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Radiometric Measurements Over Bare and Vegetated Fields at 1.4 GHz and 5 GHz Frequencies

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June 1981

Goddard Space Flight Center
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ABSTRACT

Results of radiometric measurements over bare and vegetated fields with dual polarized microwave radiometers at 1.4GHz and 5GHz frequencies are presented. The measured brightness temperatures over bare fields are shown to compare favorably with those calculated from radiative transfer theory with two constant parameters characterizing surface roughness effect. The presence of vegetation cover is found to reduce the sensitivity to soil moisture variation. This sensitivity reduction is generally more pronounced the denser the vegetation cover and the higher the frequency of observation. The effect of vegetation cover is also examined with respect to the measured polarization factor at both frequencies. With the exception of dry corn fields, the measured polarization factor over vegetated fields is found appreciably reduced compared to that over bare fields. A much larger reduction in this factor is found at 5GHz than at 1.4GHz frequency.

RADIOMETRIC MEASUREMENTS OVER BARE AND VEGETATED FIELDS AT 1.4GHz AND 5GHz FREQUENCIES

1. INTRODUCTION

Although many passive microwave experiments on the remote estimate of soil moisture content have been conducted at both aircraft and satellite altitudes (Schmugge et al., 1974, 1977; Eagleman and Lin, 1976; Blanchard et al., 1981; Schmugge, 1980), measurements at ground level with microwave radiometers mounted on a mobile tower remain a fundamental means for studying the effects of soil moisture variation, soil type, surface roughness, and vegetation cover on the microwave radiometric outputs (Newton and Rouse, 1980; Njoku and Kong, 1977; Wang et al., 1980a, b; Schanda et al., 1978; Wang and Choudhury, 1981). Results of different mobile tower measurements on bare soils are generally in agreement with one another and confirm the observations made at aircraft altitudes. On measurements over vegetated fields, there is some discrepancy between the results of Newton and Rouse (1980) and those of Wang et al. (1980a) and Kirdiashev et al. (1979). At the frequency of 1.4GHz, Newton and Rouse reported a negligible vegetation effect on the radiometric outputs, while Wang et al., and Kirdiashev et al., observed a definite dependence of brightness temperature on vegetation cover. The observed dependence from the latter experiments is stronger the higher the frequency of observation and the denser the vegetation cover. Clearly more measurements are needed in order to resolve this discrepancy and to study the microwave interaction in the vegetated medium.

In this paper we report results of measurements made in both 1979 and 1980 over bare and vegetated fields. The inclusion of the 1980 measurements provides a much broader range in both soil moisture content and vegetation biomass, as compared to that reported by Wang et al. (1980a) based on 1979 data alone. The experiment procedure, test site characteristics, ground truth data collection, and microwave sensor specification are first described. This is then followed by discussions of bare and vegetated field measurement results. Conclusions derived from these results are generally supportive of earlier report by Wang et al. (1980a).

2. THE EXPERIMENT

The measurements in both 1979 and 1980 were conducted on a test site in Beltsville, Md. managed by U.S. Department of Agriculture/Beltsville Agricultural Research Center. The field soil is Elinsboro sandy loam with average texture in the top 20 cm of 63% sand, 27% silt, and 10% clay according to the U.S. Standard Classification. The radiometric measurements were made on four 18.3 m × 18.3 m plots and the surrounding grasslands. One of the four plots was planted with soybeans in rows about 61 cm apart. Within each row, the average separation between plants was ~5 cm. Another plot was planted with row corn about 76 cm apart and the plant separation in a given row averaged about [illegible]0 cm. The two remaining plots were bare and kept free of vegetation by periodically spraying with the herbicide paraquat. The area surrounding those plots was cultivated with orchard grass which was maintained at two different heights, approximately 10 cm and 30 cm. All plots and grasslands have relatively smooth soil surface with small amplitude undulation.

Two microwave radiometers were used in both 1979 and 1980 measurements, one at the frequency of 1.4GHz (L-band) and the other, at 5GHz (C-band). Both radiometers measure the brightness temperature T_B of a target in both vertical and horizontal polarizations simultaneously. The radiometers are of the Dicke type with two internal calibration references: a hot load at 300°K and a cold load at the liquid nitrogen temperature of 77°K. In addition, absolute calibrations of the radiometers were made by pointing the antennas to the sky ($T_B \simeq 5°K$ at 1.4GHz and 5GHz) and a layer of Eccosorb slabs (23 cm thick) at the ambient temperature at least once during each day of field measurements. During the course of each year's measurements, the whole sensor system was moved to a nearby lake at least twice for calibration with calm water surface. Based on these calibration results, it was estimated that the radiometric measurements made in the test site were accurate to about ±3°K at both 1.4GHz and 5GHz frequencies (Wang et al., 1980b). In the 1979 experiment, the measured bare field T_B's at 5GHz were found to be about ~8°K lower than those at 1.4GHz when soil moisture contents were ≳15% by dry weight.

It was believed at the time that a significant side lobe in the 5GHz phased-array antenna pattern located at 85° away from the main beam was the cause of the observed effect. In the 1980 experiment, therefore, the 5GHz phased-array antenna was replaced by two corrugated horns, one for each polarization. The results of the bare field measurements with the horn antennas turned out to be in fairly good agreement with those of 1979 measurements as described in the next section, indicating that the side lobe did not cause the lower T_B at 5GHz. The 3-db beamwidth in the radiation patterns of the horn antennas is ~ 15° as compared to ~ 8° for the phased-array antenna. The 1.4GHz antenna used in both years is a 1.2m dish with a 3-db beamwidth of ~ 12°.

Concurrent with the radiometric measurements, soil moisture content at the layers of 0–0.5 cm, 0–2.5 cm, 2.5–5.0 cm, and 5.0–10.0 cm at two locations within the 3-db footprint of the sensors was gravimetrically measured. Extensive gravimetric soil moisture samplings at the depths of 0-1.25 cm, 1.25-2.50 cm, 2.50-5.00 cm, and 5.00-10.00 cm at 9 different locations uniformly distributed over each plot were also made within two hours of the radiometric measurements. As an experimental test of soil moisture sampling, a gamma ray meter and a neutron meter were used to measure moisture contents down to 35 cm and in the top few centimeter respectively. Soil density in the top 2.5 cm was measured with a cylindrical container 5.08 cm in diameter and 2.54 cm in height. At the layers of 2.54–5.08 cm and 5.08–10.16 cm, the soil density was estimated from the gravimetric and the corresponding gamma ray meter data. Soil temperature of all plots was measured only at the depth of 1.25 cm and 11.25 cm during 1979 experiment. In 1980, this measurement was extended to cover five different depths at 0.25 cm, 1.25 cm, 2.5 cm, 7.5 cm, and 15.0 cm. Ambient and vegetation canopy temperatures were recorded during radiometric measurements. A nearby climate station provided data on daily rainfall, daily pan evaporation, maximum and minimum air temperatures, and total daily wind run.

