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THE EFFECTS OF LUMBER SEASONAL GROWTH RINGS ON MICROWAVE MEASUREMENTS

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Abstract—*In order to determine more accurate indicators of wood structure obtained by microwave sensing and improve our understanding of plane wave propagation through this complex material, we have undertaken a permittivity survey and experimentally investigated scattering of a plane wave, measuring its transmission over two non-parallel surfaces of a rectangular lumber sample. This novel non-destructive testing technique offers results which may significantly contribute in a more accurate propagation modeling and industrial wood quality testing.*

Index terms: microwave, non-destructive testing, free-space transmission measurement, wood

I. INTRODUCTION

The following paper looks at the effect of seasonal growth layers laid down in the wood during the life of the tree on microwave properties of the wood. During the summer period the growth rate of the tree is faster and the wood cells tend to be larger and have thinner walls than those lain down during the colder winter periods [1-3]. This summer wood is commonly called Early wood whilst the winter growth is called Late wood. Fig.1 shows a microscopic image of a wood sample where this difference in cell wall thickness and cell size can be clearly seen.

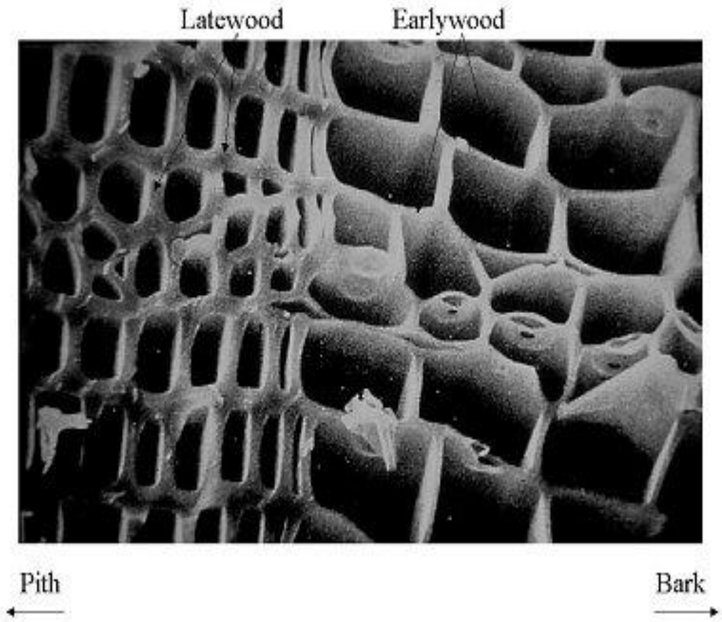

Figure 1. Microscopic image of Earlywood Latewood Structure

Wood is strongly anisotropic, both in its physical strength and in its electrical properties [2,3]. It is common to describe wood anisotropy using vectors aligned with its principal directions: axial, radial and tangential. Radial and tangential directions are related to the Earlywood/Latewood (EW/LW) layering, while the axial direction is aligned with wood grains [1], commonly running along the main vertical axis of the log.

Dielectric properties of wood are described by a permittivity tensor. Permittivity of wood is larger along wood grain and smaller across the grain, in either radial or tangential direction. Two permittivity values in transverse direction also differ, although for practical purposes, this small difference can be neglected. So, permittivity of wood is often described using two complex permittivity values: permittivity in radial and tangential direction, collectively referred to as a permittivity ‘perpendicular to grain’ or 'across the grain’, and permittivity in the axial direction, known as permittivity ‘along the grain’.

