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Effect of Surface Roughness on the Microwave Emission from Soils

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EFFECT OF SURFACE ROUGHNESS ON THE MICROWAVE EMISSION FROM SOILS

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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. The modification involves introduction of a single parameter to characterize the roughness. It is shown that this parameter depends on both the surface height variance and the horizontal scale of the roughness.

Model calculations are in good quantitative agreement with the observed dependence of the brightness temperature on the moisture content in the surface layer. Data from truck mounted and airborne radiometers are presented for comparison. The results indicate that the roughness effects are greatest for wet soils where the difference between smooth and rough surfaces can be as great as 50K.

EFFECT OF SURFACE ROUGHNESS ON THE MICROWAVE EMISSION FROM SOILS

INTRODUCTION

There have been several recent papers presenting theoretical models for the microwave emission from soils (e.g. Njoku and Kong, 1977; Wilheit, 1978; Burke et al., 1978; and England, 1977). These models considered the emission from the soil for a range of moisture and temperature profiles and studied the effect of variations of these subsurface properties on the emission from the surface. The effects of surface features, such as, roughness were not included. However, when the results of one such set of the calculations were compared with observations by airborne radiometers (Schmugge et al., 1976a) there were rather large differences (~30K) between the calculated and observed brightness temperature (T_B). These differences were attributed to surface roughness. The purpose of this paper is to show that surface roughness effects can account for these differences.

The scattering of electromagnetic waves from rough surfaces has been studied by many investigators (see Barrick, 1970; Wu and Fung, 1972; Sung and Eberhardt, 1978). These studies show that for a detailed quantitative calculation of the scattering by a rough surface, the knowledge of the statistical surface parameters are important. The roughness structure of an agricultural terrain depends upon the cultivation practice of that area. A typical surface may consist of furrows, clods and irregular, small amplitude undulations of different spatial dimensions. To study the effects of surface roughness on the observed dependence of the brightness temperature on the soil moisture a simplistic model has been developed. The surface roughness effect has been incorporated into the calculation by modifying the Fresnel reflectivity. This modification is based upon the theory developed by Ament (1953) for a conducting surface. The emphasis in this paper is to show qualitatively the effect of surface roughness on the microwave brightness temperature. The present model is simplistic because it has only one parameter to characterize the surface, namely, the standard deviation of surface height. We realize that this description may not be an exact representation of actual soil surfaces. At present the knowledge of the statistical characteristics of soil surfaces is not sufficient to formulate a model which is not only general enough but also numerically tractable to provide a quantitative description. It is, therefore, not the intention of this paper to claim that this model will provide a rigorous, quantitative description of the different aspects of the microwave emission from natural terrains but it will provide a first step for including the effects of roughness in the modeling of the emission from these surfaces.

In the calculation of brightness temperature, we have used measured soil moisture and soil temperature profiles. The calculated values of the brightness temperature are in good quantitative agreement with the values observed by truck mounted and airborne radiometers. This agreement has been demonstrated for two different wavelengths. Details for the theory and the results of the calculation are given in the following sections.

THEORY

Radiative Transfer

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

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

where I is the intensity propagating in the direction Z, 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 Eq. (1) with the source term as the temperature distribution of the soil one can write

$$T_B = (1 - r(o)) \int_{-\infty}^{0} T(z)\, K_a(Z) \exp\left(-\int_{z}^{0} K_a(Z')\, dz' \right) dz \qquad (2)$$

where r(o) is the soil surface reflectivity at normal incidence and $K_a(Z)$ is the absorption per unit length. These can be determined from the dielectric constants in the soil (Born and Wolf, 1975). Wilheit (1978) has developed a model in which the integral is evaluated by a sum over many homogeneous layers:

$$T_B = \Sigma f_i T_i \qquad (3)$$

where f_i is the fraction of the radiation incident on the air-soil interface that would be absorbed in the ith layer and T_i is the temperature of this layer. The values of f_i are determined by applying the electromagnetic boundary conditions to determine the energy fluxes entering and leaving each layer. The computations indicate that the radiation from the soil is characterized by two sampling depths: reflective and thermal. The reflectivity is characterized by changes in the real part of the index of refraction over a sampling depth: $\delta_r \cong 0.1\lambda$, where λ is the free space wavelength. The thermal sampling depth is determined by the losses deeper in the medium, and is given by

$$\delta_T = \frac{\Sigma x_i f_i}{\Sigma f_i} \tag{4}$$

where x_i is the depth of the ith layer. For a uniform dielectric this reduced to

$$\delta_T = \frac{\lambda}{4\pi \, \mathrm{Im}(n)} \tag{5}$$

For a low-loss dry soil, δ_T will be an order of magnitude larger than δ_r, while for a wet soil, it will be only slightly larger. A similar theoretical treatment has been developed by Tsang et al. (1975). This formalism is simpler and has yielded brightness temperature values which are within 1 or 2 K of their results for the same moisture and temperature profiles.

Roughness Effects

It has been shown in Tolstoy and Clay (1966) that if the scattering surface is a satistically 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 specularly scattered at an angle θ by a rough surface is given by

$$\langle E_{sc}\rangle = R_0(\theta) E_{inc} \int_{-\infty}^{\infty} W(z)\, e^{2ik_z z}\, dz \tag{6}$$

where W(z) is the height distribution of the surface and R_0 is the reflection coefficient of a smooth surface. A typical rough surface corresponds to identifying the spectrum with a Gaussian distribution of zero mean and variance σ^2:

$$W(z) = \frac{1}{\sigma\sqrt{2\pi}} \exp\,[-z^2/2\sigma^2] \tag{7}$$

For this spectrum, the average amplitude is given by

$$\langle E_{sc}\rangle = R_0(\theta)\, E_{inc} \exp[-2\sigma^2 k_z^2]. \tag{8}$$

