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Soil Moisture

A Multi-Frequency Measurement of Thermal Microwave Emission From Soils: The Effects of Soil Texture and Surface Roughness

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A MULTI-FREQUENCY MEASUREMENT OF THERMAL MICROWAVE EMISSION FROM SOIL: THE EFFECT OF SOIL TEXTURE AND SURFACE ROUGHNESS

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ABSTRACT

An experiment on remote sensing of soil moisture content was conducted over bare fields with microwave radiometers at the frequencies of 1.4 GHz, 5 GHz, and 10.7 GHz during July – September of 1981. Three bare fields with different surface roughnesses and soil textures were prepared for the experiment. Ground truth acquisition of soil temperatures and moisture contents for 5 layers down to the depths of 15 cm was made concurrently with radiometric measurements. The experimental results show that the effect of surface roughness is to increase the soils' brightness temperature and to reduce the slope of regression between brightness temperature and moisture content. The slopes of regression for soils with different textures are found to be comparable, and the effect of soil texture is reflected in the difference of regression line intercepts at brightness temperature axis. The result is consistent with laboratory measurement of soils' dielectric permittivity. Measurements on wet smooth bare fields give lower brightness temperatures at 5 GHz than at 1.4 GHz. This phenomenon is not expected from current radiative transfer theory, using laboratory measurements of the relationship between dielectric permittivity and moisture content for different soil-water mixtures at frequencies $\leq$5 GHz.

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A MULTI-FREQUENCY MEASUREMENT OF THERMAL MICROWAVE EMISSION FROM SOILS: THE EFFECT OF SOIL TEXTURE AND SURFACE ROUGHNESS

1. INTRODUCTION

The effects of surface roughness and texture structure are known to play a dominant role in thermal microwave emission or radar backscatter from soils. A number of experiments on soil moisture remote sensing have been conducted in the past decade at both ground level and aircraft altitudes to study these effects [1] - [8]. Ulaby et al. studied radar responses to bare fields of various surface roughness conditions and found, depending on incidence angles, a strong dependence of backscattering coefficient on surface roughness over the frequency range of 1-8 GHz. They also found that the correlation between radar backscatter and soil moisture content was much improved when the latter was normalized to the field capacity of soils. Newton and Rouse [3] made their measurements on Miller clay with the soil surface prepared in three different conditions: smooth, medium rough, and very rough. Their results showed a general increase of brightness temperature with surface roughness. Choudhury et al. [1] incorporated the surface roughness effect into a radiative transfer theory [9] and compared it with data obtained from both ground level and airborne microwave radiometers [3] - [5]. Schmugge [5] analyzed radiometric data from aircraft flights at both 1.4 GHz and 10.7 GHz frequencies and showed a good correlation between brightness temperatures and soil moisture contents expressed in percent field capacity of soils. Quantitative measurements and analyses on both soil texture and surface roughness effects have been made with the same radar system [6] - [7]. But similar efforts with the same radiometer system have not been reported to the best of our knowledge.

In this paper we report results of an experiment conducted over bare fields during July September of 1981. The measurements were made with three radiometers mounted on a mobile tower at frequencies of 1.4 GHz, 5 GHz, and 10.7 GHz. Two test sites managed by USDA

Beltsville Agricultural Research Center were selected for these measurements. The soil in the first test site is Elinsboro sandy loam which consists of 67% sand, 19% silt, and 14% clay. Previous measurements over this test site have been reported elsewhere [8], [10], [11], [12]. The soil in the second site is Mattapex silty loam whose texture consists of 32% sand, 43% silt, and 25% clay. A very smooth bare field in the first site and two bare fields, one smooth and the other rough, in the second site were prepared for the experiment. The radiometric measurements were made alternately between the two test sites so that both soil texture and surface roughness effects could be studied with the same set of radiometers. The uncertainty in the measured data due to sensors' calibration, which could be severe when data sets obtained by different sensors are to be compared, is thus minimized.

2. THE EXPERIMENT

All three radiometers measure brightness temperatures of targets in both vertical and horizontal polarizations simultaneously. The antennas of these radiometers are such that they all have a comparable 3-db beamwidth of ~13°. The radiometers are of Dicke type with two internal calibration loads: a hot load at 310°K and a cold load at liquid nitrogen temperature of 77°K. Absolute calibrations of the radiometers are made with three external targets of known brightness temperatures: a cold sky at ~5°K, a calm water surface which gives a range of brightness temperatures over incidence angles of 10°-60°, and a layer of Eccosorb slabs 23-cm thick whose brightness temperature is practically equal to the ambient temperature. Both sky and Eccosorb calibrations of the radiometers are made at least once during each day of field measurements. The sensors' calibrations with a calm water surface are made twice during the course of the experiment. The results of these calibrations are shown in Figure 1a, b, and c for radiometers at 1.4 GHz, 5 GHz, and 10.7 GHz in sequential order. Only a few representative data points obtained with sky and Eccosorb calibrations are entered in the figure for the sake of clarity. Applying a linear regression to each of the six data sets (two polarizations for each of three frequencies) gives a correlation coefficient in excess of 0.99. Based on these calibration results, it is estimated that the accuracy

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of the radiometric measurements is about ±3°K, with the exception of the 1.4 GHz vertically polarized data. As clearly shown in Figure 1a, the 1.4 GHz vertically polarized calibration data over the calm water surface (brightness temperatures of 105°K–180°K over incidence angles of 10°–60°) appear to have a steeper slope compared to the one derived from the linear regression. The reason for this observed phenomenon is unknown and is currently under investigation. Therefore, the 1.4 GHz vertically polarized data are not included in the comparison with emission model calculations. This will not affect the main conclusions of this paper.

The radiometric measurements over the three bare fields in the two test sites were made with incidence angle θ varying from 10° to 70° in 10° steps. Ground truth acquisition of soil moisture contents at the layers of 0–0.5 cm, 0–2.5 cm, 2.5–5.0 cm, and 5.0–10.0 cm, and of soil temperatures near the surface, and at the depths of 1.25 cm, 3.75 cm, 7.5 cm, and 12.5 cm, was made concurrently with the radiometric measurements. Soil moisture content in the deeper layer of 10–15 cm was measured within two hours of radiometric measurements over each field. Soil bulk density in the layers of 0–2.5 cm, 2.5–5.0 cm, 5.0–10.0 cm, and 10.0–15.0 cm was also measured several times in each field during the course of the experiment. Mechanical and chemical analyses were made on soil samples taken from each of the three fields at the layers of 0–5 cm, 5–10 cm, 10–15 cm, and 15–30 cm. The soil texture in each field turned out to be rather uniform with depth and the average percent values of sand, silt, and clay are given in Table 1. Based on this texture information, the wilting point and field capacity of each field soil were estimated from the formulas of Wang and and Schmugge [13] and Schmugge [5] and listed in the last two columns of the table. As a measure of surface roughness conditions, a few photographs of surface profiles were taken in each field using the method previously employed by Newton [14]. These photographed profiles were analyzed and standard deviations (σ) about mean surfaces were calculated. The average σ value for each of the three fields was derived and also given in Table 1. Notice that the surface conditions of the three fields and the soil textures between the two test sites are markedly different.

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Table 1
The Characteristics of Fields Used for Microwave Radiometric Measurements

Field No.	Soil Type	Surface Characteristics		Soil Texture, %			Computed Wilting Point, cm^3/cm^3	Field Capacity cm^3/cm^3
		Appearance	RMS Roughness cm	Sand	Silt	Clay		
1	Elinsboro Sandy Loam	Very Smooth	0.21	67	19	14	0.097	0.236
2	Mattapex Silty Loam	Smooth	0.73	32	43	25	0.167	0.351
3	Mattapex Silty Loam	Rough	2.45	32	43	25	0.167	0.351

Multifrequency radiometric measurements over these fields would provide a unique opportunity to study the effects of soil texture and surface roughness on the thermal microwave emission from soils.

3. THE MEASUREMENT RESULTS

A typical variation of the measured brightness temperatures, $T_{BP}(\theta)$'s (subscript P can either be V for vertical polarization or H for horizontal polarization), with incidence angle θ is shown in Figure 2a, b, and c for 1.4 GHz, 5 GHz, and 10.7 GHz frequencies. The measurements were made on August 13, 1981 over both smooth and rough fields in the second test site. About 2 cm of rain fell over the test area during the night prior to the measurements. The volumetric soil moisture content W was uniform down to a 10 cm depth and was measured to be ~0.250 cm^3/cm^3 in the smooth field and ~0.259 cm^3/cm^3 in the rough field during the time of radiometric measurements. The soil temperature T_S was also uniform down to the same depth and measured to be ~20°C in both fields. The measured $T_{BP}(\theta)$ variation with θ for the smooth field at all three frequencies was similar to that reported for the sandy loam field [10]-[11]. Although there was not much difference in both T_S and W between the two fields, $T_{BP}(\theta)$'s measured over the rough field were much higher than those over the smooth field for $\theta \leq 50°$. This increase in T_B with surface roughness was previously observed and reported by Newton and Rouse [3].

