Microwave Dielectric Spectrum of Vegetation— Part II: Dual-Dispersion Model

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Abstract—This paper is the second in a series evaluating the microwave dielectric behavior of vegetation material. It draws upon the data presented in Part I to develop a Debye–Cole dual-dispersion dielectric model consisting of a component that accounts for the volume fraction occupied by water in free form and another that accounts for the volume fraction occupied by the mixture comprised of water molecules bound to bulk-vegetation molecules. To determine the dielectric dispersion properties of the latter, measurements were made for sucrose-water solutions of known volume ratios. The proposed dielectric model is found to give excellent agreement with data over a wide range of moisture conditions and over the entire 0.2–20 GHz range examined in this study.

I. INTRODUCTION

IN PART I of this two-part series, we described the experimental system used for making wide-band dielectric measurements and presented sample data to illustrate the nature of the variation of the dielectric constant of vegetation material ϵ as a function of several physical and electromagnetic parameters. The present paper draws upon the data obtained in this program to develop a dielectric mixing model for vegetation.

Available models for the dielectric constant of vegetation treat the vegetation as a simple mixture of bulk vegetation and water [1], [2], with the water sometimes subdivided into a *bound*-water component and a *free*-water component [2]. Bound water refers to water molecules that are tightly held to organic compounds by physical forces, and free water refers to water molecules that can move within the material with relative ease.

In these models the free-water component is assigned the dielectric dispersion properties of bulk water and the bound-water component is assumed to have dielectric properties similar to those of ice. As will be demonstrated in this study, bound water exhibits a dielectric behavior far different from that of ice, and this difference is responsible, in part, for the shortcomings of previously published dielectric models for vegetation [1], [2].

II. DIELECTRIC SPECTRUM OF WATER

Direct dielectric measurements of oven-dried samples of various types of vegetation material, which henceforth

shall be referred to as bulk vegetation material, give the following results:

$$1.5 \leq \epsilon_v' \leq 2.0$$

$$\epsilon_v'' \leq 0.1$$

for $0.5 \leq f \leq 20$ GHz. Although these measurements were made at 22°C, there is no reason to expect ϵ_v to have a temperature dependence.

In contrast to the nondispersive behavior of the bulk vegetation material, bulk water is highly dispersive at microwave frequencies because its dielectric relaxation frequency f_0 lies in the microwave band. More specifically, f_0 of pure (distilled) water is equal to 9 GHz at 0°C and increases nonlinearly with increasing temperature to 17 GHz at 20°C, and to higher frequencies at correspondingly higher temperatures.

The fluid contained in vegetation material may be extracted from the material by suction. To extract a certain amount of fluid, the differential pressure that needs to be applied is far greater for a relatively dry piece of vegetation than for a fresh leaf. This is because for the relatively dry leaf, the contained water is tightly bound to the bulk vegetation material, whereas for the fresh leaf some of the water is almost totally "free."

An isolated water molecule possesses a permanent electric dipole moment. If an electric field is applied, the molecule will orient itself such that its dipole moment is aligned with the field. The orientation response to an infinitely fast step variation of applied electric field is characterized by an exponential function of the form exp $(-t/\tau)$ with time constant τ. This time constant is called the relaxation time and is governed by the interaction of the H_2O molecule with its environment and by the temperature T. If the water molecule is under the influence of nonelectrical forces, such as physical forces, its response to an applied electric field is impeded by these forces, which has the equivalent effect of increasing the relaxation time τ. Hence, τ of a bound-water molecule should be much longer than that of a free-water molecule. Correspondingly, the relaxation frequency $f_0 = (2\pi\tau)^{-1}$ of a bound-water molecule should be much lower than that of a free-water molecule.

To provide the background necessary for the model developed in Section III, we shall now give a brief review of the dielectric properties of free water (assumed to be the same as those of bulk water) and bound water. In gen-

eral, free water may contain dissolved salts; hence, our review will consider the case of saline water.

As mentioned earlier, the dielectric properties of bound water are not well understood, and because bound water molecules cannot exist in bulk, it is not possible to measure their dielectric properties directly. Hence, special experiments were conducted, as discussed in Section II-B below, to measure and model the dielectric spectrum of bound water-host mixtures.

