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EFFECT OF SOIL TEXTURE ON THE MICROWAVE EMISSION FROM SOILS

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National Aeronautics and
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16. Abstract

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In an earlier paper (Schmugge et al., 1974) studying the use of microwave radiometers for soil moisture sensing a dependence of the emission on soil type or texture was observed. This dependence was studied more thoroughly in subsequent experiments. These experiments have indicated that the effects of soil texture can be accounted for by expressing the measured soil moisture as a percent of field capacity for the soil In this paper we will present the basis for this conclusion and the data supporting it.

The use of microwave radiometers for the remote sensing of soil moisture has been studied extensively from aircraft and field platforms. These radiometers measure the thermal emission from the soils in the frequency range 1 - 30 GHz (wavelength region between 1 and 30 cm). The magnitude of this emission depends on the temperature of soil and on the dielectric or emissive properties of the soil. It is this latter quantity which contains the dependence on soil texture. The dielectric properties of a soil are strongly dependent on its moisture content because of the large contrast between the dielectric constant (ϵ) of liquid water (~ 80 at $\lambda = 21$ cm) and that of the soil minerals. The large value of ϵ for water results from the ability of the electric dipole moment of the water molecule to align itself along an applied field If the dipolar molecular rotation is prevented as it is in ice ($\epsilon = 3.5$) or hindered by being tightly bound to a soil particle the value of ϵ will be reduced. It is this latter fact that causes the dependence of ϵ for soils on their texture, clay soils with a larger effective surface area can hold more water in this tightly bound state than sandy soils. (Bauer, et al., 1972). This relationship between texture and dielectric constant will be quantified.

Dependence of Soil-Water Parameters on Texture

The binding of the water to soil particle can be described in terms of the pressure potential. At low moisture levels, the pressure potential is the tension with which water is held by soil particles. In the intermediate range, the pressure potential is determined largely by the radii of curvature of water films between soil particles. In Figure 1, representative plots of the relation between volumetric water content and pressure potential are presented (Idso et al , 1975) The zero potential level is the saturated soil situation. The locations of the −1/3-bar and −15-bar pressure levels are indicated because they are frequently taken to be the pressure levels for the field capacity (FC) and wilting point (WP) conditions of the soil. This convention will be followed here. The amount of water in the soil at field capacity is that which remains in a soil two or three days after having been saturated and after free drainage has practically ceased. As the name implies, the wilting point is the moisture level at which plants experience difficulty drawing water from the soil. Thus, the FC and WP soil-moisture values give a quantitative measure of the water-holding capacity of a soil The difference between the two is the available water capacity in the soil. As the curves in Figure 1 indicate, FC and WP depend on soil type. The values for the four soils are presented in Table 1.

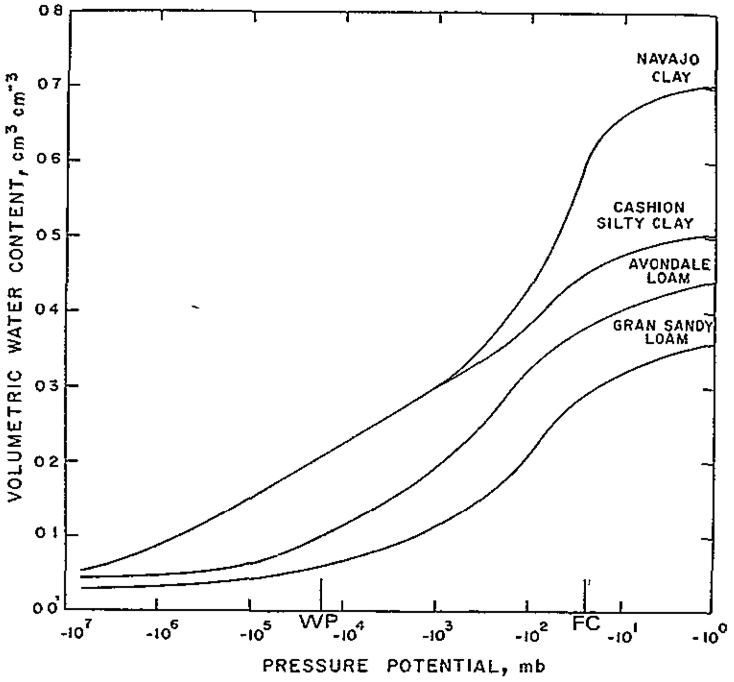

Figure 1. Volumetric soil water content versus soil water pressure potential for four different soils (Idso, 1975).

Table 1
Moisture Content of Selected Soils at WP, FC, and Saturated Conditions

Soil	WP at −15 bar (cm^3/cm^3)	FC at −1/3 bar (cm^3/cm^3)	Saturation at 0 bar (cm^3/cm^3)
Navajo Clay	0 22	0.55	0.70
Cashion Silty Clay	0.22	0.33	0.50
Avondale Loam	0.11	0.25	0.44
Gran Sandy Loam	0.06	0.15	0.36.

Thus, the available water capacity of the silty clay is no greater than that of the Avondale Loam, even though the magnitudes are much greater

In the later sections of the paper we will attempt to show that the value of WP determines the transition value for the dielectric behaviour of the water in the soil from the bound condition to the free condition. Since it would be very difficult to obtain curves like those in Figure 1 for the soils in all the sampled fields, we attempted to relate FC and WP to the soil textures of the sampled fields. This was based on the work of Salter and Williams (1969) who used regression analysis to relate particle-size composition (soil texture) to the available water capacity for a soil. They concluded that the moisture characteristics could be calculated from texture information with reasonable accuracy, that is, the upper and lower limits of available water capacity could be estimated to within 10 or 20 percent of the measured values Therefore, a multiple linear regression and correlation analysis were made on 100 sets of soil textures and moisture characteristics, that is, the moisture contents at the −1/3-bar (FC) and −15-bar (WP) potentials These measurements were made on soils from the Phoenix area (Private communication, Phoenix Soil Conservation Office, 1974) and from the Rio Grande Valley of Texas (Heilman et al., 1969). The range of textures included in the regression is indicated on a texture triangle in Figure 2 which is a scatter plot of the soils used.

The results of the correlation analysis for the texture and the moisture parameters presented in Table 2. It is seen that WP and FC are highly correlated (negatively) with the sand fraction and

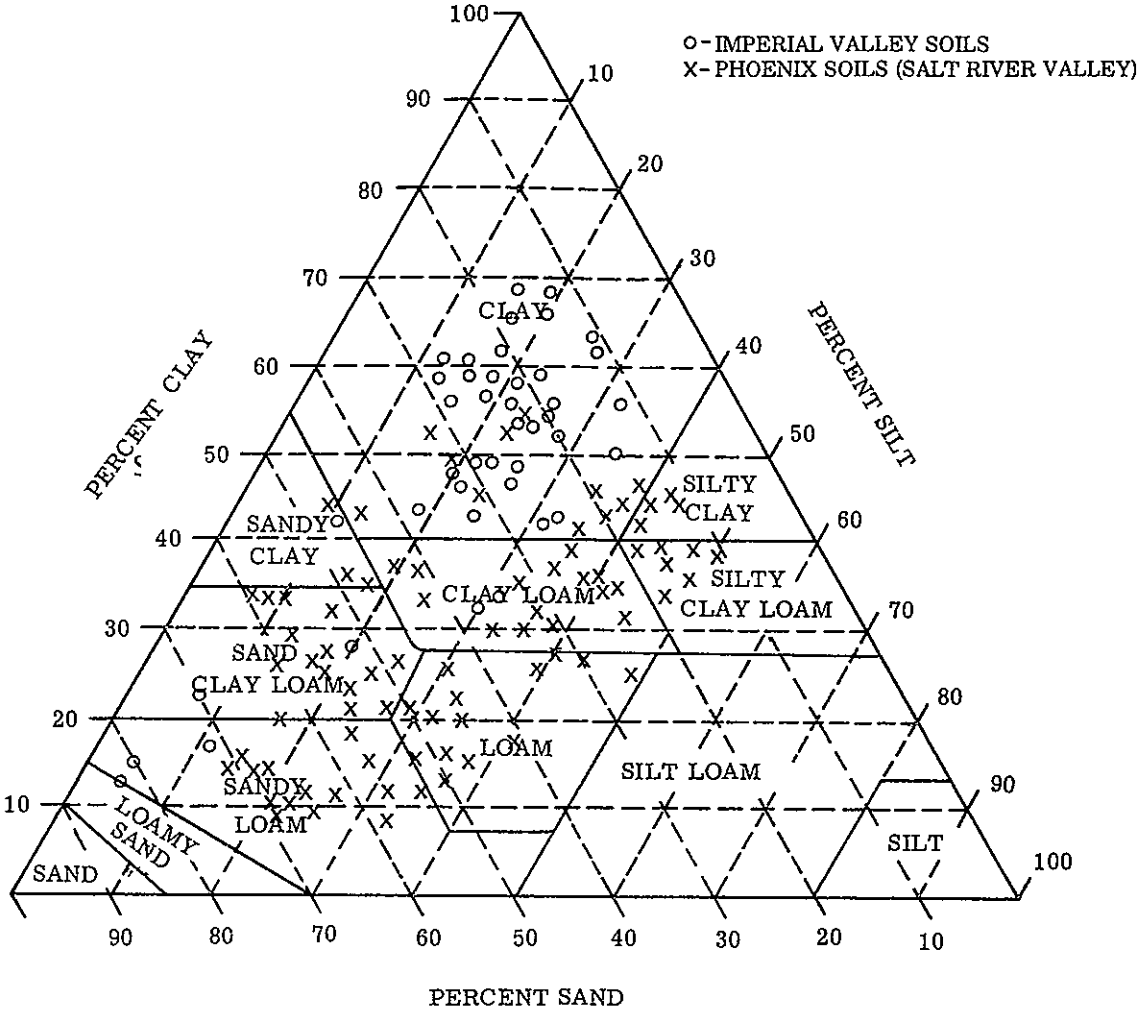

Figure 2. Soil texture triangle showing the soils used in deriving the FC and WP relationships

