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Remote Sensing of Soil Moisture Content Over Bare Fields at 1.4 GHz Frequency

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ABSTRACT

A simple method of estimating moisture content W of a bare soil from the observed brightness temperature T_B at 1.4GHz is discussed in this paper. The method is based on a radiative transfer model calculation (Wilheit, 1978), which has been successfully used in the past to account for many observational results (Choudhury et al., 1979), with some modifications to take into account the effect of surface roughness. Besides the measured T_B's, the three additional inputs required by the method are the effective soil thermodynamic temperature, the precise relation between W and the smooth field brightness temperature $T_B{}^s$, and a parameter specifying the surface roughness characteristics. The soil effective temperature can be measured, and the procedures of estimating surface roughness parameter and of obtaining the relation between W and $T_B{}^s$ are discussed in detail.

It is pointed out that dual polarized radiometric measurements at an off-nadir incident angle θ are sufficient to estimate both surface roughness parameter and W, provided that the relation between W and $T_B{}^s$ at the same θ is known. Since the relation between W and $T_B{}^S$ is known only at $\theta = \theta°$ for Adelanto loam, the method of W estimate is demonstrated with two sets of experimental data at $\bar{\theta} = \theta°$, one from a controlled field experiment by a mobile tower and the other, from aircraft overflight. The results from both data sets are encouraging when the estimated W's are compared with the acquired ground truth of W's in the top 2cm layer. An offset between the estimated and the measured W's exists in the results of the analyses, but that can be accounted for by the presently poor knowledge of the relationship between W and $T_B{}^S$ for various types of soils. An approach to quantify the relationship between W and $T_B{}^S$ for different soils and thus improve the method of W estimate is suggested.

CONTENTS

LIST OF FIGURES

REMOTE SENSING OF SOIL MOISTURE CONTENT OVER BARE FIELDS AT 1.4GHz FREQUENCY

1. INTRODUCTION

Microwave emission from a bare soil depends on moisture content, soil temperature, soil type and surface roughness. To remotely estimate the soil moisture content of a bare field by the technique of microwave radiometry requires a reasonable handling of the three remaining factors of soil temperature, soil type, and surface roughness. A number of experiments in the past decade have not only shown a strong correlation between the soil moisture content W in the top few cm layers and the brightness temperature T_B as measured by the microwave radiometers, but also provided means of minimizing the effects of these three factors (Schmugge, 1980; Schmugge et. al., 1974; Burke et. al., 1979; Choudhury et. al., 1979; Newton, 1977; Njoku and Kong, 1977). For example, by normalizing the measured brightness temperature to the effective physical temperature of soils, it was possible to retain the strong correlation between the normalized T_B and W relatively independent of soil temperature (Schmugge, 1978; Newton, 1977; Wang et. al., 1980). The effect of soil types on the microwave emission could be quantified by expressing W in percentage of field capacity (Schmugge, 1978). And from the available data obtained in the past few years (Choudhury et. al., 1979; Wang et. al., 1980) it appears possible to parameterize the surface roughness effect. Thus, the microwave emission processes from bare soils could be modelled and observed data interpreted with a reasonable degree of confidence.

The ultimate objective of soil moisture remote sensing is to invert the observed T_B to obtain an estimate of W. In the following discussion, a simple approach on the bare soil inversion is presented. The discussion is limited to the measured data at 1.4GHz, since most of the past measurements are made at that frequency. It is shown that dual polarized brightness temperature measurements at incident angles of 30°-50° could be used to determine the surface roughness factor and polarization mixing coefficient. These parameters combined with the measured T_B give an estimate of W in the top 0-2cm layer. Two sets of T_B data, one from the mobile tower measurement and the other from the low altitude aircraft flight, are used as examples to estimate W. In both examples, an offset is observed when the estimated W (or field capacity FC) and the measured ground truth of W are compared. For the mobile tower measurements, the offset can be accounted for by the soil type effect. For the aircraft measurements, the imperfect knowledge of the relation between FC and smooth field $T_B{}^s$, which is essential in the inversion discussed in this paper, is believed to be the main cause of the offset. Finally, methods to improve the precision of the W estimate from the T_B measurements are suggested and discussed.

2. MICROWAVE EMISSION MODEL

a. Radiative Transfer. The radiative transfer model for microwave emission from soils used in this study was developed by Wilheit (1978). In this model the air-soil system is divided into N dielectrically homogeneous layers, the first layer being the air in contact with the soil surface, and the remaining N-1 layers within the soil medium. If $f_{pj}(\theta)$ (where j is the layer index, θ is the angle of incidence, and p is the polarization index) is the fraction of electromagnetic energy absorbed in the jth layer, then

$$f_{pj}(\theta) = \frac{S_{j-1} - S_j}{S_1} \qquad (1)$$

where S_{j-1} is the electromagnetic energy entering the jth layer at the (j-1)th interface, S_j is that for the (j+1)th layer at the jth interface, and S_1 is the incident energy at the first interface. The values for $S_1, \ldots, S_j$ are obtained by applying the Poynting's theorem to the electromagnetic fields from the solutions of the Maxwell's equations. If T_j denotes the thermodynamic temperature of the jth layer, then the brightness temperature $T_{Bp}(\theta)$ observed outside the soil medium is given by

$$T_{Bp}(\theta) = \sum_{j=2}^{N} f_{pj}(\theta)\, T_j + R_p(\theta)\, T_{sky} \qquad (2)$$

where T_{sky} is the brightness temperature equivalent of sky radiation incident on the soil, and $R_p(\theta)$ is the reflectivity of soil. By energy conservation Wilheit (1978) obtains:

$$\sum_{j=2}^{N} f_{pj}(\theta) = 1 - R_p(\theta) \tag{3}$$

Given the soil moisture and temperature profiles and knowing the relationship between the moisture content and the dielectric constant of soils (Wang and Schmugge, 1980), $T_{Bp}(\theta)$ can be readily calculated from Eqs. (2) and (3).

Eq. (2) can also be written in terms of the effective soil temperature T_{eff} as

$$T_{Bp}(\theta) = [1 - R_p(\theta)]\, T_{eff} + R_p(\theta)\, T_{sky} \tag{4}$$

where, from Eq. (3)

$$T_{eff} = \frac{\sum_{j=2}^{N} f_{pj}(\theta)\, T_j}{\sum_{j=2}^{N} f_{pj}(\theta)} \tag{5}$$

T_{eff} is found to be rather insensitive to incident angle, polarization, and soil moisture content W, although thermal temperature and W do not vary independently. On the other hand, $R_p(\theta)$, which varies strongly with W, is only weakly dependent on soil temperature (through the slight dependence of the soil water's dielectric constant on temperature). Since $R_p(\theta)$ for soil is normally $\lesssim 0.4$ and $T_{sky} \simeq 5°K$ (at 1.4GHz), the second term in Eq. (4) represents only a small fraction of the first term. In a number of circumstances, it is convenient to normalize $T_{Bp}(\theta)$ with respect to T_{eff} and study the variations of the normalized $T_{Bp}(\theta)$ with $R_p(\theta)$ (or equivalently with W).

