MODELLING THE POLARIZATION DEPENDENCE OF THE ATTENUATION IN VEGETATION CANOPIES

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ABSTRACT

The loss factor $L(\theta,p)$ of a vegetation canopy is defined as the total attenuation for propagation through the canopy at angle θ relative to nadir,

$$L(\theta,p) = \exp\left(\int_0^{h\sec\theta'} \kappa_p(\theta',z)dz \right), \qquad (1)$$

where $\kappa_p(\theta',z)$ is the p-polarized extinction coefficient of the canopy at depth z below the canopy surface for propagation at a refraction angle θ', and h is the canopy height. The three major constituents of a canopy are its (1) leaves, (2) stalks, and (3) fruit. This paper describes a model developed for computing $L(\theta,p)$, based on two assumptions: first, that the leaves may be treated as randomly distributed discs, and secondly, that the stalks are vertical cylinders. The vertical structure of the stalks leads to a strong polarization dependence, as predicted by the model and supported by experimental observations. Loss measurements made at 10.2 GHz for wheat and soybean canopies are discussed and compared to model calculations.

Keywords: microwaves, vegetation attenuation, wheat, soybeans.

1. INTRODUCTION

In order to utilize the potential of microwave remote sensors to monitor agricultural targets, an understanding of the interaction between electromagnetic energy and crop canopies is necessary. Empirical models with theoretical bases have been applied to measured data, both active and passive, with encouraging results (Refs. 1,2,3,4). In these models, a vegetation canopy is treated as a uniform layer (or layers) over a soil surface. Hence, any backscattering (or emission) from the underlying soil is attenuated by the canopy. Attenuation is, therefore, an essential component of these models.

Unfortunately, reasonable values for attenuation through vegetation canopies based upon experiments are not readily available (Refs. 5,6,7). Furthermore, the effects upon attenuation of changes in frequency, incidence angle, and polarization, as well as percent moisture, plant dimensions, etc., are unknown. In an attempt to begin filling this information gap, two experiments were conducted during the summer of 1983. They were designed to determine the one-way attenuation through a wheat canopy and a soybean canopy. The methodology used in the soybean experiment is the same as that described by Ulaby and Jedlicka (Ref. 8), whereas the methodology used in the wheat experiment is entirely new.

The loss factor $L(\theta,p)$ of a vegetation canopy is defined in terms of the extinction coefficient $\kappa_p(\theta',z)$ by (1). The extinction coefficient represents the sum of two separate mechanisms, i.e., scattering and absorption. Both mechanisms depend upon the dielectric constant and the geometry of the canopy components. For simplicity, the canopy has been assumed to be uniform horizontally, varying only along its vertical profile. Hence, it is necessary to integrate κ_p along the path of propagation.

To further simplify the model somewhat, the canopy may be modeled as a collection of discrete layers of uniform material; thus, the integration becomes a summation,

$$L(\theta,p) = \exp\left(\sum_i \kappa_p(\theta',i)\, h_i \sec\theta' \right). \qquad (2)$$

For a wheat canopy, the number of layers may be set at two: the top layer being composed of head material and the lower layer of stalks and leaves. Depending on the stage of growth, either component in the lower layer may dominate. The random structure of soybeans, however, makes layering difficult; therefore, they are treated as a uniform volume.

2. WHEAT

2.1 Experiment Description

The transmitter section of a 10.2-GHz truck-mounted radar was used as the source in a canopy transmission experiment designed to measure the attenuation properties of wheat stalks and

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heads. The receiver was a small (7- x 5-cm aperture) X-band horn antenna connected via a detector to a logarithmic power scope. The experiment consisted of the following steps: with the transmitting antenna approximately 10 m above the soil and transmitting at 10.2 GHz (60° incidence angle, vertically polarized), the receiving antenna was placed in the field within the main beam of the transmitting antenna. This receiving antenna was mounted on a structure that enabled the operator to continuously vary its height above the soil from 132 cm down to 23 cm. The height of the receiving antenna was output as a voltage via a potentiometer. Thus, by monitoring the output of both the power meter and the height-voltage, information about attenuation versus height was available. To remove effects due either to the antenna beamwidths or to any other related problems, the system was calibrated without canopy between the antennas, at the same range and incidence angle. The result of this calibration was then removed from the data, thus leaving only canopy effects.