(positively) with the clay fraction. The correlation with the silt fraction is poor for both parameters. Since only two of the texture parameters will be independent variables, the choice of clay and sand is obvious

Table 2
Correlation Matrix Between Texture and Soil Water Parameters

	Gravimetric Values		Volumetric Values	
	FC	WP	FC	WP
SAND	−0.86	−0.82	−0.84	−0.77
SILT	0.49	0.32	0.38	0.23
CLAY	0 81	0.93	0.90	0.95

The results of the regression for WP, expressed in weight percent, were

$$WP = 7.2 - 0.07 \times SAND + 0.24 \times CLAY \qquad (1)$$

where SAND and CLAY represent their respective soil fractions in percent The multiple correlation coefficient for this regression was 0.945. The regression results for FC are

$$FC = 25.1 - 0.21 \times SAND + 0\ 22 \times CLAY \qquad (2)$$

with a multiple correlation coefficient of 0.904. The coefficient of variation (standard estimate of error divided by the mean) was 0.15 for both of these regressions.

Since the density values for the soils used in this analysis were available, a regression analysis was performed to obtain WP and FC in terms of volumetric water content (Wang & Schmugge, 1979). The results are:

$$WP = 0.068 - 0.00064 \times SAND + 0.0048 \times CLAY \qquad (3)$$

with a multiple correlation coefficient of 0.96 and

$$FC = 0.30 - 0.0023 \times SAND + 0.005 \times CLAY \qquad (4)$$

with a multiple correlation of 0.94. The coefficients of variations are 0.13 for these regressions. The moisture characteristics of a soil depend on many factors in addition to soil texture, such as bulk density of the undisturbed soil and percent organic matter, but texture (sand, silt, and clay fractions) was the only parameter that could easily be determined for all of the soils involved It is presumed that basing the regression on the actual field soils used in the soil surveys adequately takes these factors into account These regressions for FC and WP on a volumetric yield slightly higher correlation and lower coefficient of variation than those based on gravimetric moisture content.

Dependence of the Dielectric Constant of Soil Texture

As noted in the introduction it is the large dielectric constant for water as compared to those for the soil minerals which makes the microwave approaches useful for soil moisture sensing. The frequency dependence of the dielectric properties of water are described by a Debye relaxation spectrum given by

$$\epsilon(\omega) = \epsilon_\infty + \frac{\epsilon_s - \epsilon_\infty}{1 + i\omega\tau} \tag{5}$$

were $i = \sqrt{-1}$, ϵ_s is the low frequency ($w\tau \ll 1$) value of ϵ, and τ, the relaxation time, is a measure of the time required for the water molecule it align itself with an applied field. This expression is plotted for liquid and solid (ice) water in Figure 3. For liquid water $1/\tau \approx 10^{10}$ Hz while for ice $1/\tau \approx 10^3$. Thus if the frequency of the electric field oscillation is too high the dipole moment of the H_2O molecule will not become aligned and its dielectric contribution will be reduced to the high frequency value, ϵ_∞.

When water is first added to a soil it will be tightly bound to the particle surface and will not be able to rotate freely. As more water is added the molecules are further away from the particle surface and are more free to rotate, after about 8 or 9 layers the molecules behave as free water and contribute significantly to the dielectric properties of the soil. In measurements of the dielectric properties of soils Hoekstra and Delaney (1974) observed a frequency dependence similar to that presented in Figure 3 with the exception that the soil water has a range of relaxation times longer than that of liquid H_2O.

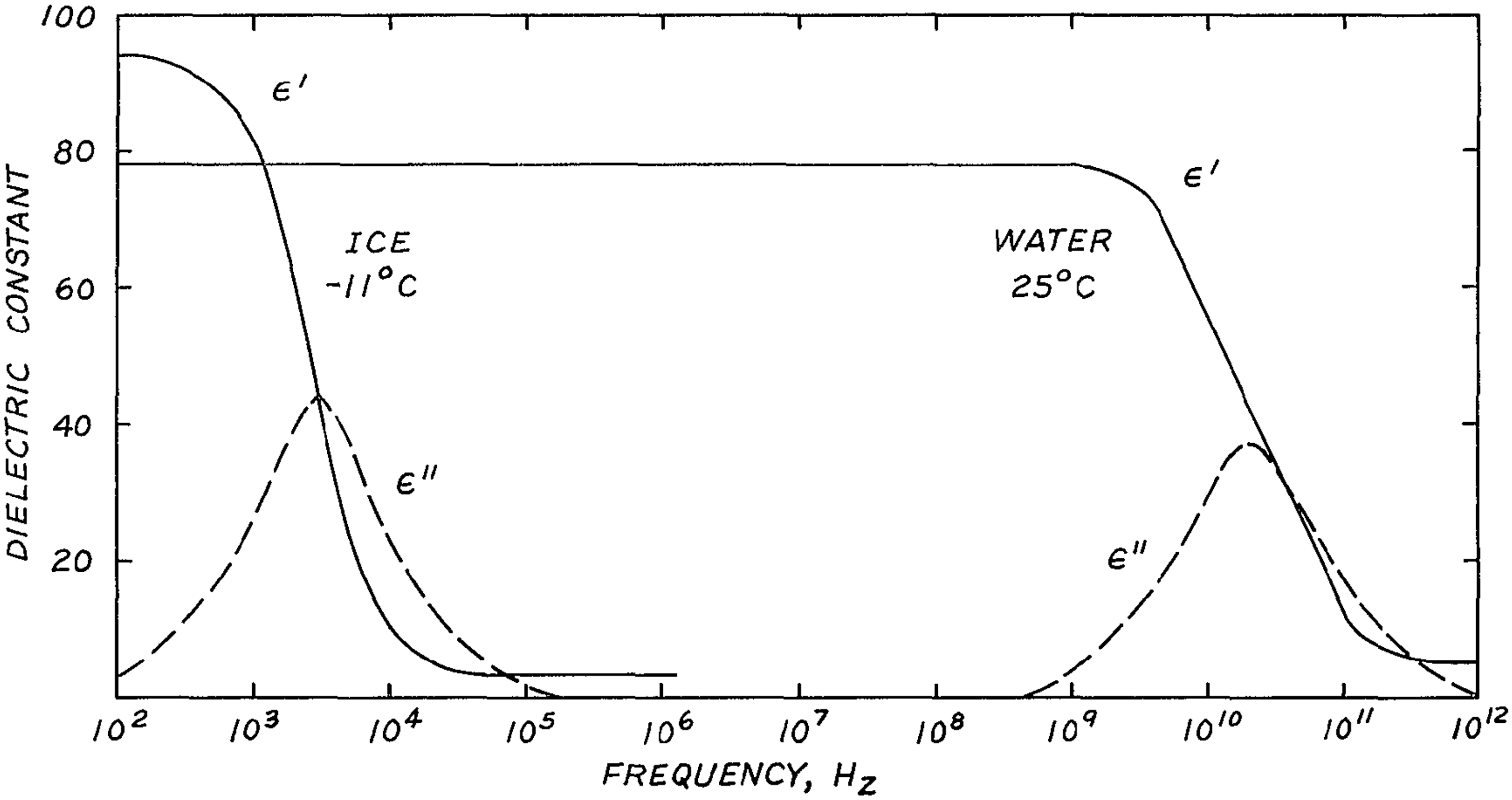

Figure 3. The dielectric behavior of ice and liquid water as a function of frequence (Hoekstra and Capillino, 1971)

Laboratory measurements of the dielectric constant for three soils ranging from a sandy loam to a heavy clay at a wavelength of 21 cm are presented in Figure 4. The characteristics of the 3 soils are given in Table 3 along with calculated values of emissivity. For all three soils there is a region at low moisture levels where there is a slow increase in ϵ and above this region there is much steeper increase in ϵ with moisture content. It can be seen that the region of slowly increasing ϵ is greater for the clay soils than for the sandy loam. This is due to the greater surface area present in the clay soils

