

THE DIELECTRIC PROPERTIES OF WET MATERIALS

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ABSTRACT

In microwave remote sensing knowledge of the dielectric properties of the materials observed (vegetation, soils) is important for the interpretation of the recorded reflection or emission and for the design of models for this reflection or emission. Although there exists no simple single law which describes the properties of a heterogeneous system when the properties of its components are known, boundaries can be indicated for the permittivity of such a system.

Heterogeneous systems containing water, as wet soils and plant material, have very complex dielectric properties due to the role of the conductivity. However, at the higher microwave frequencies, in particular above the S-band, these conductivity effects play only a minor role and the free water is most important.

When knowing the permittivity of wet materials the penetration depth can be determined. In all practical cases this depth is smaller than the wavelength used for the observations.

1. INTRODUCTION

Knowledge of the dielectric constant (permittivity) of materials is important in microwave remote sensing. It appears in the formulae for the reflectivity, the emissivity, and penetration depth. In models for the reflection or emission of complicated targets as e.g. vegetation, the dielectric properties of the component parts (stems, leaves) must be known. All the materials involved here - as e.g. soils, plant material, etc. - are heterogeneous systems which contain water. Therefore the theory for the dielectric properties of heterogeneous mixtures containing water will be treated. Through this whole century attempts have been made to relate the permittivity of a heterogeneous mixture to the permittivities of its components and many such relations have been given in the course of the years. The treatments given in the derivation of many of them are very basic. Van Beek (Ref. 1) gives a good survey. However, in the choice and application of a particular mixture relation, the special assumptions originally made in its derivation are often overlooked and as a result the position of this field of knowledge is rather chaotic. In the fifties attempts were made to clarify this situation by van Beek (Ref. 1) and de Loor (Ref. 2). The last author showed that it is impossible to describe

the permittivity of a heterogeneous mixture by only one relation.

At best boundaries can be given between which this value must lie, which boundaries come closer together the more is known about a particular mixture. This paper will treat this approach to the problem in a general way.

2. DIELECTRIC PROPERTIES OF MIXTURES

2.1 General theory

In the classical theories of Debye (Ref. 3) and Onsager (Ref. 4 and Ref. 5) to describe the dielectric properties of a liquid usually one molecule is considered as a dielectric entity with a dielectric constant (DC) ϵ_1 (and in case of a polar liquid also having a dipole moment μ) surrounded by a homogeneous and isotropic dielectric (Ref. 5). In fact this situation is better approximated by a heterogeneous mixture where foreign granules with DC ϵ_1 are imbedded in a homogeneous and isotropic dielectric with DC ϵ_0 . Now closely following the theory for non-polar liquids (thus excluding the dipole moment μ at this stage) as developed by Onsager and later extended by Scholte to ellipsoidal particles (Ref. 5 and Ref. 6), the macroscopic DC of a heterogeneous mixture ϵ_m can be calculated. We must then assume that the granules are ellipsoids of about equal size and eccentricity and oriented at random. The only variation in the theory of Onsager and Scholte we make is the generalization of attributing a DC ϵ^* to the immediate surroundings of the granule considered. The macroscopic DC of the mixture can then be written as (Ref. 2)

$$\epsilon_m - \epsilon_0 = v_1 (\epsilon_1 - \epsilon_0) \frac{1}{3} \sum_j \frac{1}{1 + \left(\frac{\epsilon_1}{\epsilon^*} - 1\right) A_j} \quad (1)$$

where v_1 is the volume filling factor of the dispersed granules and A_1 , A_2 and A_3 are the depolarization factors along the main axes of the ellipsoid. In the quantity ϵ^* we accounted for all interactions and spatial irregularities of the granules. This quantity is in fact unknown and in the literature some assumption is usually put forward to apply Eq. 1 for the calculation of ϵ_m as a function of v_1 .

