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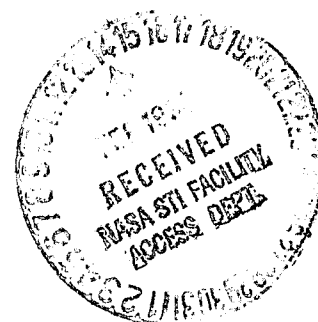
# The Dielectric Properties of Soil-Water Mixtures at Microwave Frequencies

J. R. Wang

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National Aeronautics and  
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**Goddard Space Flight Center**  
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AT MICROWAVE FREQUENCIES

J. R. Wang  
Laboratory for Atmospheric Sciences

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Greenbelt, Maryland 20771

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## THE DIELECTRIC PROPERTIES OF SOIL-WATER MIXTURES AT MICROWAVE FREQUENCIES

J. R. Wang  
Laboratory for Atmospheric Sciences

### ABSTRACT

Recent measurements on the dielectric constants of soil-water mixtures have shown the existence of two frequency regions in which the dielectric behavior of these mixtures was quite different. At the frequencies of 1.4 GHz – 5 GHz there were strong evidences that the variation of the dielectric constant  $\epsilon$  with water content  $W$  depended on soil type. While the real part of  $\epsilon$ ,  $\epsilon'$ , for sandy soils rose rapidly with the increase in  $W$ ,  $\epsilon'$  for the high-clay content soils rose only slowly with  $W$ . As a consequence,  $\epsilon'$  was generally higher for the sandy soils than for the high-clay content soils at a given  $W$ . On the other hand, most of the measurements at frequencies  $< 1$  GHz indicated the increase of  $\epsilon$  with  $W$  independent of soil types. At a given  $W$ ,  $\epsilon'$  (sandy soil)  $\cong \epsilon'$  (high-clay content soil) within the precision of the measurements.

These observational features could be satisfactorily interpreted in terms of a simple dielectric relaxation model suggested by Schwarz (1962), with an appropriate choice of the mean relaxation frequency  $f_m$  and the range of the activation energy  $\beta$ . It was found that smaller  $f_m$  and larger  $\beta$  were required for the high-clay content soils than the sandy soils in order to be consistent with the measured data. These requirements on  $f_m$  and  $\beta$  were strongly supported by the observed dependence of the soil surface area per unit weight on the soil types.

## THE DIELECTRIC PROPERTIES OF SOIL-WATER MIXTURES AT MICROWAVE FREQUENCIES

### 1. INTRODUCTION

Many measurements of complex dielectric constant of soils as a function of moisture content have been carried out in recent years (Lundien, 1971; Newton, 1977; Wang and Schmugge, 1978; Hockstra and Delaney, 1974; Davis et. al., 1976). Among several useful results from these measurements, the one concerning the soil type dependence of the functional relationship between the dielectric constant  $\epsilon$  and the moisture content  $W$  remains to be clarified further. On the one hand, the measurements at 1.4 GHz (Lundien, 1971; Newton, 1977) and 5 GHz (Wang and Schmugge, 1978) strongly suggest that the variations of  $\epsilon$  with  $W$  depend on soil types. The real part of  $\epsilon$ ,  $\epsilon'$ , for sandy soils rises more rapidly with  $W$  than that for the soils with high clay content. On the other hand, the results of measurements from Hockstra and Delaney (1974) and from Davis et. al. (1976) showed a very little dependence of the  $\epsilon' - W$  variations on soil types. The measurements of Hockstra and Delaney were limited to only a few values of  $W$  and the data points were scattered in the  $\epsilon'$  vs.  $W$  plot. However, the measurements of Davis et al., which were carried out in the frequency range  $< 1$  GHz, were made over a wide range of  $W$  and the data points showed a small scatter in the functional relation between  $\epsilon'$  and  $W$ . Thus, it appears that the effect of soil types on the relation between  $\epsilon'$  and  $W$  is frequency dependent, being weak at frequency  $< 1$  GHz and strong at frequencies  $> 1$  GHz.

Many mixing formulas were examined by Wang and Schmugge (1978) and were found inadequate to describe the dielectric behavior of soil-water mixtures at 1.4 GHz and 5 GHz. More recently, Wobschall (1977) had proposed a semi-disperse model for the dielectric property of soil-water mixtures at frequencies  $< 1$  GHz. By adjusting the two free parameters, the model could probably fit

the measured  $\epsilon' - W$  relation at low frequencies. However, it lacks the provision to account for the very different soil type dependence of  $\epsilon' - W$  relation at two different frequency regions separated at  $\sim 1$  GHz.

In this paper it is pointed out that by applying an existing theory of dielectric relaxation for a mixture (Schwarz, 1962) to different soils, the different dependence of  $\epsilon' - W$  relation on soil types at low and high frequencies can be understood qualitatively. In that theory, the dielectric relaxation for a mixture is characterized by a mean frequency of relaxation  $f_m$  and a normalized range of activation energy  $\beta$ . By assuming different values of  $f_m$  and  $\beta$  for the sandy and high-clay content soils, the different dependence of  $\epsilon' - W$  relation on soil types at two frequency regions was obtained. The choice of different  $f_m$  and  $\beta$  for different soils was consistent with the soils' texture structure and surface area per unit weight.