The curves in Figure 4 are the results from an empirical model to develop an analytical expression for ϵ of soils as a function of moisture content (Wang & Schmugge, 1979) As Hoekstra & Delaney (1974) point out in their paper the dielectric behaviour of water in soils is different from that in the bulk liquid phase, i e. the tightly bound water has dielectric properties similar to those of ice while the loosely bound water has dielectric properties similar to those of the liquid state. Therefore to obtain the dielectric properties of the moist soil a simple mixing formula is used in which the components are the soil mineral (or rock), air and water (ϵ_x) with ϵ_x being a function of the water content, W_c, in the soil At zero water content $\epsilon_x = \epsilon_{ice}$ and it increases linearly until the transition moisture w_t is reached at which point ϵ_x has a value approaching that for the liquid. The equations are:

$$\epsilon = W_c \epsilon_x + (P - W_c)\, \epsilon_a + (1 - P)\, \epsilon_r, \text{ for } W_c \leqslant W_t \tag{6}$$

with

$$\epsilon_x = \epsilon_i + (\epsilon_w - \epsilon_i) \frac{W_c}{W_t} \cdot \gamma \tag{7}$$

and

$$\epsilon = W_t \epsilon_x + (W_c - W_t)\, \epsilon_w + (P - W_c)\, \epsilon_a + (1 - P)\, \epsilon_r, \text{ for } W_c > W_t \tag{8}$$

with

$$\epsilon_x = \epsilon_i + (\epsilon_w - \epsilon_i)\gamma \tag{9}$$

where P is the pososity of the dry soil, ϵ_a, ϵ_w, ϵ_r and ϵ_i, are the dielectric constants of air, water, rock and ice respectively, and ϵ_x stands for the dielectric constant of the initially absorbed water.

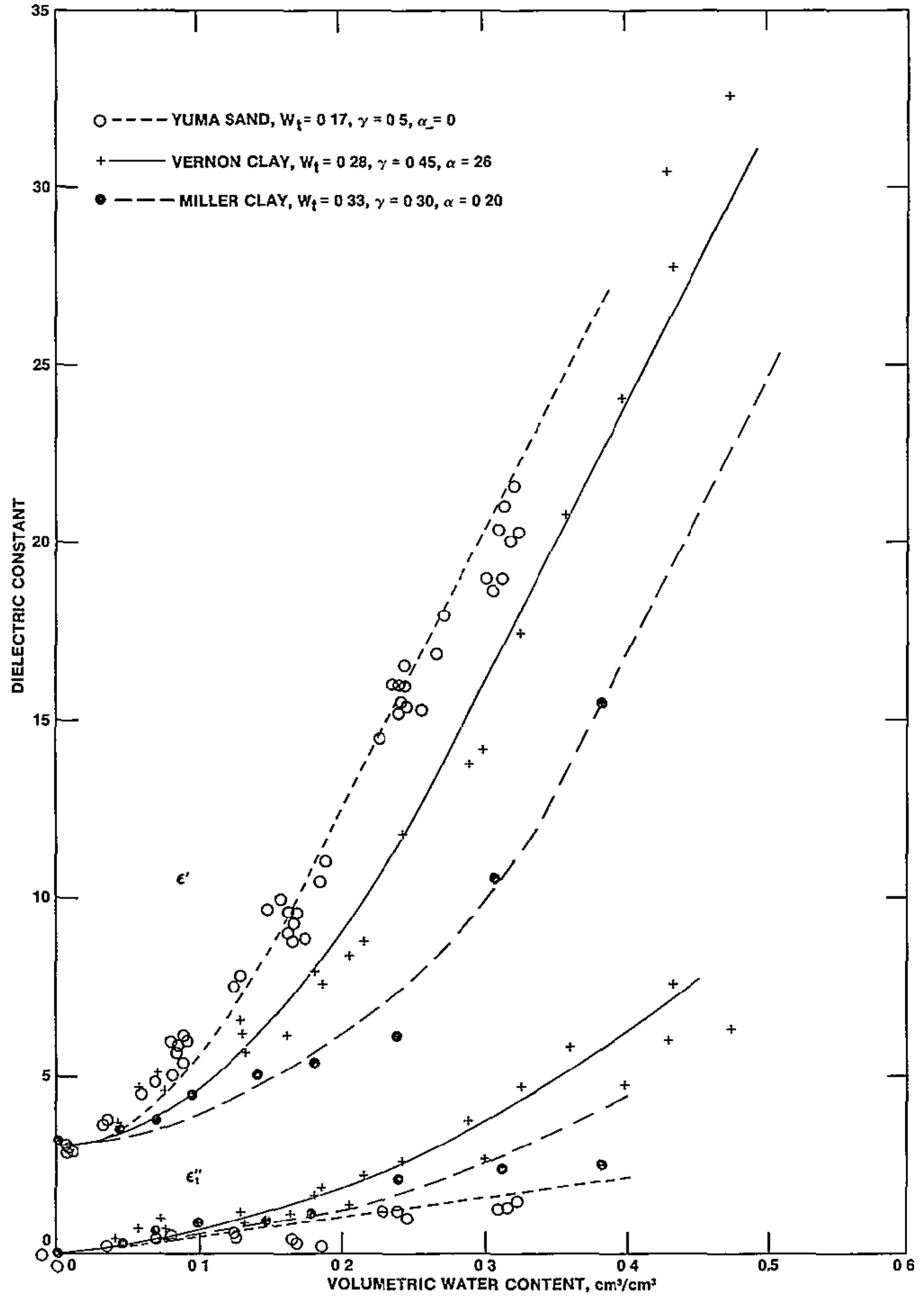

Figure 4 Laboratory measurements of the real and imaginary parts of the dielectric constant for three soils as a function of moisture content at a wavelength of 21 cm. The data for Yuma Sand and Vernon Clay Loam are from Lundien (1971) and those for Miller Clay are from Newton (1977)

Table 3
Characteristics of Soils Represented in Figure 4

	Texture			Moisture Properties			Soil Emissivities*** at				
	Sand	Silt	Clay	WP*	FC**	W_t	$W_c = 0$	0.1	0.2	0.3	0.4
				in cm^3/cm^3					cm^3/cm^3		
Yuma Sand	100	0	0	.007	.07	.17	.92	.83	.69	.59	.53
Vernon Clay Loam	16	56	28	.19	.42	.28	.92	.86	75	64	.56
Miller Clay	3	35	62	.36	.63	.33	.92	.88	.81	73	.63

* Calculated from Eq. 4
** Calculated from Eq. 5
*** Calculated using the Fresnel Equations for reflectivity at a smooth surface.

In Wang & Schmugge (1979) the values of W_t and γ were determined for 18 soils by a least squares fit to the data. These values of W_t and γ are compared with values of WP calculated from the known soil textures using equation (4) in Figure 5. The correlation coefficient for $W_t = 0.9$ and for γ it is 0.7 indicating that there is a strong dependence of both on WP and that texture data can be used to estimate the value of W_t for a soil.

The values of the emissivity presented in Table 3 give an indication of the brightness temperature (T_B) to be expected for these soils. For example at $W_c = 0.3$ the range in emissivity is 0.14 or about a 45K range in T_B, this difference in the emission for wet soils should be easily observable.

The conclusion of this section is that reasonable estimates of the dielectric constant for soils can be made both as a function of moisture content and microwave frequency if the knowledge of the soil texture or moisture characteristic is available. The frequency dependence is contained in the dielectric constant for water which is well understood (Stogryn, 1971). It is assumed that there is no frequency dependence of W_t within the microwave spectral region

Microwave Brightness Temperature Measurements

The use of microwave radiometer data obtained from aircraft platforms is well suited for verifying the dependence of microwave emissions from soils on texture because of the ability to obtain data over a large number of fields which can encompass a wide range of soil texture. The aircraft results were obtained during flights with NASA aircraft over irrigated agricultural areas around Phoenix, Arizona and in the Imperial Valley of California during March 1972 and February 1973 (Schmugge et al., 1976a) and during March 1975 over only the Phoenix area (Schmugge, 1976b) The aircraft altitude for these flights were 600 m in 1972 and 1973 and 300 m in 1975. On board the aircraft were microwave radiometers covering the wavelength range of 0 8 to 21 cm. In this paper only the results at the 21 cm and 1.55 cm wavelengths will be presented. The 21 cm radiometer was nadir viewing with a 15° (~1/4 radian) beamwidth, therefore, its spatial resolution was approximately 1/4 the aircraft altitude. The 1.55 cm radiometer is a scanning radiometer which has an angular beam width of 2.8° (~1/20 radian). This sensor was only used on the 1972 and 1973 missions