In the older theories on mixtures the influence of the surroundings is usually neglected and ϵ^* is put equal to ϵ_0 , where when we follow Onsager's treatment

$\epsilon^* = \epsilon_m$ has to be introduced (Ref. 1, Ref. 5). A thorough investigation of all available material taught empirically that ϵ^* always lies between ϵ_o and ϵ_m (Ref. 2). This implies that we can give limiting values for the DC ϵ_m when A , ϵ_i , ϵ_o and v_i are known. Even when the form of the granules (and thus A_i) is not known such limiting values for ϵ_m can be given (which limits lie now further apart). One is found after substitution in (1) of $A_i = 0; 0; 1$ (disc-shaped granules) with $\epsilon^* = \epsilon_m$, the other by substituting $A_i = 1/3; 1/3; 1/3$ (spherical granules) and $\epsilon^* = \epsilon_o$. A_i can be determined, however, from dielectric measurements and from microscope observation (Ref. 2, Ref. 7). The boundary with $\epsilon^* = \epsilon_o$ and $A_i = 1/3; 1/3; 1/3$ comes close to the mixture relation of Maxwell (Ref. 5). This relation - being the oldest mixture relation - has been used extensively. It was derived for a regular arrangement of spherical particles in a continuous phase.

Any mixture relation giving results somewhere between the boundaries given can sometimes give a reasonable approximation of the dielectric behaviour of a particular mixture. Such good results, however, are often accidental and the approach as sketched here is certainly more generally applicable, and for the variations met in heterogeneous systems also of sufficient accuracy.

Since formula 1 is not symmetric three regions can be distinguished: a region best described by a mixture of material A in a material B as continuous phase, a region with B in A and a region in between (A+B), where it is difficult to distinguish whether we have A in B or B in A. The transition point to this last region A+B is difficult to indicate but it lies usually somewhere between a volume filling factor v_i of 0.2 and 0.3. For this region - not knowing the shape factor A - the boundaries lie further apart. The lower boundary (when $\epsilon_B < \epsilon_A$) is given by using Eq. 1 with $\epsilon^* = \epsilon_o$ and assuming a mixture of A in B, the upper boundary by using Eq. 1 with $\epsilon^* = \epsilon_m$ and assuming a mixture of B in A and taking the shape factor A. as: $A_i = 1/3; 1/3; 1/3$. Since this region A+B is not of direct importance for our treatise we shall not discuss it further.

The boundaries given above also apply when losses occur. In that case complex permittivities have to be used in equation 1. Losses can be due to conductivity of one or both of the components of the mixture or can be of polar origin (relaxation losses). In the first case the mixtures can show conductivity losses as a whole and conductivity losses of the Maxwell-Wagner type. They occur at the lower frequencies, although Sillars (Ref. 8) showed that such losses also strongly depend on the shape of the granules, and that a distribution of shapes tends to "smear" the losses of the mixture over a large frequency band.

When one of the components of a heterogeneous mixture shows losses of polar origin (which for ice are at audio frequencies, for water at microwave frequencies) still the same boundaries apply. Eq. 1 has now to be solved for complex permittivities varying with frequency. It can be shown (Ref. 2) that the relaxation frequency (frequency where the dielectric loss factor ϵ'' has a maximum) of the mixture is always the same or higher than that of the relaxing component.

2.2 Interfaces and survey of losses in heterogeneous systems

Many heterogeneous systems containing water as e.g.

biological systems, soils (Ref. 9, Ref. 10), sandstones (Ref. 11), etc. show very high DC's and losses at the lower frequencies.

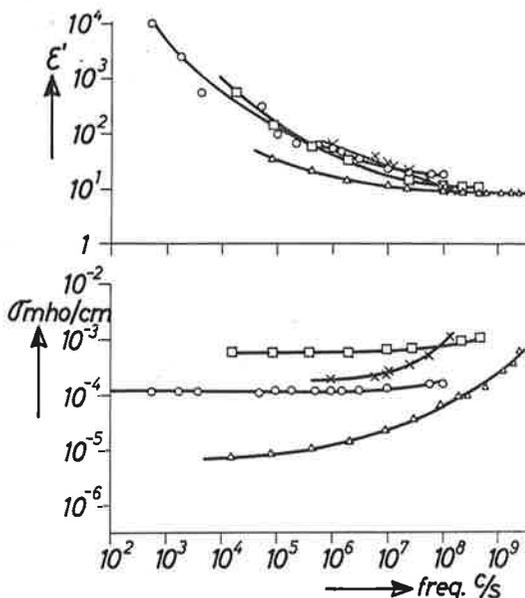


fig. 1 measurements of DC ϵ' and conductivity σ of soil after (9)0, loam after (10)x, and water-saturated sandstones after (11): fresh water Δ , salt water \square .