## 2. THE EXPERIMENTAL DATA

Figure 1 shows the plot of the measured  $\epsilon'$  as a function of  $W$ . The data points in the plot include the measurements of Lundien (1966) at 0.3 GHz for 3 different soils and at 1.4 GHz for Yuma sand. The measured results of Newton (1977) at 1.4 GHz for sand, Njoku and Kong (1977) at 0.3 GHz for sand, Hipp (1974) at 0.3 GHz for San Antonio and Puerto Rico clay loams, and Hockstra and Delaney (1974) at 0.5 GHz for three different soils are also displayed. The measurements of Davis et al. (1976) were carried out rather extensively and, therefore, only the average regression curve from their results was shown as a dashed line in the figure. Clearly, there is no systematic pattern of soil type variations based on these data. The large scatter in the data points appears to result from different measurements. For example, the measured data of Hockstra and Delaney are generally higher than those of the others. A second order polynomial regression was performed to all the data points and the resultant regression was shown as a solid curve in the figure.

The correlation coefficient is 0.98. This regression curve generally gives a higher  $\epsilon'$  than that of Davis et. al., because of the higher measured values of  $\epsilon'$  from Hockstra and Delaney.

In addition to the lack of soil type dependence, the data in Figure 1 also suggest that  $\epsilon'$  for sand at 1.4 GHz is comparable to that at low frequencies for a given  $W$ . In fact, the data displayed in Figure 6 of Njoku and Kong (1977) indicated that  $\epsilon'$  for sand at a given  $W$  was nearly independent of frequency over the range of 0.3 - 3 GHz. However, when the measurements of  $\epsilon'$  for the other soil types at 1.4 GHz and 5 GHz were considered, the effect of soil type dependence became apparent (Lundien, 1971; Newton, 1977; Wang and Schmugge, 1978). At a given  $W$ , the measured  $\epsilon'$  for high-clay content soils was always smaller than that for the sandy soils. These very different dielectric behaviors at frequencies  $< 1$  GHz and 1.4 - 5 GHz strongly suggest that the dielectric relaxation scheme for sandy soils and for high-clay content soils could be quite different. The data shown in Figure 2 also support the possible different dielectric relaxation scheme for different soils.

Figure 2 gives the measured surface areas per gm of dry soil as a function of the wilting point WP for various types of soils. Most of the data points were obtained from the report of Heilman et. al. (1966). The remaining data points were derived from the reports of Hockstra and Delaney (1974) and Rhodes et. al. (1976). WP of the soils was calculated from Eq. (1) of Wang and Schmugge (1978) knowing the soil texture. A correlation coefficient of 0.80 was obtained when a linear regression was applied to all the data points in the figure.

As clearly shown in Figure 2, the surface area per gm of soil could change by more than three times from the very sandy soils to the high-clay content soils. The amount of water required to form one layer of water molecules around the high-clay content soil particles per gm would be enough to cover three layers of water molecules around the sandy soil particles per gm. Since the activation energy of the adsorbed water from one layer to another is different (Hasted, 1973), the



dielectric relaxation frequency would be different for different layers also. Muir (1954) had actually observed a steady shift in the dielectric relaxation frequency towards high values as the number water layers in his soil sample was increased. Consequently, for a given W, the dielectric relaxation for sandy soils and for high-clay content soils could occur at different frequencies and have different frequency distributions. As a result of the different relaxation scheme, it is possible to have a soil type dependence for  $\epsilon' - W$  relation at frequencies  $> 1$  GHz, while maintaining an approximate soil type independence at  $\sim 0.3$  GHz. A simple theory on the dielectric relaxation reported by Schwarz (1962) was employed in the next two sections to illustrate the phenomenon.

### 3. THE DIELECTRIC RELAXATION

Multiple frequency measurements on the complex dielectric constants of various soil-water mixtures over the microwave region of dielectric relaxation have been rare. However, data from a limited number of measurements (Hockstra and Delaney, 1974; Njoku and Kong, 1977) indicate that the dielectric relaxation of soil-water mixture at microwave region is predominantly of Debye type. For this type of dielectric relaxation, Schwarz (1962) obtained two simple expressions for the real and imaginary parts of the dielectric increments,  $\Delta\epsilon'$  and  $\Delta\epsilon''$ , as

$$\Delta\epsilon' = \frac{\Delta\epsilon_0}{2 \ln \xi_0 - 1} \ln \frac{\xi_0^{-1} + \omega^2 \tau_m^2}{\xi_0 + \omega^2 \tau_m^2} \quad (1)$$

$$\Delta\epsilon'' = \frac{\Delta\epsilon_0}{\ln \xi_0 - 1} \tan^{-1} \frac{(1 - \xi_0) \omega \tau_m}{\sqrt{\xi_0} (1 + \omega^2 \tau_m^2)} \quad (2)$$

where  $\Delta\epsilon_0$  is the static dielectric increment and  $\omega$  is the angular frequency.  $\xi_0$  is a parameter related to the width  $\Delta\alpha$  of the activation energy by

$$\xi_0 = e^{-\frac{\Delta\alpha}{kT}} = e^{-\beta} \quad (3)$$

with T being the temperature in °K and k the Boltzman constant. The mean relaxation time  $\tau_m$  is related to the mean relaxation frequency  $f_{in}$  by

$$\tau_m = \frac{1}{2\pi f_m} \quad (4)$$

In the derivation of Eqs. (1) and (2), Schwarz (1962) assumed that the distribution function  $\rho(\alpha)$  remained constant with activation energy  $\alpha$ , subject to the condition

$$\int_0^{\infty} \rho(\alpha) d\alpha = 1 \quad (5)$$

For the soil-water mixtures considered here, the exact form of  $\rho(\alpha)$  is also not known. For simplicity, the same assumption is made in the following discussion. The dielectric relaxation is completely characterized by the parameter  $\xi_0$  and the mean relaxation time  $\tau_m$ .