Analysis performed by Wilheit (1978) also gives the moisture and temperature sampling depths – the effective depths of soil whose dielectric constant (moisture) and temperature determine the reflectivity and the effective temperature. The moisture sampling depth is about one tenth of the wavelength, and the thermal sampling depth is a few tenth of the wavelength. Thus for radiometric measurements at 21 cm (1.4GHz frequency), the moisture and temperature sampling depths are typically ~2 cm and ~6 cm respectively.

b. Surface Roughness Effect. The microwave emission model developed by Wilheit (1978) is for an ideal smooth air–soil interface. The surfaces of typical agricultural fields on which microwave observations are made for estimating soil moisture content are generally not smooth. The roughness characteristics of these fields depend on the nature of cultivation. Some fields may have relatively flat surface with small clods. Other fields may have surface with irregular small and large undulations in addition to clods. These surface roughness characteristics are difficult to quantify and are generally not measured in the practical application of microwave soil moisture remote sensing. As a result, a rigorous approach to modelling the surface roughness may have difficulty in experimental verification. Our approach presented in the following is to parameterize the surface roughness effect from the measured microwave T_B's of the fields. It is shown that the incorporation of the surface roughness parameterization to the microwave emission model of Wilheit (1978) indeed gives a satisfactory account of the measured T_B's over the bare soil.

From geometrical optics the radiation incident on a dielectric discontinuity will be reflected at an angle equal to the angle of incidence (specular reflection). For a smooth surface the surface normals are parallel at all points on the surface, and an incident collimated radiation will remain collimated after reflection. The reflectivity of such a surface is given by Fresnel equations. For a rough surface, the surface normals at all points are not necessarily parallel, and the average surface reflectivity is no longer governed by Fresnel equations. On such a rough surface the incident collimated radiation is reflected in many directions, and, by energy conservation, the reflectivity in the specular direction would be lower than the Fresnel reflectivity. A recent study (Choudhury et. al., 1979) gave the factor by which the smooth reflectivity is lowered as $\exp(-h \cos^2\theta)$, h being a parameter characterizing the roughness height.

The polarization state of radiation is defined with respect to an orthogonal co–ordinate system at the point of incidence. For a rough surface the orthogonal co–ordinate system can only be defined with respect to the mean smooth surface. If the polarization state is defined with respect to such a co–ordinate system, the radiation in a polarization state would be a linear combination of the radiations in both horizontal and vertical polarizations for a smooth surface. Based on these considerations, the horizontal and vertical reflectivities, $R_H^R(\theta)$ and $R_H^R(\theta)$, for a rough surface may be written as

$$R_H^R(\theta) = [(1 - Q)\,R_H(\theta) + QR_V(\theta)]\,\exp(-h\cos^2\theta) \tag{6}$$

$$R_V^R(\theta) = [(1 - Q)\,R_V(\theta) + QR_H(\theta)]\,\exp(-h\cos^2\theta) \tag{7}$$

where $R_H(\theta)$ and $R_V(\theta)$ are the Fresnel reflectivities, and Q is the polarization mixing coefficient.

c. <u>Results</u>. Neglecting the small contribution from the sky brightness, the brightness temperature $T_{Bp}(\theta)$ can be normalized to the effective soil temperature T_{eff} and Eq. (4) becomes

$$T_{NB_p}(\theta) = \frac{T_{Bp}(\theta)}{T_{eff}} = 1 - R_p(\theta) \tag{8}$$

Including the effect of surface roughness, the normalized brightness temperatures for horizontal and vertical polarizations, $T_{NBH}^R(\theta)$ and $T_{NBV}^R(\theta)$, can be explicitly written as

$$T_{NBH}^R(\theta) = 1 - [(1 - Q)\,R_H(\theta) + QR_V(\theta)]\,\exp(-h\cos^2\theta) \tag{9}$$

$$T_{NBV}^R(\theta) = 1 - [(1 - Q)\,R_V(\theta) + QR_H(\theta)]\,\exp(-h\cos^2\theta) \tag{10}$$

Further manipulations of Eqs. (9) and (10) give

$$X(\theta) = \frac{T_{NBV}^R(\theta) - T_{NBH}^R(\theta)}{1 - \frac{1}{2}[T_{NBV}^R(\theta) + T_{NBH}^R(\theta)]} = 2\left[\frac{R_H(\theta) - R_V(\theta)}{R_H(\theta) + R_V(\theta)}\right](1 - 2Q) \tag{11}$$

$$Y(\theta) = 1 - \frac{1}{2}\,[T_{NBV}^R(\theta) + T_{NBH}^R(\theta)] = \frac{1}{2}\,[R_H(\theta) + R_V(\theta)]\,\exp(-h\cos^2\theta) \tag{12}$$

These equations show that certain combinations of observed brightness temperatures depend only on one of the roughness parameters. They also provide an effective means of determining moisture and roughness from remote brightness observations. For example, if the surface roughness of the field is assumed not to vary with time, then the repeated observations of the normalized brightness temperatures would reflect only the varied moisture conditions. A graphical study of the observed $X(\Theta)$ and $Y(\Theta)$, overlaid with the predicted curves resulting from moisture variation of Fresnel reflectivities would give an estimate of roughness parameters. Knowing the roughness parameters of the field also allows the estimation of the corresponding moisture content by, from Eqs. (8), (9), and (10).

$$\frac{(1 - Q)\,[1 - T_{NBV}^{S}(\theta)] + Q\,[1 - T_{NBH}^{S}(\theta)]}{(1 - Q)\,[1 - T_{NBH}^{S}(\theta)] + Q\,[1 - T_{NBV}^{S}(\theta)]} = \frac{[1 - T_{NBV}^{R}(\theta)]}{[1 - T_{NBH}^{R}(\theta)]} \tag{13}$$

The relationships between the smooth field normalized brightness temperature pair, $T_{NBV}^{S}(\theta)$ and $T_{NBH}^{S}(\theta)$, and W would have to be established in this approach.