Since

$$k^2_z = (\frac{2\pi}{\lambda})^2 \cos^2\theta \tag{9}$$

The scattered intensity obtained by squaring Eq. (8) is:

$$I_s(\theta) = I_s^0 |R_o(\theta)|^2 \exp(-h \cos^2\theta) \tag{10}$$

where the roughness parameter h is given by

$$h = 4\sigma^2 (\frac{2\pi}{\lambda})^2 . \tag{11}$$

From Eq. (10), one can stipulate that the gross effect of the surface roughness on the scattered intensity can be incorporated by modifying the smooth surface reflectivity $r_{op}(\theta) = |R_o(\theta)|^2$ as

$$r_p(\theta) = r_{op}(\theta) \exp(-h \cos^2\theta) \tag{12}$$

where the subscript p designates the polarization. The surface emissivity is obtained from (12) by

$$e_p(\theta) = 1 - r_p(\theta) \tag{13}$$

To verify this result measurements were made by Waite et al. (1973) of the reflectivity for soils with different surface roughness conditions. They found that σ is not a sufficient indicator of the roughness for this model (Hancock, 1976). Table 1 is a summary of their results at a look angle of 30°. The effective σ was determined by fitting the observed frequency dependence of the reflectivity in each band to that expected from Eq. 12 for a given σ. The effective σ was always greater than the measured σ. They also found that the autocorrelation length of the roughness was also important. This latter quantity is essentially an indicator of the horizontal scale of the roughness.

Table 1
Comparison of σ's from Laboratory Measurements

Surface	Effective σ (mm)		Meas. σ (mm)	Auto-Correlation Length (mm)
	1–2 GHz	4.5–7.4 GHz		
1	5.0	5.0	2.7	89
2	6.0	7.5	2.2	12
3	16.0	8.0	3.6	18

The value of $r_{op}(\theta)$ can be determined from the Fresnel equation for the case of a uniform dielectric, or from the layered models mentioned earlier for situation with non-uniform dielectrics. In either case it is necessary to know the variation of dielectric constant for soil with its moisture content. This is presented in Figure 1 for a clay loam soil at the wavelengths to be considered in this paper, 21 (Lundien, 1971) and 1.55 (Wang et al., 1978) cm. It can be seen in Figure 1 that the addition of water has very little effect on the dielectric properties of the soil at low-moisture contents (<10 percent). Presumably this is due to the strong interaction of the water molecules with the soil particles which reduces the polarizability of the water in a thin layer around each particle. As the water content increases the water is less tightly bound and causes a greater increase in the dielectric constant for soils.

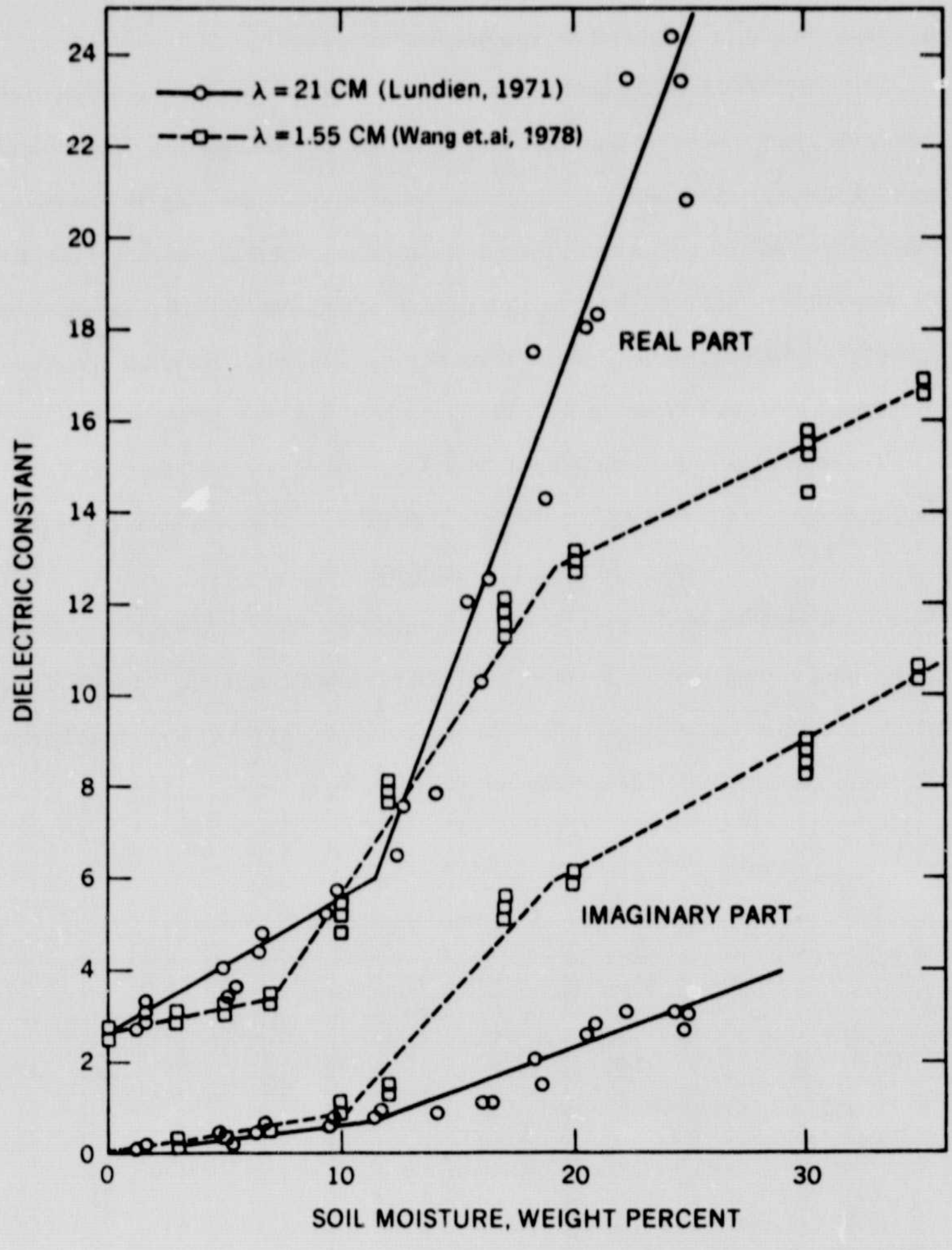

Figure 1. Laboratory measurements of dielectric constant for a soil as a function of its moisture content. These measurements are for two clay loam soils with similar textures.