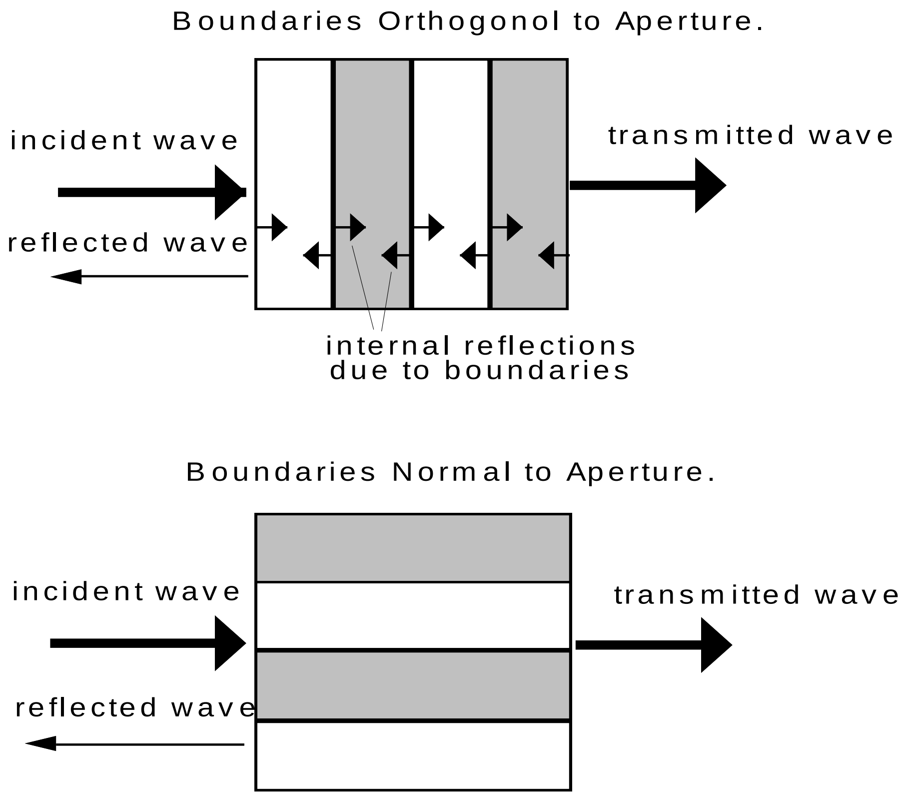

Figure 2. EW/LW layering

Many systems and techniques have been developed and proposed for the measurement of wood properties such as moisture content , basic density and grain angle (direction of wood fibres) [4], however very few have attempted to extract or account for the impact of early wood /latewood layer orientation. Previous study reported by Holmes et al. [5] indicated the potential need to incorporate the effect of EW/LW layering and the potential to improve the accuracy of moisture measurements. This EW/LW layering has the effect of ducting the microwave energy in a preferred direction as illustrated in Figure. 2.

In a previous study by Holmes at al. [5][6] coaxial probe permittivity measurements 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 3, reproduced from [5].

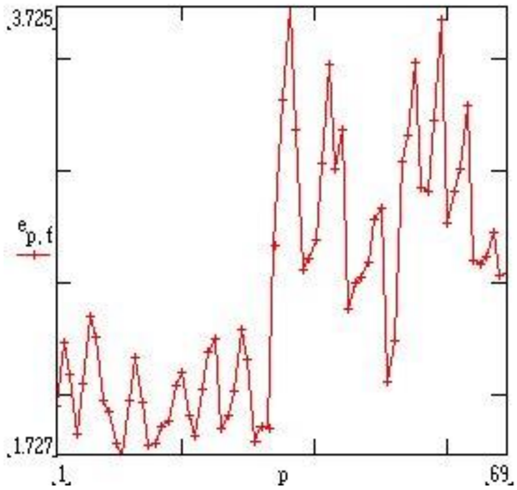

Figure 3. EWLW variation across wood sample

This EWLW experiment 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 due to a mix of heartwood and sapwood within the sample. This published graph does clearly demonstrate however the localised differences in permittivity between EW and LW.

In order to confirm the importance of seasonal growth layers in wood to microwave measurements, two separate experiments were undertaken. The first experiment is a standard waveguide permittivity measurement survey examining the effect of EW/LW layering on the measured dielectric properties. The second experiment looks at the effects on a free space scattering approach and hence examines the effects on propagation of the EW/LW layers.

II. Permittivity Measurments

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 and the microwave energy interacts with the entire volume of the sample.

Wave guide cell measurements involve inserting a sample inside a waveguide and measuring the microwave reflection from and transmission through the sample. Then using the Nicholson-Ross-Wier (NRW) algorithm [7] these two measured coefficients yield the complex permittivity of the sample material.