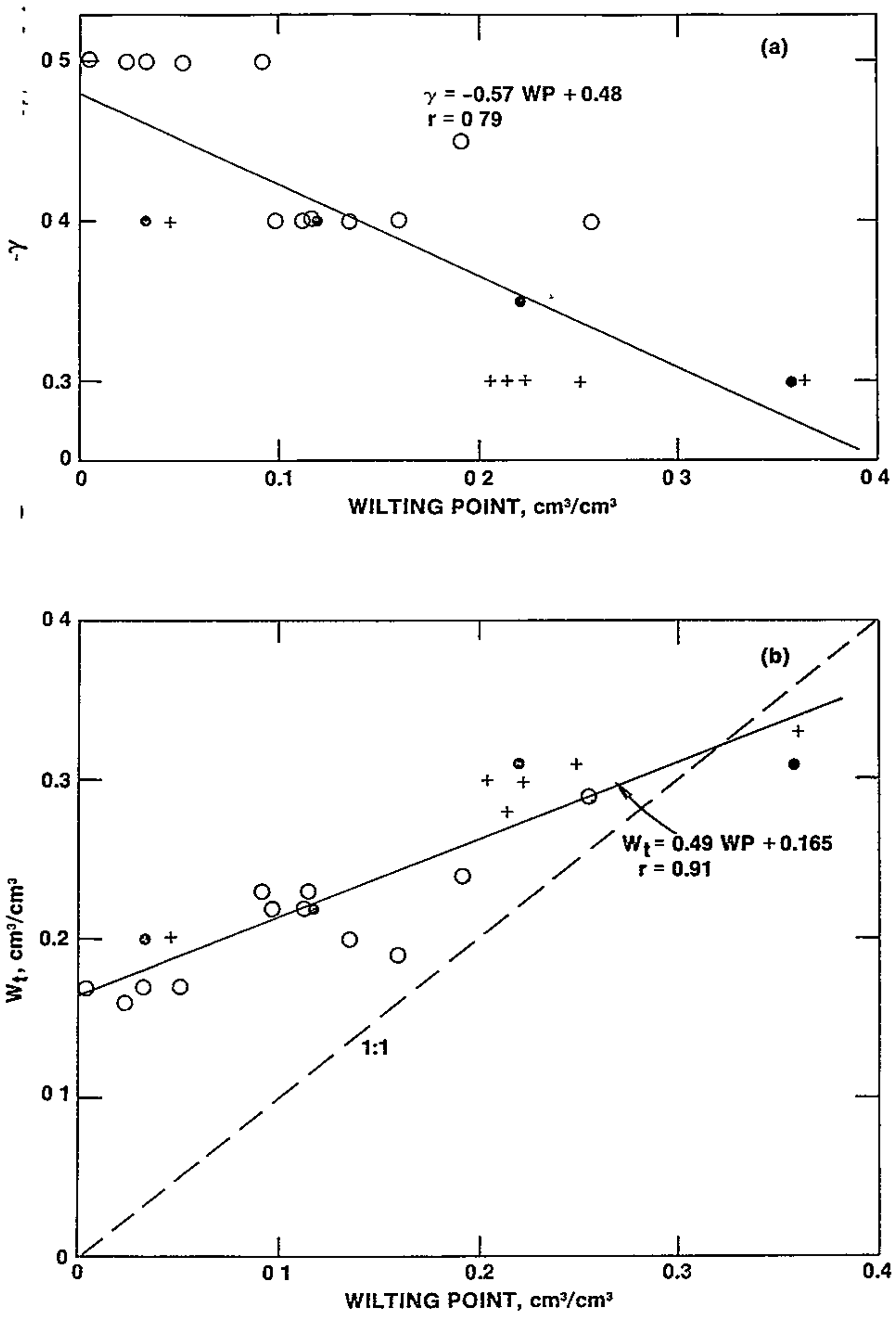

Figure 5. (a) The variation of γ from equation with the calculated value of WP. (b) the variation of W_t with the calculated value of WP. The solid lines were derived from linear regressions and the dashes line is the 1:1 line drawn for comparison (Wang and Schmugge, 1979).

The aircraft flew along flight lines centered on the agricultural fields which were at least 16 hectares (40 acres) in area. These fields generally had uniform surface and moisture conditions over their total area All the radiometer data obtained over each field were used to obtain the average brightness temperature (T_B) for the field The soil moisture measurements were made at 4 locations and for several depths in each field. The values presented here are the averages for each field. For the 1975 flights soil temperature profiles were also measured. Soil textures determination were also made for the sampled fields.

The use of a 4 point sampling pattern to obtain the average soil moisture for each field introduces a considerable level of uncertainty or error into what will be the independent variable of the regression analyses. In an analysis of intensively sampled fields, i.e. fields where 20 or more samples were taken, Bell et al. (1979) found that there was an upper limit of about 4% for the standard deviation at moisture levels above 10% by weight. If it assumed that this is the population standard deviation this implies that the level of uncertainty of the mean value for the 4 samples is approximately 4% at moisture levels above 10%. This level of uncertainty will inhibit our ability to draw quantitative conclusions from these data.

The range of soil textures encountered in these aircraft experiments is presented on a soil texture triangle in Figure 6. The region of the triangle covered by the aircraft data is similar to that for the data used in the regression analysis with the exception that aircraft data set had more fields with heavy clay soils (e.g clay content about 50%). Using Eq. 2 values of the moisture content in weight percent at field capacity (FC) were calculated for these soil textures and the results are presented in Figure 7 which is a histogram plot of the distribution of FC values. The range is from 10 to 38 with the distribution skewed toward the higher moisture values, thus half of the fields had FC values between 28 and 38%

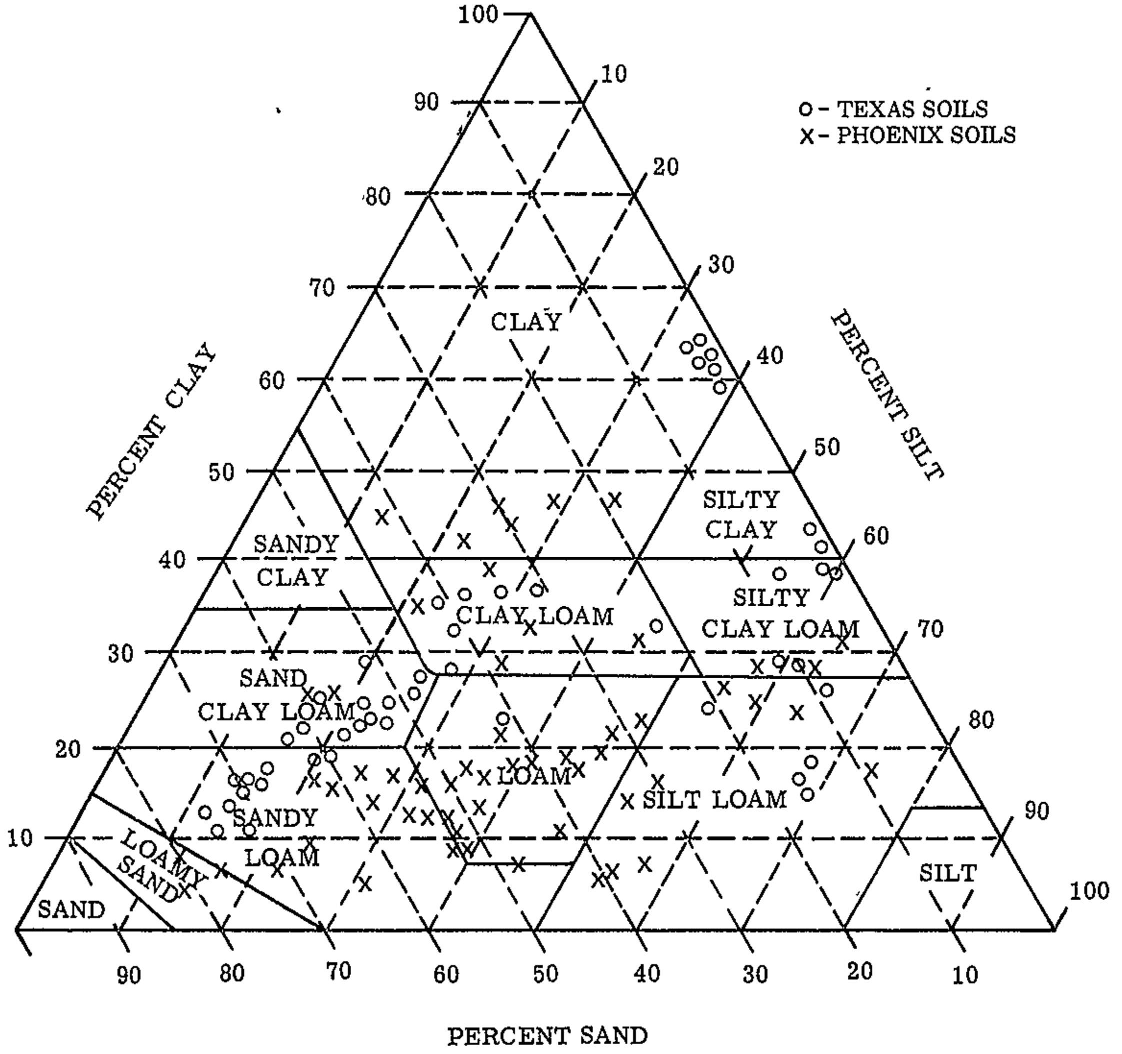

Figure 6. Soil texture triangle showing the soils for the fields observed in aircraft experiments.