At $\theta = 0$, there is no difference between $R_H(0°)$ and $R_V(0°)$ and the smooth and rough surface brightness temperatures at the same moisture content are related by:

$$1 - T_{NB}^{R}(0°) = [1 - T_{NB}^{S}(0°)]\,\exp(-h) \tag{14}$$

Knowing the moisture dependence of the smooth surface brightness temperature $T_{NB}^{S}(0°)$ and the parameter h allows an estimate of soil moisture content W from the observed $T_{NB}^{R}(0°)$. The relation between $T_{NB}^{S}(0°)$ and W was established by Mo and Choudhury (1980) for Adelanto loam. The parameter h can be estimated either by making a $T_{NB}^{R}(0°)$ measurement over the given field at the extremely dry condition or by knowing the measured high and low values of $T_{NB}^{R}(0°)$ and the corresponding range of moisture content for the field in question (Choudhury, 1978).

3. RESULTS FROM THE CONTROLLED FIELD EXPERIMENT

Part of the formulation discussed in the previous section dealt with $\theta = 0°$. For measurements with microwave radiometers mounted on a mobile tower, the data obtained at $\theta = 0°$ are generally of questionable quality because of the contribution from the energy emitted by the radiometers and backscattered from the ground surface (Carver, 1978; Wang et. al., 1980). To illustrate this effect, Figure 1 shows the measured brightness temperature at the frequency of 1.4GHz plotted as a function of height H above a smooth water surface (Wang et. al., 1980). Plots a, b, c, and d in the figure give the measured results in sequential order for $\theta = 0°$, 10°, 20°, and 40°. It is clear from plot a that at $\theta = 0°$ the effect of the radiometer's self emission is present at all H. Instead of an expected constant value (without radiometer's self emission effect) of ~110°K, T_B decreases from 250°K at H = 0.6m to ~120°K at H = 6m. For $\theta = 10°$ the effect is still present at $h \leq 3$m; at $H > 3$m, T_B stays constant with H. Beyond $\theta \geq 20°$, the effect is found to be negligible at all H. In all the 1979 field measurements, H was maintained at ~6m for $\theta \leq 30°$ and therefore the observed T_B's over the θ range from 10° to 70° should be free from the radiometer's self-emission effect. At $\theta = 0°$, the effect could be present even for a less reflecting surface of soil. As an example, Figure 2 shows the measured T_B as a function of θ for a smooth bare field in both wet and dry conditions. The smooth curves are the results of the microwave emission model calculation (Wilheit, 1978) based on the acquired ground truth of soil moisture and temperature profiles and a few adjustable parameters to be discussed later. Note that the measured T_B's at $\theta = 0°$ are higher than those at $\theta = 10°$ or 20° in both dry and wet field conditions, showing the contamination of the backscattered energy emitted by the radiometer. To obtain a set of data suitable for comparison with the $\theta = 0°$ results of the previous section, the average values of the vertically and horizontally polarized T_B's at $\theta = 10°$ were derived and regarded as T_B's at $\theta = 0°$. Since the rate of change of T_B with θ is small for $\theta \leq 10°$ and T_B at $\theta = 0°$ is expected to be larger than T_{BH} (horizontal polarization) and smaller T_{BV} (vertical polarization) at $\theta = 10°$, the derived average of T_{BH} and T_{BV} at $\theta = 10°$ should be a good approximation to the expected T_B at $\theta = 0°$.

To obtain an approximate estimate of the roughness height h and mixing coefficient Q of the bare fields used in the measurements of Wang et. al., (1980), pairs of $X(\theta)$ and $Y(\theta)$ at $\theta = 40°$ were derived from the 1.4GHz data given in the same report and plotted in Figure 3a. The soil of these bare fields is of Elinsboro sandy loam. The dielectric constant of this soil is assumed to be similar to that for Openwood Street Silt measured by Lundien (1971). Using the acquired ground truth of moisture and temperature profiles and varying the Q and h values, a series of X(40°) and Y(40°) pairs were computed by microwave emission model discussed in Section 2. With $Q = 0.14$ and $h = 0.15$, the computed pairs of X(40°) and Y(40°) give the solid curve in Figure 3a, which generally follows the variational pattern of the measured data. The calculated $T_{BV}(40^\circ)$ and $T_{BH}(40^\circ)$ are compared with the corresponding measured $T_{BV}(40^\circ)$ and $T_{BH}(40^\circ)$ in Figure 3b. The calculated $T_{BV}(\theta)$ and $T_{BH}(\theta)$ as a function of θ are shown as smooth curves for the two data sets in Figure 2. In both figures the agreement between the observed and the calculated results is quite good.

An estimation of soil moisture content W from the observed $T_{NB}^{R}(\theta = 0^\circ)$ requires the knowledge of the relation between the smooth field $T_{NB}^{S}(\theta = 0^\circ)$ and W of the soil according to Eq. (13). Since the exact relationship between $T_{NB}^{S}(0^\circ)$ and W for the Elinsboro sandy loam is not known, the one derived by Mo and Choudhury (1980) for the Adelanto loam is employed here. This relation for the soil in top 0–2 cm layer is given by

$$T_{NB}^{S}(0^\circ) = 0.991 - 1.10\,W \qquad (15)$$

Substituting Eq. (15) into Eq. (14) gives

$$W = -0.008 + 0.91\,[1 - T_{NB}^{R}(0^\circ)]\,\exp(h) \qquad (16)$$

With $h = 0.15$, the $T_{NB}^{R}(0^\circ)$'s for bare fields measured in October 1979 (Wang et. al., 1980) were substituted into Eq. (15) for estimating W's in the top 0–2 cm layer. The estimated W's were compared with those measured in the top 0–2.5 cm layer in Figure 4. Although the variations of the estimated W's generally follows with those of the measured W's, clearly there is an offset of ~0.05 cm^3/cm^3.

This offset of 0.05 cm^3/cm^3 can be totally accounted for by the difference in the variations of dielectric constant with moisture content between the Elinsboro Sandy Loam and Adlanto loam. For example, the wilting point WP (which is defined as the stage of soil–water system where soil tension is about 15 atmospheres) of Adlanto loam is ~0.152. When the two parameters characterizing the variation between dielectric constant and moisture content for WP = 0.152 were derived (Wang and Schmugge, 1980) and entered in the emission model calculations for the ground truth soil moisture and temperature profiles of 1979 measurements, the calculated $T_{NB}^{R}(0^\circ)$'s were found to be ~0.046 higher than the measured ones. Higher $T_{NB}^{R}(0^\circ)$ gives smaller estimated W from Eq. (16). To produce an offset of $0.05 cm^3/cm^3$ in W from Eq. (16) requires an increase in $T_{NB}^{R}(0^\circ)$ of 0.047, which is close to the 0.046 value resulting from emission model calculations.

