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Soil Moisture

A Multi-Frequency Radiometric Measurement of Soil Moisture Content Over Bare and Vegetated Fields

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ABSTRACT

An experiment on soil moisture remote sensing over bare, grass, and alfalfa fields was conducted during July – September 1981 with 0.6 GHz, 1.4 GHz, 5.0 GHz, and 10.6 GHz microwave radiometers mounted on mobile towers. Ground truth acquisition of soil moisture content, ambient air and soil temperatures was made concurrently with the radiometric measurements. Biomass of the vegetation cover was sampled about once a week. Soil density for each of the three fields was measured several times during the course of the experiment. The results of the radiometric measurements confirm the frequency dependence of moisture sensing sensitivity reduction reported earlier by Kirdiashev et al. (1979). The present work extends the frequency range of earlier measurements down to 0.6 GHz. Observations over the bare, wet field show that the measured brightness temperature is lowest at 5.0 GHz and highest at 0.6 GHz frequency, a result contrary to the expectation based on the estimated dielectric permittivity of soil-water mixtures and current radiative transfer model in that frequency range.

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1. INTRODUCTION

The effect of vegetation cover is one of a few major factors affecting the thermal microwave emission from soils. This effect has to be fully studied before a reliable estimate of soil moisture content for a typical agricultural field, covered with moderate vegetation, can be made through remote radiometric measurements. In recent years, some experi ɔnts with microwave radiometers have been conducted to study this effect (Kirdiashev et al., 1979; Newton and Rouse, 1980; Wang et al., 1980, 1981; Jackson et al., 1981). Results from these experiments generally show that the effect of vegetation depends on the frequency of observation and vegetation biomass: the denser the vegetation cover and the higher the frequency of observation, the larger the vegetation effect. These measurements, however, are made at frequencies >1 GHz. Quantitative observation of vegetation effect at frequencies <1 GHz has not been made to the best of our knowledge.

In this paper we report a new measurement of vegetation effect with microwave radiometers at the frequencies of 0.6 GHz, 1.4 GHz, 5.0 GHz, and 10.6 GHz. Major emphasis is placed on the 0.6 GHz observation which extends the frequency range and confirms the frequency dependence of moisture sensing sensitivity reduction due to the presence of vegetation cover reported earlier (Kirdiashev et al., 1979; Wang et al., 1980). The experiment was conducted on a test site managed by USDA Beltsville Agricultural Research Center. The measurements with 1.4 GHz, 5.0 GHz, and 10.6 GHz radiometers cover a 3-month period from July to September of 1981. The 0.6 GHz radiometer was operating only from late August to the end of September.

2. THE EXPERIMENT

The measurements were made with four radiometers at the frequencies of 0.6 GHz, 1.4 GHz, 5.0 GHz, and 10.6 GHz. All four radiometers are dual-polarized Dicke type with two internal calibration references: a hot load at 310°K and a cold load at the liquid nitrogen temperature of 77°K. Absolute calibrations with external targets for the 1.4 GHz, 5.0 GHz, and 10.6 GHz radiometers were made with calm water surface, sky, and a layer of 23-cm thick Eccosorb slabs as described in previous reports (Wang et al., 1980). Because of its small thickness, the Eccosorb target was not used for the 0.6 GHz radiometer calibration. Instead the connectors to the antenna feed were terminated with 50 ohm loads and calibration was made with the loads at ambient air temperature, room and ice water temperatures, and liquid nitrogen temperature. Figure 1 shows the results of calibration for the 0.6 GHz radiometer. Based on these calibration results, it was estimated that the 0.6 GHz field measurements were accurate to about $\pm 5°K$. A similar assessment placed a $\sim\pm 3°K$ accuracy on the radiometric measurements at the other three frequencies. All four radiometers had a 3-db beam-width of approximately 12° Measurements were made with incidence angles from 10° to 70° in 10° step over bare field as well as fields covered with dense orchard grass (~ 30 cm tall) and alfalfa (~40 cm tall). The target radiometric signals were sampled 30 times in each step. Occasionally, the 0.6 GHz radiometer would pick up interference signals of unknown origin. These interference signals gave an unusually high brightness temperature associated with a large standard deviation as the real-time data were averaged and examined. When the standard deviation of the signals was $\gtrsim 2.5°K$, the data were discarded and the experimental step resumed. With the exception of a few persistent cases, we were able to screen out most interference signals by this procedure.