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Another feature caused by surface roughness was the change in the rate of increase or decrease in $T_{BP}(\theta)$ with θ. The observed rate of change in $T_{BP}(\theta)$ with θ was smaller for the rough field compared to that for the smooth field.

Figure 3 shows the variation of the normalized $T_{BH}(\theta)$ at $\theta = 20°$ with W for all three different fields. Plots a, b, and c again denote results for different frequencies. The W values for 1.4 GHz measurements are averages over the 0–2.5 cm layer, while those for 5 GHz and 10.7 GHz in plots b and c are averages over the 0–0.5 layer. This choice of layer thickness is based on the calculations of Mo et al. [15] that the radiometric moisture sampling depth is approximately 0.06–0.1 λ where λ is the wavelength of observation. The normalized brightness temperature $T_{NBH}(\theta)$ is defined as

$$T_{NBH}(\theta) = \frac{T_{BH}(\theta)}{T_S} \tag{1}$$

with T_S measured over the same layer thickness as W. It is quite clear from the figure that for each frequency of measurements the data taken over three different fields are separable into three different groups depending on soil type and surface roughness. A linear regression applied to each of the nine data groups gives nine regression slopes and associated standard deviations listed in Table 2. The correlation coefficient and the mean standard error of estimates for $T_{NBH}(20°)$ from each of the nine data groups are also included in the table for comparison. Excellent correlation coefficients of ~0.95 are found between $T_{NBH}(20°)$ and W for the two smooth fields at all three frequencies. The slopes (absolute values) of regression for the rough field are appreciably smaller than those for smooth fields, showing the effect of surface roughness [1]. The slopes of regression at each frequency for the two smooth fields of different soil texture are more comparable, indicating that the rate of the observed $T_{NBH}(20°)$ decrease with W is only weakly dependent on soil texture. This result holds true for θ range of 10°–60° and for the regression between $T_{NBV}(\theta)$ and W also. From Table 1 the smooth silty loam field has a slightly larger surface roughness RMS than that for the

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Table 2
Parameters Derived From Regression Analyses and Radiative Transfer Calculations

Measurement Frequency	Field No.	Roughness Parameters		Individual Data Set (Figure 3)			
		h	Q	Corr. Coeff.	Reg. Slope	Std. Dev. Reg. Slope	Std. Error Estimate
1.4 GHz	1	0	0	0.95	-1.61	0.12	0.026
	2	0.30	0.01	0.97	-1.58	0.13	0.019
	3	0.59	0.12	0.83	-0.65	0.13	0.024
5 GHz	1	0	0	0.99	-1.75	0.07	0.020
	2	0.05	0.15	0.96	-1.48	0.14	0.029
	3	0.58	0.28	0.88	-0.69	0.11	0.025
10.7 GHz	1	0	0	0.97	-1.57	0.08	0.025
	2	0.11	0.20	0.94	-1.25	0.15	0.031
	3	0.60	0.30	0.81	-0.59	0.13	0.029

smooth sandy loam field. This difference in roughness could be the cause of the slightly smaller slopes observed over the smooth silty loam field at all three frequencies.

The approach adopted in the past to quantify the soil texture effect was to express the W's in terms of percent field capacity [5]-[7]. To see if this same approach is applicable to our data, we estimated the field capacities of the two different soils in Table 1 according to the formulas of Schmugge [5] and plotted $T_{NBH}(20°)$ against W in percent field capacity in Figure 4a, b, and c for three different frequencies. Linear regression analysis applied to individual and composite data groups results in the slopes and correlation coefficients indicated in the figure. Although the data points measured over two different soils are brought together, the regression slopes at all three frequencies for the silty loam field are steeper than those for the sandy loam field, suggesting an overcorrection from the field capacity approach. It is quite possible that the aircraft data [5] were normally obtained from a number of agricultural fields of not only two but many different textures,

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and that differences in slopes resulting from the field-capacity normalization approach could be masked by the scatter in the data points caused by many different surface roughness conditions.

Laboratory measurements [13], [14], [16] have shown that the variation of the real part of dielectric permittivity ϵ' with W depends on soil type. After a slow rise with W up to a transition moisture content [14] depending on soil texture, ϵ' increases rapidly with W. The rate of ϵ' increase with W above transition moisture is almost soil type independent. The observed comparable rat of $T_{NBH}(20°)$ decrease with W for the two different soils shown in Figure 3 is consistent with the results of dielectric permittivity measurements. This correspondence between $T_{NBH}(\theta)$ and ϵ' variations with W is further verified in the next sections where results of the measurements and radiative transfer calculations are compared.

4. THE MICROWAVE EMISSION MODEL CALCULATIONS

Several radiative transfer models for soil's thermal microwave emission have been developed in the past few years [9], [17], [18]. Schmugge and Choudhury [19] have compared these models using many different soil temperature and moisture profiles, and found no appreciable differences among them. Therefore, only the model developed by Wilheit will be used in the following discussion. In this model the brightness temperature $T_{BP}(\theta)$ observed outside the soil medium is given by

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

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

where θ and subscript p have been defined in the previous section. T_j and $f_{pj}(\theta)$ are the thermodynamic temperature and the fraction of electromagnetic energy absorbed in the jth layer of the N dielectrically homogeneous layers of the air–soil system, respectively. $R_p(\theta)$ is the reflectivity at air–soil interface. T_{sky} is the brightness temperature equivalent of sky and atmospheric radiation

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incident on the soil which is ~5°K at 1.4 GHz and 5 GHz, and ~6.2°K at 10.7 GHz on a clear day. Both $f_{pj}(\theta)$ and $R_p(\theta)$ are related to the dielectric permittivity of soils, which in turn depends on the soil moisture content W.

Equations (2) and (3) apply strictly to bare fields with a smooth surface. If the surface is rough, they need to be modified as discussed in the next section. Using the ground truth data of soil moisture and temperature profiles collected for the very smooth field (No. 1), $T_{BP}(\theta)$'s were calculated from these equations, employing the empirical relation between dielectric permittivity and W [13] for Elinsboro sandy loam. The calculated $T_{BP}(\theta)$'s were compared with the measured $T_{BP}(\theta)$'s at 1.4 GHz in Figure 5a and b for $\theta = 10°$ and $\theta = 40°$ respectively. A similar comparison between calculated and measured $T_{BP}(\theta)$ values in both vertical and horizontal polarizations at 5 GHz is given in Figure 6. It has been noted before [1] that when there was a rapid change in soil moisture profile, the coherent model of radiative transfer [9] tended to give high (sometimes low) $T_{BP}(\theta)$ values. We have also observed a few similar cases in our calculations, which are enclosed in the rectangular boxes in the figures.

It is clear from Figure 5 that for the 1.4 GHz measurements, the calculated $T_{BP}(\theta)$'s generally followed the measured $T_{BP}(\theta)$'s along the 1:1 line. The mean square deviation from this line is estimated to be ~ ±9°K. The 5 GHz results shown in Figure 6, on the other hand, give higher calculated $T_{BP}(\theta)$'s than the measured ones in both $\theta = 10°$ and $\theta = 40°$. Examinations of calculated and measured $T_{BP}(\theta)$'s at other θ's also indicate a similar trend. The reason for this disagreement between calculated and measured T_B's might be due to soil bulk density, which directly affects the volumetric moisture content W and therefore the soil's dielectric permittivity. For example, the average bulk density in the top 0–5 cm layer measured for the Elinsboro sandy loam soil is 1.25 g/cm^3 with a possible error of 0.10 g/cm^3. This is low compared to the bulk density measurement over a similar field of ~1.38 g/cm^3 in 1980 and of ~1.47 g/cm^3 in 1979 [12]. If the upper bound of the measured bulk density of 1.35 g/cm^3 is used in evaluating W and subsequently the soil

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dielectric permittivity, the recalculated $T_{BP}(\theta)$'s can be brought in line with the measured $T_{BP}(\theta)$'s as shown in Figure 7 for the same θ's of 10° and 40°. The mean standard deviation about the 1:1 line is ~7°K. This clearly shows the importance of a precision measurement of soil bulk density.

A comparison of Figures 5 and 6 also suggests that over the same smooth bare field at high W values the observed $T_{BP}(\theta)$'s at 1.4 GHz are generally higher than those at 5 GHz. This is illustrated more clearly in Figure 8, where the observed $T_{BP}(10°)$'s at 5 GHz are plotted against the corresponding $T_{BP}(10°)$'s at 1.4 GHz for the very smooth field (No. 1). At high $T_{BP}(10°)$'s corresponding to observations over the dry soil, the $T_{BP}(10°)$'s at 5 GHz are higher than those at 1.4 GHz. This is expected due to the fact that when soil is dry, the moisture gradient is large, with driest layer at the top of the surface. The moisture sampling depth at 5 GHz is smaller and therefore the measured $T_{BP}(10°)$'s would be higher than those at 1.4 GHz. At low $T_{BP}(10°)$'s corresponding to observations over wet soil, the measured 5 GHz $T_{BP}(10°)$'s are lower than the 1.4 GHz $T_{BP}(10°)$'s. When the soil is wet, especially many hours after the rain, the moisture profile is rather uniform in the top 15-20 cm layer. Since the real part of dielectric permittivity for a soil water mixture is somewhat smaller at 5 GHz than at 1.4 GHz [17], [20], the $T_{BP}(\theta)$'s observed over bare smooth wet field should be a little higher at 5 GHz than at 1.4 GHz. This is not observed from our measurement results as shown in Figure 8. Earlier measurements by Wang et al. [8], [11] including those at 0.6 GHz frequency also give lowest $T_{BP}(\theta)$'s at 5 GHz when smooth bare fields are wet. Improvement in the current radiative transfer models [9], [17], [18], as well as more experimental observations are needed in order to understand this phenomenon.

