Trees and Microwaves: Experiments in Non-Destructive Testing

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Abstract- Several preliminary experiments in the non-destructive testing of trees using microwaves are reported.

Index Terms- non-destructive testing, wood, live trees, microwaves

This report describes the beginnings of a grass-roots effort by two volunteers to construct a low cost method of evaluating the health and value of live trees. The project hopes to meet the needs of local forestry and mills in the Bradford area. How to evaluate live trees is a question of considerable current international interest especially in Europe. However, no definitive conclusions have yet been reached about how to do it best. Microwave radiography is one method that has been touched upon in the literature. It is the topic of this research project. Microwave illumination is desirable for imaging the internal portions of trees and logs because it is safe, potentially very portable, and potentially cheap to implement. It reveals water content and grain orientation as well as voids. Being a very new field, work in microwave radiography has been slowed by the absence of commercially available apparatus and limited understanding of how the imaging process would work. The initial studies reported here have addressed both problems. Apparatus is being constructed from scratch to meet the special needs of imaging the interior portions of trees and the basics of the imaging conditions have been revealed: Microwave imaging of individual trees will be based more on wave diffraction than on shadow casting. Microwave radiography requires actual transmission of the radiation through the specimen. New techniques that enhance sensitivity and reject noise, such as lock-in amplification, are needed.

When microwave illumination passes through the wood of a tree, what emerges on the other side is not a simple shadow casting as in x-ray radiography. Rather it is a complicated three dimensional diffraction pattern that must be translated into an image. Wood both absorbs and scatters microwaves. It alters their polarization. Trees act as cylindrical microwave lenses. These and other effects make unscrambling the image a challenging mathematical task. We are fortunate to live at a time when nearly every desktop has a powerful digital computer and when academic interest in electromagnetic scattering is at an all time peak perhaps due to its relevance to the communications industry and interest in remote sensing. In this report, we show that useful information can be obtained by processing the raw microwave image data with the fast Fourier transform. Also, this report identifies several applications: These include the inspection of the heartwood of live timber and logs for voids and abnormalities in moisture content, evaluation of grain straightness in both live trees and logs, identification of local dead spots in the cambium of live trees, determination of moisture gradients in trees and logs to estimate the likelihood of cracking and in-situ structural characterization of the wood of trees and shrubs capable of eventual correlation with microscopic analysis.

The primary purpose of this project is to create a practicable apparatus and method that foresters can use for the nondestructive of live trees.

The Nature of the Project

Dr. Lawrence Lawson, a consultant and past adjunct assistant professor of engineering and mathematics got together with Prof. Hashim Yousif, Professor of Physics at the University of Pittsburgh Bradford with the idea of generating some new locally useful technology. Recalling an off-hand remark by Dr. Susan Stout of the US Department of Forestry that a better way of evaluating black cherry would be useful, they decided to make a project out of it. Prof. Yousif is an expert on wave scattering. Larry Lawson is a solid-state scientist that works with materials imaging and is well published in the area of nondestructive testing and evaluation. It followed that their method would involve images formed from waves scattered by wood. The project at this point is a pro bono effort that is neither yet a commercial enterprise nor university-sponsored research. It was begun on the premise that if something is useful to the community, it will stimulate interest and support.

The State of the Art

An excellent review of the subject of non-destructive testing (NDT) of wood, lumber and trees is that of Bucur (2003)[1]. He identifies five current technologies all of which involve imaging scattered waves: ionizing radiation (x-ray and gamma ray), thermal, microwave, ultrasonic, and nuclear magnetic resonance (NMR). Literature exists on all of these. In the area of x-ray, he concentrates on transmission tomography. Perhaps the most ambitious project reported was that of Habermehl and Ridder[2] (1996) who actually wrapped a gamma-ray tomography system around a tree to obtain a high resolution image of its interior. X-ray tomography is now common in sawmills[3]. Thermography using infrared cameras has proven valuable for the detection of large cavities in trees in parks and public gardens[4]. It is also valuable for the inspection laminated wood products. Ultrasonic techniques can be used to form tomographic images. Ultrasound does not readily pass through air but air coupling has been successful for examining thin laminates. Coupling through a stream of water has also been used since this provides much better coupling than air. Because wood is dispersive, the use of frequencies above 1 MHz. is not highly practicable for thick sections. This limits resolution. However, ultrasonic tomography has been employed to examine standing trees (Martinis, 2002)[5]. Perhaps the most elegant imaging of trees is obtained through nuclear magnetic resonance[6]. This technique reveals much about the chemistry of the tree at very high resolution. Growth rings are clearly visible through this technique and no other at the present time. It also provides information about moisture gradients. Unfortunately it is extremely expensive and rather cumbersome. Microwave imaging also gives information about moisture gradients[7,8]. For near surface features, the resolution is as fine as the size of the detector, about 1mm. For deeper features the resolution is about the size of one wavelength. Microwave imaging is especially sensitive to the direction of the grain and to water content. It is commercially used to detect knots, determine moisture distributions and identify decay. Two modes are used, transmission and reflection. While the latter technology is established, only the former can visualize heartwood with any accuracy. This project appears to have already broken new ground in identifying the role of wave diffraction in transmission microwave radiography. Microwave imaging is already the workhorse of remote-sensing forestry. However, the techniques evolved for remote sensing are inapplicable to the task of imaging trees' interiors since remote sensing is based on reflection.