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 were measured gravimetrically at the times of radiometric measurements. Ambient air temperature, vegetation canopy temperature, and soil temperature near the surface and at the depths of 1.25 cm, 2.5 cm, 7.5 cm, and 12.5 cm were also recorded at the same times. Soil density at layers of 0 - 2.5 cm, 2.5 - 5.0 cm, 5.0 - 10.0 cm, and 10.0 - 15.0 cm was measured several times during the course of the experiment. Above-ground biomass samples of grass and alfalfa were made about once a week. The measured average wet biomass during the period of August - September relevant to this paper was $\sim 1195\ gm/m^2$ for grass and $\sim 1094\ gm/m^2$ for alfalfa. The corresponding vegetation water contents were $\sim 875\ gm/m^2$ and $\sim 863\ gm/m^2$ for grass and alfalfa respectively. The soil surfaces of all three fields were smooth according to the criteria of Choudhury et al. (1979), and the soil type is Elinsboro sandy loam which consists of 66% sand, 19% silt, and 15% clay.

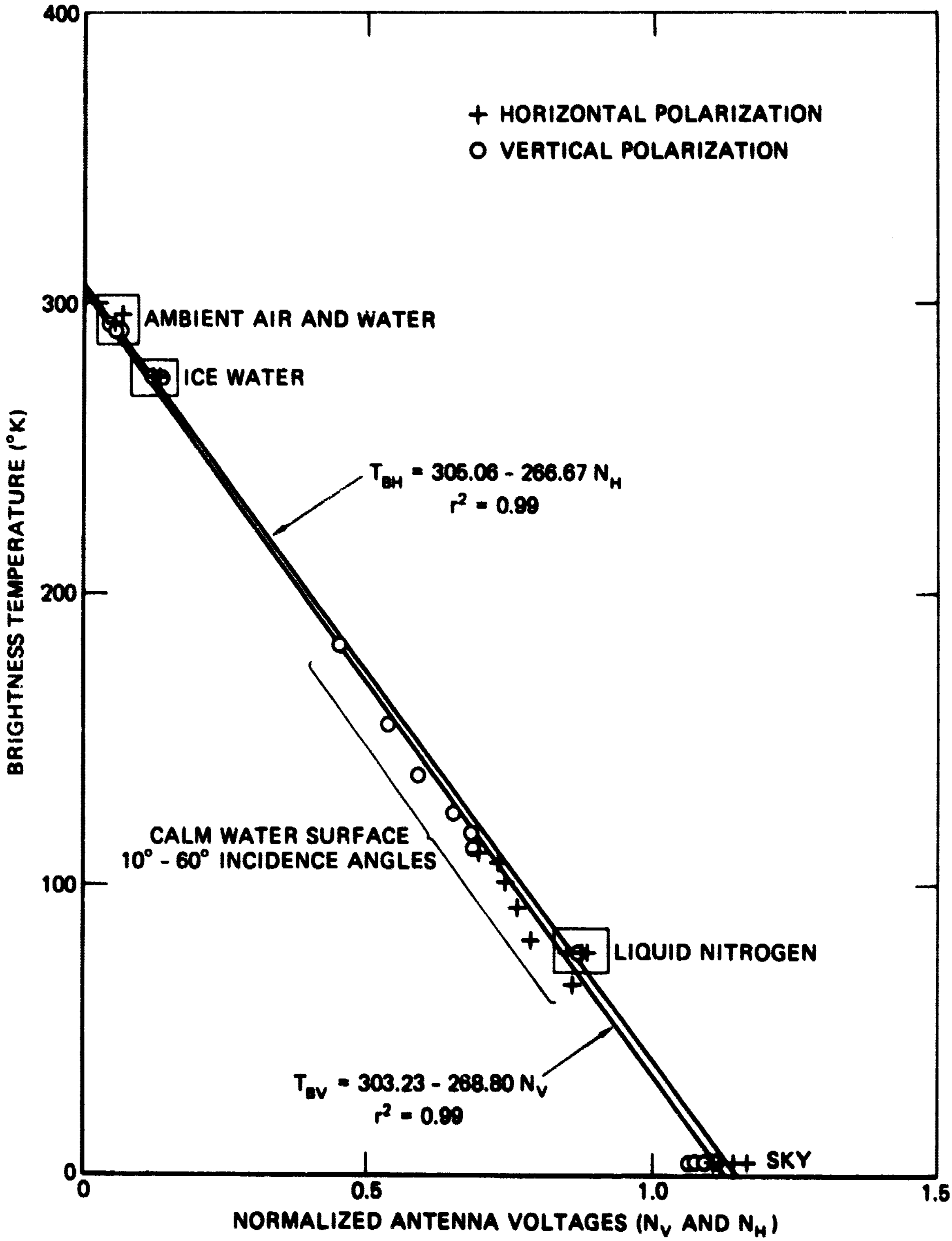

Figure 1. The calibration results of the 0.6 GHz radiometer at both vertical and horizontal polarizations.