$\Delta\epsilon_0$  is simply given by

$$\Delta\epsilon_0 = \epsilon_s - \epsilon_{\infty} \quad (6)$$

with  $\epsilon_s$  being the static relative permittivity and  $\epsilon_{\infty}$  the relative permittivity at high frequencies.

Entering  $\epsilon_s$  and  $\epsilon_{\infty}$  explicitly, the real and imaginary parts of the dielectric constant are, from Eqs. (1) and (2),

$$\epsilon' = \epsilon_{\infty} + \frac{(\epsilon_s - \epsilon_{\infty})}{2 \ln \xi_0^{-1}} \ln \frac{\xi_0^{-1} + \omega^2 \tau_m^2}{\xi_0 + \omega^2 \tau_m^2} \quad (7)$$

$$\epsilon'' = \frac{(\epsilon_s - \epsilon_{\infty})}{\ln \xi_0^{-1}} \tan^{-1} \frac{(1 - \xi_0) \omega \tau_m}{\sqrt{\xi_0} (1 + \omega^2 \tau_m^2)} + 60 \lambda \sigma \quad (8)$$

where the ionic conductivity term (de Loor, 1968) was included in the expression for  $\epsilon''$  to fit the measured data at frequencies  $\leq 0.5$  GHz in the next section.  $\lambda$  is the wavelength in cm and  $\sigma$  is the conductivity in Mho/cm.  $\epsilon_{\infty}$  for water is assumed to be  $\sim 4$  (Hasted, 1973). For soil water mixture, it is assumed to vary with water content  $W$  as

$$\epsilon_{\alpha} = \epsilon_r(1 - P) + \epsilon_a(P - W) + 4W \quad (9)$$

where  $P \cong 0.5$  is the porosity of soils, and  $\epsilon_a = 1$  is the dielectric constant of air. The dielectric constant of rocks  $\epsilon_r$  varies (Campbell and Ulrichs, 1969), but a choice of  $\epsilon_r \cong 5.0$  appears to be reasonable

considering the dielectric constant of dry soils.  $\epsilon_s$  for the mixture is difficult to estimate. Without loss of generality,  $\epsilon_s$  is assumed to vary with  $W$  according to the regression result of the data points in Figure 1 as

$$\epsilon_s = 3.14 + 23.83 W + 91.58 W^2 \quad (10)$$

#### 4. RESULTS

Based on the formulas presented in the previous section, sample calculations were made with assumed values of  $f_m$  and  $\beta = \Delta\alpha/kT$  for several different  $W$ . Table 1 gave the calculated results for  $\epsilon'$  at the frequencies of 0.3 GHz and 1.4 GHz. Values of  $\epsilon_s$  from Eq. (10) were also included in the table. At a given  $W$ , different pairs of values for  $f_m$  and  $\beta$  were chosen for typical sandy and high-clay content soils to illustrate the measurement results. The calculated  $\epsilon'$  and  $\epsilon''$  as a function of  $W$  at 1.4 GHz for both sandy and high-clay content soils were shown in Figure 3 as dashed and solid curves respectively. The measured  $\epsilon'$  and  $\epsilon''$  for Yuma sand and Long-Lake clay at the same frequency by Lundien (1971) were also included in the figure for comparison. Each data point in the figure was the average result of 2 to 3 measured values.

Clearly, the calculated  $\epsilon'$  and  $\epsilon''$  for the chosen  $f_m$  and  $\beta$  agree reasonably well with the measurement results at 1.4 GHz for both sandy and high-clay content soils. Both the calculated and measured values of  $\epsilon'$  for sandy soil were higher than those for the high-clay content soil by as much as  $\sim 6$ . On the other hand, a comparison of the calculated  $\epsilon'$  at 0.3 GHz given by Table 1 showed that  $\epsilon'$  for sandy soil was larger than that for the high-clay content soil by not more than  $\sim 2.5$  at any given  $W$ . This small difference could easily be concealed in the scatter of the measured data as shown in Figure 1 or in the report by Davis et al. (1976). An additional feature displayed in Figure 3 is that, for a given  $W$ , the higher  $\epsilon''$  value for the high-clay content soil than that for the sandy soil comes naturally as a result of the choice in  $f_m$  and  $\beta$ . There is no need to introduce the ionic conductivity term (Wang and Schmugge, 1978) to fit the data at 1.4 GHz in this model.