The Basics of the Transmission Imaging Process

Microwave imaging is a little like x-ray imaging except that microwaves are big and x-rays are very small. X-ray tomography of logs was experimental only a few years ago. However, thanks to research done at Iowa State University's center for nondestructive testing and similar centers around the world, x-ray tomography is used routinely in many sawmills to automatically determine the optimum cutting strategy for each log. X-rays penetrate wood easily. Being much smaller than light waves, x-rays cast easily interpreted sharp shadows. X-rays do not interact much with the structure of the wood. They do not see water or the grain easily. But, because they image so sharply, grain can still be identified. X-rays have drawbacks. They are potentially dangerous. The equipment that generates them is cumbrous and consumes much electric power. X-ray tomography as currently practiced requires an apparatus that totally encircles the specimen. Hence, although logs can be fed through such a machine, wrapping it around a tree in the forest is rather difficult although, using radioactive isotopes instead of x-rays, it has been done. In contrast, microwaves are relatively large waves compared to x-rays and even the size of the objects being imaged. Those used in these experiments had a wavelength of 3 cm. When used to image objects the size of tree trunks, they do not cast shadows but rather create diffraction patterns. This complicates the imaging process but does not prevent it. A similar large-wave problem faces electron microscopists when they image atoms. Another difference between x-rays and microwaves is that microwaves interact strongly with the materials of trees. This is because the rotational frequencies of biological molecules, including water, are in the microwave region of the radio spectrum. Thus, trees and other biological materials strongly absorb and scatter microwaves. Transmission through trees attenuates the microwave signal more than an x-ray one due to absorption and scattering. By the same token, sensitivity to water content is excellent and ultimately some in situ chemical analysis of trees may even be possible by identifying rotational the frequencies.

Perhaps the most desirable aspects of microwaves for the purpose of examining trees are their safety, low power consumption and potential for portability. Furthermore, unlike ultrasound for instance, microwaves pass easily through bark and are unimpeded by air gaps. The technology of microwaves is evolving. Cellular phone and direct satellite television technologies have now made available new electronic devices and techniques for extending the portability and sensitivity of the kinds of microwave circuitry needed for this project.

The first question in setting up this project was that of choosing where in the microwave spectrum to work. The choice ended up being 9.4 GHz, in what is called the x-band. The choice was based on a tradeoff of decreasing image resolution for a gain in transmissivity through the wood. The shorter the wavelength (the higher the frequency), the easier it is to form an image. But, shorter wavelengths increase the attenuation of the microwave beam by the tree. This is because at lower frequencies, the rotation of water molecules absorbs the beam. Then at higher frequencies oxygen is the main absorber. The chosen frequency of 9.5 GHz. seems a good choice for all but the largest trees – up to about 18" in diameter. For the largest trees higher power and lower frequencies will be needed.

Having chosen the wavelength, we need to determine how this affects resolution. Taking x-rays as an example, an energy efficient strategy is to scan a tiny beam of them and collect all the scattered x-ray photons with a very large detector. When this is done, the smallest resolved object is of the size of the beam. Because x-ray beams have small wavelengths, they do not spread significantly. Consequently, this strategy gives very good resolution and is now used to examine everything from airplanes to prisoners. Furthermore, the resolution of this scanning approach is closely related to that of any other imaging method through a reciprocity theorem. Roughly speaking then, if we examine how localized a beam we can generate, we will gain insight applicable to any other scheme of imaging we may later devise. In our present work, the microwave beam is radiated from a horn. After passing through the specimen, it is collected with another horn. The size of the radiated beam is related to the size of the radiating horn in a slightly complicated way. We began with a horn one wavelength in diameter. We thus knew the location to the origin of the microwaves to within one wavelength. If we were examining something very thin, we could easily image it with a resolution of 3 cm. by clapping the sending and receiving horns around the specimen. However, the beam from a one-wavelength horn is spherical in shape and spreads in all directions. If we were to try to cast a shadow of a small object, spherical waves would come off the edges of the object and at a distance the beam would appear to have flowed around it leaving only ripples and no shadow. With spherical waves, the receiver cannot much greater than one wavelength away from the object being imaged or no image will be seen. If we could get the microwaves to travel only in the direction of the horn, we could move our receiver further away and still get an image. But, in order to make the beam less spherical and more directional, we have to make the horn wider. A horn nine wavelengths in diameter radiates in a seemingly straight beam so long as we are about nine to 18 wavelengths away. We now can cast a shadow for a longer distance but at the expense of blurring that shadow by something on the order of nine times the wavelength. For imaging trees with microwaves a more sophisticated approach than casting shadows is needed. We need to take specific account of what is called *diffraction*. From what has been said, we would expect to find that we would get a diffraction pattern rather than a shadow when we try to radiograph a tree with 3 cm microwaves. Fortunately, diffraction patterns can be unscrambled and made into images.

