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# EFFECT OF SPECIES STRUCTURE AND DIELECTRIC CONSTANT ON C-BAND FOREST BACKSCATTER

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## ABSTRACT

A joint experiment between Canadian and USA research teams was conducted early in October, 1992 to determine the effect of species structure and dielectric variations on forest backscatter. Two stands, one red pine and one jack pine, in the Petawawa National Forestry Institute (PNFI) were utilized for the experiment. Extensive tree architecture measurements had been taken by the Canada Centre for Remote Sensing (CCRS) several months earlier by employing a Total Station surveying instrument which provides detailed information on branch structure. A second part of the experiment consisted of cutting down several trees and using dielectric probes to measure branch and needle permittivity values at both sites.

The dielectric and the tree geometry data have been used in the George Washington University (GWU) Vegetation Model to determine the C band backscattering coefficients of the individual stands for VV polarization. The model results show that backscatter at C band comes mainly from the needles and small branches and the upper portion of the trunks acts only as an attenuator. The paper will conclude with a discussion of variation of backscatter with specie structure and how dielectric variations in needles for both species may affect the total backscatter returns.

Keywords: Forest, backscattering, microwave.

## INTRODUCTION

A joint experiment between Canadian and USA research teams was conducted late in September, 1992 to determine the effect of species structure and dielectric constant on forest radar backscatter. Two stands, one red pine and one jack pine, in the Petawawa National Forestry Institute (PNFI) were utilized for the experiment. C and X band data was obtained from over-flights by the CCRS airborne SAR and measurements were made of tree architecture and branch and needle dielectric constants. This data was then used in the GWU vegetation model so that model and measurement results could be compared.

The two test sites were located inside the PNFI research forest which is centered at 46°00'N, 77°25'W, near Chalk River, Ontario, Canada. Both test sites were characteristic of plantation stands having even age trees which were planted on flat ground in a regular fashion. The red pine stand (*Pinus resinosa*), which has an extent of 4.0 hectares, consisted of 58 year old trees with an average diameter at breast height (dbh) of 23.5 cm and a height of 21 m. The jack pine stand (*Pinus banksiana*) consisted of 26 years old trees which had an average dbh of 20 cm and a height of 15 m;

they covered a 3.5 hectare area. The previous July (1992), as part of an optical experiment, careful architectural measurements using a vectorization technique were made of three trees in each stand. At the time of the over-flights dielectric measurements of branches and needles were made at C and X bands by using Applied Microwave portable dielectric meter with tree probes. The CCRS airborne SAR flew over the sites on September 25 and 26, 1992. The flights were coordinated with calibration test flights CCRS was performing and thus corner reflectors and active radar calibrators (ARCs) were in place for calibration purposes. On September 25th like and cross polarized data was obtained at C (5.3 GHz) and X (9.25 GHz) band for several angles of incidence. On the following day, polarimetric data was collected at C band. The weather at the time of both over-flights was clear and dry. In the present paper only C band VV polarized data will be employed.

Several researchers have been interested in tree structure and dielectric constant as a mechanism for using radar to classify trees by specie. In the literature there is some evidence that such differences exist. Leckie[1], using CCRS C and X band SAR data has demonstrated that measurable differences exist between backscatter values for different tree types in the PNFI forest. Dobson, et al[2], employing JPL SAR P, L and C band measurements made in North Michigan, has shown that both deciduous and conifer stands have discernible backscatter differences over the spring to summer time-frame. Lang, et al[3] has shown how the long straight crunks of the red pine are partially responsible for the bright returns observed at P band. Salas, et al[4] and McDonald, et al[5] have demonstrated how the dielectric constant in the active xylem responses to water conditions in the tree. These changes in dielectric constant in the outer sapwood may effect backscatter values particularly at C and X bands where the penetration of electromagnetic waves is small.

## TREE ARCHITECTURE MEASUREMENTS

Tree architecture data was collected using a new technique called "Tree Vectorization" developed at the Canada Centre for Remote Sensing. The method was developed to characterize tree architecture from a restricted data sample and to use this sample to reconstruct a statistically accurate 3-dimensional representation of the tree, Landry, et al [6]. The methodology can be used for tree and forest canopy modeling research in both microwave and optical part of the E.M. spectrum.