Table 1  
A Sample Calculation of  $\epsilon'$  for Typical Sandy and High-Clay Content Soils

W cm <sup>3</sup> /cm <sup>3</sup>	$\epsilon_s$	Clay			Sand*				
		f <sub>m</sub> (GHz)	$\beta$	$\epsilon'$ (1.4 GHz)	$\epsilon'$ (0.3 GHz)	f <sub>m</sub> (GHz)	$\beta$	$\epsilon'$ (1.4 GHz)	$\epsilon'$ (0.3 GHz)
0.05	4.56	1.84	3.50	4.00	4.44	5.46	3.00	4.38	4.55
0.10	6.44	1.60	4.00	5.02	6.03	10.10	3.00	6.28	6.43
0.15	8.78	1.54	6.50	6.24	7.46	17.80	3.00	8.67	8.77
0.20	11.57	1.54	6.50	7.75	9.59	23.70	3.00	11.48	11.56
0.25	14.82	2.47	6.50	10.29	12.81	23.70	3.00	14.70	14.82
0.30	18.53	2.64	6.00	12.79	16.32	23.70	3.00	18.37	18.52
0.35	22.70	4.11	6.50	16.48	20.54	23.70	3.00	22.49	22.69
0.40	27.32	5.28	6.00	20.84	25.73				
0.45	32.41	5.28	6.00	24.54	30.47				
0.50	37.95	9.61	7.00	30.35	36.22				
0.55	43.95	9.61	7.00	35.02	41.91				

\*No data beyond W = 0.40 in Figure 3.

The dielectric measurements of Njoku and Kong (1977) for sand were made over a wide frequency range with an adequate number of  $W$  values. To see how the theory can fit the experimental data, some of these measurement results were reproduced in Figure 4 and Figure 5 for  $\epsilon'$  and  $\epsilon''$  respectively. With  $\epsilon_s$  and  $\epsilon_\infty$  given as before, the calculated results were shown as solid curves in the figures. The  $f_m$  and  $\beta$  values chosen for each given  $W$  in the calculations were indicated in Figure 4. Values of ionic conductivity  $\sigma$  required to fit  $\epsilon''$  in the low frequency region were included in Figure 5. Clearly, the measured and calculated  $\epsilon''$  in Figure 5 generally agree quite well. The changes in  $f_m$  and  $\beta$  with  $W$  were evident from a comparison of the measured and calculated results in the figure. It is also clear from Figure 4 that the calculated  $\epsilon'$  were higher than the measured  $\epsilon'$ , especially in the high  $W$  region. This is a direct consequence of the data shown in Figure 1 in which the measured  $\epsilon'$  of Njoku and Kong were smaller than the average regression result given by Eq. (10). At  $W = 0.30 \text{ cm}^3/\text{cm}^3$ , Eq. (10) gives  $\epsilon_s = 18.5$  compared to  $\epsilon_s \cong 16.7$  from the measurements of Njoku and Kong at low frequencies.

It is possible to fit the calculated  $\epsilon'$  and  $\epsilon''$  to the measured results in Figures 4 and 5 at low  $W$  by slightly changing the values of  $\epsilon_\infty$  and  $\epsilon_s$ . For example, at  $W = 0.10 \text{ cm}^3/\text{cm}^3$ , the dashed curves in both figures were calculated with same  $f_m$  and  $\beta$  but with  $\epsilon_\infty = 3.20$  and  $\epsilon_s = 6.20$  rather than  $\epsilon_s = 6.44$  and  $\epsilon_\infty = 3.25$  given by Eqs. (9) and (10). The calculated and measured  $\epsilon'$  and  $\epsilon''$  compare fairly well in both figures. However, it is not possible to obtain a reasonable agreement between the calculated and the observed  $\epsilon'$  and  $\epsilon''$  in both figures at high  $W$ . This is so because for a Debye type dielectric relaxation, the maximum  $\epsilon''_{\text{max}} = (\epsilon_s - \epsilon_\infty)/2$  occurs only in a single frequency dielectric relaxation and  $\beta = 0$  (Schwarz, 1962). For  $W = 0.30$ , the measured  $\epsilon'$  and  $\epsilon''$  were  $\sim 16.8$  and  $\sim 8.5$  respectively, which required  $\epsilon_\infty = 0$ . A zero value for  $\epsilon_\infty$  of a soil-water mixture is unlikely considering the finite values of  $\epsilon_\infty$  for water (Hasted, 1973) and for dry soil (Geiger and Williams, 1972) at high frequencies.

## 5. DISCUSSION

Results from the previous section show that even if the static permittivity  $\epsilon_s$  is approximately independent of soil type or a given water content  $W$ , the dielectric constant  $\epsilon$  at frequencies  $> 1$  GHz could be very different for sandy and high-clay content soils. This soil-type dependence of  $\epsilon$  results from the different dielectric relaxation schemes for sandy and high-clay content soils. In general, it is necessary to choose higher mean relaxation frequency  $f_m$  and smaller activation energy range for sandy soils than for high-clay content soils in order to fit the measured data. There is a strong indication based on Figure 2 that the dielectric relaxation should depend on soil type. For example, the activation energy  $\alpha$  (which is proportional to the logarithm of relaxation time  $\tau$ ) of water molecules around the soil particles was observed to be highest in the first layer and decrease monotonously for each successive layer (Hasted, 1973). The relaxation frequency  $f$  would be low for the first layer and increase with each successive layer of water molecules. Since sandy soils have small surface area per unit weight, not much water is needed to reach the state where  $\alpha$  is equal to that for the bulk water. As a consequence, the distribution function  $\rho(\alpha)$  is such that  $f_m$  is generally high and  $\beta$  small. On the other hand, the high-clay content soils have large surface area per unit weight according to Figure 2. At any  $W$ , there is always an appreciable fraction of water in the bound state of the soil particles. As a result, when compared to sandy soils at a given  $W$ ,  $f_m$  is small and  $\beta$  large for the high-clay content soils. This inference appears to be supported by the measured results of Njoku and Kong (1972) and Hockstra and Delaney (1974) for sand and Goodrich Clay respectively. At  $W = 0.10 \text{ cm}^3/\text{cm}^3$ , these measurements gave  $f_m$  of  $\sim 15$  GHz for sand and of  $\sim 1$  GHz for Goodrich Clay.