3. THE MEASUREMENT RESULTS

Figure 2, a, b, and c, shows the measured brightness temperatures in vertical and horizontal polarizations, T_{BV} and T_{BH}, as a function of incidence angle θ at the frequencies of 0.6 GHz, 1.4 GHz, and 5.0 GHz in sequential order. The measurements were made on September 18, 1981. The volumetric water content W's measured during the radiometric measurements were quite uniform down to ~10 cm depth for all fields and were ~0.19 cm^3/cm^3 for bare field, ~0.22 cm^3/cm^3 for grass field, and ~0.20 cm^3/cm^3 for alfalfa field. The soil temperatures T_S's over the same layer were also quite uniform for all fields and were measured to be ~17°C for bare field, ~18°C for grass field, and ~18°C for alfalfa field, all of them comparable to air temperature of ~16.5°C. There were no substantial differences in both W's and T_S's among three fields and so the measured T_{BV}'s and T_{BH}'s could be compared and examined for the effect of vegetation cover.

The variations of bare field T_{BV} and T_{BH} with θ at 1.4 GHz and 5.0 GHz frequencies are analogous to these reported earlier (Wang et al., 1980). A similar variation of T_{BV} and T_{BH} with θ is also observed at 0.6 GHz frequency shown in Figure 2a. The radiometric response of vegetated fields, on the other hand, is quite frequency dependent. For example, at $\theta = 10°$ or $20°$, the measured T_{BV}'s and T_{BH}'s at 0.6 GHz over both grass and alfalfa fields are ~25°K above those measured over the bare field. The same measurements made at 1.4 GHz and 5.0 GHz respectively give ~60°K and ~95°K higher T_{BV} and T_{BH} values over the vegetated fields than those over the bare field. The separation between T_{BV} and T_{BH} at large θ is also much reduced from vegetated to bare fields. At $\theta = 40°$, the differences between T_{BV} and T_{BH} for either grass or alfalfa field are ~25°K at 0.6 GHz, ~12°K at 1.4 GHz and ~2°K at 5.0 GHz, while those for the bare field are ~50°K at all frequencies. It can be shown that at 10.6 GHz the measured T_{BV} and T_{BH} are practically equal at all θ, and their values at small θ are ~80°K higher than those measured over the bare field.

Figure 3, a, b, and c, in sequential order shows the normalized brightness temperature T_{NBH} of all three different fields at $\theta = 20°$ plotted as a function of volumetric water content W for 0.6 GHz, 1.4 GHz, and 5.0 GHz frequencies. The radiometric sampling depth generally varies with wavelength λ of observation and is estimated to be in the order of 0.06 - 0.1 λ (Mo et al., 1981). Therefore, the

