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ABSTRACT

The effect of surface roughness on the brightness temperature of a moist terrain has been studied through the modification of Fresnel reflection coefficient and using the radiative transfer equation. Model calculations are in good qualitative agreement with the observed dependence of the brightness temperature on the moisture content in the surface layer.

Introduction

There have been several recent attempts to calculate the brightness temperature using the radiative transfer model in solid medium (e.g., Stogryn, 1970; England, 1974; Tsang and Kong, 1975). These attempts were primarily directed towards the understanding of microwave emission from snow fields. Wilheit (1975) and Burke and Paris (1975) have performed model calculations for the microwave emission from soil assuming the medium to be a layered structure.

One common assumption in all these calculations is that the layer separating the medium emitting the radiation is a geometrically smooth surface. For microwave emission from snow fields or deserts, this assumption may have some justification but for a natural terrain or an agricultural field, this assumption is highly questionable. In fact, recent observation by Schmugge et. al. (1976a) of the variation of the brightness temperature with the soil moisture in the surface layer show deviation from the radiative transfer model calculations. The purpose of this paper is to show the ramification of surface roughness on the brightness temperature. The smooth surface Fresnel reflection coefficient has been modified by assuming a Gaussian height distribution such that at all points on the surface the slope is less than unity and the radii of curvature are greater than the radiation wavelength (Barrick 1970). The present study differs from the one performed by Wu and Fung (1972) for the microwave emission from sea. They used a composite-surface scattering theory to include the effect of surface roughness but did not use the radiative transfer equation to calculate the apparent temperature. Although the composite-surface model seems more appropriate for a rough surface, it is computationally prohibitive without further approximations and also introduces several parameters to characterize the surface. The model used in this paper is simpler in that it has only one parameter to characterize the surface, namely, the standard deviation in height distribution. It is shown that the present model can provide a qualitative account of the dependence of the brightness temperature on the surface layer soil moisture.

Formulation

To describe the microwave emission from the soil, we will consider the radiative transfer equation (Chandrasekhar, 1960):

$$\frac{dI}{du} = - K_e I + S \qquad (1)$$

where I is the intensity propagating in the direction u, K_e is the total extinction per unit length and S is the source term describing the contribution to the intensity due to scattering and due to the continuum thermal emission of the soil. In principle one should study this equation in conjunction with the equation describing the heating of the soil. It is this latter equation which will provide information about the thermal part of the source term. In this paper we will decouple these two equations in the sense that we will consider a given temperature distribution.

To solve the radiative transfer equation we will consider a semi-infinite medium with depth dependent temperature and moisture distributions. Since soil is a highly absorbing material (i.e., large imaginary part of dielectric constant), to a good approximation, the brightness temperature T_B or the temperature equivalent of the intensity emerging from the soil will be determined by its internal temperature distribution T(z). By integrating eqn (1) with the source term as the temperature distribution of the soil one can write (Burke and Paris (1975))

$$T_B = (1 - r_p) \int_{-\infty}^{0} T(z) \, (K_a/\cos\theta) \exp\left(- \int_{z}^{0} K_a \, dz'/\cos\theta\right) dz \qquad (2)$$

where r_p is the soil surface reflectivity for polarization p. The absorption length K_a and the angle $\cos\theta$ are related to the angle of observation θ_0 and the properties of the medium as follows (Born and Wolf, 1975).

If the complex refractive index of the soil is written as:

$$N = n\,(1 + i\kappa) = \sqrt{\epsilon}$$

then

$$\cos\theta = \frac{n\,q\,(\cos\gamma - \kappa\sin\gamma)}{[\sin^2\theta_0 + n^2 q^2 (\cos\gamma - \kappa\sin\gamma)^2]^{1/2}}$$

$$K_a = \frac{4\pi}{\lambda}\, n\,q\,(\kappa\cos\gamma + \sin\gamma)$$

where q and γ are defined by

$$q^2\cos 2\gamma = 1 - \frac{1-\kappa^2}{n^2(1+\kappa^2)^2}\sin^2\theta_0$$

$$q^2\sin 2\gamma = \frac{2\kappa}{n^2(1+\kappa^2)^2}\sin^2\theta_0$$

and λ is the free space wavelength of the radiation and ϵ is the complex dielectric constant of the medium which depends upon the wavelength and the moisture of the soil. Thus from the knowledge of the temperature and the moisture distributions, one can calculate the brightness temperature by performing the integral in eqn (2). This approach to the calculation of the brightness temperature is similar to the models developed by Wilheit (1975) and Burke and Paris (1975). The models treat the medium as consisting of layers with constant moisture and temperature.