Above-ground biomass samples and plant heights on grass, corn and soybean were made about once a week close to the time of radiometric measurements over the vegetated fields. The samples were weighted and dried to determine water content. During the 1980 measurements, leaf area index and percent vegetation cover were also included in the biomass sampling. Figure 1 shows the time variation of the total biomass in Kg/m^2 for 10cm grass, 30cm grass, corn, and soybean fields. Only one month of measurements was made in 1979 when corn plants were already wilted. Soybean reached maturity at the beginning of that year's measurement and the total biomass decreased rapidly as the plants were wilting with time. The measured soybean biomass and wilted corn biomass in 1980 were smaller than the corresponding ones in 1979 although both plants were grown the same way in two years. The average height of 10 cm grass was ~ 16 cm and that for the 30 cm grass was ~ 25 cm in 1980. The biomass of both fields were comparable because the grass is less dense in the 30 cm grass field compared to the 10 cm grass field. The fact that the soil moisture content in all plots remained dry (<10% in top 2 cm) most of the time in 1980 could be the reason for the plant's decreased growth. The horizontal bars at the top of the figure indicate the time periods the 5GHz (C-band) and 1.4GHz (L-band) radiometers were operative. In the 1980 measurement, the entire sensor system stopped functioning between July 18 and August 20 after it was struck by a severe thunderstorm.

3. BARE FIELD RESULTS

Figure 2a shows the normalized brightness temperature T_{NB} observed at 1.4GHz frequency and at the incidence angle $\theta = 10°$ plotted against the soil moisture content W (% by dry weight) measured at the top 2.5cm layer. Figure 2b gives the similar plot for radiometric measurements at 5GHz frequency. T_{NB} is defined as

$$T_{NB} = \frac{T_B}{T_S} \qquad (1)$$

where T_B is the measured brightness temperature and T_S is the physical temperature of soil obtained at the depth of 1.25cm. Both T_B and T_S are expressed in °K. Another method of normalizing T_B is to use effective soil temperature T_{eff} (Choudhury et al., 1981) in place of T_S. From all the temperature and moisture profiles we measured over both bare and vegetated fields during

1979 and 1980 experiments, the estimated difference between T_S at 1.25 cm and T_{eff} is not more than 2°K.

In both plots, most of the 1980 data points are limited to the region of low W, while the 1979 data points, to the region of high W. For W's between 8% and 15% the measured T_{NB}'s in two different years fit together nicely indicating the consistency of the measurements. A linear regression analysis of the combined two-year data in Figure 2a gives a correlation coefficient r^2 of ~0.91 between T_{NB} and W. A similar analysis gives a r^2 of 0.86 for 5GHz measurements shown in Figure 2b. Notice that the regression line for the 5GHz data is steeper than that for the 1.4GHz data. This is consistent with the emission model calculations of Mo et. al. (1980) in which the calculated T_B's at a given frequency are plotted as a function of W in the top 2 cm, 5 cm, 9 cm, and 15 cm layers. The regression line becomes steeper as W's are evaluated over a deeper layer. Since the sampling depth at 5GHz is smaller than that at 1.4GHz, and most variation in W occurs at the top layer of the soil, the observed T_B's at 5GHz should correspond to a wider range in W than that at 1.4GHz. It can be shown that when T_{NB}'s at 5GHz are plotted against W in the top 0.5 cm layer, the slope in the regression line is reduced appreciably.

Based on the data taken in 1979, Wang et al. (1980a) showed that the measured brightness temperature can be predicted fairly well by a radiative transfer model (Wilheit, 1978) with two constant parameters characterizing the field surface roughness (Choudhury, 1978; Choudhury et al., 1979; Wang and Choudhury, 1981). Using the same roughness height h = 0.15 and polarization mixing coefficient Q = 0.13 derived from the 1979 measurements (Wang and Choudhury, 1981), brightness temperatures T_B's at 1.4GHz of the bare fields with moisture and temperature profiles measured in 1979 and 1980 were computed with the same radiative transfer theory and the dielectric permittivity model (Wang and Schmugge, 1980). The computed T_B's are compared with the measured values in Figure 3a and b, for incidence angles of $\theta = 10°$ and $\theta = 50°$, respectively. A similar analysis is made on the 5GHz data and the results are shown in Figure 4a and b for $\theta = 10°$ and $\theta = 50°$, respectively. The h and Q values used in the radiative transfer calculation at this frequency are 0.06 and 0.08, respectively. It can be seen that a reasonable agreement is found between the calculated and measured T_B's at two widely different incidence angles.

According to Choudhury et al. (1979) and Choudhury (1978), the rougher the soil surface the higher the h and Q values are required to match the radiative transfer calculations to the observational results. The higher h and Q values used at 1.4GHz then suggest that soil's microwave emission is less sensitive to surface roughness at 5GHz than at 1.4GHz frequency. Whether this is a true effect or due to a weakness in the model calculation remains to be studied fully in the future. A conclusive test of the frequency dependence on surface roughness in soil's thermal microwave emission will have to be made with multiple-frequency measurements over surfaces prepared in a number of different roughness distributions. This can be done more readily on a high-clay content soil than a sandy soil like the one reported in this paper.

A close examination of Figures 3 and 4 reveals that there is a slight difference of ~5-7°K between the measured and calculated T_B's at high T_B values, with the exception of the 1.4GHz and $\theta = 10°$ data set in Figure 3a. The calculated T_B's are higher than the measured ones at 1.4 GHz frequency and $\theta = 50°$, while at 5GHz frequency the calculated T_B's are lower than the measured ones at both $\theta = 10°$ and $\theta = 50°$. One of the reasons could be the positive interference effect of the coherent radiative transfer model possible for dry soils (Schmugge and Choudhury, 1980). Another reason could be the deficiency in the emission model calculations using radiative transfer theory (Wilheit, 1978) and the empirical dielectric permittivity model (Wang and Schmugge, 1980) in the low W region. For example, the real part ϵ' of dielectric permittivity for dry soil samples measured by Davis et al (1976) averages about 2.29. The data compiled by Wang (1980) give an average ϵ' for dry soil of 3.14, while the empirical model of Wang and Schmugge (1980) gives $\epsilon' = 3.25$ at $W = 0$. This large variation in ϵ' for dry soil is comparable to the change of ϵ' with W in a soil-water mixture at low W. A change of ϵ' for dry soil from 3.25 to 2.70 in the dielectric empirical model gives a corresponding change of 2-5°K in the calculated T_B's for the measured 1980 soil moisture and temperature profiles. Additional sources of uncertainty could come from the imprecise measurements of soil bulk density as well as some difference in the surface roughness for fields used in two different years of measurements.

4. VEGETATED FIELD RESULTS

Data obtained in the 1979 experiment (Wang et al., 1980b) have been studied for $\theta = 10°$ and reported by Wang et al. (1980a) and Jackson et al. (1981). In the following, data sets from both the 1979 and 1980 measurements are analyzed at $\theta = 40°$ for vegetation effect in terms of radiometric response and polarization characteristics. Figure 5a shows the measured horizontally polarized T_{NB} at 1.4GHz frequency and at $\theta = 40°$ as a function of W for bare field as well as fields covered with 10cm grass and 30cm grass. Figure 5b shows the similar plot for soybean and corn fields. The corresponding data measured at 5GHz frequency are plotted in the same way in Figure 6a and b. The soybean data points enclosed in the rectangles in both figures were taken over the period when the plant height was <17cm and the canopy coverage was <8%. As expected the radiometric response during this period was comparable to that for bare field at similar W's. Similarly, the enclosed corn data points in Figure 5b were obtained during July 10–August 22 of 1980 when the total plant biomass was high. The T_{NB}'s as indicated by these data points were higher than those measured in the remaining time periods (corn was dry) at a comparable level of W's, qualitatively showing the vegetation effect. Applying a linear regression to each of five data sets shown in Figure 5a and b, excluding those data points enclosed by rectangles, gives correlation coefficients r^2 of 0.91, 0.96, 0.53, 0.81, and 0.87 sequentially for bare, 10cm grass, 30cm grass, soybean and corn fields. The same regression analysis on the data shown in Figure 6a and b, gives r^2 of 0.86, 0.74, 0.07, 0.61, and 0.74 for five different fields in the same sequential order. Notice that the slopes of the regression lines for the vegetated fields are reduced compared to those for the bare fields. The slope reduction is generally higher the larger the water content in the vegetation and the higher the frequency of observation. This is in general agreement with previous studies of Kirdiashev et al. (1979), Wang et al. (1980a), and Jackson et al. (1981).

