Radio Science, Volume 28, Number 4, Pages 549–558, July–August 1993

Microwave propagation constant for a vegetation canopy at X band

Ahad Tavakoli, Kamal Sarabandi, and Fawwaz Ulaby
The Radiation Laboratory, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor
(Received August 9, 1991; revised August 20, 1992; accepted September 14, 1992.)

An equivalent-medium model is developed for vegetation media to relate the propagation constant γ, associated with propagation of the mean field through a vegetation canopy, to the geometrical and dielectric parameters of the canopy constituents at high frequencies. The model is intended for media containing vertical dielectric cylinders, representing the stalks, and randomly oriented, arbitrary shaped thin dielectric disks, representing the leaves. The formulation accounts for absorption and scattering losses by both stalks and leaves. A resistive sheet model in conjunction with the physical optics approximation is used to model scattering by the canopy leaves, which is valid when the leaf dimensions are larger than a wavelength. The model is found to be in good agreement with experimental results at 10.2 GHz. The experimental component of the study included measurements of the attenuation loss for horizontally polarized and vertically polarized waves transmitted through a fully grown corn canopy. The measurements were made at incidence angles of 20°, 40°, 60°, and 90° relative to normal incidence. The proposed model is suitable for cornlike canopies, provided the leaves are larger than λ in size.

1. INTRODUCTION

Electromagnetically, most vegetation canopies are treated as inhomogeneous media at microwave frequencies because the scattering elements (leaves, branches, etc.) are comparable to λ in size. Propagation in a vegetation medium can be modeled using the radiative transfer theory [Ulaby et al., 1986; Tsang et al., 1985] which accounts for both absorption and scattering by the elements constituting the medium. Stalks, branches and tree trunks have been successfully modeled as dielectric cylinders [Karam et al., 1988; Ulaby et al., 1987; Mougin et al., 1990; Lopes and Mougin, 1990], and leaves are modeled as thin circular disks [Lang and Sidhu, 1983; Levine et al., 1985].

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Paper number 92RS02456.
0048-6604/93/92RS-02456$08.00

The present study is a continuation of a previous report [Ulaby et al., 1987] that examined microwave propagation through a vegetation canopy with vertical stalks. The stalks were represented by infinitely long, vertically oriented dielectric cylinders, and the leaves were modeled as randomly oriented circular disks with dimensions much smaller than a wavelength. Model calculations were compared with attenuation measurements made for a corn canopy at 1.6, 4.75, and 10.2 GHz. It was concluded that the dielectric-cylinder representation for the stalks was appropriate over a wide range of frequencies. However, the quasi-static model assumed for the leaves was not suitable at 10.2 GHz because the leaf dimensions were comparable to or larger than λ. In this paper, we will model the leaves as randomly oriented thin dielectric sheets of arbitrary shapes and surface dimensions that are larger than a wavelength. A closed form solution is derived for the propagation constant of a vegetation canopy composed of vertically oriented stalks and randomly oriented leaves of arbitrary shapes, and the results are compared with the measured 10.2-GHz data. Section 2 contains a summary of the experimental procedure used to acquire the reported data, and in section 3 we derive the theoretical expressions used in the model calculation.

2. EXPERIMENT

Measurements of the transmission loss through a corn canopy were made at incidence angles of 20°, 40°, 60°, and 90° at 10.2 GHz (X band) for both vertical and horizontal polarizations. The 90°-case represents horizontal propagation through the canopy. The transmitter for the 20°, 40°, and 60° measurements was placed on a truck-mounted platform at a height of 11.5 m above the ground surface (Figure 1), and the receiver was placed underneath the canopy. For the 90° measurement, the transmitter platform was placed on the truck bed, and the receiver was placed on a wooden platform, whose height above the ground was the same as that of the transmitter. To measure the attenuation characteristics of the medium, the arrangement shown in Figure 2 was used to get statistically independent samples. The receiving platform was placed on a rail system on which it slid in synchronism with the motion of the truck as it was pulled by a rope connected to the truck through a pulley system. The receiver consisted of a dual- polarized corrugated horn antenna connected to a microwave detector, which was, in turn, connected to a power meter through a 50-m coaxial cable. The output of the power meter was recorded on a strip-chart recorder for immediate display in the field as well as on a digital cassette recorder (using an HP 85 computer) for later analysis. By cutting and removing the corn plants from an approximately 3-m wide