The dielectric constant variation can be represented by the straight lines which are linear regression fits in these regions for the two wavelengths.

The effect of surface roughness on the emissivity of the soil as a function of soil moisture at the 21 cm wavelength is presented in Figure 2 for several values of h. These values were calculated assuming uniform moisture and temperature profiles using the Fresnel coefficient for the smooth surface case. The curves show a behavior similar to that of the dielectric constant presented in Figure 1, i.e. slow decrease of emissivity for soil moistures below about 10% and a much sharper decrease above this value. In general the effect of surface roughness is to increase the emissivity with increase being larger for the wet soil case.

The contrast in T_B between wet and dry soil is presented in Table 2 assuming a soil temperature of 300K. At $\theta = 0°$ the increase in emissivity due to roughness is given by

$$\Delta e = r_{op} (1 - \exp(-h)) \tag{14}$$

When r_{op} is small, i.e. for dry soils, Δe will be small, e.g. the range is 0.04 for dry soils which from Table 2 corresponds to 12K range for T_B due to surface roughness. For wet soil r_{op} is larger and the surface roughness effect will be much larger. At the 25% moisture level, the increase in emissivity $\Delta e = 0.28$ corresponding to a 81K T_B increase.

Table 2

Calculated T_B's for a Soil Temperature of 300K

	r_{op}	$h = 0$	$h = 0.3$	$h = 0.6$	$h = 1.0$
Dry SM = 0%	0.06	282	288	294	294
Wet SM = 25%	0.44	168	201	228	249
$\Delta T_B = 1$ $[T_B(dry) - T_B(wet)]$		114	87	63	45

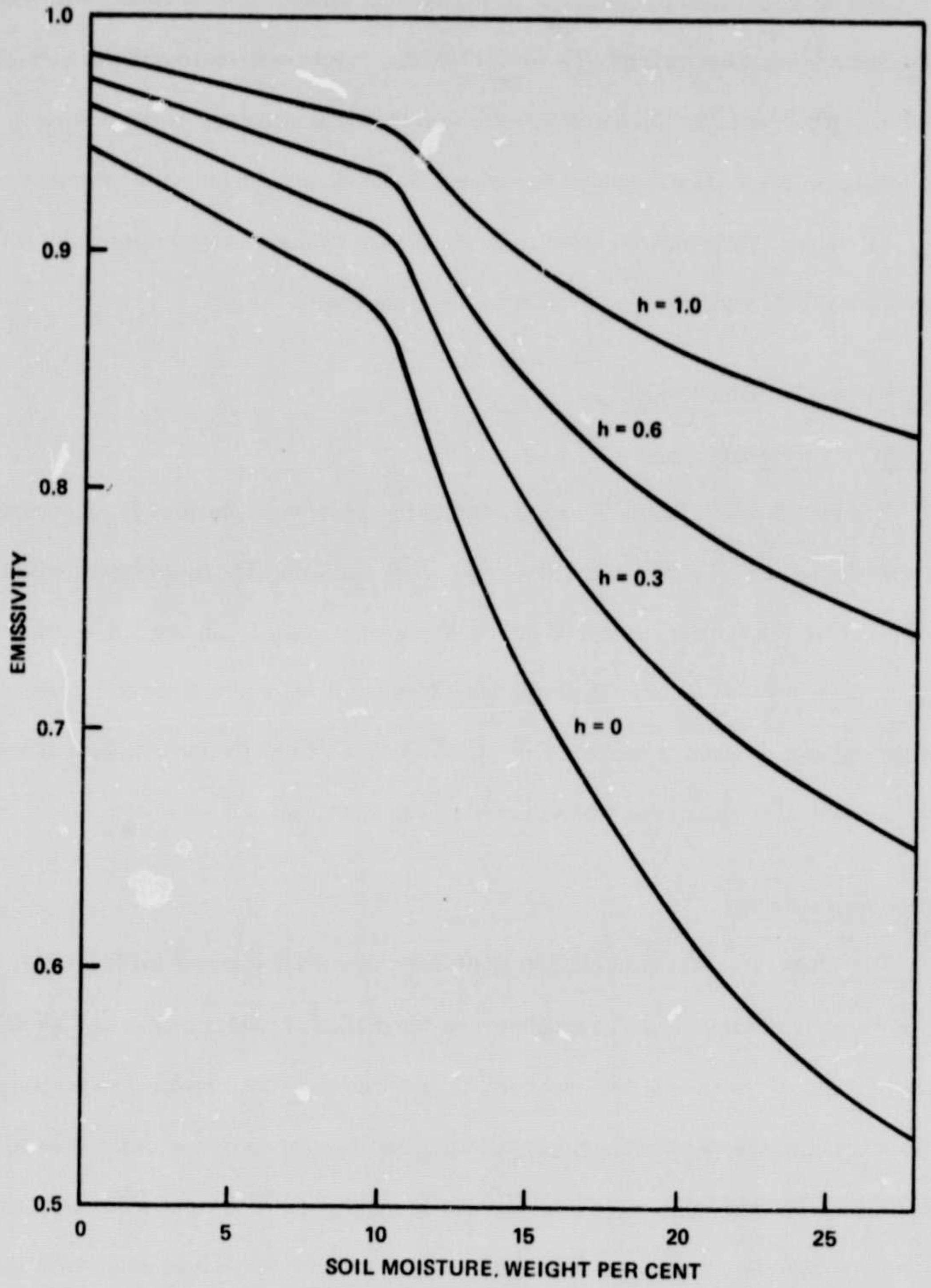

Figure 2. Calculated values of the emissivity for a soil using several values of roughness parameter h. The calculations use the dielectric constants presented in Figure 1 for the 21 cm wavelength.

The net effect then is to decrease to the dynamic range of the T_B change with soil moisture changes, e.g. a decrease of ΔT_B from 114K for smooth surfaces to 63K for a rough surface with h = 0.6. From this discussion it is seen that it is necessary to have some knowledge of the surface roughness to make an unambiguous soil moisture estimate from a T_B observation. By comparing these calculations with radiometric observations for realistic situations should yield a range of values for the parameter h.