There are many techniques for determining the dielectric constant of a material filling a waveguide, however the NRW method is universally seen as the most accurate and also accommodates imperfections in sample preparation such as sample faces and wall air gaps. The NRW method works well for all frequencies away from the TEM mode resonances that occur when the sample is a multiple of half wavelengths in the waveguide, and also for high to medium loss materials.

The permittivity of the material is determined by the equation;

$$\varepsilon = \frac{c^2}{\omega^2}\left[\left(\frac{2\pi}{\lambda_c}\right)^2 - \frac{1}{L^2}(\ln Z + j2\pi n)^2\right]/u_r$$

Where

for non-ferrous materials the relative permeability $u_r = 1$

c is the speed of light

ω is the angular frequency

λ_c is the cut-off wavelength of the waveguide

L is the waveguide cell electrical length

and

$$Z = \frac{x+1}{2y} \pm \sqrt{\left(\frac{x+1}{2y}\right)^2 - 1}$$

And

$$x = (S_{21}S_{12} - S_{11}S_{22})e^{2\gamma_{0(L_{air}-L)}}$$

And

$$y = (S_{21} + S_{12})e^{\gamma_{0(L_{air}-L)}}$$

Where γ_o is the free space propagation constant and S11,S12,S22,S21 are the measured S parameters from the network analyser. In essence the permittivity is determined by the measurement of the group delay through the measurement cell and the correct value of n is determined using this.

The samples used in this experiment came from the samples used to determine density from a previous trial and have been stored in a sealed plastic bag for over 12 months hence allowing the sample moisture contents to equilibrate. The final sample moisture contents achieved was 10.3 +/- 0.1 % and their density values had previously been determined by Scion.

The samples where cut to as best as possible to give the two extremes of Earlywood \Latewood orientation (flat and quarter sawn). Most samples density's chosen lay in the around 350 kg/m3 +/- 10Kg/m3 however two samples were chosen around 450Kg/m3. In addition, the percentage of late wood for the volume of the sample was measured.

The measurements were made using an H band waveguide (4-8GHz) 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 [7] algorithm.

As expected due to the low moisture content of the samples and the tightly bound nature of the remaining water in the wood cells, the permittivity values measured with respect to frequency were essentially constant across the measured frequency range as shown below for six of the samples in Figure 4 .

