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## Thermal Microwave Emissions from Vegetated Fields: A Comparison Between Theory and Experiment

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A COMPARISON BETWEEN THEORY AND EXPERIMENT

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**ABSTRACT**

The radiometric measurements over bare field and fields covered with grass, soybean, corn, and alfalfa were made with 1.4 GHz and 5 GHz microwave radiometers during August-October 1978. The measured results are compared with radiative transfer theory treating the vegetated fields as a two-layer random medium. It is found that the presence of a vegetation cover generally gives a higher brightness temperature  $T_B$  than that expected from a bare soil. The amount of this  $T_B$  excess increases with increase in the vegetation biomass and in the frequency of the observed radiation. The results of radiative transfer calculations generally match well with the experimental data. However, a detailed analysis also strongly suggests the need of incorporating the soil surface roughness effect into the radiative transfer theory in order to better interpret the experimental data.

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## THERMAL MICROWAVE EMISSION FROM VEGETATED FIELDS: A COMPARISON BETWEEN THEORY AND EXPERIMENT

### 1. INTRODUCTION

A considerable effort has been devoted to the remote measurements of soil moisture content by passive microwave sensors in recent years. Ground measurements by truck-mounted microwave radiometers were conducted by Newton (1), Njoku and Kong (2), and Wang et. al. (3). Schmugge (4) and Schmugge et. al. (5,6) reported results from a series of measurements by airborne multi-frequency microwave radiometers. At satellite altitudes, correlation studies between the brightness temperatures as measured by radiometers aboard Nimbus 5 and Skylab and surface soil moisture contents have been made by Eagleman and Lin (7), MacFarland (8), Schmugge et. al. (9), and MacFarland and Blanchard (10). Results from these measurements and studies strongly suggest the potential of using microwave radiometers for remote soil moisture estimation. However, the major emphasis from these reports was on bare soil measurements. The effect of vegetation cover had been explored only rarely. For example, Newton (1) had briefly discussed the effect of vegetation cover on the brightness temperature based on the simple model calculation of Sibley (11).

In this paper, the radiometric measurements over bare fields as well as fields covered with corn, soybean, alfalfa, and grass are reported. The measurements were made with radiometers at 1.4 GHz and 5 GHz frequencies during August-October of 1978. The data obtained showed a definite effect of vegetation cover on the measured brightness temperature when the water content of the vegetation canopy was  $\geq 0.1 \text{ gm.cm}^{-2}$ . For a given soil moisture content  $\geq 10\%$  by dry weight, the presence of the vegetation was to increase the brightness temperature of the scene. The amount of this increase in the brightness temperature was larger for higher vegetation water content. In addition, the 5 GHz results were generally observed to show a larger effect due to vegetation than the

1.4 GHz results. A radiative transfer theory (12, 13, 14) is applied to the soil-vegetation system in which the vegetation layer is modelled by a dielectric whose permittivity consists of a mean and a randomly fluctuating component. The randomly fluctuating component is characterized by correlation functions which are Gaussian horizontally and exponential vertically. It is found that the theoretical model can account for most of the observed effects due to vegetation cover.

## 2. THEORETICAL BACKGROUND

The theoretical model used for comparison with the experimental results in the following sections is extracted from a series of theoretical works previously developed by Tsang and Kong (12, 13, 14). Therefore, only a brief description of the formulation will be given here. Basically, a ground surface covered with a layer of vegetation is treated as a two-layer random medium shown in Figure 1. The soil is located at  $z \leq -d$  and is characterized by soil temperature  $T_2$  and complex dielectric permittivity  $\epsilon_2$ . The vegetation layer has a height of  $d$ , temperature of  $T_1$ , and a medium permittivity function  $\epsilon_1(\vec{r})$ ,  $\vec{r}$  being the position vector.  $\epsilon_1(\vec{r})$  can be written as (12)

$$\epsilon_1(\vec{r}) = \epsilon_{1m} + \epsilon_{1f}(\vec{r})$$

$$\epsilon_{1m} = \epsilon'_{1m} + i\epsilon''_{1m}, \epsilon'_{1m} \gg \epsilon''_{1m} \quad (1)$$

$\epsilon_{1m}(\vec{r})$  is the mean of  $\epsilon_1(\vec{r})$ ;  $\epsilon'_{1m}(\vec{r})$  and  $\epsilon''_{1m}(\vec{r})$  are its real and imaginary parts, respectively.  $\epsilon_{1f}(\vec{r})$  is the fluctuating part of  $\epsilon_1(\vec{r})$  and is described by the correlation function

$$\langle \epsilon_{1f}(\vec{r}_1) \epsilon_{1f}(\vec{r}_2) \rangle = \delta \epsilon'_{1m} \exp \left[ -\frac{(x_1 - x_2)^2 + (y_1 - y_2)^2}{\ell_x^2} - \frac{|z_1 - z_2|}{\ell_z} \right] \quad (2)$$

The variance of the fluctuation  $\delta$ , the horizontal correlation length  $\ell_x$ , and the vertical correlation length  $\ell_z$  characterize the randomness of the vegetation medium.

The radiative transfer equation in medium 1, for  $0 < \theta < \pi$ , is

$$\cos \theta \frac{d}{dz} T_j(\theta, z) = \kappa_a T_1 - \kappa_{e_j}(\theta) T_j(\theta, z) + \sum_{\alpha'} \int_0^\pi d\theta' \sin \theta' P_{j\alpha'}(\theta, \theta') \cdot T_\alpha(\theta', z) \quad (3)$$

where  $\kappa_a = 2 \text{Im}(k_1)$ ,  $\text{Im}(k_1)$  being the imaging part of the propagation constant  $k_1$  in medium 1.  $\beta \equiv V$  or  $H$  stands for either vertical or horizontal polarization. The summation  $\alpha'$  is over both polarizations. The scattering phase function  $P_{\beta\alpha'}(\theta, \theta')$  and the extinction coefficients  $\kappa_{e\beta}(\theta)$  for given  $\delta$ ,  $\ell_1$ , and  $\ell_2$  can be found in Tsang and Kong (13).

The boundary conditions are, for  $0 < \theta < \pi/2$ ,

1) at  $z = 0$ :

$$T_j(\pi - \theta, z=0) = t_{01\beta}(\theta) T_{\text{sky } \beta}(\theta_0) + r_{01\beta} T_j(\theta, z=0) \quad (4)$$

where  $T_{\text{sky } \beta}(\theta_0)$  is the sky brightness temperature with polarization  $\beta$  at the observation angle  $\theta_0$  in the air region.  $\theta$  and  $\theta_0$  related by Snell's law.

2) at  $z = -d$ :

$$T_j(\theta, z = -d) = r_{12\beta}(\theta) T_j(\pi - \theta, z = -d) + t_{12\beta}(\theta) T_2 \quad (5)$$

In Eqs. (4) and (5) the transmissivities are denoted by  $t_{01\beta}$  and  $t_{12\beta}$  and the reflectivities by  $r_{01\beta}$  and  $r_{12\beta}$ .