Fig. 1 gives an example. Even with the assumption of conducting granules (or inclusions) we cannot explain these high values. In all considerations given up till now, it has always been assumed that the constituents of the mixture do not influence each other's properties, and boundary layers between the components were assumed either to be absent or to have negligible effects on the calculations. This assumption no longer applies here. The first effect coming into play are charged double layers due to the counter ion atmosphere around a granule by an external field (Ref. 12). This effect can be introduced in the theory as given before by attributing a dipole moment to a granule (or inclusion) in the same way as in the classical theories Debye and Onsager extended the theory for non-polar liquids to that of polar liquids (Ref. 5). Size and shape of the granules or inclusions influence the relaxation frequency associated with this effect (Ref. 12). Since many sizes and shapes usually are present in the complicated systems now under consideration a large spread in relaxation times is to be expected. The same applies for the second phenomenon described by O'Konski (Ref. 13). According to this theory the granule or inclusion can be considered as a conducting inclusion at the lower frequencies. Of both phenomena the first is effective to about a 100 kHz, where the effects of the last can extend into the microwaves.

All the losses together make that the conductivity σ ($\epsilon'' = 60 \lambda \sigma$; with λ the wavelength in cm and σ in Mho/cm) becomes reasonably constant over a fairly large frequency interval as fig. 1 also

demonstrates.

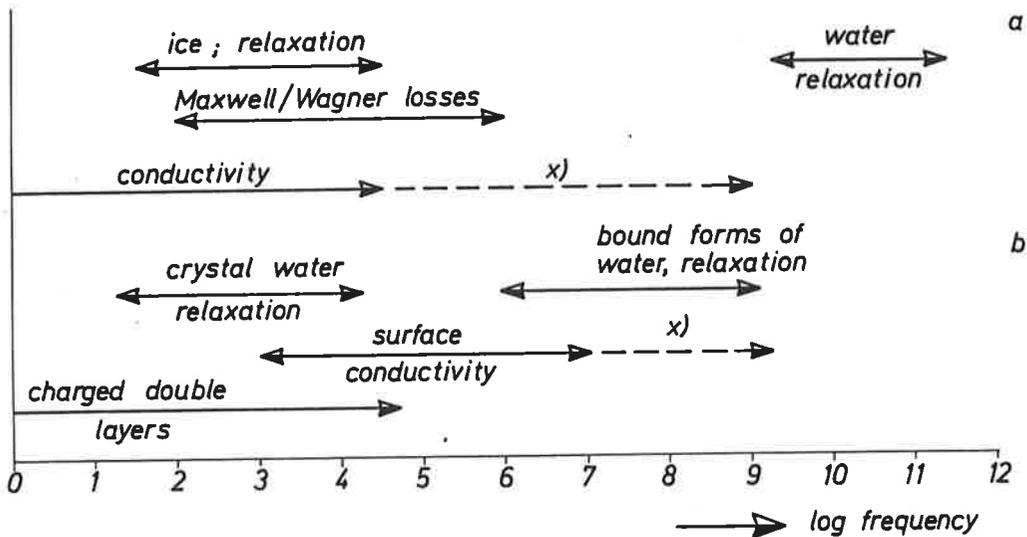


fig. 2 survey of losses in heterogeneous mixtures containing water; a. without interfaces, b. with interfaces present.

Fig. 2 summarizes all losses which can occur in heterogeneous systems containing water. Different regions can be distinguished. At the lower frequencies many effects are interwoven which make unraveling of the different phenomena nearly impossible. At microwave frequencies the situation is much simpler: only the relaxation losses due to the polar losses of the free water are of importance.

In the region in between: $10^7 - 10^9$ Hz just below the microwaves, conductivity phenomena still play a role but also losses of polar origin of an intermediate form of bound water (intermediate between the free water and the very tightly bound water with a more or less 'ice-like' structure (Ref. 14, Ref. 15).

Knowledge of the interplay of these losses with the conductivity losses and the polar losses of the free water are of great importance for a good understanding of the phenomena occurring in this frequency region and at microwave frequencies.