We will now consider the effect of the soil surface roughness on the brightness temperature. A first principle account of this effect is extremely difficult and far from being of practical use. In this paper we will consider the following simpler approach which requires modification of eqn (2).

For a vertically stratified medium, the electric field within the medium can be represented by

$$\vec{E} = \vec{E}_0 \exp\,[i\,(k_x x + k_z z + k_y y)] \qquad (3)$$

where k_x, k_y, and k_z are the x, y and z components of the complex wave vector with z-axis being perpendicular to soil surface. This wave will now be considered to be scattered by the interface of the medium and the free space.

It has been shown by Tolstoy and Clay (1966) that if this interface is a statistically rough surface such that there is no correlation between the amplitudes of the waves scattered by two points on the surface, then the scattered intensity can be obtained by the absolute square of the average scattered amplitude. It has further been shown that if E_{inc} represents the scattered amplitude by a perfectly smooth and perfectly reflecting surface, then the average amplitude that will be scattered by a rough surface is given by

$$\langle E_{sc} \rangle = R_0 E_{inc} \int_{-\infty}^{\infty} W(z)\, e^{ik_z z}\, dz \tag{4}$$

where W(z) is the height distribution of the surface and R_0 is the reflection coefficient of a smooth surface. The result for a smooth surface can be obtained trivially by identifying the distribution with a delta function. A typical rough surface corresponds to identifying the spectrum with a Gaussian distribution of zero mean and variance σ:

$$W(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-z^2/2\sigma^2\right] \tag{5}$$

For this spectrum, the average amplitude is given by

$$\langle E_{sc} \rangle \doteq R_0 E_{inc} \exp\left[-2\,\sigma^2 k_z^2\right]. \tag{6}$$

By demanding the continuity of phase at the interface we can write for a wave in x-z plane

$$k_x = \left(\frac{2\pi}{\lambda}\right) \sin\theta_0$$

Since within the medium we have:

$$k_x^2 + k_z^2 = \left(\frac{2\pi}{\lambda}\right)^2 \epsilon$$

so that

$$k_z^2 = \left(\frac{2\pi}{\lambda}\right)^2 [\epsilon - \sin^2 \theta_0] \qquad (7)$$

Thus the scattered intensity is obtained from equation (6):

$$I_s = I_s^0 \, |R_0|^2 \exp [-h (\mathrm{Re}\, \epsilon - \mathrm{Sin}^2 \theta_0)] \qquad (8)$$

where Re ϵ represents the real part of dielectric constant and the roughness parameter h is given by

$$h = 4 \left(\frac{2 \sigma \pi}{\lambda}\right)^2 \qquad (9)$$

From this result, one can stipulate that the gross effect of the surface roughness on the scattered intensity can be incorporated by modifying the smooth surface reflectivity r_{op} $(= |R_0|^2)$ as

$$r_p = r_{op} \exp [-h (\mathrm{Re}\, \epsilon - \mathrm{Sin}^2 \theta_0)] \qquad (10)$$

where the subscript p designates the polarization.

Note that this result differs from the result obtained in the radar cross-section analysis (Barrick, 1970):

$$r_p = r_{op} \exp (- h \cos^2 \theta_0) \qquad (11)$$

because in the present case the energy is incident on the interface from within the soil as opposed to the radar case where the energy is incident from air.

Results and Discussion

Experimental results reported in this paper were obtained during aircraft flights over the Phoenix, Arizona area and the Imperial Valley of California during March 1972 and February 1973 (Schmugge et. al. 1976a) and flights over only the Phoenix area during March 1975 (Schmugge 1976b). The surface roughness characteristics were those resulting from the agricultural practices of the two areas. The dominant method of irrigation is the flooded furrow. The furrow separation was about one meter and the furrow height was about 20 cm. Superimposed on these corrugations were clods, which were generally less than 5 cm.