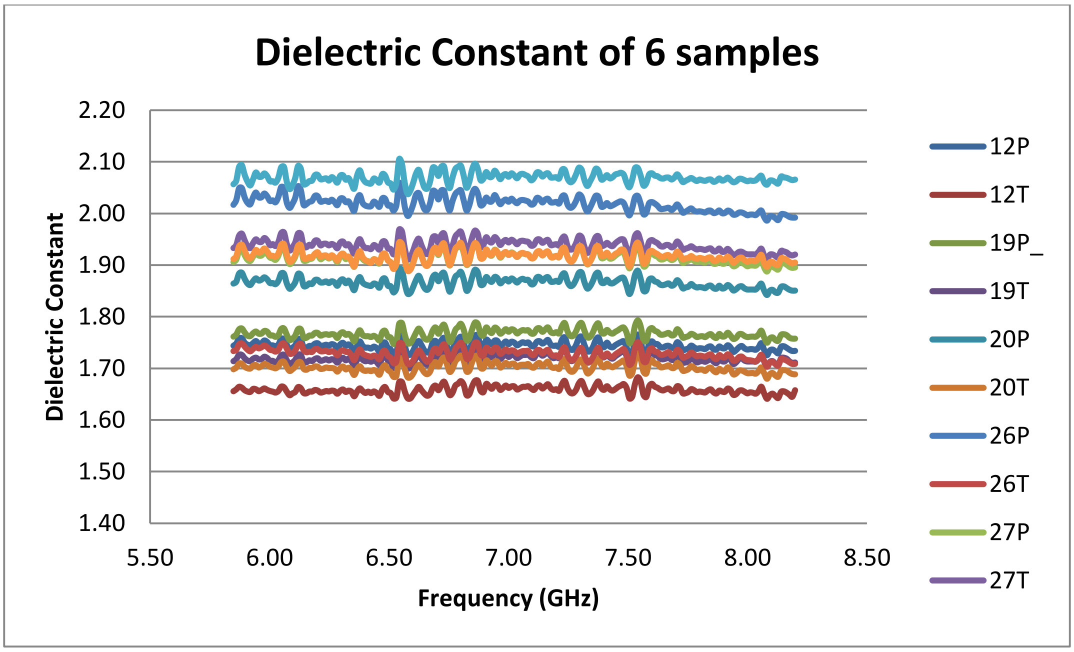

Figure 4. Dielectric constant versus frequency for 6 samples both Parallel and Tangential to

When we assess the dielectric constant for the all the samples with respect to percentage of latewood in each sample the plot shown in Figure 5 was produced.

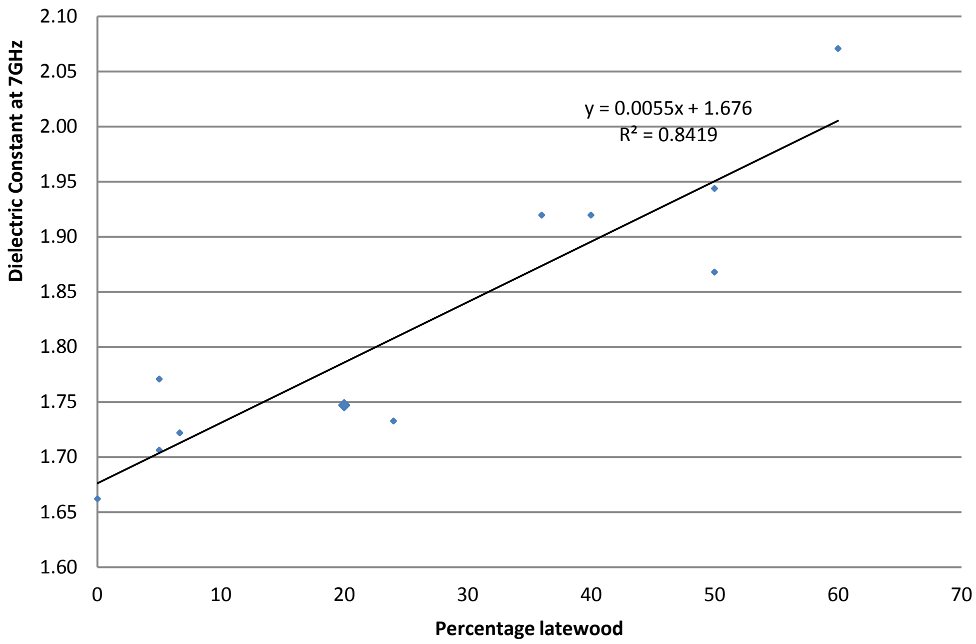

Figure 5. Measured Dielectric constant at 7GHz versus percentage late wood in the sample

From this plot we can see immediately that there is a strong linear correlation between the measured dielectric constant and the percentage of latewood in the sample giving an R^2 value of 0.84.

A second correlation with respect to basic density was also produced and presented in Fig. 6. This Figure also demonstrated, as expected, that basic density also represents a major contributor to the overall permittivity of the wood sample with an R^2 value of 0.78.

In order to determine whether the latewood ratio was influenced by basic density a further correlation was performed between basic density and latewood ratio. The result of this is shown in Fig. 7. This showed that there appears to be little correlation between these two factors and this is support by a very poor R^2 value of 0.57.