3. APPLICATION TO REMOTE SENSING

3.1 General

We shall treat the two cases of mixtures with a low water content (water particles in a continuous phase: A in B) and with a high water content (water as continuous phase: B in A) somewhat more extensively. We then consider the mixture A in B as representative for materials as snow, soils, sandstone, etc. and the mixture B in A for e.g. plant material.

Figure 3 describes the dielectric properties of pure water and seawater at $T = 20^\circ\text{C}$, where figure 4 gives the Cole-Cole loci $\epsilon'' = f(\epsilon')$

(Ref. 5, Ref. 14). At the low frequency end of the locus for sea water we see the influence of the conductivity. The total loss factor ϵ'' is the sum of the dipolar losses (ϵ''^{dip}) and the conductivity losses (ϵ''^{c}). When we subtract ϵ''^{c} ($= 60 \lambda \sigma$) from ϵ'' we obtain ϵ''^{dip} and the locus $\epsilon''^{\text{dip}} = f(\epsilon')$ will become a semi-circle for sea water also. This applies for heterogeneous mixtures also. We first must subtract the conductivity losses ϵ''^{c} before we can plot the function $\epsilon'' = f(\epsilon')$. Since ϵ_i , resp. ϵ_o , now is complex, this locus is a conformal transformation from the (ϵ', ϵ'') -plane, resp. the $(\epsilon'_o, \epsilon''_o)$ -plane, to the $(\epsilon'_m, \epsilon''_m)$ -plane. As we have seen for water the function $\epsilon'' = f(\epsilon')$ is a semi-circular locus (Cole-Cole arc (Ref. 5, Ref. 14)). This is not the case for all the transformations through the available mixture relations (Ref. 2), but it does apply for the boundaries used here.

Then we can write:

$$\epsilon'_m = \epsilon_{m\infty} + \frac{\epsilon_{ms} - \epsilon_{m\infty}}{1 + (\lambda_m/\lambda)^2} \quad (2a)$$

$$\epsilon''_m = \frac{\epsilon_{ms} - \epsilon_{m\infty}}{1 + (\lambda_m/\lambda)^2} \cdot (\lambda_m/\lambda) \quad (2b)$$

Where ϵ_{ms} and $\epsilon_{m\infty}$ are the 'static' DC (before relaxation starts) and the 'high frequency' DC (when relaxation is over) of the mixture and λ_m the wavelength belonging to the relaxation frequency.

Since we deal with microwave remote sensing, conductivity effects play only a minor role and, when still present, only at the lower microwave frequencies. So only the dipolar losses of the

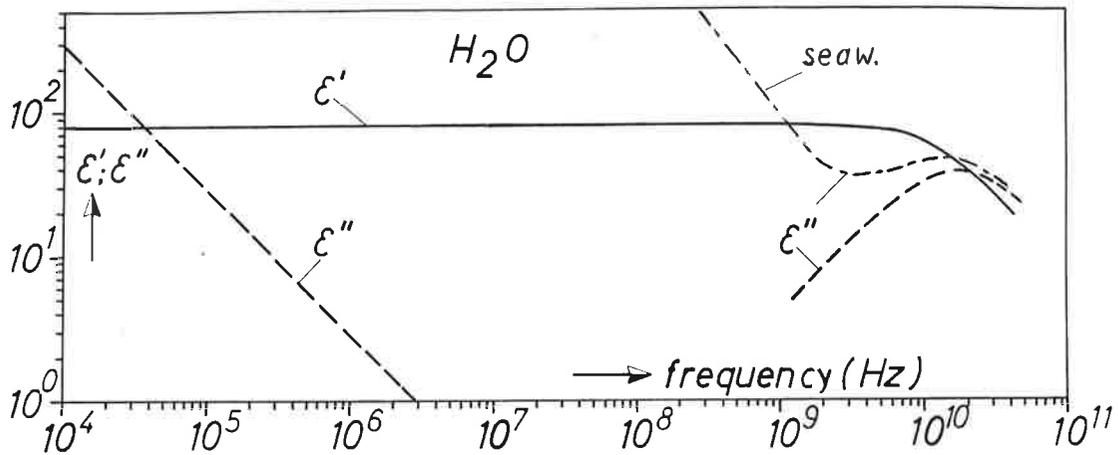


fig. 3 dielectric properties of water as a function of frequency

free water remain of importance and - again at the lower microwave frequencies - the dipolar losses of intermediate forms of water (Ref. 14, Ref. 15 and Ref. 21).