The vectorization method involves data collection at three different levels: the trunk inventory, the branching structure, and the foliage data collection. Each has a specific methodology and provides a separate set of data. The spatial distribution of the supporting or the primary branches, is characterized through the trunk inventory. The branch structure is specified by a vectorized sampling method, and concurrently, foliage data is recorded for individual branch components. Finally, the information, which is collected at all levels, is combined at the final stage and used for tree reconstruction.

Briefly, the sampling strategy proceeds by first making a trunk inventory. The spatial distribution of all major branches that leave the trunk along with their diameter and elevation angle are recorded. The branch structure is defined by sampling a sufficient number of primary branches to get a representative variation of the branch structure along the tree height axis.

The structure of these selected branches is characterized in terms of branch segments. Each segment corresponds to that portion of the branch between two branch nodes or ramification points. A selected number of connected branch segments or paths are designated for sampling and the spatial location of each segment's nodes is recorded using a survey instrument (Wild TC1000 Total Station). The precision of this instrument is more than adequate for these purposes since it is within 3 mm in a 2 km range, and within 3 seconds of arc in horizontal and vertical angles. Each sampled segment is tagged and attributes such as segment number, connecting segment numbers, diameter and foliage information are recorded.

From the sampled branch information and the trunk inventory, the 3 dimensional architecture of the complete tree can be reconstructed. The reconstruction is not exact since similarity principles are employed to reconstruct whole branches from the sampled portions. The reconstructed branches are then used to represent other primary branches on the trunk that were not selected for sampling. In this way an approximate representation of the tree in terms of segments whose coordinates are known is obtained. The method is discussed in more detail in Landry [6].

The vectorized sampling and reconstruction technique has been used to model one typical tree in the red pine stand and one in the jack pine stand. From the reconstructed trees, segment data has been used to determine branch paths. Since the segments in each branch are not necessarily collinear, the reconstructed branches are, in general, curved. Since branches used in the scattering model are cylinders, the reconstructed branches were replaced by cylinders that have the mean diameter and the mean elevation angle of the reconstructed branch. These averages are defined by weighting each segment's diameter or elevation angle by its length. These mean branches or cylinders are then classified into size categories based on their diameter and branch length distributions; these distributions are determined from all the reconstructed branches in the tree. The branch classes are listed in Table 2. A twig class has been created since twigs don't usually occur at nodes and thus must be treated specially. Also, the branch class 0 tends to reflect the terminal segments found in the tree. The terminal segment class and twig class have similar statistics in terms of mean diameter and length.

The probability density functions of branch

length, mean branch diameter and mean branch elevation angle and the density of branches per cubic meter were derived for each branch class. The number of needles was calculated by using the information collected per segment (total length of segment with needles, percentage of needles and number of needles per unit of length), and then, by summing segment values over the whole tree.

#### DIELECTRIC CONSTANT MEASUREMENTS

Detailed measurements of the dielectric constant for a red pine and a jack pine tree were made using a dielectric probe. The use of a dielectric probe to obtain dielectric constant values was preferred over the empirical approach used by the authors in the past since the probe measures the dielectric constant directly. The empirical approach estimates the dielectric constant and this estimate is primarily dependent upon moisture contents of the vegetation. Important electromagnetic parameters, such as ionic conductivity is usually assumed to be the same for all parts of a tree. The aim of the probe measurements, in the present experiment, was to investigate: 1) differences in the dielectric constants of different species, 2) differences in the dielectric constant in the same species. At the time of the experiment, it was thought that at C band, the trunk of a tree is less important than the crown. Therefore, the dielectric constant measurements were limited to the branches and the needles only. The measurements on branches were done in the fields, whereas, the clusters of needles were sealed in plastic bags and their dielectric constant was measured in the laboratory.