RESULTS AND DISCUSSION

Experimental Details

The experimental results to be discussed in this paper were obtained from a portable tower (cherry picker) platform and from an aircraft platform. The tower measurements were done at Texas A&M University from a 25 m height using 21 cm and 2.8 cm wavelength radiometers (Newton, 1977). The radiometer measurements were supported by observation of the soil moisture and temperature at several depths down to 15 cm. The surface roughness profiles were also observed so that values of σ^2 can be estimated.

Field Measurements

The results from the field measurements are presented in Figure 3 for fields with surfaces having 3 different levels of roughness. A rough plowed field; a medium rough field that had been disced; and a field that had been dragged smooth. The calculated values were obtained using the moisture and temperature profiles that were observed at the time of the measurements. The values of h were selected to yield good agreement with the observed points for each roughness level. The observed T_B's for the smooth field are in good agreement with those listed in Table 2 for h = 0. In all three cases the agreement between the

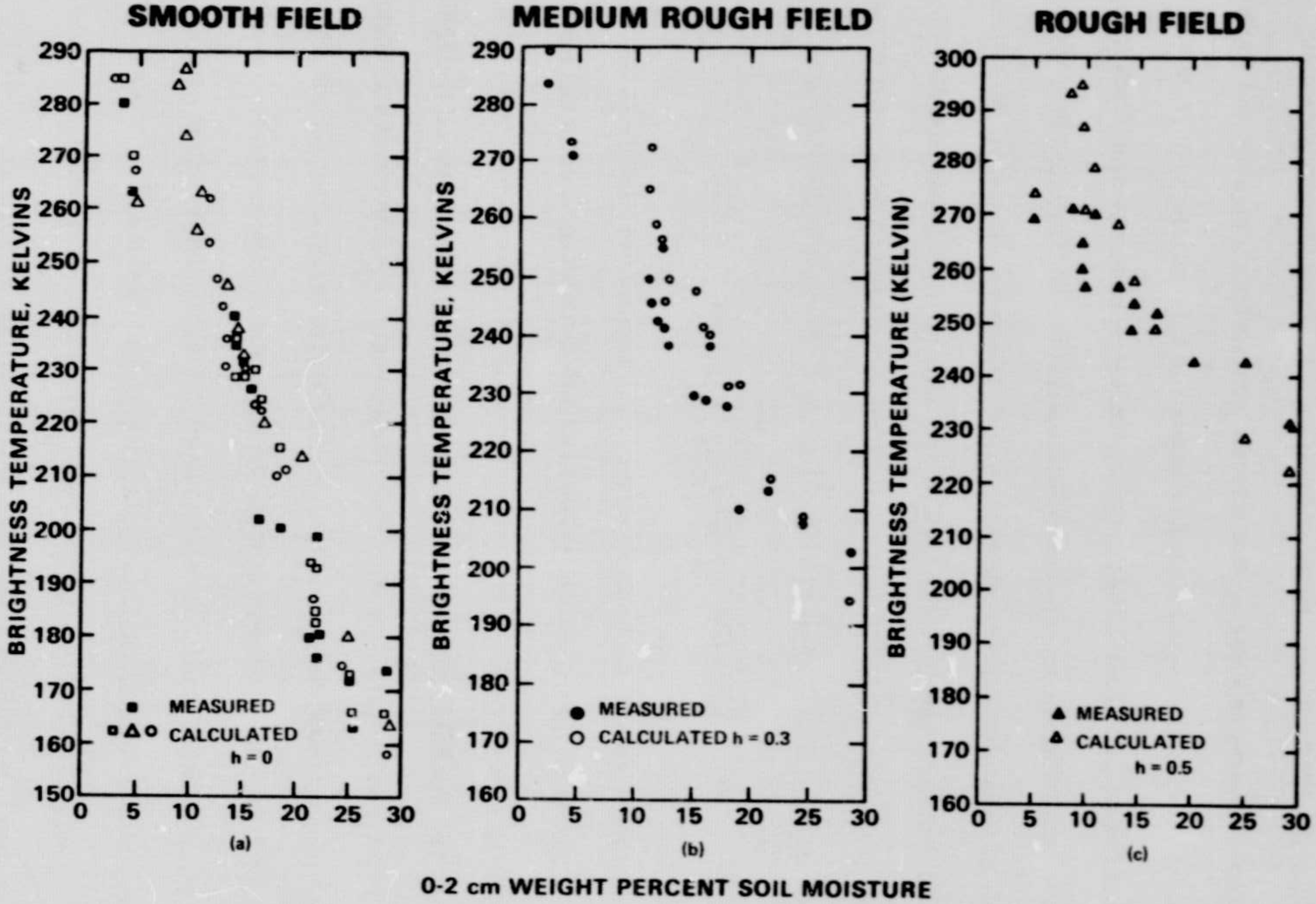

Figure 3. Comparison of calculated and measured values of T_B at $\lambda = 21$ cm for fields with 3 levels of surface roughness. Measurements made from truck mounted at Texas A&M University (Newton, 1978). In 3a the calculations were done for the profiles observed in all three fields.

observed and calculated values is good at the wet and dry ends but there are differences of 10 to 15K at the middle moisture levels i.e. about 15%. Recalling Figure 1 the middle moisture level is the region where T_B changes most rapidly with soil moisture, this also tends to be the region where there is the greatest uncertainty in soil moisture determination.

An additional factor contributing to the scatter at these middle moisture levels is the fact that the calculations were performed with a coherent model. Therefore, there is the possibility of resonances occurring when a sharp dielectric gradient is present. We believe this caused the higher values of T_B (>285K) for the three points in Figure 3c at about 10% moisture. In the extreme case the dielectric constant changed from a value of 6 at a depth of 1.6 cm to 19.5 at 3.5 cm. A quarter wavelength in the soil for this case is given by

$$\frac{\lambda_m}{4} = \frac{\lambda_o}{4\sqrt{\epsilon}} \cong \frac{21}{4\sqrt{6}} = 2.1 \text{ cm} \qquad (15)$$

where λ_m is the wavelength in the medium. As a result constructive interference occurs causing an increase in the transmission through the surface (i.e. emissivity) for this case. To verify this hypothesis the calculations were performed as a function of wavelength from 30 to 15 cm. The maximum, 295K, occurred at 21 cm wavelength and T_B fell off to 285K at 27 and 15.5 cm wavelengths. The sharp dielectric gradient in this case was caused by the transition from values on the low moisture portion (10%) of the dielectric curve in Figure 1 to a point (20%) on the steep portion of the curve in a relatively short distance. Therefore in applying any coherent model one has to be aware of the possibility of these resonances occurring so that false interpretations from the model can be avoided.

