Dielectric Properties of Wood for Improved Internal Imaging

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Abstract. This paper describes the measurement of the dielectric properties of the typical log features of Heartwood, Sapwood and internal Branches. Measurements were made using the waveguide cell technique covering the frequency range of 2.3 to 6.5GHz. This has shown that for the desired contrast between heartwood and Sapwood to be achieved the imaging system must operate above 4GHz. Additional work was undertaken to establish a method to correct these measurements for variations in basic density and Earlywood\Latewood banding, giving rise to a potential moisture content estimation error of 0.63%. This will lead to improved spatial location of features of interest.

1 Introduction

The cost of any manufacturing process can be minimized by assessing the raw material quality at the earliest possible stage. In the case of the timber industry, assessment of log quality would be most ideally performed in the forest. At this early stage, logs could be graded and assigned to the most appropriate timber processor and so leading to optimized use of the timber resource.

When a tree is pruned at six years the branches and high-density timber remain within the tree at time of harvest. This defect core affects the strength and stability of the final lumber and it is desirable to process this defect core separately. Currently there is no means of detecting the defect core within the log at the time of breakdown and this result in an inferior product. This has been one of the prime motivators behind many forestry companies ceasing to prune its trees and move to re-engineered timber products. The second problem of compression wood has a similar effect but is caused primarily by the tree growing in a fashion where it is leaning, such as when planted on banks.

The development of internal imaging systems provide the saw-miller with information about the interior of the log which will have the effect of improving

S.C. Mukhopadhyay et al. (Eds.): Advancement in Sensing Technology, SSMI 1, pp. 93–104.
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lumber quality (both strength and stability) and maximise the economic return from the log to the processor by reducing wastage.

Timber quality is influenced by structural defects in the log as well as material properties such as basic density (density of dry matter) and moisture content (mc). Many inspection procedures exist to assess structural defects on logs using either visual techniques or measured at the time of felling. Current techniques to measure basic properties of logs are of limited accuracy and so of limited use to the timber processor.

1.1 Microwave Imaging

The development of electromagnetic and microwave systems for the interior imaging of logs has been ongoing for many years. Commercial Ground Penetrating Radar (GPR), Microwave Tomography and Synthetic Aperture Radar systems (SAR) have been employed in these studies. Whilst all of these have shown promise and can reveal features within the log, they all suffer from the same problems of poor image contrast and spacial resolution.

The use of existing commercial GPR system has become the most common tool used by researchers to investigate the possibilities of such imaging systems. Such systems operated around the 1000GHz region and are designed to be portable allowing ease of trialing in the field. One such study undertaken by Parker (2006) applied this technique to logs for the detection of internal branching with some success. In this trial a third of internal branches were detected and accurately positioned, a third were detected but not accurately located, and the remainder were unseen by the technique. An example of the resulting log images from this trial is shown below in figure1.

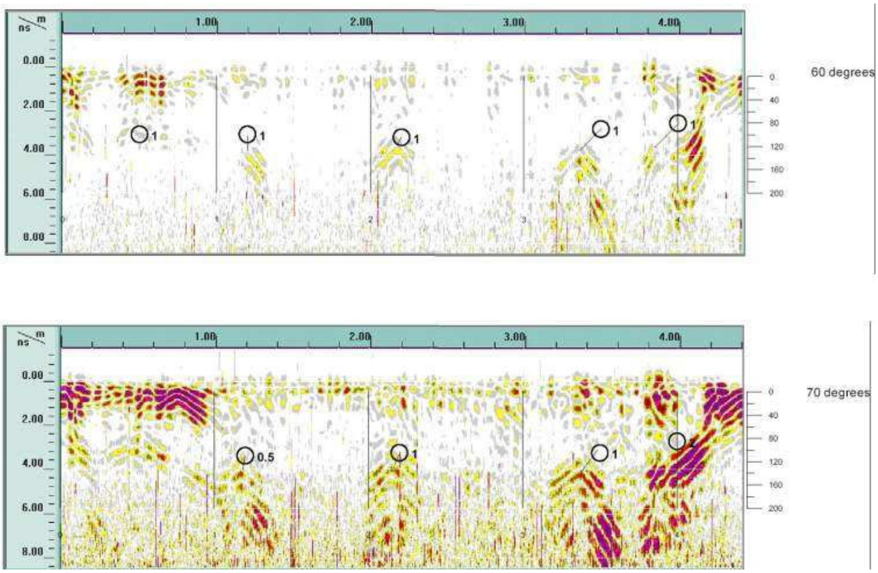

Fig. 1. GPR image of sample Log

In order to improve the performance of these systems and locate features such as Sapwood, Heartwood and internal branches, a more detailed study of the dielectric properties of these log components is needed. An additional obstacle for such systems is that from the time the tree is cut down up to the time of scanning, the logs moisture is being lost and hence the dielectric properties within the log are changing.

