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# Estimation of X-Band Scattering Properties of Tree Components

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**Abstract**—An X-band FM-CW very fine range resolution scatterometer was used to acquire backscattering data for individual branches for a number of tree species. Using a model to describe the scattering source function,  $d\sigma/dR = f(\eta, \kappa)$ , and an experimental procedure for selected removal of plant parts, allows the estimation of  $\eta$ , the volume backscatter coefficient, and  $\kappa$ , the volume extinction coefficient. It is found that 1) leaves are strong attenuators as well as scatterers, 2) the albedo,  $\omega = \eta/\kappa$ , at a given angle of incidence, is nearly independent of the tree type, 3) the tree limbs are good attenuators but rather poor scatterers, and 4) the albedo changes as a function of the angle of incidence and for deciduous trees is also a function of the season.

## I. INTRODUCTION

FOR MORE THAN three decades the focus of microwave measurements on vegetation has been primarily on determining the backscattering coefficient  $\sigma^0$  [1]. Recent new theories [2] of microwave backscattering require a more complete knowledge of the sources within the vegetative canopy that contribute to the backscattered power for their validation. A deeper understanding of the sources of backscattering would also lead to better interpretation of SIR/SAR images. Graf and Rode [3] were the first to use a pulsed radar to study a solitary fir tree to identify the scattering centers. Ulaby *et al.* [4] used a defoliation technique to determine the scattering centers of a row crop. This technique, however, cannot be effectively used in forest canopies, the study of which is gaining emphasis due to the importance of global geochemical cycles, forest damage due to acid rain, pollution, and general deforestation. Because of this increased interest, a number of new measurements using FM-CW radar systems at X-, C-, and L-band have now been reported (Zoughi *et al.* [5], [6], Wu, *et al.* [7], Pitts *et al.* [8], Paris [9], Wu [10], and Sieber [11]). Although the quality of the data collected in most of these measurements has been high, most of these studies have been qualitative.

Recently, Paris [9] and Pitts *et al.* [8] have developed analytical methods to extract the biophysical characteristics of plum and peach trees and aspen canopies, respec-

tively, at C-band frequency. The underlying ideas behind these approaches are somewhat similar but differ significantly in their implementation. The technique used by Paris [9] allows a calculation of only the attenuation properties but can be modified to calculate the backscattering coefficient also. Pitts *et al.* [8] developed an analytic model to describe the backscattering cross section per unit range as a function of slant range when a plane wave penetrates a homogeneous vegetation canopy. The measurement data are inverted using this model to extract the biophysical properties.

This paper presents an analysis of the X-band data collected by Zoughi *et al.* [6] using the model developed by Pitts *et al.* [8] to calculate the volume extinction and backscattering properties of the components of various tree species.

## II. DATA COLLECTION

A very-fine resolution FM-CW radar scatterometer operating at 10 GHz was used to study the backscattering properties of individual branches of pine, pin oak, American sycamore, sugar maple, walnut, and creeping juniper. The details of data collection are given in [5] while the radar scatterometer and its properties are given in detail in the paper by Zoughi *et al.* [6]. For the purpose of this paper it is sufficient to note that the system has a range resolution of 11 cm and a beam radius of 8 cm at a target range of 4 m. The system is thus ideal for studying the properties of canopy components. Measurements were made in succession with the intact branch, removing leaves from the branch, removing small twigs, petioles, and then the main stem. All of the measurements were taken with VV polarization at 30 and 50 degree beam incidence angle with respect to the ground. Each measurement represents a mean of 10 independent data samples. Data were acquired in August 1984 and again in October 1984.

Fig. 1 shows a plot of the volume backscattering coefficient (total scattering cross section per unit volume) as a function of slant range for pin oak at 50-degree incidence angle. The ordinate is expressed in units of decibel referred to 1 mW (i.e., the power is in milliwatts expressed in units of decibel). Two components are clearly seen. The first component, the main peak to the left, is due to vegetation and the second peak is due to the return from the ground.