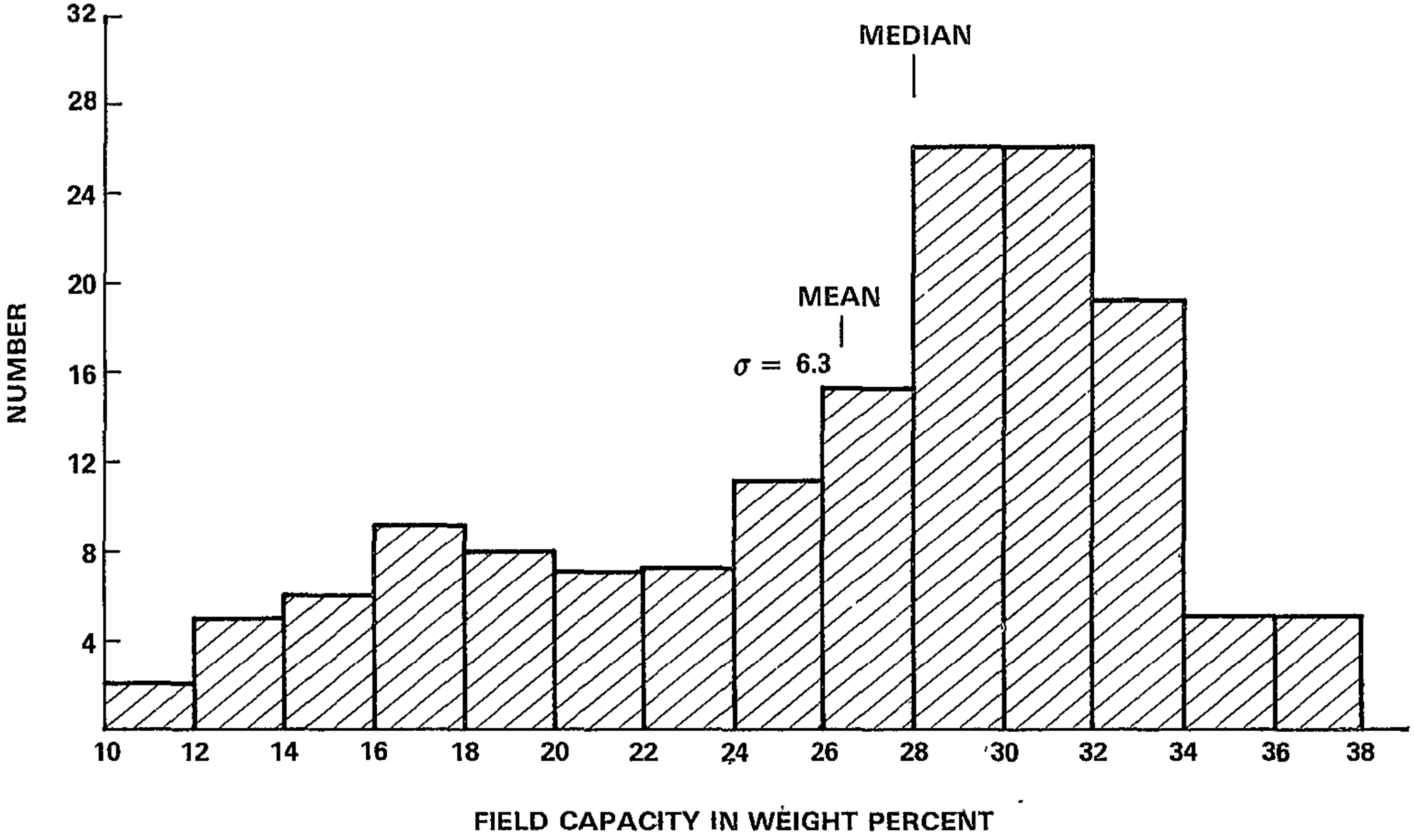

Figure 7.- Histogram of the calculated values of FC for the soils indicated in Figure 6.

1.55 cm Results

The values of the 1.55 cm T_B for each field were obtained by averaging over all the individual values that fell within the field boundary. In Figure 8 these values of T_B are compared with the ground measurements of soil moisture in the surface cm for the light soils (sandy loam and loam) and heavy soils (clay loam and clay). These texture determinations were made by the agricultural consultants of the Salt River Project who were doing the ground sampling In many cases the values plotted are the averages of the two passes over each field. The results for the two passes agreed within 2 or 3K for the dry fields and 5 or 6K for the wet fields. The standard deviations were 3 to 4K for the dry, and 8 to 10K for the wet, reflecting the greater variation in soil moisture expected for a wet field. The large amount of scatter in the data for the dry fields is the result of the range of surface temperature observed during the different flights. The range of brightness temperature is the same for both soil types and there is a clear linear decrease of brightness temperature with soil moisture The slope is less steep for the heavier soils because of the greater range of soil moistures that is possible for them. If the soil moisture is expressed as the percent of FC, this difference can be accounted for as shown in Figure 9. Visually, the scatter in the data is somewhat smaller, and quantitatively, the correlation coefficient for these data is slightly greater than for the light and heavy soils separately. The horizontal error bars are estimates of the uncertainties in the surface soil moisture determinations.

These results gave the first indication of a soil texture effect and of a way to normalize for it. The scanning nature of the 1.55 cm radiometer made possible the acquisition of data for a large number of fields with only a few flights. Unfortunately, it became apparent that a radiometer operating at this short a wavelength had a very limited sampling depth in the soil and was also limited to essentially bare soil situations. Thus the prime focus in later experiments was on longer wavelength systems, especially 21 cm.

21 cm Results

A preliminary analysis of the results at the 21 cm wavelength indicated a dependence on soil texture similar to that shown at the 1.55 cm wavelength. In order to quantify this dependence,

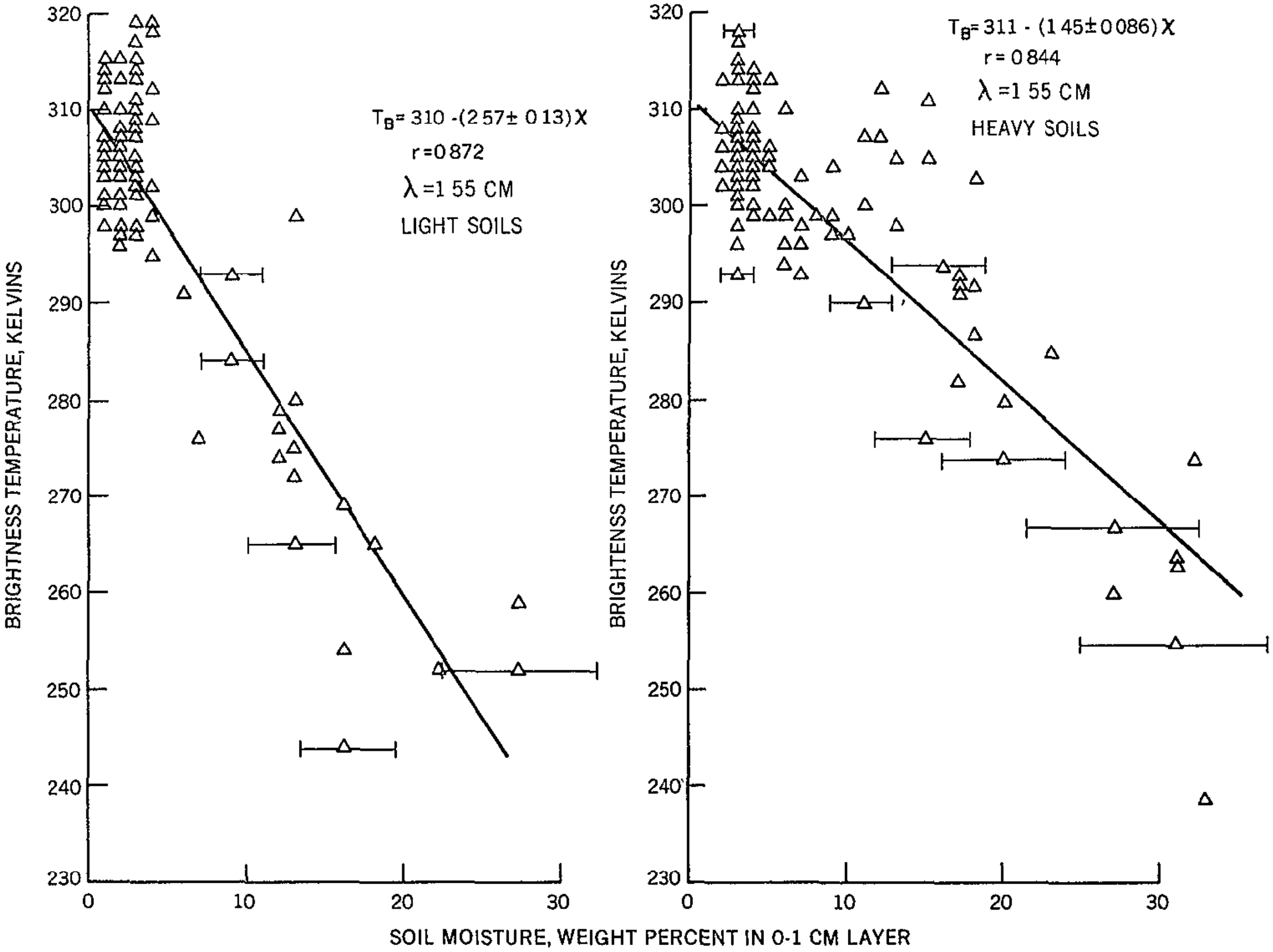

Figure 8. Plot of 1.55 cm values of T_B versus weight percent soil moisture for light and heavy soils (Schmugge, et. al 1976).