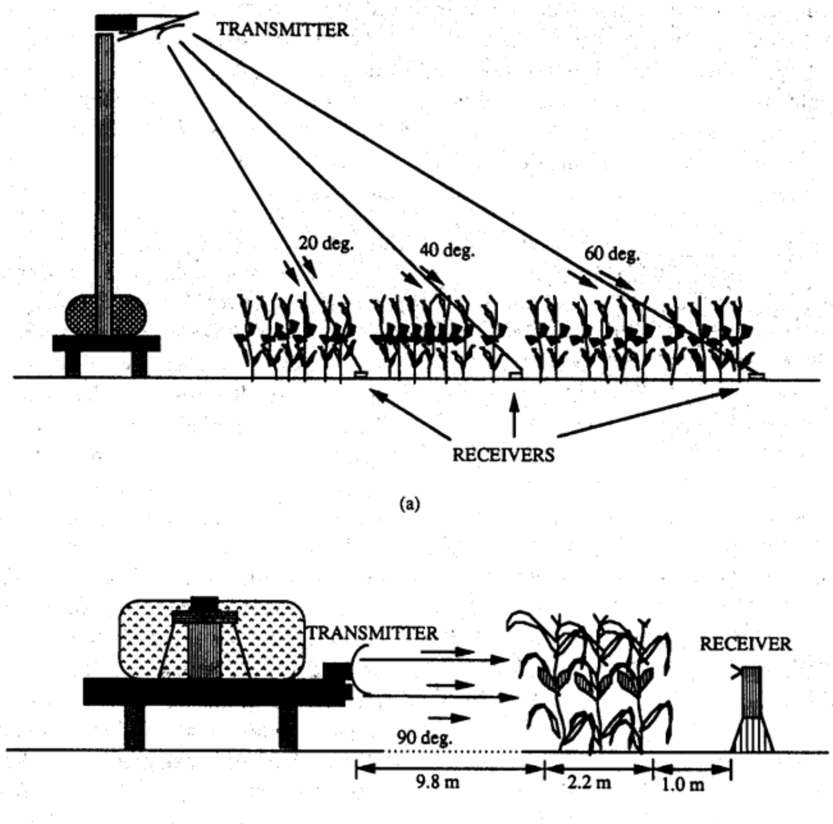


Fig. 1. Configuration used for the transmission measurements at (*a*) 20°, 40°, 60°, and (*b*) 90°.

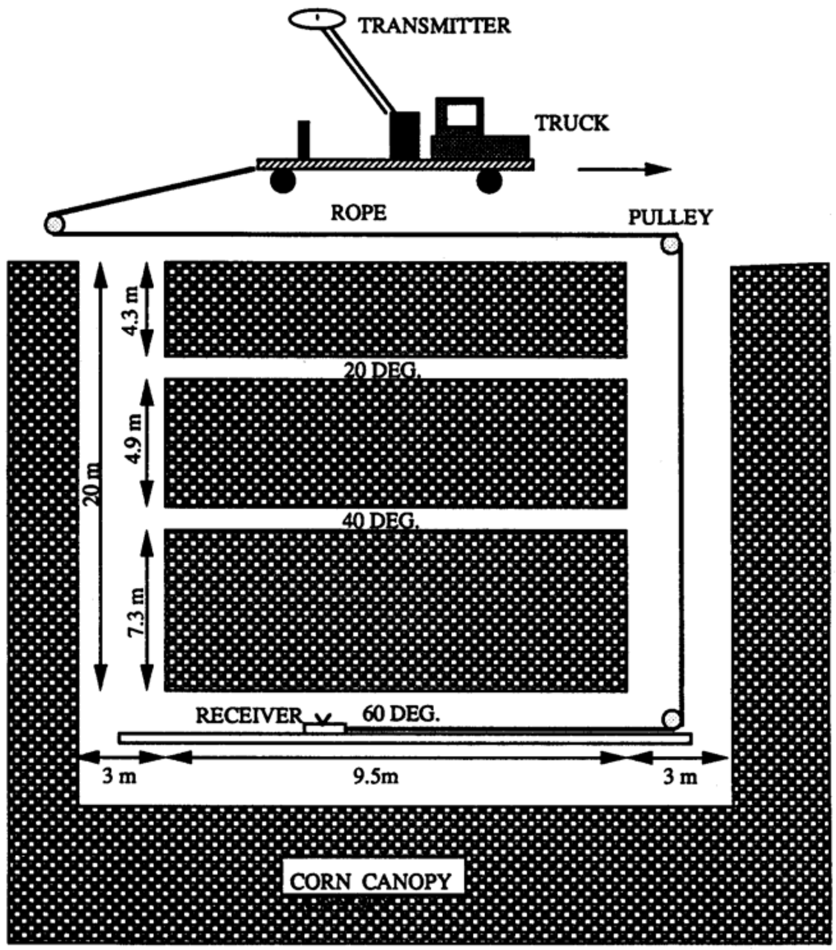


Fig. 2. The pulley system was used so that as the truck moved forward, the transmit and receive antennas moved in space at exactly the same speed, thereby maintaining line of sight.