A. Free Water

The relative dielectric constant of bulk saline water is given by the Debye equation [3, pp. 2022–2025]

$$\epsilon_f' = \epsilon_{f\infty} + \frac{\epsilon_{fs} - \epsilon_{f\infty}}{1 + (f/f_{f0})^2} \tag{1a}$$

$$\epsilon_f'' = \frac{(f/f_{f0})(\epsilon_{fs} - \epsilon_{f\infty})}{1 + (f/f_{f0})^2} + \frac{\sigma}{2\pi\epsilon_0 f}. \tag{1b}$$

The subscript f denotes free water, ϵ_{fs} and $\epsilon_{f\infty}$ are the static and high-frequency limits of ϵ_f', $\epsilon_0 = 8.854 \times 10^{-12}$ F · m^{-1} is the permittivity of free space, f is the frequency in hertz, and σ is the ionic conductivity of the aqueous solution in siemens per meter. For computational purposes, $\epsilon_{f\infty}$ usually is taken equal to 4.9 and treated as independent of both the temperature T and salinity S of the solution. The salinity is defined as the total mass of solid salt in grams dissolved in 1 kg of solution and is expressed in parts per thousand (‰) on a weight basis. The other parameters of the dispersion equation, ϵ_{fs} and f_{f0}, are functions of both T and S and are given by empirically generated polynomial functions [4]. For pure water ($S = 0$) at $T = 0°C$, these functions yield $\epsilon_{fs} = 87.1$ and $f_{f0} = 9$ GHz.

For $S \leq 10‰$ and $T = 22°C$ (room temperature), (1) may be approximated as

$$\epsilon_f = 4.9 + \frac{75}{1 + jf/18} - j\frac{18\sigma}{f} \tag{2}$$

where f is in gigahertz and σ may be related to S by

$$\sigma \cong 0.16S - 0.0013S^2 \quad S \cdot m^{-1}. \tag{3}$$

B. Bound Water

From the standpoint of dielectric theory, a water molecule is considered to be in the "bound" condition if its response to a suddenly applied electric field is inhibited as a result of some force acting upon it. Although we know that when a water molecule is in the bound condition its relaxation time τ becomes longer than when in the free state, we have no relationships by which we can quantitatively link the type of force and its magnitude to the increase in τ. In order to study the dielectric properties of bound water as they pertain to vegetation material, we have chosen to conduct dielectric measurements for sucrose-water mixtures. Sucrose was chosen because 1) it is a good example of the organic substances present in veg-

etation and 2) the binding arrangement of sucrose-water molecules is well known, which allows us to compute the bound water concentration in any given mixture. A sucrose molecule can bind to six water molecules, and the molecular weights of sucrose and water are 342.3 and 18.0, respectively. Hence, in a sucrose-water mixture in which the number of water molecules is equal to six times the number of sucrose molecules, the mass ratio of bound water to sucrose is given by

$$R = \frac{w_{bw}}{w_s} = 6\left(\frac{18.0}{342.3}\right) \cong \left(\frac{6}{19}\right). \tag{4}$$

The volume fractions of sucrose and bound water are

$$v_s = \rho_{bw}(\rho_{bw} + R\rho_s)^{-1} \tag{5}$$

$$= (1 + R\rho_s)^{-1} \tag{5a}$$

and

$$v_{bw} = 1 - v_s \tag{6}$$

where $\rho_s = 1.58$ g · cm^{-3} is the bulk density of sucrose and $\rho_{bw} = 1$ g · cm^{-3} was used in (5) to obtain (5a). These values lead to $v_s \cong 2v_{bw} \cong 0.667$.

Dielectric measurements were conducted from 0.1 to 20 GHz for a sucrose-water solution at room temperature (22°C). The data was fitted to a Cole–Cole dispersion equation of the form

$$\epsilon_b = \beta_{b\infty} + \frac{\epsilon_{bs} - \epsilon_{b\infty}}{1 + (jf/f_{b0})^{1-\alpha}} \tag{7}$$

where ϵ_{bs}, $\epsilon_{b\infty}$, and f_{b0} have the same definitions given earlier in connection with (2), and α is a relaxation parameter. Fig. 1 compares the measured dielectric spectrum with that calculated according to the Cole–Cole equation. The parameters of the Cole–Cole equation were selected to optimize the fit of the model to the data. Their values are $\epsilon_{b\infty} = 2.9$, $\epsilon_{bs} = 57.9$, $f_{b0} = 0.18$ GHz, and $\alpha = 0.5$, which result in

$$\epsilon_b = 2.9 + \frac{55}{1 + (jf/0.18)^{0.5}}. \tag{8}$$

The data fit the model exceptionally well; the linear correlation coefficient between ϵ_b' (measured) and ϵ_b' (calculated) is 0.99, and the same is true for ϵ_b''. Cole–Cole plots of (2) and (8) are shown in Fig. 2.