2.2 Results

From six locations within the same field (separated by approximately one meter) canopy attenuation profiles were recorded under two conditions. First a profile was made under normal conditions. Then, the wheat heads were removed, and from the same position, another profile was made of the same area. A sample plot is shown in Figure 1. Notice that the profile of the canopy with the heads intact shows higher attenuation than the profile with the heads removed. Also note the strong oscillations in the profile that includes the heads. To examine the effect of the heads alone, the difference between the two curves was plotted against the height of the receiving antenna. By multiplying the height scale by $\tan\theta$, the x-scale was converted into horizontal distance from the receiving antenna in the direction of the transmitting antenna. A sample plot for one of the six locations is shown in Figure 2. In addition to the overall level of approximately 11 dB, notice the oscillatory behavior indicated in Figure 2. The spacing between peaks is roughly 20 cm, which corresponds to the row spacing. This may be explained as a clustering of heads every 20 cm, whereas in between, the density drops. Based on such head-attenuation values from all six locations, a histogram of the head attenuations was produced. From these data, the mean head attenuation under these conditions was found to be approximately 8.3 dB, which corresponds to an attenuation coefficient of 52 dB m^{-1}.

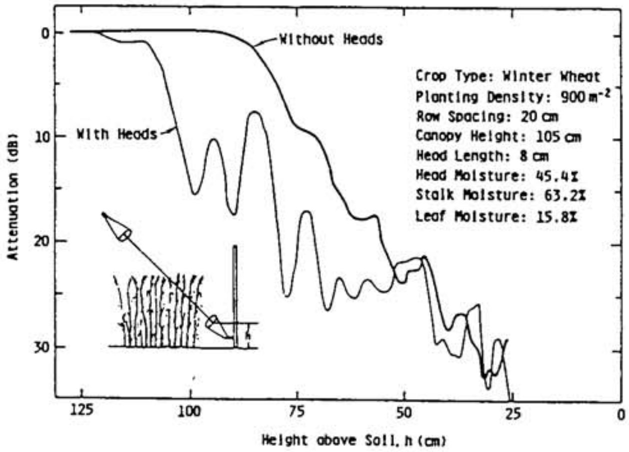

Fig. 1. Example of data acquired using the vertical-attenuation device.

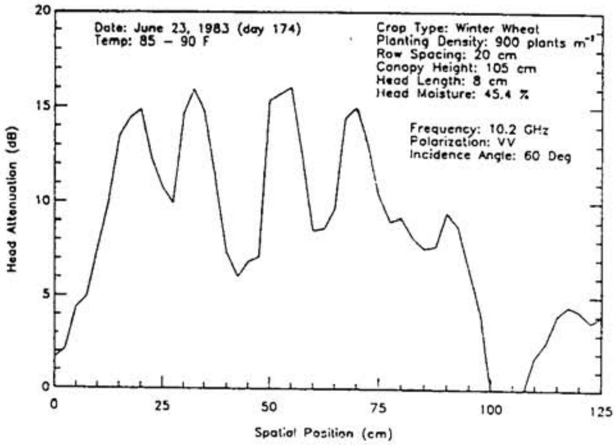

Fig. 2. Plot of head attenuation as a function of horizontal position.

In addition to information about head attenuation, stalk-attenuation data are also available from this series of measurements. By taking the overall attenuation attributable to the stalks (the leaves are neglected, as they contain only 16% moisture, whereas the stalks contain 63%) and dividing by the height of the stalks determined from each plot of attenuation versus height, an attenuation coefficient due to stalks is obtained for each location. The mean of the measurements for six locations is 30.4 dB m^{-1}, with a standard deviation of 12.4 dB m^{-1}.