5. THE PARAMETERIZATION OF SURFACE ROUGHNESS

The microwave radiometric response to surface roughness of agricultural fields has been explored by Choudhury et al. [1], Choudhury [21], Newton and Rouse [3] and Wang and Choudhury [8]. The major emphasis in these studies was on experimental observations, and the surface roughness model formulation was of phenomenological nature [21]. A rigorous approach requires a proper handling of wave scattering from random rough surface [22] and will not be attempted

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here. It turned out that the available observational results could be interpreted fairly well by the model. In the model the effect of surface roughness was taken into account by modifying Fresnel reflectivities with two additional roughness parameters, a roughness height h and a polarization mixing factor Q, i.e.,

$$R_H{}^R(\theta) = [(1-Q)\,R_H(\theta) + Q\,R_V(\theta)]\exp[-h\,G(\theta)] \tag{4}$$

$$R_V{}^R(\theta) = [(1-Q)\,R_V(\theta) + Q\,R_H(\theta)]\exp[-h\,G(\theta)] \tag{5}$$

Here $R_H{}^R(\theta)$ and $R_V{}^R(\theta)$ are rough field reflectivities in horizontal and vertical polarizations respectively. $R_H(\theta)$ and $R_V(\theta)$ are the corresponding Fresnel reflectivities for a smooth surface. The dependence of the function $G(\theta)$ on θ was taken to be $\cos^2\theta$ by Choudhury [21] and Wang and Choudhury [8]. It is shown in the following that the $\cos^2\theta$ dependence is much too strong. The data set used by Wang and Choudhury was obtained from a relatively smooth field and the sensitivity was not good enough to test θ dependence of surface roughness.

Equations (2), (3), (4), and (5) could be combined together to calculate $T_{BP}(\theta)$'s which could be compared with results of measurements made over fields with a rough surface. This was done for field 2 and field 3 (respectively, the smooth and rough silty loam fields; see Table 1) using the measured soil moisture and temperature profiles and the empirical model of dielectric permittivity [13] for the soil with wilting point of 0.167 cm^3/cm^3. The parameters h and Q, and the function $G(\theta)$ were varied to match the measured data. When $G(\theta) = \cos^2\theta$ was assumed and $h \geq 0.5$, the calculated $T_{BV}(\theta)$'s were found to decrease monotonically with increasing θ, which was not observed from measurements over the rough field as shown in Figure 2. $G(\theta) \cong 1$ was found to be consistent with measurement results over θ range of 10°–60° at all three frequencies. The estimated h and Q values with $G(\theta) = 1$ are given in Table 2 for comparison with the measured RMS surface height variations σ's of the fields in Table 1. It is clear that both h and Q increase with σ as previously concluded by Choudhury et al. [1]. Our results here further indicate that the frequency dependence of Q is strong, while that of h is not.

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Figure 9a and b show the comparison of calculated and measured $T_{BH}(\theta)$'s for fields 2 and 3 at 1.4 GHz for $\theta = 10°$ and $\theta = 40°$ respectively. A similar comparison for both polarizations at 5 GHz is shown in Figure 10. Notice that with the h and Q values given in Table 2, the calculated $T_{BP}(\theta)$'s compared favorably with the measured $T_{BP}(\theta)$'s. The standard deviation of all data points from the 1:1 line is on the order of ~7°K for the 1.4 GHz and ~9°K for the 5 GHz measurements. An analogous result is obtained for the 10.7 GHz measurement with a standard deviation of ~10°K. These two figures also show a much larger $T_{BP}(\theta)$ variation for field 2 than that for field 3, although the range of soil moisture variations is about the same for both fields. This again suggests a reduction in soil moisture sensing sensitivity due to surface roughness pointed out in Section 3.

To show the goodness of fit between calculated and measured $T_{BP}(\theta)$'s at all θ's and frequencies, we define the quantity $\Delta T_{BP}(\theta)$ as

$$\Delta T_{BP}(\theta) = T_{BP}{}^{M}(\theta) - T_{BP}{}^{C}(\theta) \qquad (6)$$

where the calculated and measured $T_{BP}(\theta)$'s are designated by superscripts C and M respectively. For each θ, polarization, and frequency, $\Delta T_{BP}(\theta)$'s are evaluated for all the measured data over field 2 and field 3. The mean values of $\Delta T_{BP}(\theta)$'s are calculated and plotted as a function of θ in Figure 11. The standard deviations of $\Delta T_{BP}(\theta)$'s are on the order of 8–9°K over θ range of 10°–60°, comparable to those in Figures 9 and 10. For all frequencies and polarizations, the mean $\Delta T_{BP}(\theta)$'s are $\leq 2°K$ and their variations with θ are small over θ range of 10°–50°, indicating an adequate surface roughness model given by Equations (4) and (5). The nearly constant separation of ~3°K between the vertically and horizontally polarized $\Delta T_{BP}(\theta)$'s over θ range of 10°–50° at 10.7 GHz is most likely due to the existance of a constant bias in either one or both of the two data sets of different polarizations arising from the sensor calibrations.

6. DISCUSSION

One of the critical elements in the field experiment discussed above is the measurement of the soil's bulk density. The determination of the soil bulk density has a significant bearing on the

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interpretation of the experimental results, because it directly affects the estimates of volumetric moisture content W and therefore the dielectric permittivity of a soil-water mixture. The average dry bulk density in the top 0–2.5 cm layer measured in 1981 for the smooth sandy loam field was 1.25 g/cm^3 as compared to 1.47 g/cm^3 measured for a similar field in 1979 [11], although both fields were prepared in the same way a few months before the actual measurements took place. The low bulk density measured in 1981 could be the main reason for the calculated brightness temperature T_{BP}'s at 5 GHz and 10.7 GHz being higher than the measured ones for that smooth field. On the other hand, the 1979 radiometric data at 5 GHz compared favorably with radiative transfer calculations using the measured soil moisture and temperature profiles only when surface roughness height h = 0.06 and polarization mixing factor Q = 0.08 were included in the calculations [11]. This clearly indicates what the uncertainty in the bulk density determination could do to the interpretation of the experimental results. Accurate measurement of this parameter is needed in any field experiment of the kind discussed here in order to interpret the experimental results more precisely.

A major surprise in the results of our field experiments conducted in recent years [10], [11], [23], including the one reported here, was that T_{BP}'s measured simultaneously at frequencies $\leq$5 GHz over smooth bare fields with high W gave lowest values at 5 GHz and highest values at 0.6 GHz. When this was first found in the 1979 experiment with only 1.4 GHz and 5 GHz radiometers, it was suspected that the effect could be caused by a significant side lobe in the 5 GHz phased-array antenna [10]. In the subsequent experiment of 1980, the phased-array antenna was therefore replaced by two corrugated horns in the 5 GHz radiometer system. It turned out that the lower T_{BP}'s were again observed at 5 GHz than at 1.4 GHz over a smooth field of high W [11]. In our 1981 experiment another radiometer at 0.6 GHz was also included for measurements over the same sandy loam field in the first test site. The measured T_{BP}'s were found to be highest at 0.6 GHz and lowest at 5 GHz when the field soil was wet [22]. This appeared to be supported by a similar bare field measurement at 0.775 GHz and 1.4 GHz made by Njoku and O'Neill [24]. They

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found that T_{BP}'s were lower at 0.775 GHz than at 1.41 GHz when W's were ≤ 0.05 cm^3/cm^3. Around W $\cong$ 0.10 cm^3/cm^3 the measured T_{BP}'s at 0.775 GHz and 1.41 GHz were about equal. Unfortunately, they did not have measurements for W $\gtrsim$ 0.14 cm^3/cm^3. If the regression slopes of their T_{BP} vs W plots were extended beyond W > 0.10 cm^3/cm^3, the T_{BP}'s at 0.775 GHz would be higher than those at 1.41 GHz. This observed radiometric response at frequencies $\leq$ 5 GHz should be examined more closely both theoretically and experimentally in the future.

7. SUMMARY

Three bare fields of different surface roughnesses and soil textures were prepared for a soil moisture remote sensing experiment with 1.4 GHz, 5 GHz, and 10.7 GHz microwave radiometers. The major conclusions resulting from this experiment are as follows.

- The rate of decrease in the observed brightness temperature with soil moisture content is similar for soils of different textures. The soil texture effect is reflected in the difference of the regression line intercepts at the brightness temperature axis.