In Table 3 the values of $\sigma_{measured}$ for the fields are listed along with those calculated from Equation 11 using the observed values of h.

Table 3
Comparison of σ's from Field Measurements

Field	h	Effective	Measure
Smooth	0	0	0.9 cm
Med. Rough	0.3	0.9 cm	2.6 cm
Rough	0.5	1.2 cm	4.3 cm

The parameter h increases with increasing roughness but does not do so as rapidly as expected from the measured σ's. For example, the ratio of the σ^2 for the rough and medium rough cases is 2.7 while the ratio of the h's is 1.7.

The effective σ's for these cases are less than the measured values. This is opposite from the situations presented in Table 1 for the laboratory measurements. This difference probably results from the different horizontal scales of the roughness in the two situations.

Aircraft Measurements

The aircraft results were obtained during flights with NASA aircraft 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 aircraft altitude for these flights were 600 m in 1972 and 1973 and 300 m in 1975. On board the aircraft were microwave radiometers covering the wavelengths range of 0.8 to 21 cm. In this paper only the results at the 21 cm and 1.55 cm wavelengths will be presented. The 21 cm radiometer was nadir viewing with a 15° (~ 1/4 radian) beamwidth, therefore its spatial resolution was approximately 1/4 the aircraft altitude. The 1.55 cm radiometer is a scanning radiometer which has an angular beam width of 2.8° (~ 1/20 radian). This sensor was only used on the 1972 and 1973 missions.

The aircraft flew along flight lines centered on the agricultural fields which were at least 16 hectares (40 acres) in area. These fields generally had uniform surface and moisture conditions over their total area. All the radiometer data obtained over each field were used to obtain the average brightness temperature (T_B) for the field. The soil moisture measurements were made at 4 locations and for several depths in each field. The values presented here are the averages for each field. For the 1975 flights soil temperature profiles were also measured. Soil textures determination were also made for the sampled fields.

Because of the range of soil texture, from sandy loams to clays, that are present at both of these sites it is necessary to account for the different water bolding capacities of these soils. This was done by normalizing the measured soil moistures to the field capacity levels (FC) for each soil. The amount of water in a soil at FC is that which remains two or three days after having been saturated and after free drainage has practically ceased. This level is determined to a large extent by the soil texture i.e. particle size composition. The value of FC for each field was estimated on the basis of the soil textures that were measured for that field (Schmugge, 1978).

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.

Plots of T_B versus the soil moisture in various layers for the 1972 and 1973 flights are presented in Figure 4. We note that the range of T_B is not as great as that expected for a smooth surface.