2.3 Absorption Loss Factor of Canopy Stalks

From a mathematical point of view, a canopy consisting of stalks (the leaves and fruit or grain will be ignored for the present) may be modeled as an assembly of similar, parallel, thin, cylindrical dielectric rods. According to Born and Wolf (Ref. 10), if the volume fraction of the rods is << 1, then the assembly will behave as a uniaxial crystal, with its optic axis parallel to the axes of the rods. In meeting the requirement that the rods be thin, it is equivalent to $d \ll \lambda$ where d is the rod diameter and $\lambda = \lambda_0/\sqrt{\varepsilon_v'}$. Here λ_0 is the free-space wavelength and ε_v' is the relative permittivity of the rod (stalk) material. When the size condition is violated, the loss value obtained may still prove to be a useful estimate, albeit a rough one, of the true loss attributed to stalks.

For a vegetation canopy such as wheat, the stalk diameter d is approximately 0.2 cm, and the volume fraction of the stalks, v_{st}, is typically between 10^{-3} and 10^{-2}. When the stalks are very moist,

$\varepsilon_v' \approx 30$, which means that even at X-band ($\lambda_o = 3$ cm), $d << \lambda$.

A uniaxial crystal is an anisotropic dielectric medium with

$$\vec{\varepsilon} = \hat{x}\,\varepsilon^x + \hat{y}\,\varepsilon^y + \hat{z}\,\varepsilon^z, \tag{3}$$

where $\varepsilon^x = \varepsilon^y$, and the optic axis is along the z-axis. Its properties are such that the horizontal component of an incoming electromagnetic wave propagates through an "ordinary" medium with an associated $\varepsilon_o = \varepsilon^x$, and the vertical component is broken into two waves, namely, an "ordinary" wave, which propagates through the medium with an associated ε_o, and an "extraordinary" wave, which propagates through the medium with an associated $\varepsilon_e = \varepsilon^z$.

Given ε_v and v_{st}, ε^x and ε^z may be computed using the dielectric mixing formulas given by Polder and Van Santen (Ref. 11) for needle-like inclusions. When the host or background medium is air ($\varepsilon = 1$), the expressions for ε^x and ε^z become

$$\varepsilon^x = \varepsilon^y = 1 + 2\,v_{st}\left(\frac{\varepsilon_v - 1}{\varepsilon_v + 1}\right) \tag{4}$$

$$\varepsilon^z = 1 + v_{st}\,(\varepsilon_v - 1). \tag{5}$$

The attenuation coefficient for a horizontally polarized wave is given by

$$\alpha_h = \frac{2\pi}{\lambda_o}\,n_o'', \tag{6}$$

where

$$n_o'' = |\mathrm{Im}\{\sqrt{\varepsilon_o}\}|. \tag{7}$$

Since v_{st} is very small, it can be shown that $\varepsilon_o'' << 1$ and

$$\alpha_h \doteq \frac{\pi}{\lambda_o}\,\varepsilon_o''. \tag{8}$$

For a vertically polarized wave, the attenuation coefficient is

$$\alpha_v = \frac{2\pi}{\lambda_o}\,n_v'' \tag{9}$$

where

$$n_v'' = n_o''\cos^2\theta + n_e''\sin^2\theta \tag{10}$$

with

$$n_e'' = |\mathrm{Im}\{\sqrt{\varepsilon_e}\}|. \tag{11}$$

The expression in (10) is somewhat simpler than the one presented in (Ref. 10), since $\varepsilon_o' \approx \varepsilon_\ell' \approx 1$, and therefore the phase velocities are very nearly equal.