- The effect of surface roughness is to increase the soil's thermal microwave emission and decrease the slope of the regression between a soil's emissivity and moisture content. This effect is more pronounced the rougher the soil surface.

- A simple phenomenological surface roughness model with two parameters, roughness height and polarization mixing factor, appears to fit the observed data well.

- For a smooth bare field the observed brightness temperature at 5 GHz is smaller than that at 1.4 GHz when the field soil is wet. Since the dielectric permittivities measured at these two frequencies are comparable, the observed phenomenon can not be accounted for by the current radiative transfer model (e.g. Wilheit, 1978).

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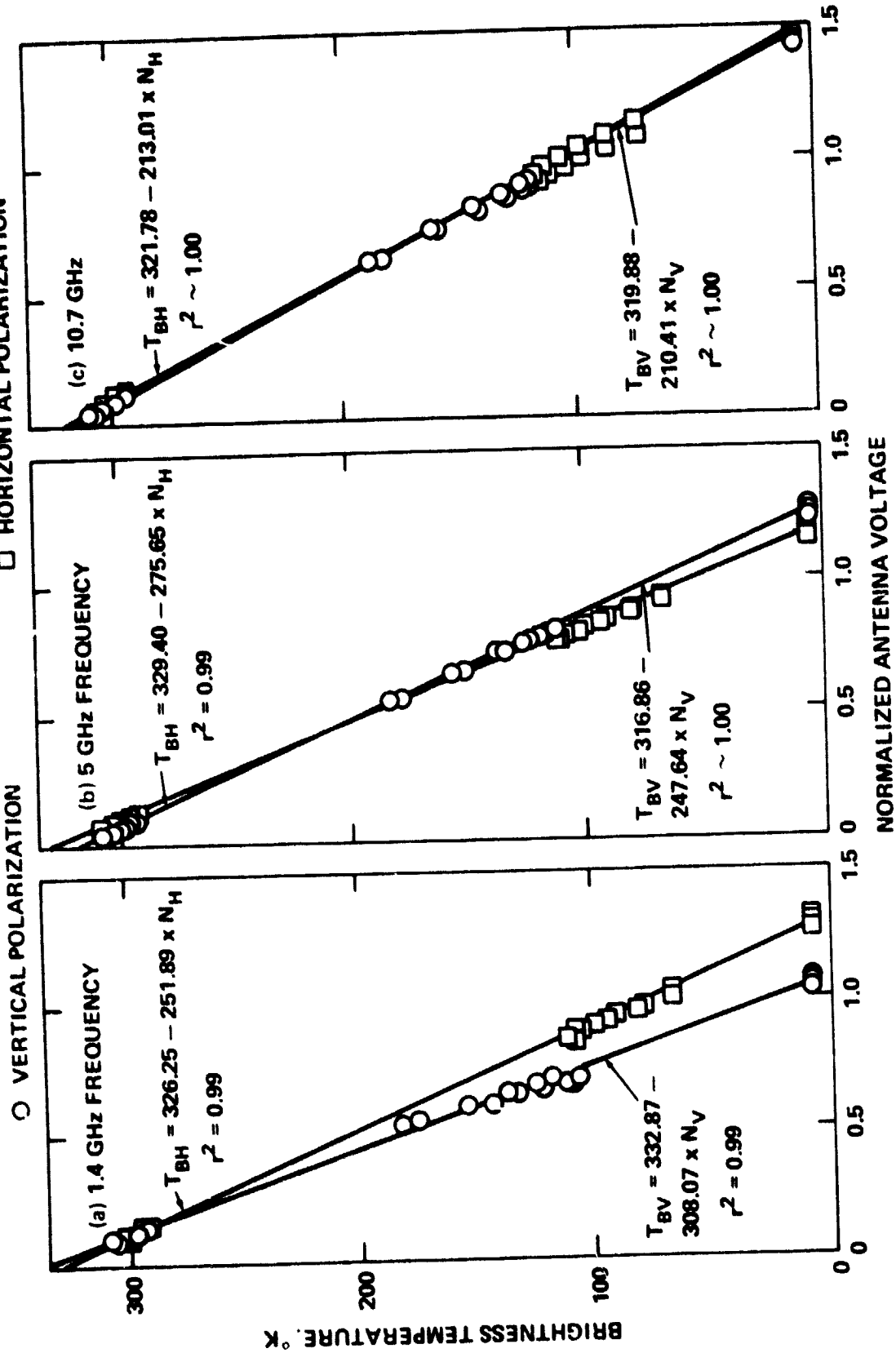

Figure 1. The Calibration Results of Microwave Radiometers at (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz Frequencies.

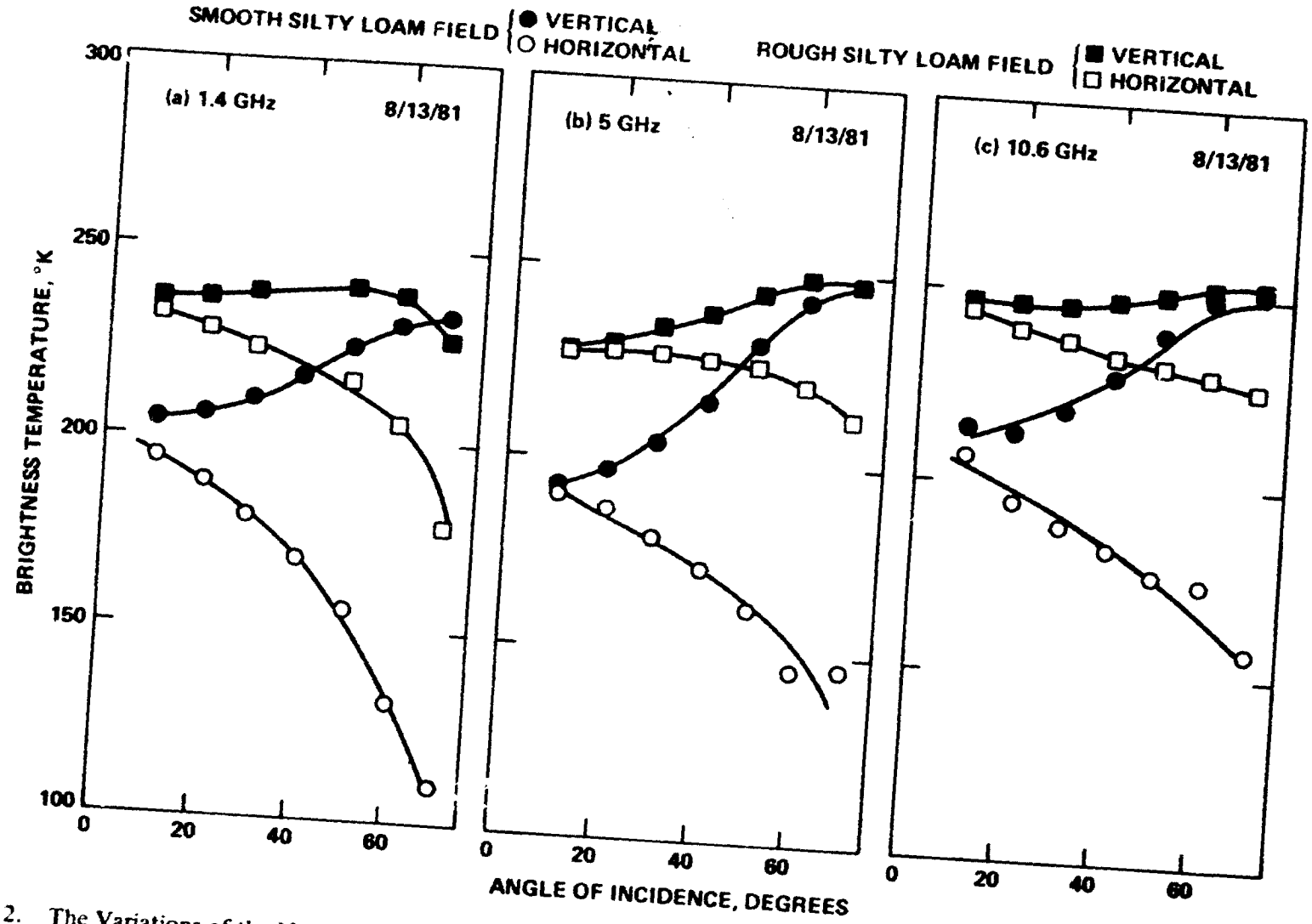

Figure 2. The Variations of the Measured Brightness Temperatures as a Function of Incidence Angle for (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz Frequencies. The Soil Temperature for Both Smooth and Rough Field was ~ 20°C. The Volumetric Soil Moisture Content for the Smooth Field was ~ 0.250 cm^3/cm^3 and for the Rough Field was ~ 0.259 cm^3/cm^3 in the Top 0–10 cm Layer.

