Temporal and Spatial Variations in Dielectric Constant and Water Status of Dominant Forest Species from New England

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Temporal and spatial characteristics of microwave dielectric properties and water status of several forest species were investigated during the 1990 and 1991 growing seasons as part of the NASA FED MAC. Data presented were acquired from Durham, New Hampshire (white pine, eastern hemlock, and American beech), and Howland, Maine (eastern hemlock and red spruce). Dielectric properties of trunk wood were measured using C-band, L-band, and P-band dielectric probes. For the Durham specimens, electrical resistance was measured using a digital ohmmeter. Water status of the trees studied was determined either by use of a Scholander pressure bomb on branch samples or by fresh weight/dry weight assessment of wood core samples. Results indicate the following:

1) Radial dielectric profiles matched the regions of the functional sapwood such that the sapwood was characterized by a higher dielectric than the bark and heartwood tissues. 2) A hysteresis exists between diurnal variations in branch water potential and trunk sapwood dielectric. 3) The dielectric properties were positively correlated with wood core moisture content, while the electrical resistance was poorly correlated with moisture content. 4) Using categories of electrical resistance measurements as a qualitative assessment of relative ion concentrations, the dielectric measurements were not sensitive to the different ion concentrations within the xylem and phloem exudate. These results support the view that dielectric properties are strongly correlated with moisture status in trunk wood and that diurnal variations in dielectric are related to diurnal fluctuations in water potential. The lag between changes in branch water potential and trunk dielectric varies, depending on the structure, evaporative demand, and water storage capacity of the sapwood.

INTRODUCTION

One of the main goals of the Forest Ecosystem Dynamics (FED) project is to determine what forest biophysical parameters can be extracted from remotely sensed observations. These parameters can then be used in forest ecosystem models to enhance our understanding of how the northern hardwood transitional and boreal forests may be altered by global climate change (Levine et al., 1992). Vegetation water content is a key factor in determining how the forest energy balance will respond to climate change. Visible reflectance and thermal emittance data have been correlated to leaf water status, but extrapolation to canopy scale has met with little success due to canopy architecture and intercanopy shading (Weber and Ustin, 1991). However, since radar backscatter is not dependent on solar illumination effects, and water has a high dielectric, which, in turn, influences backscatter properties, microwave remote sensing may be used to monitor water status in forest canopies.

With the launch of several synthetic aperture radar (SAR) satellite systems during the early and mid-1990s, researchers will be able to analyze long-term microwave data sets covering boreal and northern hardwood transitional forests. However, prior to using the data for seasonal and interannual analyses, the effect of diurnal variations in trunk and canopy water status on radar backscatter needs to be examined. Since radar backscat-
ter is dependent on the target's geometric and dielectric properties, the relation between a tree's biophysical characteristics such as moisture content and its dielectric properties must be well understood in order to relate the radar backscatter with vegetation moisture content. It is especially important to investigate the diurnal changes in dielectric properties at the lower radar frequencies (longer wavelengths) because longer wavelengths penetrate vegetation more (Brisco et al., 1990), and, hence, could provide more information about the canopy, branches, and trunks of the forest stands.

As part of the FED project, P-band (440 MHz), L-band (1.25 GHz), and C-band (5.3 GHz) dielectric properties and water potential (Ψ) of eastern hemlock (Tsuga canadensis) and red spruce (Picea rubens) was investigated in July and September 1990 and June 1991. Pyrometer, temperature, and relative humidity measurements were also acquired during the July investigation. These in situ measurements were made as part of the NASA Multisensor Aircraft Campaign (MAC) conducted at International Paper’s (IP) Northern Experimental Forest (NEF) near Howland, Maine. The dielectric and water potential measurements were taken in support of several NASA AIRSAR overflights. Additional C-band dielectric and water potential, as well as electrical resistance and moisture content, measurements were taken on cores from eastern hemlock, white pine, and American beech at the University of New Hampshire’s College Woods in Durham, New Hampshire during September 1991. The Durham field work was performed as a follow-up to the Howland, Maine FED MAC exercise with the intent of assessing the effect of varying ion concentrations of the wood moisture on the dielectric measurements. In this article, we report our experimental findings of the relationships between tree water status (e.g., xylem water column tension or wood moisture content) and tree electrical properties (e.g., real and imaginary relative dielectric constant and electrical resistance).