The values of $\epsilon_{b\infty}$ and ϵ_{bs} are not markedly different from the corresponding parameters for free water; at $T = 22°C$, $\epsilon_{f\infty} = 4.9$ and $\epsilon_{fs} = 80$. The relaxation frequency, on the other hand, is lower by two orders of magnitude; $f_{b0} = 0.18$ GHz compared to $f_{f0} = 18$ GHz at $T = 22°C$. Another important difference is the magnitude of α, which is equal to 0.5 for the bound-water sucrose solution, compared to zero for free water. The parameter α governs the shape of the dispersion spectrum.

III. DIELECTRIC MODEL FOR VEGETATION

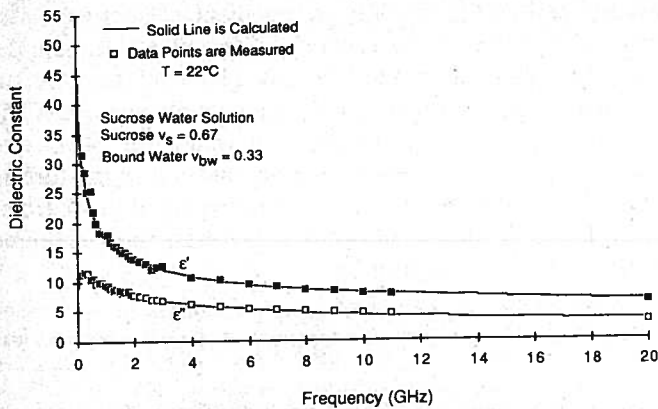In previous dielectric models for vegetation [1], [2], the vegetation-water mixture was treated as an inhomoge-

Fig. 1. Measured ($\square$ and $\blacksquare$) dielectric spectrum of sucrose-water solution and theoretical spectrum (——) calculated according to (8).
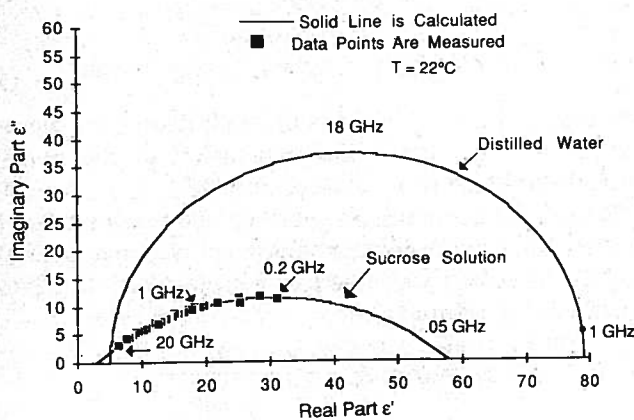

Fig. 2. Cole–Cole diagrams for distilled water and sucrose solution.

neous medium comprised of discrete water particles dispersed in the bulk vegetation material (as host). The water particles were assigned a shape (such as spherical or cylindrical) in order to fit the dielectric mixing model to data. Such a model is unrealistic for vegetation because the water inside a leaf, for example, is closer to being spatially continuous rather than discrete. Hence, we shall model the dielectric constant of vegetation ϵ_v as a simple additive mixture of three components: 1) ϵ_r, a nondispersive residual component, 2) $v_{fw}\epsilon_f$, a free-water component, where v_{fw} is the volume fraction of free water and ϵ_f is its dielectric constant, and 3) $v_b\epsilon_b$, a bulk vegetation-bound water component, where v_b is the volume fraction of the bulk vegetation-bound water mixture and ϵ_b is its dielectric constant. Thus

$$\epsilon_v = \epsilon_r + v_{fw}\epsilon_f + v_b\epsilon_b \qquad (9)$$

with ϵ_f and ϵ_b given by (2) and (8), respectively.

At room temperature ($T = 22°C$), ϵ_v is given by

$$\epsilon_v = \epsilon_r + v_{fw}\left[4.9 + \frac{75.0}{1 + jf/18} - j\frac{18\sigma}{f}\right]$$
$$+ v_b\left[2.9 + \frac{55.0}{1 + (jf/0.18)^{0.5}}\right] \qquad (10)$$

where f is in gigahertz and σ in siemens per meter. Here, σ is the ionic conductivity of the free-water solution. We shall refer to the model given by (10) as a Deybe–Cole dual-dispersion model.

One of the unknown properties of the mixture is the water distribution between free and bound fractions. The total water volume fraction v_w, which also is known as the volumetric moisture content M_v, consists of a free-water part v_{fw} and a bound-water part v_{bw}

$$v_w = M_v = v_{fw} + v_{bw}. \qquad (11)$$

The volume fraction v_b in (10) represents the volume of the bulk vegetation-bound water mixture, which includes v_{bw}

$$v_b = v_{bv} + v_{bw} \qquad (12)$$

where v_{bv} is the volume fraction of bulk vegetation in the vegetation-bound water mixture. The total bulk vegetation volume fraction is $v_v = v_{bv} + v_{uv}$, where v_{uv} is unbound vegetation material. Because vegetation also contains air

$$v_v + v_w + v_a = 1 \qquad (13)$$

where v_a is the air volume fraction.