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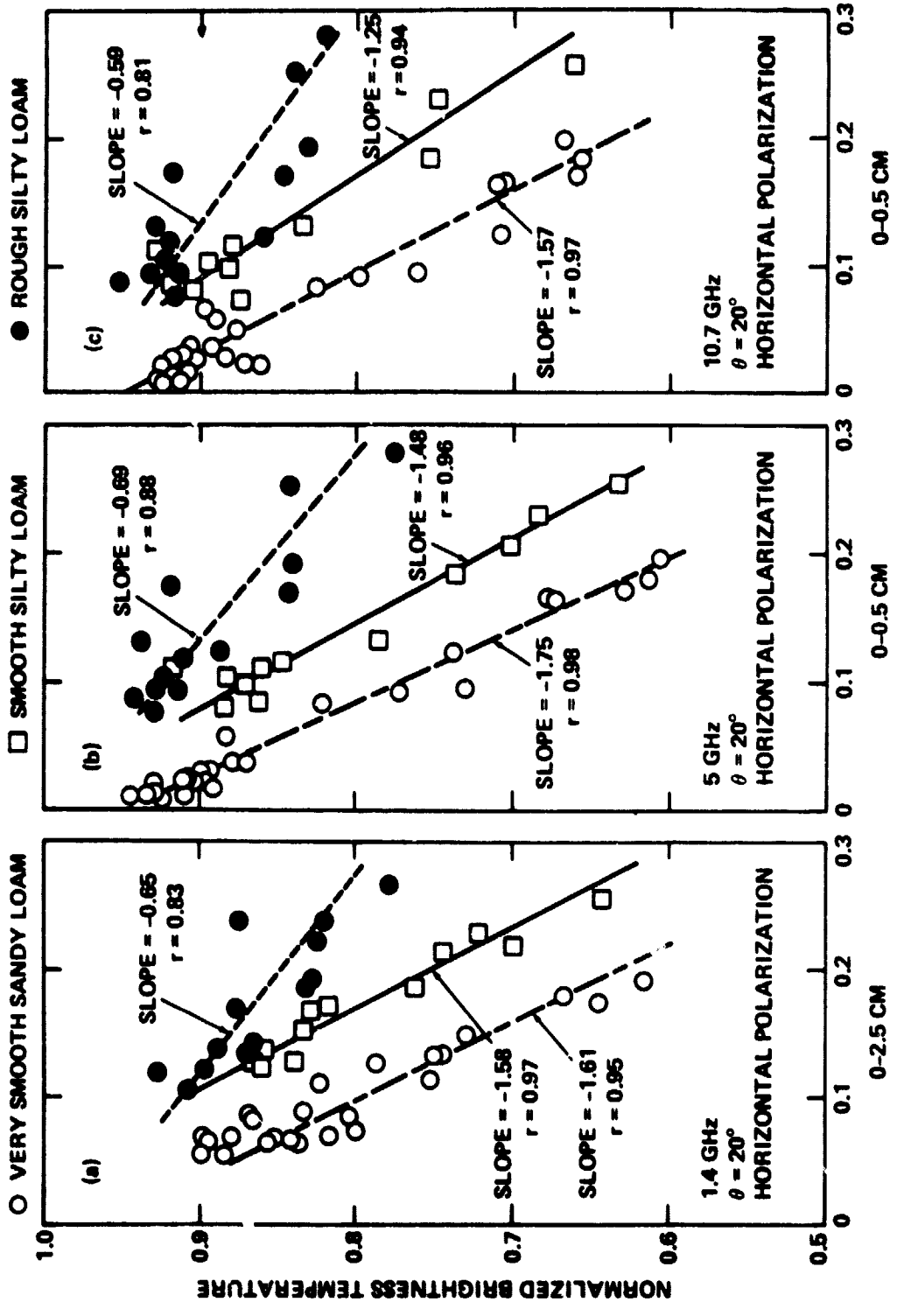

Figure 3. The Variations of the Normalized Brightness Temperature with Volumetric Water Content for (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz Measurements. Data from Three Fields of Different Soil Texture and Surface Roughness are Represented by Different Symbols.

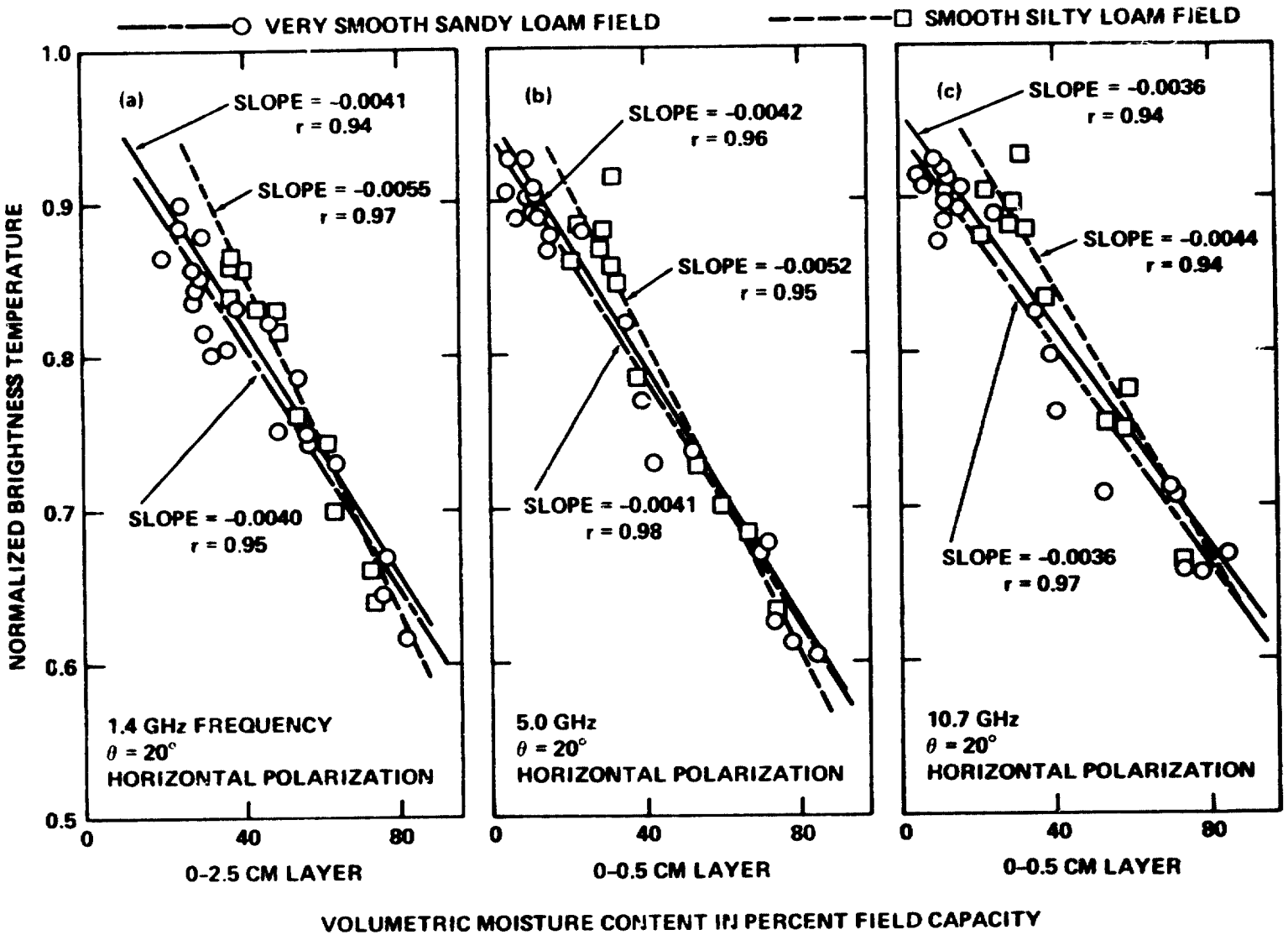

Figure 4. The Functional Dependence of the Normalized Brightness Temperature on Volumetric Water Content Expressed in Percent Field Capacity for the Two Smooth Fields with Different Soil Textures: (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz. The Solid Lines are Regression Results of the Composite Data.