Considerable work has been performed in the application of microwave energy to sawn lumber for the determination of grain angle, defects and knot locations. Microwave sensing systems such as those developed by King (1985), Skaar (1972) and Holmes (2011) rely on the transmission and reflection characteristics of sawn timber, but little or no effort has been expended into examining how microwave sensing would perform on unprocessed timber.

Electromagnetic sensors essentially measure either the energy transmitted or reflected back from a material. The composition and structure of the material give rise to a measurable signature that then can be related to other physical properties such as moisture content or density. This defines the microwave signature of a material arises from a physical constant known as permittivity, (dielectric constant) which relates the electric flux density (**D**) illuminating the material to the electric field strength intensity (E), inside the material. Often the permittivity of a material is expressed as a multiplier of the permittivity of free space (ε_0) and is then known as relative permittivity (ε_r). **D** and **E** are both vector quantities and contain both phase and magnitude information.

$$\overline{D} = \varepsilon_o \cdot \varepsilon_r \cdot \overline{E}$$

The magnetic field component of the microwave energy similarly has a physical constant of permeability but only ferrous materials have a relative permeability of greater than one and in the context of the types of measurements undertaken in this work, it will always be assumed to be one.

As wood is an anisotropic media for the propagation of electromagnetic waves, the energy reflected and transmitted are highly dependent upon the grain angle, basic density and moisture content (which would attenuate the transmitted wave in the timber). Both the grain angle and moisture content of the internal branch stubs are considerably different from the surrounding sapwood; this suggests that the energy incident upon the branch stub would show as a significant feature within the image. As the timber in the sapwood region without knots has a grain angle which is orthogonal to the incident electric and magnetic fields, and higher moisture content, hence much of the microwave energy is reflected back towards the source.

1.2 Practical Considerations

Many factors affect how electromagnetic energy interacts with timber. Grain angle, the heterogeneous structure of wood, density and moisture content, all effect the measurements. If possible, variation due to the properties which are not of interest must be either eliminated or minimized.

Studies into the application of microwaves to the imaging and measurement of timber properties have been performed have primarily been confined to examination of timber that has been dried to below the fibre saturation point (FSP). Work performed by King (1985) showed that below the FSP, effects due to basic density are small compared to the dominant mc effects, but however are still measurable.

Extracting the density information requires that the anisotropic nature of the wood due to early wood / late wood (EW/LW) bands be minimized. As grain angle will introduce marked effects on the reflected microwave energy, it is desirable to select a measurement site at which the grain angle could be considered to be normal to the plane of incidence. In the case of logs, applying energy into the side of the log will fix the EW/LW boundaries as orthogonal to the plain of incidence.

To reduce the effects of the non-homogeneity of timber due to the EW/LW bands, a sensor structure is required which will interact with a large volume of wood to perform an averaging function. A suitable sensing structure to perform this averaging task is an open-ended waveguide. This is a radiating structure which, as well as interacting with a larger sample surface area, will also allow for microwave energy to penetrate significantly into the sample.

A second factor which will have a direct influence on the microwave measurement is moisture content. In the case of the freshly felled logs, we have assumed that the moisture content can be considered constant and hence basic density will become the dominant factor influencing the measurement. Details underlying this assumption can be found in a paper by Cown (1992).

To determine the characteristics of various structural features of logs, a series of experiments were conducted. A permittivity survey of Pinus radiata bark types using an open ended coaxial probe showed that the variation in permittivity between different bark types (eg. clumpy and slimy barks) was large. In addition, the survey showed that the electromagnetic loss factor of the bark material was extremely high which would suggest that much of the incident energy would be attenuated in the bark rather than the woody tissue itself. For these reasons, it was determined that for performing microwave measurements of logs it would be desirable for the bark to be removed.