4. DATA FROM AIRCRAFT FLIGHTS

The data obtained from the airborne microwave radiometer experiments normally show a larger scatter in the T_B vs. W plot when compared to a similar plot of data obtained from a controlled field experiment by radiometers mounted on a mobile tower. This is mainly because many bare fields with different soil types and surface roughnesses are included in the airborne radiometer experiments. Figure 5 shows a T_B at 1.4GHz vs. FC (field capacity FC is defined as the stage of soil-water system when the soil tension is about 1/3 atmosphere) plot reproduced from the report of Choudhury et. al., (1979) for aircraft flight data taken in 1972 and 1973 over Phoenix, Arizona (Schmugge et. al., 1976). Although the effect of soil type is minimized by normalizing the moisture content to percentage of FC, the large scatter of data points is evident. The effect of soil temperature may be present, but judging from the large scatter even within each year's data set, the surface roughness effect is likely to be the dominant factor. The solid and dashed curves in the figure are the results of the emission model calculations with different surface roughness factors of 0 and 0.45, using the moisture and temperature profiles measured by the personnel at the U.S. Water Conservation Laboratory at Phoenix (Jackson, 1973). Clearly, a large difference in T_B due to different surface roughnesses at same W is expected from the theoretical calculations.

Estimation of W from the observed T_B's of an aircraft flight data set requires a different approach to establish the relationship between $T_{NB}^{S}(0^\circ)$ and W and to estimate the factor h from

Eq. (14). First, FC rather than W is used in order to minimize the soil type effect. In the following example, the relationship between T_{NB}^S and FC was derived from the smooth field data set obtained by Newton (1974) with a mobile tower. The result (for 0–2 cm layer) was given by (Choudhury, 1978):

$$FC = -1.49 + 169.6 [1 - T_{NB}^S(0°)] \tag{17}$$

Secondly, because bare fields of many different surface roughnesses were involved in the measurements, only the average value for h would be used. The h value estimated for the March 1975 aircraft flight data was 0.6 (Choudhury et. al., 1979). Combining Eqs. (14) and (17) with h = 0.6, the estimated FC's from the observed T_{NB}^R's at $\theta = 0°$ were derived and compared with the acquired ground truth of FC's in Figure 6. Although the variations of the estimated and the measured FC's follow the 1:1 slope, the estimated FC's are about 10% lower than the measured ones.

The reason for the ~10% FC offset most likely originates from the relationship between FC and T_{NB}^S as given by Eq. (17). That relationship is derived from the radiometric measurements by a mobile tower at $\theta = 0°$ (Newton, 1975). As noted in the previous section, the radiometric measurements by a mobile tower at $\theta = 0°$ might include contributions from the radiometer's self-emitted energy backscattered from the flat soil surface. A higher $T_{NB}^S(0°)$ would lower the estimated FC and it only needs a small fraction of the self-emitted energy to account for the observed offset. For example, a 10% change in FC from Eq. (17) requires a corresponding change in $T_{NB}^S(0°)$ of 0.03 which is approximately equal to a ~8°K change in brightness temperature. Contributions from the radiometer's self-emission of 8°K or higher at $\theta = 0°$ in the mobile tower measurements over a flat bare field were rather common in the experimental data reported by Wang et. al., (1980).

5. DISCUSSION

A simple method of estimating the soil moisture content at the top few centimeter layer of bare soil from the observed brightness temperature is presented in the previous sections. Besides the required inputs of the measured brightness temperature normalized to the effective soil temperature, the method calls for the determinations of the surface roughness height h (or polarization mixing coefficient Q) and of the functional relationship between the soil moisture content W and the smooth bare field normalized brightness temperature T_{NB}^{S}. The two examples given in the last two sections clearly illustrate these needs. Although the estimated W's (or field capacity FC's) generally follow the measured W's (or FC's), an offset exists in the estimated W vs. measured W plots from either the mobile tower measurements or the aircraft experiments, suggesting an insufficient knowledge of W and T_{NB}^{S} relation and possibly of the factor h.

It was pointed out in Section 4 that h determined from the aircraft data and used in the estimate of FC was the average value of many fields with different surface roughnesses. The use of h determined in this way may result in an appreciable uncertainty in the FC estimate for an individual field. A better way of obtaining the appropriate roughness parameters is first to generate a family of theoretical curves for X and Y pairs with h and Q values at off-nadir angle (e.g., $\theta = 40^\circ$) using many different moisture profiles. The radiometric measurements over many individual fields are made at the same θ in both vertical and horizontal polarizations. The experimental pair of X and Y values are then derived from the measured $T_{NBV}^{R}(\theta)$ and $T_{NBH}^{R}(\theta)$ and compared with the theoretical curves to obtain Q and h for each field. The estimate of W (or FC) from the measured $T_{NBV}^{R}(\theta)$ and $T_{NBH}^{R}(\theta)$ is then made from Eq. (13), if the relationships between W and $T_{NBV}^{S}(\theta)$ and $T_{NBV}^{S}(\theta)$ are known.

The effect of soil type on the soil moisture estimate can be taken into account by either one of the two methods below. The first method is to estimate the moisture content in terms of percent field capacity FC from the observed $T_{NBV}^{R}(\theta)$ and $T_{NBH}^{R}(\theta)$. The true moisture content of individual fields can then be obtained by conversion from FC, knowing the texture structure of the fields. The precise knowledge of the functional dependence between FC and the smooth field brightness temperature pair, $T_{NBV}^{S}(\theta)$ and $T_{NBH}^{S}(\theta)$, is required. The second method is to generate a number of pairs of linear equations relating W and $T_{NBV}^{S}(\theta)$ and $T_{NBH}^{S}(\theta)$ similar to Eq. (14) for $\theta = 0°$. Each pair of equations give the linear relations between W and $T_{NBV}^{S}(\theta)$, and between W and $T_{NBH}^{S}(\theta)$ for a given soil type. This can be accomplished by assuming soils of many different textures and, for each soil texture, making brightness temperature calculation with many different soil moisture and temperature profiles (Mo and Choudhury, 1980). The end product of this exercise is a functional dependence of the coefficients α and β, which appear in the linear relation between W and $T_{NBV}^{S}(\theta)$ (or $T_{NBH}^{S}(\theta)$), on soil type. The existence of such a functional dependence enables one to choose the proper values of α and β for a field of known soil texture and an estimate of W can be obtained from the measured $T_{NBV}^{R}(\theta)$ and $T_{NBH}^{R}(\theta)$ through Eq. (13).