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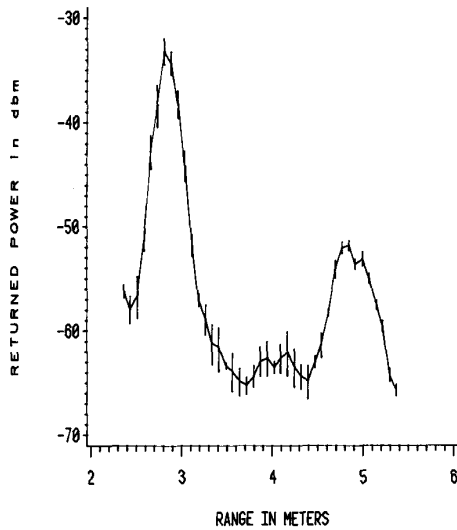


Fig. 1. Power returned (in decibels referred to 1 mW) versus range from an intact Pinoak branch in August at 50 degree angle of incidence.

The radar equation is used to convert decibels referred to 1 mW to radar cross section in square meters.

$$\sigma(m^2) = \frac{P_r(4\pi)^3 R^4}{P_t G_t G_r \lambda^2}$$

where  $P_r$  is the power received in milliwatts ( $10 \exp(x/10)$ ),  $x$  is decibels referred to 1 mW received,  $P_t$  is power transmitted in milliwatts ( $10 \exp(19/10)$  since power transmitted is 19 dbm),  $\lambda$  is  $3.0 \times 10^{-2}$  m for the X-band source, and  $G_r = G_t = 10 \exp(36/10)$  since the antenna gain is 36 db. If one converts these data to the total scattering cross section per unit range,  $d\sigma/dR$ , and plots the data in units of square meter per meter as a function of range, the peaks appear to be sharp and very well separated. The data were visually examined and data past the minimum between the two peaks were rejected to exclude the ground. It is these data that have been used to estimate the volume attenuation and backscattering of the components of vegetation.

### III. ANALYSIS

In an earlier paper Pitts *et al.* [8] developed a source distribution function, defined as the contribution  $d\sigma$  to the total backscattering cross section from an element of range  $dR$  at  $R$ , for a plane wave incident on a homogeneous, plane top, semi-infinite deep canopy. This result is given by

$$\frac{d\sigma}{dR} = 2\eta e^{-2\kappa(R-R_0-r \tan \theta)} \int_{-r}^{x \max} \sqrt{r^2 - x^2} e^{2\kappa x \tan \theta} dx \quad (1)$$

where  $x \max = (R - R_0)/\tan \theta - r$  for  $r < R_0 + 2r \tan \theta$  and  $x \max = r$  otherwise.  $R_0$  is the beam entrance range,  $r$  is the beam radius, and  $\theta$  is the incidence angle measured from the nadir. The parameters  $\eta$  and  $\kappa$  are the volume backscattering and volume attenuation coefficients in units of square meter per cubic meter. The observed data

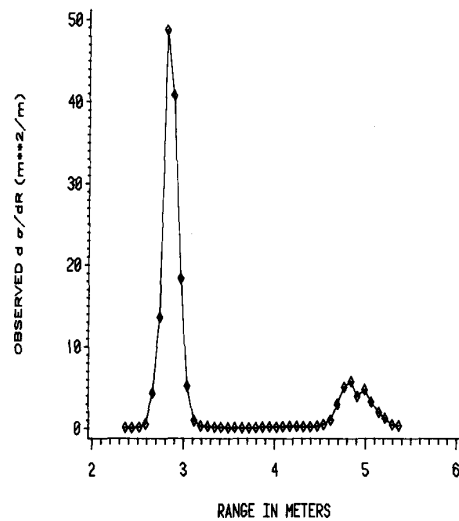


Fig. 2.  $d\sigma/dR$  versus range for an intact Pinoak branch in August at 50 degree angle of incidence.