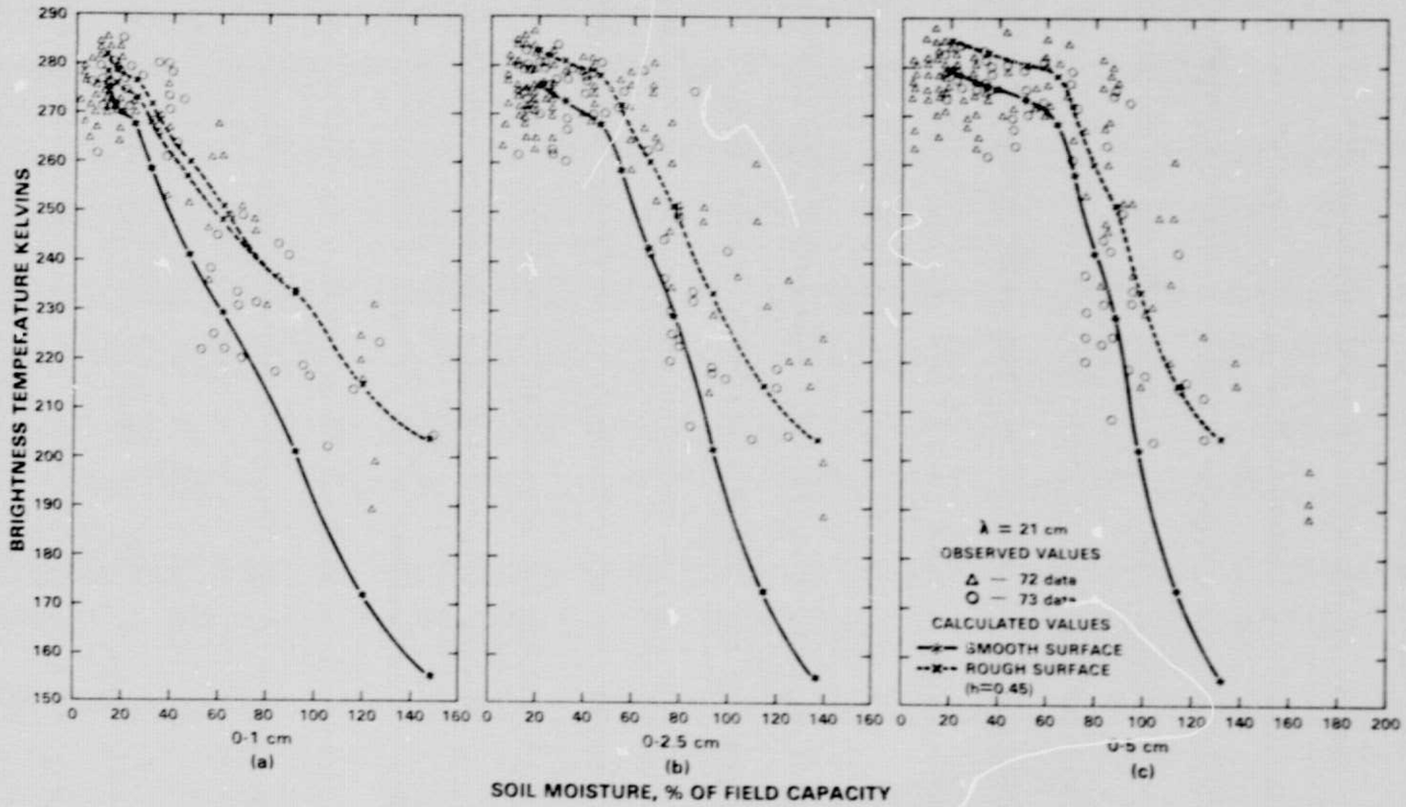

Figure 4. Aircraft observations of T_B at $\lambda = 21$ cm during 1972 and 1973 flights over Phoenix compared with soil moisture in 3 depths of the soil. The two dashed curves in 4a indicate the difference produced by using the 72 and 73 temperature profiles.

Calculations using the layered model (Wilheit, 1978) were performed using moisture and temperature profiles measured by the personnel at the U.S. Water Conservation Laboratory at Phoenix (Jackson, 1973). The soil moisture and temperature profiles were observed at frequent intervals after a heavy irrigation on March 2, 1971. These data from the same area at the same time of year were assumed to be reasonable estimates of the situations occuring during the 1972 aircraft overflights. It should be noted that the moisture and temperature profiles had been obtained from a smooth field, while the microwave radiometer results were obtained from rough-surfaced fields. The moisture profiles were rather uniform when wet, but dried rapidly at the surface after 5 or 6 days producing sharp moisture and dielectric constant gradients just below the surface. The calculations were performed for the early afternoon (1:30 p.m.) profiles of each day. The corresponding temperature profiles are probably quite representative of the actual situation for the 1972 flights. For the 1973 flights, occurring early in February, the temperatures were somewhat cooler. The surface temperatures as observed by the aircraft IR sensor were found to be about 15K lower than that observed during March. The February temperature profiles were then 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.

The dielectric constants used in the calculation were those presented in Figure 1. These values are for soils having texture similar to the Avondale clay loam soil at the Water Conservation Laboratory.

The solid curves in Figure 4 are the calculated values assuming a smooth surface (h = 0). It is clear that the aircraft T_B's do not get as low as those calculated for the smooth surface. The form of the calculated curve however does agree with the observations i.e. little variation out to about 50% of FC and then the rapid decrease in T_B.

The dashed curves in Figures 4a, b and c are for h = 0.45 and it is seen that the range of calculated T_B's is in good agreement the observed range and that the roughness factor has its greatest effect at the higher levels of moisture as predicted by Eq. (14).

In observing the variation of T_B with soil moisture in the 3 layers, we note the linear decrease T_B with the soil moisture in the 0-1 cm layer, but for the 0-2.5 and 0-5 cm layers there is a region at low soil moistures for which there is little variation of T_B. Above this level there is a sharp decrease in T_B. This behavior is similar to that presented in Figure 2 and that the location of the break point for the 2.5 cm curve, at approximately 50% of FC, is good agreement with the location presented in Figure 2, assuming a FC of 20-25% for a clay loam soil. Because of this agreement, we will assume that the radiometer is responding to the moisture variations in the top 2 or 2.5 cm.

In Figures 5 and 6 the results from the 1975 flights are presented. Figure 5 presents the results from the pre-dawn flights and Figure 6 from the mid-day flights. Essentially, the same dependence of T_B on soil moisture is observed for these flights as for the 1973 flights. The calculated values in this case used the moisture and temperature profiles that were measured in each field at the time of the flights. The rough surface curves are a visual best fit to the calculated points. Note that the T_B difference between the AM and PM flights due to soil temperature changes is explained by the calculations.

The best agreement is obtained in each case for h = 0.6 which is slightly larger than the result for the 72–73 data. The reason for this difference is unknown, and because of the scatter in the data may, indicate the uncertainty of our estimates for the value of h. The scatter in the calculated points about the curves is due to two causes: first, the variations in the soil moisture profiles having the same average 0–2 cm or 0–5 cm average moisture levels; and secondly, the variations in soil temperature.

