General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

E84-10019

SM-G2-04285

TM-83937

AgRISTARS

A Joint Program for Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing

"Made available under NASA sponsorship in the interest of early and wide dissemination of Earth Resources Survey Program information and without liability for any use made thereof."

Soil Moisture

Passive Microwave Sensing of Soil Moisture Content: Soil Bulk Density and Surface Roughness

SEP 1983
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

J. R. Wang

(E84-10019) PASSIVE MICROWAVE SENSING OF SOIL MOISTURE CONTENT: SOIL BULK DENSITY AND SURFACE ROUGHNESS (NASA) 32 p HC A03/MF A01 CSCL 02C

N84-11556

Unclas
G3/43 00019

MAY 1982

TM-83937

PASSIVE MICROWAVE SENSING OF SOIL MOISTURE CONTENT: SOIL BULK DENSITY AND SURFACE ROUGHNESS

J. R. Wang

May 1982

Laboratory for Atmospheric Sciences
NASA/GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

BIBLIOGRAPHIC DATA SHEET

1. Report No. TM-83937	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Passive Microwave Sensing of Soil Moisture Content: Soil Bulk Density and Surface Roughness		5. Report Date May 1982 6. Performing Organization Code Code 913
7. Author(s) J. R. Wang		8. Performing Organization Report No.
9. Performing Organization Name and Address Code 913 NASA/Goddard Space Flight Center Greenbelt, Maryland 20771		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address NASA/Goddard Space Flight Center Greenbelt, Maryland 20771		13. Type of Report and Period Covered Technical Memorandum 14. Sponsoring Agency Code

15. Supplementary Notes

This activity was supported by the AgRISTARS Soil Moisture and Conservation Projects.

16. Abstract

Microwave radiometric measurements over bare fields of different surface roughnesses were made at the frequencies of 1.4 GHz, 5 GHz, and 10.7 GHz to study the frequency dependence as well as the possible time variation of surface roughness. The presence of surface roughness was found to increase the brightness temperature of soils and reduce the slope of regression between brightness temperature and soil moisture content. The frequency dependence of the surface roughness effect was relatively weak when compared with that of the vegetation effect. Radiometric time-series observation over a given field indicated that field surface roughness might gradually diminish with time, especially after a rainfall or irrigation. This time variation of surface roughness served to enhance the uncertainty in remote soil moisture estimate by microwave radiometry. Three years of radiometric measurements over a test site revealed a possible inconsistency in the soil bulk density determination, which turned out to be an important factor in the interpretation of radiometric data.

17. Key Words (Selected by Author(s)) Soil Moisture, Remote Sensing Microwave Radiometry	18. Distribution Statement Unlimited

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia

22161

GSFC 25-44 (10/77)

PASSIVE MICROWAVE SENSING OF SOIL MOISTURE CONTENT: SOIL BULK DENSITY AND SURFACE ROUGHNESS

ABSTRACT

Microwave radiometric measurements over bare fields of different surface roughnesses were made at the frequencies of 1.4 GHz, 5 GHz, and 10.7 GHz to study the frequency dependence as well as the possible time variation of surface roughness. The presence of surface roughness was found to increase the brightness temperature of soils and reduce the slope of regression between brightness temperature and soil moisture content. The frequency dependence of the surface roughness effect was relatively weak when compared with that of the vegetation effect. Radiometric time-series observation over a given field indicated that field surface roughness might gradually diminish with time, especially after a rainfall or irrigation. This time variation of surface roughness served to enhance the uncertainty in remote soil moisture estimate by microwave radiometry. Three years of radiometric measurements over a test site revealed a possible inconsistency in the soil bulk density determination, which turned out to be an important factor in the interpretation of radiometric data.

PASSIVE MICROWAVE SENSING OF SOIL MOISTURE CONTENT: SOIL BULK DENSITY AND SURFACE ROUGHNESS

1. Introduction

A number of experiments on the remote sensing of soil moisture content have been conducted with both active and passive microwave sensors in the past decade (Ulaby et. al., 1978, 1979; Schmugge, 1978, 1980; Schmugge et. al., 1974; Njoku and Kong, 1977; Blanchard et. al., 1981; Choudhury et. al., 1979; Schanda et. al., 1978; Newton and Rouse, 1980; Newton, 1977; Wang et. al., 1980, 1982a, b, c). These experiments have provided some basic understanding of the effects of soil texture, surface roughness, and vegetation cover on the responses of microwave radiometer and radar systems. Theoretical models, both vigorous and phenomenological, have also been developed to account for these effects based on the experimental results (Burke et. al., 1979; Choudhury et. al., 1979; Wang and Choudhury, 1981; Fung and Ulaby, 1978; Jackson et. al., 1982). In conducting these experiments, ground truth data on soil temperature and moisture content and soil bulk density at various depths were acquired and ultimately used for analysis with data collected by microwave sensors. The ground truth data describing the status of soils at the times of the experiments, with some statistical uncertainty, were used as a basis for assessing the promise and limitation of radar and radiometer systems as effective soil moisture remote sensors. The possibility that the acquired ground truth data might not be reliable enough to evaluate a remote sensor has not been seriously questioned.

In this paper we explore an important parameter in the ground truth data acquisition, namely, the soil bulk density. Among the three commonly acquired ground truth parameters over a bare field, the soil bulk density, the soil temperature, and the soil moisture content in percent by dry weight, the soil bulk density probably is the most difficult one to determine precisely. The soil temperature can be easily measured to ± 1°C accuracy by a well calibrated temperature probe. The moisture content in percent by dry weight of a soil sample can be determined easily to within ± 1%.

Most uncertainties in the determination of these two parameters come from their spatial variation over a bare field. The uncertainty in the soil bulk density measurement, on the other hand, is much more difficult to estimate and its source may originate from sampling procedures as well as the person doing the sampling. The soil bulk density is used in converting the soil moisture content in percent by dry weight into volumetric soil moisture content, a quantity which more uniquely determines the dielectric permittivity of a soil-water mixture (Wang and Schmugge, 1980). This uniqueness in the relationship between dielectric permittivity and volumetric moisture content is essential in microwave emission model calculations and the interpretation of experimental results.

Three years of experimental data obtained with microwave radiometers at the frequencies of 1.4 GHz and 5 GHz over a test site during 1979-1981 were used for the present study. The soil in this test site was Elinsboro sandy loam which consisted of 67% sand, 19% silt, and 14% clay (Wang et. al., 1982c). Another test site providing bare fields of different soil texture and surface roughness was included in the 1981 experiment. The field soil in this test site was Mattapex silty loam which consisted of 32% sand, 43% silt, and 25% clay. Two more radiometers at the frequencies of 10.7 GHz and 0.6 GHz were added in the 1981 experiment (Wang et. al., 1982b). In the following discussion the effects of uncertainty in soil bulk density determination on the radiometric interpretation of surface roughness and soil texture were illustrated. The responses of radiometers to the possible change of surface roughness with time were examined. The frequency dependence of soil's microwave emission on surface roughness was analyzed. The experimental results of Newton and Rouse (1980) were also included in the analyses.

2. The Effect of Soil Bulk Density

If a reliable method can be developed to make a precision measurement of volumetric moisture content directly, then the soil bulk density determination is of little value in the soil moisture remote sensing experiment with microwave radiometers or radars. This is so because the variation of dielectric constant, and therefore a soil's thermal microwave emission or backscatter, with soil

moisture content is quite unique when the moisture content is expressed in volume basis. To illustrate this, Figures 1 and 2 show the measured dielectric constant of Long Lake Clay as a function of soil moisture content expressed in percent by dry weight (W_W) and in volume (W_V) respectively (Lundien, 1971). The measurements are made with soil samples (total number N = 108) in three different compactive efforts with forces of 5.74, 11.83, and 18.47 Newtons/cm^2. The corresponding average bulk densities p's of the soil samples are 1.09, 1.18, and 1.21 g/cm^3. Applying a polynomial regression to each of four data sets (two for the real part ϵ' and another two for the imaginary part ϵ'' in both figures) regardless of compactive effort results in the four smooth curves with associated correlation coefficient r and standard error of estimates d shown in the figures. The regressions are performed for up to 5 degree polynomials and only the results with best r and d values are shown here. Notice that, because of the lack of data points at small W_V or W_W, the intercepts at ϵ' and ϵ'' axes of the regression results are much higher than those measured for other dry soils (Lundien, 1971; Topp et. al., 1980; Wang and Schmugge, 1980).

Clearly, r's are higher and d's smaller for the data shown in Figure 2 than those in Figure 1. A close examination of Figure 1 reveals that the measured ϵ' and ϵ'' values for soil samples with least compactive effort (5.74 N/cm^2) are generally lower than those of high compactive efforts (11.83 and 18.47 N/cm^2). This is due to the fact that the dominant contributions to ϵ' and ϵ'' come from water and, for a given W_W, soil samples with least compactive effort contains least amount of water. When p's of soil samples are taken into account and W_V's are used (as in Figure 2), the differences in ϵ' and ϵ'' values due to different compactive efforts are minimized and both r and d values improve. This comparison of Figures 1 and 2 clearly shows the preference of acquiring soil moisture content in volume basis.

The ground truth acquisition in support of remote sensing of soil moisture experiments with microwave sensors (Ulaby et. al., 1978, 1979; Njoku and O'Neill, 1982; Newton and Rouse, 1980; Wang et. al., 1982c) generally requires measurements of both p and W_W in order to arrive at W_V.