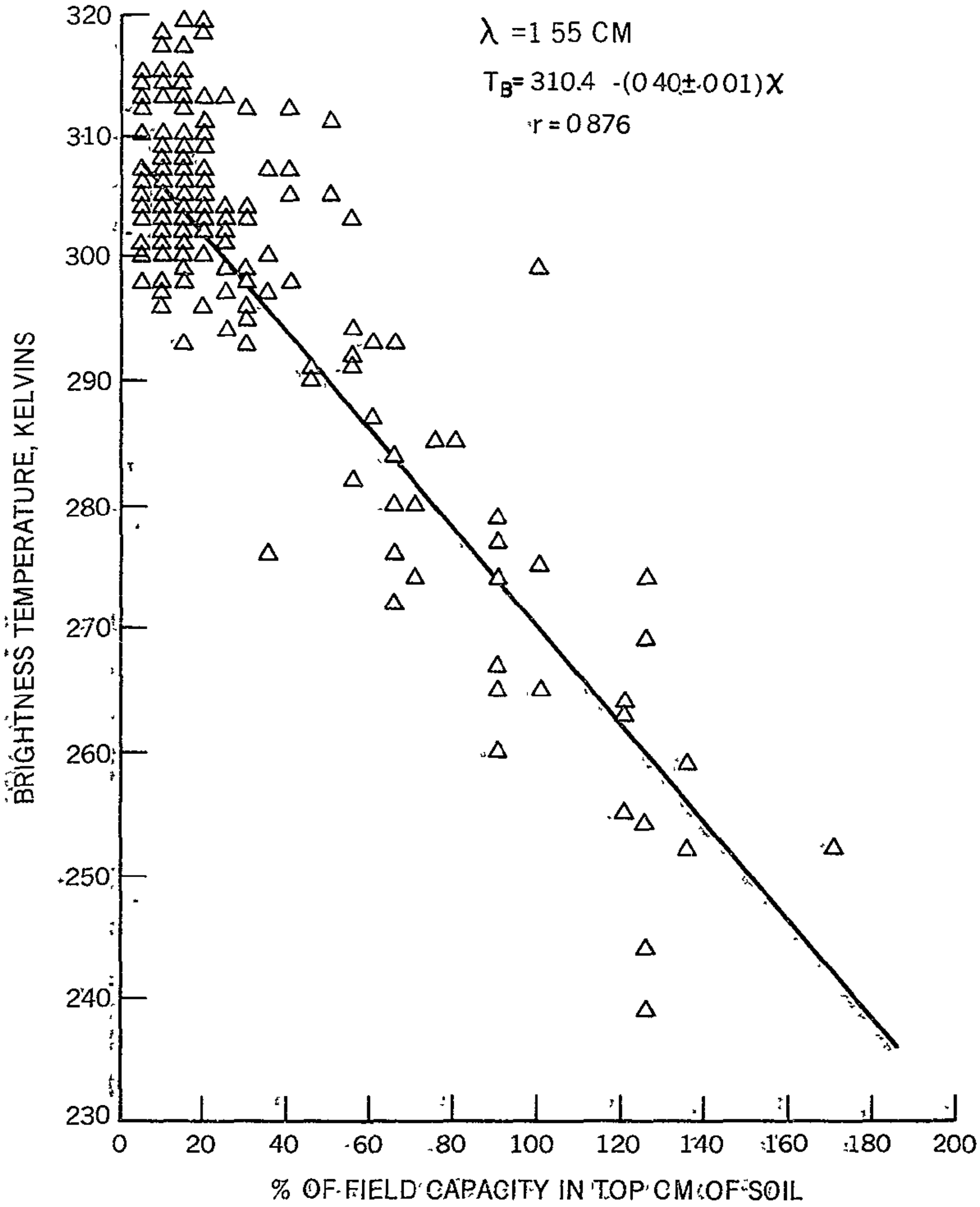

Figure 9. Plot of 1.55 cm values of T_B versus soil moisture expressed as percent of FC (Schmugge, et. al. 1976).

the 21 cm data were divided into 3 soil classes having approximately equal populations using the histogram information given in Figure 6. They were: light soils FC $\leqslant$ 23%, medium soils FC 23% $\leqslant$ FC $<$ 30% and heavy soils 30% $\leqslant$ FC. Even though the populations of each group were approximately the same there are some differences. The light soil class covers a wider range of values for FC, 10 to 23%, compared to only 7 or 8% for the medium and heavy classes. The moisture distributions were not the same in the three classes, in particular there were fewer dry cases (SM $<$ 10% & high T_B) for the heavy soils class compared to the numbers of dry cases for the other two groups. This latter fact will have an effect on the values of the intercepts derived in the regression analyses on these data.

Regression analysis of T_B versus the soil moisture in the surface cm layer were performed on each group separately and on the total population. The surface cm layer was chosen because theoretical calculations of T_B vs soil moisture in this layer indicated a linear response (Schmugge, et al., 1976, Choudhury, et al., 1979). Comparisons with the moisture in thicker layers indicated a bi-linear behaviour similar to that observed for the dielectric constants, Figure 4. The soil moisture values were expressed in 3 ways: weight percent, percent of FC, and percent of WP (the wilting point). The results of T_B plotted versus weight percent are in Figure 10 and versus percent of FC are in Figure 11 The parameters of the regressions are summarized in Tables 4-6.

As would be expected the slopes in Figure 10 decrease as the soils become heavier due to the greater moisture range observed for the heavier soils and the larger values of the transition moisture, W_t, that would be expected for the heavier soils In this figure it is clear that there is a definite difference in the behaviour of the three soil classes. Part of the difference in slope between the medium and heavy soil classes is due to the decrease in the intercept for the heavy soil class resulting from the small number of dry cases (high T_B) in this class. When the same data are plotted versus percent of FC, Figure 11, the slopes of the three classes are in better agreement with each other, e g the probable errors of the slopes overlap even for the two extreme cases which was not true when plotted versus weight percent. The regression results of T_B versus WP, given in Table 6, show an even greater degree of agreement of the slopes for the three soil classes. However in spite