Even with the insufficient knowledge of the relation between W (or FC) and $T_{NB}^{S}(0°)$, the results shown in Figures 4 and 6 from the simple method of estimating the soil moisture content are indeed encouraging. The offsets in both figures should be reduced if a more precise relation between W and $T_{NB}^{S}(0°)$ was used. More radiometric measurements, especially at off-nadir incident angles with both vertical and horizontal polarizations, with a variety of soils are desired in order to test the method more fully.

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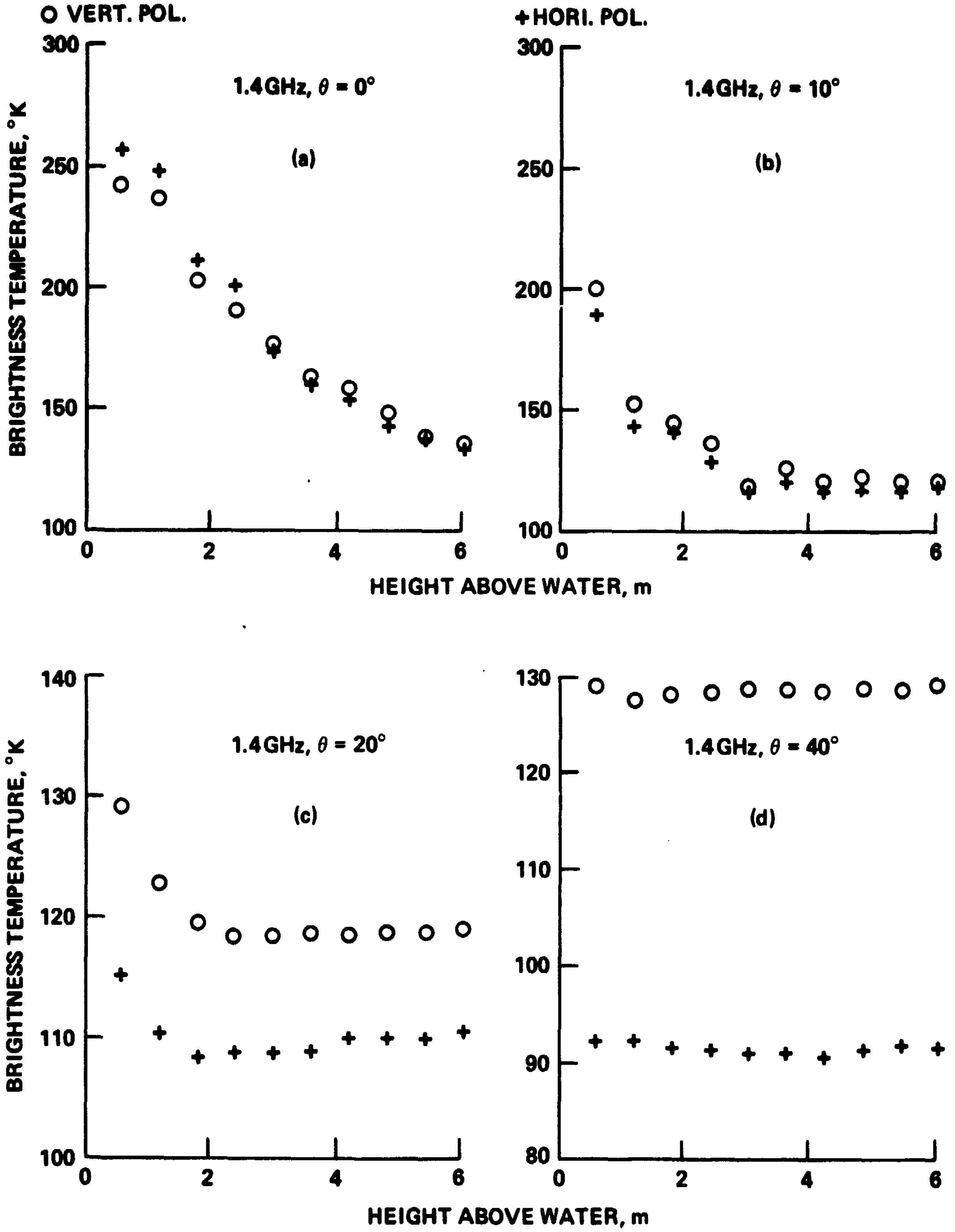

Figure 1. The measured brightness temperature at 1.4GHz plotted vs. the height of the radiometer above a smooth water surface for incident angles θ of 0°, 10°, 20°, and 40°. Note that, at θ = 0°, the effect of the radiometer's self emission is present at the maximum reachable height of ~6 m.