The live crown of a red pine and a jack pine tree was divided into three segments. A typical branch from each segment was selected. The branch was cut into three parts. To study the differences in dielectric constant as a function of depth inside a branch, the cross-section of a branch was divided into three annular regions. The region just beneath the bark was called outer region. The center part, looking into the cross-section of branch was called inner region. The remaining area between the outer and inner regions was called middle region. Probe measurements across the cross-section of a branch segment were taken in each of the regions. It was found that values for the center and middle regions were of the same order. As a result, the center region was expanded to encompass the middle region to simplify the discussion. Fig. 1 shows a typical branch cross section with the two regions labeled. The outer region has a width  $L_{out}$  while the radius of the center region is  $L_{ct}$ .

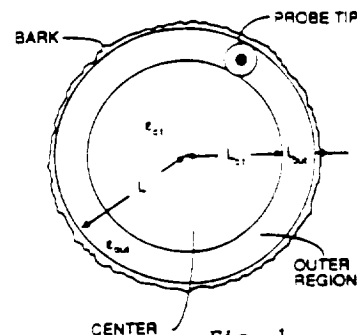


Fig. 1  
Dielectric measurements over the cross-section of a branch

As an illustration, the real part of the measured dielectric values from a red pine tree for the center and outer regions are plotted in Fig. 2. The imaginary part is found to follow the same trend, and therefore is not shown in the figure. The differences in the dielectric constant (both real and imaginary parts) between the outer and center regions exist for branches of all diameters. The high values of dielectric constant that are observed in the outer region are most likely due to sap and water transport layers that exist there. The region has a thickness,  $L_{out}$ , of .3mm. This thickness is determined by the probe tip width. It should be noted from Fig. 2 that the outer and center dielectric appear to converge as the diameter of the branch becomes smaller. This is because the minimum resolution of the probe tip makes it increasingly difficult to resolve outer and center regions for small branch diameters. It should be mentioned here that the data from all segments of the tree are merged together to obtain Fig. 2.

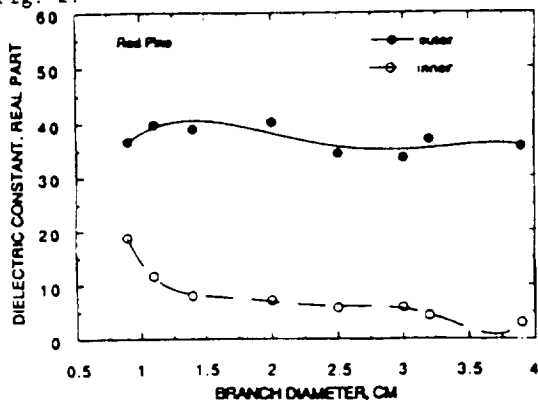


Fig. 2  
Dielectric variations with branch diameter

In order to measure the dielectric constant of needles, a hose clamp was used to bundle the needles tightly together. The clamp was squeezed so as to remove the air gaps among the needles. Care was taken not to crush the needles by over-squeezing the clamp. The bundle was cut in half to obtain a flat face of the needles. A mean of five probe readings taken across the cross-section of the bundle was used to specify the dielectric constant of the needles. Four bundles of needles were used for dielectric constant measurements.

TABLE 1  
Comparison of Mean Values of Real and Imaginary Part of Dielectric Constant

| Scatterer Type | Red Pine               | Jack Pine    |
|----------------|------------------------|--------------|
| Branch         | Center (16.7, 3.9)     | (3.8, 2.0)   |
|                | Outermost (37.1, 16.7) | (25.3, 10.5) |
| Needles        | (13.4, 5.4)            | (13.3, 5.6)  |

It took 4 days to complete dielectric constant measurements. The measurements for branches of a red pine tree were made mostly during the mornings and the jack pine data were collected in the afternoon. The calibration accuracy of the probe was checked periodically by using standard liquids such as butanol, ethanol, methanol, formamide, etc. Table 1 summarizes

average results from branches and needles for red pine and jack pine trees. The species difference are clearly noticed in the case of branches, while, for needles such differences are not found. We also determined wet and dry weights of the branch segments and the needles. The moisture contents were determined from this data for both species. No significant differences in moisture contents were discovered between the red pine and jack pine trees.