Several physical models may be postulated to describe how the water is divided between bound and free fractions and how the air volume fraction v_a varies with v_w, but it is difficult to verify the accuracy of such models. With regard to v_a, it is easy to relate it to v_w if we assume that the vegetation material either 1) maintains a constant volume as it gains or loses water (i.e., does not shrink as it dries out), or 2) changes its volume by exactly the volume of the water it gains or loses (i.e., it shrinks perfectly). Neither extreme is realistic, and many possible in-between scenarios may be constructed. With regard to the distribution of water in the material, we expect most of the water to be in bound form when the water content is low and in free form when the water content is high, but no verifiable models exist that define how the water should be apportioned between the two forms.

Because it is difficult to construct a realistic physical model for the vegetation material, we decided to assume that the form of the model given by (10) is valid, and then use the model to determine the magnitudes of ϵ_r, v_{fw}, v_b, and σ and their variations with M_g, the gravimetric moisture content, by fitting the model to the data. Once this has been realized, we will then use the results to construct a physical model for the distribution of water in vegetation. Finally, we shall examine the physical model in terms of the general expectations stated above.

Of the various vegetation materials examined in this study, corn leaves were the most extensively measured. The dielectric measurements were conducted for 24 moisture conditions extending from a gravimetric moisture content of 0.04 to a high of 0.68, and the frequency coverage extended from 0.5 to 20.4 GHz. The frequency range consisted of 30 individual measurements, but in some cases higher order moding occurred at certain fre-

quencies that necessitated deletion of that data. (The consequence of moding is that the reflection measurements produce unacceptably large values of ϵ' and ϵ'', thereby making it easy to detect invalid results.) Moding occurred only for high moisture samples at frequencies above 10 GHz. However, if moding occurred at a given frequency, it did not follow that it occurred at higher frequencies. The corn leaves data set consisted of 624 data points, where a data point represents measurements of ϵ' and ϵ'' of a given sample (and hence moisture condition) at a given frequency.

The spectral data for ϵ_v' and ϵ_v'' measured for a given moisture state were used in conjunction with (10) to select values for ϵ_r, v_{fw}, v_b, and σ such that the error between the measured data and that calculated by (10) is a minimum in a mean-square sense. Upon repeating this process for all 24 moisture states, the results shown in Figs. 3 to 5 were obtained. The points in Fig. 3 represent the values of ϵ_r determined according to the above process and the solid curve is a second-order function fitted to the points. Similar statements apply to v_{fw} in Fig. 4 and v_b in Fig. 5. The parameter σ was found to be essentially constant, exhibiting very small variations with M_g. The functional forms are

$$\epsilon_r = 1.7 - 0.74\,M_g + 6.16\,M_g^2 \qquad (14)$$

$$v_{fw} = M_g(0.55\,M_g - 0.076) \qquad (15)$$

$$v_b = 4.64\,M_g^2/(1 + 7.36\,M_g^2) \qquad (16)$$

$$\sigma = 1.27. \qquad (17)$$

According to this model, the residual dielectric constant ϵ_r, which affects ϵ_v' only, varies from 1.7 for perfectly dry vegetation to about 4.5 for $M_g = 0.7$. Thus, its range is rather narrow and its relative importance is small. Ideally, ϵ_r should be constant independent of moisture, and the fact that it is not a constant is attributed to the imperfect structure of the model given by (9). Both volume fraction parameters, v_{fw} and v_b, increase with increasing M_g but at different rates. The free-water volume fraction v_{fw} exhibits a quadratic- or exponential-like dependence on M_g in that it increases very slowly with M_g until M_g reaches about 0.2 and then v_{fw} increases at a much faster rate for higher values of M_g. In contrast, v_b increases rapidly with increasing M_g over the range 0.1 to 0.4 and then v_b appears to slow down beyond $M_g = 0.4$, as if approaching a plateau.