The calculations on  $\epsilon'$  and  $\epsilon''$  in the previous section were made with the same static permittivity  $\epsilon_s$  from Eq. (10) for both sandy and high-clay content soils. This assumption may not be valid in reality. A different value of  $\epsilon_s$  requires different  $f_m$  and  $\beta$  in order to fit the measured data.

For example, if  $\epsilon_s = 21$  at  $W = 0.30 \text{ cm}^3/\text{cm}^3$ , a choice of  $f_m = 1.73$  and  $\beta = 8.25$  gives  $\epsilon' = 12.83$  and  $\epsilon'' = 3.17$  at 1.4 GHz which compare favorably with the measured values of  $\epsilon'$  and  $\epsilon''$  for Long Lake Clay shown in Figure 3. At 0.3 GHz the same calculation gives  $\epsilon' = 16.10$  which is close to the value obtained for the same soil in Table 1. This example clearly points out the lack of uniqueness in the choice of  $f_m$  and  $\beta$  if  $\epsilon_s$  is not known. Precision multiple frequency measurements of  $\epsilon'$  and  $\epsilon''$  over the region of dielectric relaxation for many different soils are needed in order to understand the phenomenon quantitatively.

The soil type dependence of  $c$  discussed above suggests that the brightness temperatures at a given  $W$  for soils with different texture structures would be different at frequencies  $> 1$  GHz. Schmugge et al. (1976) actually observed such an effect at 1.4 GHz and 10.7 GHz from the airborne radiometric measurements of agricultural fields of many different soils. In order to improve the correlation between the measured brightness temperature and soil moisture content, they had to quantify the soil types by normalizing the soil moisture content to the field capacity of soils. Since most of the dielectric measurements in the frequency region 0.3 – 1 GHz result in an approximate soil type independence for  $\epsilon'$ , it is expected that the radiometric measurements of soil moisture content in that frequency range could also be independent of soil types.

## 6. CONCLUSIONS

A simple dielectric relaxation model suggested by Schwarz (1962) was used to describe the observational features in the dielectric behavior of the soil-water mixtures. With the different choice in the values of the mean relaxation frequency and the range of the activation energy for sandy and high-clay content soils, the model was able to reproduce the observed soil type dependence of the dielectric constant at frequencies  $> 1$  GHz. At low frequencies  $\sim 0.3$  GHz the same model calculation generated values of dielectric constant nearly soil type independent, in accordance

with many observational results. The physical rationale behind the choice of different mean relaxation frequency and the range of activation energy for different soils is that the surface area per gm of soil strongly depends on soil types. As a result, the distribution of activation energy for water in the mixture at a given water content is expected to be different for different soils. However, the choice of these parameters to fit the observed data was not unique. Precision measurements of the dielectric constants over a wide frequency range for many soils with a wide texture variation are required in order to quantify the soil-type dependence of the dielectric relaxation of the soil-water mixtures.

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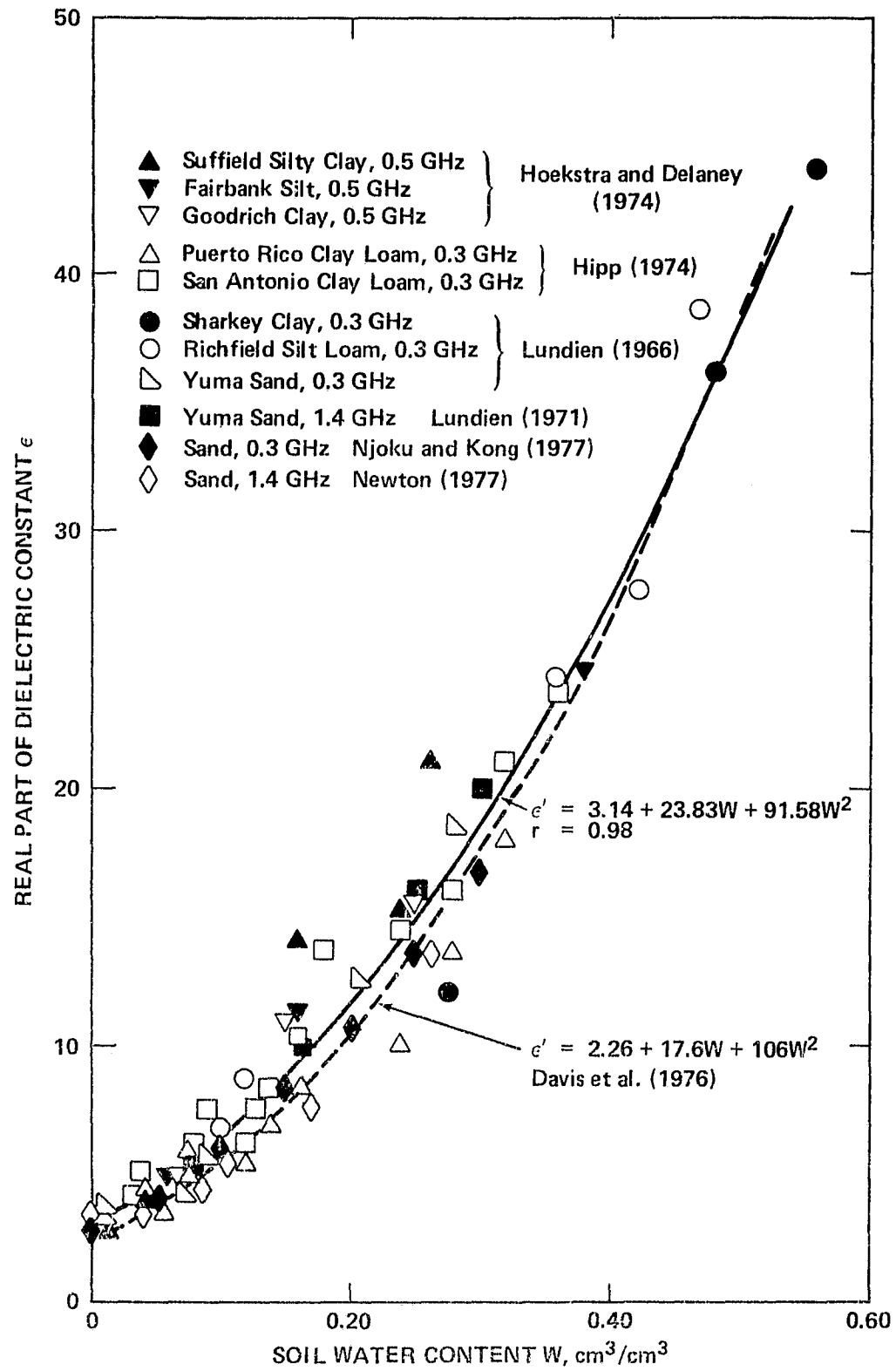