BACKGROUND

Electrical Properties of Vegetation

The dielectric constant is a measure of a substance’s ability to store and conduct electrical energy and is represented as a complex number, $\varepsilon = \varepsilon’ - j\varepsilon''$. As water is a strong conductor (high dielectric) and the remaining constituents of vegetation are poor conductors with near-unity relative permittivity, the dielectric property of vegetation is dominated by water content. Trees exhibit diurnal variations in their water content due to transpiration water loss and subsequent recovery. Consequently, the dielectric properties of the water conduct- ing tissues may exhibit a similar diurnal profile due to water's high dielectric constant. Several studies have examined this relationship for conifer and deciduous species. Salas et al. (1991) and Ranson et al. (1992) presented preliminary results of this work relating water potential and dielectric properties of red spruce and eastern hemlock sapwood. Way et al. (1991) and Weber and Ustin (1991) measured large diurnal variations in the dielectric properties in the trunks of black walnut as well as diurnal variations in the microwave backscatter from the walnut orchard. Dobson et al. (1991) also measured diurnal variations in the dielectric constant of loblolly pine trunks. The daily minimum in dielectric occurred near midday, at the peak of the transpirational water loss period. McDonald et al. (1991) recorded X-band and L-band backscatter measurements that varied with changes in canopy moisture, so it appeared that truck-mounted scatterometer responses matched the in situ dielectric and water potential measurements. McDonald et al. (1992) concluded that the dielectric in the tree bole responded directly with changes in leaf water potential for pine, cedar, eucalyptus, sweetgum, and oak.

Several studies have investigated the relationship between electrical resistance, water potential, and water content. Dixon et al. (1977) demonstrated that electrical resistance was correlated to water potential in white spruce (Picea glauca). Electrical resistance has also been used to detect and monitor stages of decay in red spruce and balsam fir (Abies balsamea) by Shortle and Smith (1987). Electrical resistance of wood in living trees depends on water content, temperature, and mobile ion concentration. However, above the fiber saturation point in moisture content and at stable temperatures, variation in electrical resistance is mainly due to ion concentration (Shigo and Shortle, 1986). As sapwood and heartwood in living trees are commonly above fiber saturation point, correlating resistance and dielectric constant may provide insight regarding the sensitivity of dielectric measurements to ion concentrations.

Water Movement in Trees

Vegetation structure dictates how water moves through the soil-plant-atmosphere continuum under given environmental conditions. Hence, there can be significant differences in diurnal and seasonal water fluxes through forest canopies containing mixed species. Diurnal changes in water potential and water content in leaves, branches, and stems are due to evaporation into submatal cavities, followed by a replenishment of water from branches and stems. The rate of change in water content depends on evaporative demand (vapor pressure deficit) and the branch and stem storage capacities (Gates, 1991). Trees use three mechanisms for storage of water: elastic storage, capillary storage, and "cavitation.
release” (Tyree and Yang, 1990). Leaf water potential typically reaches a minimum after midday due to moisture evaporation through the open stomata. At this point there is a decreasing water potential gradient from the roots to the leaves. Hinckley et al. (1978) reviewed research on water potential and water content for different tissues of conifers and hardwoods. They discussed the lag in changes of water content from the leaves to the roots due to differences in water potential propagating through the conducting sapwood. Vessel elements found in the sapwood of hardwoods have greater conductivities than the smaller trachieds found in conifers. In addition, conifer and hardwood sapwood have different capacitances and potential transpirational supplies, causing the lag in changes of water content to be longer for conifers than hardwoods (Hinckley et al., 1978). Schulze et al. (1985) measured a 2–3 h lag between transpirational water loss at the leaves and water flow through the stems of larch (Larix) and spruce, Brough et al. (1986) found essentially no lag between decreasing water potential and xylem water content for apple trees.

MATERIALS AND METHODS

The NEF is an ideal site to examine the value of microwave data for distinguishing forest stand characteristics due to the wide range in stand size, age, composition, and shape. The NEF is a 7000 ha site located 56 km north of Bangor, Maine near Howland, Maine (45°12'N, 68°44'W). The topography within the NEF is flat to gently rolling with a total elevation range of 67 m. This research forest contains a combination of small plantations and larger areas of natural regeneration. There are three major forest types in the natural regeneration areas: mixed hardwoods (aspen, birch), hemlock–spruce–fir, and hemlock-mixed hardwoods. The measurements from July 1990 and June 1991 were taken from a hemlock stand (hemlock-mixed hardwoods area), whereas the September 1990 measurements were taken near a sensor calibration site (hemlock–spruce–fir area). The majority of the soils are glacial till that vary from well to poorly drained and are closely related to specific forest types. These soil drainage characteristics change over small spatial patterns, causing the forest stands to be variable in type, size, and areal shape.