So to calculate ϵ_m we must know the total amount of free water. The bound water can be considered as belonging to the other phase, since its DC will be low and of the same order of magnitude as that other phase. Methods are available to determine this total amount of free water (Ref. 14, Ref. 16 and Ref. 17), but we shall not consider them here.

3.2 Mixtures with a low water content

We shall treat two special cases as examples of how the theory can be used. Fig. 5 gives results reported by Poley et al (Ref. 11) on fresh water-saturated sandstones at 500 MHz, outside the region where the conductivity plays the major role and where the polar losses of water are still small.

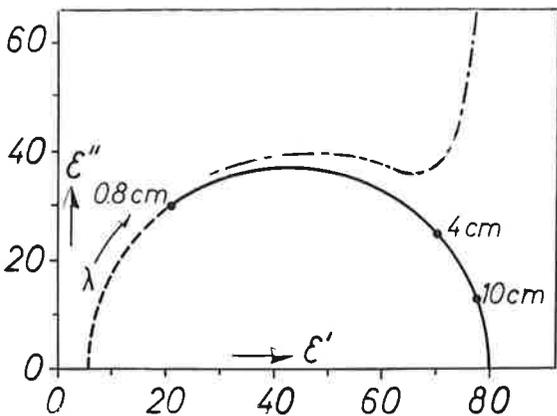


fig. 4 Cole-Cole arcs for pure water (drawn line) and sea water (dashed line).

The boundaries for the DC ϵ_m are included (U: upper boundary; L: lower boundary) using the following quantities in formula 1:

$\epsilon_i = 80$, $\epsilon_o = 4.37$ with $A_i = 1/3$; $1/3$; $1/3$ and $\epsilon_i^* = \epsilon_o$ for L and $A_i = 0$; $1/3$; 1 with $\epsilon_i^* = \epsilon_m$ for U . All measured values lie near the upper boundary indicating that the shape factors A_i involved deviate from those belonging to spherical inclusions. Calculations as given in (Ref. 7) can give an indication of these values.

The example given above is still a good two-phase mixture: water particles embedded in sandstone. The theory, however, can also be applied to materials as snow and soil. When water is added to such materials we in fact obtain three-phase mixtures, but we can approximate them reasonably well as two-phase mixtures by considering the dry soil, or dry snow, as the continuous phase.

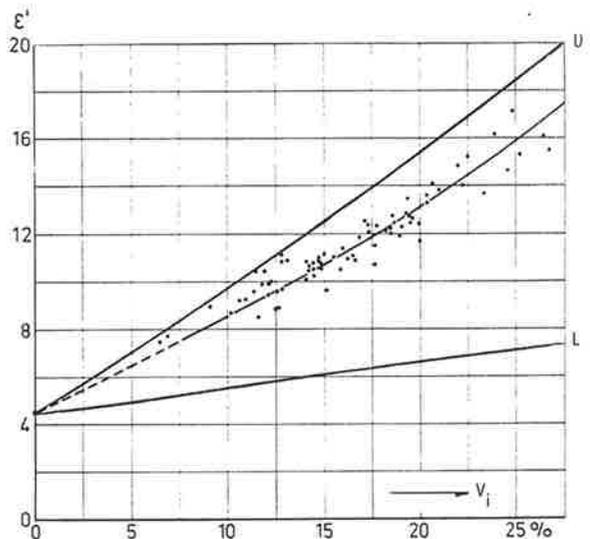


fig. 5 DC of fresh water - saturated sandstones as a function of porosity at 500 MHz. After (Ref. 11) with boundaries.

When water penetrates these materials, the shape factor A will certainly not be a constant as a function of the volume filling factor v_i , but the

application of our general boundaries takes this into account.