#### FOREST MODEL

The forest is modeled as a two layered random medium with a rough surface beneath. The tree components such as branches, needles, and trunks are distributed in the medium according to their measured orientation statistics. The distorted Born Approximation is used to compute the total backscattering coefficient,  $\sigma_{\theta}^0$ , for the forest.

The total return can be expressed as a sum of the direct, direct-reflected and surface backscatter terms; however at C band the main contribution is observed to be from the direct term only. The geometric parameters of the forest medium; such as density, scatterer sizes and orientations are obtained from the tree vectorization data. For modeling purposes, the small size branches and the twigs of the vectorization method were classified as secondary, and the branches which were larger were named as primary. The probability density function for the needles for both red pine and jack pine stands were chosen as  $\sin 2\theta$ , for  $0 \leq \theta \leq 90$  degrees. The secondary and primary branches for these stands were assigned uniform distributions whose end points were estimated from the vectorized data.

The dielectric measurements were made for the outer and center parts of the branches, as seen in Fig. 1. The data for these regions was used to determine the dielectric constant of an equivalent, homogeneous branch of the same size. As seen in Fig. 1, the outer part of the branch, which has the highest dielectric value is assumed to be as thick as the probe tip. The thickness of the center and outer parts are denoted by  $L_{ct}$  and  $L_{out}$  respectively.  $\epsilon_{ct}$  and  $\epsilon_{out}$  represent the dielectric constants for these regions and are determined from the measurements. An average dielectric value,  $\epsilon_{av}$  for an equivalent branch of the same size is then calculated by using

$$k n_{av} L = k n_{out} L_{out} + k n_{ct} L_{ct} \quad (1)$$

where  $n$  is the refractive index and is given by the square root of the dielectric constant. The right hand side of Eq. (1) represents the complex phase from the branch surface to its center. This is equated to the complex phase for a homogeneous branch of permittivity  $\epsilon_{av}$ . It should be noted

that this approach will be valid only for the cases when the skin depth exceeds  $L$ . As the skin depth gets smaller, the dielectric constant should approach the dielectric value of the outer part. However, Eq. (1) will not differentiate between these cases and will underestimate the average permittivity when the skin depth is less than  $L$ . Table 2 below summarizes the values for the model parameters for red pine and jack pine stands as derived from the vectorized geometric data and Eq. (1). The trunk layer has been excluded since at C band backscattering coefficient originates mainly from the tree crown.

TABLE 2  
Model Parameters for Red Pine and Jack Pine Trees

| Red Pine   |       |             |           |                             |                 |
|------------|-------|-------------|-----------|-----------------------------|-----------------|
| Scat. Type | Kind  | Length (cm) | Rad. (cm) | Density (#/m <sup>3</sup> ) | $\epsilon_{av}$ |
| NEEDLE     |       | 10.30       | 0.06      | 7786.0                      | 1.4-15.4        |
| SEC. BR.   | twig  | 4.20        | 0.32      | 9.13                        | 6.7-115.3       |
|            | br. 0 | 19.30       | 0.33      | 6.13                        | 6.7-115.3       |
|            | br. 1 | 26.50       | 0.47      | 9.48                        | 6.7-112.2       |
| PRI. BR.   | br. 2 | 105.50      | 0.75      | 0.30                        | 6.2-17.3        |
|            | br. 3 | 234.00      | 1.05      | 0.38                        | 13.5-16.6       |
| Jack Pine  |       |             |           |                             |                 |
| Scat. Type | Kind  | Length (cm) | Rad. (cm) | Density (#/m <sup>3</sup> ) | $\epsilon_{av}$ |
| NEEDLE     |       | 3.10        | 0.05      | 39360.0                     | 13.4-15.6       |
| SEC. BR.   | twig  | 7.35        | 0.14      | 50.9                        | 25.0-110.0      |
|            | br. 0 | 8.29        | 0.10      | 91.80                       | 25.0-110.0      |
|            | br. 1 | 19.00       | 0.14      | 70.10                       | 25.0-110.0      |
| PRI. BR.   | br. 2 | 32.10       | 0.24      | 27.50                       | 25.0-110.0      |
|            | br. 3 | 53.00       | 0.38      | 2.11                        | 20.0-18.0       |
|            | br. 4 | 172.50      | 0.68      | 1.55                        | 13.0-16.0       |