Hardware

The source of the microwaves used in this study is a 2K25 Reflex Klystron. This is a vacuum tube. It delivers about 25 mW. of microwave energy. It has an advantage over Gunn diode sources of having better frequency stability. Although its power is very low, the source seemed adequate to the task at hand provided that clever signal processing was used. The system is shown below.

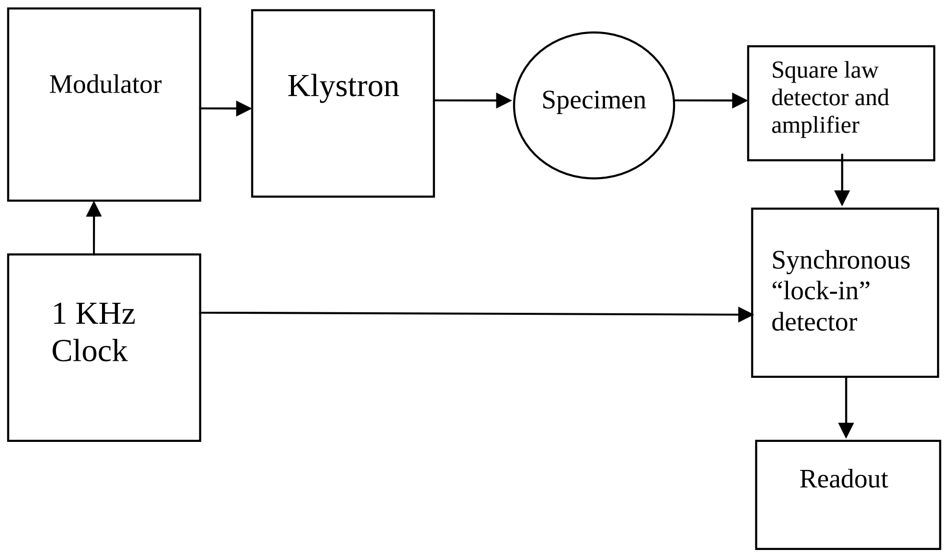


Figure 1, Block diagram of test circuitry

The klystron is chopped at a low frequency (1KHz) by switching it in and out of its "b" mode. Unlike in conventional modulation, the klystron is either totally on or totally off. Any signal received in its off period is pure noise. Since this tells us what the noise is like, a synchronous detection scheme can be employed to identify a signal even when buried in noise: During the on period the signal is integrated. During the off period the noise is collected and subtracted from the signal. There are possible variations on this scheme. Signals can be recovered from beneath 100dB of noise.

After passing through the specimen, the signal is detected and fed to a low-noise preamplifier directly attached to the detector. The synchronous detector (still under construction) uses the AD630 signal processing integrated circuit. The readouts consist of an oscilloscope, a digital meter and an A/D computer input.

In most measurements the source and specimen are fixed in one position. The detector is moved either in a circle when the data are degrees) or along a line perpendicular to the beam. The beam is strongly polarized and in some tests the detector, which is also strongly polarized, is rotated. Because, microwaves interact strongly with the water in the bast fibers, the magnetic vector of the beam must be parallel to the grain for maximum transmission. Should the grain not remain parallel, the polarization of the source beam may become rotated when it reaches the receiver. Hence the receiver itself must rotate. Accurate fixturing is a current concern since inaccurate fixturing results in noise and errors.

In order to limit the spread of the beam, a wide horn is desirable at the source. Furthermore, the detector is susceptible to waves that pass around the tree or are reflected off objects. Hence the horn should the source directly into a tree without leakage. Taking these two considerations together resulted in a horn design in which the horn is the width of the tree and closely fitted to it.

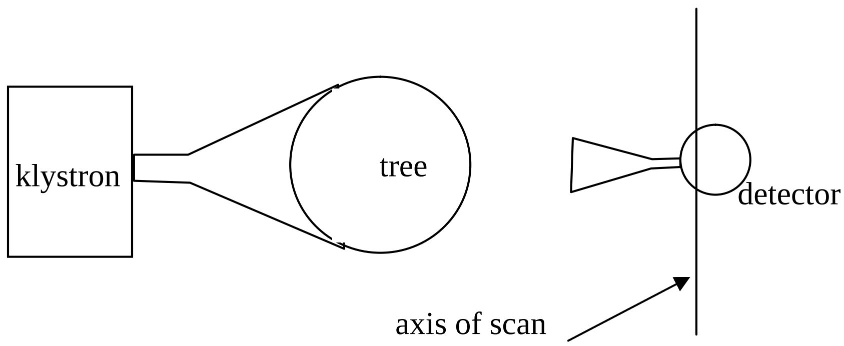


Figure 2, Layout of preliminary heartwood scan

The sketch above shows the configuration for imaging heartwood. While testing horns, a somewhat fortuitous discovery was made. Once a wave begins propagating down a horn, it will continue to do so in much the same manner if an extension is attached over the original horn – even if the extension does not make a perfect electrical connection to the first horn at all points. This has led to the used of clip-on horns. The graph below shows the relative performance of an aluminum clip-on horn.