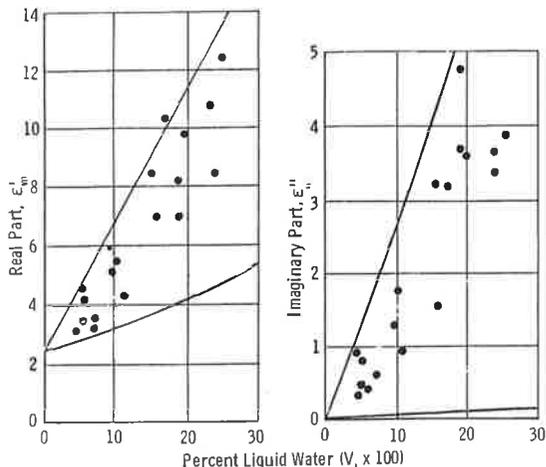


fig. 6 DC of snow as a function of liquid water content at 6 GHz. After (Ref. 18) as reported by (Ref. 19). With calculated boundaries.

An example is given in figure 6. Measurements are given on snow (Ref. 18) as reported by Stiles and Ulaby (Ref. 19).

The boundaries as calculated by us are included in the figure. Here we used $\epsilon_0 = 62.5 - j 38.1$ (water of 0°C at 6 GHz (Ref. 14)) and $\epsilon_0 = 2.5$ (given by the measurements; extrapolation to $v_l = 0$).

The measurements spread over a band, which again lies closest to the upper boundary. The spread is easy of explanation: the way in which the water comes in the mixture (shape factor A) will vary from sample to sample, but again with a certain preference for non-spherical (water) particles. Using these measurements at 6 GHz we can now predict ϵ_m also for other microwave frequencies and within closer boundaries. We shall do this for 10 GHz. We first determine the Cole-Cole arcs for the two boundaries and ϵ_m for a series of values of v_l at 6 and 10 GHz. We can calculate ϵ_m ($\epsilon_{is} = 88$, $\epsilon_0 = 2.5$) and $\epsilon_{ico} = 5.5$, $\epsilon_{ms} = 2.5$) (Ref. 14). Fig. 7 gives an example for $v_l = 0.2$. We now introduce the range of values found in fig. 6 for the chosen value of v_l (thick line in fig. 7).

The highest value coincides with the value given by the upper boundary the lowest value measured is indicated by an open point. Using this value and ϵ_{ico} we can now draw a Cole-Cole arc, which now is the improved lower boundary for all microwave frequencies for this value of v_l . The value for 10 GHz is also indicated by an open point. After we have done this operation for a number of values of v_l we obtain fig. 8: a prediction for the boundary values of $\epsilon_m = f(v_l)$ between which the DC for snow will be at 10 GHz.

3.3 Mixtures with a high water content

This case is of particular importance for the determination of the dielectric properties of plant material. There are not many measurements available,

but again we can infer from them the values we may expect.

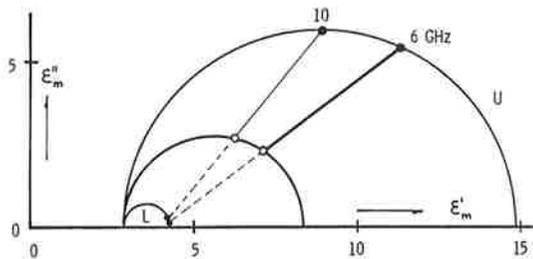


fig. 7 Cole-Cole arcs for snow with a liquid water content of $v_l = 0.2$. Boundaries (U:upper, L:lower) and new lower boundary inferred from the data of figure 6.

Ref. 17 gives measurements on a group of such mixtures. From them we take figure 9. It gives the Cole-Cole arcs $\epsilon''_{mdip} = f(\epsilon'_m)$ for three model mixtures: Agar 4% ($\sigma = 0.85$ m Mho/cm), agar 8% ($\sigma = 1.7$ m Mho/cm), 2% agar with 25% starch ($\sigma = 2.3$ m Mho/cm).

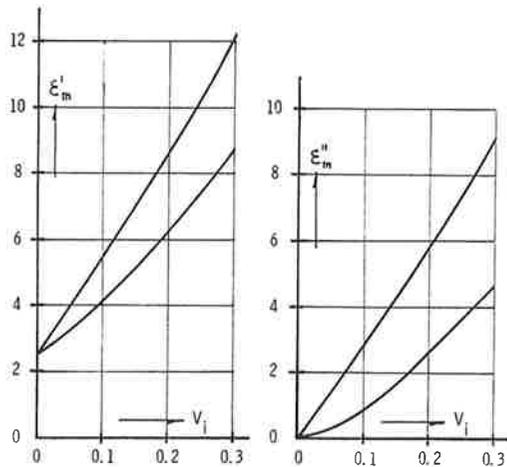


fig. 8 boundaries for the DC of snow as a function of liquid water content at 10 GHz, predicted.