A plot of the ratio between the measured horizontally polarized brightness temperatures at 5GHz and 1.4GHz frequencies against W is shown in Figure 7. At W ≥ 11% this ratio for the bare field averages about 0.95, while that for the vegetated fields is ≥ 1.0 with the exception of two data points from corn field. This ratio, therefore, provides a means to distinguish bare fields from vegetated fields when W is relatively high. The ratio for the 10cm grass, 30cm grass, and soybean fields decreases with decrease in W over the entire W range of 2–28%. For W ≤ 10% the ratio for the bare field increases with decrease in W. It is likely that at W ≤ 5% the bare and vegetated fields can be distinguished by examining this ratio also.

Another interesting parameter to study is the polarization factor P which is defined as

$$P = \frac{T_{BV}(\theta) - T_{BH}(\theta)}{\frac{1}{2}\left(T_{BV}(\theta) + T_{BH}(\theta)\right)} \qquad (2)$$

where subscripts V and H denote vertical and horizontal polarizations respectively. A comparison of this parameter at 5GHz and 1.4GHz frequencies and $\theta = 40°$ is shown in Figure 8. P for bare fields varies from 0.1 to 0.56 at 5GHz and from 0.16 to 0.48 at 1.4GHz over the entire W range of 4–24%. With the exception of two data points from 30cm grass field and data points from corn field, P's measured at 5GHz frequency over the vegetated fields are ≤ 0.1. Those two data points over 30cm grass field with $P \simeq 0.14$ at 5GHz and $P \simeq 0.20$ at 1.4GHz were made not long after the grass were mowed. They are generally outside the region of bare field data points in the same figure. Some of the data points obtained from corn field measurements are well mixed with those from bare field measurements. Those data were taken when the corn plants have already wilted.

Table 1 summarizes the main features observed in Figures 5, 6, 7 and 8. From this table, it is found highly possible to separate the bare field from vegetated fields and determine its W by remote sensing with dual polarized microwave radiometers at 5GHz and 1.4GHz frequencies when W is ≥ 7%. For example, if a set of measured data gives P ≥ 0.22 at 5GHz, then the measurements could have been made only over either bare or dry corn fields. Examinations of other factors like P at 1.4GHz as well as T_{NB} at both frequencies and their ratio suggest high probability of separating bare and dry corn fields statistically. The soil moisture content W can then be determined from the regression relationship given in Figures 5 and 6.

5. DISCUSSION

In the previous sections we presented results of two-year experiment on remote sensing of soil moisture content over bare and vegetated fields using dual polarized microwave radiometers at 1.4GHz and 5GHz frequencies mounted on a mobile tower. These results generally agree with earlier reports of Wang et al. (1980a). Kirdiashev et al. (1979), and Jackson et al. (1981a). For measurements over bare fields we have shown that the measured brightness temperatures at both frequencies can be predicted fairly well by existing radiative transfer model (e.g. Wilheit, 1978) with known relationship between dielectric permittivity and soil moisture content. When soil is relatively dry, there is a slight deviation between calculated and measured brightness temperatures. This slight deviation could be due to the deficiency in the radiative transfer model or the dielectric permittivity model. A difference in the surface roughness distributions between bare fields used in two years of measurements or the uncertainty in the measurements of soil bulk density profile could easily make a few °K difference in the calculated brightness temperatures. To further improve the agreement between the measured and calculated brightness temperatures requires a refinement of above-mentioned modeling and/or measurement techniques.

Another interesting feature regarding the bare field measurement results is that the roughness height h and mixing ratio Q used in the soil microwave emission model calculations are smaller at 5GHz than at 1.4GHz frequency. The smaller h and Q values at 5GHz are needed in order to account for the observed lower brightness temperature by ~3°K relative to that at 1.4GHz when moisture content W in the top 2.5cm layer is $\geq$ 12% by dry weight. A comparison of bare field data obtained in both 1979 and 1980 experiments suggests that the 5GHz antenna side lobe problem (Wang et al., 1980b) can not be totally responsible for the observed low brightness temperatures. This then points to the possibility that for the type of bare fields (which were flat with small random amplitude undulation) the measurements were made, the thermal microwave emission might depend less on surface roughness at 5GHz than at 1.4GHz. Another possibility could be due to the weakness of the emission model calculation. More experiments and modelling effort are required in order to establish the frequency dependence of surface roughness. A recent measurement by Newton et al. (1981) shows a larger surface roughness effect at 5GHz and 10.6GHz than at 1.4GHz frequency.

Results of analysis given in Section 4 generally confirm the earlier reports of Kirdiashev et al. (1979), Wang et al. (1980a), and Jackson et al. (1981) on the effect of vegetation cover: the higher the frequency of observation and the larger the vegetation biomass, the stronger the vegetation effect on the microwave emission from the underlying soil. They are also in general agreement with the airborne radiometric measurements recently made over Chickasha, Oklahoma and Taylor Creek, Florida (T. Jackson, personal communication). Newton and Rouse (1980) however reported a negligible effect of vegetation cover from a similar radiometric measurement at 1.4GHz. From a tabulation of sorghum biomass data provided by the report of Newton and Lee (1974), the total biomass of the sorghum fields used in the measurements of Newton and Rouse (1980) is estimated to range from $\sim 3 Kg/m^2$ to $\sim 6 Kg/m^2$ with an average plant moisture of $\sim 70\%$. Comparing with the biomass data shown in Figure 1, the sorghum fields should be as dense as our soybean fields near maturity. Clearly, there is a definite discrepancy between the radiometric measurements conducted by Newton and Rouse and those of ours reported in this paper. More measurements are desirable not only to resolve this discrepancy but also to study qualitatively the physics of microwave interactions in the vegetated medium.

The presence of vegetation cover also reduces the measured polarization factor as defined in Eq. (2). As shown in Table 1, this factor increases monotonically with increase in moisture content for bare soil at both 1.4GHz and 5GHz frequencies. With the exception of the dry corn field, the measured factor at 5GHz is limited to $\leq$ 0.1 for the vegetated fields over wide range of moisture content 2–30%. As more data become available in the near future, a detailed study of this factor could help delineate field type and determine field surface moisture content.