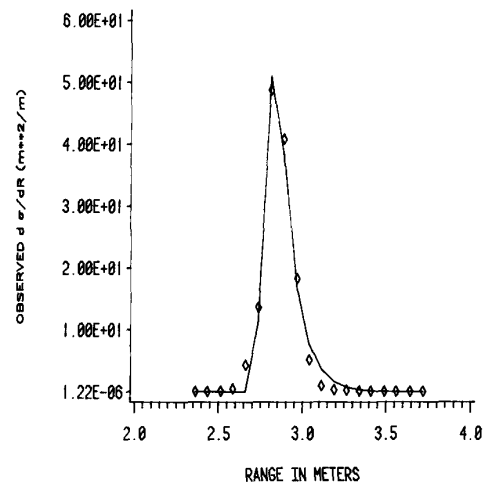


Fig. 3. A fit of the model of (1) to the Pinoak intact branch data (50 degrees August). The solid line is the best fit line to the data points (diamonds).

(Fig. 2) are fitted to (1) plus a noise term by minimizing the mean square error between the calculated  $d\sigma/dR$  from (1) and the observed  $d\sigma/dR$ , using a modification of a technique due to Tyapkin [12]. This provides an objective estimate of the four parameters,  $\eta$ ,  $\kappa$ ,  $R_0$ , and noise and their associated errors. Fig. 3 is a graph of observed data fitted by (1). The squares are observed data points and the solid line is the fitted curve. In the case of sugar maple, sycamore, and creeping juniper the vegetative part of the data clearly showed two or more peaks, indicating the presence of multiple backscatter sources. Equation (1) was then modified to add a second source with a new set of  $\eta$ ,  $\kappa$ , and  $R_0$ . Thus, the model has seven free parameters (see Pitts *et al.* [8]). Fig. 4 shows an example of this fit for the case of juniper. The fit of the model to the observed data is qualitatively good.

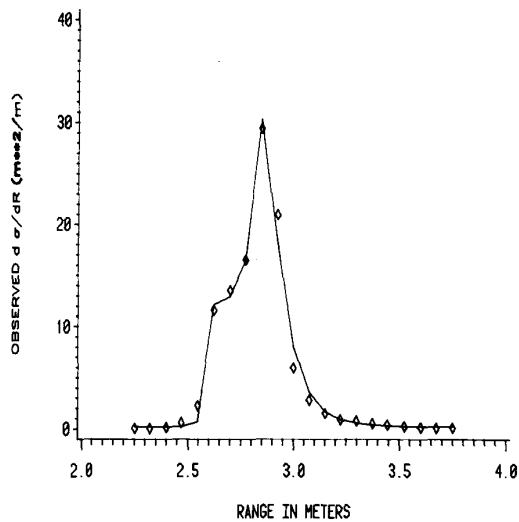


Fig. 4. A fit of the two component model to the Juniper data at 50 degrees in August. The two component model is a slight modification of (1) in which a second source term is added (see [8]).

#### IV. RESULTS

Table I gives the results of the volume attenuation coefficient  $\kappa$ , the volume backscattering coefficient  $\eta$ , and their associated errors  $\sigma_\kappa$  and  $\sigma_\eta$ , for each tree type at incidence angles of 30 and 50 degrees. Although these incidence angles were measured with respect to the ground, it has been assumed that these angles are also with respect to the tree branches. This implies that the tree branches are horizontal. No measurements of the branch angles were taken; however, since these were typically the lowest branches this assumption is likely to be reasonable. The value of  $\eta$  and  $\sigma$  are arbitrarily multiplied by a scale factor of  $10^7$ . It should be noted from this table that the volume extinction coefficient drops by about 30 percent and the scattering coefficient by an order of magnitude once the leaves or needles are removed. This shows leaves to be both strong attenuators and scatterers of this radiation. The leaf size of the deciduous trees is about 5–8 times the wavelength and thus no resonance is expected. An interesting way to look at these data is to make a scatter plot of  $\eta$  versus  $\kappa$  at a fixed angle of incidence and time of year. For a fixed value of albedo,  $\omega = \eta/\kappa$ , independent of branch type, this should be a straight line. Fig. 5 shows such a plot for the August data at 50 degrees. Within the uncertainty, this plot shows that the albedo is nearly independent of the type of branch. Fig. 6 is a plot, similar to that of Fig. 5, at 30 degree angle of incidence. The branches used in this set are not necessarily those used in Fig. 5. This graph shows again that the albedo is approximately a constant, but the line is quite a bit steeper than at 50 degrees. This also shows that the albedo changes significantly as a function of angle. Two points, Juniper2 (B) and Juniper1 (N) do not fall on this line. These points are derived from  $d\sigma/dR$  distributions with two peaks and show a different behavior because they are looking at different objects than the single peak  $d\sigma/dR$  distribution.