The real value of $\epsilon''_m = \epsilon''_{mdip} + \epsilon''_{mo}$.

In figure 10 we plot the values for ϵ_{ms} so obtained, together with the boundaries. The values for the agar model mixtures approach the lower boundary, but here this is due to the high amount of bound water (order of 1.5 g/cm³) (Ref. 17)). The values for potato (P), starch (S) and meat (M) come closer to the values we may expect for plant material.

Shifts in relaxation time are small here (when at all present) for the mixture, so we can use that given for water. This makes it easy to predict the values for plant material when knowing the

amount of solid material in it by using formula 1 (calculation of ϵ''_{ms}) in combination with 2 and adding ϵ''_{ms} . The conductivity σ can be determined at DC or 1 kHz with an ordinary conductivity meter.

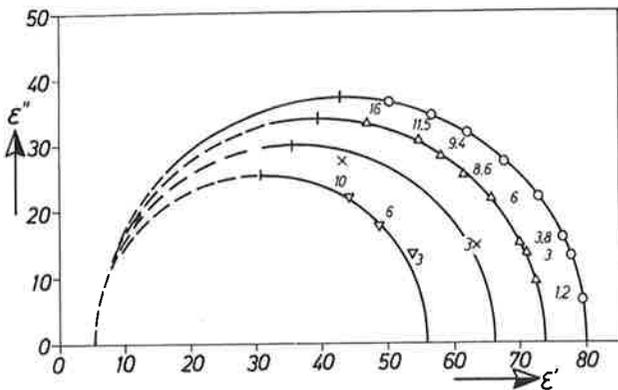


fig. 9 measurements $\epsilon''_{ms} = f(\epsilon')$ for water 0, and three model mixtures: agar 4% Δ , agar 8% \times and starch ∇ . After (Ref. 17). Frequencies indicated at the measurement points in GHz.

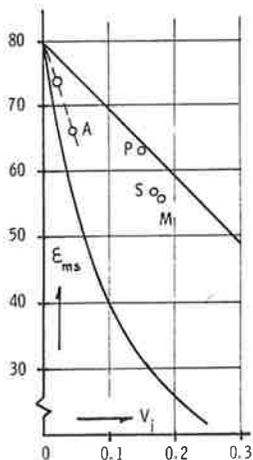


fig. 10 $\epsilon''_{ms} = f(V_i)$: calculated boundaries with measured values after (Ref. 17). A : agar, P: potato, S : starch and M: meat.

4. PENETRATION DEPTH

Some remarks on the penetration depth are useful. It is often claimed that fairly large penetration depths would be possible at microwaves. Knowing the dielectric properties of the materials involved we can calculate the penetration depth D and see whether this is true. The penetration depth can be calculated with the aid of the following formulae:

$$P = P_0 e^{-2\alpha d}$$

with P : power at depth d , P_0 : power at the surface and

$$\alpha = \frac{2\pi}{\lambda} \sqrt{|\epsilon|} \cdot \sin \frac{1}{2} \delta$$

with λ the wavelength used, $|\epsilon| = \sqrt{\epsilon'^2 + \epsilon''^2}$ and δ the loss-angle ($\tan \delta = \epsilon''/\epsilon'$).

The penetration depth is defined by $2\alpha D = 1$, so the depth where the power is attenuated to $1/e$ (37%). So:

$$D = \frac{1}{2\alpha} = \frac{\lambda}{4\pi\sqrt{|\epsilon|} \cdot \sin \frac{1}{2} \delta} \quad (3)$$

Since even for the driest materials (e.g. dry sand) $\sqrt{|\epsilon|} > 1.5$, $\sin \frac{1}{2} \delta$ must be smaller than $1/6\pi = 0.053$ and thus $\tan \delta < 0.106$ to make D larger than λ , the wavelength used. This value is reached at a few percent moisture already in most materials. This means that in most cases D/λ will be smaller than 1 or: the penetration depth will usually be smaller than the wavelength used.