The college woods is a 98 ha managed site located at the University of New Hampshire and used for research, education, and recreation. The majority of the area is natural regeneration with mixed hardwood and hemlock–white pine stands. There is also a large stand of old growth white pine. The important soil groups contain rocky sandy loam, silt loam, and loamy sand and clay soils. Our measurements were taken in a hemlock–white pine stand and a mixed hardwood stand with Hollis–Charlton rocky sand loam soil.

Water potential measurements were made by placing branch samples in a Scholander pressure bomb (PB) as described by Tyree et al. (1973). Pruning poles were used to cut the branches from the midcanopy. PB readings were taken from 7 a.m. until 4:30 p.m. at approximately 30-min intervals. PB measurements were performed on two to three branch samples to ensure accuracy.

The relative dielectric constant measurements were made using portable dielectric probes (PDPs) developed by Applied Microwave Corporation. These probes consist of a control box attached to an RF unit. The control box uses a battery, calculator, and other electronics to interface and process the microwave signal sent from the RF unit. The RF unit contains the microwave electronics and a coaxial cable that attaches to the probe tip. The probe tip must be in full contact with the surface to be measured in order to ensure an accurate measurement. The probe calculates the dielectric constant by measuring the change in impedance of the capacitor (open-ended coaxial cable) in contact with the test material. The magnitude and phase of the reflection coefficient are measured and used with calibration factors to determine the relative dielectric constant. The magnitude of the calibration factor is derived by a least squares regression of measured reflection coefficients from known dielectrics. The phase calibration factor is determined by open circuit and short circuit measurements. A detailed explanation of the portable dielectric probes function is given in the manual for the portable dielectric probe (Applied Microwave Corporation, 1989).

The internal calibration of the P-band probe was checked by comparing the measured dielectric constants of several materials with known dielectrics. Water, ethylene glycol, methanol, carbon tetrachloride, and Teflon were used as test dielectrics for the calibration check. A regression analysis of the actual and probe measured dielectric constants showed that the probe dielectric permittivity values were slightly higher (regression line: \( Y = 1.08X + 1.83 \)), but the bias was consistent (\( r^2 = 0.985 \)). The imaginary dielectric (\( e' \)) measurements were less stable and, hence, should be evaluated with caution. Measurements made by Jackson (1990), using an L-band PDP, led to similar conclusions.

All Howland PDP measurements of trees were taken about 0.5 m above the soil line, and all core samples were extracted at breast height (1.3 m). The radial dielectric profiles were obtained by initially measuring the \( e' \) of the surface of the bark, with subsequent

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1 Manufacturers cited for clarity, and endorsement by either University of New Hampshire or NASA is neither intended nor implied.
measurements taken progressively further into the tree trunks. Holes were drilled into the trunk at the different depths (measured in centimeters) using a drill bit that was the same size as the PDP tip. To facilitate good contact between the PDP tip and the tree, the end of the drill bit had been filed flat in order to drill a flat surface. The hole was carefully cleaned of wood chaff prior to inserting the probes. The diurnal dielectric measurements were taken in the functional sapwood tissue just inside the cambial layer of the hemlock by inserting the PDP tip to the proper depth and securing the probe in place for the duration of the measurements (8–10 h). Because the cambial zone is only a few cells thick, it is extremely difficult to take the dielectric measurements in the cambial zone. Furthermore, the fragile cambial cells are easily damaged by the electric drill. Hence, all our diurnal measurements were taken in the first or second year sapwood. For the June 1991 measurements, to further prevent any movement of the probe tips, we first placed the probe tips through wood blocks prior to inserting and securing them into the tree. Plumber’s putty was used to keep the tip in place and prevent drying of the contact area. This enabled us to take hourly C-, L-, and P-band PDP measurements at depths of 1 cm, 2 cm, and 4 cm. All diurnal dielectric and PB data were collected over the same time period for a given day. The C-band diurnal profiles were collected automatically. During the 17 July dielectric measurements, pyranometer, temperature, and relative humidity were collected.

All resistance measurements were taken with a Shigometer Model OZ-67 (Osmose Wood Preserving Co.) designed to measure electrical resistance in the range of approximately 5–500 kΩ for healthy wood and wood associated with infection and defense processes in living trees (Shigo and Shortle, 1986). In these tissues, the dominant component of electrical resistance is the activity of dissociated ions in the wood moisture. The ohmmeter electrode consisted of twin 7-mm stainless steel electrodes held in a retainer with a spacing of 12 mm. The principle flow path for the test current was between the electrode pins. A larger field effect is negligible under these conditions.