Calculations were performed at wavelengths of 1. 55, and 21 cm using moisture and temperature profiles observed at the U. S. Water Conservation Laboratory at Phoenix in March 1971 (see Schmugge et. al. 1976a). These profiles can be assumed to be reasonable estimates for the actual situation for the data obtained in March 1972. For the data obtained in February 1973, the surface temperature was found to be about 15K lower than that observed during March. The February temperature profiles were obtained from the observed March temperature profiles by adjusting the gradient to fit the observed surface temperature for February data and assuming two profiles to be equal at about 50 cm. For the data obtained in March 1975, the calculations were performed using the actual ground measurement of the temperature and moisture profiles at each site (Blanchard 1975). The dependence of the real and the imaginary part of the dielectric constant on the weight percent of soil moisture for different wavelengths used in this calculation were obtained by Schmugge et. al. (1976a) through the linear regression fit of the data. The results for 1.55 and 21 cm wavelength is shown in fig. 1.

The results of our calculation are shown in fig. 2 and 3 for 1.55 and 21 cm wavelengths at nadir observation. For 1.55 cm wavelength, the experimental results clearly reflect the surface temperature difference observed during March and February flights because at this wavelength the radiation originates from very thin surface layer (less than 1 or 2 cm). For 21 cm wavelength on the other hand the radiation originates from deeper in the soil and as a result there is overlap of the data observed in February and in March. Let us now consider the effect of surface roughness on the brightness temperature at these two wavelengths. On purely physical basis one would expect that as the wavelength increases, the effect of surface roughness will decrease because at the longer wavelengths less of the structure of the reflecting surface will be observed by the radiation. The results of our calculation clearly demonstrate this fact. The magnitude of the roughness parameter which indicates the structure observed by the radiation is significantly larger for 1.55 cm ($h \approx 0.05$) than that for 21 cm wavelength ($h \approx 0.01$). The large effect of the surface roughness is easily seen in these figures. The flattening of the brightness temperature curve for large values of soil moisture observed experimentally can be accounted for by the surface roughness.

In fig. 4 we show the data obtained in 1975 and the calculated brightness temperatures for 21 cm wavelength at nadir observation. The calculation was performed using the actual ground truth measurement for each test site for which the brightness temperatures were observed. Although both observed and calculated values are scattered we see that the inclusion of surface roughness provides good qualitative agreement. One should also note in this figure that a linear regression analysis of the brightness temperature and the moisture will produce an excellent correlation but the slope of the line depends upon the roughness. This observation has the implication that for any wavelength a linear regression analysis may produce excellent correlation coefficient but the regression coefficient of that analysis is not universal in the sense that that it will depend upon the roughness of the surface.

The above discussions clearly demonstrate that for natural agricultural terrain the effect of surface roughness on the brightness temperature is quite significant if the soil moisture is large. Our calculation indicates that there is flattening of the brightness temperature for the larger moisture values at all wavelengths. The exact moisture value for which the flattening begins depends upon the dielectric properties of the soil at that wavelength. We realize that at present we cannot calculate the value of the roughness parameter, h, from a first principle consideration and it has been treated as an adjustable parameter.

Furthermore, the values of the parameter h which give agreement with the observed brightness temperature at 1.55 and 21 cm wavelengths are not related with each other as inverse square of the wavelength which is expected on the basis of eqn (9). The surface height variance σ calculated using eqn (9) shows that the roughness scale important for 21 cm wavelength is in the millimeter range and for 1.55 cm it is of order tenth of millimeter. This variance is the same order of magnitude as was observed by Wu and Fung (1972). So that roughness with amplitudes up to about 1 cm may be the primary cause of the increased brightness temperature, and not the corrugations of the furrowed fields common to this area. We are currently formulating the problem so as to model the agricultural terrain as a composite rough surface by following the procedure given in Wu and Fung (1972). Through such a formulation one may remove the shortcomings of this model and provide a better answer to the question of the effect on surface roughness.

Conclusion

The problem of microwave emission from a rough half space medium has been studied using the radiative transfer equation.