Let us take an average soil as an example. In fig. 1, among others, the dielectric properties of two soils are given for the lower frequencies. The values of Smith-Rose (Ref. 9) apply for an average soil in Europe. When we extend the curves of figure 1 to the microwave region with the aid of the measurements of Lundien (Ref. 20) and Hoekstra and Delaney (Ref. 21) and the theoretical considerations given in paragraph 3.2, we obtain figure 11 giving D/λ as a function of frequency. We see that D/λ remains far below 1 for all frequencies. So $D/\lambda < 1$. At C- and X-band we may not expect penetration depths larger than 2 to 1 cm. Yet we know from many observations that soil moisture can be measured at those frequencies. (Ref. 22).

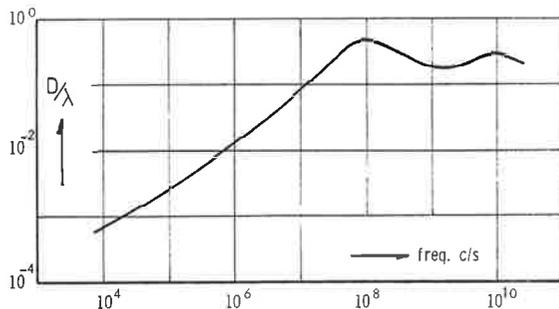


fig. 11 penetration depth $D < \lambda$. D/λ as a function of frequency for an average soil.

This would mean that either the moisture of the top soil is a measure for the moisture at larger depths also, or that we observe it indirectly with the aid of an indicator. For example: the fact that Ulaby (Ref. 22) finds a better correlation with moisture at a somewhat greater depth for soils covered with vegetation than in bare soils could indicate that the vegetation plays a role in that case: the value quoted comes closer to the depth associated with the root zone. When this true, the real indicators for soil moisture must still be found.

5. DISCUSSION AND CONCLUSION

The dielectric properties of heterogeneous mixtures

have been discussed. The theory can be applied for the understanding of the dielectric properties of the materials met in microwave remote sensing. Although it is impossible to give one relation for the DC of a heterogeneous mixture - and in particular a mixture containing water - boundaries can be given between which its DC must lie. These boundaries come closer together the more is known about a particular mixture. This approach of using boundaries is in fact very useful in microwave remote sensing since there will always be a spread in the dielectric properties of the materials involved due to their natural variability.

The behaviour of heterogeneous systems containing water is very complicated at the frequencies below the microwaves. However, in the microwave region only the free water is important since the bound water has properties comparable to those of the other phase. This fact eventually may explain the observation made by Ulaby (Ref. 22) that the relation of the backscatter to water tension is more or less independent of soil type.

When knowing the DC of the materials involved the theoretical reflection, emission and penetration depth can be determined. Usually further modelling will be necessary to come to the actual backscatter or emission of a natural target due to complications as roughness, etc. The penetration depth for soil is smaller than the wavelength used for the observation in all practical cases.

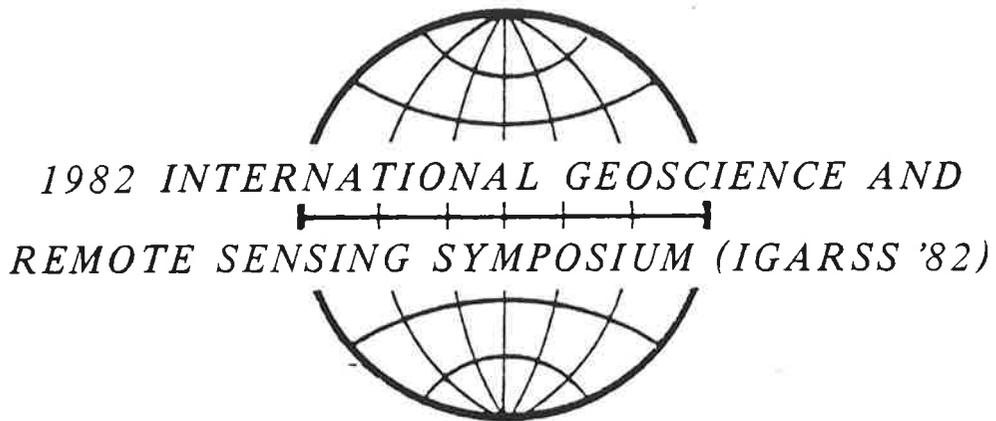
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