The radiative transfer equation (3) subject to the boundary conditions (4) and (5) can be solved by using Gaussian quadrature method (14). The brightness temperature  $T_{B\beta}(\theta_0)$  as observed by a radiometer over a vegetated field is then given by

$$T_{B\beta}(\theta_0) = t_{01\beta}(\theta_0) T_j(\theta_0, z=0) + r_{01\beta}(\theta_0) T_{\text{sky } \beta}(\theta_0) \quad (6)$$

### 3. THE EXPERIMENT

The measurement program was carried out at the Agricultural Research Center test site in Beltsville, Md. during Aug.-Oct. 1978. The crops grown at the test site during the times of the measurements included corn, soybean and alfalfa. These crops were grown separately in small plots surrounded by dense grassland. The size of the plots, the heights, wet and dry biomasses, row separations, temperatures and the conditions of the crops during the measurement periods were summarized in Table 1. The data on the bare field and the surrounding grassland over which the radiometric measurements were made were also included in the table. The size of the bare and the alfalfa fields was small and the radiometric measurements were limited to an incident angle of  $\sim 15^\circ$ . After the corn was cut and removed on October 31, residual dry corn stalks of height up to  $\sim 10$  cm and some small

Table 1  
A Tabulation of Ground Truth Data and Field Descriptions

Vegetation Type	Plot Size	Vegetation Height cm	Biomass, g/cm <sup>2</sup>		Soil Moisture %	Row Separation cm	Soil Temperature °K	Canopy Temperature °K	Air Temperature °K	Remarks
			Wet	Dry						
Corn	15 <sup>m</sup> X 15 <sup>m</sup>	~200	0.415	0.071	23	76	300	303	305	fully grown
Dry Corn	15 <sup>m</sup> X 15 <sup>m</sup>	~200	0.415	0.071	18	76	289	290	290	wilted
Soybean	15 <sup>m</sup> X 15 <sup>m</sup>	~ 70	0.232	0.037	24	50	298	300	301	fully grown
Grass	-	~ 10	0.803	0.569	15	-	289	289	290	-
Alfalfa	6 <sup>m</sup> X 6 <sup>m</sup>	~ 25	0.243	0.098	12	-	288	289	290	-
Cut corn	15 <sup>m</sup> X 15 <sup>m</sup>	~ 10	-	-	14	76	289	-	289	10-cm stalks remain
Bare	6 <sup>m</sup> X 6 <sup>m</sup>	-	-	-	Varies	-	Varies	-	Varies	-

pieces of dry leaves remained on the field. Other than this, the cut-corn field was in every respect similar to a bare soil field. The soil surfaces of all the plots were smooth and the soil types were a mixture of Elkton silty loam and Elinsboro sandy loam.

The microwave sensors used in the measurements were two Dicke radiometers at the frequencies of 1.42 GHz and 5 GHz. The 1.4 GHz radiometer had a phased array antenna with a 3 db beamwidth of  $\sim 15^\circ$  and was used in either horizontal or vertical polarization. The 5 GHz radiometer had two corrugated-horn antennas each with a 3-db beam width of  $\sim 17^\circ$  and could make measurements with both polarizations simultaneously. Both radiometers were mounted on a platform at the tip of a cherry-picker boom which could scan from nadir to zenith. The sensor control panel and the data collection system were housed inside a nearby van. The calibrations of the radiometers were made by measuring the responses to sky radiation and to a 23 cm thick Ecosorb slab at ambient temperature.

Soil temperature and moisture data at depths of 0-1 cm, 1-3 cm, 3-6 cm, and 6-9 cm were collected concurrently with the radiometric measurements. The biomass samples of the vegetation were also acquired close to the time of the radiometric measurements. Generally, the fields with vegetation cover had relatively uniform temperature and moisture profiles.

#### 4. THE EXPERIMENTAL RESULTS

a. The 1.4 GHz results. The measured brightness temperature at incident angle  $\theta_0$  of  $15^\circ$  is shown in Figure 2 as a function of soil moisture content in the top 0-3 cm layer. The brightness temperature is normalized to the soil temperature in the top 0-3 cm layer to reduce the scatter caused by soil temperature variation from one measurement to another. To extend the bare soil data over a wider moisture range, the bare field data obtained during the 1979 experiment at the same test site are also included in the figure. The data points from the 1979 measurements are the averages of the vertically polarized values at  $\theta_0 = 10^\circ$  and  $\theta_0 = 20^\circ$ , which should give a good estimate of the brightness temperature at  $\theta_0 = 15^\circ$ . It is clear from the figure that the normalized brightness temperature  $T_N$  for bare fields measured in 1978 are slightly higher than those measured in 1979. This is partly due to the uncertainty in the system calibrations and partly

due to the different plots used in the two years of measurements. The soil type in the plots used for the 1979 experiment is Elinsboro sandy loam which is lighter compared to the mixture of Elkton silty loam and Elinsboro sandy loam for the plots used in the 1978 experiment. Neglecting such a small difference in the two years of measurements, a linear regression analysis on the combined data set gives a correlation coefficient of  $\sim 0.87$  between  $T_N$  and the soil moisture content  $W$  of the top 0-3 cm layer. For a given  $W$ ,  $T_N$ 's of the vegetated fields are higher than those of the bare soil.

Figure 3 shows the dependence of (vertically polarized)  $T_N$  of  $\theta_0$  for bare soil (with up to  $\sim 10$  cm of corn stalks remained), corn, and soybean. Notice that the soil moisture contents are different from one field to another. Hence, it is difficult to assess quantitatively the effect due to vegetation cover alone on the  $\theta_0$  dependence of  $T_N$ . Qualitatively, however, the presence of the biomass tends to flatten the otherwise steep increase of  $T_N$  with  $\theta_0$ . This flattening of  $T_N$  dependence on  $\theta_0$  is enhanced with the increase in biomass.

b. The 5 GHz results. The field measurements of the brightness temperature as a function of soil moisture content at  $\sim 5$  GHz frequency have not been reported in the literature. The measurements carried out in 1978 were limited to a small moisture range and the results were shown in Figure 4. The 5 GHz measurements carried out in 1979 appears to have a bias of  $\sim 8^\circ\text{K}$  (3) and therefore are not included in the figure for comparison. Judging from the available measurements (1, 3, 5) and theoretical calculations (2), however, the radiometric response at 5 GHz for dry bare soil is not expected to be very different from that at 1.4 GHz and 10.7 GHz. Therefore, assuming that  $T_N$  at  $W = 4\%$  is  $\sim 0.90$  (Figure 2), a straight line is drawn through this point and the bare field data points to approximately represent the functional dependence of  $T_N$  on  $W$  in the top 0-3 cm layer. Clearly, the measured  $T_N$ 's from the grassland and the fields with alfalfa and dry corn are all higher than that expected from a bare soil field.

The  $\theta_0$  dependence of  $T_N$  for bare soil (cut corn field) and dry corn is shown in Figure 5. Note that the soil temperatures for both bare and dry corn fields are the same but the soil moisture contents are different; the bare field is  $\sim 14\%$  and the dry corn field is  $\sim 18\%$ . The  $T_N$ 's for the dry corn field are generally higher than those of the bare field.

c. The effect of vegetation cover implied by the combined 5 GHz and 1.4 GHz results. Figure 6 shows the variations of the observed normalized brightness temperature difference  $\Delta T_N$  at  $\theta_0 = 15^\circ$  with the water content  $W_V$  of the vegetation per unit area. The  $\Delta T_N$ 's were obtained from Figures

2 and 4 at the given values of soil moisture content of the vegetated fields.  $W_V$  in  $\text{gm/cm}^2$  was simply the difference between the wet and dry biomasses listed in Table 1. Two features are observed from this figure. First,  $\Delta T_N$ 's at both 1.4 GHz and 5 GHz increase with  $W_V$ . Secondly, for a given  $W_V$ ,  $\Delta T_N$ 's at 5 GHz are higher than those at 1.4 GHz. For the case of alfalfa (low  $W_V$ )  $\Delta T_N$ 's at 5 GHz is about equal to  $\Delta T_N$  at 1.4 GHz within the error of the measurements. These observed features are consistent with the measurements results of Kirdiashev et. al. (15) and Wang et. al. (3). The dependence of  $\Delta T_N$  on  $W_V$  as shown in the figure, however, is not unique. It also depends on the value of the underlying soil moisture content.