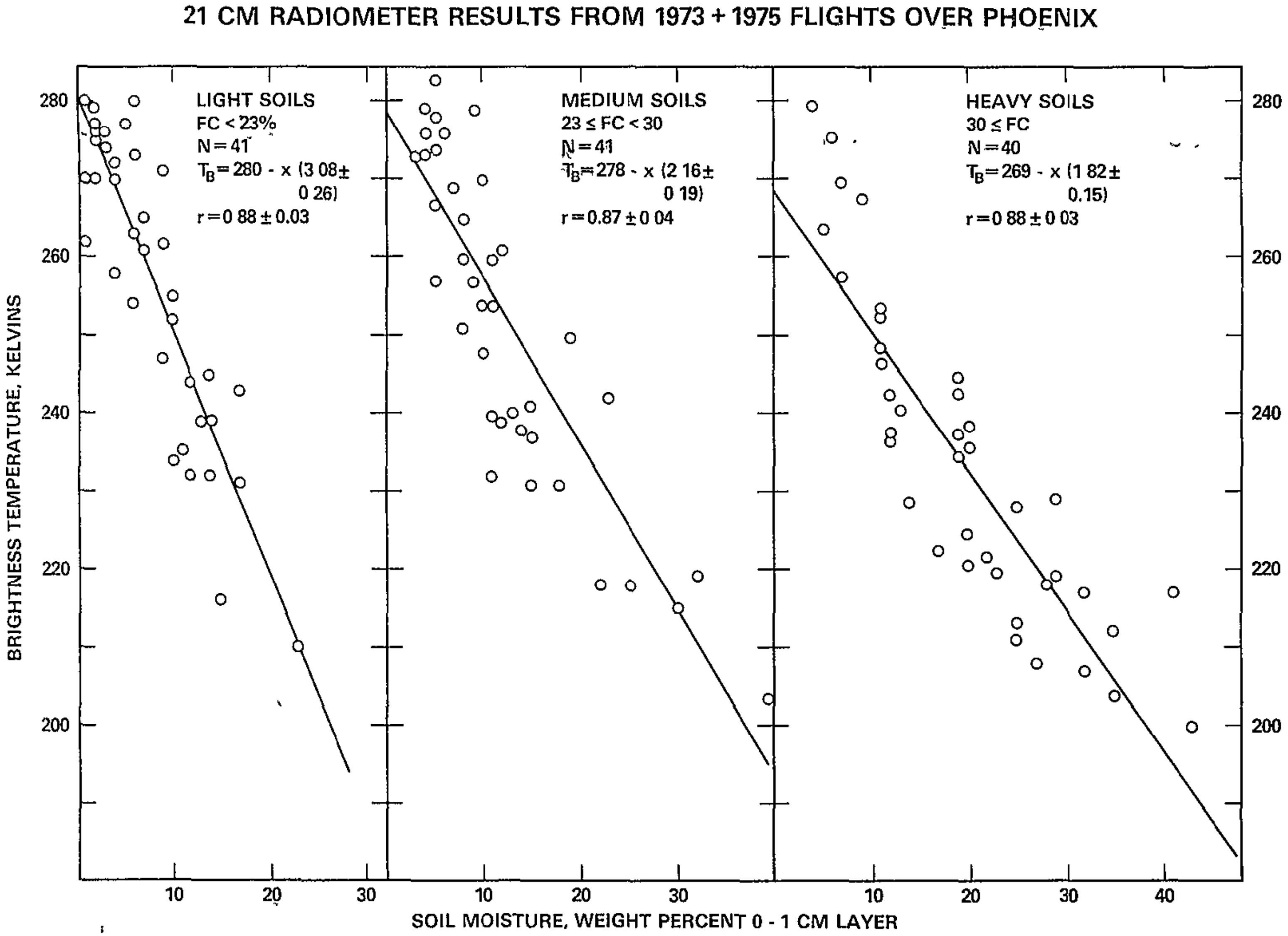

Figure 10. Plot of 21 cm values of T_B versus weight percent soil moistures for soils divided into three classes of soil textures defined by the calculated values of FC. The boundaries were selected to produce equal populations in the three classes.

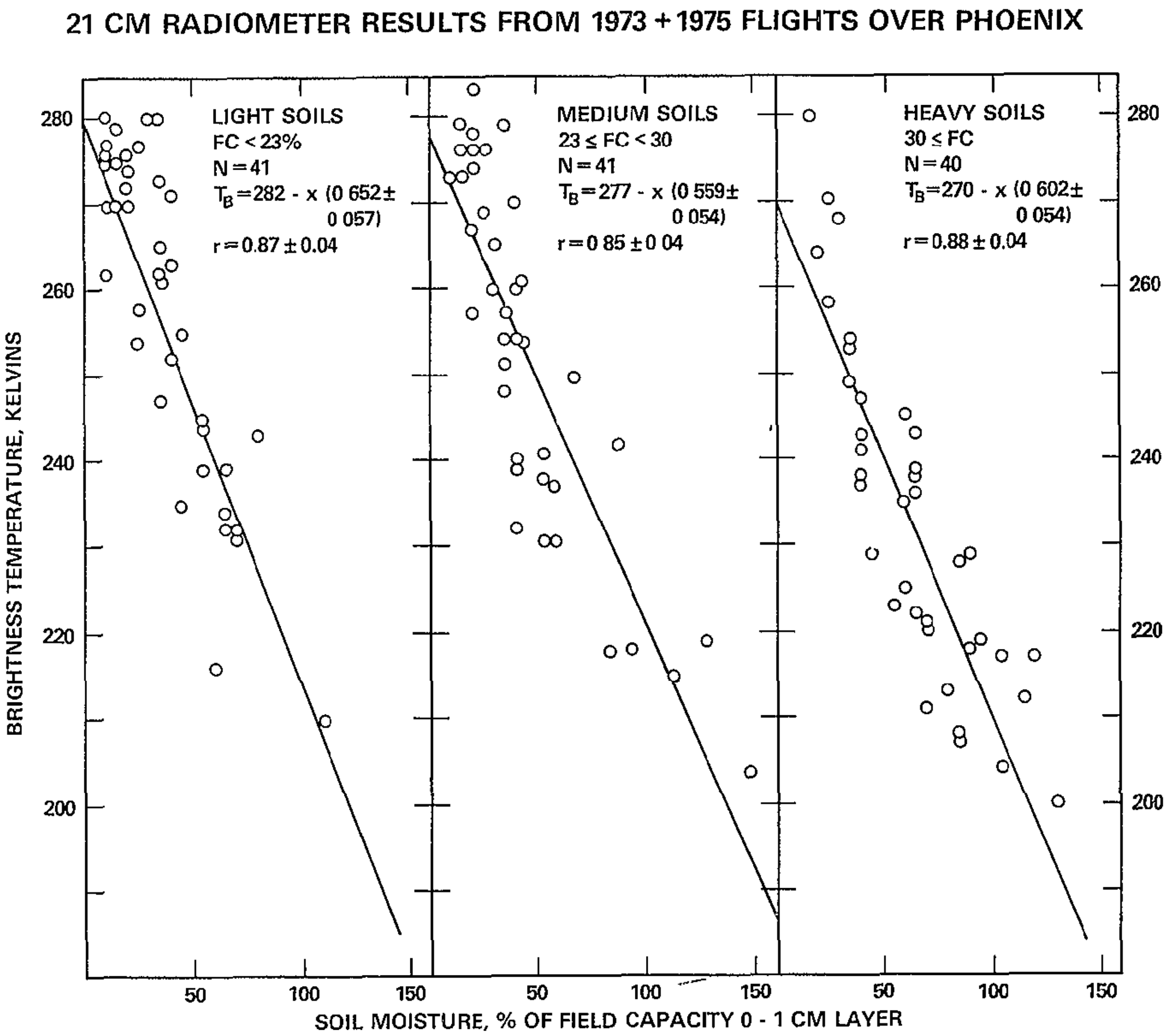

Figure 11. Plot of 21 cm values of T_B versus soil moisture expressed as a percent of FC for same three classes of soils used in Figure 10.

Table 4
Regression Results T_B vs weight percent

	N	Intercept	Slope	Correlation Coefficient, r
Light Soils $FC < 23\%$	41	280	3.08±.26	0.88±.03
Medium Soils $23 \leqslant FC < 30\%$	41	278	2.16±.19	0.87±.04
Heavy Soils $30\% \leqslant FC$	40	269	1.82±.15	0.88±.03
All Soils	122	275	2.10±.09	0.89±.02

Table 5
Regression Results T_B vs % of FC

	N	Intercept	Slope	Correlation Coefficient, r
Light Soils $FC < 23\%$	41	282	0.65±.06	0.87±.04
Medium Soils $23 \leqslant FC < 30\%$	41	277	0.56±.05	0.85±.04
Heavy Soils $30 \leqslant FC$	40	270	0.60±.05	0.88±.04
All Soils	122	278	0.64±.03	0.88±.02

Table 6
Regression Results: T_B vs % of WP

	N	Intercept	Slope	Correlation Coefficient, r
Light Soils $FC < 23\%$	41	282	0.30±.03	0.87±.04
Medium Soils $23 \leqslant FC < 30\%$	41	277	0.29±.03	0.84±.04
Heavy Soils $30 \leqslant FC$	40	271	0.33±.03	0.86±.04
All Soils	122	278	0.33±.02	0.85±.02

of the better correlation obtained between WP and texture given by equations 1 and 3 the correlations between T_B and soil moisture expressed as a percent of WP are no better than those obtained using percent of FC as the independent variable.

In Figure 12 the data from all three soil classes are plotted together versus weight percent in 12a and versus percent of FC in 12b In Figure 12a the lighter soils (0's) are predominantly to the left of the medium and heavy soils However when plotted versus percent of FC there is a greater degree intermixing of the three soil classes. In spite of this qualitative observation of the improvement afforded by using percent of FC as the independent variable, there was no quantitative improvement in the correlation coefficient for the regressions This I believe is due to the uncertainties that are inherent in both the T_B and soil moisture values.