Hence the absorption loss factor for a canopy of stalks of height h is given by

$$L_a^{st}(\theta,v) = \exp(2\,\alpha_v\,h\sec\theta), \tag{12}$$

for vertical polarization and for horizontal polarization it is

$$L_a^{st}(\theta,h) = \exp(2\,\alpha_h\,h\sec\theta). \tag{13}$$

2.4 Application to Experimental Data

As mentioned earlier, the mean stalk attenuation for V polarization at 10.2 GHz was measured to be 30.4 dB m^{-1} with a standard deviation of 12.4 dB m^{-1}. On the basis of the measured plant parameters, a volumetric water content of 35% was computed. Based on measurements of wheat stalks made by Ulaby and Jedlicka (Ref. 8) at 8 GHz, the stalks were found to have a dielectric of 10.81 - j4.53. By applying the mixing formulas reported by Polder and Van Santen for needle-like inclusions comprising a volume fraction of 0.00363, the dielectric along the vertical or z-direction was computed to be 1.036 - j0.01644, whereas the horizontal or x- or y-direction was 1.006 - j0.00042. Based on these values, the model for uniaxial media gives an index of refraction for a vertically polarized wave propagating at an angle of 60° from the optical axis of 1.014 - j0.00611, which corresponds to a one-way attenuation of 21.1 dB m^{-1}. The measured value of 30.4 dB m^{-1} is within one standard deviation (12.4 dB m^{-1}) of the computed value.

2.5. Absorption Loss Factor for Wheat Heads

A similar polarization-dependent attenuation behavior was observed for wheat heads by Lopes (Ref. 13). This again implies a uniaxial-like behavior yielding a larger absorption factor for vertical polarization than for horizontal. The situation is complicated, however, by the fact that the heads are not as uniformly vertical as the stalks. Also their dimensions are larger (relative to λ at X-band), which means that a substantial part of the attenuation may be due to scattering. Accurate measurements have yet to be devised to quantify the latter effect.

Ignoring these added complexities, a computation of the loss due to absorption is possible. The heads may be modeled as prolate spheroids whose major axes are all vertically parallel. The dielectric constant is given by

$$\varepsilon_e = \varepsilon^z = 1 + \frac{v_h\,(\varepsilon_h - 1)}{1 + A_z\,(\varepsilon_h - 1)},$$

$$\varepsilon_o = \varepsilon^x = 1 + \frac{v_h(\varepsilon_h - 1)}{1 + A_x(\varepsilon_h - 1)} \tag{14}$$

where

$$A_z = \frac{1 - e^2}{2\,e^3}\left[\ln\left(\frac{1 + e}{1 - e}\right) - 2e\right] \tag{15}$$

$$A_x = A_y = (1 - A_z)/2 \tag{16}$$

and

$$e = \left[1 - (a/c)^2\right]^{1/2}; \qquad c > a = b, \tag{17}$$

where a and b represent the x- and y-dimensions, and c denotes the z- or vertical dimension. Also, v_h and ϵ_h are the volume fraction and dielectric constant of the inclusion material (heads) and the dielectric of the host medium (air) is 1. Eccentricity, e, is given in terms of the ratio of the minor axes (a or b) to the major axis (c).

In applying these formulas to the 1983 experiment reported earlier, first it is necessary to obtain a value for ϵ_h. Nelson and Stetson (Ref. 10) reported values for the dielectric constant of winter wheat grain as a function of gravimetric moisture (wet basis) up to 24% over a frequency range from 250 Hz to 12.1 GHz. From their findings it is possible to extrapolate a moisture of 45% and to correct for the difference in bulk density using the results given by Nelson (Ref. 15). From this we obtain a value for the head dielectric of 6.92 - j4.74. The ground-truth data permit calculation of the volume fraction, which was found to be 0.01016. Now the only variable left unknown is the eccentricity. Physically, the head measures about 8 cm in length and about 1 cm in diameter, yielding a value for a/c of 1/8. This variety of wheat is characterized by "awns," i.e., it has hairlike fibers extending from the heads in a vertical direction. If we include the awns in the length measurement, then the a/c term is 1/15. Using these two values, we compute values for n_e'' and n_o'' of 0.0169 and 0.0012 for the awnless case and 0.0206 and 0.0011 for the case with awns.

These values, when figured for a frequency of 10.2 GHz and an incidence angle of 60°, yield values of vertical attenuation through an 8-cm layer of heads of 3.86 dB for the awnless case and 4.86 dB for the case with awns. The uniaxial crystal properties have been included in the above calculations. The reported value for measured attenuation is 8.3 dB with a standard deviation of about 3.5 dB. As neither the non-vertical head distribution nor the loss due to scattering has been accounted for, a definite conclusion cannot be drawn.