## 5. A COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL RESULTS

The radiative transfer theory summarized in Section 2 is applied in the following to match the experimental data obtained over the vegetated fields. In situ measured ground truth data of soil moisture content  $W$ , soil temperature  $T_2$ , vegetation height  $d$  and vegetation temperature  $T_1$  are used in the theoretical calculations. The relative dielectric permittivity  $\epsilon_2$  of soil with a given  $W$  is determined by the empirical model of Wang and Schmugge (16), based on the soil type and the measured soil density of  $\sim 1.5 \text{ g/cm}^3$ . The total biomass and water content of the vegetations were measured. The permittivity  $\epsilon_1$  of the vegetation layer, the variance  $\delta$ , and the correlation lengths  $\ell_p$  and  $\ell_z$  are entered in the calculations as free parameters to best match the theoretical results with the experimental data. The values of all these parameters are included in Figures 7, 8, and 9 where theoretical curves are compared with the experimental data.

Figure 7, (a) and (b), show the calculated and the measured results of  $T_B$  at 1.4 GHz as a function of  $\theta_0$  for the fully grown corn and soybean.  $W$  and  $T_2$  for both fields were comparable, but the radiometric responses of the two fields measured on the same day are quite different. This difference in radiometric response is mainly due to a different vegetation coverage. The corn field, with a larger biomass per unit area, shows a greater shielding effect than the soybean fields. Both fields give a higher  $T_B$  than that expected from a bare field at the same  $W$ . Inferring from the straight line of Figure 2, a bare field at  $W = 24\%$  would have a  $T_B \simeq 190^\circ \text{K}$  at  $\theta_0 = 15^\circ$ .

Figure 8, (a) and (b), shows a comparison of the measured and the calculated  $T_B$ 's at 1.4 GHz vs.  $\theta_0$  for the dry corn and the bare fields. The bare field is the same corn plot except the dry corn plants have just been cut and removed, leaving  $\sim 10 \text{ cm}$  tall corn stalks (near roots) behind. Note that  $T_2$ 's

for the two fields at the times of radiometric measurements are the same, but  $W$  for the dry corn field is  $\sim 18\%$  as compared to  $\sim 14\%$  for the cut-corn field. The  $T_B$ 's of the dry corn field are generally higher than those of the cut-corn field showing the effect of the vegetation cover, even though the corn plants are fairly dry. The parameters  $\delta$ ,  $\ell_p$  and  $\ell_z$  for both dry corn and bare fields remain the same as those for the fully grown corn field in the calculations of  $T_B$ 's. The height of the vegetation for the cut-corn field is assumed to be 10 cm because of the residual corn stalks. A comparison of the  $\epsilon_1$ 's in the figure reveals that an unusually large imaginary part of  $\epsilon_1$  is required to match the calculated  $T_B$ 's with the measured ones for the bare field. This implies that surface roughness effect may be a more dominant factor affecting the microwave emission from soil than the residual corn stalks. It has been shown by Choudhury et. al. (17) that the presence of surface roughness tends to increase the brightness temperature of soil, similar to the effect of the vegetation cover discussed in this paper.

A comparison of the measured and calculated  $T_B$ 's as a function of  $\theta_0$  at 5 GHz frequency is given in Figure 9, (a) and (b), for the dry corn and bare fields respectively. The values of the parameters  $T_1$ ,  $T_2$ ,  $\epsilon_2$ ,  $\delta$ ,  $\ell_p$ ,  $\ell_z$ , and  $d$  entered in the calculations of  $T_B$ 's for both fields are the same as those used in Figure 8 for the 1.4 GHz case. It is clear that the matching of the theoretical results to the experimental data at 5 GHz is not as good as those shown in Figures 7 and 8 for 1.4 GHz cases. Furthermore, the imaginary part of  $\epsilon_1$ ,  $\epsilon_1''$ , for dry corn required to fit the measured data is considerably small at 5 GHz than at 1.4 GHz. There are two possible reasons for the higher  $\epsilon_1''$  at 1.4 GHz than at 5 GHz required in the theoretical calculations. First, many substances at small  $W$  are observed to have dielectric relaxation in the microwave region shifted toward low frequencies  $< 2$  GHz (18, 19). As a result, it is possible to have  $\epsilon_1''(1.4 \text{ GHz}) > \epsilon_1''(5 \text{ GHz})$  for the dry corn, in contrast to the fresh bulk water where the dielectric relaxation is  $\approx 25$  GHz and  $\epsilon_{\text{water}}''(1.4 \text{ GHz}) < \epsilon_{\text{water}}''(5 \text{ GHz})$  always. However, to fit the radiative transfer theory with the observed results requires  $\epsilon''(1.4 \text{ GHz}) \cong 4\epsilon''(5 \text{ GHz})$  for the dry corn layer. It is not clear that the low frequency dielectric relaxation at small  $W$  alone is responsible for it. A direct laboratory measurement of  $\epsilon''$  at 1.4 GHz and 5 GHz of the dry corn would throw more light on the matter. Secondly, as noted in

Table 1, the corn was planted in rows about 76 cm apart. In the measurements over the dry corn field, a good portion of the bare soil was exposed directly to the radiometers. The surface roughness effect of soil might play a more dominant role than the dry corn under the circumstance. The importance of the surface roughness effect was implied previously in the comparison of theoretical and measured results between dry corn and bare fields at 1.4 GHz (Figure 8). A similar comparison at 5 GHz between the two fields in Figure 9 also gave the same implication. Since the surface roughness effect of soil was not incorporated in the radiative transfer theory used here, the vegetation medium alone was assumed to be responsible in the theoretical calculation to match the data. Consequently, larger  $\epsilon_1''$  at lower frequency was needed because of less absorption and scattering.

## 6. DISCUSSION

The experimental data and theoretical calculations discussed in the previous sections can be summarized in the following. First, at the soil moisture content  $W > 10\%$ , the presence of vegetation cover gives a higher brightness temperature  $T_B$  than that expected from a bare soil. The amount of this  $T_B$  excess generally increases with the increase in vegetation biomass and the frequency of the observed radiation. Secondly, a radiative transfer theory is used to calculate the expected  $T_B$ . A field covered with vegetation is modelled as a layer of medium with a random fluctuating dielectric permittivity on top of the earth characterized with a non-fluctuating dielectric permittivity. With a few parameters to characterize both vegetation and bare soil, results from theoretical calculation match quite well with the observed data. The imaginary part of the relative permittivity  $\epsilon_1''$  for the vegetation cover at 1.4 GHz used in the theoretical calculations was found to decrease from the fully grown corn to dry corn case (in order to match the observation), qualitatively this is consistent with the observed decrease in the corn biomass. A comparison of the measured and the calculated results between soybean and fully grown corn fields also suggests a close relation between  $\epsilon_1''$  and the biomass per unit area. Thirdly, different types of vegetation cover require different sets of values for the variance of permittivity fluctuation  $\delta$  and the correlation lengths  $\ell_p$  and  $\ell_r$ . More experimental data are needed to study the variation of  $\delta$ ,  $\ell_p$  and  $\ell_r$  with the vegetation types.

The  $\epsilon_1$ 's of the vegetation medium used in the theoretical calculations are not derived from the acquired ground truth given in Table 1, because the volume ratio  $V$ 's of the plants to air are not measured. To make an estimate of  $\epsilon_1$  of the fully grown corn field, the measured value of  $V = 0.3\%$  for the dry corn field planted in the same way in 1979 (20) and the ground truth data in Table 1 are entered in the formulas given by Fung and Ulaby (21). This results in an estimated  $\epsilon_1 = 1.10 + i0.00724$ , assuming a value of 4 for the density ratio of the water to solid material of the fully grown corn. The density ratio is not crucial in the approximate estimate of  $\epsilon_1$ . For example, the density ratios of 3 and 5 give  $\epsilon_1 = 1.1 + i0.00821$  and  $\epsilon_1 = 1.09 + i0.00650$  respectively. Both of these estimates are much smaller than the one used in the theoretical calculations of Figure 7(a). One reason for the large difference in  $\epsilon_1$  could be due to the soil surface roughness effect discussed briefly in the previous section. Since the surface roughness effect is not incorporated in the theory, it requires the use of larger  $\epsilon_1$  to match theoretical calculations with experimental results. Another reason could be due to the use of  $V$  value measured for the dry corn. The fully grown corn has a higher water content and is likely to have a higher  $V$  than that for the dry corn. A higher  $V$  would give a larger estimated  $\epsilon_1$  closer to the one given in Figure 7(a). An estimate of  $\epsilon_1$  for dry corn is not made because of the possible shift of dielectric relaxation towards low frequencies for the tightly bound water in corn. The formulas for dielectric relaxation given by Fung and Ulaby (21) may not be valid under the circumstance.