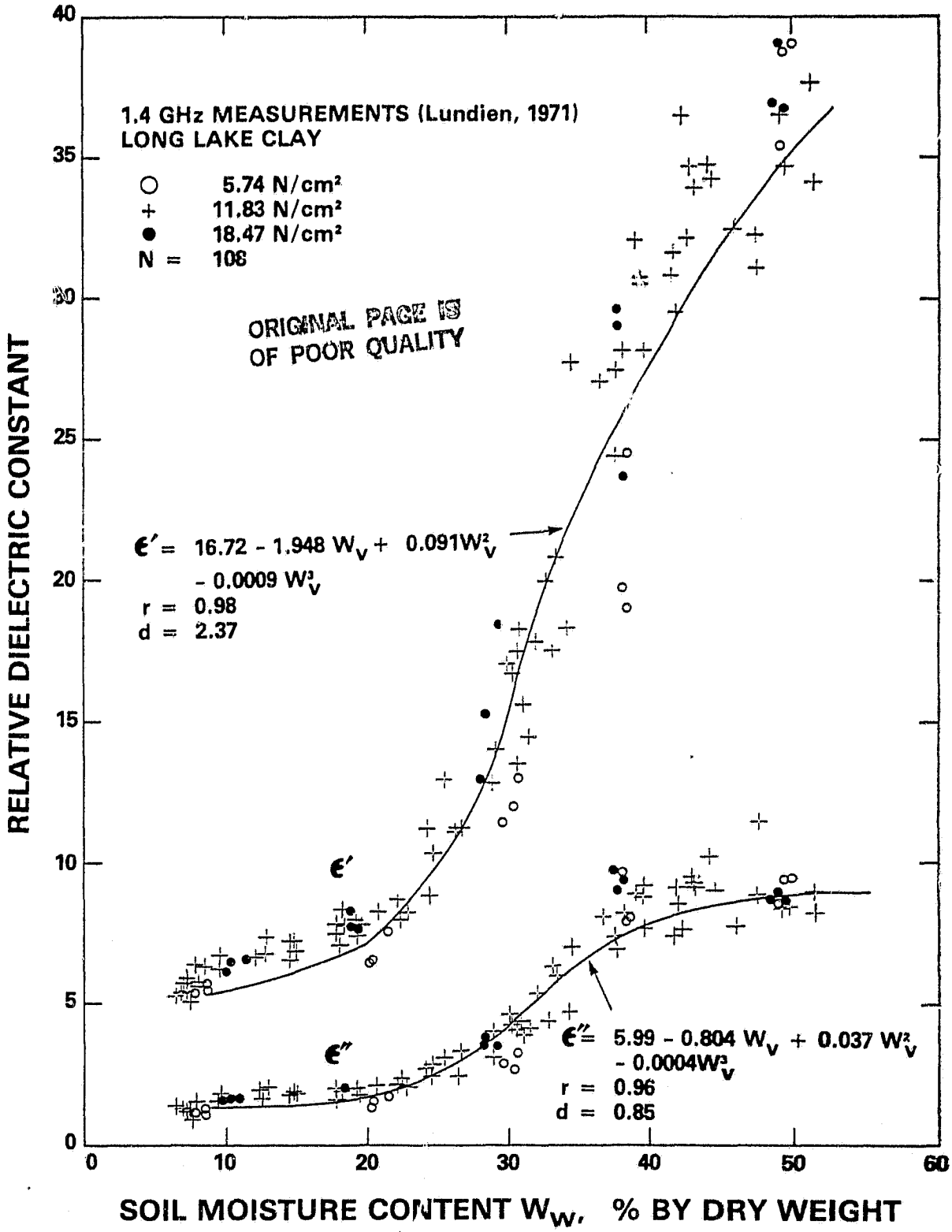

Figure 1. The variation of measured dielectric constant at 1.4 GHz frequency with soil moisture content expressed in percentage of dry weight for Long Lake Clay. Three different compactive efforts were applied to the soil samples in the measurements.

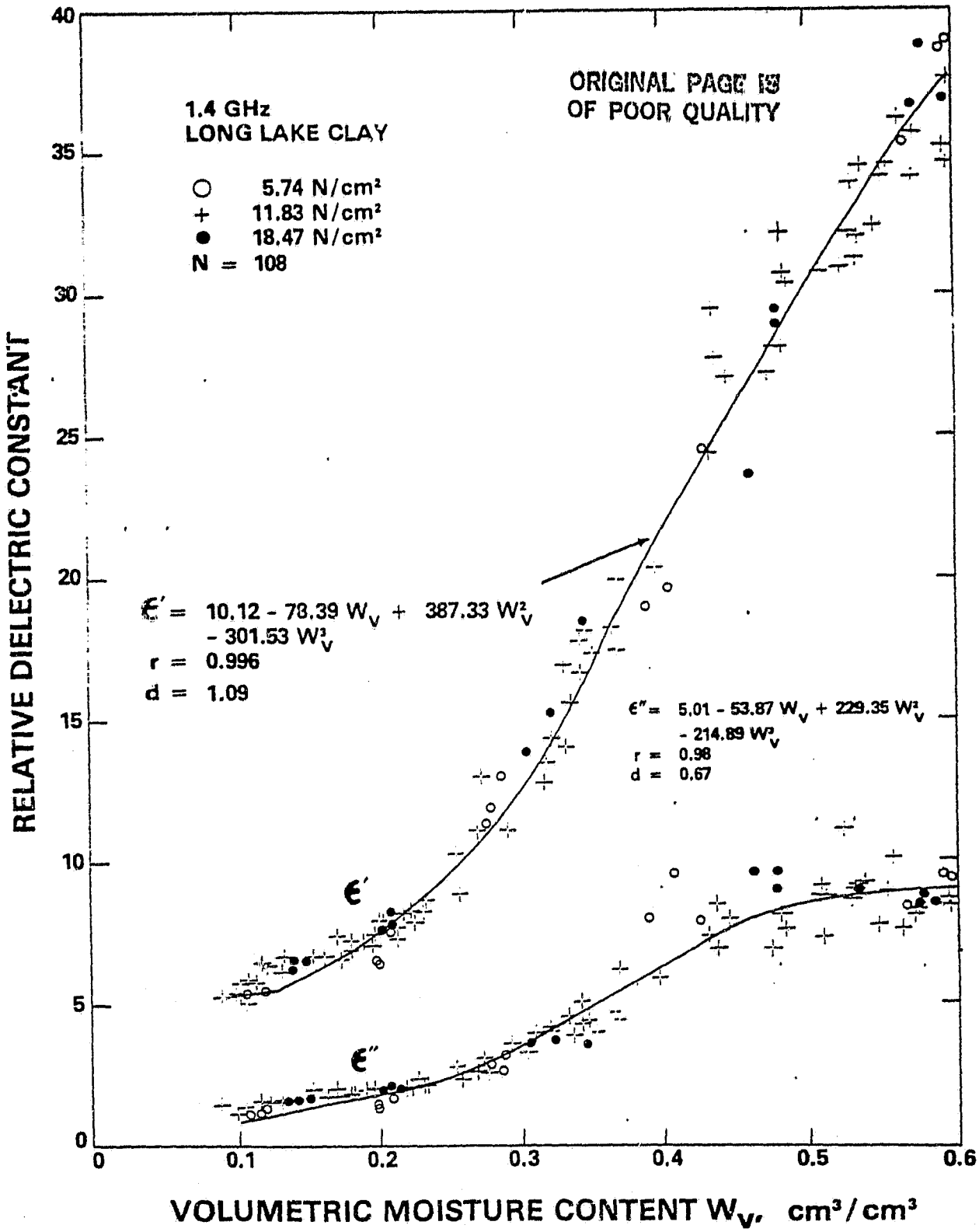

Figure 2. The variation of measured dielectric constant at 1.4 GHz frequency with volumetric soil moisture content for Long Lake Clay. Three different compactive efforts were applied to the soil samples in the measurements.

ORIGINAL PAGE IS
OF POOR QUALITY

Measurements of W_W's with good precision are not difficult, but the determinations of p's are more often associated with significant uncertainties. To illustrate this, we show in Figures 3 and 4 the measured normalized brightness temperatures T_{NB}'s obtained during 1979-1981 plotted as a function of W_V and W_W respectively. Data from both 1.4 GHz (a) and 5 GHz (b) frequencies at 20° incidence angle and horizontal polarization are shown. The W_V's and W_W's are evaluated at two different layers of 0-2.5 cm and 0-0.5 cm for 1.4 GHz and 5 GHz measurements because of the difference in the sampling depth (Mo et. al., 1980). T_{NB} is defined as

$$T_{NB} = \frac{T_B}{T_S} \tag{1}$$

where T_B is the measured brightness temperature and T_S is the soil's thermal temperature measured at two different layers corresponding to the two frequencies. All three years of data are obtained over the same general area of the first test site (sandy loam soil) so that the effect of spatial soil texture variation is minimized. The fields used for the experiments are 15M X 15M in size and are all prepared in the same way so that there is not much of a difference in surface roughness in different years of measurements.