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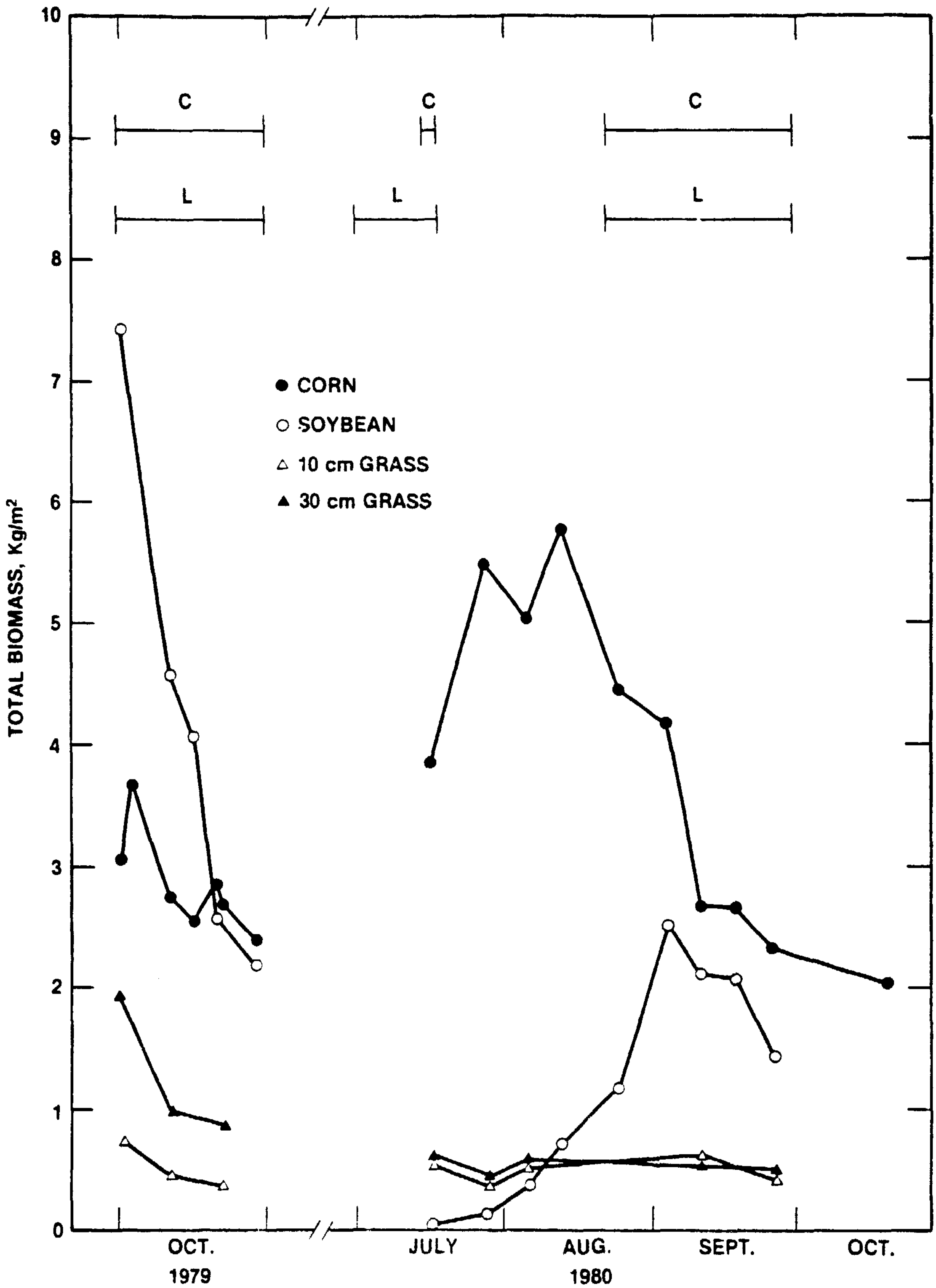

Figure 1. Time variation of vegetation total biomass in 1979 and 1980 experiments. The line segments on top portion of the figure indicate the time periods when 1.4 GHz (L-band) and 5 GHz (C-band) radiometers are operative.

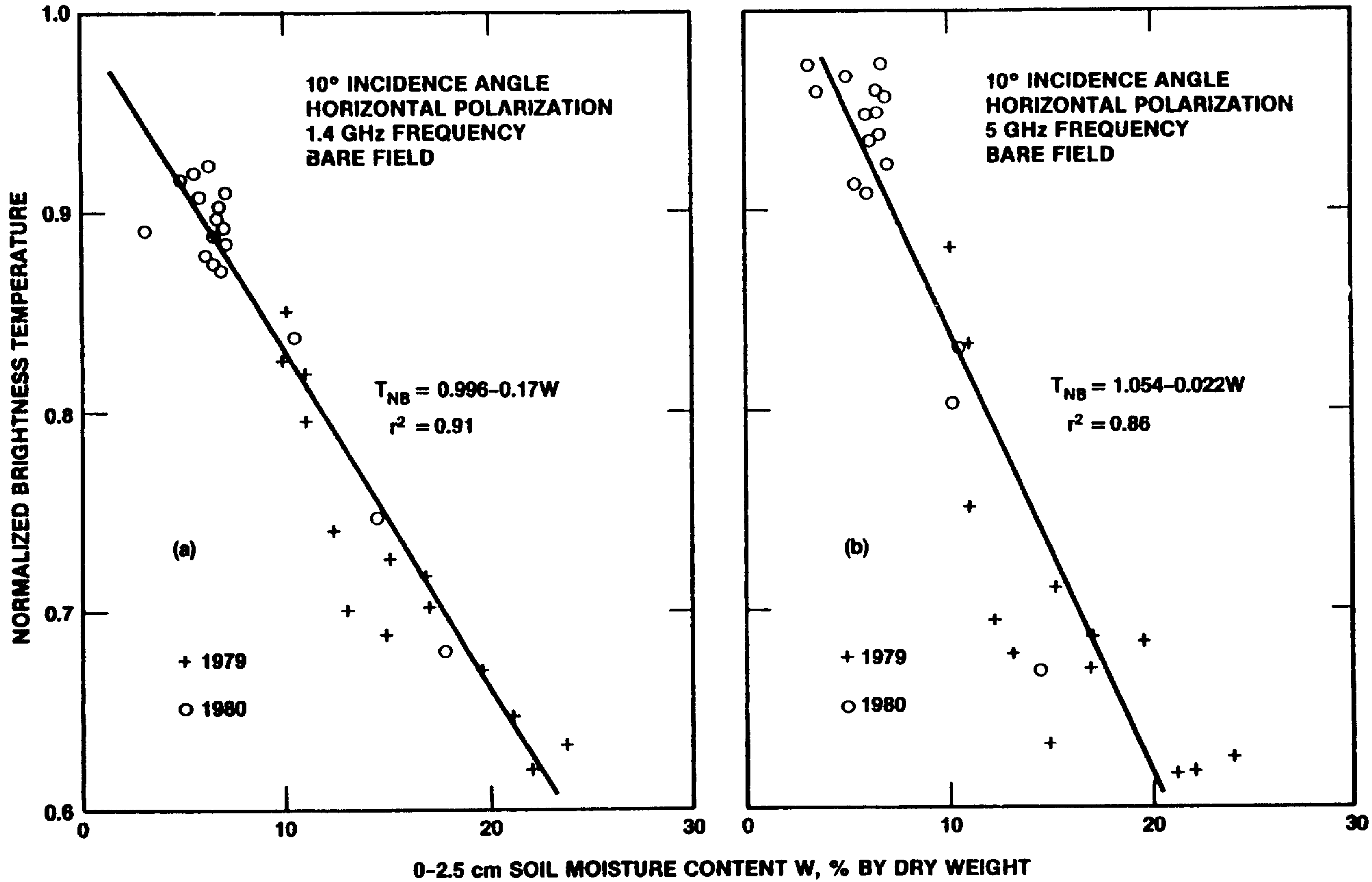

Figure 2. The variation of normalized brightness temperatures with soil moisture content in the top 2.5 cm layer: (a) 1.4 GHz frequency and (b) 5 GHz frequency. The measurements were made over bare fields in both 1979 and 1980 at 10° incidence angle and horizontal polarization.