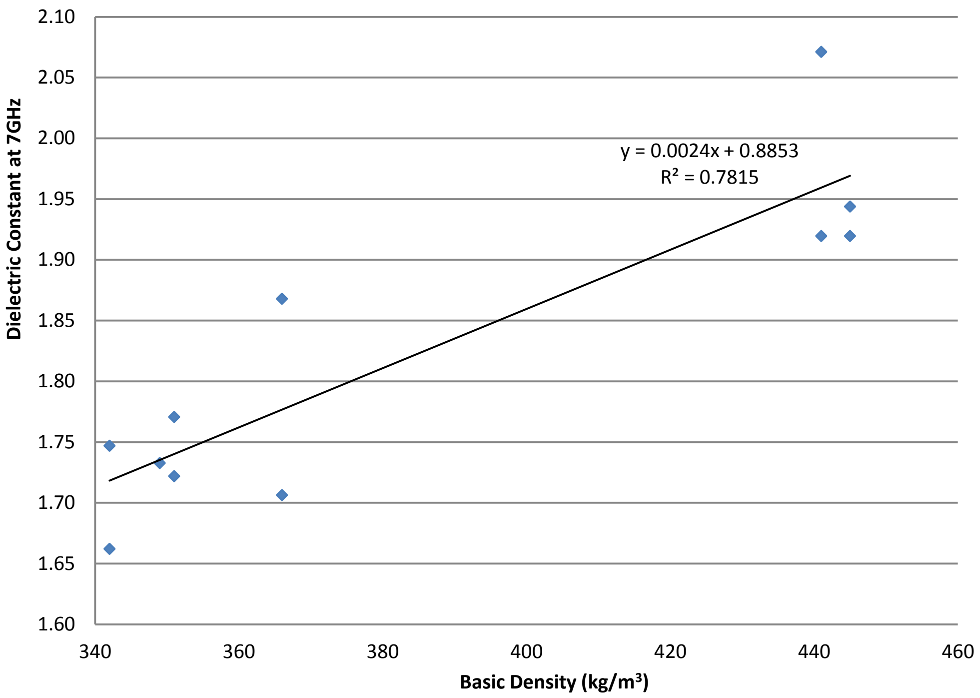

Figure 6. Measured Dielectric constant at 7GHz versus Basic Density

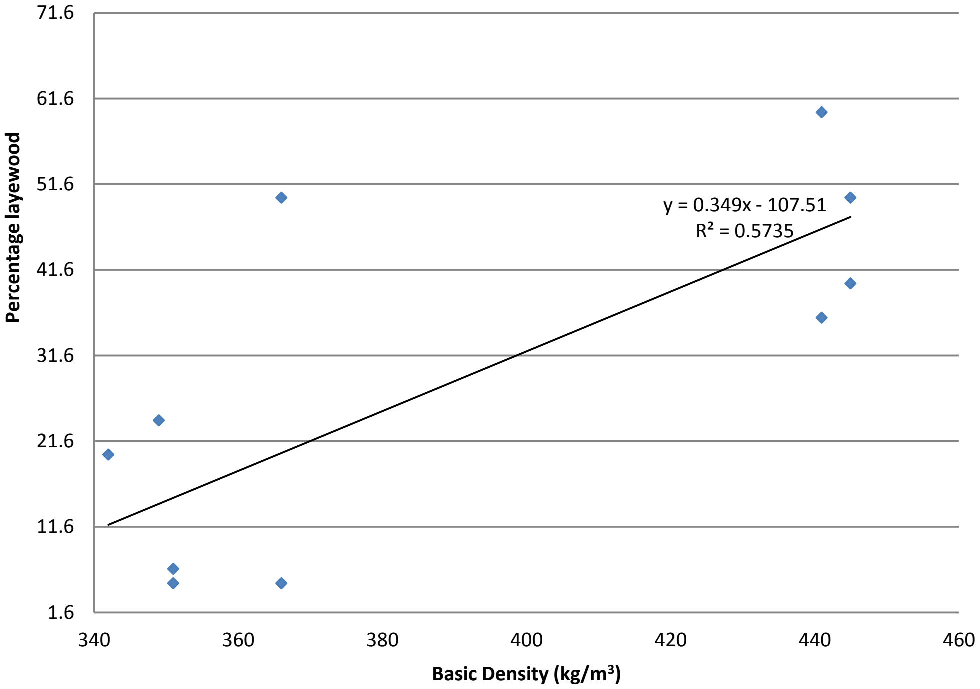

Figure 7. Percentage Latewood versus Basic Density

An alternative approach is to use the density independent function developed at the USDA by Trabelsi and Nelson [8] to remove the effects of basic density from the permittivity measurement. 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 independence of density was reported by Trabelsi et al. [8] and has the form

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

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

The function was applied to the measured permittivity data and the subsequent results are presented in Fig. 8. Again the results showed a good correlation between the density independent factor Ψ and the percentage of latewood in the sample giving a much improved R^2 value of 0.91.