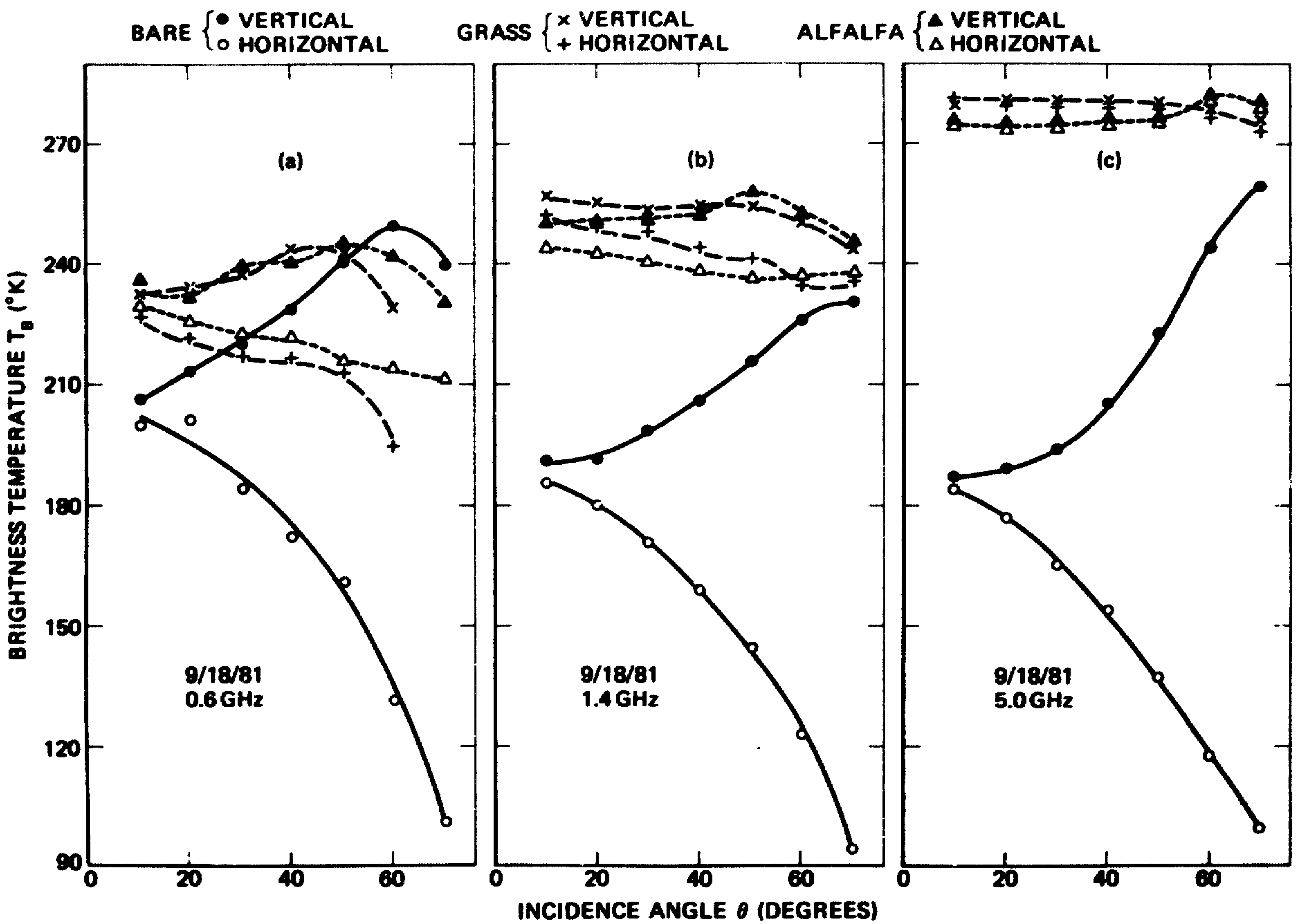

Figure 2. The measured brightness temperatures of bare, grass, and alfalfa fields plotted as a function of incidence angle for: (a) 0.6 GHz, (b) 1.4 GHz, and (c) 5.0 GHz frequencies.