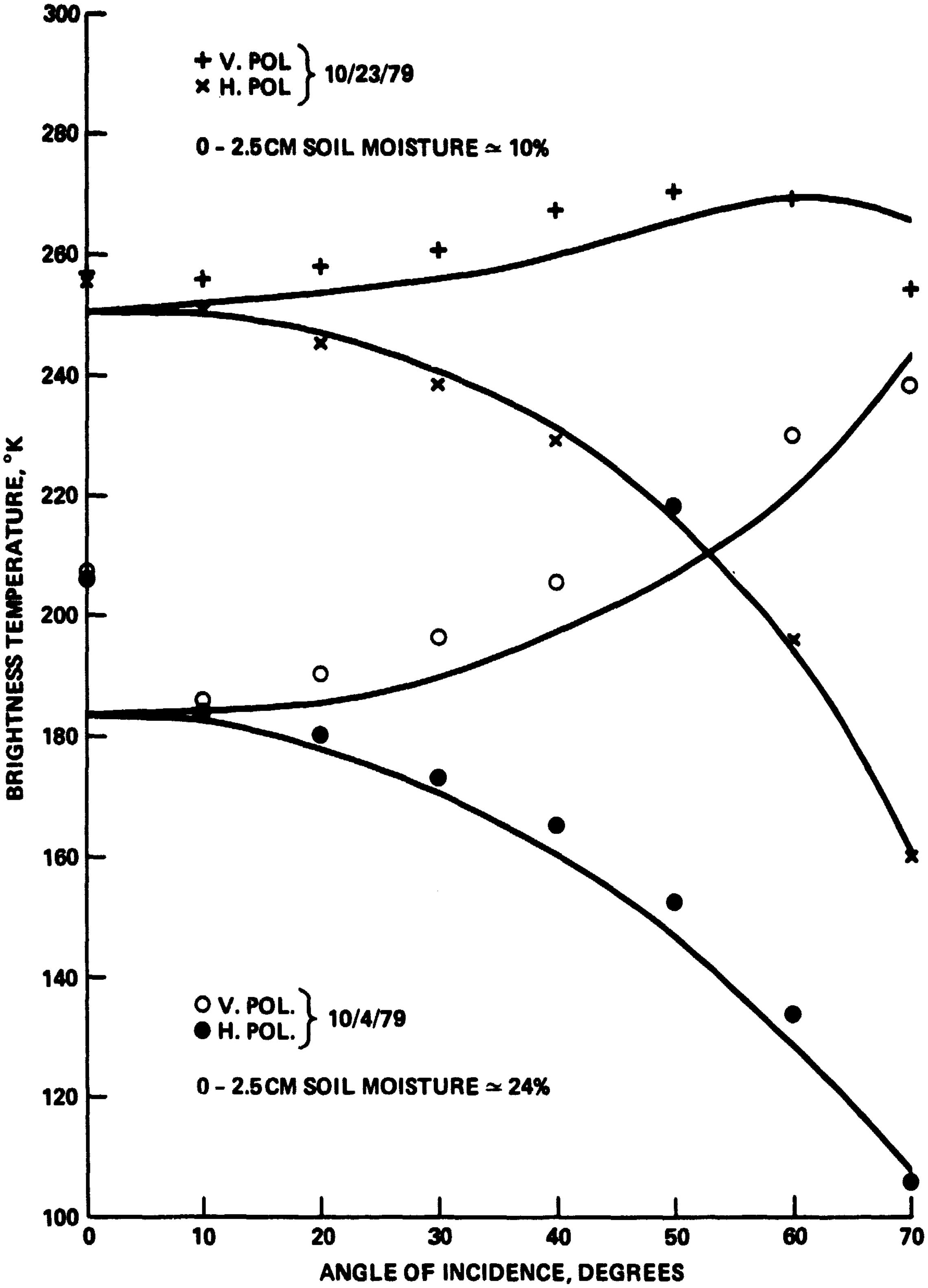

Figure 2. The measured brightness temperatures plotted as a function of incident angle θ for both wet (a) and dry (b) field conditions. At $\theta = 0°$, the observed T_B's are higher than the expected values, showing the contribution of the self-emitted energy backscattered from the ground surface.

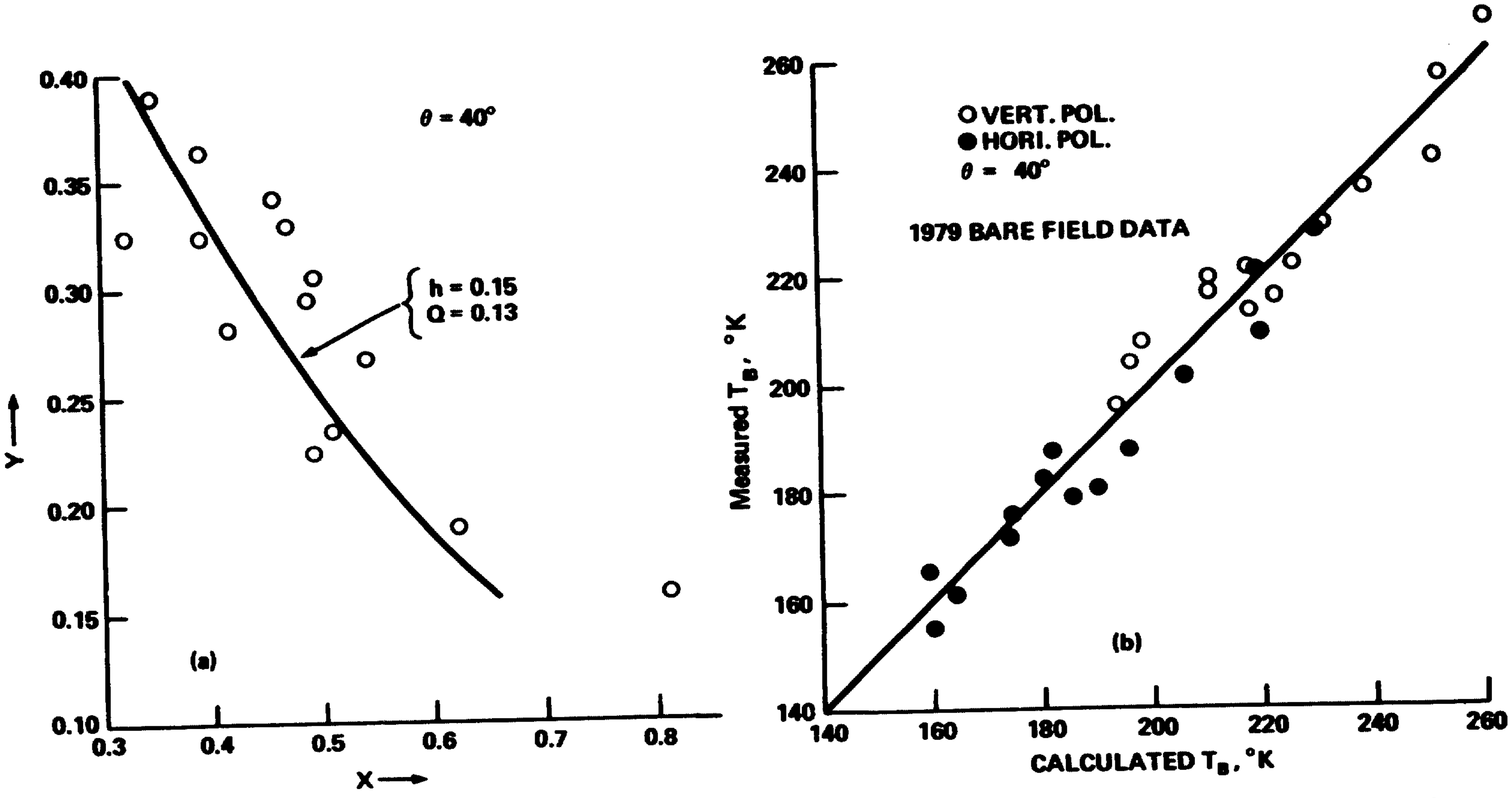

Figure 3. (a) The graphical determination of roughness parameters from the observed brightness temperature at $\theta = 40°$.
(b) A comparison of the calculated and measured brightness temperatures at $\theta = 40°$.