TABLE I  
EXTINCTION AND SCATTERING PROPERTIES OF TREE BRANCHES—UV  
POLARIZATION

August ( 30 deg)					
Tree	Condition	$\kappa$	$\sigma_\kappa$	$\eta \times 10^7$	$\sigma_\eta \times 10^7$
Pinoak	branch intact	4.57	0.49	7088	608
Pinoak	rem leaves	3.85	0.71	3349	452
Pinoak	rem 2 sm stems	2.56	0.56	2055	351
Pinoak	rem 2 sm stems	4.37	1.13	3516	676
Pinoak	branch intact	4.53	0.19	20143	582
Pinoak	rem leaves	6.81	23.4	444	1154
Pinoak	rem sm twigs	5.97	8.69	1074	1298
Pinoak	rem sm stems	7.33	6.39	2493	1828
Walnut	branch intact	4.34	1.29	5769	1339
Walnut	rem leaves	3.33	1.99	1860	911
Juniper1	spot 1	7.11	9.89	1072	1311
Juniper2	spot 1	6.32	2.86	3967	1340
Juniper	spot 2	3.09	1.14	1593	505
Juniper	spot 3	3.33	0.70	2758	394
Juniper	spot 4	4.58	0.61	5817	624
Juniper	spot 5	2.92	0.62	2902	444
August ( 50 deg)					
Pinoak	branch intact	6.05	3.83	11192	7841
Pinoak	rem leaves	4.53	31.0	224	984
Pinoak	rem sm twigs	7.13	387.	46	2368
Pinoak	rem sm stems	3.98	273.	16	872
Sugar Maple	branch only	3.69	9.61	2346	2944
Sugar Maple2	branch only	5.90	5.44	4531	1881
Sugar Maple	rem sm twigs	9.27	72.4	1308	8546
Sugar Maple1	rem fruits	2.21	19.3	138	685
Sugar Maple2	rem fruits	8.49	57.0	558	3029
Sycamore1	branch only	2.29	2.14	1473	876
Sycamore2	branch only	6.06	4.37	4131	2058
Sycamore	rem leaves	5.46	4.32	3540	2190
Walnut	branch intact	5.20	3.01	18473	725
Walnut	rem leaves	6.51	33.9	304	1185
Walnut	rem sm twigs	10.3	44.1	523	1656
Juniper	spot 1	6.09	9.56	3627	4609
Juniper	spot 2	3.07	1.14	1590	518
Juniper	spot 3	3.04	1.31	3863	1228
Juniper	spot 4	2.71	2.88	883	643
Juniper1	spot 5	6.52	2.53	4862	1430
Juniper2	spot 5	15.3	19.6	4024	4602
Pine	branch only	8.11	1.11	14880	1685
Pine	rem 5 cones	4.78	1.58	3769	1035
Pine	rem needles	5.52	8.82	747	905
Pine	rem sm stems	4.52	18.3	257	785
October (30 deg)					
Pinoak	branch intact	5.05	6.48	1285	1339
Pinoak	rem leaves	8.85	31.2	1178	3452
Pinoak	rem sm twigs	3.09	9.27	319	696
Pinoak	rem sm stems	7.88	31.3	910	3718
October ( 50 deg)					
Pinoak	branch intact	2.75	1.72	2063	1001
Pinoak	rem leaves	5.71	16.3	957	2335
Pinoak	rem sm twigs	4.48	7.06	831	1087
Pinoak	rem sm stems	2.13	14.9	110	602

Fig. 7 shows the 50-degree data when the leaves were removed. It includes all cases in which not only the leaves but also the small stems and small branches have been removed. For a given branch type, the attenuation decreases by approximately 30 percent but the value of  $\eta$  decreases by a factor of 10, thus reinforcing the fact that the leaves are good scatterers. This is confirmed by examining the data from October when the leaves had fallen from the deciduous trees. It is again quite clear that the scattering coefficients drop off significantly, thus confirming the important role of leaves as both scatterers and attenuators. However, the values of the scattering coefficient  $\eta$  are unusually low compared to agricultural crop canopies. These values are also very low compared to canopy models of Eom and Fung [16].