The dependence of the brightness temperature on the soil moisture of natural agricultural fields can be explained if one takes into consideration the surface roughness. The effect of roughness on the brightness temperature has been found to be most severe when the moisture is large. Specifically it has been shown that the brightness temperature curve has a natural tendency of flattening when the moisture increases to certain value (found to be about 100 percent of field capacity at the 1.55 cm wavelength). The effect of this flattening is to reduce the dynamic range of the brightness temperature variation with soil moisture. Further observations of the brightness temperature for high values of the soil moisture is needed to verify the usefulness and the accuracy of the model.

Acknowledgement

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Illustrations

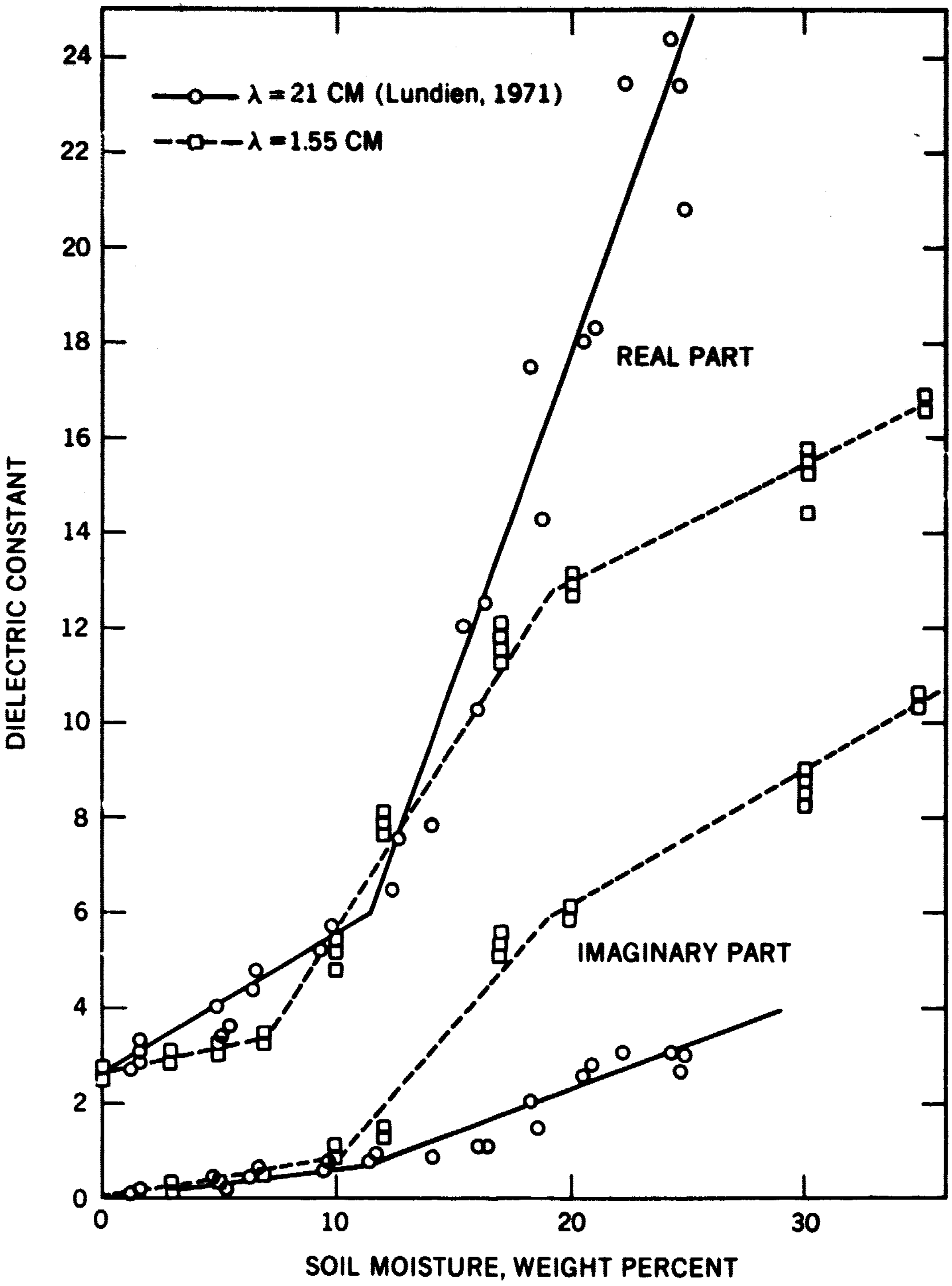

Figure 1. The dielectric constants for 21 cm and 1.55 cm wavelengths.