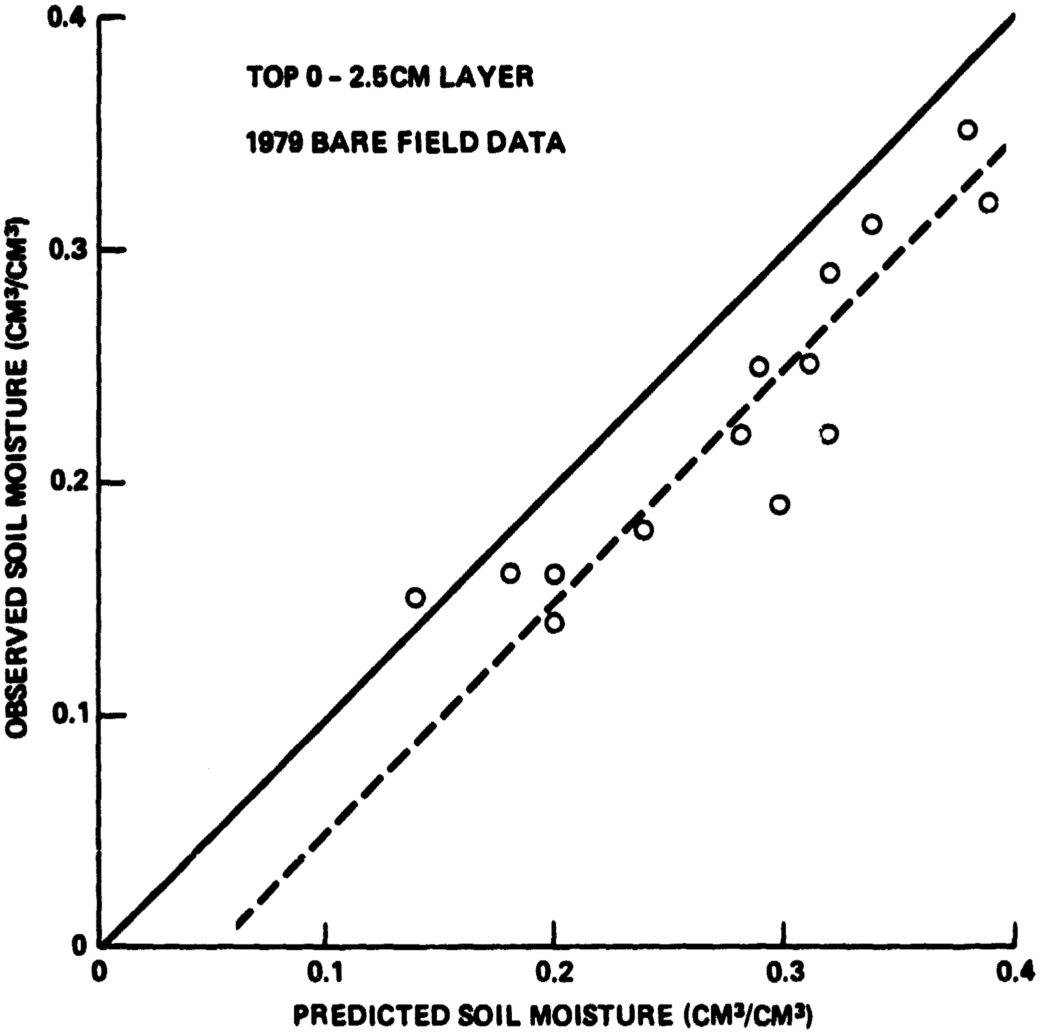

Figure 4. A comparison of the estimated and the measured soil moisture contents in the top 2cm layer.

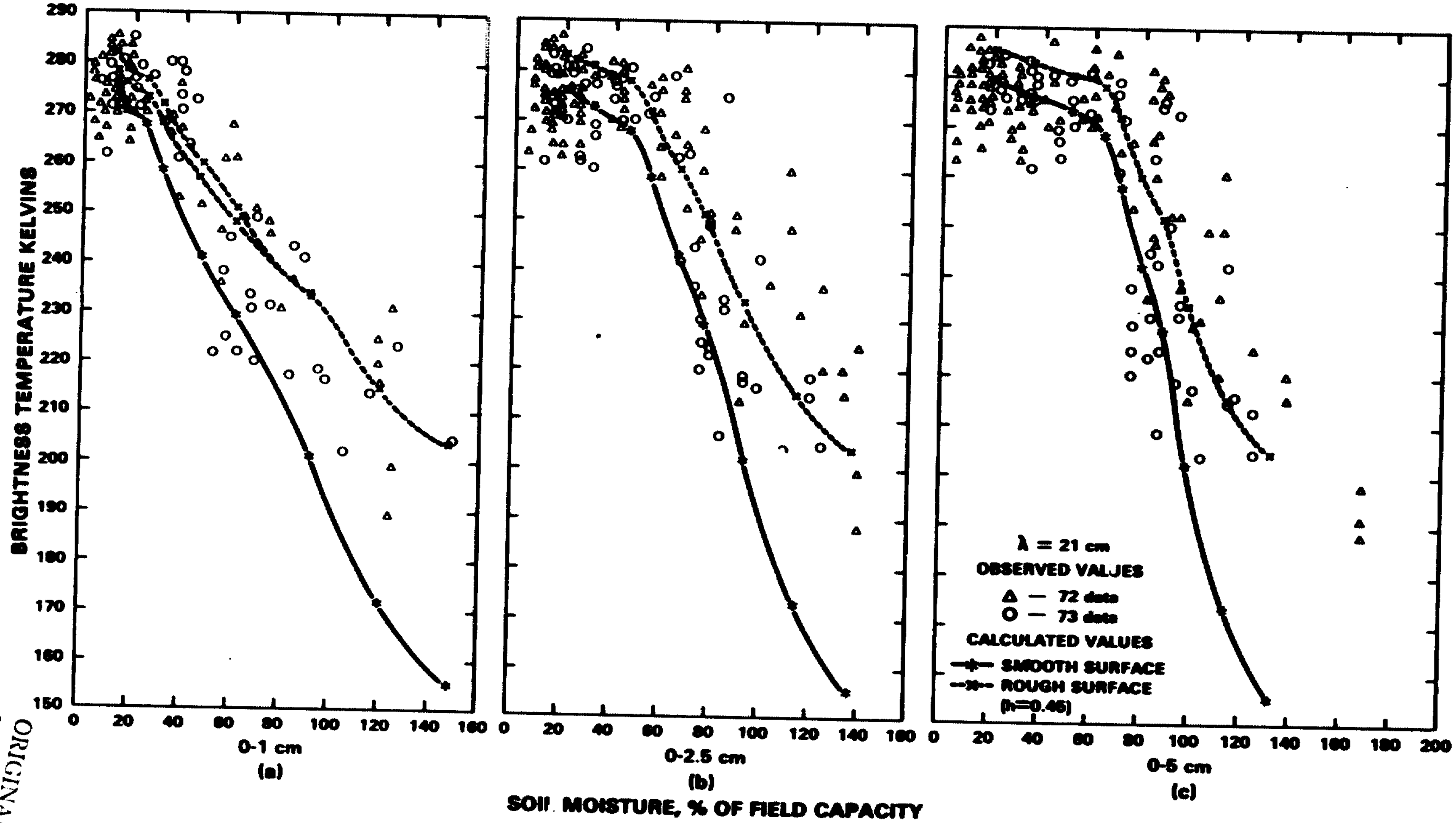

Figure 5. Aircraft observations of brightness temperature at 1.4GHz during 1972 and 1973 flights over Phoenix compared with soil moisture (percent of field capacity) in the top 0-1cm, 0-2.5cm, and 0-5cm layer (Choudhury et. al. 1979).