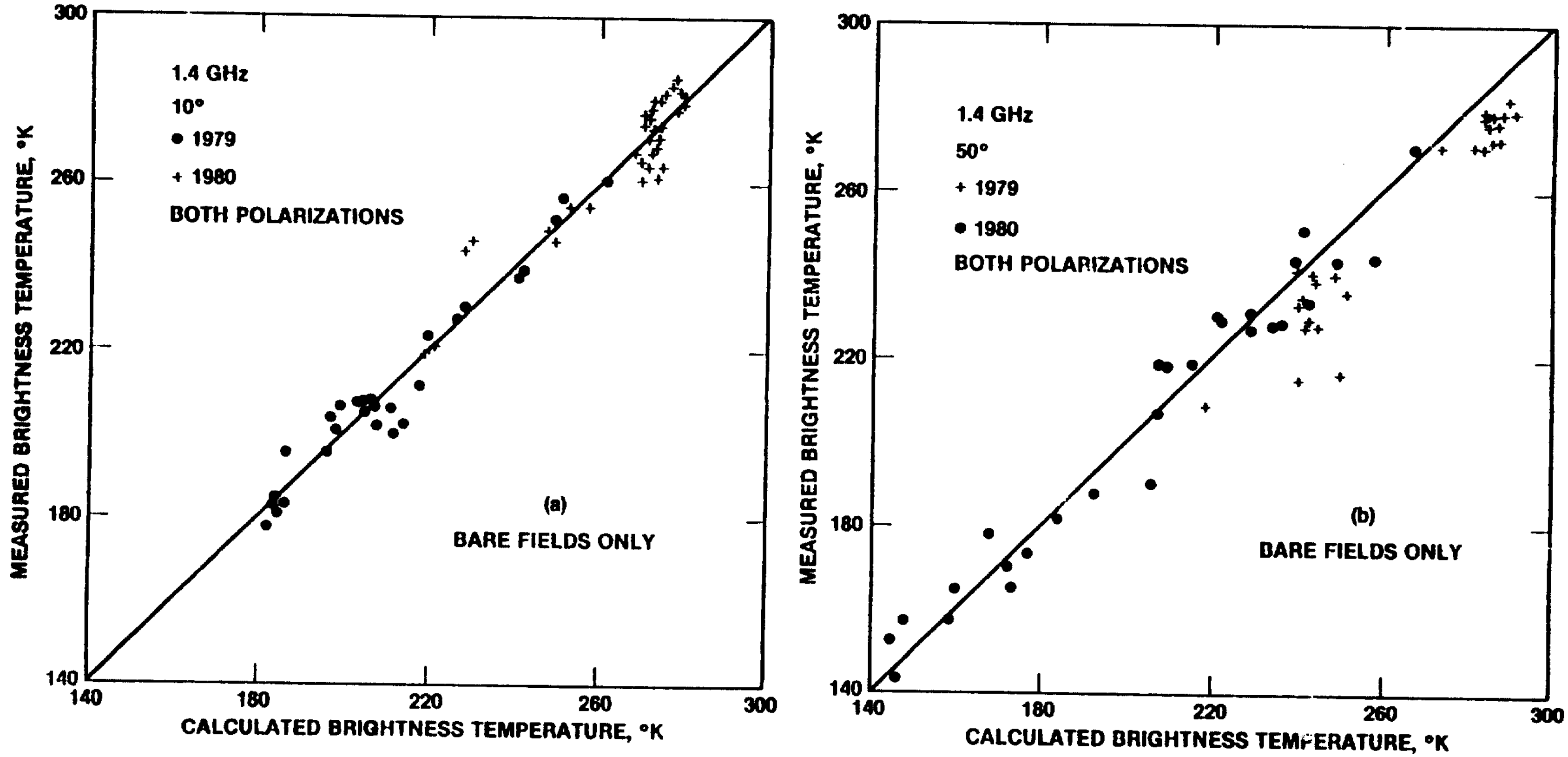

Figure 3. A comparison of measured and calculated brightness temperatures for bare fields at 1.4 GHz frequency: (a) 10° incidence angle and (b) 50° incidence angle. Brightness temperatures at both vertical and horizontal polarizations are included for comparison.