Previous measurements over bare agricultural fields (3, 17) have strongly suggested the presence of the surface roughness effect even though the fields may be relatively smooth. The comparison between theoretical calculations and the experimental results for the dry corn and bare fields discussed in the previous section also implied the existence of the surface roughness effect. Clearly, more work is needed in the development of the radiative transfer theory to include the surface roughness effect in order to interpret the measured results over the vegetated fields more adequately.

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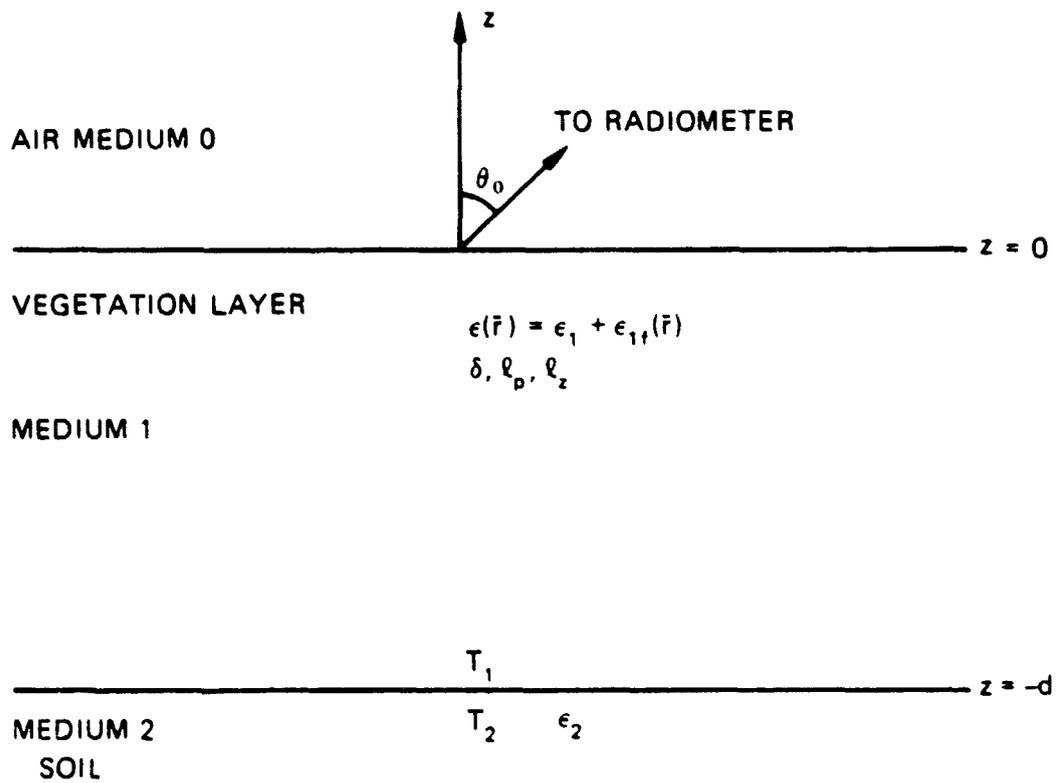


Figure 1. Geometrical configuration of the theoretical model.

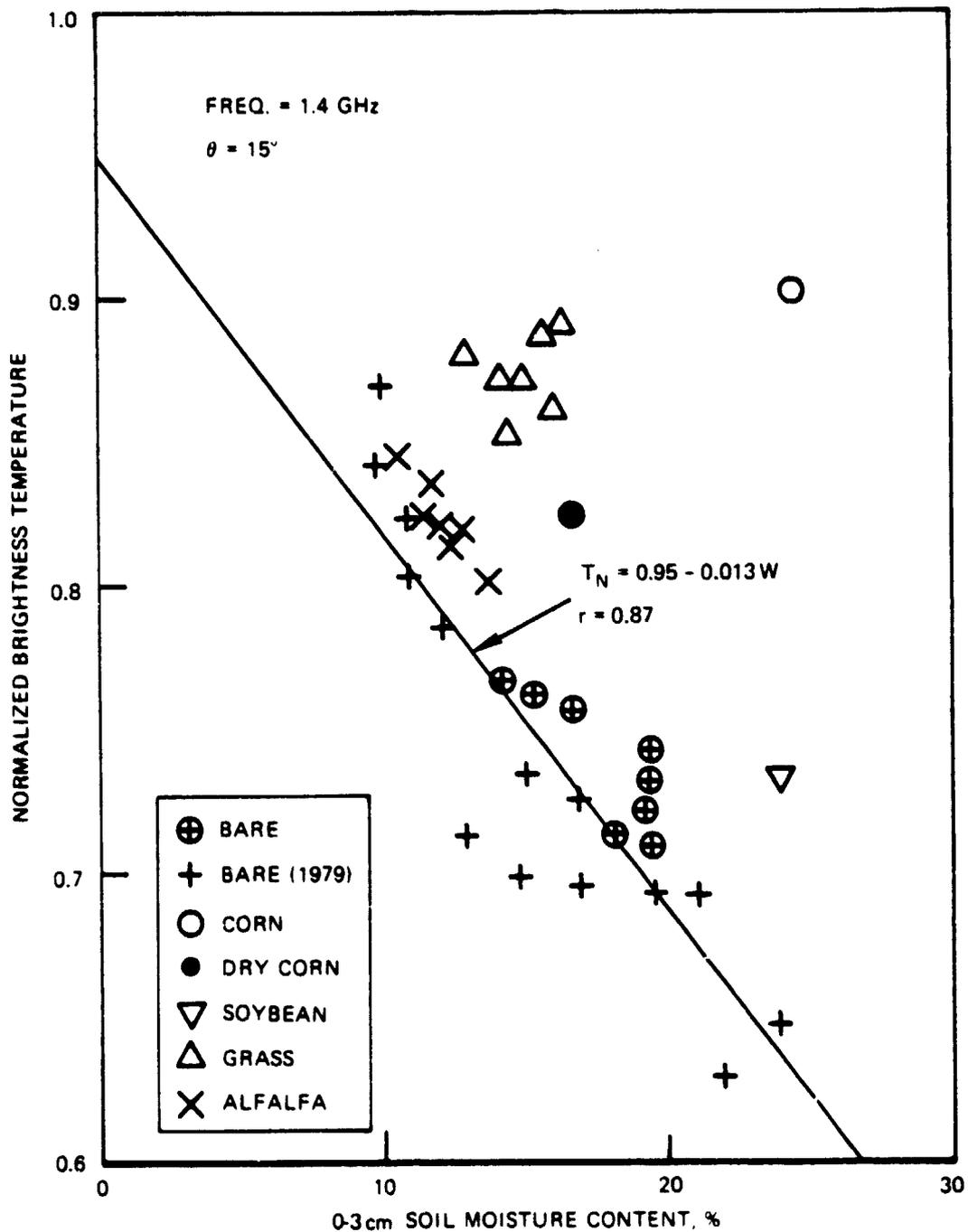


Figure 2. The normalized brightness temperature vs. soil moisture content in the top 0-3 cm layer. The bare soil data of 1979 are obtained from Wang et al. [3]. The regression line is derived for bare field only.