strip on both ends of the canopy area (Figure 2), it was possible to establish a free-space reference signal for the measurements. Furthermore, the stability of the signal across each of the 3-m wide strips provided an indication of the presence (or absence) of multiple ground reflections. The canopy loss factor L is defined in decibels as

$$L = 10\log\left(\frac{P_0}{P_r}\right) \qquad (1)$$

where P_r is the power received when the canopy is present and P_0 is the free space level received under identical conditions (antenna pointing, range between transmitter and receiver, etc.) but without an intervening canopy between the transmitter and the receiver. In addition, field measurements were performed to determine the density of plants, the row spacing, the average leaf and stalk sizes, and their corresponding volume fractions in the medium. Furthermore, samples were processed in the laboratory to determine their gravimetric moisture contents for estimating the dielectric constant of the canopy constituents based on the formulas available in the literature [El-Rayes and Ulaby, 1987; Ulaby and El-Rayes, 1987]. Table 1 presents a summary of the system specifications and canopy parameters. Fig-

TABLE 1a. Characteristics of the Measurement System: Incidence Angle Information

	Distance, m			
	20°	40°	60°	90°
Transmitter and receiver	11.7	14.3	22.0	13.0
Transmitter height	11.5	11.5	11.5	1.2
Receiver height	0.3	0.3	0.3	0.3
Slant path in canopy	2.6	3.2	4.8	2.2

The Antenna beam widths for the transmitter and receiver and 4.7° and 24.7°, respectively.

TABLE 1b. Characteristics of the Canopy Parameters

Parameter	Value
Average row spacing	0.76 m
Average plant spacing	0.20 m
Plants per unit area	6.6
Stalk diameter	2.8 cm at base
	1.8 cm at 1.2 m
	0.6 cm at top
Stalk gravimetric moisture	0.69
Leaf gravimetric moisture	0.82
ϵ (Stalk)	22.0 $+i$ 9.0
ϵ (Leaves)	29.5 $+i$ 12.0
Leaf area per unit volume	0.78
Average leaf thickness	0.27 mm

ures 3a and 3b are examples of the power recorded at 60° for horizontal and vertical polarizations, and their corresponding attenuation histograms are shown in Figures 3c and 3d. The relatively flat levels at the end of each record represent the free-space reference level of the received signal. The canopy transmission loss $L(x)$ is measured in decibels relative to this reference level. At this frequency, $L_V(x)$ and $L_H(x)$ are quite similar to one another and their means and standard deviations are about the same. This insensitivity to polarizations at 10.2 GHz is very different from the behavior at 1.6 GHz [Ulaby et al., 1987] which exhibits much greater attenuation for vertical polarization than for horizontal polarization. At 1.6 GHz, scattering in the medium is dominated by the vertically oriented stalks, whereas at 10.2 GHz, the scattering is dominated by the randomly oriented leaves. This explanation is supported by the results reported in section 4.

3. THEORETICAL MODEL

The following development pertains to a vegetation canopy composed of vertically oriented stalks (or trunks) and randomly oriented leaves. The canopy is modeled as a slablike region containing leaves and stalks. The stalks are modeled as infinitely long cylinders pointing in the z direction; and the leaves as thin (compared to the wavelength) dielectric sheets of arbitrary shape, but with surface dimensions that are larger than the wavelength. We seek an expression for the propagation constant g of an equivalent dielectric medium such that it is applicable at any incidence angle θ relative to the z direction for both H and V polarization configurations. The slab contains two-dimensional scatterers (stalks) with identical dielectric properties but not necessarily identical diameters, and statistically similar three-dimensional scatterers (leaves) with prescribed orientation and size distributions.

3.1. *Equivalent-medium model*

Figure 4 represents a narrow layer of the canopy. It is assumed that the scatterers are sparse and interaction between them is negligible. The incident field travels in the x direction and can be represented as

$$\vec{U}^{\text{inc}} = \hat{p}e^{ik_0x} \tag{2}$$

where $e^{-i\omega t}$ is assumed and suppressed and $\hat{p}$ is a unit vector representing the polarization. The total field at the observation point $P(x_0, 0, 0)$ is composed of three parts: (1) the direct incident field at P, (2) the field due to scattering by the three-dimensional scatterers (leaves), and (3) the field scattered by the two-dimensional scatterers (stalks). The fields corresponding to terms (2) and (3) will each be derived separately and then will be added to the incident field at point P. For a sparse medium, the incident field on the nth leaf located at (x_n, y_n, z_n) is represented by

$$\vec{U}_n = \hat{p}e^{ik_0x_n} \tag{3}$$

Assuming that the observation point is far away from the slab, the scattered field due to this leaf observed