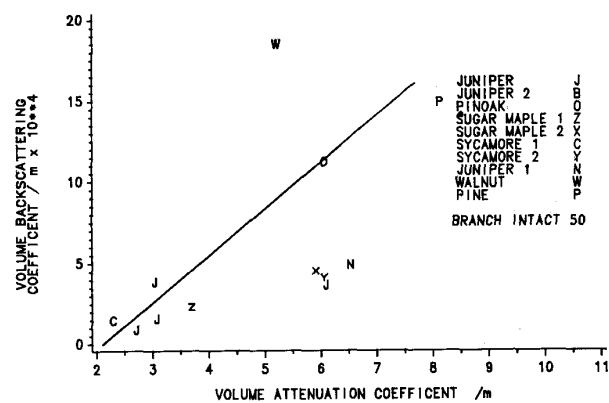


Fig. 5. A scatter plot of  $\eta$  and versus  $\kappa$ . Leaves intact,  $\theta = 50$  degrees in Aug. A line of constant albedo is shown for comparison with the data. The points far removed from the line are points in which the observed  $d\sigma/dR$  distribution had two peaks, indicating two different scattering sources.

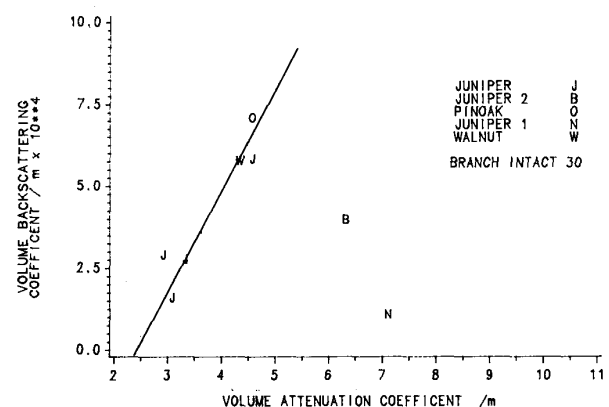


Fig. 6. A scatter plot of  $\eta$  versus  $\kappa$ . Leaves intact,  $\theta = 30$  degrees in August. A line of constant albedo is included for comparison. Both outliers have a two peaked  $d\sigma/dR$ .

Fung [2] has reviewed a number of current theories of microwave scattering as applied to vegetation. However, these models apply to the canopy as a whole and not to a single branch. The model of Brown and Curry [13] was developed using the data of Stutzman *et al.* [14] and some forestry data on the fractional volume occupied by foliage, and fractional volume of moisture in wood [15]. Similarly, the model of Eom and Fung [16] is based on the single leaf scattering phase function but is extended to a canopy by using the doubling method. Thus, the low measured values compared to the models are due to the fact that models are not applicable to individual branches.

In the present experiment, the range resolution is 11 cm and the beam radius is 4 to 8 cm (depending on range). The leaves of the deciduous trees are between 7.5 and 10.6 cm in radius. Thus, on the average, the beam intercepts only one leaf in cross section. From the shape of the  $d\sigma/dR$  versus  $R$  curve (Fig. 2), it can be seen that the total branch thickness is less than approximately 0.5 m. Thus, these data do not represent canopy data. This might explain why the value of single scattering albedo is more