3. SOYBEAN ATTENUATION EXPERIMENT

A sliding-horn experiment (Ref. 8) was conducted for a fully developed soybean canopy. Figure 3 shows the arrangement of the experiment. The experiment was performed three times to improve the statistical quality of the data. Figure 4 shows the resulting attenuation-versus-position data.

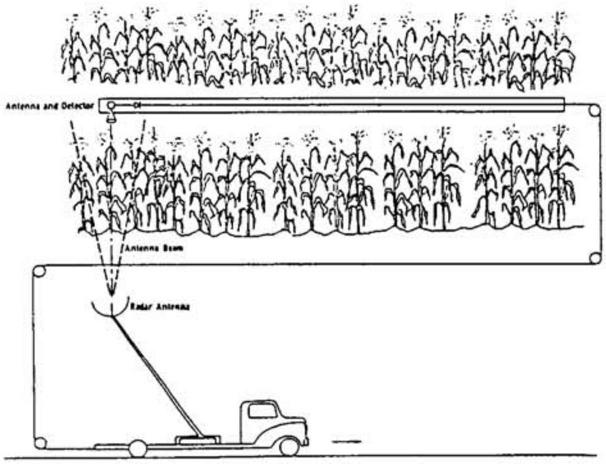

Fig. 3. Plan of the experiment setup for measuring soybean-canopy attenuation by using the sliding-horn technique.

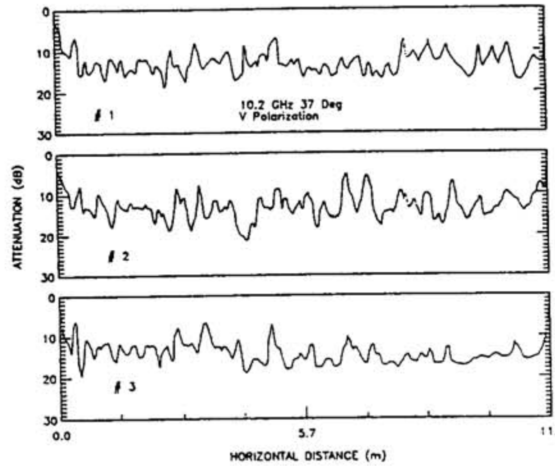

Fig. 4. Measured attenuation through a soybean canopy as a function of position based on three trials.

3.1. Experiment Results

Both the mean and the standard deviation of one-way canopy attenuation were computed for the three trials after excluding 0.5 m from either end due to possible edge effects. These results are shown in Table 1, along with the number of discrete samples or elements into which the data were segmented, and the distance each element represents, as well as the offset needed to correct the raw data. The means for trials 1 and 2 are quite consistent, whereas that for trial 3 is off by about one decibel.

TABLE 1

Sliding Horn - Soybean Data, July 20, 1983
10.2 GHz, 37°, V-Polarization

Trial	Slope Correction (dB)	Total No. of Pixels	Mean Attenuation (dB)	Std. Dev. (dB)	No. of Pixels Used	Pixel Size (cm)
1	5	479	13.2	2.36	438	2.39
2	3	469	13.4	2.89	428	2.44
3	8	448	14.4	2.40	409	2.55
			13.8	2.61	1275	

A plot of a histogram computed for all three trials combined is shown in Figure 5. The distribution is seen to approximate a normal or Gaussian distribution, with a mean of 13.6 dB and a standard deviation of 2.6 dB.