A linear regression applied to all the data points in each of the four plots in Figures 3 and 4 results in the regression slopes, r's and d's shown. The r = 0.89 and d = 0.043 obtained in Figure 3a for regression between T_{NB} and W_V at 1.4 GHz are worse than the r = 0.94 and d = 0.032 in Figure 4a obtained for the similar regression between T_{NB} and W_W at the same frequency. The analogous comparison between Figure 3b and Figure 4b also shows better r and d values for regression between T_{NB} and W_W at 5 GHz frequency. The reason for the differences in the r and d values between the results of Figures 3 and 4 is clearly displayed by the data obtained from different years of measurements. The data points of 1981 measurements in Figures 3, a and b, are well separated from those of 1979-1980 measurements. The data points shown in Figure 4, a and b, on the other hand, are much better mixed. Since the only difference between Figures 3 and 4 comes from the expressions W_V and W_W, the poorer r and d values in Figure 3 must be

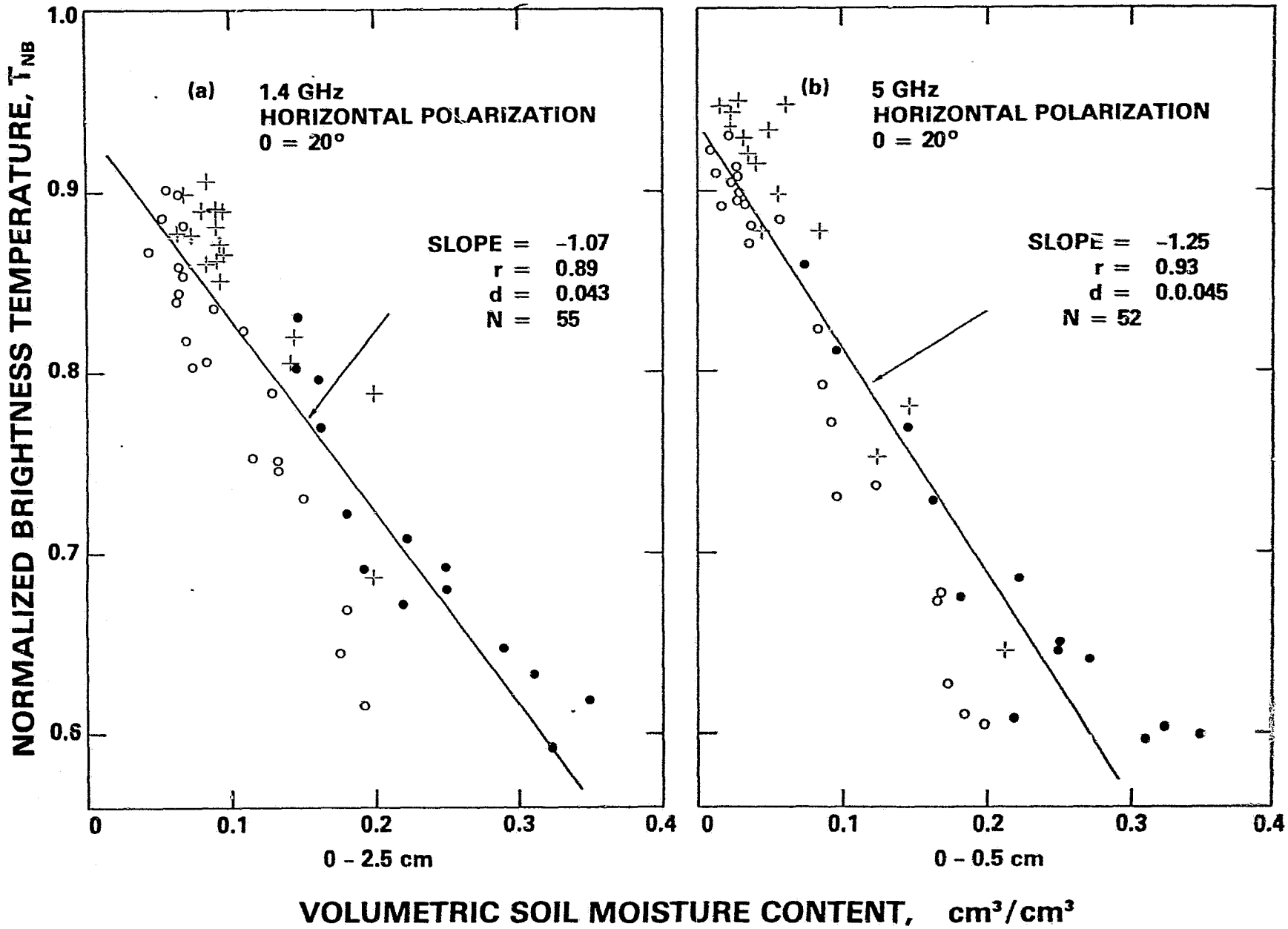

Figure 3. The normalized brightness temperature measured at 1.4 GHz and 5 GHz frequencies vs. volumetric moisture content. The measurements were made for three consecutive years over fields with Elinsboro sandy loam: • 1979; + 1980; ○ 1981.

ORIGINAL PAGE IS
OF POOR QUALITY

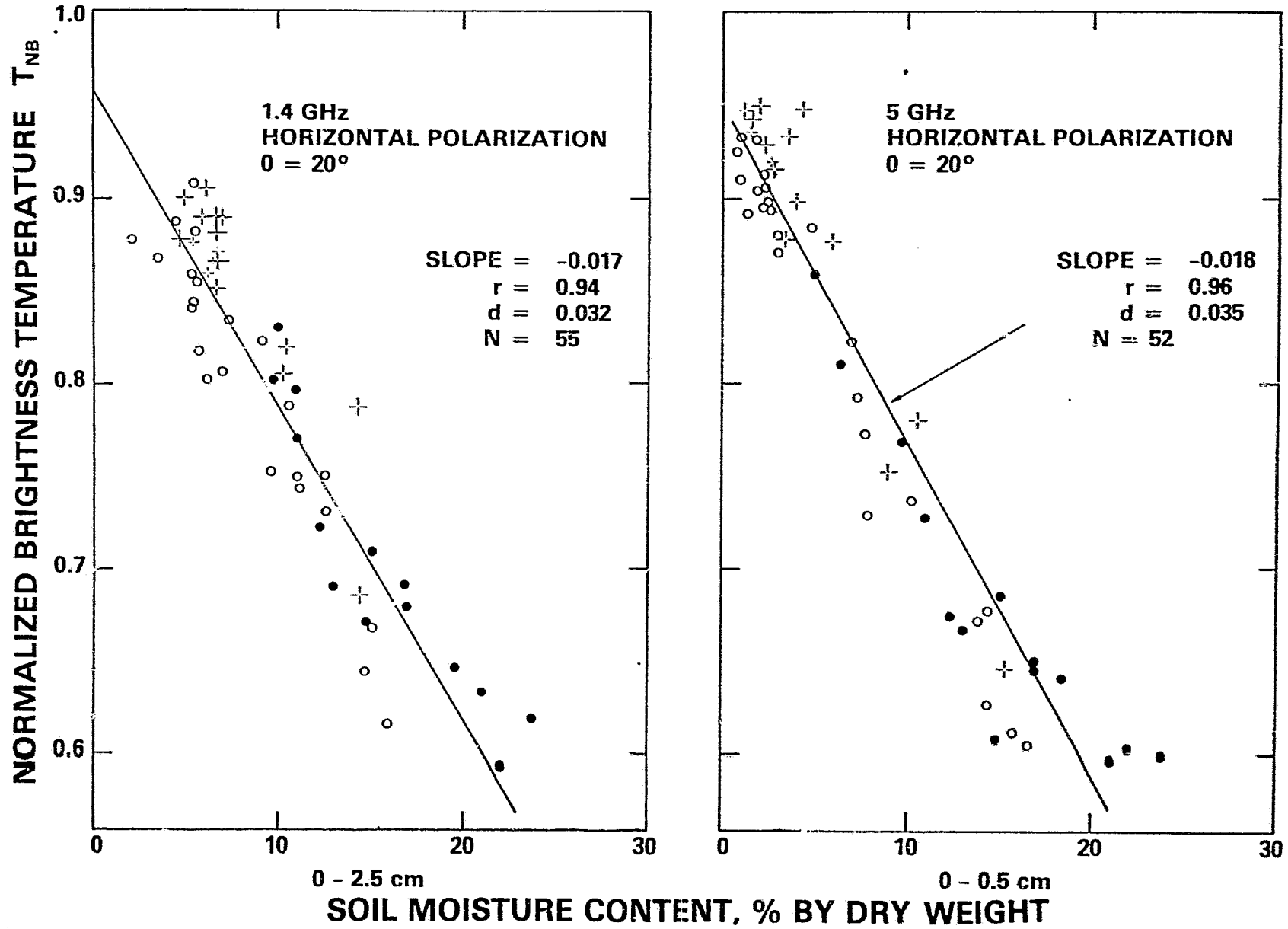

Figure 4. The normalized brightness temperature measured at 1.4 GHz and 5 GHz frequencies vs. soil moisture content in percent by dry weight. The measurements were made for three consecutive years over fields with Elinsboro sandy loam: ● 1979; + 1980; ○ 1981.

ORIGINAL PAGE IS
OF POOR QUALITY

ORIGINAL PAGE IS
OF POOR QUALITY

predominantly due to the introduction of p. The measured average p's for the bare fields in the top 2.5 cm layer are 1.47 g/cm^3 in 1979, 1.38 g/cm^3 in 1980, and 1.25 g/cm^3 in 1981 with an estimated uncertainty of ~ 0.1 g/cm^3. The measurements of p in 1979 and 1980 were made with a cylindrical container 2.5 cm in height and 5 cm in diameter. A different sampling procedure was adopted by different personnel in the 1981 measurements.

The uncertainty in the determination of p's could very well be one of the reasons that a small vegetation cover effect was reported at 1.4 GHz frequency (Newton and Rouse, 1980). Plotting T_{NB} against W_V in the top 2 cm layer for both smooth bare and vegetated fields, Newton and Rouse found that data points from both fields were well mixed and concluded that vegetation effect was negligible at 1.4 GHz frequency. With the amount of biomass measured for the vegetated field (Newton and Lee, 1974), it was estimated by Wang et. al. (1982a) that some vegetation effect should be observable. A close examination of the ground truth data report (Newton and Lee, 1974) gave p = 1.55 g/cm^3 for the smooth bare field and p = 1.05 g/cm^3 for the smooth vegetated field in the top 2 cm layer. Since both bare and vegetated fields consisted of the same soil type and were prepared in the same way, it was unusual that p's between the two fields should differ so much. It can be shown that if T_{NB}'s from both fields were plotted against W_W's in the top 2 cm layer, the effect of vegetation cover was indeed observable.

3. The Effect of Surface Roughness

The microwave radiometric measurements of surface roughness effect have been made by Newton and Rouse (1980) and more recently by Wang et. al. (1982c). It is found from these studies that the effect of surface roughness generally increases the soils' thermal microwave emission and reduces the slope of regression between T_{NB} and W_V. A particular result shared by both of these studies but not explicitly discussed in the reports is that the correlation coefficient r derived from regression between observed T_{NB} and W_V tends to degrade from smooth to rough fields (except the 10.7 GHz measurement of Newton and Rouse). This degradation could be due to the difficulty in soil moisture ground truth sampling of inhomogeneous field when surface is

ORIGINAL PAGE IS
OF POOR QUALITY

rough. Another possible cause is the time variation of surface roughness. This latter possibility is examined in this section.