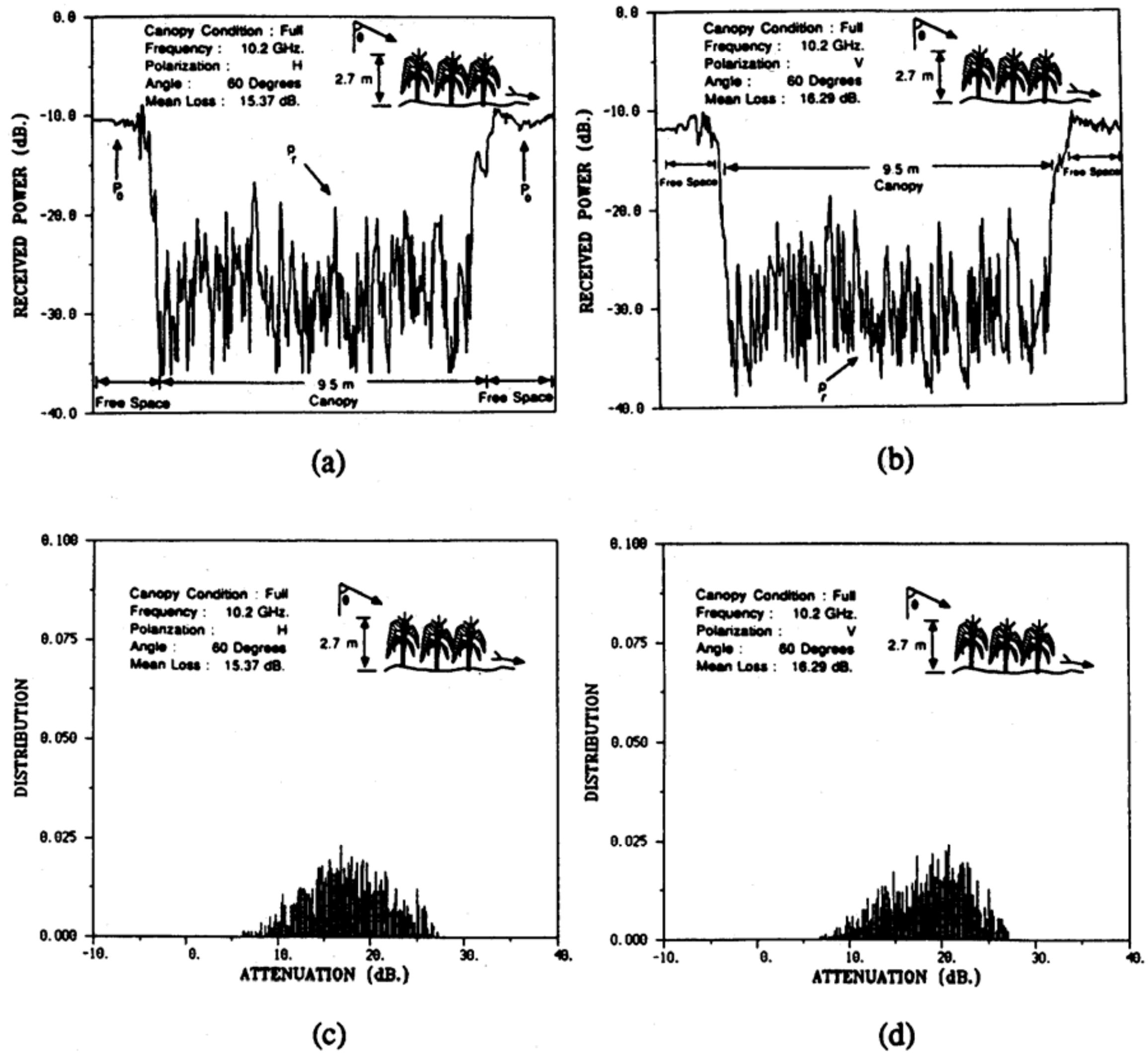


Fig. 3. Received power as a function of spatial position for (*a*) H polarization, (*b*) V polarization, and corresponding histograms (*c*) H polarization, and (*d*) V-polarization.