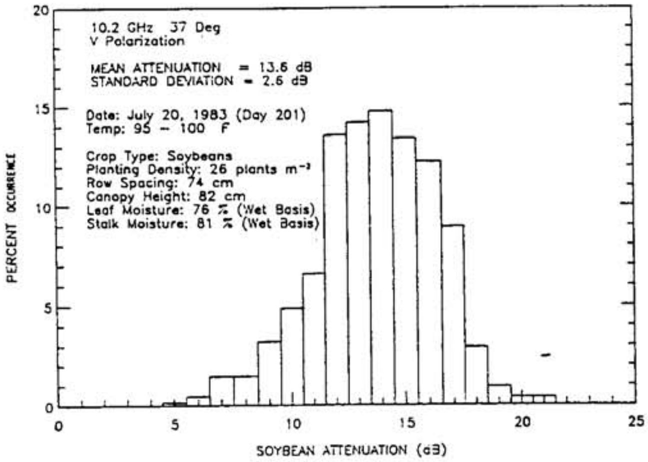

Fig. 5. Histogram of one-way attenuation through the soybean canopy.

3.2 Comparison with Past Results and with the Model

The experiment described above is a repetition of a series of similar measurements made in 1982 at the University of Kansas (Ref. 8). On Day 215, the canopy height was comparable to that used in this report, i.e., about 85 cm, and a one-way attenuation of about 15 dB was reported.

It is assumed that the attenuation follows a secθ behavior, i.e.,

$$\alpha(\theta;\mathrm{dB}) = \alpha(0;\mathrm{dB}) \cdot \sec\theta, \qquad (18)$$

where θ is the incidence angle, and $\alpha(\theta;\mathrm{dB})$ is the attenuation in dB at an angle θ. Using this model, the data obtained at 37° may be computed for an angle of 52°; the result is a one-way attenuation of 17.7 dB. Assuming a standard deviation of about 2.5 dB (from the 37° data) and a comparable standard deviation in the previous data, the measurements agree.

If the vegetation canopy is modeled as a collection of randomly oriented discs (which is a reasonable approximation for a soybean canopy because of leaf shape), then comparison with a theoretical model becomes possible. The equivalent dielectric of such a medium is

$$\varepsilon_m = 1 + \frac{V_v}{3}(\varepsilon_v - 1)(2 + \frac{1}{\varepsilon_v}) \qquad (19)$$

where ε_m is the equivalent dielectric constant of the medium and the subscript v denotes vegetation material.

Jedlicka also reported measurements of ε for corn and wheat leaves as a function of volumetric water content at around 8 GHz. Using values for ε_v reported for corn leaves by Ulaby and Jedlicka (Ref. 8) and a computed volumetric water content of 54%, a dielectric of 20.6 - j9.1 was obtained for the leaves. A volume fraction of the canopy material (leaves and stalks) was computed to be 0.00282. This yields an equivalent dielectric of the medium of 1.038 - j0.01707. From this, the one-way attenuation may be computed using

$$\alpha(\mathrm{dB}) = 2 \cdot 4.34 \cdot \frac{2\pi}{\lambda_0} \cdot n'' \cdot h \sec\theta, \qquad (20)$$

where λ_0 is the free-space wavelength, n" is the imaginary part of the index of refraction, and h is the thickness of the medium. For $n'' = |\mathrm{Im}\sqrt{\varepsilon}|$ = 0.00838, f = 10.2 GHz, and θ = 37°, a one-way attenuation of 15.95 dB is predicted, whereas 13.67 dB is the mean attenuation measured. Again, an uncertainty of the order of ± 2.5 dB is associated with the measurement.

4. CONCLUSIONS

Measurements of the one-way attenuation through canopies of wheat and soybeans were made at 10.2 GHz. These data should supplement those already available for use in modeling backscattering and emission. Theoretical models that estimate the absorption loss factor of the various canopy constituents agree with these data as well as with previously reported attenuation measurements. The attenuation due to scattering was not discussed, yet both the measurements and the models indicate that the absorption is the dominant mechanism of extinction. The geometry of the stalks in a wheat canopy results in a polarization-dependent absorption coefficient that varies by two or more orders of magnitude, depending upon the choice of polarization, frequency, and incidence angle, as well as upon the prevailing canopy conditions. A similar, though less dynamic, behavior was seen in the wheat-head absorption coefficient. Due to the random nature of leaf distribution in the soybean canopy, no polarization dependence was seen.

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