Figures 5 and 6 show the observed T_{NB}'s plotted as a function of W_V from data sets of Wang et. al. (1982c) and Newton and Rouse (1980) respectively. Plots a, b, and c in Figure 5 gave, in sequential order, the results of the 1.4 GHz, 5 GHz, and 10.7 GHz measurements made in 1981. The data are obtained from three bare fields with two different soil textures and three different surface roughness as indicated in the figure. As pointed out in the previous section, the soil bulk density p measured in 1981 appears to be low compared with those of the previous two years. Since the uncertainty in the measurement is ~ 0.1 g/cm^3, the upper bounds of the measured p's (0.1 g/cm^3 is added to the average p's measured in each layer) are used in evaluating W_V in Figure 5. This modification in p's has no bearing on the discussion pertaining to this section, but will be of certain significance in the next section when sensitivity reduction in soil moisture sensing due to surface roughness is discussed. The W_V values used in Figure 6 were derived from data report of Newton and Lee (1974). Their radiometric measurements were made only at 1.4 GHz and 10.7 GHz frequencies. Applying a linear regression to each data group of measurement frequency and surface roughness in both Figures 5 and 6 results in the regression slopes, r's and d's shown. With the exception of the 10.7 GHz data in Figure 6b, all regression slopes decrease with an increase in surface roughness. It is not clear why the smaller regression slope is observed for the smooth field than for the medium rough field in the 10.7 GHz results in Figure 6b. One of the possibilities could be due to the difference in the weathering of soil surface roughness between the two fields. As an illustration the data points obtained from 10.7 GHz measurements over the medium rough field in Figure 6 are separated into two groups, one group taken before July 11 and the other, after July 12, 1974. The data group obtained earlier generally has higher T_{NB}'s than the one obtained later at a comparable W_V level. This observation suggests a possible change in the field surface roughness with time.

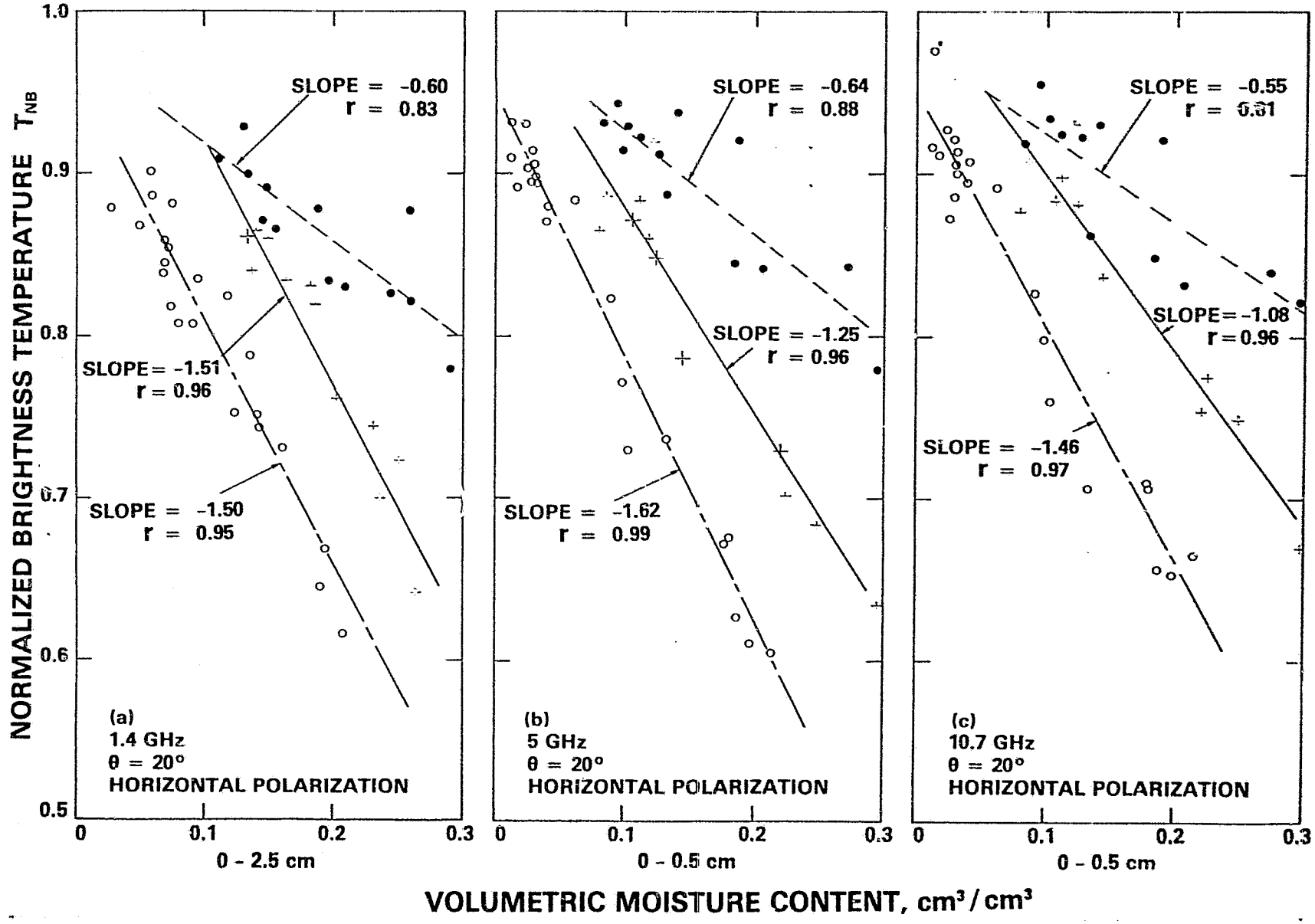

Figure 5. The measured variation of normalized brightness temperatures with volumetric soil moisture content at (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz frequencies. Data were derived from the 1981 measurements of Wang et. al. (1982c): o very smooth field (sandy loam); + smooth field (silty loam); ● rough field (silty loam).

ORIGINAL PAGE IS
OF POOR QUALITY

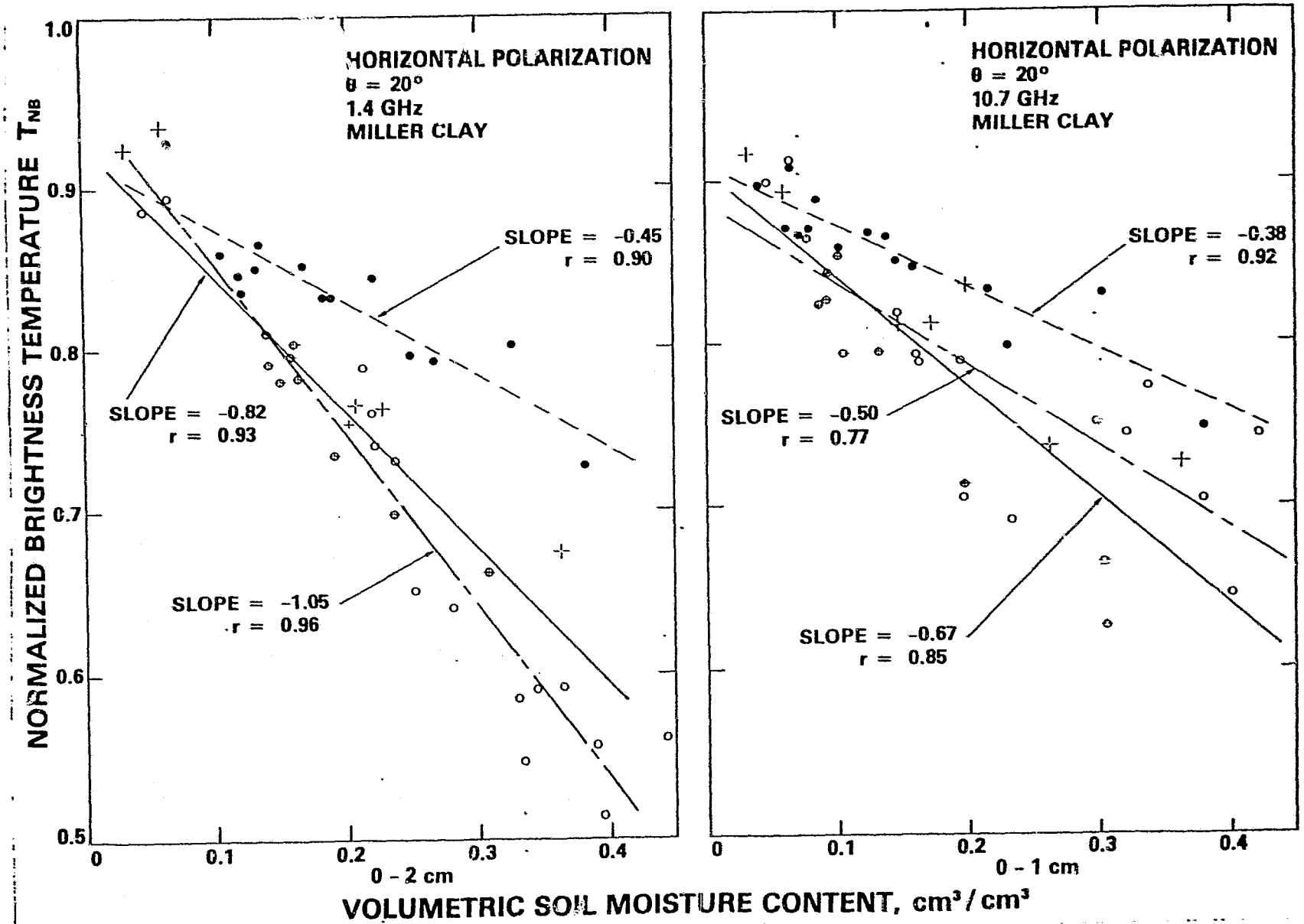

Figure 6. The measured variation of normalized brightness temperatures with volumetric soil moisture content at (a) 1.4 GHz and (b) 10.7 GHz frequencies. Data were derived from the 1974 measurements over fields of Miller Clay by Newton and Rouse (1980 and references therein): o smooth field; + medium rough field before July 11 (⊕ after July 12); ● very rough field.