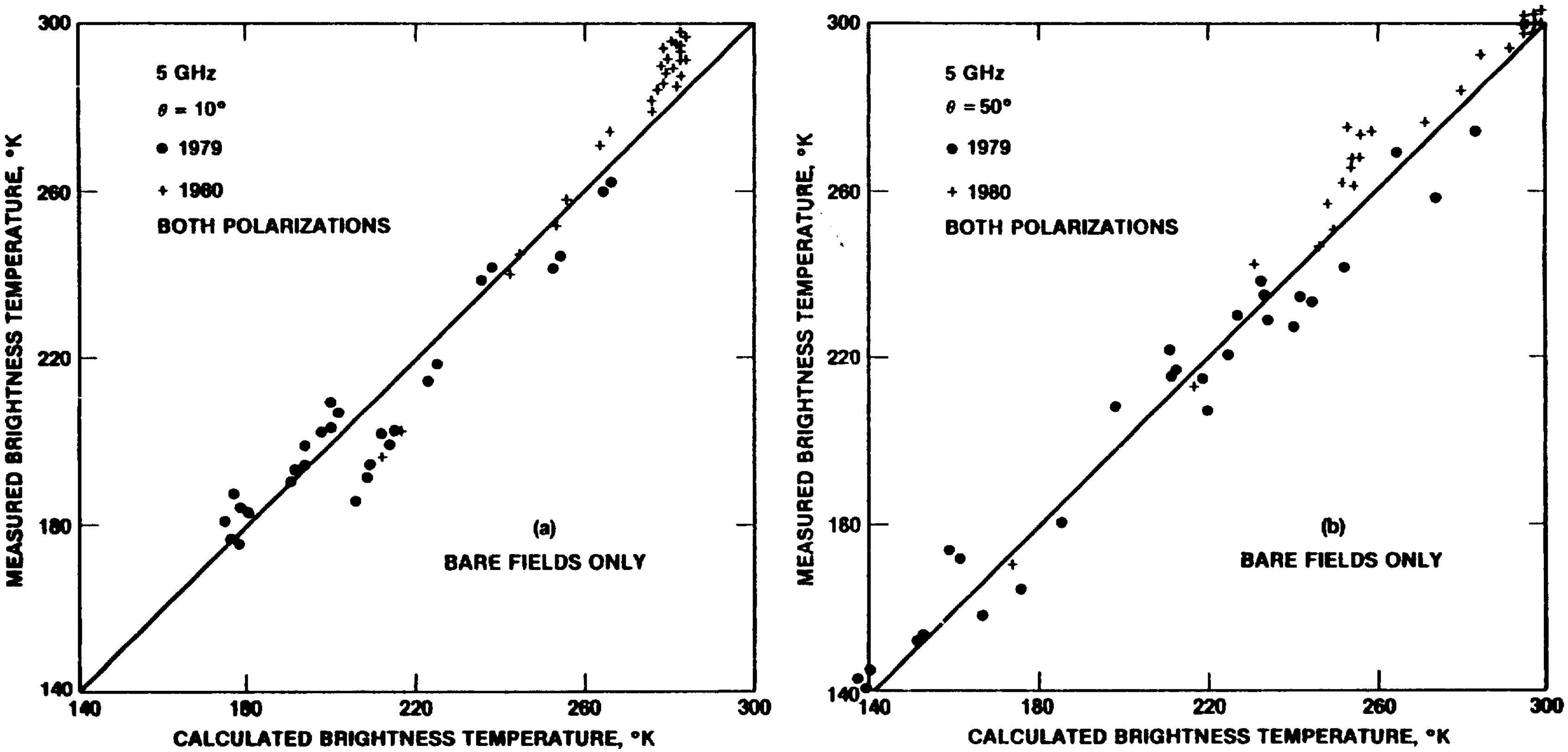

Figure 4. A comparison of measured and calculated brightness temperatures for bare fields at 5 GHz frequency: (a) 10° incidence angle and (b) 50° incidence angle. Brightness temperatures at both vertical and horizontal polarizations are included for comparison.

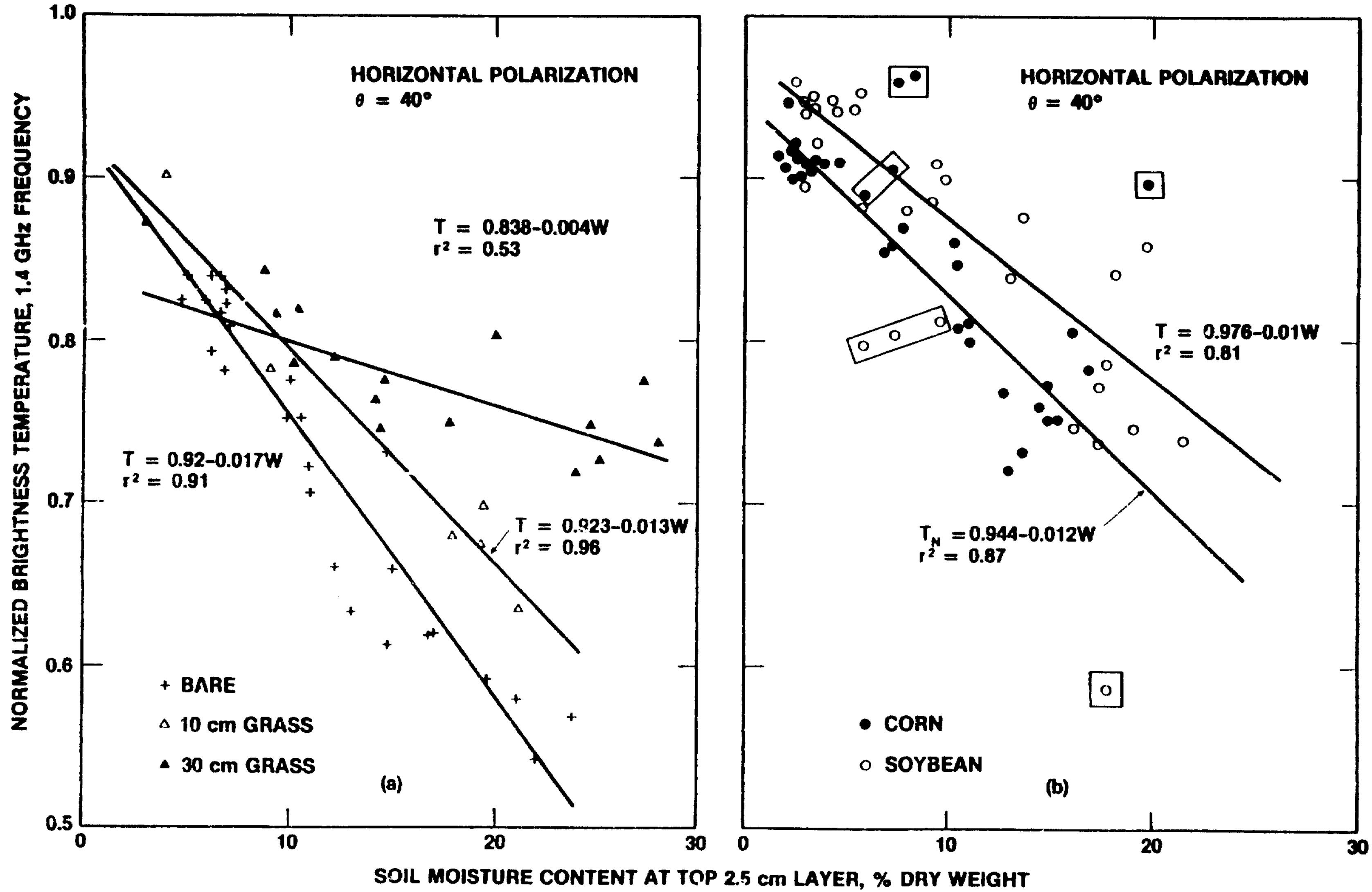

Figure 5. The normalized brightness temperatures at incidence angle of 40° plotted as a function of soil moisture content in the top 2.5 cm layer for bare and vegetated fields: (a) bare, 10 cm grass, and 30 cm grass fields and (b) soybean and corn fields. The measurements were made at 1.4 GHz and horizontal polarization.