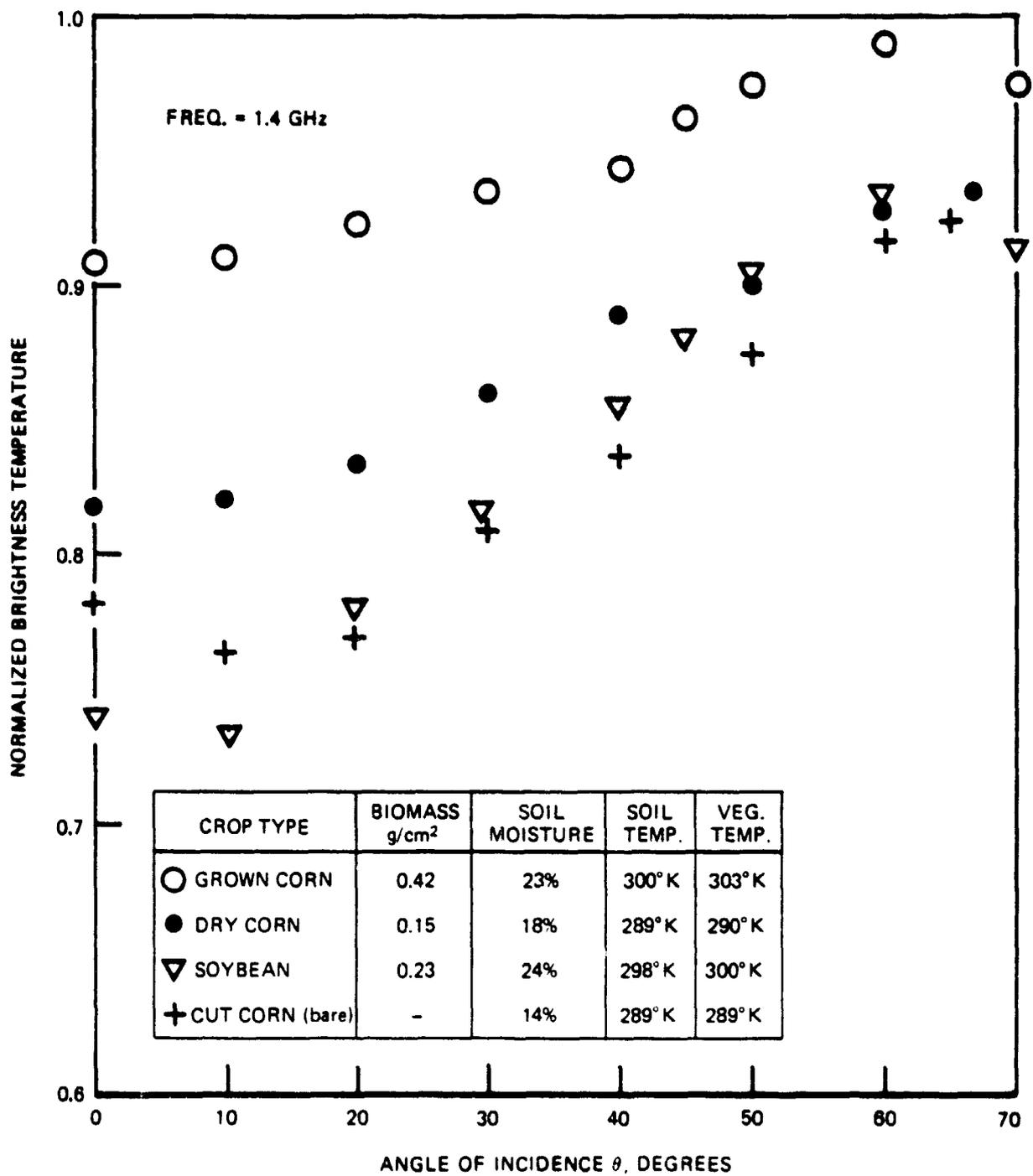


Figure 3. The normalized brightness temperature at 1.4 GHz vs. incident angle for various crops.

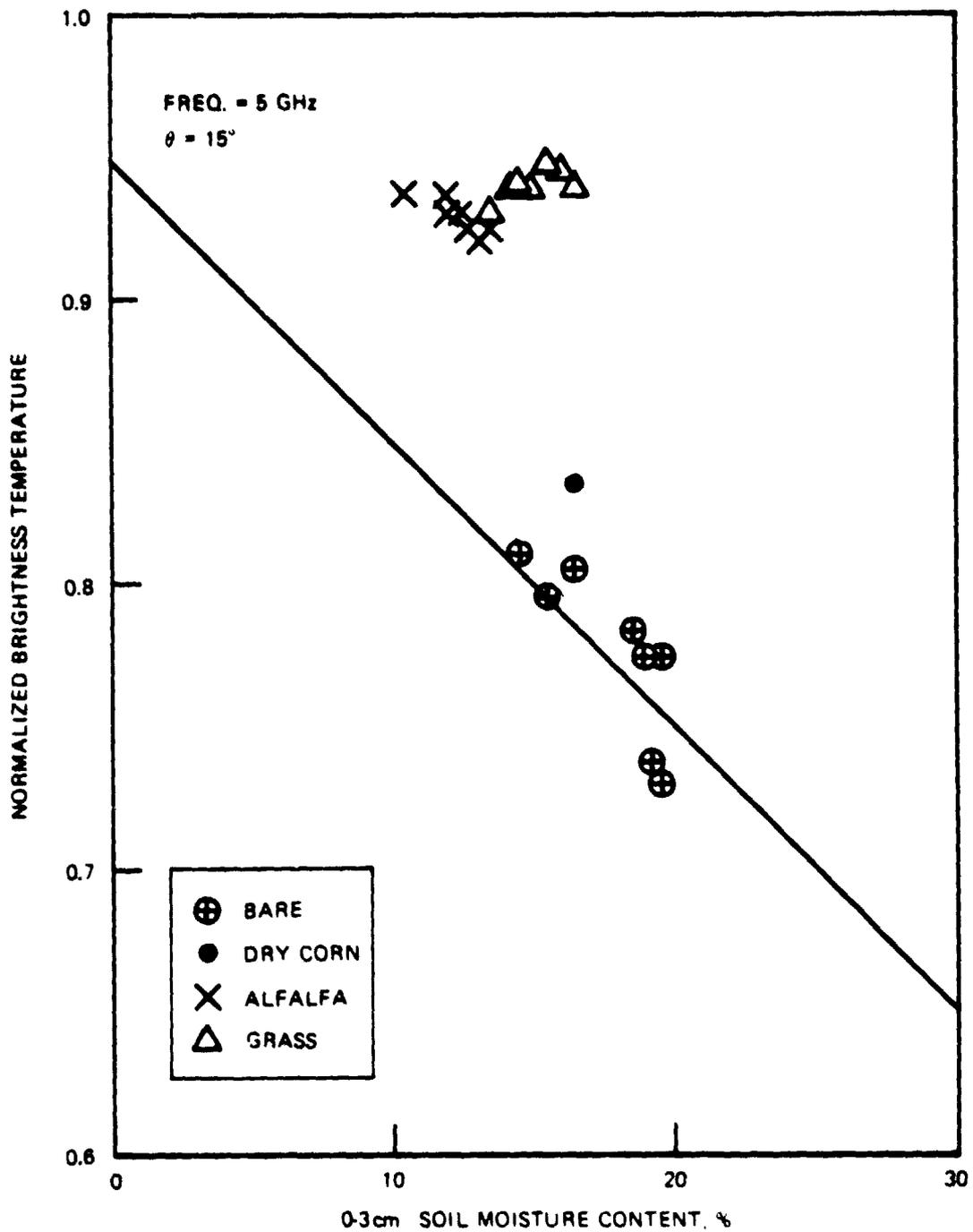


Figure 4. The normalized brightness temperature vs. soil moisture content in the top 0-3 cm layer.