Figure 1. The measured real part of dielectric constants as a function of water content for many soils at the frequencies of 0.3 GHz, 0.5 GHz and 1.4 GHz. At 1.4 GHz only the results of sandy soil measurements were shown.



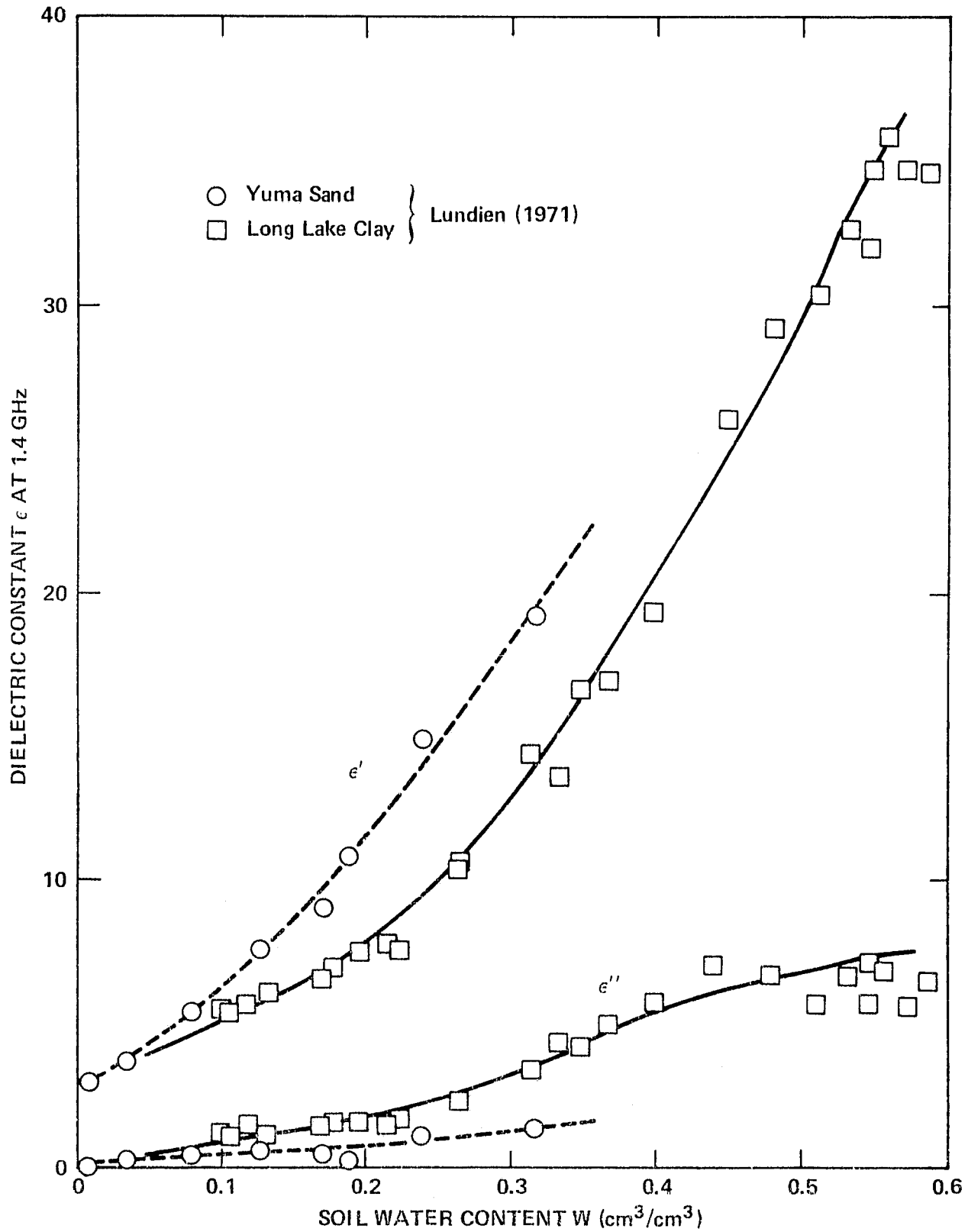


Figure 3. The calculated and measured dielectric constants of sandy and high-clay content soils as a function of water content at 1.4 GHz. The calculations were made with parameters  $f_m$  and  $\beta$  given in Table 1.