ORIGINAL PAGE IS
OF POOR QUALITY

To explore more fully the possible time variation of surface roughness, we plot the residual R of regression, i.e., the difference between the measured T_{NB} and T_{NB} estimated from linear regression at a given W_V, as a function of time in Figure 7 for the data derived from Figure 6 and in Figure 8 for the data derived from Figure 5. The arrows A and B in Figure 7 indicated the times when there were appreciable increases in W_V's in all three fields. The measured W_V's in the top 0-1 cm layer for the smooth, medium rough, and very rough fields respectively were 0.066, 0.060, and 0.065 cm^3/cm^3 on June 27 and were 0.421, 0.361, and 0.380 cm^3/cm^3 on July 10. From July 11 to July 12, as indicated by arrow B, the measured W_V's changed from 0.322 to 0.401 cm^3/cm^3 for the smooth field, from 0.147 to 0.301 cm^3/cm^3 for the medium rough field, and from 0.137 to 0.215 for the very rough field. Similarly, the arrows in Figure 8 gave the times when changes in the measured W_V's were observed. The numbers associated with the arrows were the total amounts of rainfalls in cm recorded by a raingage at the test site where the smooth and rough silty loam fields of NASA/GSFC experiment were situated.

If there is no change in field conditions, then the variation of R with time would be random and no correlation between R and time should be observed. There is a substantial scatter in the data points in both Figures 7 and 8 and analyzing the change of R's with time statistically is difficult. Qualitatively there appears to be an observable change in R with time and this change is smaller at 1.4 GHz than at 5 GHz or 10.7 GHz frequency. For example, most of the R values before July 10 in Figure 7 are positive (higher measured T_{NB} than estimated), while most of those after July 10 are negative. The rapid change from positive to negative R values appears to be associated with the increase in W_V indicated by the arrows. The variation of R with time at 1.4 GHz in Figure 8a does not give much a slope, while those at both 5 GHz and 10.7 GHz frequencies definitely show a general decrease in R with time. These observations strongly suggest that at least for 5 GHz and 10.7 GHz measurements the surface roughness of the bare fields becomes smoother with time. The change of surface roughness with time or with application of water to the fields (as implied by Figure 7) will introduce some uncertainty in estimating soil moisture content remotely by microwave radiometers.

ORIGINAL PAGE IS
OF POOR QUALITY

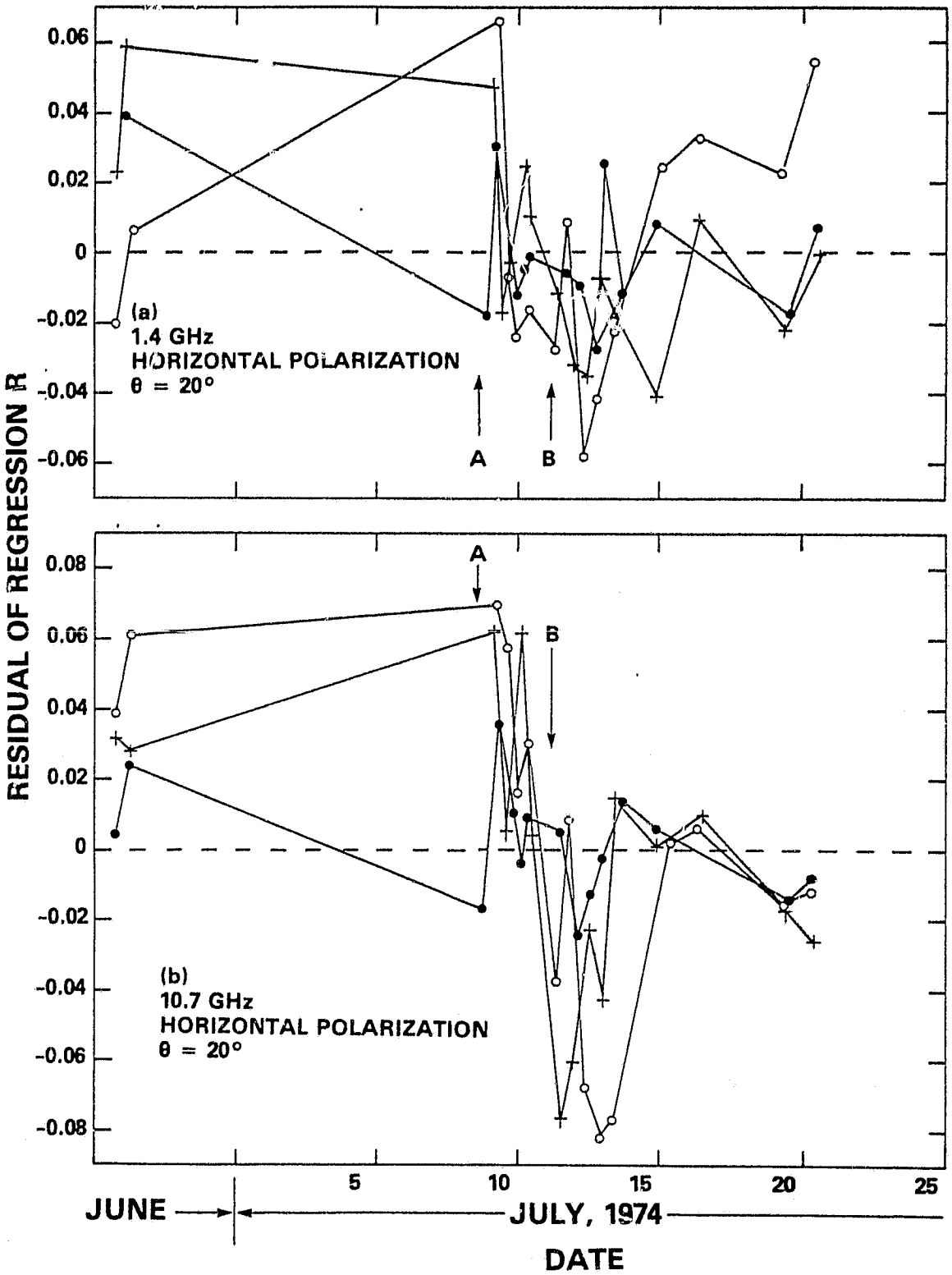

Figure 7. Time variation of residuals from the regressions of data in Figure 6: ○ smooth field; + medium rough field; ● very rough field. Arrows A and B indicated the times when substantial changes in surface soil moisture were observed.

ORIGINAL PAGE IS
OF POOR QUALITY

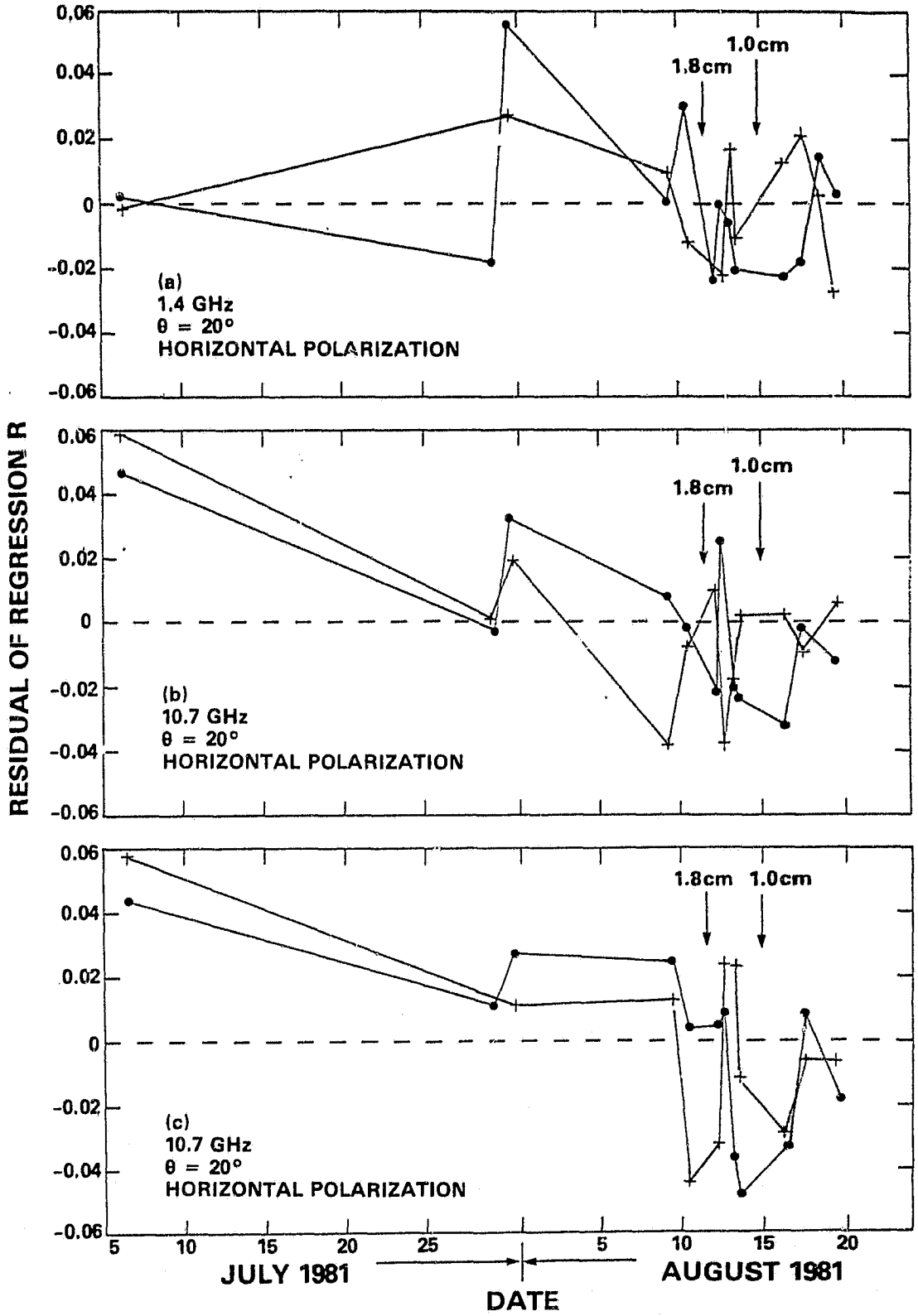

Figure 8. Time variation of residuals from the regressions of data in Figure 6: + smooth field; ● rough field. The numbers associated with the arrows were the amounts of rainfall recorded during August 10-20 when intensive radiometric measurements were made over the two fields.