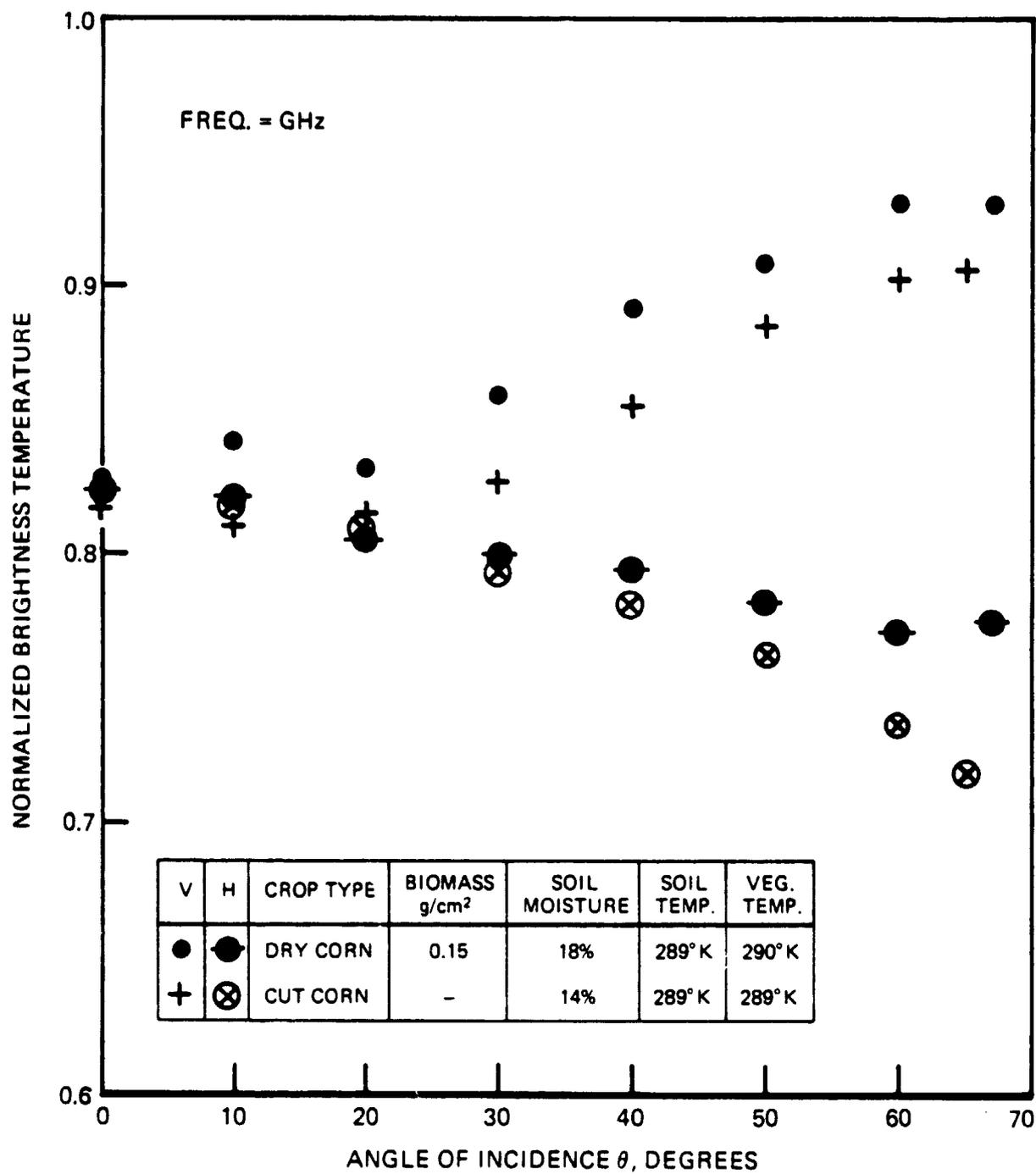


Figure 5. The normalized brightness temperature at 5 GHz vs. incident angle for dry corn and cut-corn fields.

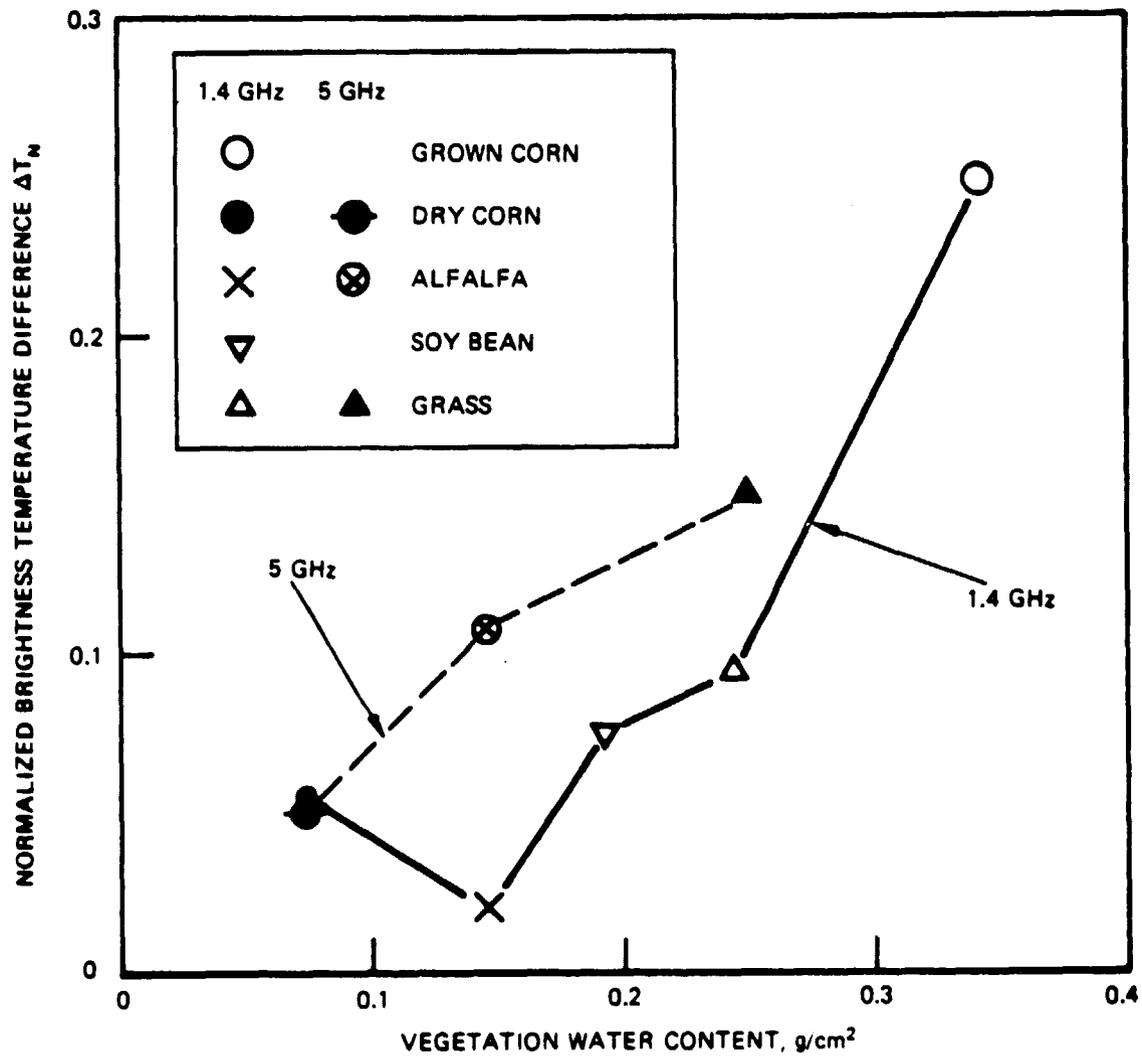


Figure 6. The differences in the normalized brightness temperatures between vegetated and bare fields vs. water content of vegetations.