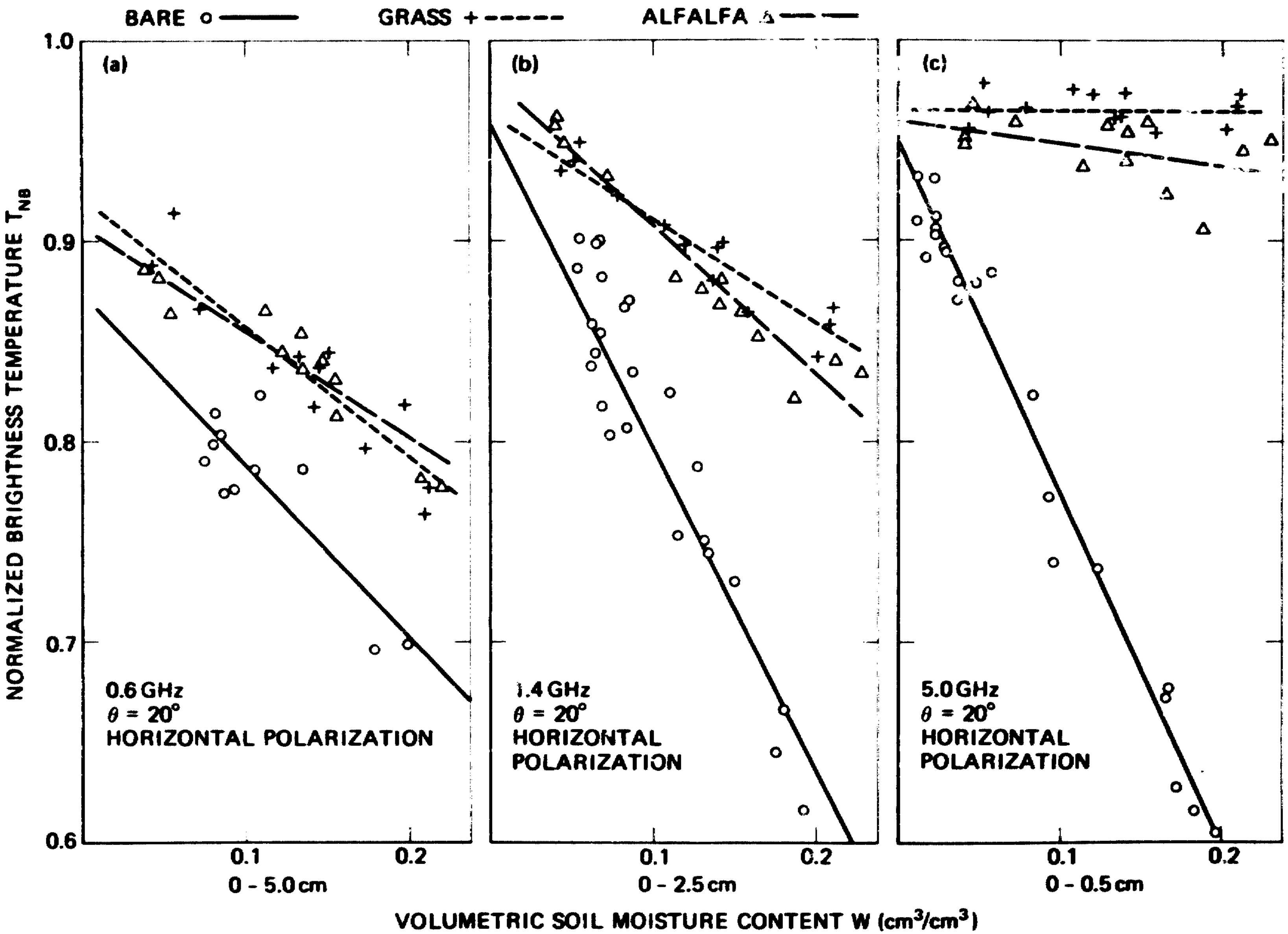

Figure 3. The normalized brightness temperatures at incidence angle of 20° and horizontal polarization plotted as a function of volumetric water content for: (a) 0.6 GHz, (b) 1.4 GHz, and (c) 5.0 GHz frequencies.

W values used in the figure are averaged over 0 – 5 cm layer for 0.6 GHz, 0 – 2.5 cm layer for 1.4 GHz, and 0 – 0.5 cm layer for 5.0 GHz frequency. T_{NBH} is defined as the ratio of the measured T_{BH} at a given frequency to soil temperature T_S at the corresponding layer. The bare field data at 1.4 GHz and 5.0 GHz frequencies are derived from the entire measurement period of July – September. The data from both vegetated fields cover only the period of August – September when 0.6 GHz radiometer is operational so that adequate comparison of results from different frequencies can be made. Notice that the decreases of T_{NBH} with W for bare field at all three frequencies are similar to those observed previously (Schmugge, 1980; Newton and Rouse, 1980; Wang et al., 1980). However, the rate of T_{NBH} decrease with W at 0.6 GHz is not as steep as that at other two frequencies. At small W, the measured T_{NBH} is low at 0.6 GHz and increases with frequency of observation. This is expected from the fact that for small W, a large moisture gradient exists near the soil's surface and the highest frequency radiometer responds to the driest surface layer. At high W $\simeq 0.2\ cm^3/cm^3$ when soil moisture and temperature profiles are rather uniform, the observed T_{NBH}'s are lowest at 5.0 GHz and highest at 0.6 GHz. Bare field measurements in the same test site during 1979 – 1980 also give higher T_{NBH}'s at 1.4 GHz than those at 5.0 GHz when $W > 0.18\ cm^3/cm^3$ (Wang et al., 1981). This phenomenon needs to be explored further both theoretically and experimentally.