1.3 Coupling Microwave Energy into the Log

If we consider the log to act as a dielectric rod then any incident electromagnetic energy tends to be contained within the tree and little energy radiates externally. In particular the incident wave is focused towards the centre of the tree. This focusing effect of the energy has been described by Keam (1994) for an infinite dielectric rod, and Neelakantaswamy (1973) in the construction of antennas with much reduced side lobes. In the case of the high moisture content living tree, the electromagnetic waves are focused within the tree and are quickly attenuated within the tree and little is re-radiated. This effect is desirable in this application as scatterers external to the log have little effect on the measured fields.

2 Permittivity Measurments

The following presents the methods and results of a series of microwave permittivity measurements performed on timber samples taken from freshly felled logs. From each of three logs, samples of heart, Sap and Branch wood were taken and dimensioned to fit into waveguide cells. This work is the first step in the development and understanding of the potential of microwave based systems in the imaging of freshly felled logs.

Waveguide cell measurements were selected as the best means to provide the bulk permittivity of the various types of wood, this was due to the fact that both transmission and reflection data is measured. As Wood is anisotropic in nature the waveguide cells were designed in a square cross-section allowing the samples to be cut as cubes. The cubic samples could then be rotated and measured to allow us to see this anisotropic effect in the measured results.

Waveguide cells were fabricated to cover the 2.3 to 4.2 GHz band, and other cells to cover the frequency range 4.5 to 9 GHz. As the waveguide cells are square in cross section, the possibility of more than one mode of wave propagation exists. Within our measured data this effect did occur once the cell length exceeded a half wavelength within the material, and hence the presented results show only the single moded region from 2.3 to 3 GHz for cell 1 and 4.5 to 6.5 GHz for cell 2.

The measurements were undertaken using an Agilent PNA vector network analyzer and each sample was weighed after measurement. The PNA is a two port device which allowed the measurement of microwave reflection and transmission coefficients. Using these measured microwave parameters the permittivity was calculated using the standard Nicholson-Ross-Wier (1968) algorithm.

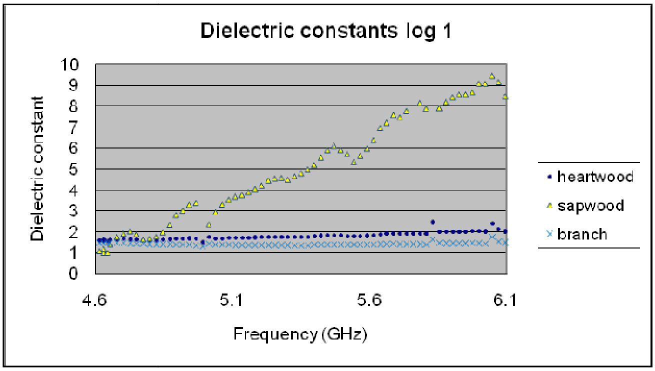

Fig. 2. Dielectric constant of wood types in sample log 1

The Dielectric constants (real part of permittivity) of both Branch and Heart wood at the frequencies measured are similar. The Loss Factor of both Branch and Heart wood whilst similar shows some small frequency dependence in the Branch wood which is not apparent in the Heart wood. As the reflection from the boundary of two media comprises both dielectric constant and loss factor there should be a small but still measurable reflection between Branch and Heartwood

The Sapwood samples showed that at the lower band 2.3-3 GHz region, the measured dielectric constant and loss factor to be low, so as to make the sapwood almost transparent in a image. Both the dielectric constant and loss factor showed, as expected, a frequency dependence increasing rapidly as we approach 10GHz due to the large free water component within the sapwood structure.

3 Density Effects

This section looks at the effect of basic density on the accuracy of the wood measurements and examines potential methods to compensate for its impact.

3.1 Dielectric Models

The initial approach to accounting for density variations was to develop a model that describes the dielectric behavior of a material by using the permittivity of the individual constituents. The most commonly used model would be a volumetric one, which simply sums the permittivity of each part, multiplied by its fraction of the volume. Hence, a simple model would be the permittivity of dry wood plus water plus air. Then using the frequency dependence of the sum (usually the water component as the permittivity of air and solids change slowly with frequency) the individual volume fractions of each constituent can be determined.