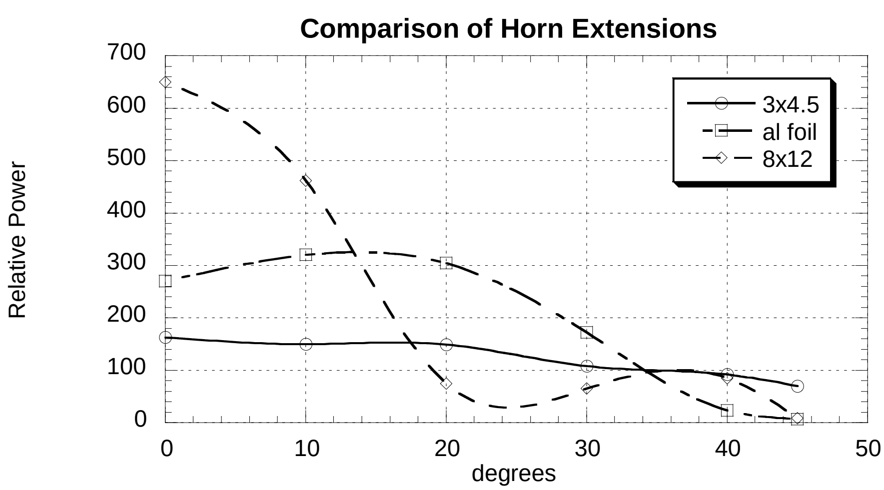
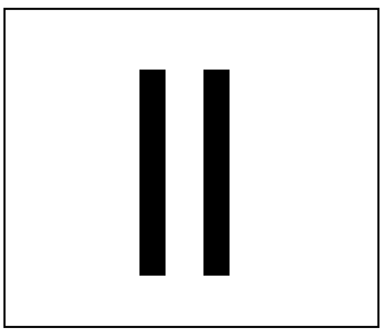


Figure 3, Radiated Power vs. Angle

The horn to which the extension is clipped is the 3x4.5 cm horn. Considerable gain in signal strength is obtained by adding a wider horn because the wave is more directional. We see that even a piece of aluminum foil crumpled into the shape of a horn provides some gain. An advantage of clip on horns is that they can be easily fabricated to conform closely to any tree.

Our first experiment was to see what would happen if we were to try to cast a shadow of a metal plate with two slits in it as shown at left below. The slits are approximately 1" wide and 4' apart. The detector is several feet in front of the plate. It is scanned as shown above in the illustration for imaging a tree.

Experimental Results



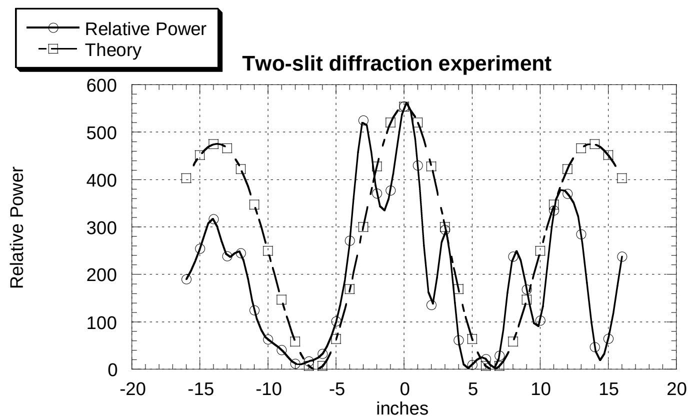


Figure 4a,b, Plate with two slits (left, a); Diffraction data for plate (right, b).

The result was a diffraction pattern rather than a shadow. The graph at the right compares the observed pattern with one calculated for the same slits in an infinite plate. It shows ripple effects from the finite size of the plate and from standing waves off of objects in the laboratory. It illustrates the need to prevent stray radiation.

In this illustration, the experimental result is marred by numerous ripples that resulted from extraneous radiation. As a first step to correct this problem, a screen box was built to entirely contain the source. It has proven a great help. Additional work on fixturing is needed. In all the preliminary data presented in this report, a number of hand-held components were required.