The Durham dielectric and resistance measurements were taken on wood cores extracted with an increment borer (12 mm in diameter) from white pine, eastern hemlock, and American beech. We realized that the diurnal changes in moisture content between cores cannot be addressed, but our objectives were to assess the effect ion concentrations and moisture content of the cores on our dielectric and resistance measurements. Ranson et al. (1992) have shown that taking dielectric measurements along tree cores or by inserting the probe tip into the tree produces similar results. The PDP and ohmmeter (Shigometer Model OZ-67, Osmose Wood Preserving Co.) were used to measure dielectric constant and resistance values, respectively, at approximately 1-cm intervals along the core. After measuring the dielectric and resistance, the cores were sectioned into 1-cm pieces and placed in plastic bags to prevent drying prior to weighing. Core sections were weighed wet to the nearest 0.01 g, dried at 60°C for 1 week, and reweighed. Moisture content was expressed as a percent of dry weight ([wet weight − dried weight] / dried weight) × 100. Based on the sample size and accuracy of the weight measurements, the moisture content measurements are estimated to be within 3% of the actual value. The relative sampling volumes for the resistance, dielectric, and moisture content measurements were 0.08 cm³, 0.02 cm³, and 4.5 cm³, respectively.

RESULTS
Spatial Variation Measurements

Howland Data
Figure 1 presents P-band and L-band radial dielectric profiles for an eastern hemlock. These radial profiles are typical of all species studied and probe frequencies used. The distinctive peak at 1 cm matches the zone of functional sapwood (water transport component of the active secondary xylem), whereas the zones of low dielectric values are characteristic of lower moisture content in the bark and heartwood tissues. The variation in profiles for inter- and intraspecies comparisons showed that the peaks had varying magnitudes and widths. For example, Figure 2 presents a P-band radial profile for a red spruce that has a smaller peak.

Durham Data
Figures 3 and 4 show real and imaginary dielectrics and moisture content for radial profiles of white pine core samples. The real and imaginary profiles appear to be

Figure 1. P-band and L-band radial dielectric profiles for an eastern hemlock from Howland, Maine on 10 June 1991.
correlated with moisture content. In fact, these profiles were consistent for all three species tested (i.e., hemlock, beech, and white pine). The Figure 4 profile is quite different than most of the radial profiles measured. Figure 5 shows the correlation ($r^2 = 0.653$) between real dielectric and moisture content for all three species. Large variations in water content occurred within centimeters along a radial core (Fig. 3), and, hence, could even occur within the 1-cm sections. The electrical resistance measurements were not correlated with moisture content.

We verified that electrical resistance measurements with the ohmmeter were dependent on ion concentrations of aqueous solutions. We tested this with various potassium chloride solutions at concentration from 0.050 mM to 5.000 mM. C-band dielectric measurements, on the other hand, were unresponsive to variations in ion concentrations of the solution. This was expected since the dielectric constant values were outside the calibration range of the C-band probe.

Temporal Variation Measurements

Howland Data
Eleven sets (four hemlock and seven red spruce) of diurnal pressure bomb and dielectric measurements were recorded. Two hemlock and four red spruce were measured on up to two separate days. Both species exhibited the similar diurnal water potential pattern. The morning measurements started low ($\Psi = -0.2$–$-0.5$ MPa) with a steady increase in water deficit,

Figure 3. Radial C-band dielectrics and moisture content for a white pine (tree #2) from Durham, New Hampshire on 27 September 1991.
peaking in the early afternoon ($\Psi = -1.2 - 2.3$ MPa). During the afternoon the tension in the water column relaxed as the tree recovered from the water stress by decreasing transpiration and extracting stored water. Figure 6 shows this typical diurnal pattern measured on 17 July 1990. One interesting feature presented in this figure is that between 9 a.m. and 10 a.m. there is a drop in the water deficit. This was due to a cloud passing in front of the sun, resulting in rapid stomatal closure, which in turn resulted in a decrease in transpirational water loss. Pyronometer, temperature, and relative humidity data was also recorded for the 17 July 1990. The pyronometer data recorded several significant cloud events on 17 July (Fig. 7). Data for the C-band dielectric profile, collected simultaneously with the pressure bomb data on 17 July 1990, are shown in Figure 8. Overall trends were similar for other P-band, L-band, and C-band measurements. The dielectric permittivity ($\varepsilon'$) and loss factor ($\varepsilon''$) data demonstrated the same trends. They remained essentially static from early morning to midday, at which time they underwent a gradual, steady decrease. The 17 July dielectric profile showed a temporary drop in the dielectric constant from 9 a.m. to 10 a.m. This coincided with the aforementioned drop in water deficit shown in Figure 6.