ORIGINAL PAGE IS
OF POOR QUALITY

4. Frequency Dependence of Surface Roughness Effect

Previous studies on the effect of soil surface roughness using microwave radiometric measurements are based on a phenomenological model with two adjustable parameters (Choudhury et. al., 1979; Wang and Choudhury, 1981; Wang et. al., 1982c). While the model gives a reasonable description of the observational results over the incidence angles of 10°-50° (Wang et. al., 1982c), to provide a physical meaning to the two adjustable parameters is difficult. Thus in order to avoid analyzing the surface roughness effect based on a specific model, the following approach is adopted for the treatment of the measured data. It is noticed from Figure 5 of the previous section that the presence of surface roughness reduces the slope of regression between T_{NB} and W_V, a phenomenon analogous to the effect of vegetation cover reported by Wang et. al. (1980, 1982a, b) and by Jackson et. al. (1982). Generally, the rougher the soil's surface the more reduction in regression slope is observed. As a measure of the surface roughness effect a slope reduction factor β is introduced here, which is defined as the ratio between a regression slope such as those given in Figure 5 and a corresponding one derived from a perfectly smooth field. Since the radiometric response of a perfectly smooth field can not be measured, it is necessary to theoretically generate a reference data set in a comparable form to Figure 5. To do this the ground truth data of soil temperature and moisture profiles collected during the radiometric measurements were used in the radiative transfer calculations (Wilheit, 1978), using the empirical model of dielectric permittivity for soil-water mixtures (Wang and Schmugge, 1980). Nine groups of calculated T_B's (at incidence angle of 20°) coresponding to nine data groups in Figure 5 were then normalized in the same manner indicated by Eq. (1). The resultant T_{NB}'s from calculations were correlated with the W_V's in the 0-2.5 cm layer at 1.4 GHz and in the 0-0.5 cm layer at 5 GHz and 10.7 GHz frequencies. The results of the linear regression analyses between the calculated T_{NB}'s and W_V's for each of 9 groups were listed in Table 1 for comparison with the corresponding ones derived from the radiometric measurements. Additional entries in the table came from the similar analyses on measurement results of Newton and Rouse (1980), which were shown in Figure 6, and the RMS roughness height σ associated with each field derived from Wang et. al. (1982c) and Newton and Rouse (1980).

Table 1. The estimated slope reduction factor β for fields with different surface roughnesses. The data for the sandy and silty loam fields were derived from measurements of Wang et. al. (1982c), while those for Miller Clay fields from Newton and Rouse (1980).

Field Type	Frequency of Observation GHz	Regression based on Measured T_{NB}'s			Regression based on Calculated T_{NB}'s			Slope Ratio β
		Slope	Corr. Coeff.	Std. Error of Estimate	Slope	Corr. Coeff.	Std. Error of Estimate	
Very Smooth Sandy Loam Field $\sigma = 0.21$ cm	1.4	−1.50 ± 0.11	0.95	0.026	−1.84 ± 0.10	0.97	0.024	0.82 ± 0.07
	5.0	−1.62 ± 0.06	0.99	0.020	−1.56 ± 0.04	0.99	0.013	1.04 ± 0.05
	10.7	−1.46 ± 0.08	0.97	0.025	−1.43 ± 0.06	0.98	0.020	1.02 ± 0.07
Smooth Silty Loam Field $\sigma = 0.73$ cm	1.4	−1.51 ± 0.15	0.96	0.023	−1.86 ± 0.13	0.98	0.021	0.81 ± 0.10
	5.0	−1.25 ± 0.12	0.96	0.029	−1.28 ± 0.05	0.99	0.011	0.98 ± 0.10
	10.7	−1.08 ± 0.11	0.96	0.026	−1.33 ± 0.07	0.99	0.017	0.81 ± 0.09
Rough Silty Loam Field $\sigma = 2.45$ cm	1.4	−0.60 ± 0.09	0.83	0.024	−1.34 ± 0.18	0.92	0.034	0.54 ± 0.11
	5.0	−0.64 ± 0.10	0.88	0.025	−1.35 ± 0.06	0.99	0.014	0.47 ± 0.08
	10.7	−0.55 ± 0.13	0.82	0.029	−1.43 ± 0.09	0.98	0.021	0.38 ± 0.09
Smooth Miller Clay Field $\sigma = 0.36$ cm	1.4	−1.05 ± 0.09	0.96	0.037	−1.03 ± 0.05	0.99	0.020	1.02 ± 0.10
	10.7	−0.50 ± 0.12	0.77	0.051	−1.15 ± 0.09	0.96	0.038	0.44 ± 0.11
Medium Rough Miller Clay Field $\sigma = 1.07$ cm	1.4	−0.86 ± 0.09	0.94	0.028	−1.09 ± 0.08	0.97	0.025	0.79 ± 0.10
	10.7	−0.68 ± 0.12	0.84	0.042	−1.18 ± 0.09	0.97	0.029	0.58 ± 0.11
Very Rough Miller Clay Field $\sigma = 2.15$ cm	1.4	−0.45 ± 0.06	0.90	0.021	−1.06 ± 0.05	0.99	0.017	0.42 ± 0.06
	10.7	−0.37 ± 0.05	0.91	0.017	−1.14 ± 0.07	0.98	0.023	0.33 ± 0.05

ORIGINAL PAGE IS
OF POOR QUALITY

Some difficulty was found in generating the reference data set from the measurements of Newton and Rouse (1980) when the measured texture of their field soil (Miller clay) was used in the empirical model of Wang and Schmugge (1980) to estimate the dielectric permittivity of the soil for input into the radiative transfer calculations. The calculated T_{NB}'s were generally higher than the measured T_{NB}'s at 1.4 GHz frequency not only for the smooth field but for the medium rough field as well. Using the measured dielectric permittivity for Miller clay (Newton and Rouse, 1980) in the radiative transfer calculations essentially gave the same results. Earlier calculations and comparisons with the measured data (Choudhury et. al., 1979) were possible only when a measured variation of dielectric permittivity with water content for a lower clay content soil was used. This discrepancy between calculations and observations could be due to any one of the following three factors, namely, the measured real part of the dielectric permittivity for Miller clay was too small, or the measured T_{NB}'s over bare fields were too low, or a deficiency in the radiative transfer model used in the calculations. The results given in Table 1 were derived by assuming that the dielectric permittivity of Miller clay measured by Newton and Rouse was too small. A soil with smaller wilting point (soil tension of 1/3 atmosphere) of 0.2 cm^3/cm^3 compared to Miller clay (~0.34 cm^3/cm^3) was accordingly used in the empirical model of Wang and Schmugge (1980) to estimate the soil's dielectric permittivity for input in radiative transfer calculations. This procedure is adequate as long as the surface roughness and its frequency dependence derived from the data of Newton and Rouse (1980) are discussed in a relative sense.

Figure 9a, b, and c shows the variation of β with measured surface RMS roughness height σ at the frequencies of 1.4 GHz, 5 GHz, and 10.7 GHz. The σ value stands for the standard deviation of the mean air-soil interface measured for each of the bare fields reported by Wang et. al. (1982c) and by Newton and Lee (1974). A direct comparison between the results from the two different measurements was not possible because of the difficulty discussed in the previous paragraph. Except for the 10.7 GHz measurements of Newton and Rouse (1980), the rest of the data points in Figure 9 show that β generally decreases with an increase in σ. This observed