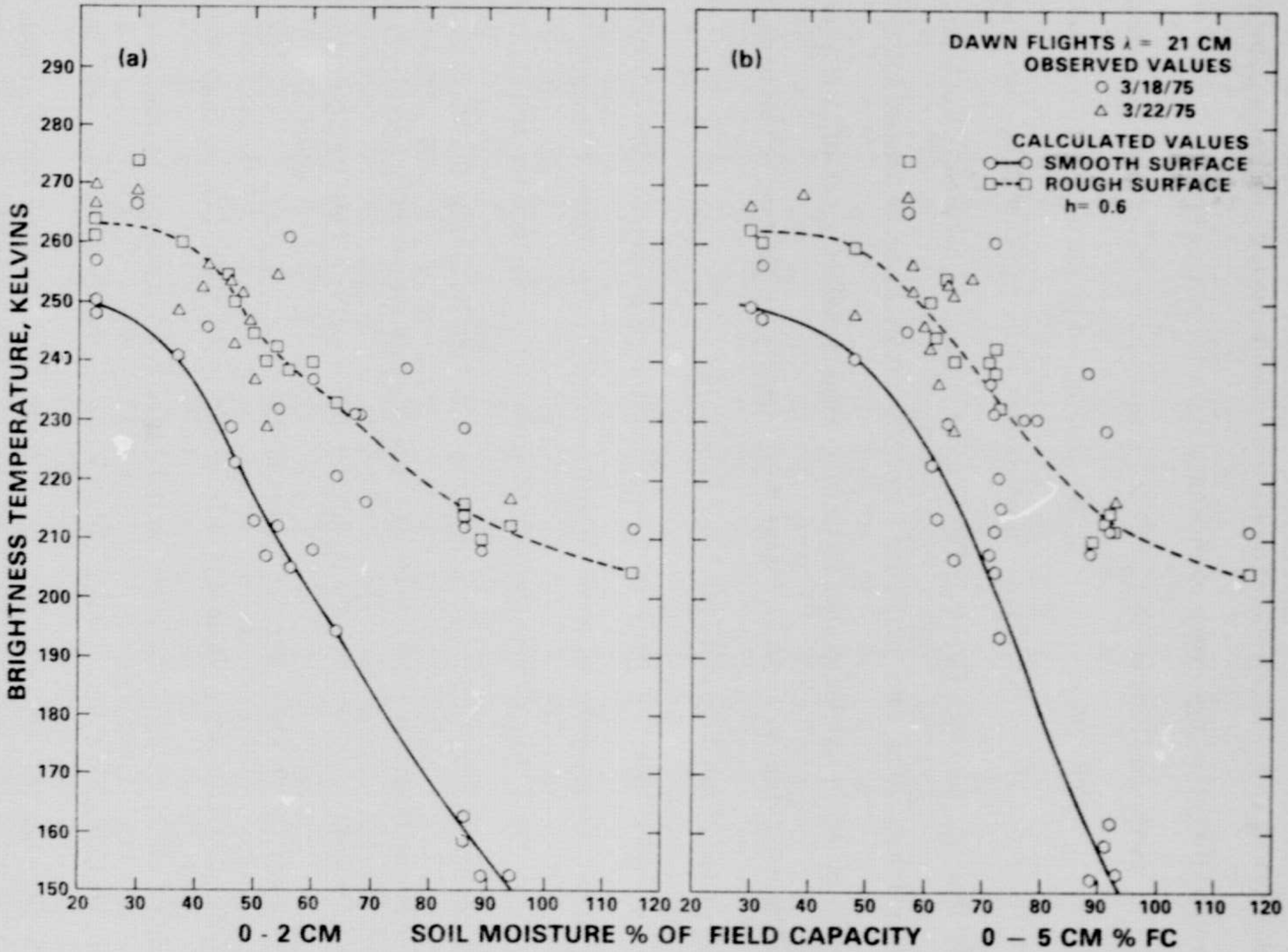

Figure 5. Aircraft observations of T_B at $\lambda = 21$ cm during 1975 dawn (6–7 AM) flights over Phoenix compared with soil moisture in two depths of the soil.

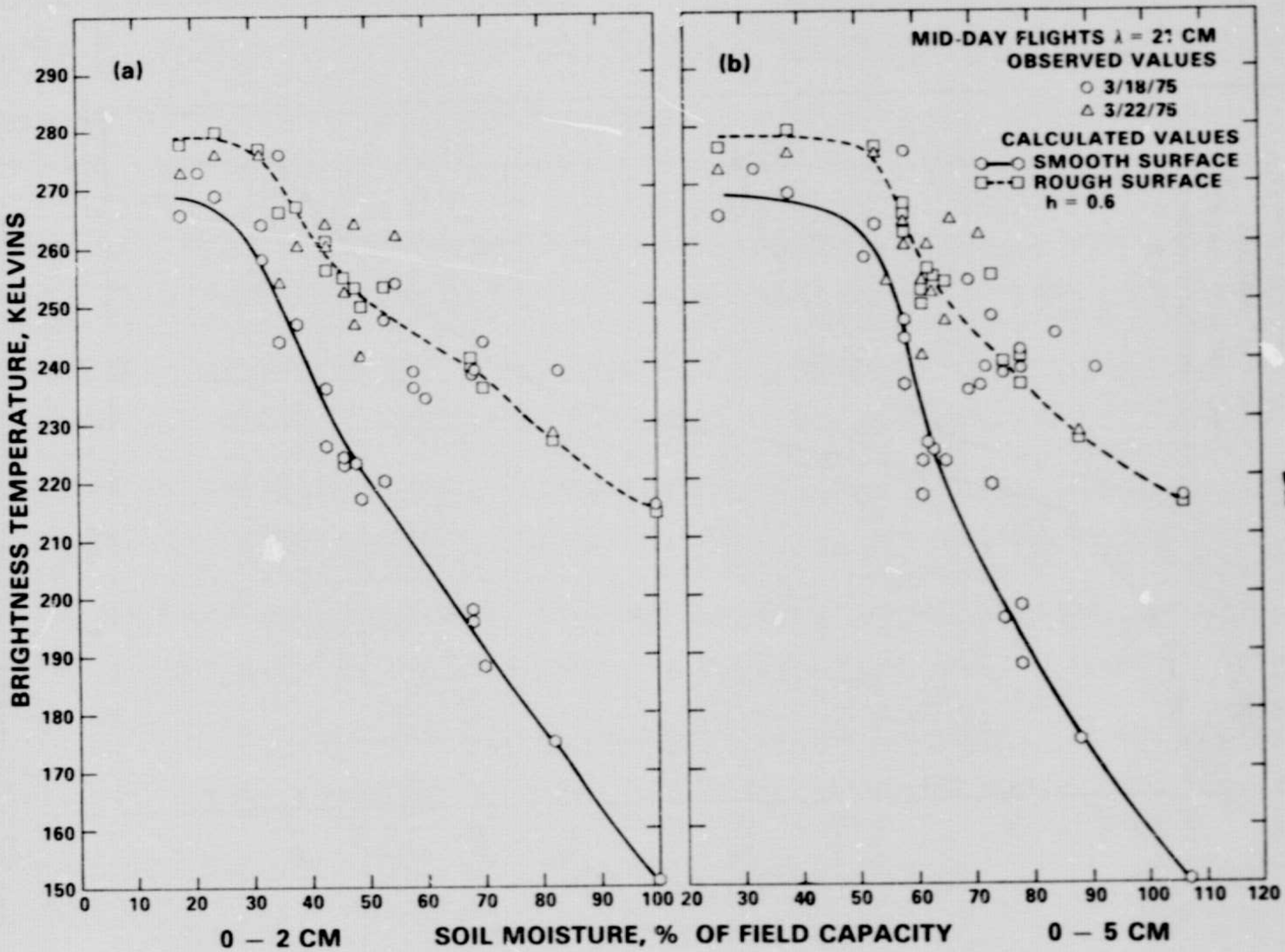

Figure 6. Aircraft observations of T_B at $\lambda = 21$ cm during 1975 mid-day (1–2 PM) flights over Phoenix compared with soil moisture in two depths of the soil.