Figures 9a and 9b present diurnal C-band dielectric at three depths and a water potential profile for a red spruce at a site with saturated, poorly drained soil. The profiles for water potential and dielectrics at 1 cm are similar to those shown in Figures 6 and 8. However, at 2 cm and 4 cm, the magnitude, as well as the dynamic range of the dielectric measurements, was less, and the hysteresis between changes in dielectric and water potential was longer.

**DISCUSSION AND CONCLUSIONS**

The results from the Howland radial dielectric profiles were not surprising. It is well known that vegetation tissues with higher water content would have higher dielectric properties. Clark and Gibbs (1957) showed that the outer (functional) sapwood of eastern hemlock has significantly higher average water content, as measured by percent dry weight, than the bark, inner sapwood, and heartwood tissues. Typically, the cambial zone will have the highest water content to provide the high turgor pressures needed for growth (Hinckley et al., 1978). The differences in the red spruce and hemlock profiles could be due to anatomical differences in sec-
Temporal-Spatial Variations in Dielectric Constant

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and/or translocation of elaborated macromolecules. All water within the tree is either bound or free. The hydrophilic forces of the bulk vegetation binds a percentage of the water molecules. Under normal conditions, the ratio of free to bound water is high. This ratio is important because free water molecules have a high dielectric constant similar to liquid water whereas the bound molecules have a low dielectric constant similar to ice (Ulaby and Jedlicka, 1984). As the water potential gradient propagates through the water transport tissue, free water is pulled from storage areas toward the leaves. However, we know from Hinkley et al. (1978), Schulze et al. (1985), and Gates (1991) that trachieds in conifer sapwood have low conductances and provide a relatively long potential transpirational supply of water, causing a lag effect between the efflux of water from storage within the sapwood and relaxation of the water tension in the leaves. Vessel elements in hardwood sapwood have higher conductances and a shorter period of potential transpirational supply, reducing the lag between changes between leaf water potential and sapwood water storage. The length of this lag also depends on the tissue's relative position to the transpiring surface (leaves). The longer the distance, the longer the lag time. These differences in sapwood conductivities and water storage capacitance explain why the Way et al. (1991) and Weber and Ustin (1999) results differ from ours, since they measured essentially no lag between the drop in water potential and dielectric for black walnut trees (hardwood), while we saw a definite lag for the conifers we studied. In addition, dendrologists have measured the swelling and contraction of mature trees in response to diurnal changes in water status, documenting that the smaller branches contract first followed by larger branches, and finally the trunk. Lag times ranging from minutes to hours have been noted between branch contraction and trunk contraction (Zimmerman, 1963). This contraction and efflux of stored water would decrease the volumetric water content within the penetration depth of the probe's electromagnetic field, causing a drop in the dielectric constant. Tyree and Yang (1990) demonstrated with an acoustic emission counter that cavitation events seldom occur in hemlocks at water potentials below -2.0 MPa; hence, cavitation release is unlikely to have occurred due to the light water stress (greater than -1.7 MPa). However, the water storage mechanisms used is difficult to pinpoint except that the origin of the water efflux is most likely due to elastic and/or capillary storage.

The dominant contributor to the electrical resistance of wood is its moisture content. At very low moisture levels, the electric current is conducted by the cell wall materials and is dependent on the proportion of lignin to cellulose, latewood to earlywood, and the spatial orientation of the wood cells. Dried wood is a poor electrical conductor and resistance is measured in multiples and tens of megaohms.

With measurable moisture content, below the fiber saturation point, the electrical resistance is proportional to moisture content. The moisture itself contributes to lower the resistance as well as providing a flow path for dissociated, mobile ions. This is the basis for the use of an ohmmeter to determine the moisture content of logs and lumber. These measurements are usually in the low megaohm range and are affected only in a minor way by wood composition, structure, and orientation.

Wood in living trees is commonly above the fiber saturation point in moisture content. Activity of mobile ions becomes the dominant component of electrical resistance (Shigo and Shortle, 1986). Moisture contents between the fiber and wood saturation points have a negligible effect on electrical resistance. Infection processes prior and during wood degradation result in increased concentrations of mobile ions, especially potassium, that lower electrical resistance (Smith and Shortle, 1988). These measurements are in the lower half of the kiloohm range. This is the basis for the use of the ohmmeter to evaluate the relative concentration of mobile ions in living trees.