Applying a linear regression to data points associated with each of the three frequencies and fields results in nine regression lines shown in Figure 3. The correlation coefficients, regression slopes and their standard deviations, and RMS deviations of data points from their respective regression lines are given in Table 1. It is clear from the figure that the presence of vegetation cover gives higher T_{NBH}'s and smaller regression slopes compared to those of the bare field. Furthermore, this slope reduction is enhanced with the increase in the frequency of observation. Since the sensitivity of soil moisture sensing is defined as the slopes of these regression lines (Wang et al., 1980), the effect of the vegetation cover is to reduce the sensitivity. At the frequencies of 5.0 GHz and 10.6 GHz, the sensitivity of soil moisture sensing approaches zero for the types of vegetation reported here. The moisture sensing sensitivity relative to the bare field for all four frequencies are also included in Table 1. The percent sensitivity reductions at 1.4 GHz and 5.0 GHz are comparable to the earlier measurements over a 30-cm grass field (Wang et al., 1980).

Table 1

Regression Results of Normalized Brightness Temperature and Soil Moisture Content for Bare, Grass, and Alfalfa Fields

Frequency	Field Type	Correlation Coefficient	Regression Slope and Error	RMS Residual	Sensitivity Relative to Bare Field
0.6 GHz	Bare	0.83	−0.85 ± 0.18	0.024	–
	Grass	0.92	−0.64 ± 0.08	0.017	0.75 ± 0.18
	Alfalfa	0.95	−0.52 ± 0.05	0.012	0.61 ± 0.15
1.4 GHz	Bare	0.95	−1.61 ± 0.12	0.026	–
	Grass	0.95	−0.52 ± 0.05	0.011	0.32 ± 0.04
	Alfalfa	0.97	−0.74 ± 0.05	0.013	0.46 ± 0.05
5.0 GHz	Bare	0.99	−1.75 ± 0.07	0.020	–
	Grass	0.07	+0.01 ± 0.04	0.009	~0
	Alfalfa	0.43	−0.11 ± 0.06	0.015	0.06 ± 0.03
10.6 GHz	Bare	0.97	−1.57 ± 0.08	0.026	–
	Grass	0.03	~0 ± 0.03	0.008	~0
	Alfalfa	0.12	−0.02 ± 0.04	0.013	~0.1 ± 0.2

Kirdiashev et al. (1979) reported measurements over fields covered with vegetation of different kinds with radiometers in the wavelength range of 3 - 30 cm (1 - 10 GHz). Their results are reproduced as solid smooth curves in Figure 4 where relative sensitivity is plotted against the wavelength of observation. The results of our measurements are also included in the figure for comparison. It is quite clear that the frequency dependence of the relative sensitivity follows closely in shape with the curves of Kirdiashev et al. (1979). Our results indicate that our grass and alfalfa fields behaved more like a broad leaf than a small grain.

4. CONCLUSION

An experiment on soil moisture remote sensing was conducted on bare, grass, and alfalfa fields with radiometers at the frequencies of 0.6 GHz, 1.4 GHz, 5.0 GHz, and 10.6 GHz. The results from this experiment extend the frequency range of observation down to 0.6 GHz and confirm the frequency dependence of sensitivity reduction due to the presence of vegetation cover reported earlier (Kirdiashev et al., 1979; Wang et al., 1980). For the type of vegetated fields reported here, the vegetation effect is appreciable even at 0.6 GHz frequency. Measurements over the bare soil gives an unexpected result. When soil is wet, the measured brightness temperature is lowest at 5.0 GHz and highest at 0.6 GHz. Since there is no significant difference in the real part of the measured dielectric constant at high soil moisture content in the frequency range of 0.6 - 5.0 GHz (Njoku and Kong, 1977), it is expected that the brightness temperature measured in the same frequency range over a wet soil would also be comparable. The measurement result shown above is contrary to this expectation. More measurements as well as theoretical studies are required in order to fully understand this phenomenon.