The volume fraction v_b represents the total volume of bulk vegetation material and water forming the bound mixture. The division among its component parts, v_{bv} and v_{bw}, is governed by the specific types of mechanisms responsible for the bonding between the molecules of the bulk vegetation materials and the water molecules. If we assume that the sucrose-water bond is typical and use the fact that for such a bond the sucrose-to-water volume ratio is $2:1$ (Section II-B), then $v_{bw} = v_b/3$. This relationship, which is the basis of the right-hand scale in Fig. 5, leads
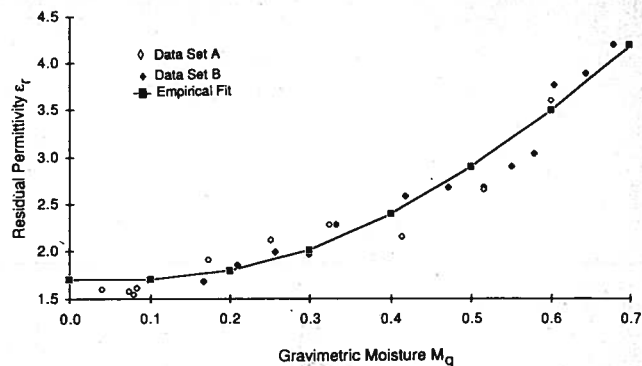

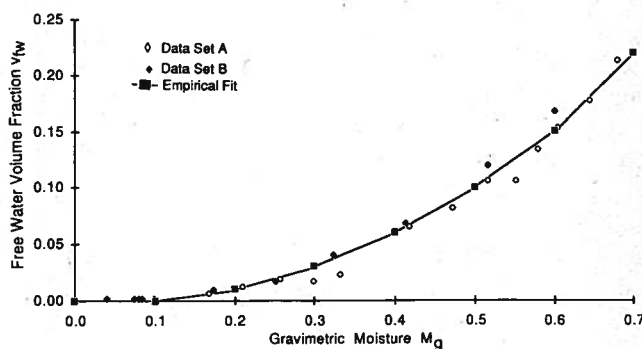Fig. 3. Variation of the residual term ϵ_r with gravimetric moisture M_g.

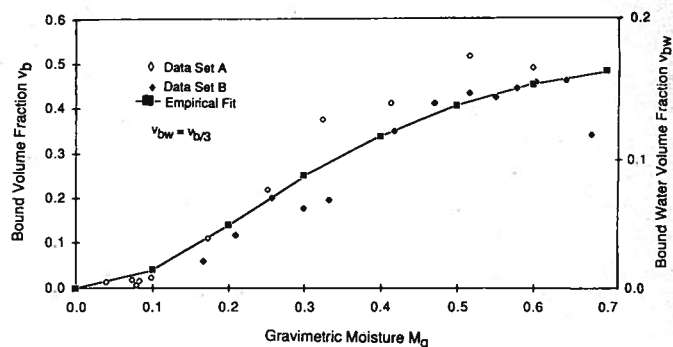Fig. 4. Variation of the free-water volume fraction with gravimetric moisture.

Fig. 5. Variation of v_b with M_g. The right-hand vertical axis is based on the assumption that $v_{bw} = v_b/3$.
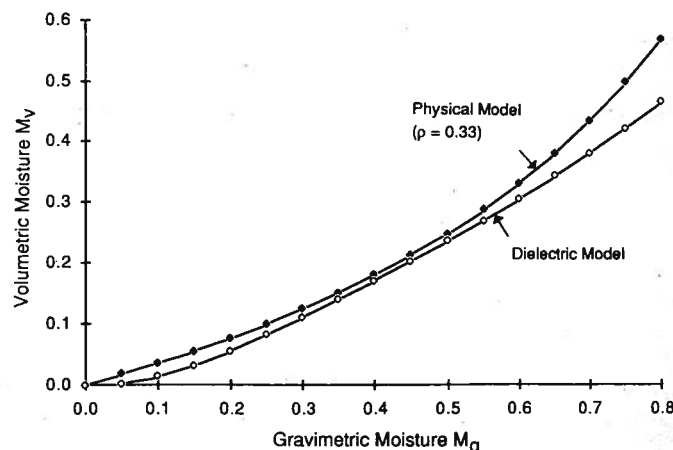