The results from the Durham study provided insight into several phenomena. The white pine profiles of dielectric, resistance, and moisture varied considerably from tree to tree as seen by comparing Figures 3 and 4. Heartwood with a relatively high moisture content (shown in Fig. 4) and low electrical resistance (not shown) indicated infection and decay (Shigo and Shortle, 1986; Shortle and Smith, 1987). Due to the active formation of internal boundaries to the spread of infection, chemical and physical differences in wood properties can occur over short (<5 mm) distances (Shortle and Smith, 1990; Smith and Shortle, 1988). This variation in moisture and resistance could be due to infection and/or subsequent decay of the heartwood tissues. Shortle and Smith (1987) related decay rates in red spruce and balsam fir with resistance of extracts from the wood. They found that the resistance measurements were sensitive to wood decay prior to visible wood degradation. All core samples used in the analysis had no visible signs of wood degradation.

The correlation between dielectric and moisture content was encouraging considering that the PDP measurements sampling volume is less than 1% of the total volume of the 10 mm x 9.5 mm disks used to determine the moisture content. Clark and Gibbs (1957) showed that eastern hemlock has distinct differences in water content over seasons, between individual trees, and in vertical and horizontal gradients within individual trees. The poor correlation between resistance and water content was expected since previous research (Shigo and Shortle, 1986) had shown that at moisture contents at
or above fiber saturation point (most wood in living trees) electrical resistance measurements are dependent on concentrations of mobile ions, and not water content.

Using the resistance measurements as a qualitative indicator of relative ion concentrations, we examined the sensitivity of the dielectric probes to varying ion concentrations. Dielectric measurements were split into two “treatments”: high resistance (> 280 kΩ) and low resistance (< 280 kΩ). Given uniform temperature and moisture content above fiber saturation, areas with lower resistance had higher concentrations of mobile ions than areas of high resistance (Shigo and Shortle, 1986). These data sets were plotted (Figures 10a,b,c, and d) and regressed to examine the correlation with water content. Singh et al. (1990), Klein and Swift (1977), and Ulaby et al. (1986) have measured the variation in real and imaginary dielectrics of sea water as a function of salinity (ion concentration), and found that, at 5.3 GHz, as salinity increased, real dielectrics dropped slightly and imaginary dielectrics increased. Low versus high relative ion concentrations did not appear to significantly alter the distribution or magnitude of the real and imaginary dielectrics for varying moisture contents. The dielectric and resistance residuals, determined from the linear regression approximation by differencing actual and predicted values were uncorrelated. If variations in real dielectric were due to ion concentrations, then, as the resistance decreases.

Figure 10b. Real part of C-band dielectric constant versus moisture content for high resistance levels (> 280 kΩ) with regression line ($r^2 = 0.68$).

Figure 10c. Imaginary part of C-band dielectric constant versus moisture content for low resistance levels (< 280 kΩ) with regression line ($r^2 = 0.46$).

Figure 10d. Imaginary part of C-band dielectric constant versus moisture content for high resistance levels (> 280 kΩ) with regression line ($r^2 = 0.68$).
(increased ion concentration), the residuals would become more negative because the real dielectric would drop relative to the predicted dielectrics.

In summary, we found that healthy sapwood was characterized by a higher dielectric than bark or heartwood tissues, and that this was related to differences in water content. In fact, we found a positive relationship between actual wood water content and dielectrics (real, $r^2 = 0.69$; imaginary, $r^2 = 0.64$). Based on our results and previous work, the technique measuring radial dielectric profiles from extracted wood cores gives reliable results. This technique, of course, would not be appropriate for diurnal measurements of the same tree. The occurrence of high dielectric and moisture value within the normally drier heartwood suggests that dielectric measurements are sensitive to areas of bacterial or fungal infection. Similar results for Siberian pine are reported by Ranson et al. (1992). Using categories of electrical resistance measurements as a qualitative indicator of relative ion concentrations showed dielectric measurements to be insensitive to the changes in ion concentrations analyzed in this study.

These dielectric, resistance, and water status analyses have provided some insight as to how dielectric properties of vegetation can vary temporally and spatially. However, since water status of individual stand, single or mixed species, can vary drastically, it is extremely difficult to extrapolate to the canopy scale, and, hence, will require generalization. The generalizations themselves may need to be tailored to each specific application.

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