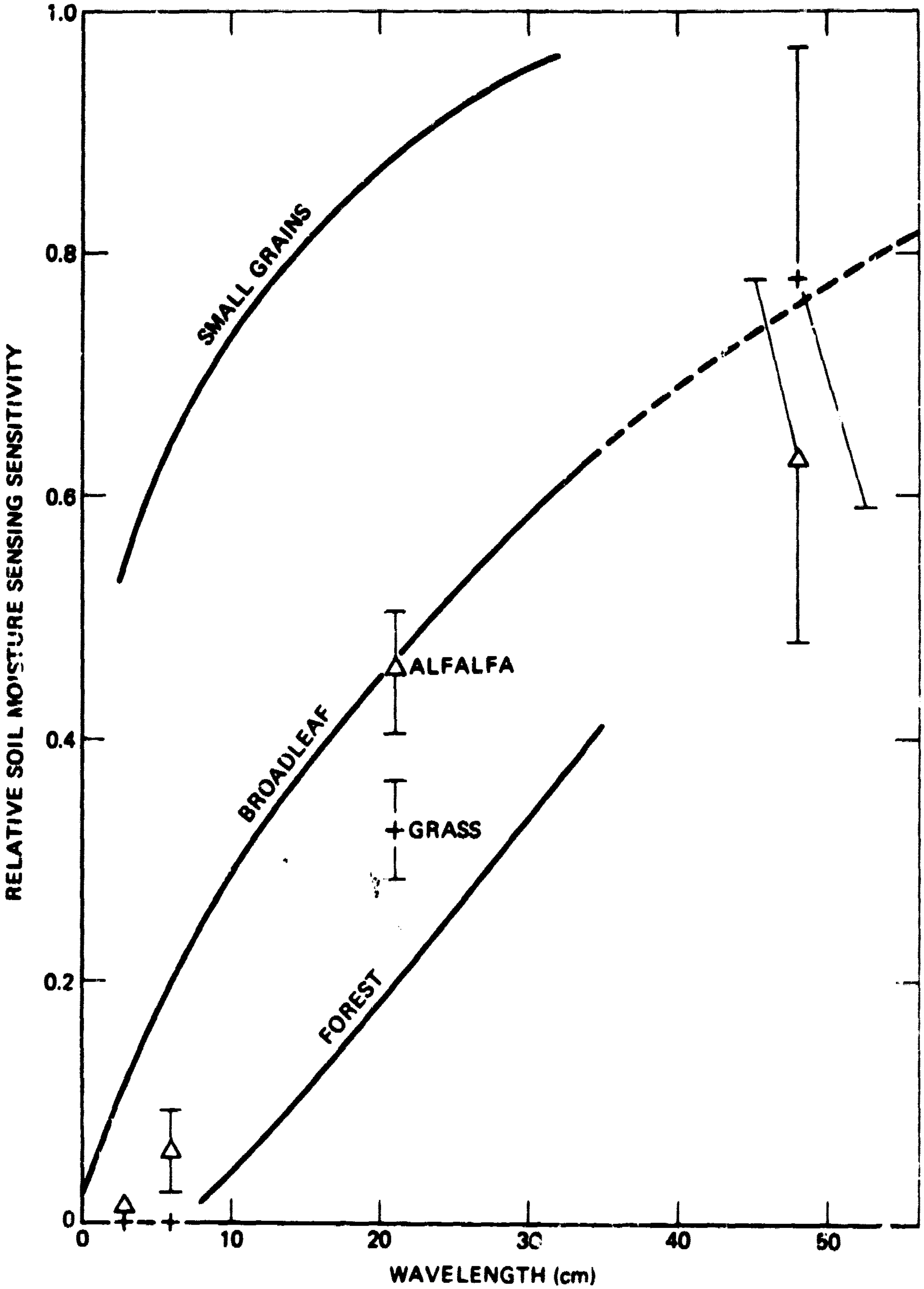

Figure 4. The variation of relative soil moisture sensing sensitivity with wavelength of observation for vegetated fields. The sensitivity is normalized to that of bare field.

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FIGURE CAPTIONS

Figure 1. The calibration results of the 0.6 GHz radiometer at both vertical and horizontal polarizations.

Figure 2. The measured brightness temperatures of bare, grass, and alfalfa fields plotted as a function of incidence angle for: (a) 0.6 GHz, (b) 1.4 GHz, and (c) 5.0 GHz frequencies.

Figure 3. The normalized brightness temperatures at incidence angle of 20° and horizontal polarization plotted as a function of volumetric water content for: (a) 0.6 GHz, (b) 1.4 GHz, and (c) 5.0 GHz frequencies.

Figure 4. The variation of relative soil moisture sensing sensitivity with wavelength of observation for vegetated fields. The sensitivity is normalized to that of bare field.