Fig. 6. Comparison of the physical model given by (19) with the prediction of the dielectric model and (18).
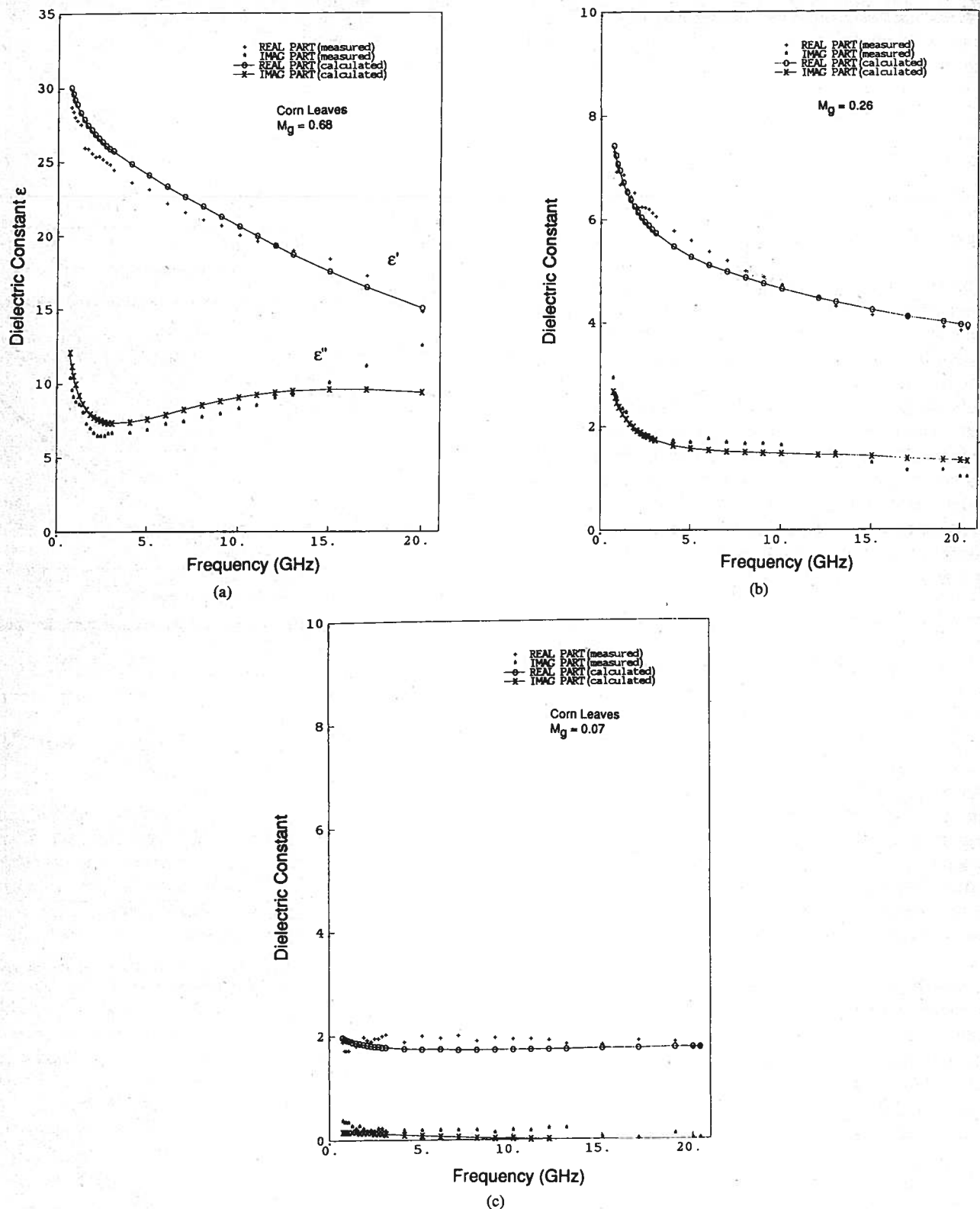
Fig. 7. Comparison of the dielectric spectrum predicted by the model with measured data at (a) $M_g = 0.68$, (b) $M_g = 0.26$, and (c) $M_g = 0.07$.

to

$$M_v = v_w = v_{fw} + \frac{v_b}{3}. \qquad (18)$$

Using the expressions given by (15) and (16) and the preceding equation, M_v was calculated as a function of M_g, and then plotted in Fig. 6 and labeled M_v (dielectric

model). The other curve, labeled M_v (physical model), depicts the variation of M_v with M_g on the basis of