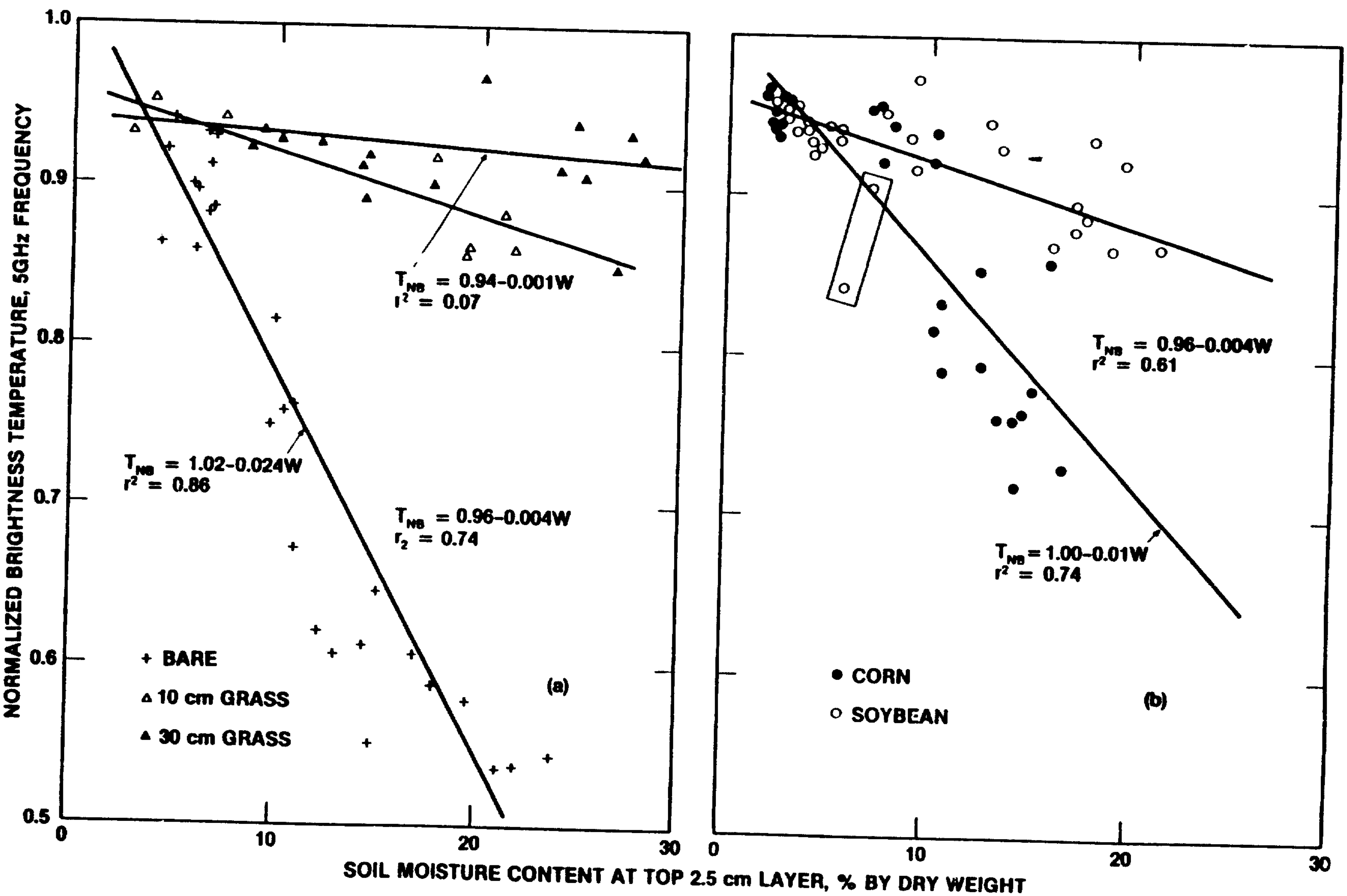

Figure 6. The normalized brightness temperatures at incidence angle of 40° plotted as a function of soil moisture content in the top 2.5 cm layer for bare and vegetated fields: (a) bare, 10 cm grass, and 30 cm grass fields and (b) soybean and corn fields. The measurements were made at 5.0 GHz and horizontal polarization.

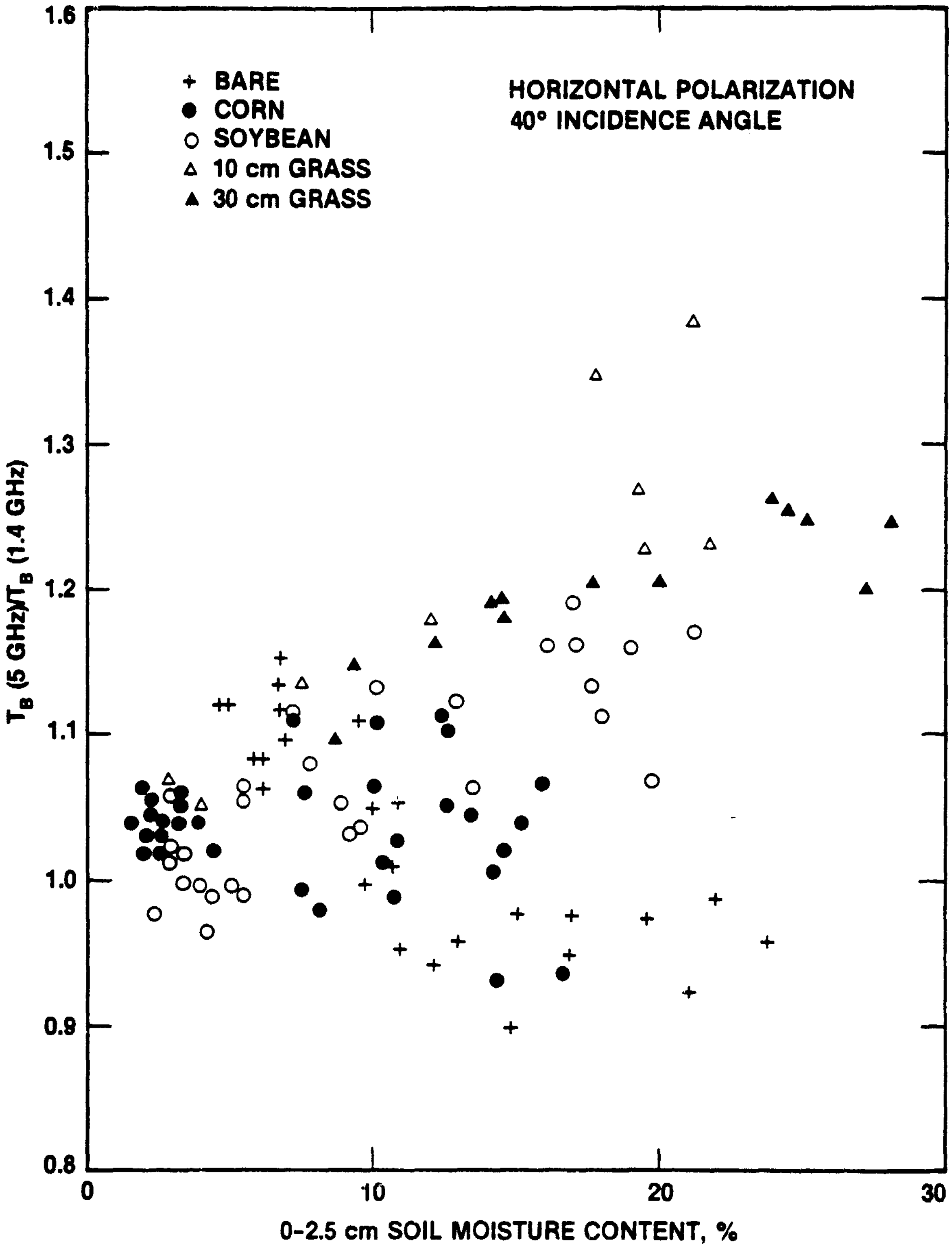

Figure 7. The ratio of measured brightness temperatures at 5 GHz and 1.4 GHz plotted as a function of soil moisture content in the top 2.5 cm layer for bare and vegetated fields. The measurements were made at 40° incidence angle and horizontal polarization.