$$\varepsilon = \varepsilon_{water} \cdot V + \varepsilon_{wood} \cdot (1 - V)$$

Where V is the volume fraction of water in the mixture. This simplistic model can then used to determine the moisture content from the measured

$$V = \frac{\varepsilon - \varepsilon_{wood}}{\varepsilon_{water} - \varepsilon_{wood}}$$

Hence the moisture content by percentage dry basis can be found as

$$mc = \frac{V}{1 - V} \cdot 100 \quad (\%)$$

In this work, both the published data and the experimental permittivity data were measured. Figure 3 shows that the permittivity of wood below 33% moisture content, the Fibre Saturation Point (FSP), is essentially constant over the 4 to 8 GHz range. In essence, the remaining water within the wood structure is so tightly bound that it no longer contributes significantly to the dielectric losses. This gives wood below FSP a very slow variation in dielectric properties with frequency.

Without any change in permittivity, the model approach cannot be considered a useful approach for removing the basic density effect.

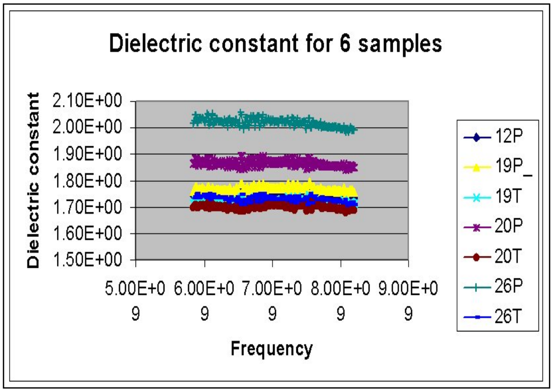

Fig. 3. Dielectric constant versus Frequency for 6 samples

3.2 Density Independent Function

An alternative approach is to use the density independent function developed at the USDA by Trabelsi and Nelson. This is a commonly used method for microwave sensors to remove the effect of density from their measurements. The universal permittivity based method for determining moisture content independent of density was reported by Trabelsi (2003)and has the form

$$\Psi = \sqrt{\frac{\varepsilon''}{\varepsilon' \cdot (a_f \varepsilon' - \varepsilon'')}}$$

Where a_f is a constant that is a function of frequency and the resulting function Ψ varies linearly with moisture content.

Figure 4 shows the density independent function versus moisture content for a range of wood densities spanning 300 to 700 KG/m3 using data from Torgovnikov(1993). It can be easily seen that as the moisture content drops below the FSP, the function no longer accounts for the density variation.

The explanation for the failing of the density independent function is in the nature of the water binding below the FSP. The water in this region is heavily bound in the structure of the wood and the dielectric properties of the water approach that of ice. This means that the remaining water no longer contributes significantly to the dielectric losses, and the loss factor (ε”) becomes small.

However, what this figure does show is that above the FSP we can easily negate the effects of density and accurately extract the moisture content. This in turn would also let us accurately determine the density so that it can be used later as a correction in measurements below the FSP.

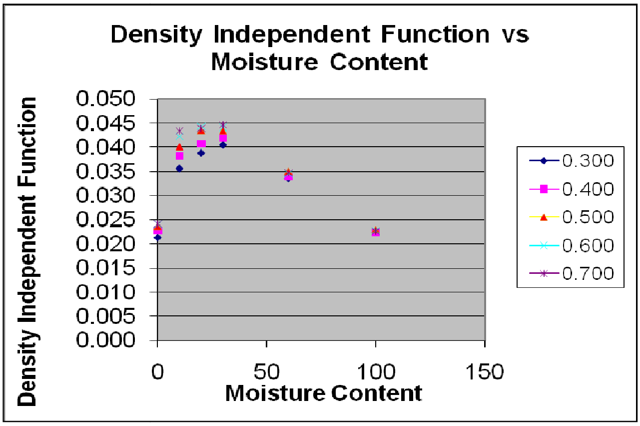

Fig. 4. Density independent function versus moisture content for published data

Using the fact that we can use the density independent function in the earlier phases of drying to determine the basic density, we can apply this as a correction to the measurements made below the FSP.

The plot in Figure 5 shows the experimental measurements made on 12 samples at 10% moisture content. The two solid lines represent published data for 400 and 300 kg/m3 respectively, the measurement data ranges from 340 to 440 Kg/.m3.