$$M_v = M_g \rho / [1 - M_g(1 - \rho)] \qquad (19)$$

where ρ is the bulk density of the dry vegetation material. This relationship is based on the "shrinking" model,
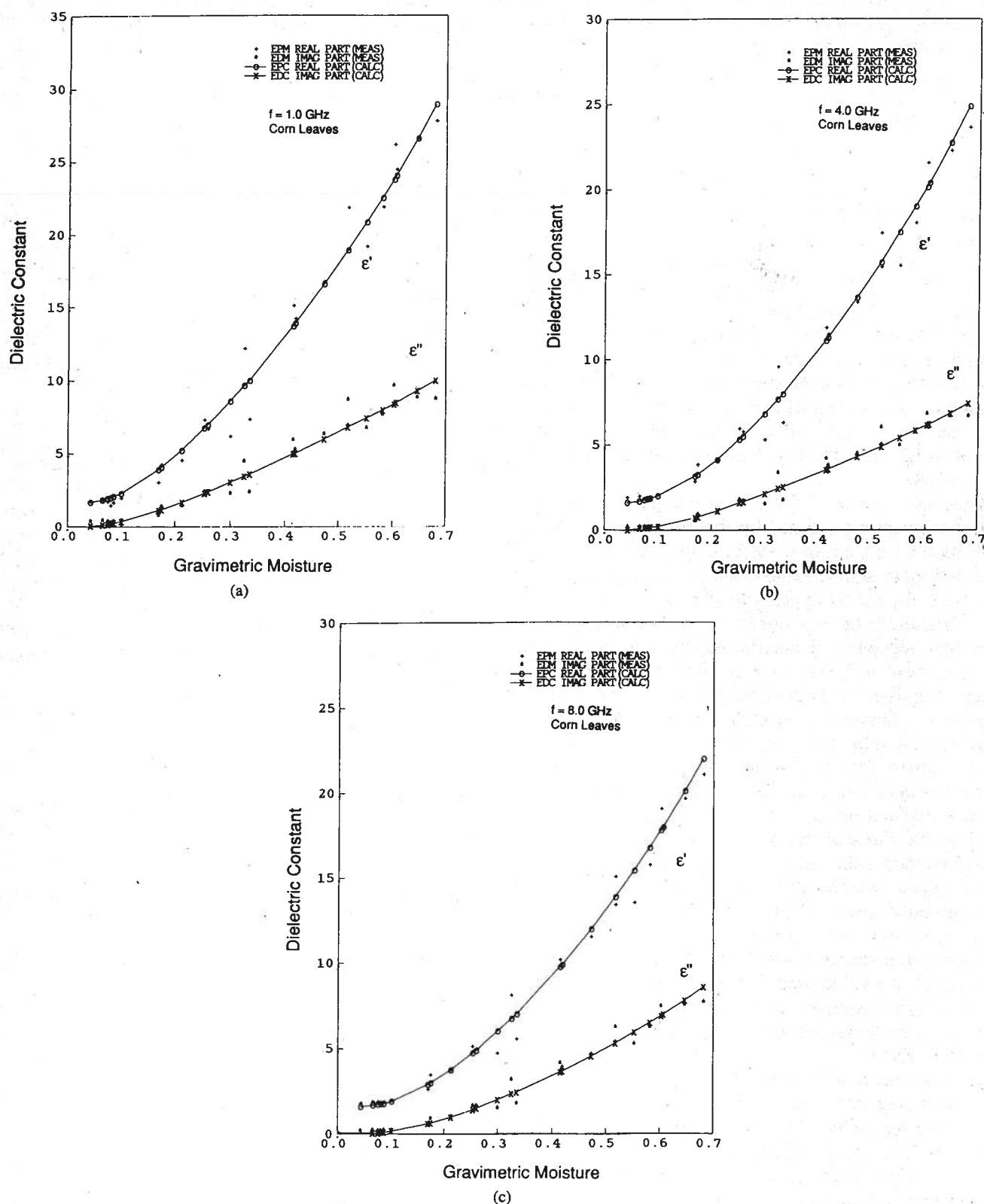
Fig. 8. Comparison of the dielectric variation with moisture as predicted by the model with data at (a) 1 GHz, (b) 4 GHz, and (c) 8 GHz.

which assumes that when vegetation loses water, its volume decreases by an amount equal to that of the lost water. The value of $\rho = 0.33$ g $\cdot$ cm^{-3} was determined from measurements of the weight and volume of dry corn leaves. (The volume was measured using a displacement method in oil). We observe that the two curves in Fig. 6 exhibit the same trend and are close in magnitude. This agreement gives support to the validity of the dielectric model given by (10).

The result $\sigma = 1.27$, as predicted by the model, cor-

responds to a salinity $S = 8.5\%$ (from (3)). The additional result that σ was found to be approximately constant with M_g suggests that the amount of salt dissolved in the free-water solution increases with increasing M_g at exactly the same rate that v_{fw} increases with M_g.

IV. Comparison with Data

The model defined by (10) and the auxiliary relations given by (14)–(17) was evaluated by comparing it with spectral data measured for corn leaves at specific moisture contents and with data measured as a function of moisture content at specific microwave frequencies. Typical examples of these two types of comparison are given in Figs. 7 and 8. The spectral data in Fig. 7 were selected to illustrate the comparison between theory and experiment at a high moisture content of 0.68, an intermediate value of 0.26, and a low value of 0.07. The dielectric variation with M_g is illustrated in Fig. 8 at frequencies of 1.0, 4.0, and 8.0 GHz.