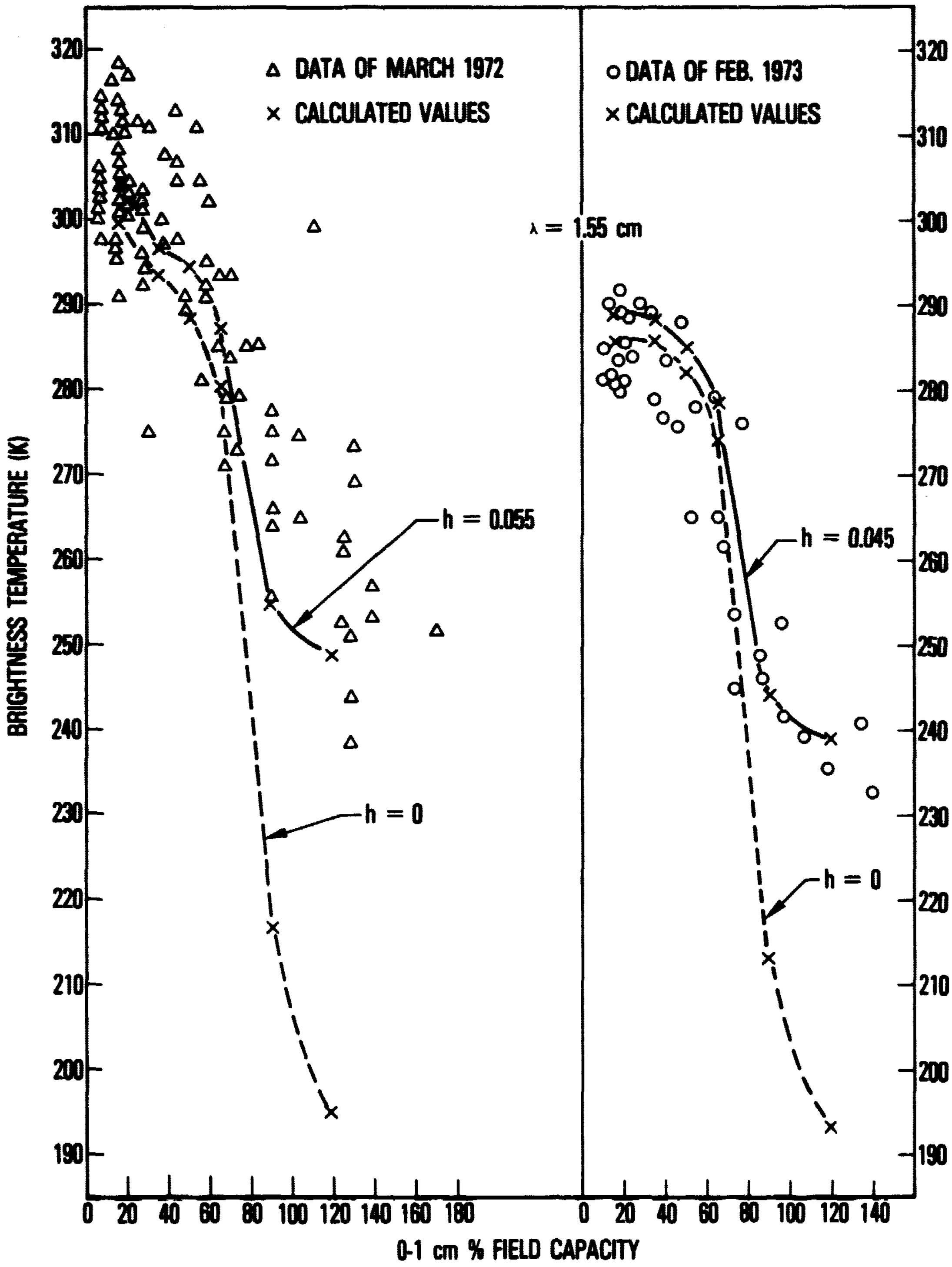

Figure 2. The brightness temperatures for 1.55 cm wavelength at nadir observation.