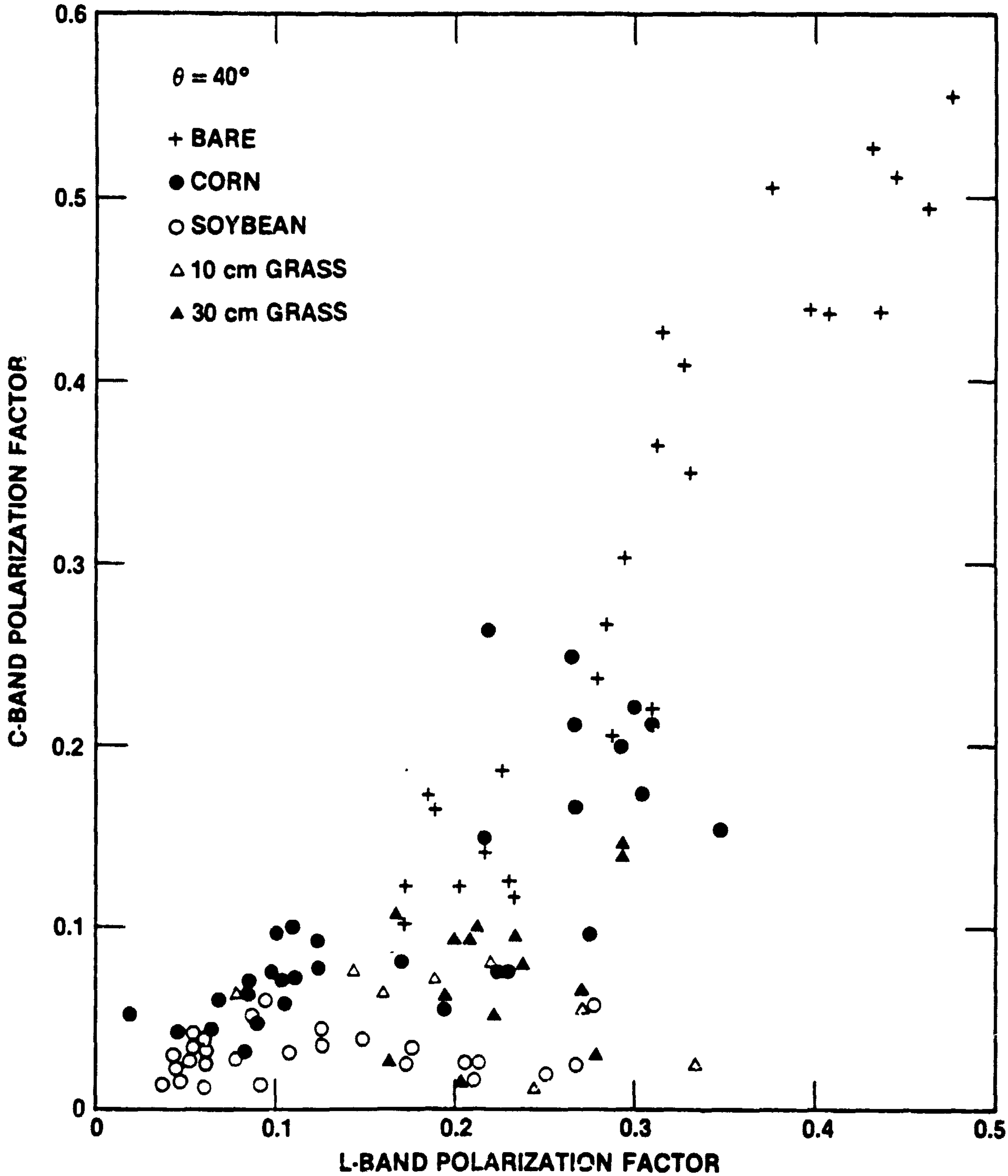

Figure 8. A comparison of the measured polarization factors at 1.4 GHz and 5 GHz frequencies for bare and vegetated fields. Data were taken at 40° incidence angle.

Table I

A Summary of Results Derived from Figures 5, 6, 7, and 8.

Field Type	0–2.5 cm Soil Moisture	$T_B(5GHz)/T_B(1.4GHz)$	P(40°, 5GHz)	P(40°, 1.4GHz)	T_{NB}(40°, 5GHz)	T_{NB}(40°, 1.4GHz)
Bare	4– 7%	1.06–1.16	0.10–0.24	0.16–0.29	0.86–0.94	0.78–0.84
	7–11%	1.00–1.11	0.22–0.35	0.28–0.33	0.68–0.82	0.70–0.78
	11–24%	0.90–0.99	0.36–0.56	0.31–0.48	0.53–0.65	0.56–0.73
Corn	1– 8%	1.00–1.10	0.03–0.10	0.02–0.17	0.86–0.97	0.85–0.96
	8–12%	0.98–1.11	0.05–0.20	0.02–0.22	0.79–0.94	0.80–0.86
	12–17%	0.93–1.11	0.06–0.26	0.08–0.35	0.72–0.86	0.73–0.90
Soybean	2– 7%	0.96–1.07	0.01–0.04	0.04–0.11	0.92–0.97	0.88–0.96
	7–11%	1.03–1.14	0.03–0.05	0.09–0.17	0.91–0.95	0.88–0.91
	11–22%	1.05–1.20	0.01–0.04	0.04–0.28	0.87–0.94	0.73–0.88
10 cm grass	2– 5%	1.04–1.07	0.05–0.07	0.08–0.09	0.93–0.95	0.87–0.90
	6–12%	1.13–1.18	0.06–0.08	0.14–0.17	0.78–0.94	0.78–0.83
	14–22%	1.22–1.39	0.01–0.08	0.19–0.33	0.86–0.92	0.63–0.70
30 cm grass	8–11%	1.09–1.15	0.10–0.11	0.17–0.22	0.92–0.93	0.78–0.85
	12–28%	1.16–1.27	0.02–0.14	0.16–0.29	0.89–0.97	0.72–0.81

FIGURE CAPTIONS

Figure 1. Time variation of vegetation total biomass in 1979 and 1980 experiments. The line segments on top portion of the figure indicate the time periods when 1.4GHz (L-band) and 5GHz (C-band) radiometers are operative.

Figure 2. The variation of normalized brightness temperatures with soil moisture content in the top 2.5cm layer: (a) 1.4GHz frequency and (b) 5GHz frequency. The measurements were made over bare fields in both 1979 and 1980 at 10° incidence angle and horizontal polarization.

Figure 3. A comparison of measured and calculated brightness temperatures for bare fields at 1.4GHz frequency: (a) 10° incidence angle and (b) 50° incidence angle. Brightness temperatures at both vertical and horizontal polarizations are included for comparison.

Figure 4. A comparison of measured and calculated brightness temperatures for bare fields at 5GHz frequency: (a) 10° incidence angle and (b) 50° incidence angle. Brightness temperatures at both vertical and horizontal polarizations are included for comparison.

Figure 5. The normalized brightness temperatures at incidence angle of 40° plotted as a function of soil moisture content in the top 2.5cm layer for bare and vegetated fields: (a) bare, 10cm grass, and 30cm grass fields and (b) soybean and corn fields. The measurements were made at 1.4GHz and horizontal polarization.

Figure 6. The normalized brightness temperatures at incidence angle of 40° plotted as a function of soil moisture content in the top 2.5cm layer for bare and vegetated fields: (a) bare, 10cm grass, and 30cm grass fields and (b) soybean and corn fields. The measurements were made at 5.0 GHz and horizontal polarization.

FIGURE CAPTIONS (Continued)

Figure 7. The ratio of measured brightness temperatures at 5 GHz and 1.4 GHz plotted as a function of soil moisture content in the top 2.5 cm layer for bare and vegetated fields. The measurements were made at 40° incidence angle and horizontal polarization.

Figure 8. A comparison of the measured polarization factors at 1.4 GHz and 5 GHz frequencies for bare and vegetated fields. Data were taken at 40° incidence angle.