The next area of experimentation was determining the extinction properties of woods since these determine the limits of thickness of tree that can be inspected. The wood specimens below were semi-green (except for lumber and flakeboard), and approximately 1" thick. As wood dries, the extinction coefficient, alpha, diminishes and the effect of polarization decreases. Intensity obeys this equation:

$$I_{received} = I_{incident} \quad \exp(-\alpha\ x), \qquad (1)$$

where x is the thickness in inches.

TABLE 1, Attenuation coefficients at 9.4 GHz.

MATERIAL	POLARIZATION of E	ATTENUATION ALPHA reciprocal inches
Black Cherry sapwood	perpendicular	1.1
Black Cherry sapwood	parallel	very large
Black Cherry bark	perpendicular	0.04
Black Cherry bark	parallel	0.89
Maple, waterlogged	perpendicular	1.2
Maple, decayed	parallel	very large
Maple bark	perpendicular	0.04
Maple bark	parallel	0.89
Douglas Fir lumber	perpendicular	0.46
Douglas Fir lumber	parallel	0.89
Commercial Flakeboard	arbitrary	0.49

Tests were also performed to determine the index of refraction of wood at 9.5 GHz. These agreed within experimental error with calculations based on interpolating tables in *Handbook for Radio Engineers* shown below.

TABLE 2, Dielectric Constants at 9.4 GHz.

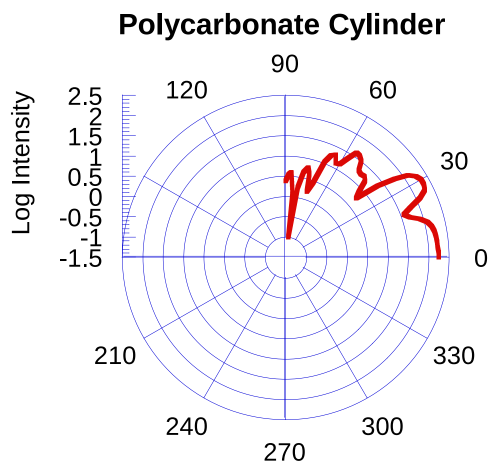
Wood	Relative Dielectric Constant	Index of Refraction
Douglas Fir	1.80	1.34
Mahogany	1.75	1.32
Yellow Birch	2.00	1.41
Yellow Poplar	1.45	1.20

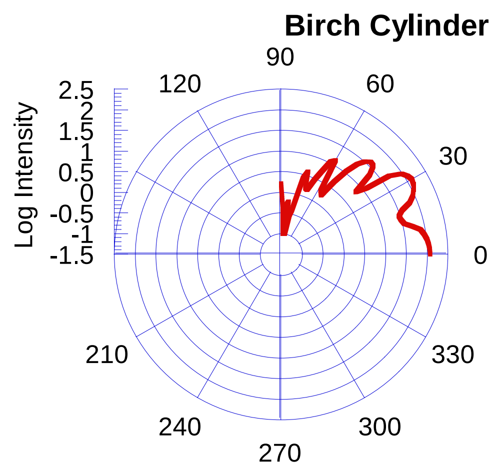
Reflection tests were also performed on samples of Bradford Area Black Cherry to estimate its index of refraction. The result, given the noise of measurement, could not be distinguished from that for Douglas Fir.

The scattering behavior of woods and ideal dielectric materials was studied next. When electromagnetic radiation falls on almost any material, some of it is re-radiated. The re-radiated wave may go off in a different direction and have a different polarization than that of the incident wave that fell on the material originally. Scattering properties depend on the material and its shape. Knowledge of the scattering properties of wood is needed in order to interpret images of it.

Initial results showed that the individual bast fibers of wood scatter and absorb strongly. Comparisons were made with idealized samples. A one-inch thick piece of black cherry was placed in a configuration in which the polarization of the source and detector was rotated relatively 90 degrees. In this configuration no signal was received in the absence of a specimen. Inserting a sample the black cherry resulted in a signal. As expected, the signal was strongest with the grain at 45 degrees to the angles of polarization, since that allows the fibers to both absorb and re-radiate in such a way that generates a wave polarized at 90 degrees to the incident one. To examine this phenomenon further, a thin tube (4mm.dia.) filled with Ringers solution was used to represent a single bast fiber since it is still small relative to the wavelength. The received signal (between crossed polarizations) was proportional to the sine of twice the angle. This suggests that the water and salt content results in both absorption and re-radiation only along the axis of the fiber. Since the signal is proportional to the sine of twice the angle, there was no signal received when the tube was oriented along either the source or detector E-axis of polarization. This is expected. Yet, the sample of black cherry showed some signal no matter what its orientation was. One interpretation is that the wood contains oriented scattering paths (fibers?) in multiple directions. If so, microwave tests can be devised to determine their quantity and orientation. These should be relatable to microscope examinations.

Since trees are made of cylindrical structures on many length scales, tests were performed to visualize the scattering characteristics of cylinders of wood and reference materials. One specimen was a polycarbonate cylinder a little less than one wavelength in diameter. Given extensive calculation, the scattering pattern from this idealized specimen may be calculated from first principles[9,10,11]. Scattering from a cylinder of wood is much harder to predict since wood has a complex structure. However, both results are somewhat similar.