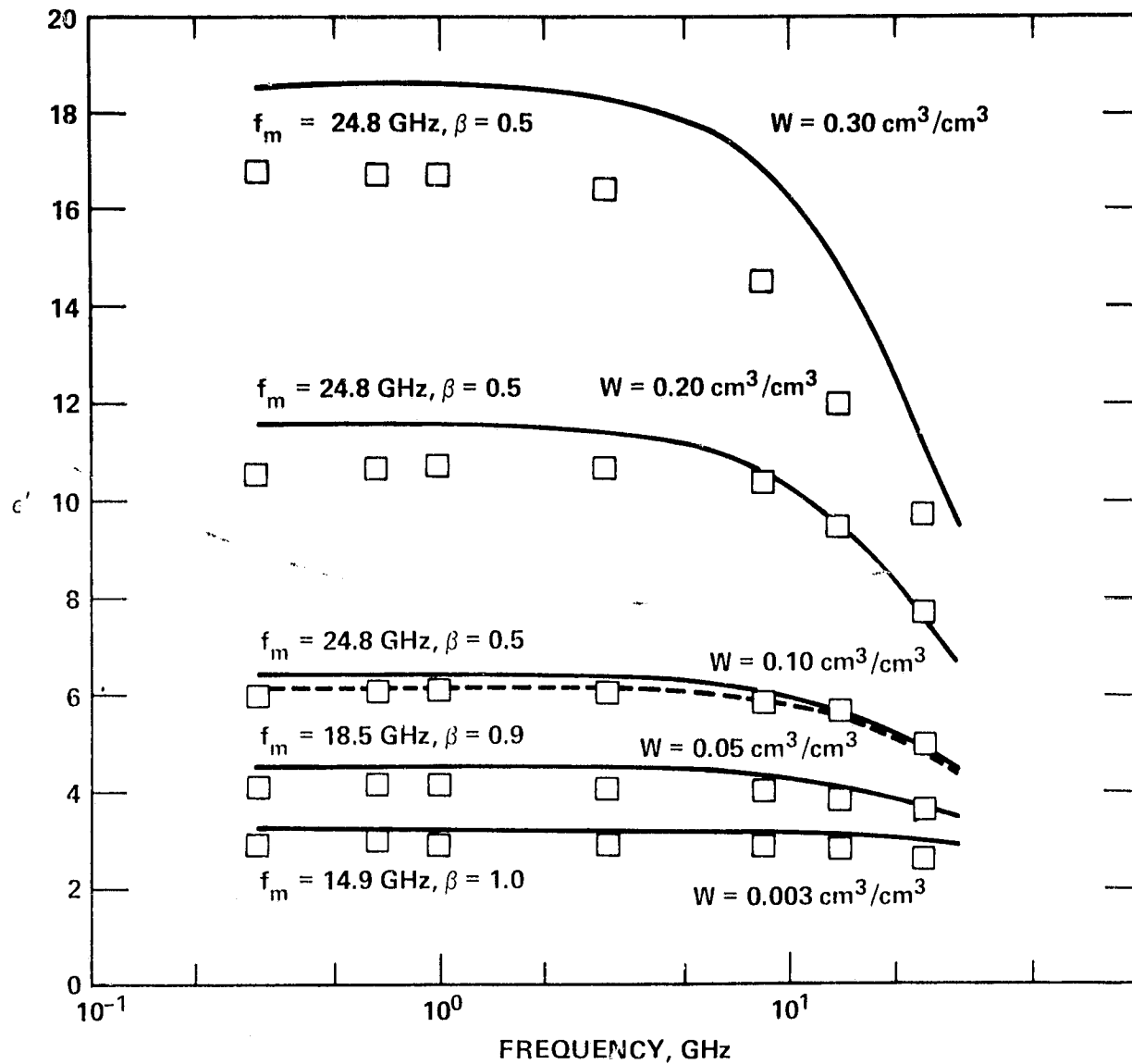


Figure 4. The calculated and measured real part of dielectric constant for sand as a function of frequency and water content. The measurements were made by Njoku and Kong (1977).