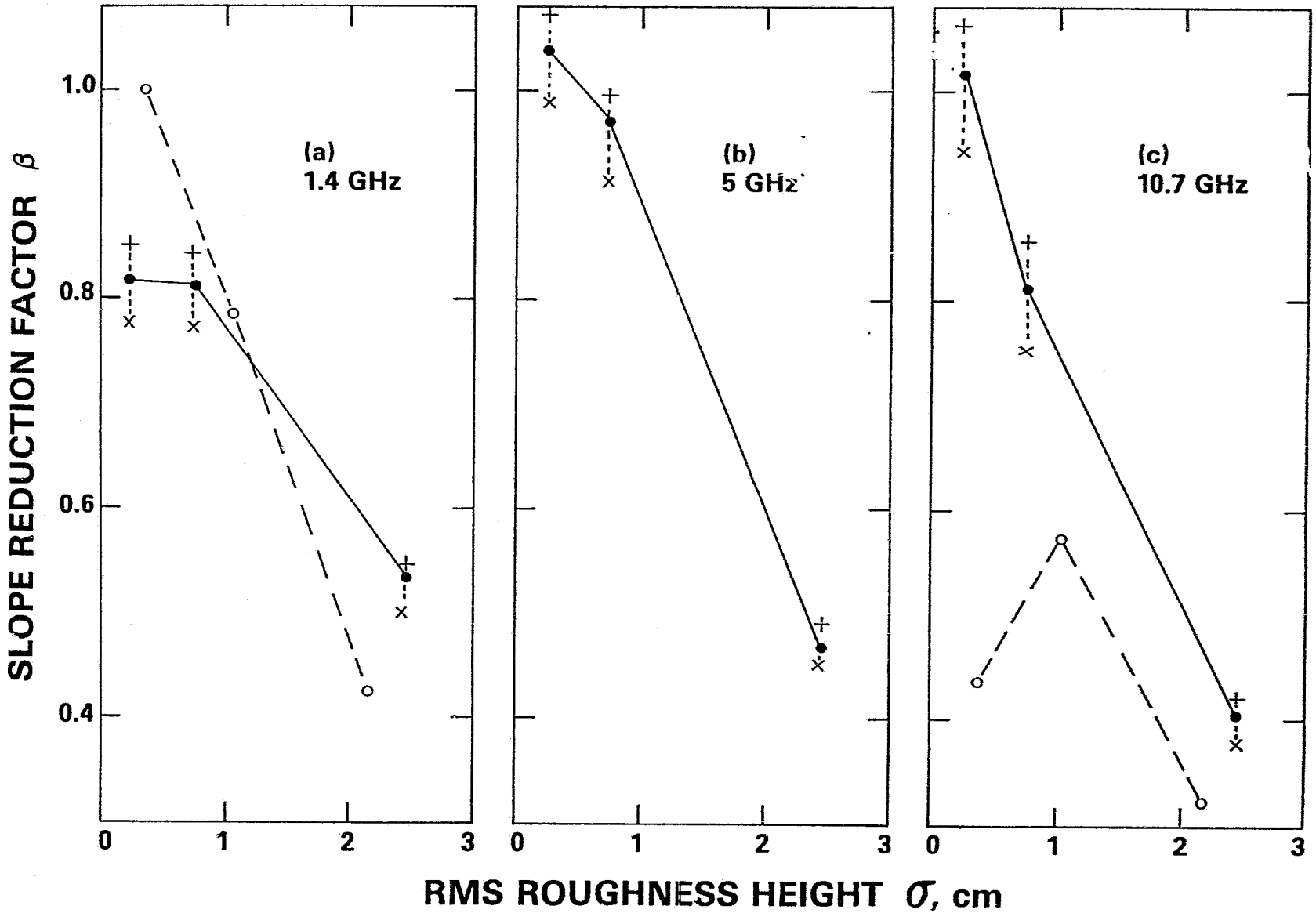

Figure 9. The variations of the slope reduction factor with RMS surface roughness height at (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz frequencies: ● data from Wang et. al. (1982c); ○ data from Newton and Rouse (1980 and references therein). The results of analyses for soil bulk densities of p − 0.1 g/cm^3 (+) and p + 0.1 g/cm^3 (x) were also included in the figure.

ORIGINAL PAGE IS
OF POOR QUALITY

change in β with σ from the measurements of Wang et. al. (1982c) further indicates a slight frequency dependence, namely, the higher the frequency of observation the steeper the rate of β decrease with increasing σ. At 10.7 GHz β decreases rapidly and almost linearly with an increase in σ. Only a moderate decrease in β at 5 GHz and practically no change in β are observed as σ increases from 0.21 cm to 0.73 cm.

Figure 10 shows the variation of β with the wavelength λ of observation, the data points derived from Wang et. al. (1982c) being connected by light lines and those from Newton and Rouse (1980) by dashed lines. The heavy solid curve showing the strong dependence of β on λ is derived by Wang et. al. (1982b) for the effect of vegetation cover (the derivation of β here is slightly different but equivalent). The strong dependence of β on λ was also reported by Kirdiashev et. al. (1979) on several types of vegetation covers. Compared to the effect of vegetation, the dependence of β on λ due to surface roughness is relatively weak, with the exception of smooth field results derived from Newton and Rouse (1980).. This suggests that it is possible to use a multiple-frequency radiometric approach to distinguish a vegetated field from a bare field. But using the same approach to unravel the effect of surface roughness could be quite difficult.

Figure 9 also shows the effect of uncertainty in the soil bulk density (p) measurements on β. The analyses leading to the results of Table 1 were repeated here for the data set of Wang et. al. (1982c), with volumetric moisture contents W_V's evaluated from two different p's of p – 0.1 g/cm^3 and p + 0.1 g/cm^3. The outcome of these analyses as shown in the figure indicates that a 0.1 g/cm^3 error in the p measurements could result in an error of $\sim\pm$ 0.04 in β estimate.

5. Conclusions

Three factors on the remote sensing of soil moisture experiments with microwave radiometers are discussed in this paper. The first one deals with the effect of soil bulk density on the interpretation of the measured radiometric data. It is pointed out that the variation of soils' dielectric permittivity with moisture content is better defined when the moisture content is expressed in

ORIGINAL PAGE IS
OF POOR QUALITY

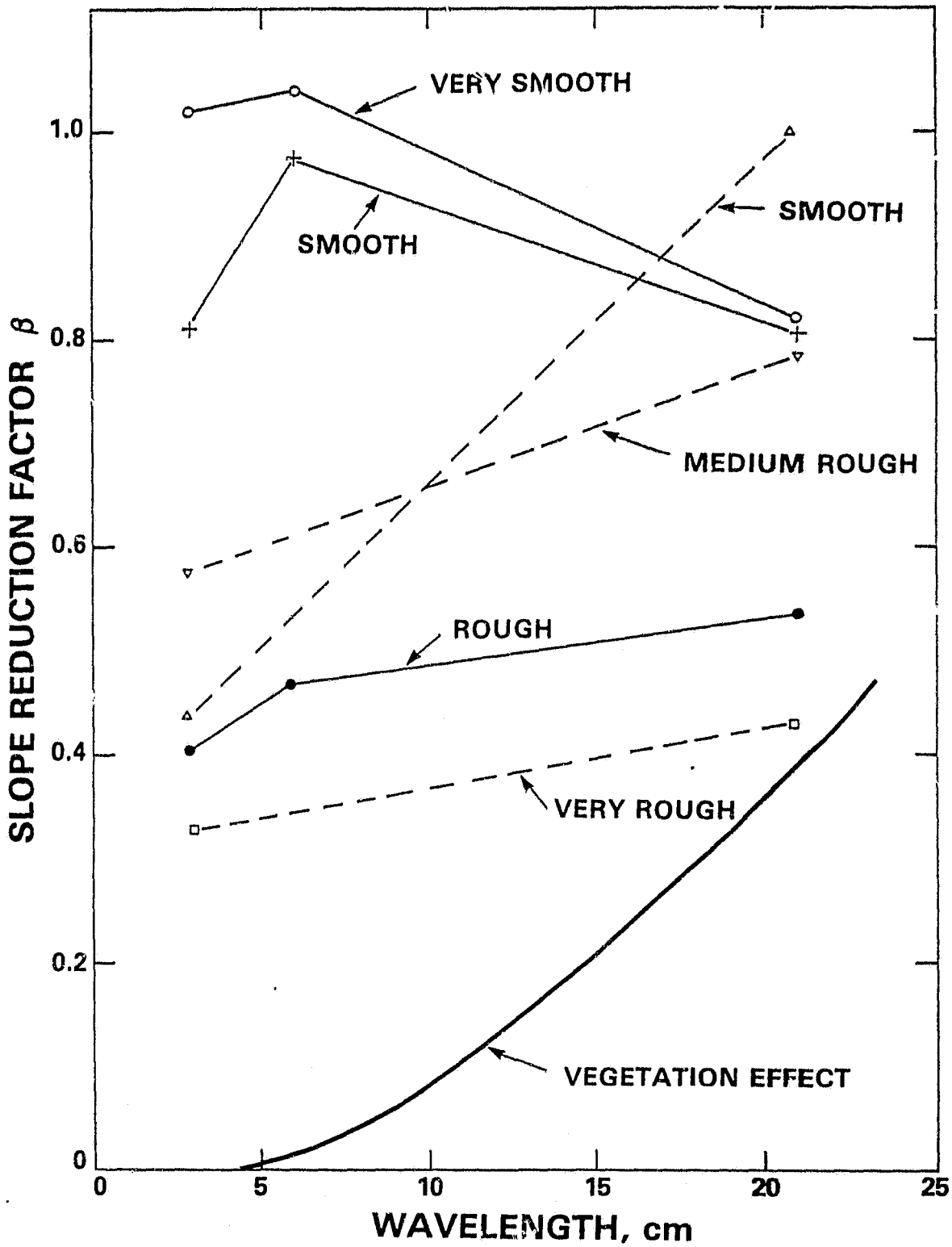

Figure 10. The wavelength dependence of slope reduction factor for fields with different surface roughnesses. The data points from the measurements of Wang et. al. (1982c) are connected by light lines, while those of Newton and Rouse (1980), dashed lines. The heavy solid curve shows the effect of vegetation reported by Wang et. al. (1982b).

ORIGINAL PAGE IS
OF POOR QUALITY

volume than in percent by dry weight. This in turn suggests the need of acquiring the volumetric soil moisture content in the field experiment so that the measured brightness temperatures can be interpreted more uniquely. The technique of measuring volumetric soil moisture content generally requires determination of both soil bulk density and soil moisture content in percent by dry weight. A precision measurement of soil bulk density is a non-trivial procedure as evidenced from the three-year microwave radiometer experiment of Wang et. al. (1980, 1982a, b, c) discussed in Section 2. The uncertainty associated with the soil bulk density determination directly affects the interpretation of surface roughness effect

The second and third factors discussed above are the measured frequency dependence and the possible time variation of surface roughness. The effect of surface roughness is found to increase a soil's brightness temperature and reduce the slope of regression between the brightness temperature and moisture content, confirming the studies earlier (Choudhury et. al. 1979; Newton and Rouse, 1980; Wang et. al., 1982c). The effect is stronger the rougher the surface of the soils. There is some observed frequency dependence of surface roughness over 1.4-10.7 GHz range, but this frequency dependence is relatively weak compared to that due to the effect of vegetation cover (Wang et. al. 1982b, Kirdiashev et. al. 1979). Time series observation with microwave radiometers also indicates a possible time variation of surface roughness. This tends to introduce additional noise in the scatter plot of brightness temperature and soil moisture content, and therefore slightly enhances the uncertainty in remotely estimating surface soil moisture content with microwave radiometric measurement.