### RESULTS AND DISCUSSION

In this section the attenuation and backscatter predictions of the GWU Vegetation Model for both red pine and jack pine stands will be examined. Also, the reasons for different backscatter returns for these species and their sensitivity to dielectric variations will be analyzed. The discussions will involve VV polarization only.

Using the parameters given in Table 2, the attenuation due to each scatterer type in both red pine and jack pine stands have been estimated. As it can be seen from Table 3, the main factor causing attenuation in the red pine forest is the needles; whereas for the jack pine both needles and the primary branches play an equally important role.

TABLE 3  
Total Incoming Attenuation (dB)  
for VV Polarization

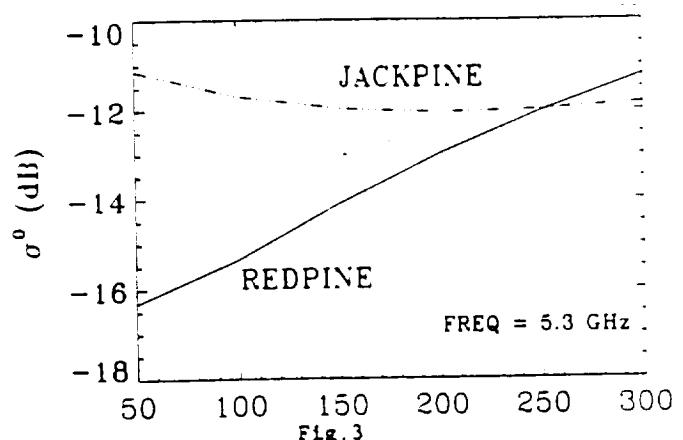
| Scat. Type | Jack Pine | Red Pine |
|------------|-----------|----------|
| NEEDLE     | 5.68      | 6.90     |
| SEC. BR.   | 3.48      | 3.00     |
| PRI. BR.   | 5.73      | 1.46     |
| Total      | 14.89     | 11.36    |

The model predictions for the backscatter coefficients for each of these species is given in Table 4. If the individual returns for each of the scatterer components are compared, one can observe that the major contribution in the red pine stand is obtained from the needles; whereas for the jack pine forest it is the secondary branches that give the highest returns. The fact that the needles have the highest return in the red pine stand can be explained by the low density of the secondary branches, and also by long needles. On the other hand; the density of the secondary branches in jack pine is much higher compared to the red pine and thus their contribution to backscattering coefficient can surpass that of needles which are very small in size.

The sensitivity of the backscatter returns to the dielectric constant of needles is examined in Fig. 3. One can observe the variations in the total backscattering coefficient as the dielectric constant of the needles for both red pine and jack pine stands is varied from 50 to 300 of their nominal values, given in Table 2. It is seen that the red pine returns increase by as much as 5 dB, while the response from the jack pine stays almost constant.

TABLE 4  
Backscatter Coefficient (dB) for VV Polarization

| Kind     |       | Red Pine | Jack Pine |
|----------|-------|----------|-----------|
| NEEDLE   |       | -17.99   | -22.58    |
| SEC. BR. | twig  | -32.93   | -23.44    |
|          | br. 0 | -25.98   | -22.86    |
|          | br. 1 | -26.68   | -15.32    |
| PRI. BR. | br. 2 | -36.76   | -18.77    |
|          | br. 3 | -20.95   | -38.54    |
|          | br. 4 | *****    | -20.04    |
| Total    |       | -15.33   | -11.68    |
| Measured |       | -13.55   | -12.07    |



Ratio of the change in the dielectric constant from the nominal value (%)

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