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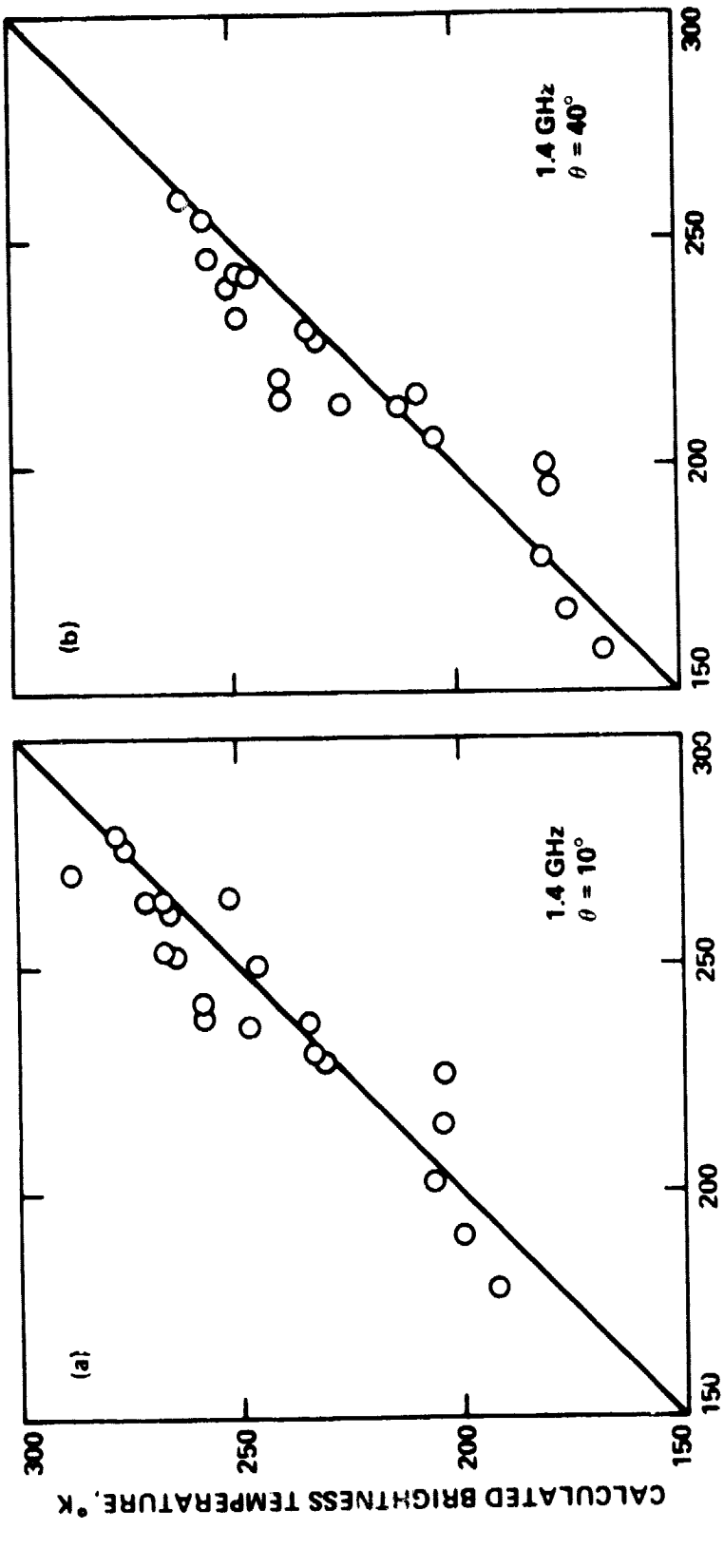

Figure 5. A Comparison of the Calculated and Measured Brightness Temperatures at 1.4 GHz for (a) 10° and (b) 40° Incidence Angles. The Data are Derived from the very Smooth Sandy Loam Field Only.

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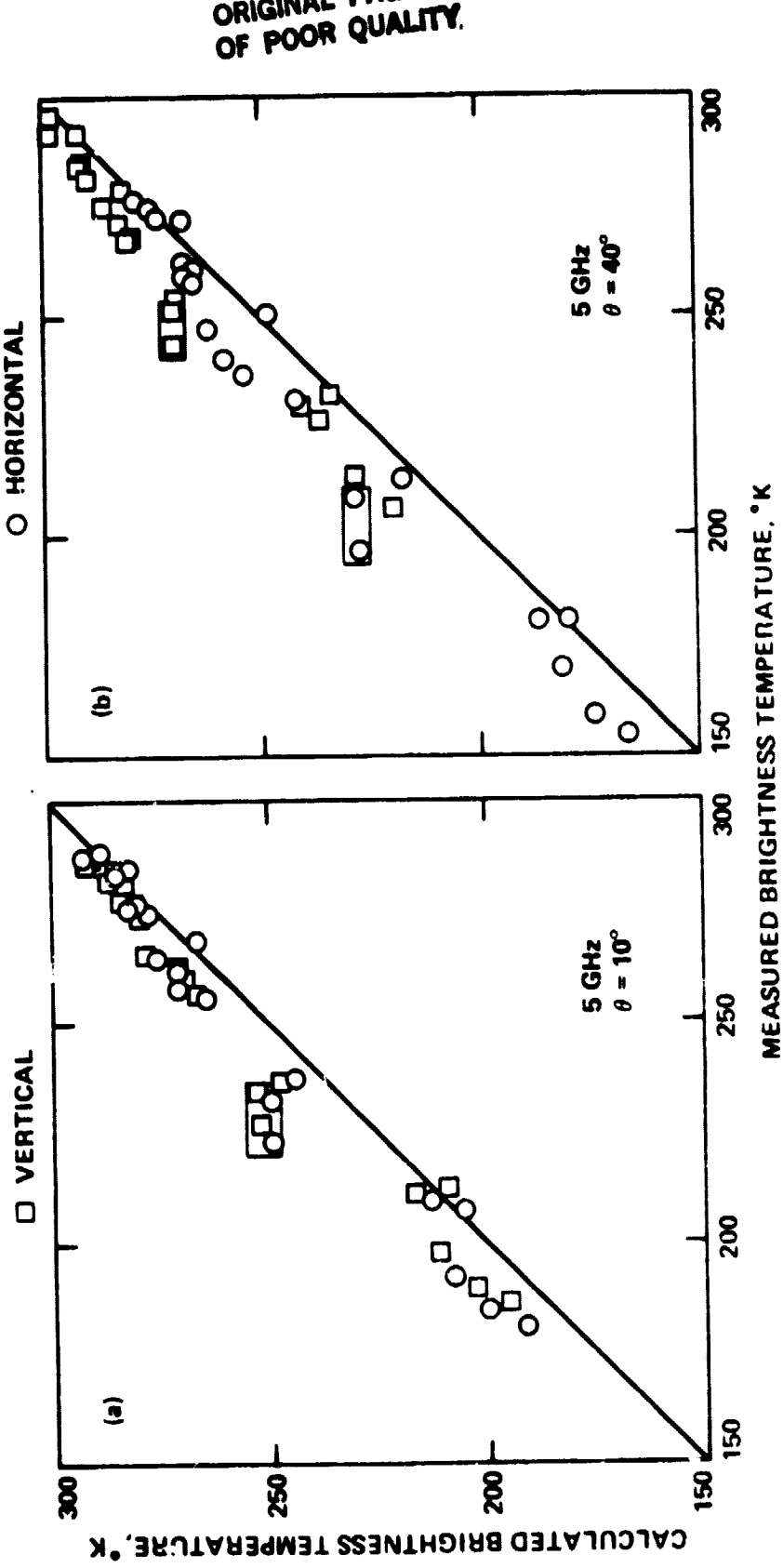

Figure 6. A Comparison of the Calculated and Measured Brightness Temperatures at 5 GHz for (a) 10° and (b) 40° Incidence Angles. The Data at Both Vertical and Horizontal Polarizations are Derived from the very Smooth Sandy Loam Field Only. The Data Points Enclosed in the Rectangles are Explained in the Text.

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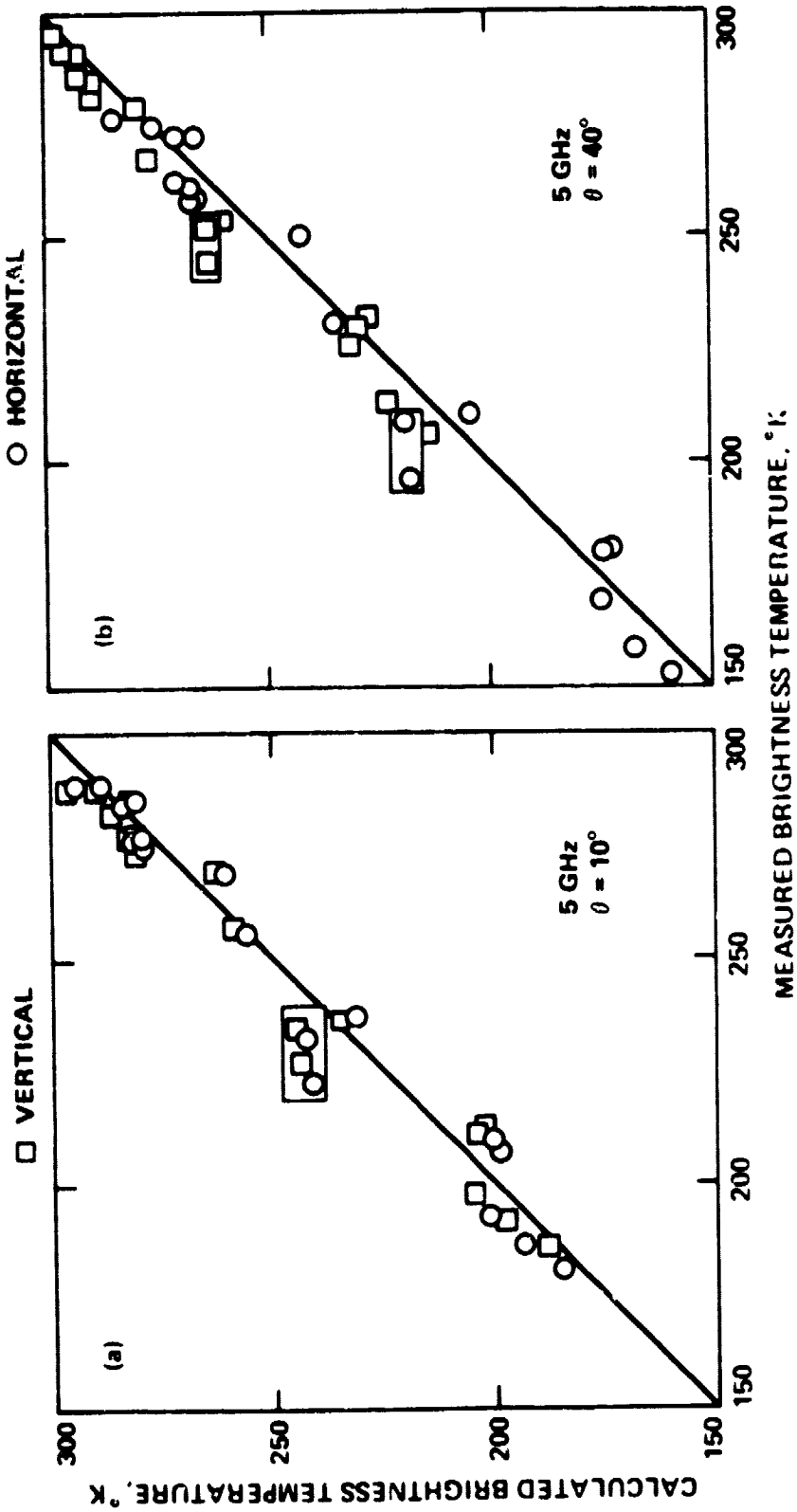