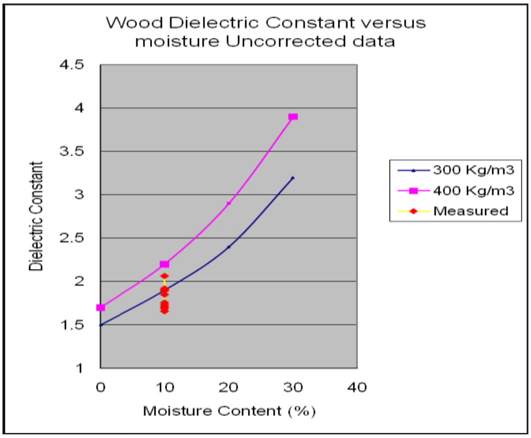

Fig. 5. Moisture content versus dielectric constant with no density correction

The degree in spread of the data, if density was not known, would yield an RMS error in moisture content estimation of 3.59% with a mean of 0.2%. If we now correct the data using the density previously determined, in this case normalize to 300KG/m3, the resulting Figure 6 is found. This yields an RMS error of 1.38% with a mean of 0.012%.

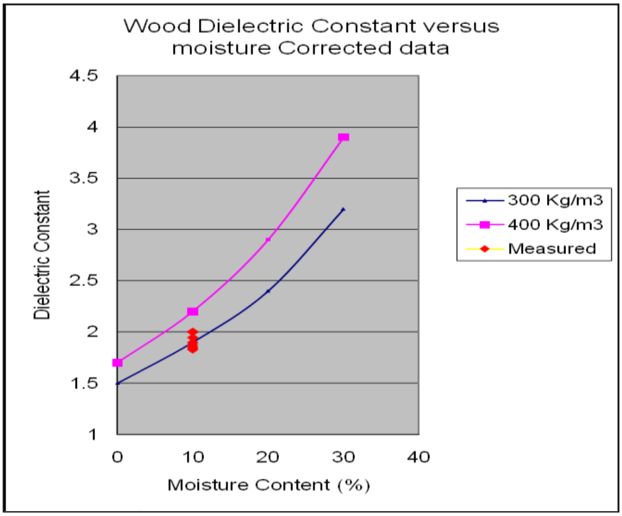

Fig. 6. Density corrected dielectric constant versus moisture content

This figure shows an improved result however, there still exists a significant error (> 1%).The normalization process is simple as the variation due to density is a simple linear function, as shown in Figure 7. In this Figure measured data is from all measurements made and the trend line comes from those published by Torgovnikov (1993) for moisture contents of 10%.

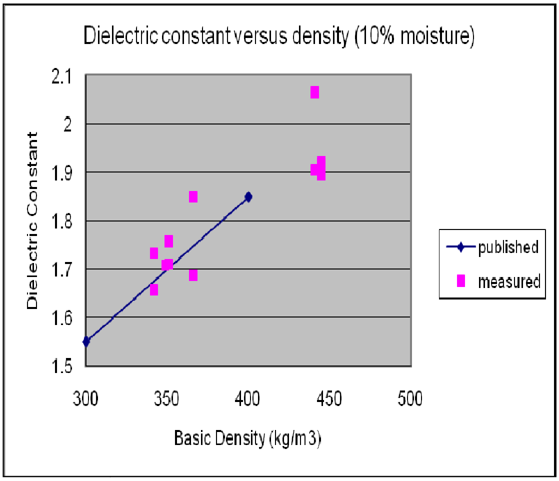

Fig. 7. Dielectric Constant versus Basic Desity

Although he does not directly mention the effect of the early wood late wood layer orientations, Torgovinikov (1993) does present measurements on polarization of the applied field and also the ratio of Early wood (EL) to Late wood (LW). The following section looks at the effect of this EW/LW layer orientation on the permittivity of wood.

4 EarlyWood/LateWood Layer Orientation

The following section looks at the effect of Earlywood /Latewood (EW/LW) layer orientation on inferring moisture content from permittivity measurements.

Wood has an anisotropic structure that arises from the cell pattern laid down in a defined direction by seasonal changes while the tree is growing. This EW/LW layering has the effect of ducting the microwave energy in a preferred direction

The change in polarization of the microwave fields due to EW/LW layering has given rise to many systems proposed for the measurement of grain angle. One such system was developed by King (1985), which involved a rotating antenna that used the angle of the antenna and a maximum in the received signal to determine the grain angle of lumber.