Statistical analysis of the 624 available measurements against the values predicted by the model gives a linear correlation coefficient of 0.99 for both ϵ'_v and ϵ''_v, and the estimated mean square error is 1.0 for ϵ'_v and 0.3 for ϵ''_v.

Overall, the model appears to provide an excellent fit to the data and is far superior in that respect to any of the traditional vegetation dielectric models used in the past. This statement is based on a detailed evaluation [5] of several empirical and theoretical models including the Polder–Van Santen mixing formulas [6], the De Loor model [7], the semi-empirical model due to Birchak et al. [8], and others [5]. The model also provides a physical interpretation of how water in plant material is distributed between free and bound.

A possible shortcoming of the model is the fact that it was developed using data for only one material: corn leaves. On the other hand, evaluation of the model against data measured for corn stalks, soybean leaves, aspen leaves, balsam fir trunk, potatoes, apples, and other types of vegetation material has revealed the following:

1) For ϵ'_v, the value predicted by the model (as defined by (10) and the associated expressions given by (14)–(17)) agrees with the measured value within ± 20 percent of the measured value.

2) For ϵ''_v, the relative error is within ± 20 percent also, but only at frequencies above 5 GHz. This is due to salinity variations, which become unimportant when $f \gtrsim 5$ GHz. If the salinity is known and used to compute σ according to (3) and the latter is used in (10), the ± 20-percent relative error may be extended down to 0.5 GHz.

3) If both the gravimetric moisture M_g and the density of the vegetation material are known and used to compute M_v through (19), the ± 20-percent relative error may be reduced to ± 5 percent by using expressions for ϵ_r, v_{fw}, and v_b that are based on M_v instead of M_g. These expressions are

$$\epsilon_r = 1.7 + 3.2 M_v + 6.5 M_v^2 \qquad (20)$$

$$v_{fw} = M_v(0.82 M_v + 0.166) \qquad (21)$$

$$v_b = 31.4 M_v^2 / (1 + 59.5 M_v^2). \qquad (22)$$

Moreover, the model becomes equally applicable to woody material such as tree trunks and branches.

In summary, the dielectric model given by (10) and the auxiliary equations (20)–(22) provides a good estimate of ϵ'_v for leaves, stalks, branches, and trunks. If the dry density ρ is unknown, the auxiliary equations given by (14)–(16) may be used instead, but the relative error will be as much as 20 percent for leaves and stalks and much larger for material with densities markedly different from the 0.33-g $\cdot$ cm^{-3} value implicit in the expressions (14)–(16). Similar statements apply to ϵ''_v provided a reasonable estimate of the salinity S is available to use in (3) in order to compute σ.

V. Conclusions

Examination of measured dielectric spectra for vegetation material led to the development of a Deybe–Cole dual-dispersion model consisting of a Debye relaxation term representing the free water contained in the vegetation material and a Cole relaxation term with a relaxation parameter $\alpha = 0.5$ representing the bound water–bulk vegetation mixture. The model provides an excellent fit to the measured data and has led to the development of a physical model for the distribution of water in vegetation between free and bound forms.

References

[1] A. K. Fung and F. T. Ulaby, "A scatter model for leafy vegetation," IEEE Trans. Geosci. Electron., vol. GE-16, no. 4, pp. 281–286, Oct. 1978.
[2] F. T. Ulaby and R. P. Jedlicka, "Microwave dielectric properties of plant materials," IEEE Trans. Geosci. Remote Sensing, vol. GE-22, pp. 406–414, 1984.
[3] F. T. Ulaby, R. K. Moore, and A. K. Fung, Microwave Remote Sensing, vol. 3. Dedham, MA: Artech, 1986, Appendix E.
[4] A. Stogryn, "Equation for calculating the dielectric constant of saline water," IEEE Trans. Microwave Theory Tech., vol. MIT-19, pp. 733–736, 1971.
[5] A. M. El-Rayes and F. T. Ulaby, "Microwave dielectric behavior of vegetation material," Univ. Michigan Tech. Rep., RL-022132-3-T, 1986.
[6] D. Polder and J. H. Van Santen, "The effective permittivity of mixtures of solids," Physica, vol. XII, no. 5, pp. 257–271, 1946.
[7] G. P. DeLoor, "Dielectric properties of heterogeneous mixtures containing water," J. Microwave Power, vol. 3, pp. 67–73, 1968.
[8] J. R. Birchak, C. G. Gardner, J. E. Hipp, and J. M. Victor, "High dielectric constant microwave probes for sensing soil moisture," Proc. IEEE, vol. 62, no. 1, pp. 93–98, Jan. 1974.

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