at $P(x_0, 0, 0)$ is given by

$$\vec{U}_n^1 = e^{ik_0 x_n} \frac{e^{ik_0 r_n}}{k_0 r_n} \vec{S}(\hat{r}_n) \tag{4}$$

where r_n is the distance between the nth leaf and the observation point and $\vec{S}_n(\hat{r}_n)$ is the scattering amplitude of the leaf for scattering in direction $\hat{r}_n$ (Figure 4). Since the medium is sparsely populated (vegetation volume fraction in a canopy is typically less than 1%), multiple scattering between the leaves may be ignored. Thus the total scattered field at the observation point is the superposition of contributions of all individual leaves in the slab; that is,

$$\vec{U}^1 = \sum_n e^{ik_0 x_n} \frac{e^{ik_0 r_n}}{k_0 r_n} \vec{S}_n(\hat{r}_n) \tag{5}$$

If N, the number of leaves per unit volume in the

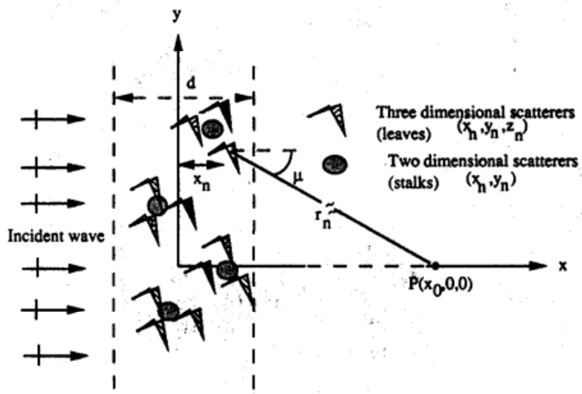


Fig. 4. Geometry of a narrow slab containing leaves and stalks and the observation point P.

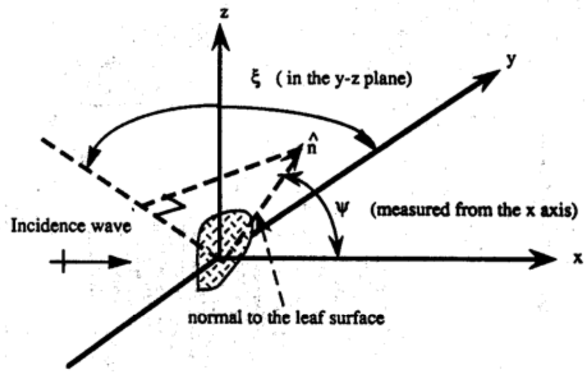


Fig. 5. Scattering geometry for an arbitrary shaped thin dielectric leaf.

medium, is large, then the summation in (5) can be approximated by

$$\vec{U}^1 = N \iiint e^{ik_0 x'} \frac{e^{ik_0 r'}}{k_0 r'} < \vec{S}(x_0; x', y', z') > dx'dy'dz' \tag{6}$$

where $< \vec{S}(x_0; x', y', z') >$ is the scattering amplitude averaged over the prescribed size and orientation distributions. To evaluate (6), two changes of variables are in order: (1) the integration in $y' - z'$ plane can be performed by cylindrical variables ρ' and ϕ', and (2) the integration with respect to ρ' and x' can be performed by changing to variables ν and μ as defined by

$$\begin{aligned} \nu &= x' \\ \mu &= \tan^{-1} \frac{\rho'}{x_0 - x'} \end{aligned} \tag{7}$$

In (7), μ is the angle between forward scattering direction (x axis) and observation the point P (Figure 4). Thus (6) becomes

$$\vec{U}^{-1} = N \int_0^{2\pi} \int_{-d/2}^{d/2} e^{ik_0 \nu} \left[\int_0^{\frac{\pi}{2}} < \vec{S}(\pi - \mu) > \frac{e^{ik_0 \frac{x_0 - \nu}{\cos\mu}}}{k_0 \cos\mu} (x_0 - \nu) \tan\mu d\mu \right] d\nu d\phi' \tag{8}$$

If the observation point is far away from the slab, that is $k_0 x_0 >> 1$, then the integrand of (8) rapidly changes with small changes in μ for values of μ away from zero ($\mu = 0$ is the stationary phase point). Therefore the integral is dominated by the contribution of the integrand around the stationary phase point, where the integrand can be approximated by its Taylor series expansion; that is,

$$\vec{U}^{-1} \approx N \int_0^{2\pi} \int_{-d/2}^{d/2} e^{ik_0 \nu} \left[\int_0 < \vec{S}(\pi) > \frac{e^{ik_0 (x_0 - \nu)\left(1 + \frac{\mu^2}{2}\right)}}{k_0} (x_0 - \nu) \mu d\mu \right] d\nu d\phi' \tag{9}$$

Direct evaluation of (9) leads to

$$\vec{U}^1 \approx e^{ik_0 x_0} \frac{i2\pi N d}{k_0^2} < \vec{S}(\pi) \tag{10}$$