This EW/LW experiment (Figure 8) showed the cyclic variation in permittivity due to the EW/LW regions. The step change is due to the second sample having a significantly higher basic density. This graph does demonstrate the difference in permittivities of EW and LW. Holmes (2011) undertook coaxial probe permittivity measurements, which were made on a number of sawn lumber samples. The measurements where made every 5mm and the permittivity for two samples was plotted versus distance across the sample to produce figure 8.

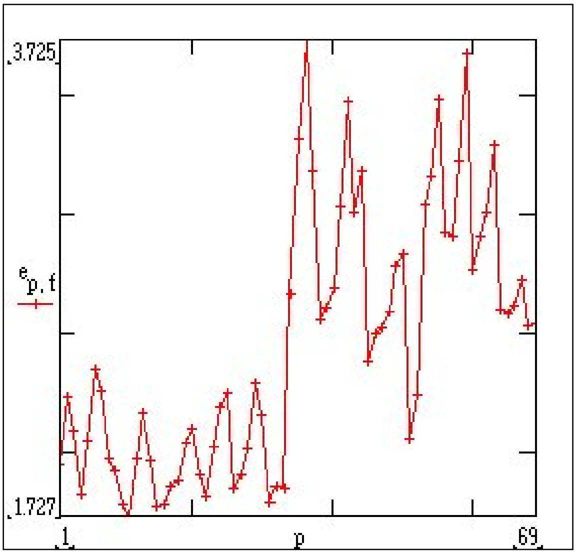

Fig. 8. EWLW variation across wood sample

The measurements undertaken in the previous sections purposefully covered the full range of EW/LW layer orientations so as to reflect flat, intermediate and quarter sawn lumber.

Hence to examine the effect of this, the data covering flat and intermediate sawn were chosen to repeat the error analysis. Figure 9 below using only this data shows that the RMS error in moisture content using density correction is now reduced to 0.63%.

Hence, we can see that much of the residual error in the previous section can be demonstrated to be due to the effect of EW/LW layer orientation.

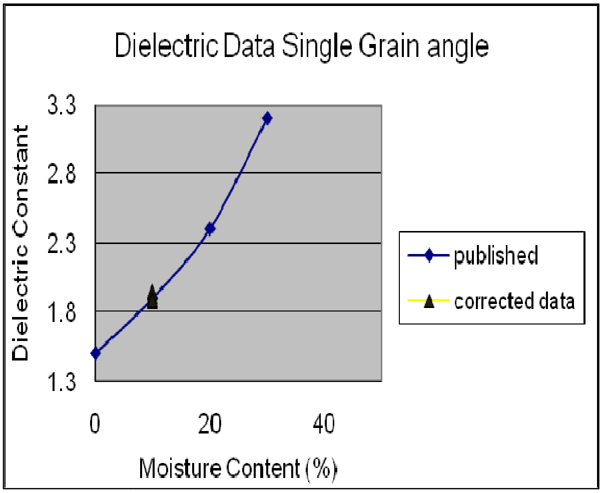

Fig. 9. Density corrected measurements for flat and quarter sawn samples

5 Conclusions

These experiments have provided us with the bulk permittivity data for various log samples and wood types, whilst averaging out the effects of smaller structural effects such as basic density and EW/LW bands.

In order to achieve a useful image with sufficient contrast we require that the differing structures have permittivity's which are sufficiently different. These differences will create a significant reflection at the media boundaries. From this work, we have shown that measurements at frequencies greater than 4GHz is required to clearly differentiate between Sapwood, branches and Heartwood

Resolution is also an issue in microwave images, which is usually handled by either increasing frequency and/or frequency bandwidth or by performing multiple measurements separated spatially as in Synthetic Aperture Radar.

The permittivity difference between early and late wood is large and if an imaging system has sufficient resolution then these structures will be clearly visible in the image.

Penetration into a media is also a commonly held concern as the moisture present in the material is seen to absorb the microwave energy. However, little attention is given to the manner in which the water molecule is bound within the material, and as this work has shown it gives rise to a lower attenuation than expected.

This work has also shown that there is the potential to accurately determine the moisture content of the log, whilst catering for the large variation in basic densities. This has the benefit of allowing for spatial corrections to be made to the image and hence the accurate positioning of features of interest, such as internal branches and the heart sapwood boundary.

Acknowledgment. The Authors would like to thank Scion and its staff for funding this work and their work on sample gathering and preparation.

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