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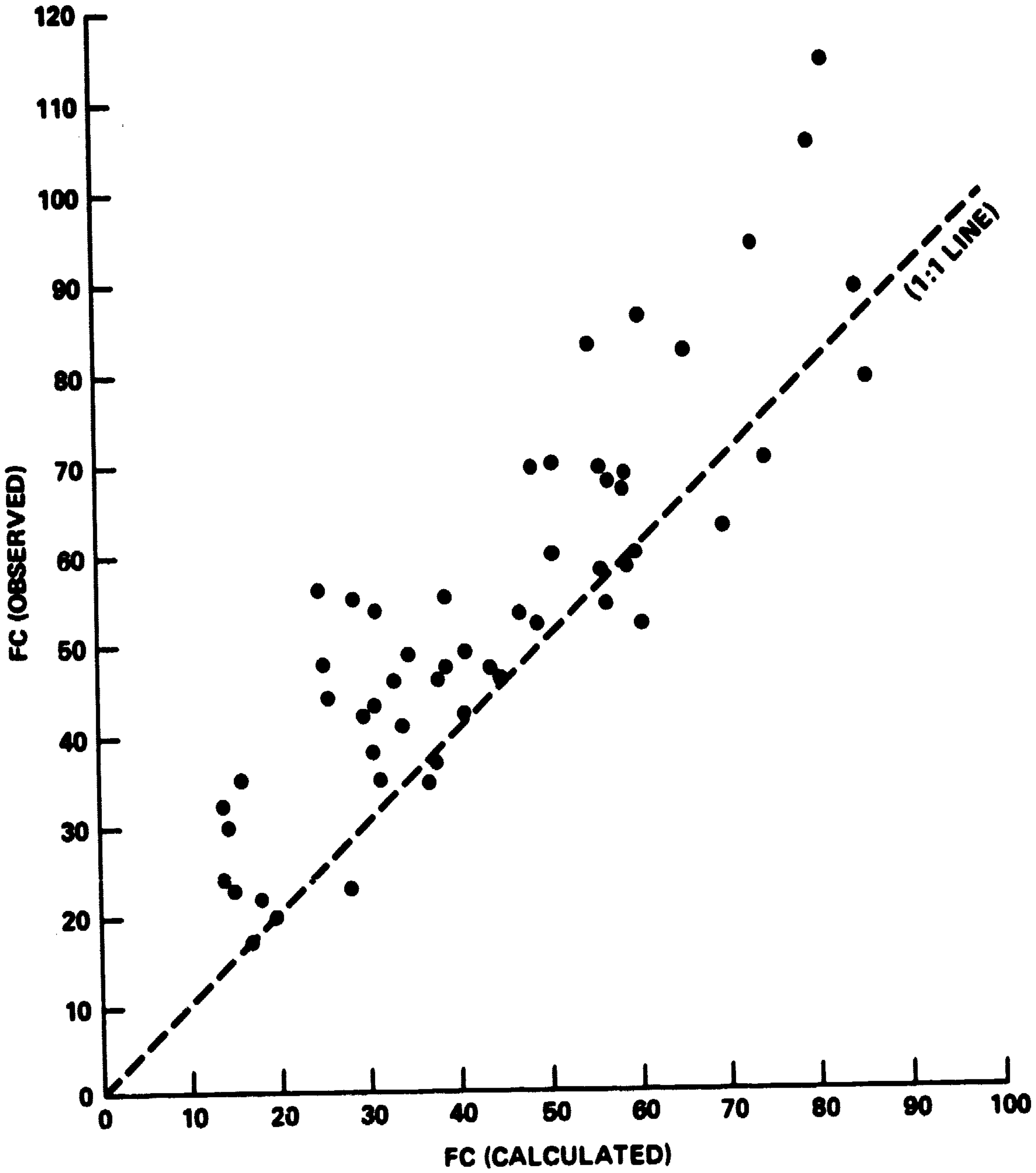

Figure 6. A comparison of measured and estimated values of soil moisture content in the top 2cm surface layer from aircraft observations of 1975.

FIGURE CAPTIONS

Figure 1. The measured brightness temperature at 1.4GHz plotted vs. the height of the radiometer above a smooth water surface for incident angles θ of 0°, 10°, 20°, and 40°. Note that, at $\theta = 0°$, the effect of the radiometer's self emission is present at the maximum reachable height of ~6m.

Figure 2. The measured brightness temperatures plotted as a function of incident angle θ for both wet (a) and dry (b) field conditions. At $\theta = 0°$, the observed T_B's are higher than the expected values, showing the contribution of the self-emitted energy backscattered from the ground surface.

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16. Abstract

A simple method of estimating moisture content W of a bare soil from the observed brightness temperature T_B at 1.4GHz is discussed in this paper. The method is based on a radiative transfer model calculation (Wilheit, 1978), which has been successfully used in the past to account for many observational results (Choudhury et. al., 1979), with some modifications to take into account the effect of surface roughness. Besides the measured T_B's, the three additional inputs required by the method are the effective soil thermodynamic temperature, the precise relation between W and the smooth field brightness temperature T_B^s, and a parameter specifying the surface roughness characteristics. The soil effective temperature can be readily measured, and the procedures of estimating surface roughness parameter and of obtaining the relation between W and T_B^s are discussed in detail.

It is pointed out that dual polarized radiometric measurements at an off-nadir incident angle θ are sufficient to estimate both surface roughness parameter and W, provided that the relation between W and T_B^S at the same θ is known. Since the relation between W and T_B^S is known only at $\theta = 0^\circ$ for Adlanto loam, the method of W estimate is demonstrated with two sets of experimental data at $\theta = 0^\circ$, one from a controlled field experiment by a mobile tower and the other, from aircraft overflight. The results from both data sets are encouraging when the estimated W's are compared with the acquired ground truth of W's in the top 2cm layer. An offset between the estimated and the measured W's exists in the results of the analyses, but that can be accounted for by the presently poor knowledge of the relationship between W and T_B^S for various types of soils. An approach to quantify the relationship between W and T_B^S for different soils and thus improve the method of W estimate is suggested.

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