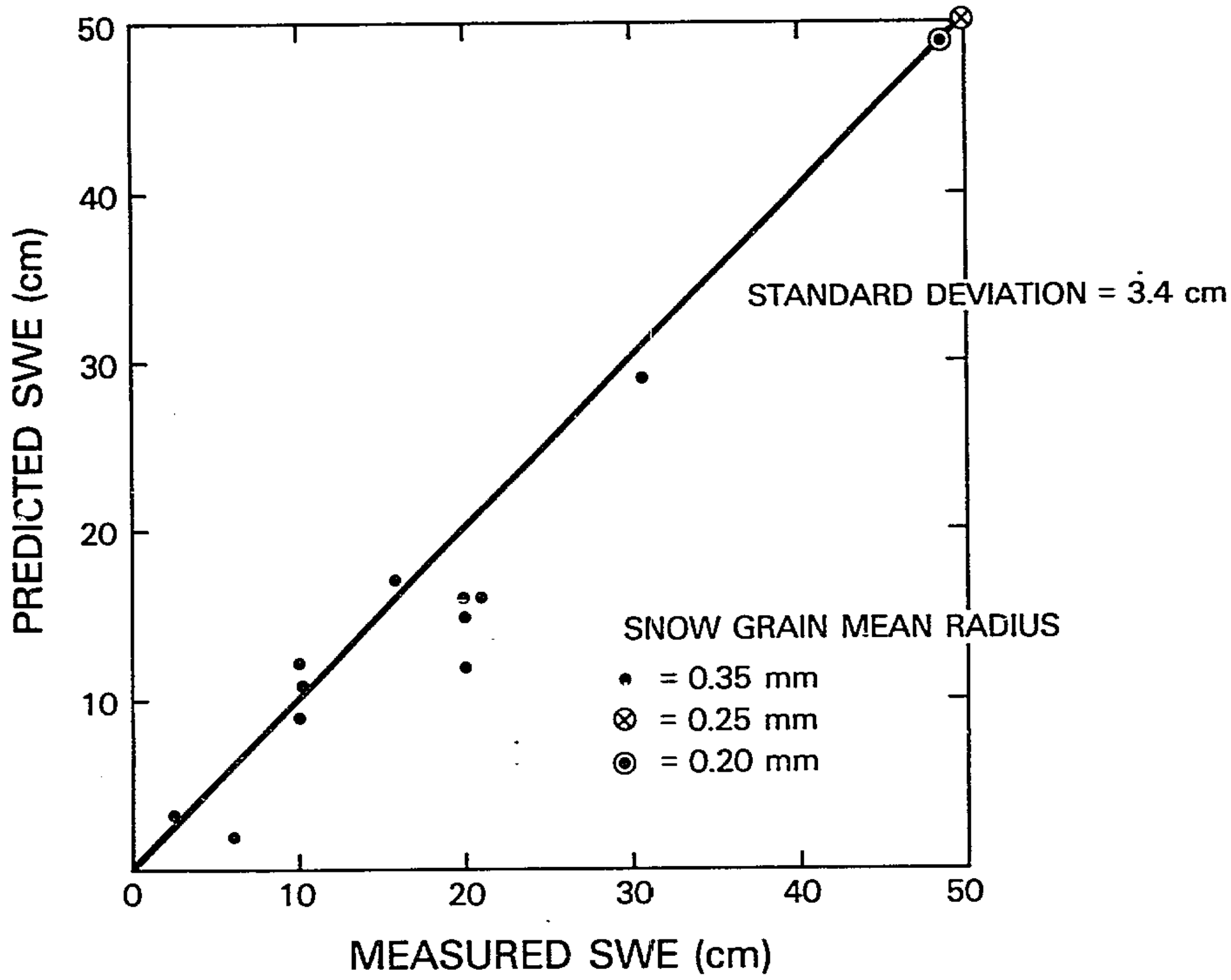

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