Figures 5,6, Intensity (power/area) at angles from 0 to 90 degrees.

The chart above on the left shows the scattering pattern for a polycarbonate cylinder 2.1cm. in diameter. The incident beam points in the zero-degree direction. The first scattering peak appears to be in the 30-degree direction. On the right we see the same test on a birch dowel 3 cm. in diameter. The intensity we received was the sum of the incident beam (at 0 degrees) and the scattered beam. The scattered beam interacts ("interferes") with the incident beam to produce characteristic undulations in the received intensity. These two materials may be said to have differing *scattering signatures* in the 40 to 90 degree region. Both scattering patterns show radiation being re-emitted at 90 degrees. Besides illustrating material properties, this observation suggests a technique for high resolution examination of cambium. Microwaves enter the tree from the side and are scattered. The detector, placed in contact with the bark, receives scattered microwaves after they pass through the cambium just beneath it.

For comparison we also examined scattering from a polycarbonate cylinder either

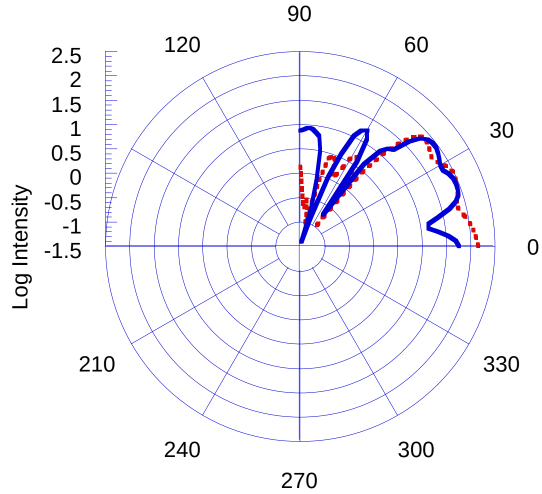


Figure 7, Intensity (power/area) at angles from 0 to 90 degrees for PVC cylinder.

empty or filled with water. The dashed line represents the empty cylinder. The solid line represents the filled cylinder. The cylinder is 5.8 cm. in diameter and has a wall thickness of 0.635 cm. Clearly scattering from the wall seems to dominate that from the liquid. This is because the wall is relatively thick. This scattering condition loosely resembles that of a void in a cylindrical bolt. We can see differences in behavior especially near zero and 90 degrees showing that it is here possible to distinguish the filled from the empty cylinder from their scattering patterns.

Perhaps more immediately significant to the testing of trees were tests on bolts, sections of tree branch. For convenience in laboratory testing the branches chosen were 15 inches in circumference. One long bolt was cut in half and a rectangular hole was bored through the center of one of the halves, Fig. 8. The hole was roughly 1x3 cm. The transmitted radiation through the two pieces was compared. Examination of the solid piece at a beam orientation of zero degrees showed several peaks or foci at different distances in front of it. Perhaps the strongest of these was located 2 7/8" from its surface.

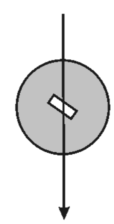


Figure 8, Cross-section of bolt showing rectangular hole. (Arrow indicates direction of imaging radiation.)

Suspecting that this might result from the focusing of the microwaves by the log as a cylindrical lens, the location of such a focus was calculated by deriving the following equation through geometric optics:

$$X = \frac{R}{2}\left(\frac{2-n}{n-1}\right), \qquad (2)$$

where n is the index of refraction (1.3 in this case), R is the radius of the cylinder and X the distance in front of the cylinder at which the focus is located. This equation was tested with ordinary light on some acrylic cylinders and seemed in good agreement. It predicted the location of the focus of the tree trunk to be 2.9 inches in front of it – about the distance observed.
2.9" focus. Since a thick lens can be resolved into two thin ones, for features within the branch itself, the Fraunhofer condition would be expected to apply at greater distances in front of the branch on the order of 6 inches or 15 cm. So, measurements were made by scanning along a line 15 cm. from the center of the specimen as shown in Fig. 2 above. The results of the scans are shown below. These are diffraction patterns rather than direct images. However they can be converted into

Fraunhofer diffraction is observed when either the detector is a very long distance away from the diffracting object or when a lens is introduced between the diffracting object and the detector. In the latter case, Frounhofer diffraction is observed at the focus of the lens. So, for an object behind the tree branch, the Fraunhofer condition would apply near the

direct images taking the inverse Fourier transform.