Following a similar approach, we can derive an expression for the total field due to scattering by the stalks. The field incident on the mth stalk located at (x_0, y_0) is given by

$$\vec{U}_m = \hat{p} e^{ik_0 x_m} \tag{11}$$

which gives rise to a scattered field at point $P(x_0, 0, 0)$ as given by

$$\vec{U}_m^S = e^{ik_0 x_m} \sqrt{\frac{2}{\pi k_0 \rho_m}} e^{i(k_0 \rho_m - \frac{\pi}{4})} \vec{T}_m(\vec{\rho}_m) \tag{12}$$

where $\vec{T}_m(\vec{\rho}_m)$ is the scattering amplitude of the stalk for scattering in direction $\vec{\rho}_m$ and ρ_m is the distance between the stalk and the observation point. If the slab contains M stalks per unit area, the total scattered field at P due to the stalks, derived in manner similar to that used previously for the leaves is

$$\vec{U}^S \approx e^{ik_0 x_0} \frac{2Md}{k_0} < \vec{T}(\pi) > \tag{13}$$

where $< \vec{T}(\pi) >$ is the forward scattering amplitude of the stalks, averaged over the specified diameter distribution.

The total field at the observation point P is

$$\vec{U}^t = \vec{U}^i + \vec{U}^1 + \vec{U}^S$$
$$\vec{U}^t = e^{ik_0 x_0} \left[\hat{p} + \frac{2Md}{k_0} < \vec{T}(\pi) > + \frac{i2\pi Nd}{k_0^2} < \vec{S}(\pi) > \right] \tag{14}$$

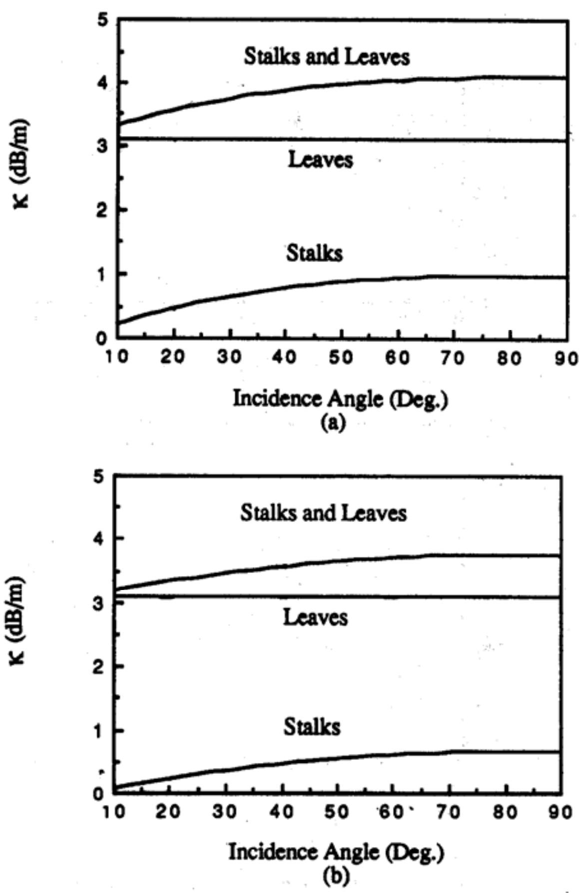


Fig. 6. Comparison between the contributions of the stalks and leaves to the extinction coefficient at (a) V polarization, and (b) H polarization.

Now, if we represent the thin layer of scatterers by an equivalent homogeneous dielectric slab with index of refraction n, the total field at P would be

$$\vec{U}^t = \hat{p} e^{ik_0 x_0} e^{i(n-1)k_0 d}$$
$$\approx \hat{p} e^{ik_0 x_0} [1 + i(n-1)k_0 d] \tag{15}$$

The Taylor series expansion used in the above approximation is justified by the fact that d is small, $n' = \text{Re}[n] \approx 1$, and $n'' = \text{Im}[n] << 1$. Upon equating (14) and (15), we obtain the following expression for the index of refraction of the equivalent medium

$$n = n' + n''$$
$$n_p = 1 - \frac{i2M}{k_0^2} < T_p(\pi) > + \frac{2\pi N}{k_0^3} < S_p(\pi) > \tag{16}$$

where $S_p(\pi) = \vec{S}_p(\pi)$ and $T_p(\pi) = \vec{T}_p(\pi) \cdot \hat{p}$. The subscript p is used with n_p to emphasize its dependence on the wave polarization vector $\hat{p}$. The propagation constant of the equivalent medium γ is related to n by $\gamma = k_0 n$, and the loss factor L corresponding to propagation over a distance d is given by

$$\text{L} = 4.343 k_p \text{d} = 8.686 k_0 n'' d, \ \text{dB} \tag{17}$$

where k_p is the power extinction coefficient of the medium. In the above derivation no assumption on particular shape and sizes of the scatterers are made. By selection of appropriate models for single scatterers, the model can predict the average power of the propagating wave.