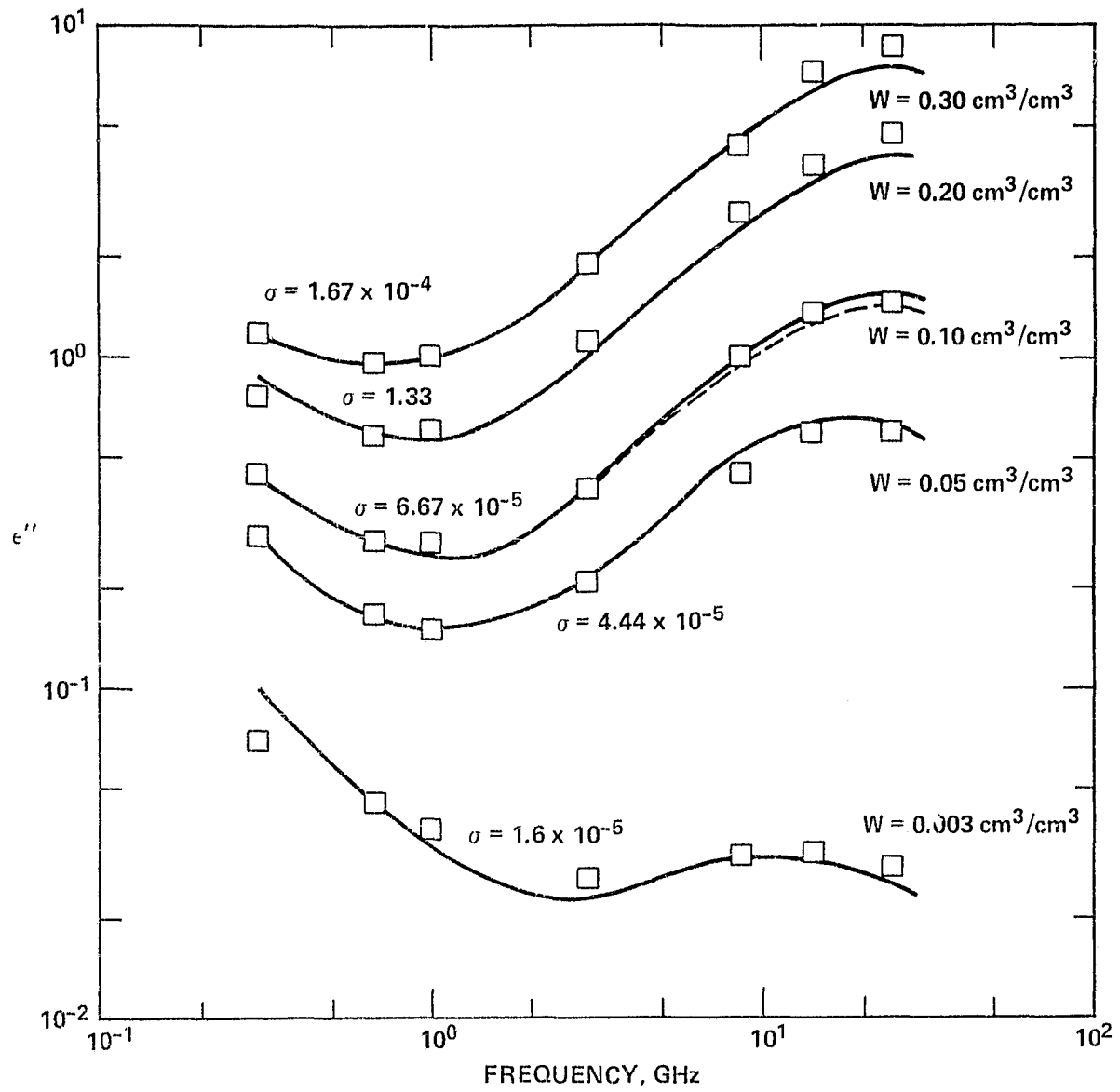


Figure 5. The calculated and measured imaginary part of dielectric constant for sand as a function of frequency and water content. The measurements were made by Njoku and Kong (1977).

## FIGURE CAPTIONS

Figure 1. The measured real part of dielectric constant as a function of water content for many soils at the frequencies of 0.3 GHz, 0.5 GHz and 1.4 GHz. At 1.4 GHz only the results of sandy soil measurements were shown.

Figure 2. The measured surface area per gm of dry soils as a function of wilting point for many soil types.

Figure 3. The calculated and measured dielectric constants of sandy and high-clay content soils as a function of water content at 1.4 GHz. The calculations were made with parameters  $f_m$  and  $\beta$  given in Table 1.

Figure 4. The calculated and measured real part of dielectric constant for sand as a function of frequency and water content. The measurements were made by Njoku and Kong (1977).

Figure 5. The calculated and measured imaginary part of dielectric constant for sand as a function of frequency and water content. The measurements were made by Njoku and Kong (1977).



## BIBLIOGRAPHIC DATA SHEET

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16. Abstract  Recent measurements on the dielectric constants of soil-water mixtures have shown the existence of two frequency regions in which the dielectric behavior of these mixtures was quite different. At the frequencies of 1.4 GHz – 5 GHz there were strong evidences that the variation of the dielectric constant $\epsilon$ with water content $W$ depended on soil types. While the real part of $\epsilon$ , $\epsilon'$ , for sandy soils rose rapidly with the increase in $W$ , $\epsilon'$ for the high-clay content soils rose only slowly with $W$ . As a consequence, $\epsilon'$ was generally higher for the sandy soils than for the high-clay content soils at a given $W$ . On the other hand, most of the measurements at frequencies $< 1$ GHz indicated the increase of $\epsilon'$ with $W$ independent of soil types. At a given $W$ , $\epsilon'$ (sandy soil) $\cong \epsilon'$ (high-clay content soil) within the precision of the measurements.  These observational features could be satisfactorily interpreted in terms of a simple dielectric relaxation model suggested by Schwarz (1962), with an appropriate choice of the mean relaxation frequency $f_m$ and the range of the activation energy $\beta$ . It was found that smaller $f_m$ and larger $\beta$ were required for the high-clay content soils than the sandy soils in order to be consistent with the measured data. These requirements on $f_m$ and $\beta$ were strongly supported by the observed dependence of the soil surface area per unit weight on the soil types.			
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