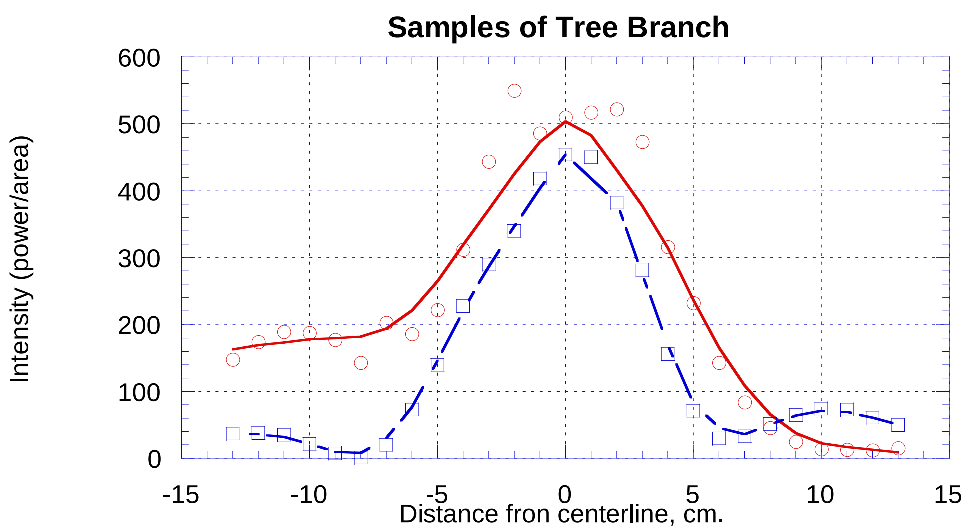


Figure 9, Scans of bolts: solid (lower), with central void (upper)

The lower curve represents the solid specimen. The upper curve represents the sample containing the central hole. As expected, the transmissivity is higher for the specimen with the hole. The curve is also wider. Side lobes resulting from the sharpness of the boundary of the specimen are less defined for the specimen with the hole.
For comparison, models were generated for both specimens. That for the specimen with the hole is shown below. The rectangular hole (at 45 degrees) is the peak near the center.

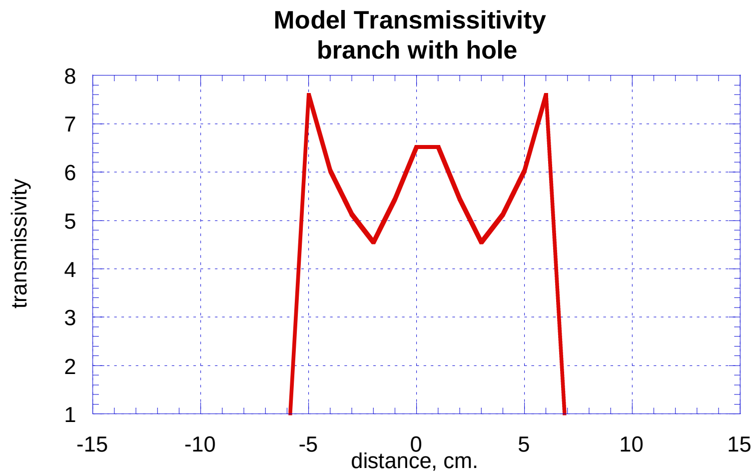


Figure10, Optical density at 9.4 GHz. of bolt containing a void.

The hole increases the near center transmissivity. Were the scans shown above performed under the Fraunhofer condition, we would expect that the Fourier transform of the transmissivity models would match to the observed diffraction patterns shown in Fig. 9 above[12]. Below are the Fourier transforms of the transmissivity models of both the unflawed specimen and that with the bored hole.

In the graphs below, the solid line represents the unflawed specimen while the dotted line represents the one with the hole. The flawed specimen shows a higher wider central peak with lessened side lobes as does the observed diffraction pattern. There is also a resemblance to the scattering patterns of the filled and empty cylinder since the latter lacked the lobe peaking at 20 degrees that the former possessed. We can apply an intuitive understanding of the Fourier transform to understand these results. The peak for the flawed specimen is higher than for the solid specimen because there is less material on account of the hole (void). The peak for the flawed specimen is wider because we can imagine the flaw as being like a neutral density filter or mask placed in front that for the unflawed condition. The resulting density is the product of these two functions. Hence the transform is the convolution of them. Convolutions widen features.

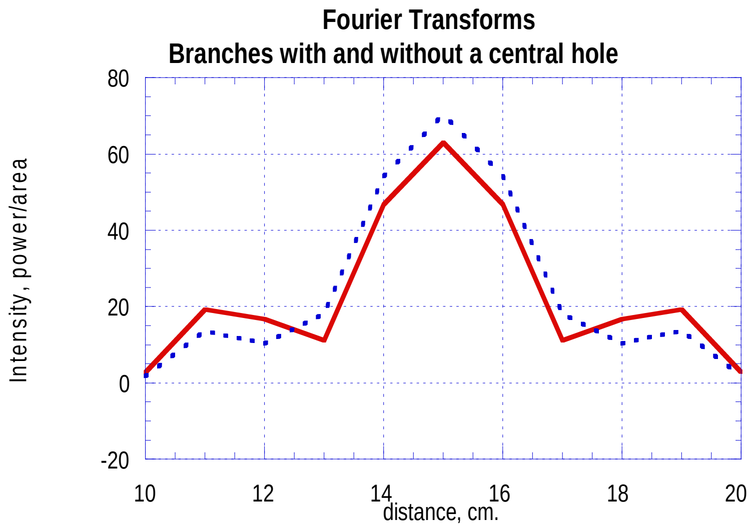


Figure 11, Scan results (diffraction patterns) for bolts: solid (lower), with central void (upper) based on physical calculation.