Finally, an observed feature displayed in both Figures 9 and 10 but not discussed in the text is the smaller slope reduction factor at 1.4 GHz than at either 5 GHz or 10.7 GHz frequency from the measurements of Wang et. al. (1982a, b) over a very smooth field. This factor is $\simeq 1$ at 5 GHz and 10.7 GHz frequencies, showing the closeness in the calculated and measured regression slopes between brightness temperature and soil moisture content. At 1.4 GHz this factor is $\simeq$ 0.82, suggesting an observed regression slope appreciably smaller than the calculated one. This

phenomenon is related to the previous report of Wang et. al. (1982b) that for volumetric soil moisture content $\geqslant 0.18\ cm^3/cm^3$, the observed brightness temperature at small incidence angle is lowest at 5 GHz and highest at 0.6 GHz frequency. When soil is dry near the air-soil interface highest brightness temperature is observed at 5 GHz and 10.7 GHz frequencies. The case for dry surface soil can be understood in terms of shallower sampling depth at higher frequency of observation (Mo et. al., 1980). But the observation on the smooth wet soils is contrary to that expected from radiative transfer calculations based on the measured frequency dependence of soils' dielectric permittivity (Wang and Schmugge, 1980). Further experimental as well as theoretical studies are required to understand this unexpected phenomonon.

ORIGINAL PAGE IS
OF POOR QUALITY

REFERENCES

Blanchard, B. J., McFarland, M. J., Schmugge, T. J., and Rhoades, E., (1981), Estimation of soil moisture with API algorithms and microwave emission, *Water Resources Bull., 17(5)*, 767-774.

Burke, W. J., Schmugge, T. J., and Paris, J. F., (1979), Comparison of 2.8 and 21 cm microwave radiometer observations over soils with emission model calculations, *J. Geophys. Res., 84*, 287-294.

Choudhury, B. J., Schmugge, T. J., Newton, R. W., and Chang, A., (1979), Effect of surface roughness on the microwave emission from soils, *J. Geophys. Res., 84*, 5699-5706.

Fung, A. K., and Ulaby, F. T., (1978), A scatter model for leafy vegetation, IEEE Trans. Geosci. Remote Sensing, *GE-16(4)*, 281-286.

Jackson, T. J., Schmugge, T. J., and Wang, J. R., (1982), Passive microwave sensing of soil moisture under vegetation canopies, *Water Resources Res.*, in press.

Kirdiashev, K. P., Chukhlantsev, A. A., and Shutko, A. M., (1979), Microwave radiation of the earth's surface in the presence of vegetation cover, Radiotekhnika & Electronika, *24*, 256-264.

Lundien, J. R., (1971), Terrain analysis by electromagnetic means, Tech. Rep. 3-693, Rep. 5, U.S. Army Waterways Exp. Stn., Vicksburg, Miss.

Mo, T., Schmugge, T. J., and Choudhury, B. J., (1980), Calculations of the spectral nature of the microwave emission from soils, NASA TM82002.

Newton, R. W., (1977), Microwave remote sensing and its application to soil moisture detection, Remote Sensing Center, Texas A&M University, College Station, TX., Tech. Rep. RSC-81.

Newton, R. W., and Rouse, J. W., (1980), Microwave radiometer measurements of soil moisture content, *IEEE Trans. Ant. Propag., AP-28(5),* 680-686.

Newton, R. W., and Lee, S. L., (1974), Joint soil moisture experiment at Texas A&M University: ground data report, Tech. Rep. RSC-61, Texas A&M University, College Station, TX.

Njoku, E. G., and Kong, J. A., (1977), Theory for passive microwave remote sensing of near-surface soil moisture, *J. Geophys. Res., 82,* 3108-3118.

Njoku, E. G., and P. E. O'Neill, (1982), Multifrequency microwave radiometer measurements of soil moisture, *IEEE Trans. Geosci. Remote Sensing,* in press.

Schanda, E., Hofer, R., Wyssen, D., Musy, A., Meylan, D., Marzier, C., and Godd, W., (1978), Soil moisture determination and snow classification with microwave radiometry, *Proc. 12th Intern. Symp. Remote Sensing Environ.,* 1779-1789, Ann Arbor, Michigan.

Schmugge, T. J., (1978), Remote sensing of surface soil moisture, *J. Appl. Meteor., 17,* 1549-1557.

Schmugge, T. J., (1980), Effect of texture on microwave emission from soils, *IEEE Trans. Geosci. Remote Sensing, GE-18,* 353-361.

Schmugge, T. J., Gloersen, P., Wilheit, T., and Geiger, F., (1974), Remote sensing of soil moisture with microwave radiometers, *J. Geophys. Res, 79,* 317-323.

Topp, G. C., Davis, J. L., and Annan, A. P., (1980), Electromagnetic determination of soil moisture content: measurement in coaxial transmission lines, *Water Resources Res., 16(3),* 574-582.

Ulaby, F. T., Batlivala, P. P., and Dobson, M. C., (1978), Microwave backscatter dependence on surface roughness, soil moisture, and soil texture: Part I—bare soil, *IEEE Trans. Geosci. Electron., GE-16,* 286-295.

Ulaby, F. T., Bradley, G. A., and Dobson, M. C., (1979), Microwave backscatter dependence on surface roughness, soil moisture, and soil texture: Part II—Vegetation covered soil, *IEEE Trans. Geosci. Electron., GE-17,* 33-40.

Wang, J. R., and Choudhury, B. J., (1981), Remote sensing of soil moisture content over bare field at 1.4 GHz frequency, *J. Geophys. Res., 86(C6),* 5277-5282.

Wang, J. R., and Schmugge, T. J., (1980), An empirical model for the complex dielectric permittivity of soils as a function of water content, *IEEE Trans. Geosci. Electron., GE-18(4),* 288-295.

Wang, J. R., Shive, J. C., and McMurtrey, J. E., (1980), Microwave remote sensing of soil moisture content over bare and vegetated fields, *Geophys. Res. Letters, 7(10),* 801-804.

Wang, J. R., McMurtrey, J. E., Engman, E. T., Jackson, T. J., Schmugge, T. J., Gould, W. I., Glazar, W. S., and Fuchs, J. E., (1982a), Radiometric measurements over bare and vegetated fields at 1.4 GHz and 5 GHz frequencies, *Remote Sensing Environ.,* in press.

Wang, J. R., Schmugge, T. J., McMurtrey, J. E., Gould, W. I., Glazar, W. S., and Fuchs, J. E., (1982b), A multi-frequency radiometric measurement of soil moisture content over bare and vegetated fields, *Geophys. Res. Letters, 9(4),* 416-419.

Wang, J. R., O'Neill, P. E., Jackson, T. J., and Engman, E. T., (1982c), A multi-frequency measurement of thermal microwave emission from soils: the effects of soil texture and surface roughness, submitted for publication to *IEEE Trans. Geosci. Remote Sensing.*

Wilheit, T. T., (1978), Radiative transfer in a plane stratified dielectric, *IEEE Trans. Geosci. Electron., GE-16,* 138-143.

FIGURE CAPTIONS

Figure 1. The variation of measured dielectric constant at 1.4 GHz frequency with soil moisture content expressed in percentage of dry weight for Long Lake Clay. Three different compactive efforts were applied to the soil samples in the measurements.

Figure 2. The variation of measured dielectric constant at 1.4 GHz frequency with volumetric soil moisture content for Long Lake Clay. Three different compactive efforts were applied to the soil samples in the measurements.

Figure 3. The normalized brightness temperature measured at 1.4 GHz and 5 GHz frequencies vs. volumetric moisture content. The measurements were made for three consecutive years over fields with Elinsboro sandy loam: ● 1979; + 1980; ○ 1981.

Figure 4. The normalized brightness temperature measured at 1.4 GHz and 5 GHz frequencies vs. soil moisture content in percent by dry weight. The measurements were made for three consecutive years over fields with Elinsboro sandy loam: ● 1979; + 1980; ○ 1981.

Figure 5. The measured variation of normalized brightness temperatures with volumetric soil moisture content at (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz frequencies. Data were derived from the 1981 measurements of Wang et. al. (1982c): ○ very smooth field (sandy laom): + smooth field (silty loam): ● rough field (silty loam).

Figure 6. The measured variation of normalized brightness temperatures with volumetric soil moisture content at (a) 1.4 GHz and (b) 10.7 GHz frequencies. Data were derived from the 1974 measurements over fields of Miller clay by Newton and Rouse (1980 and references therein): ○ smooth field; + medium rough field before July 11 (⊕ after July 12); ● very rough field.

Figure 7. Time variation of residuals from the regressions of data in Figure 6: ○ smooth field; + medium rough field; ● very rough field. Arrows A and B indicated the times when substantial change in surface soil moisture was observed.

Figure 8. Time variation of residuals from the regressions of data in Figure 6: + smooth field; ● rough field. The numbers associated with the arrows were the amounts of rainfall recorded during August 10-20 when intensive radiometric measurements were made over the two fields.

Figure 9. The variations of the slope reduction factor with RMS surface roughness height at (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz frequencies: ● data from Wang et. al. (1982c); ○ data from Newton and Rouse (1980 and references therein). The results of analyses for soil bulk densities of p - 0.1 g/cm^3 (+) and p + 0.1 g/cm^3 (x) were also included in the figure.

Figure 10. The wavelength dependence of slope reduction factor for fields with different surface roughnesses. The data points from the measurements of Wang et. al. (1982c) are connected by light lines, while those of Newton and Rouse (1980), dashed lines. The heavy solid curve shows the effect of vegetation reported by Wang et. al. (1982b).