Figure 7. A Comparison of the Calculated and Measured Brightness Temperatures at 5 GHz for (a) 10° and (b) 40° Incidence Angles when the Upper Bound of the Measured Soil Bulk Density is Used in Soil Moisture Estimates and therefore in Radiative Transfer Calculations.

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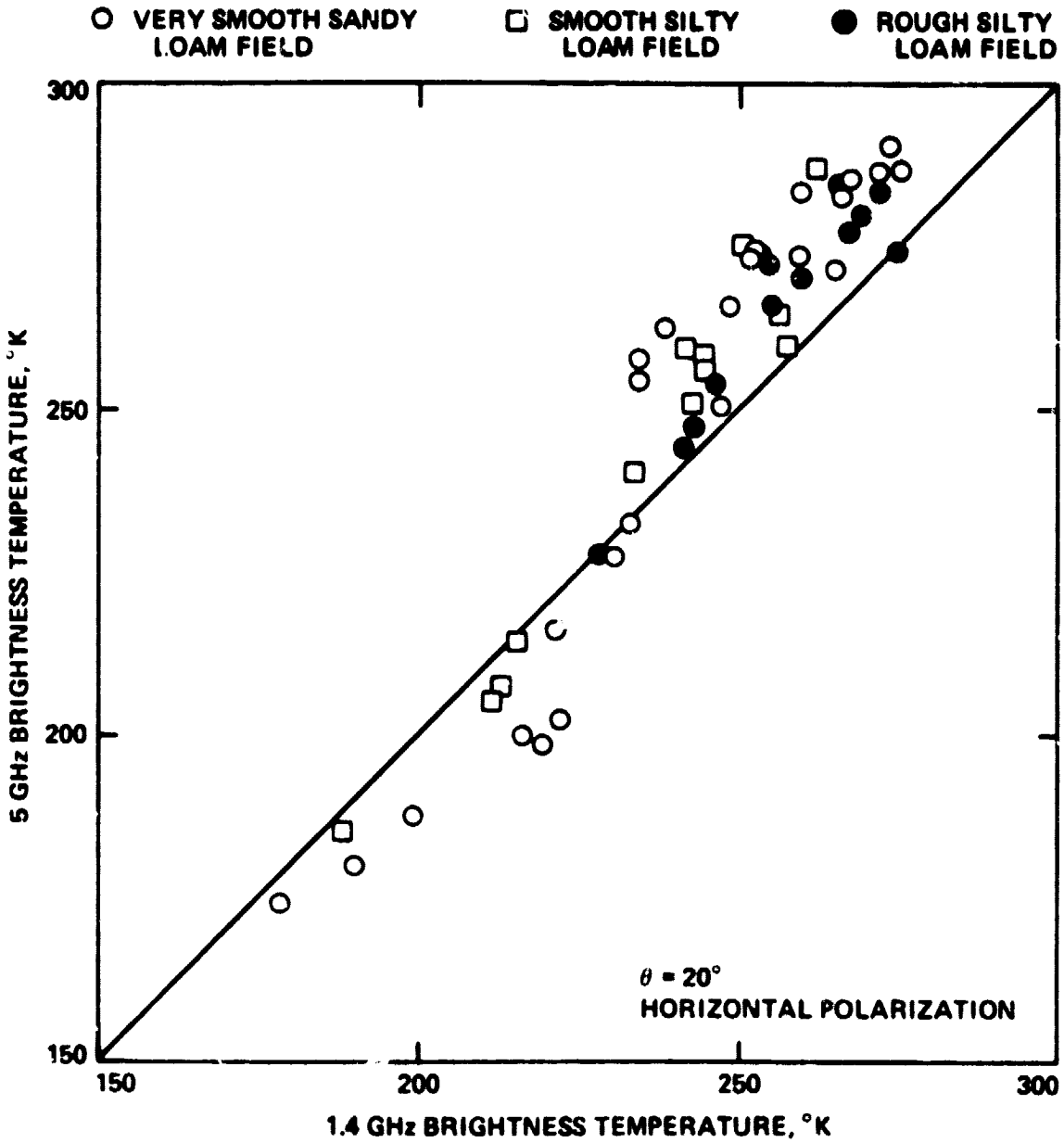

Figure 8. A Comparison of the Measured Brightness Temperatures at 1.4 GHz and 5 GHz for All Three Different Fields. Data at 20° Incidence Angle and Horizontal Polarization are Used.

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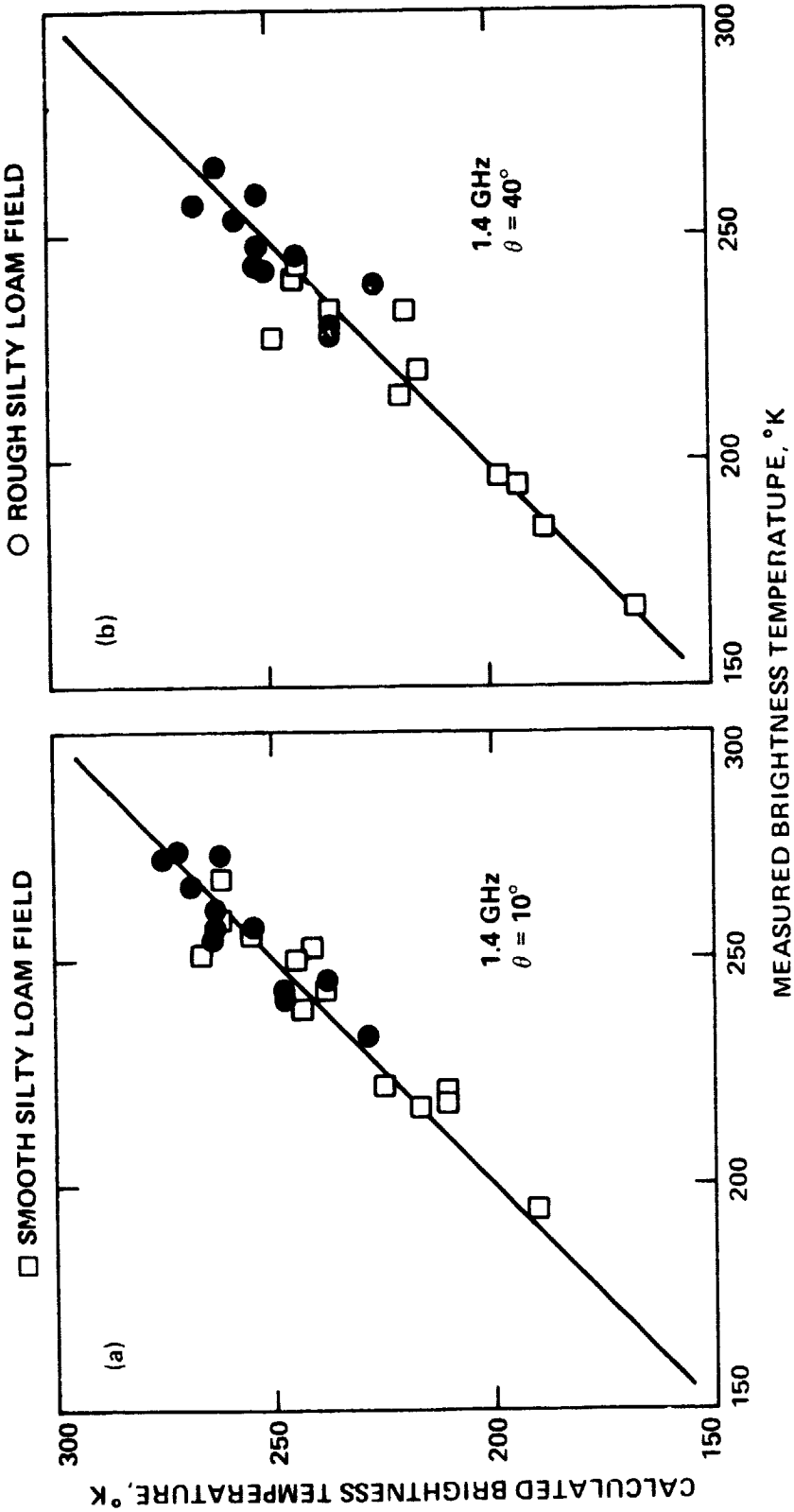

Figure 9. A Comparison of the Calculated and Measured Brightness Temperatures at 1.4 GHz for (a) 10° and (b) 40° Incidence Angles. Horizontally Polarized Data from Both Silty Loam Field are Used in the Comparison.