Figure 12 shows the equivalent shadow image of the specimen with the void obtained by inverse Fourier transformation of its diffraction pattern. It is an approximation of what would be seen if the bolt were x-rayed. Notice that in a diffraction pattern, as obtained by microwave scanning, the central peak does not by itself reflect the presence of absence of solid material in the center of the specimen.

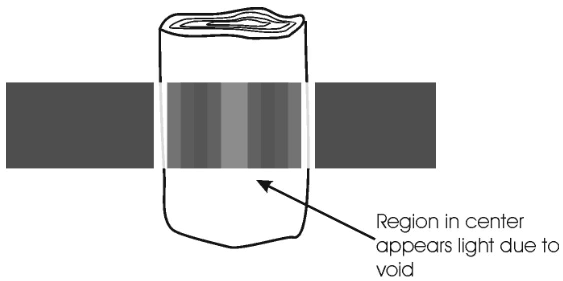


Figure 12, Inverse Fourier transform of Fig. 11 (upper) for voided bolt plotted as an overlaid image onto a sketch of the bolt itself

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Discussion

The experiments we have performed so far indicate the applicability of microwave nondestructive testing (NDT) to wood and live trees. We have demonstrated detectable differences in microwave transmissivity between bolts with and without voids. We have reaffirmed the well-known sensitivities of microwave transmissivity to grain direction and water content. We have sketched the microwave scattering properties of wood and determined tables of extinction coefficients and related parameters for various woods. We have identified two possible imaging conditions: a near-surface one using backscattered microwave illumination and a Fraunhofer one for examining heartwood. We still have a way to go before we have a little box that foresters could carry about to look inside the wood of trees with. This goal, however, does not seem out of reach. We can image grain direction and as is already established in the literature, locate knots in logs. Furthermore, while we have not yet given this much attention, determining moisture gradients in trees and logs seems easily achievable.

At this point, we may begin to visualize some possible techniques and their hardware. Since imaging the heartwood of live trees was the initial challenge, this should be discussed first. A practicable device would consist of a source of microwaves – probably a diode rather than a vacuum tube – coupled to a horn that would rest against the tree to be examined. Horns are now routinely made out of light weight plastic. The receiver would probably be an array of planar detectors rather than a single scanning one. The array would obtain data at many points at once. This would save much time and effort. The combination of source and detector array would probably be mounted on a semicircle to facilitate positioning it around a tree. Data would be read into a laptop computer. The computer would convert the input diffraction pattern into a one-dimensional image of the tree, as in Fig. 12, by unscrambling the diffraction pattern through inverse Fourier transformation.

The astute reader may have noticed that no mention has been made about acquiring phase information. Information about the phase of the waves forming the diffraction pattern is needed to carry out the inverse transformation. There are two basic ways of getting this information. The first is to do it properly by measuring it directly. One way of doing this is to have a piece of cable connecting the source to the detector and a device that mixes the source signal in differing amounts with the received one. This is microwave holography. The second approach is based on the limited number of possible features that an image of a tree can contain. An approximation of the true image in the absence of phase information can be obtained by having the computer match the received diffraction data against a library of known diffraction data. This amounts to assuming phase information. One gross simplification applies in any case where the pattern is symmetrical: the phase is everywhere zero. This is genuinely the case for solid trunks of circular cross section and those with voids near the center as in the cases above. The failure of applying this gross assumption to say an image of a tree with say a piece of metal in it on one side would be that the approximated image would show pieces of metal on both sides.

The experimental results and apparent discoveries summarized in this report were obtained at the cost of but a few hundred dollars and a few hundred man hours. With this modest expenditure, not enough scientific fact has actually been nailed down to even make a publishable paper. On the other hand, a door to the future has been opened. Microwave radiography looks like it will probably become a valuable tool in forestry and production. This is the beginning.

There remain two problems that need to be addressed. One is that the Frounhofer condition is not strictly met. Finite element method or similar numerical calculations would have to be used instead of the simplified approach used here. A second problem is an experimental one, the boundary condition describing the surroundings of the experiment has been tacitly assumed to be absorbing. This is not met. Significant reflection is present even in the outdoors. The apparatus itself is reflective[1]. Anti-reflection techniques, perhaps related to "radar stealth" will need to be adapted to the task.

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