3.2. *Scattering amplitudes of stalks and leaves*

As was mentioned previously, the stalks can be modeled as infinitely long cylinders. Because the wave is obliquely incident on the cylinders, the scattering amplitude T will be a function of the incidence angle θ. Also, M, the number of cylinders per unit area in the plane of propagation (defined as the plane containing the direction of the propagation and the y axis), is related to the number of plants per unit area on the ground, M_g by

$$M = M_g \sin\theta \tag{18}$$

The V and H polarized forward scattering amplitudes of the cylinders are given by

$$T_V(\theta, \pi) = \frac{1}{\sin\theta} \sum_{n=-\infty}^{\infty} C_n^{TM}(\theta)$$

$$T_H(\theta,\pi) = \frac{1}{\sin\theta}\sum_{n=-\infty}^{\infty} C_n^{TE}(\theta) \quad (19)$$

where the functions $C_n^{TM}(\theta)$ and $C_n^{TE}(\theta)$ are given by Ruck et al. [1970] for incidence at any angle ψ relative to the surface normal of the cylinder ($\psi = \pi/2 - \theta$). A leaf can be considered a resistive sheet whose resistivity R in ohms per unit area is given by [Sarabandi, 1989]

$$R = \frac{iZ_0}{k_0\tau(\epsilon - 1)} \quad (20)$$

where Z_0 is the free space impedance, *tau* is the leaf thickness and ϵ is the relative dielectric constant of the leaf. When $R = 0$, the sheet appears perfectly conducting and when $R = \infty$, it ceases to exist. The sheet is an electric current sheet whose strength is proportional to the tangential electric field and is related to R. The scattering properties of a leaf can be derived by using the physical optics approximation for a finite size sheet in conjunction with the electric current supported by an infinite resistive sheet. The reflection coefficients of an infinite resistive sheet for V and H polarizations are

$$\Gamma_V = \left(1 + \frac{2R\cos\psi}{Z_0}\right)^{-1}$$
$$\Gamma_H = \left(1 + \frac{2R\sec\psi}{Z_0}\right)^{-1} \quad (21)$$

where ψ is the incidence angle with respect to the normal to the sheet surface. For a plane wave traveling in the x direction and a leaf whose normal to the surface is defined by the angles y and x (Figure 5), the forward scattering amplitude is given by

$$S_V(\pi) = -\frac{iAk_0^2}{2\pi}\cos\psi\left[\Gamma_V\cos^2\xi + \Gamma_H\sin^2\xi\right]$$
$$S_H(\pi) = -\frac{iAk_0^2}{2\pi}\cos\psi\left[\Gamma_V\cos^2\xi + \Gamma_H\sin^2\xi\right] \quad (22)$$

where A is the leaf area and Γ_V and Γ_H are as defined before [Sarabandi, 1989]. In the propagation model, we need an ensemble average of the forward scattering amplitude of the leaves. The average forward scattering amplitude for randomly oriented leaves can be obtained by averaging $S(\pi)$ over all possible orientation angles; thus

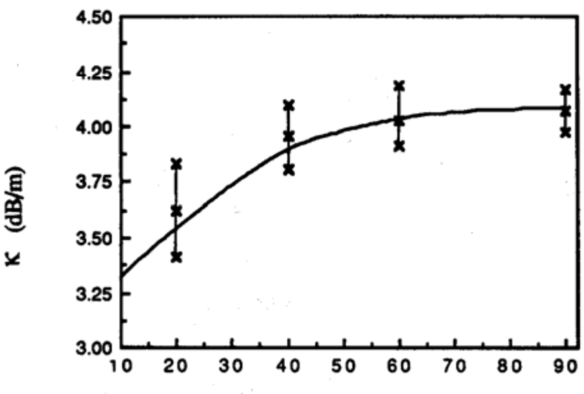
$$< S_{V,H}(\pi) > = < S(\pi) > = \frac{1}{4\pi}\int_0^{2\pi} d\xi \int_0^{\pi} S_{V,H}(\pi)\sin\psi d\psi \quad (23)$$

Since Γ_V and Γ_H are independent of ξ, the integration over ξ can be easily performed to give