DISCUSSION

The results presented here show that there is a clear dependence of the microwave emission from general agricultural fields on their soil texture. This was obvious qualitatively, but not quantitatively since the results presented in Figure 12 do not show an improved correlation when expressing soil moisture as a percent of FC compared to weight percent. However, the fact that the correlation did not decrease when the uncertainty of the independent variable increased by dividing one noisy variable, soil moisture, by another, FC, with an equal level of uncertainty indicates that there must be some physical significance to the approach. The reason is due to the noise, or uncertainty, that is inherent in the data used here both with the dependent variable, T_B, and the independent variable, soil moisture. As was discussed earlier the uncertainty in the ground measurements of soil moisture was estimated to be 3 to 4% for soil moisture (SM) values above 10% for a $\Delta SM/SM = 0.2$ at moisture levels of 15 to 20% Similarly the regression for FC yielded a $\Delta FC/FC$ of 0.2, the resultant uncertainty in the ratio, $Z = SM/FC$, then would be:

$$\frac{\Delta Z}{Z} = \left[\left(\frac{\Delta SM}{SM}\right)^2 + \left(\frac{\Delta FC}{FC}\right)^2\right]^{1/2} \simeq 0.3 \qquad (10)$$

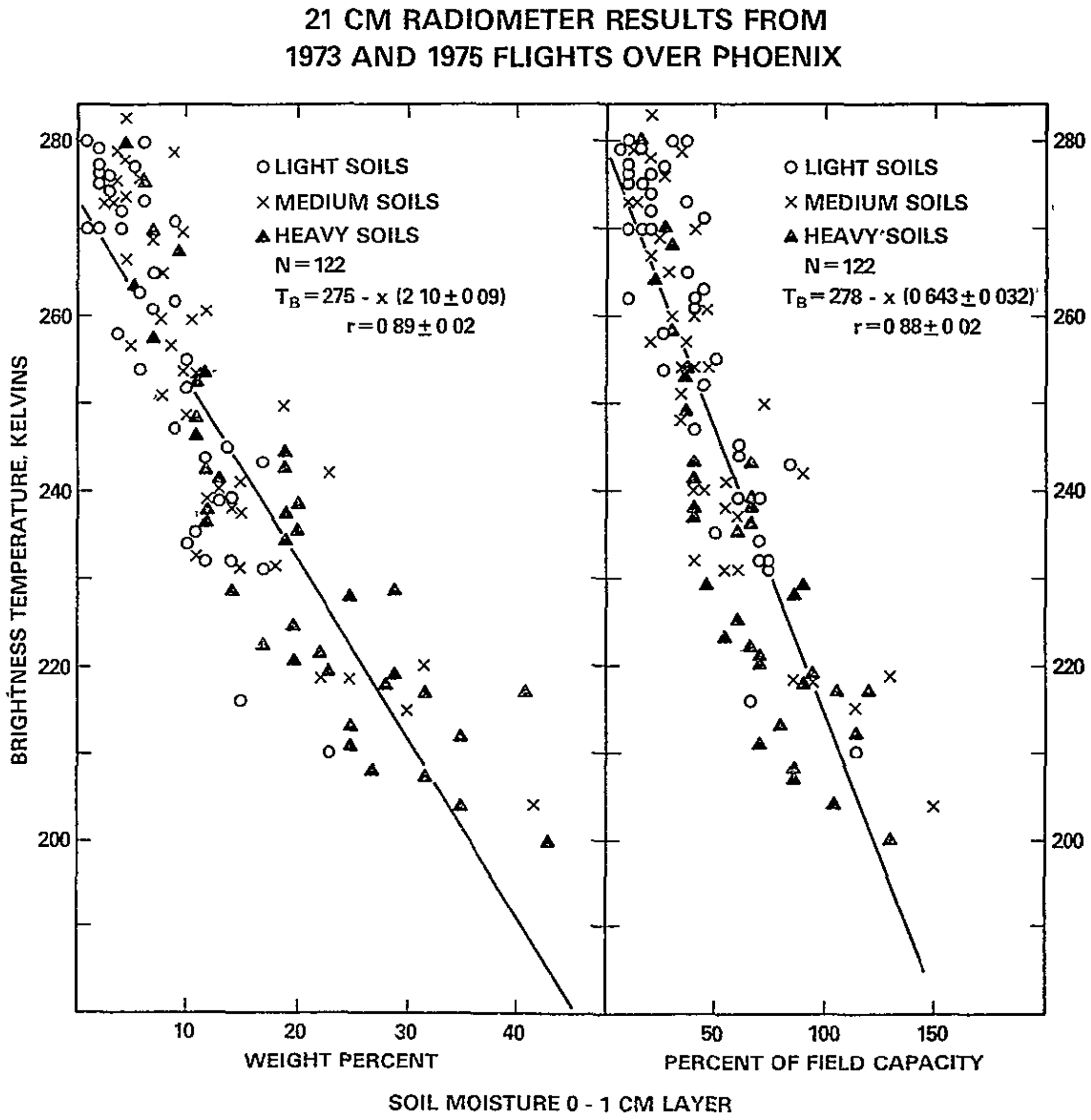

Figure 12. Plot of 21 cm values of T_B for all soils versus (a) soil moisture expressed as weight percent and (b) soil moisture expressed as a apercent of FC.

As a result a decrease would be expected in the correlation between T_B and the ratio SM/FC if there were no significance to it, which was not the case. Thus we conclude there is some significance to using the value of FC for a soil to normalize for soil differences.

The uncertainties in the values of T_B can be attributed to a number of causes one of which is the fact that the experiments were done over a several year period and involved two NASA aircraft (the CV-990 in 1972&73 and the P-3A in 1975) with different instruments. In each experiment the radiometers were calibrated by taking data over water targets whose T_B value can be accurately calculated. As a result the estimated uncertainty in the T_B is ±5K at the low T_B range (~200K) and less than ±2K at the high T_B range (~280K).

A greater source of uncertainty in T_B arises from the variations in the surface roughness of the fields studied. Choudhury et al (1979) have shown that the effect of surface roughness is to increase the emissivity of the soil surface by an amount

$$\Delta e = r_o\ (1 - \exp\ (-h)) \tag{11}$$

where r_o is the reflectivity for the smooth surface and h is an empirically determined roughness parameter which is proportional to the rms height variations of the surface, $h = 0$ for a smooth surface For dry fields fields, $r \leqslant 0\ 1$, the effect will be small, for wet fields $4 = 0.4$, the effect, correspondingly larger. The data presented here were for bare fields which had surface roughnesses determined by the agricultural practices of the two areas The dominant method of irrigation is the flooded furrow with a furrow separation of about one meter and furrow height of about 20 meter. Superimposed on these corrugations were soil clods, which were generally less than 5 cm. For these fields the range of the parameter h, which yielded the best fit to the data was 0.45 to 0 6. The effect of this range on the observed values of T_B is given in Table 7. The range of Δe is less than, but still comparable, to that expected for the difference between the Yuma Sand and Miller Clay soils presented in Table 3, i e. $\Delta e = 12$ Recall that this result is for an extreme range of soil textures, the range of textures for the fields observed in aircraft data is perhaps, only about 2/3 as great, so that the range of emissivity difference expected for soil textures differences is about the same as that expected for the uncertainity in surface roughness. As a result it is surprising that the aircraft data was able to detect any soil texture dependencies and this probably was due to the large amount of data that was available covering a good range of textures.

Table 7
Estimated effect of Roughness Variations

h	$1 - \exp(-h)$	Δe for $r = .4$	ΔT_B for $T = 300K$
0.45	.36	.14	43K
0.60	.45	.22	66K

It may be possible to get around this problem in field experiments in which it should be possible to make the microwave measurements for fields with controlled roughnesses but different textures. This has been done to a certain extent in active microwave or radar experiments (Ulaby, et al., 1979; Dobson and Ulaby, 1979) at the University of Kansas Measurements of the backscatter coefficient σ_o display a similar dependence on soil texture to that presented in Figure 10. The slope of the σ_o versus soil moisture curve was greater for a loam soil than for a heavy clay soil but the slopes essentially agreed when the soil moistures were expressed in percent of FC.

The fact that the regressions were performed versus the soil moisture in a 0 - 1 cm layer should not be taken to infer that the radiometer only responds to the moisture in this layer. The observed and calculated linear relationships result from the comparison of the moisture in a thinner layer for our ground measurements than the layer which the microwave radiometer is actually measuring (Barton, 1978). If the two layers were in consonnance the T_B vs SM curve would be similar to the dielectric constant curve, i.e. approximately bi-linear behaviour with a region slow change in T_B at low moisture levels followed by a more rapid change of T_B at the higher moisture levels. This behaviour is observed when T_B is compared with the soil moisture in the 2 5 and 5 cm layers of the soil (Choudhury, et al., 1979)

The next step in this analysis will be to test the possibility that the pressure potential of the soil water can be inferred directly from the microwave observations. Relationships such as those developed by Clapp and Hornberger (1978) can be used to estimate the pressure potential from the measured soil moisture content using the known textural class of the soil This approach has been tied with the active microwave backscatter data obtained by the University of Kansas with results comparable to those obtained percent of FC for normalizing the moisture content (Dobson & Ulaby, 1979)

The ability to express the moisture content in terms of a percent of FC for a soil means that it is not necessary to know the soil type to determine the state of the soil water from remotely sensed observables. An example of how this may be used directly is given in the paper by Davies and Allen (1973) in which they parameterized the evapotranspiration from the soil in terms of the percent of FC for the moisture in the 0 - 5 cm layer of the soil for either bare soil of shallow rooted vegetation. This analysis was extended by Barton (1979) using soil moisture data obtained with an airborne microwave radiometer.

CONCLUSIONS

Due to the differing amounts of water that can be tightly bound to soil particles there is a dependence of a soil's dielectric properties on its texture. This dependence has been observed in laboratory measurements of the dielectric constant of soils and in both active and passive microwave observations of soil moisture directly. Therefore to obtain an absolute measurement of the soils moisture content with a microwave remote sensor some knowledge of the moisture characteristics for the soil will be required. Alternatively it has been shown that the state of the moisture in the surface layer of the soil, expressed as a percent of FC, can be measured directly. This latter information may, in some applications, be more important than the absolute content.

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