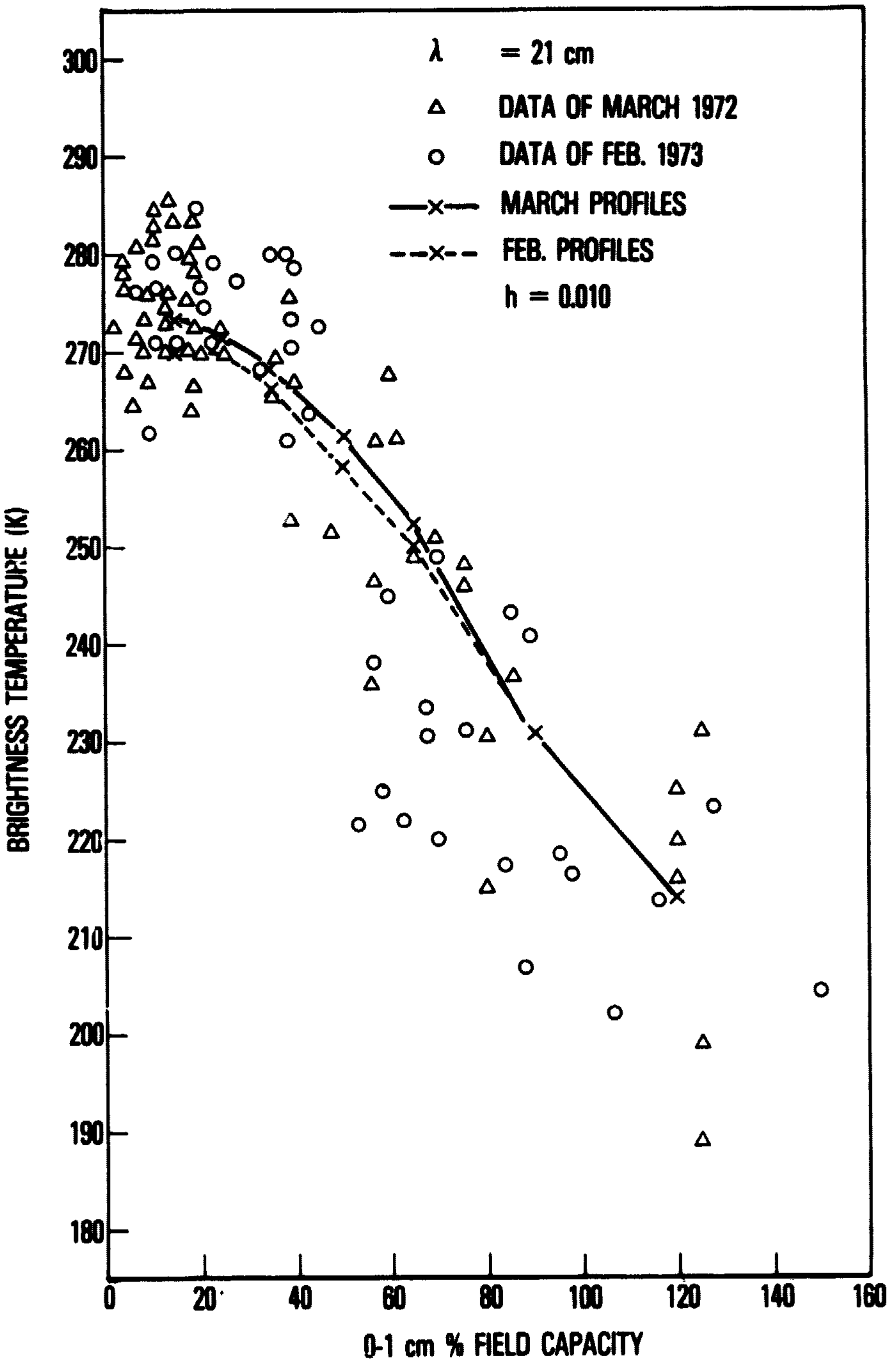

Figure 3. The brightness temperatures for 21 cm wavelength at nadir observation, 1972 and 1973 data.