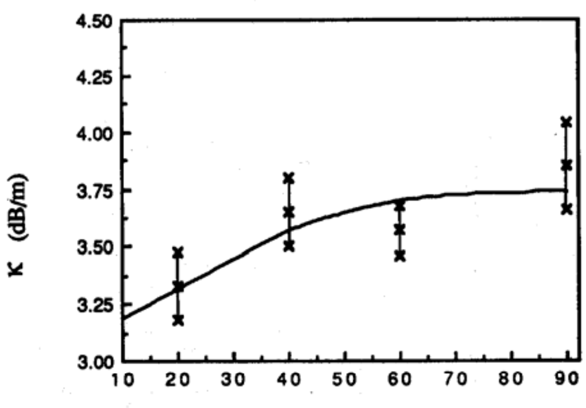
$$< S(\pi) > = \frac{iAk_0^2}{8\pi}\int_0^{\pi}\int_0^{\pi}(\Gamma_V + \Gamma_H)\cos\psi\sin\psi d\psi \quad (24)$$

Upon substitution of the values of Γ_V and Γ_H in (24), the following relation is obtained:

$$< S(\pi) > = -\frac{iAk_0^2}{8\pi}\left\{\int_0^{\pi}\left(1 + \frac{2R\cos\psi}{Z_0}\right)^{-1}\cos\psi\sin\psi d\psi + \int_0^{\pi}\left(1 + \frac{2R}{Z_0\cos\psi}\right)^{-1}\cos\psi\sin\psi d\psi\right\} \quad (25)$$



(a)



(b)

Fig. 7. Comparison between the calculated extinction coefficient and the measured data for a corn canopy of stalks and leaves at (a) V polarization and (b) H polarization.

By setting $\alpha = \cos\psi$, $< S(p) >$ assumes the form

$$< S(\pi) > = -\frac{iAk_0^2}{8\pi}\left\{\int_{-1}^{1}\frac{\alpha}{1+\frac{2R}{Z_0}\alpha}d\alpha + \int_{-1}^{1}\frac{\alpha^2}{\alpha+\frac{2R}{Z_0}}d\alpha\right\} \quad (26)$$

which leads to the result

$$< S(\pi) > = -\frac{1Ak_0^2}{8\pi}\left\{\frac{Z_0}{R} - \frac{4R}{Z_0} + i4\pi\frac{R^2}{Z_0^2} + \left[\frac{4R^2}{Z_0^2} - \frac{Z_0^2}{4R^2}\right]\ln\left(\frac{Z_0+2R}{Z_0-2R}\right)\right\} \quad (27)$$

Because the physical optics approximation was used in the derivation of $< S(\pi) >$, equation (27) is valid for leaves with surface dimensions larger than a wavelength. Upon substituting (19) and (27) in (16), we obtain the following expressions for the equivalent dielectric constant of the canopy:

$$n^{V,H} = 1 - \frac{i2M_g}{k_0^2}\sum_{n=-\infty}^{\infty} C_n^{TE,TM}(\theta) - \frac{i\zeta}{4k_0}$$
$$\left\{\frac{Z_0}{R} - \frac{4R}{Z_0} + i4\pi\frac{R^2}{Z_0^2} + \left[\frac{4R^2}{Z_0^2} - \frac{Z_0^2}{4R^2}\right]\ln\left(\frac{Z_0+2R}{Z_0-2R}\right)\right\} \quad (28)$$

where ζ is the leaf area per unit volume. It can be seen that as long as the leaves are large compared with λ, the exact sizes and numbers of leaves are not needed in the computations, and only the knowledge of ζ suffices.

4. COMPARISON OF THEORY WITH EXPERIMENTAL OBSERVATIONS

Figure 6 displays the contributions of the stalks and leaves to the total extinction coefficient $k_p(\theta)$ according to the formulation given above and the data given in Table 1. The simulation reconfirms the experimental observation that the attenuation loss in the medium is dominated by the leaves at x band. Since the leaves are assumed to have uniform angular distributions, the dependence of the extinction coefficient to the incidence angle is only caused by the stalks. Figure 7 shows the calculated angular variation of the extinction coefficient including the data measured at 20°, 40°, 60°, and 90°, presented in the form of the mean value of the measured extinction coefficient and the associated standard deviation. Overall, good agreement is observed between the measured data and the theoretical curves at both vertical and horizontal polarizations.

5. CONCLUSION

The propagation model developed in this paper accounts for both the scattering and intrinsic absorption by stalks and leaves. In this treatment the surface sizes of the leaves must be larger than a wavelength. Good agreement between theory and experiment is obtained at various incidence angles for both polarizations.

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K. Sarabandi, A. Tavakoli, and F. Ulaby, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109.