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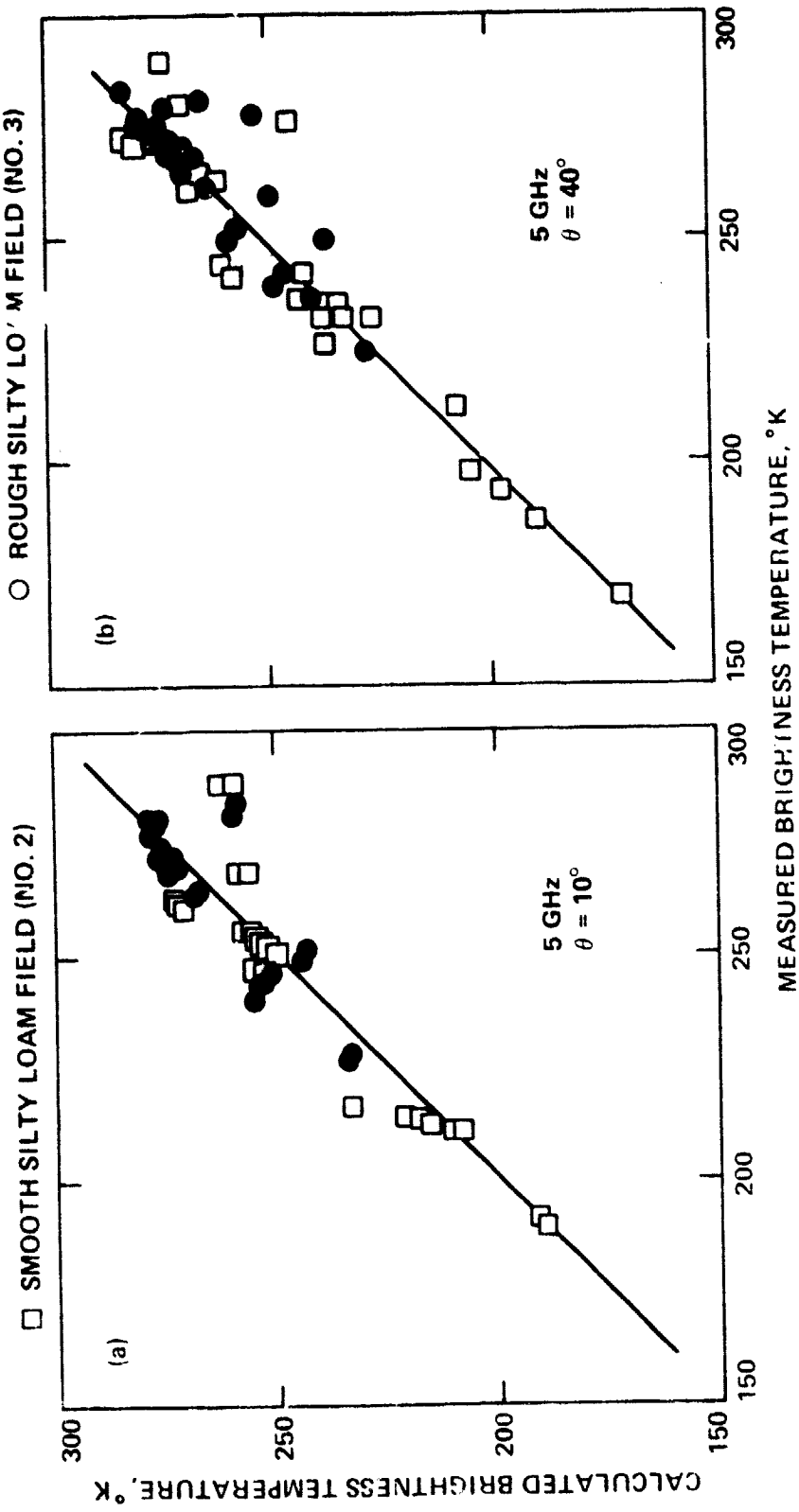

Figure 10. A Comparison of the Calculated and Measured Brightness Temperatures at 5 GHz for (a) 10° and (b) 40° Incidence Angles. Data Obtained from Both Silty Loam Fields in Both Polarizations are Used in the Comparison.

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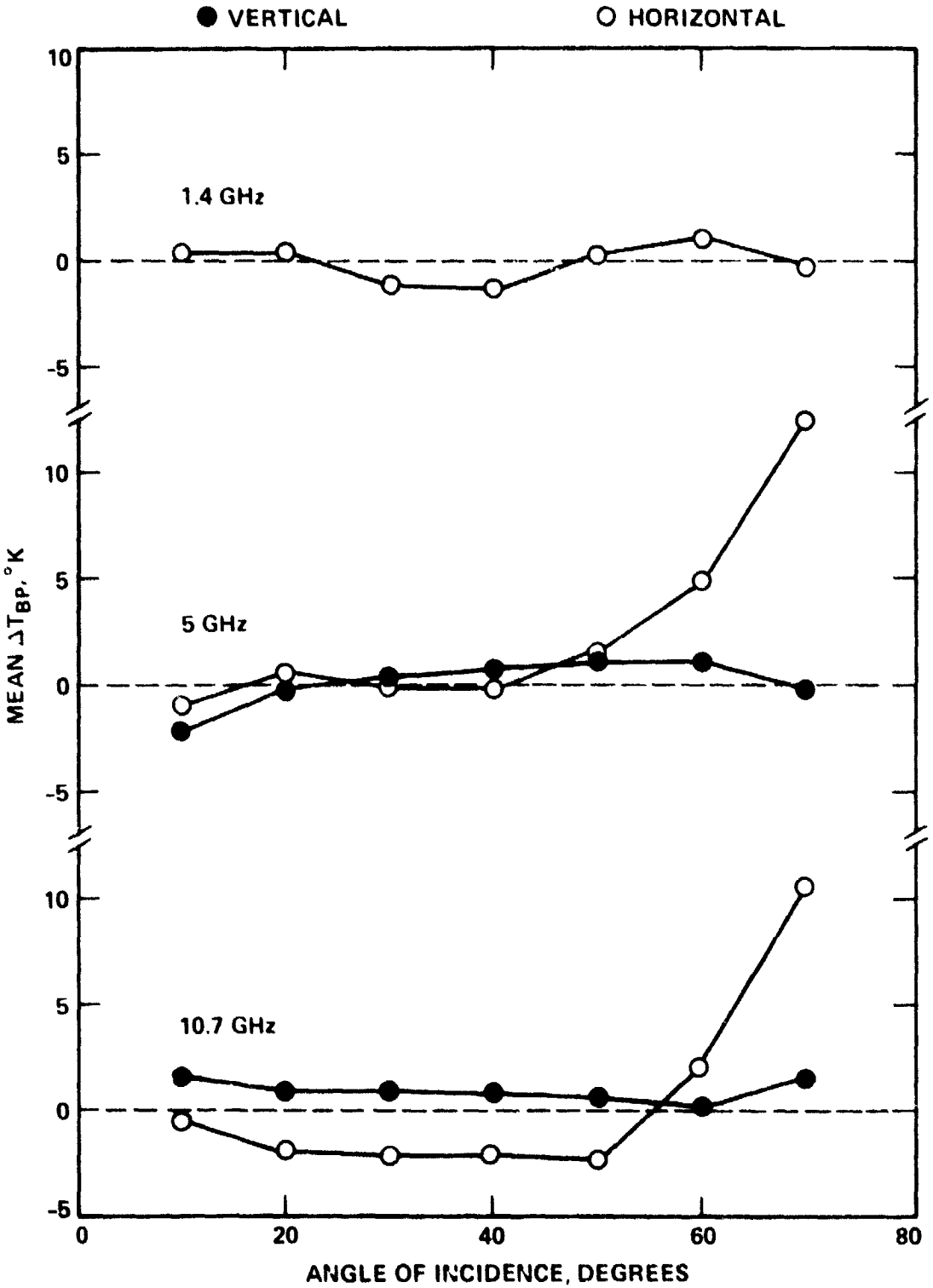

Figure 11. The Variation of the Average Difference Between Calculated and Measured Brightness Temperatures with Angles of Incidence.

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FIGURE CAPTIONS

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