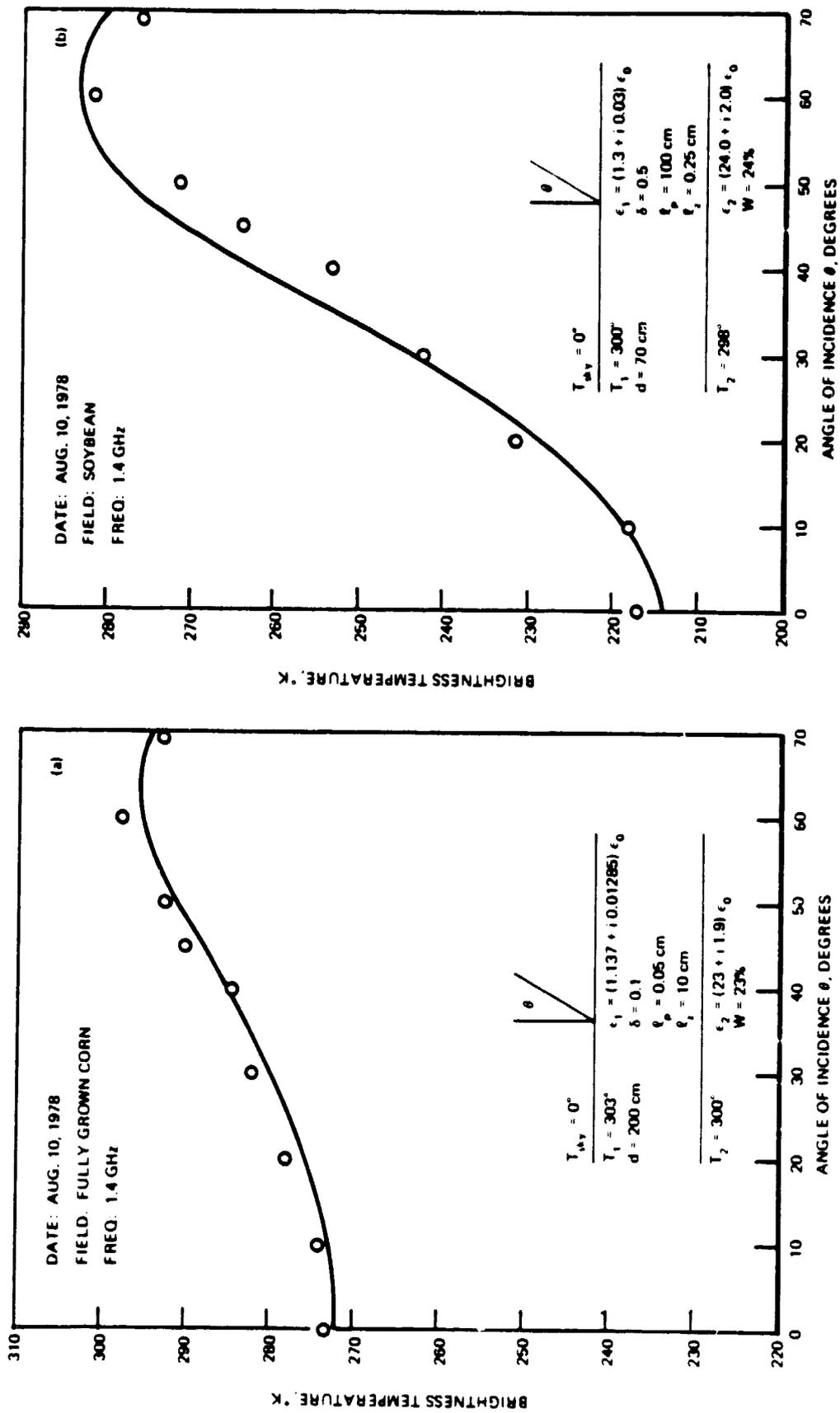


Figure 7. A comparison of the measured and calculated brightness temperatures at 1.4 GHz as a function of incident angles: (a) fully grown corn field and (b) soybean field.

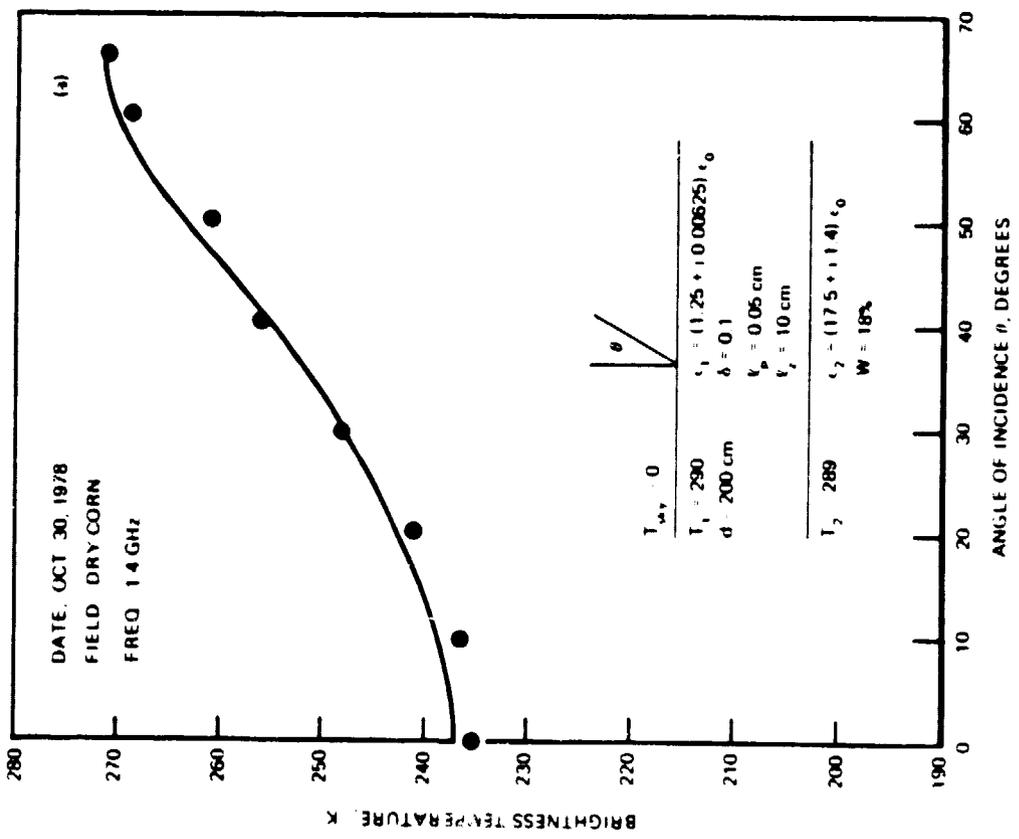
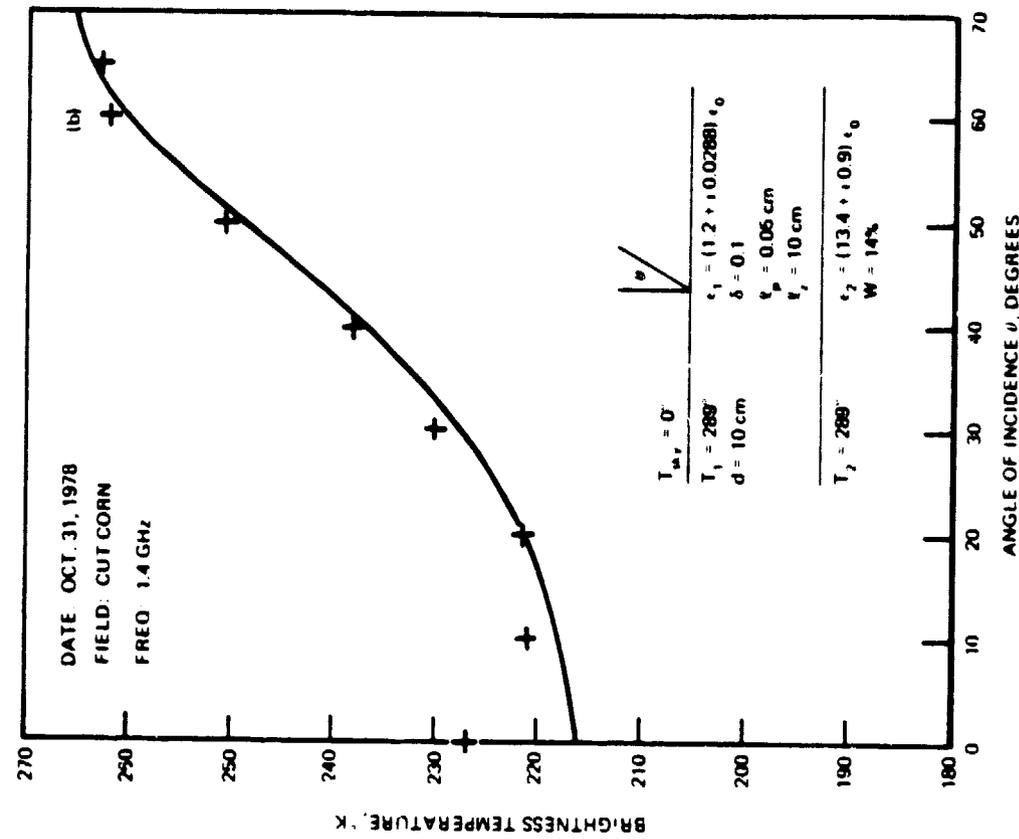