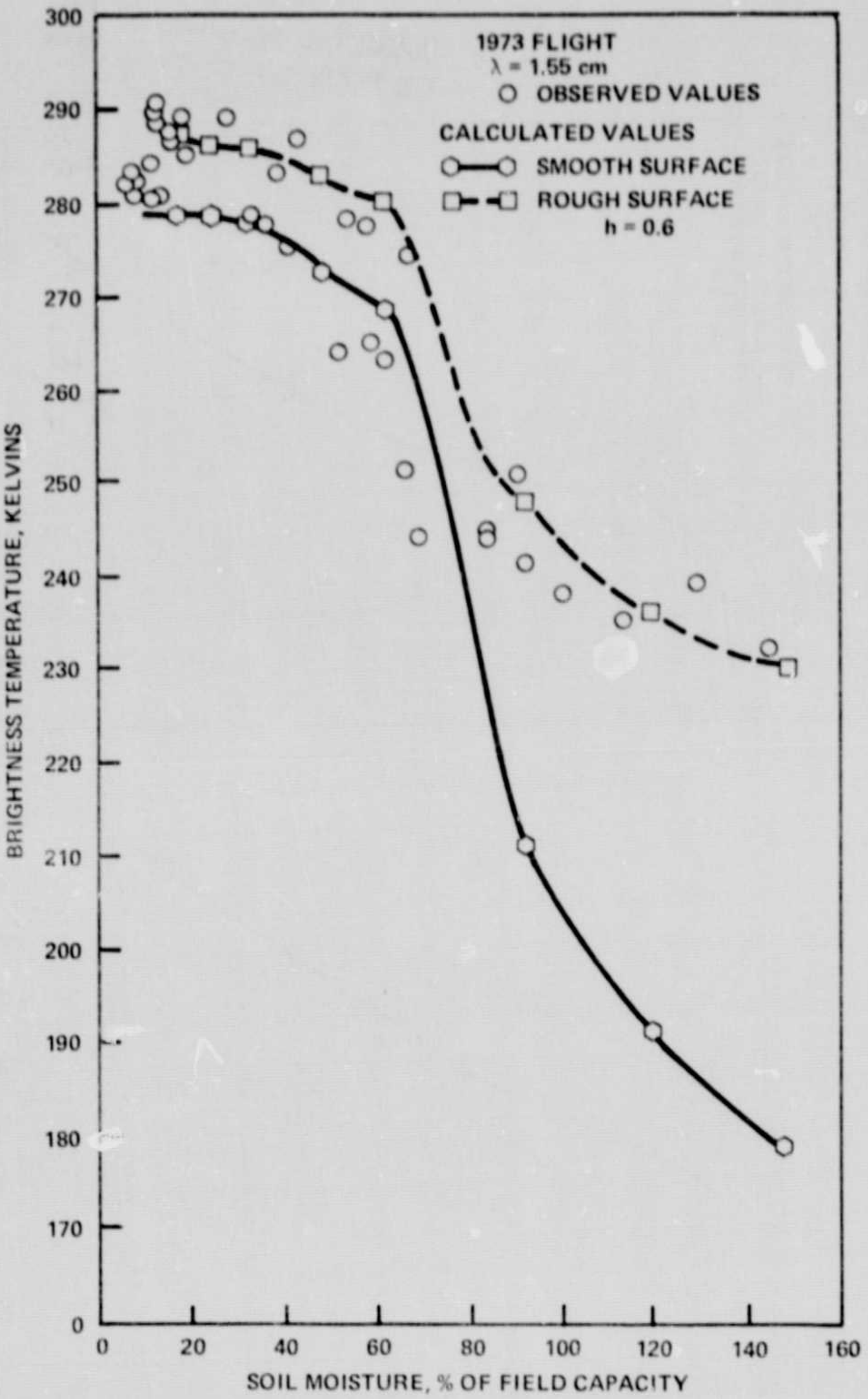

Figure 7. Aircraft observation of T_B at λ = 1.55 cm during flight over Phoenix compared with the soil moisture in the surface cm of the soil.

The values of h obtained for the aircraft data generally fall in between those obtained for the medium rough and rough cases for the field measurement results (Figure 3). This indicates that for the Phoenix region none of the observed fields approached the smooth category and an assumption that agricultural fields are in the medium rough to rough (i.e. h ≃ 0.5) may be reasonable for future calculations at this wavelength.

The data at 1.55 cm are presented in Figure 7. They are also described by an h of 0.6, the fact that h does not scale with wavelength is indicative of the shortcomings of the model. In this case, it appears that different portions of the roughness spectrum will contribute at the different wavelengths. It is also clear that certain of our assumption concerning the roughness are violated.

CONCLUSIONS

A one parameter model for estimating the effect of surface roughness on the microwave emission from soils has been developed and compared with radiometer measurements from both tower and aircraft platforms. By a suitable choice of the parameter, h, the model, when combined with a radiative transfer model for the soil, yields good agreement with the observed brightness temperatures. An effective range for the parameter was found to be from 0 for a smooth surface to 0.6 for a rough plowed surface. From the derivation of the model the parameter h is expected to be proportional to the variance of the surface height. However when compared with the measured variance for the tower measurements this dependence was not verified. A similar result was found in laboratory measurements of surface reflectivity (Hancock, 1976). These latter measurements indicate that the horizontal scale of surface roughness, i.e. surface slopes, is also important in determining the magnitude of the parameter h. Because of this factor it does not appear possible to extrapolate the value of h from the measurements presented here at the 21 cm wavelength to other wavelengths and additional measurements at other wavelengths will be required to determine the dependence of h on wavelength.

At the 21 cm wavelength the value of 0.5 for h appears to be representative of the conditions observed in the aircraft data acquired over the agricultural area around Phoenix. Therefore with this model for roughness, radiative transfer model calculations should yield accurate estimates of the values of T_B for a wide range of moisture and temperature conditions.

Further work will be required to determine the wavelength dependence of h and to determine if the model can accurately predict the polarization differences expected for off-nadir observations.

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