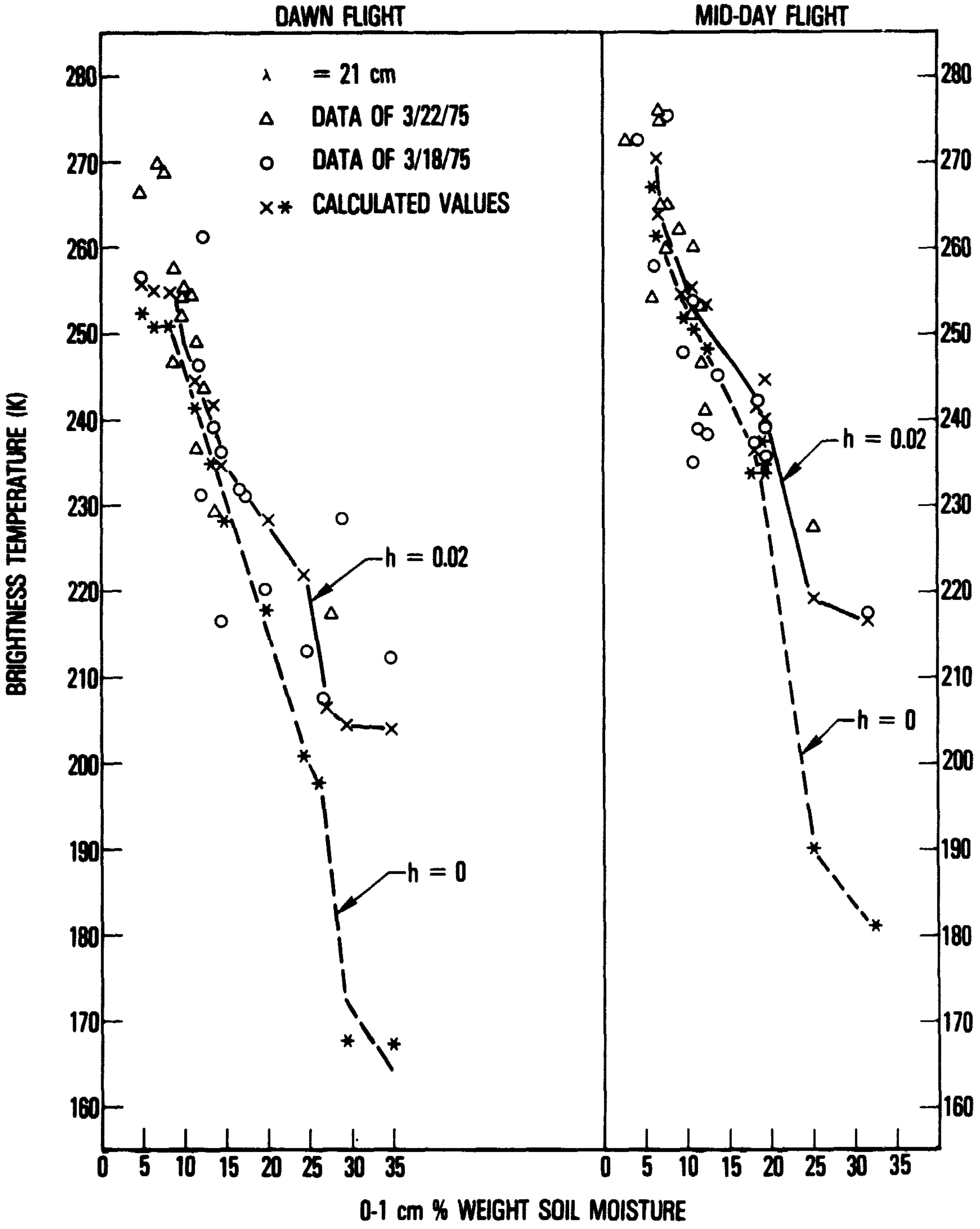

Figure 4. The brightness temperature for 21 cm wavelength at nadir observation, 1975 data.