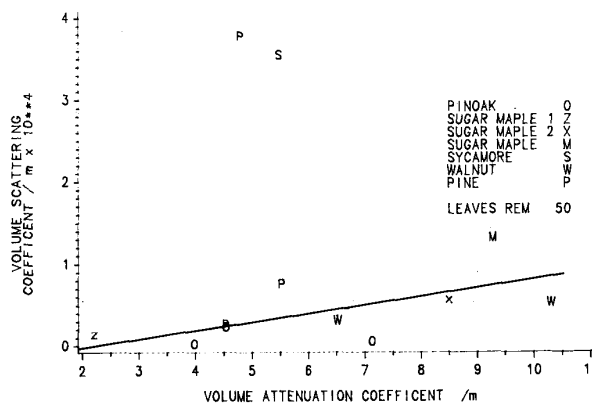


Fig. 7. A scatter plot of  $\eta$  versus  $\kappa$ . Leaves removed,  $\theta = 50$  degrees in August. A line of constant albedo is shown for comparison with the data. The outliers again come from observed  $d\sigma/dR$  two peaked distributions.

like that of a single leaf and so much lower than crop canopies at similar wavelength [17]. Thus, care must be exercised in comparing these values to those of a model canopy. These results should instead be used for single leaf or branches only.

### V. CONCLUSIONS

Data from a very fine resolution X-band FM-CW radar on branches of various tree types have been analyzed to extract the two biophysical parameters of volume extinction and scattering coefficients. It is found that 1) leaves are both good attenuators as well as scatterers of X-band radiation, 2) the albedo from the branches with leaves changes significantly as a function of the incidence angle, 3) the albedo from these branches is significantly lower than the albedo observed in agricultural crop canopies, and 4) these results can be understood if one imagines that because of the very fine range and spatial resolution one is typically sampling a single leaf and not the branch or tree as a whole.

### ACKNOWLEDGMENT

We would like to thank Professor A. Fung of the University of Texas at Arlington for discussions about the use of his canopy model and the results of this analysis.

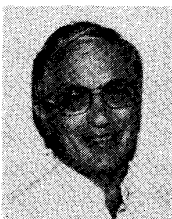
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**Gautam D. Badhwar** received the Ph.D. degree in physics from the University of Rochester, Rochester, NY, in 1967.

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His current research includes investigations of the effects of atmospheric degradation on remotely sensed optical imagery and derivation of physical models associated with the observation of key agricultural and forest canopy characteristics from remotely sensed data. Previous activities include participation in studies of space plasmas,

measurements of chlorine in the upper atmosphere, and analysis of dynamic topography of the Antarctic circumpolar current utilizing remotely sensed data.

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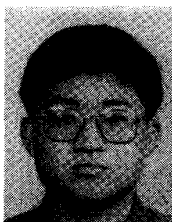


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From 1981 until 1987, he was employed by the Radar Systems and Remote Sensing Laboratory at the University of Kansas in various capacities. He served as a graduate research assistant until 1983, and as an assistant project engineer until 1987. He has been involved in radar remote-sensing research in the areas of geology (lithology) and de-

termination of backscattering sources in various types of vegetation canopies (crops and trees) and surface targets. Since August 1987, he has been with the Electrical Engineering Department at Colorado State University as an assistant professor.

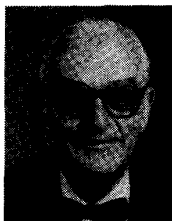
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He has worked at RCA Victor, Washington University, and Cornell University. From 1951 to 1955 he was Research Engineer—Section Supervisor at Sandia Corporation, working in radar backscatter. From 1955 to 1962 he was Professor and Chairman of the Electrical Engineering department at The University of New Mexico, where he also did research in radar backscatter and sub-

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Professor Moore is past chairman of Commission F of USNC of URSI, and a member of ASEE, ASP, AAAAS and AAUP. He received the 1978 Outstanding Technical Achievement Award from the IEEE Council on Oceanic Engineering. He also was the recipient of the 1978 Alumni Achievement Award, presented by the School of Engineering and Applied Sciences of Washington University in St. Louis, Missouri. He has also been awarded the IEEE Geoscience and Remote Sensing Society Distinguished Achievement Award for 1982, the IEEE Centennial Award in 1984, and the Louise E. Byrd Graduate Educator Award from the University of Kansas in 1984. He has served in various capacities for professional societies.