Figure 8. A comparison of the measured and calculated brightness temperatures at 1.4 GHz as a function of incident angles: (a) dry corn field and (b) cut-corn field.

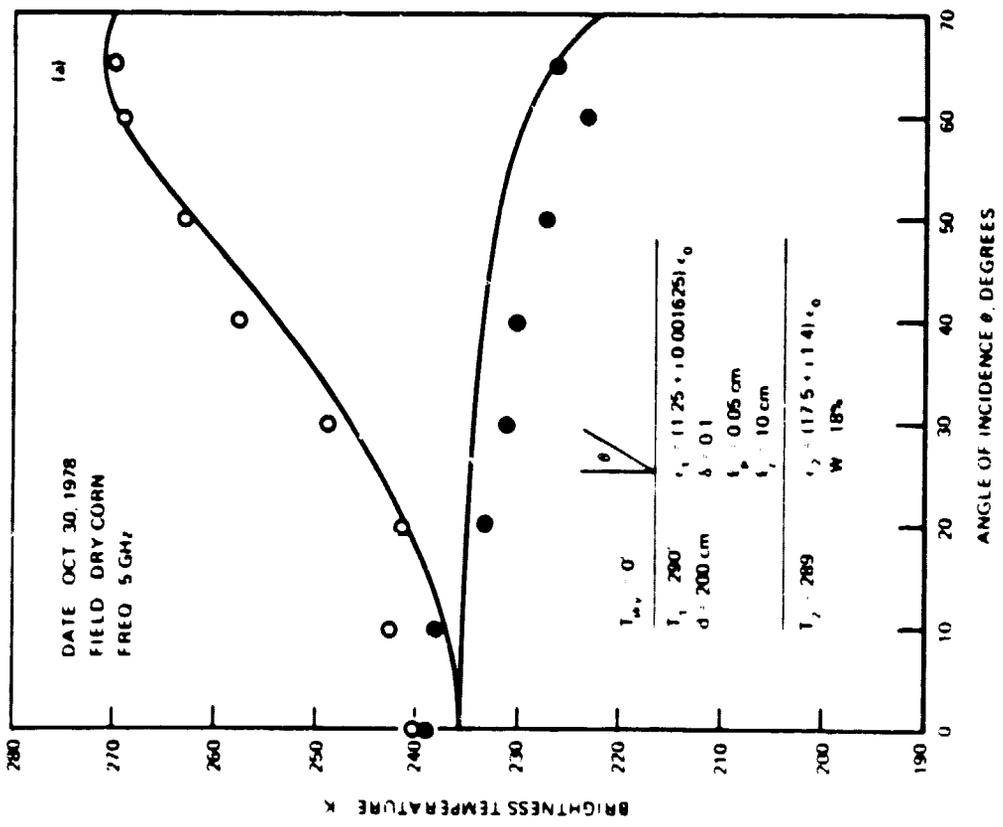
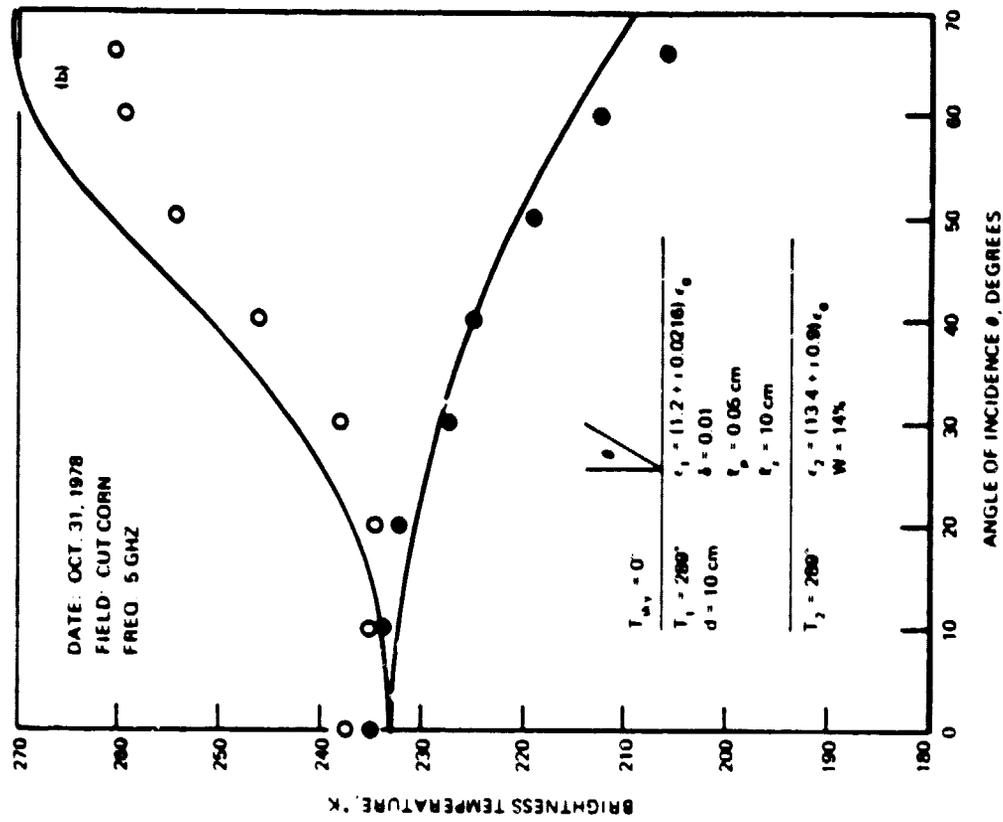


Figure 9. A comparison of the measured and calculated brightness temperatures at 5 GHz as a function of incident angles: (a) dry corn field and (b) cut-corn field.

## FIGURE CAPTIONS

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- Figure 2. The normalized brightness temperature vs. soil moisture content in the top 0-3 cm layer. The bare soil data of 1979 are obtained from Wang et. al. [3]. The regression line is derived for bare fields only.
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- Figure 5. The normalized brightness temperature at 5 GHz vs. incident angle for dry corn and cut-corn fields.
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