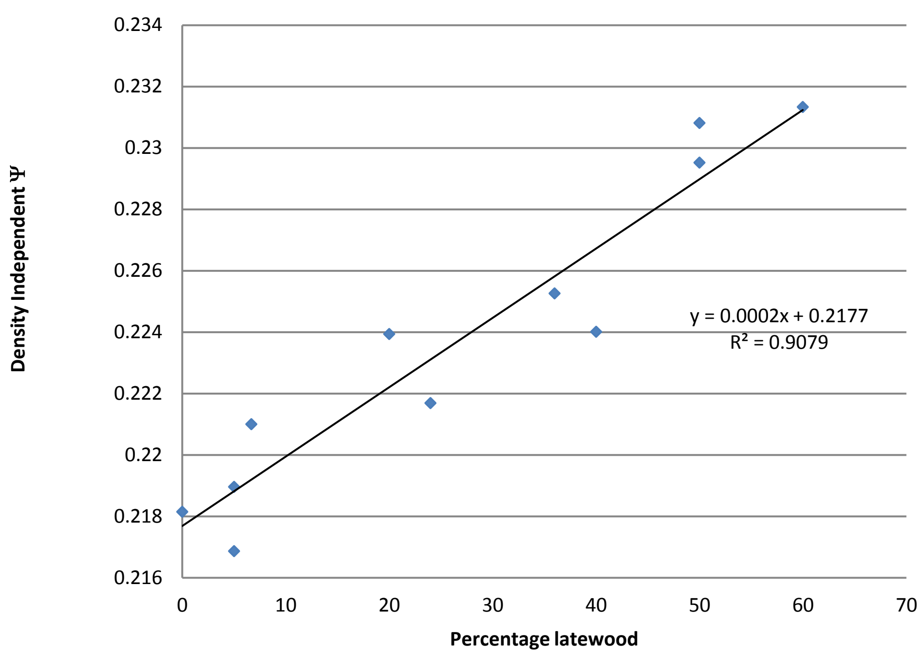

Figure 8. Density Independent Factor at 7GHz versus Percentage Late wood

III. FREE-SPACE SCATTER MEASUREMENT

Non-destructive, non-contact inspection of material properties is commonly performed using a free-space transmission measurement system with receiving and transmitting antennas in a co-linear arrangement [9]. This technique was used in the wood testing industry [4], but limited success was achieved in propagation modeling, due to a great complexity of wood structure. Wood is an anisotropic, heterogeneous material, yet propagation through it is often modeled as simple plane wave propagation [10].

To get a further insight into propagation mechanisms through wood and determine a new indicator of wood structure, we have investigated scattering of a propagated plane wave measuring it over two non-parallel surfaces of a rectangular lumber sample. To achieve that, a microwave transmission measurement system with a focused beam antenna was used. To take into account wood anisotropy, we have rotated measured sample allowing incident wave to reach each sample face in turn. Findings reported in this paper further contribute to our understanding of wave propagation through wood and have not been published to date.

Measured microwave transmission coefficientwas correlated to several structural properties of wood. Initial hypothesis, that a strong scatter in sideways direction impliesa presence of defect in wood structure, was tested first. Further, a correlation between scatter magnitude and density was investigated, including the effects of both defects and slow density variation. Finally, wood was considered as a layered media, with distinctive denser early wood and less dense late wood layers. An influence of the grain angle and moisture content has not been observedin this paper.

A. *Free-Space Measurement Setup*

Measurement of transmission coefficients in dB at 201 frequency points over the frequency range of 8 to 12.4 GHz was performed using Agilent 5230C Four-port Vector Network Analyzer (PNA-L), after a full two-port calibration procedure, as shown in Fig.8. Transmitting antenna was a standard linearly-polarized horn with a pair of dielectric lenses, focusing the beam to a 6 cm spot at the distance of 17 cm. Receiving antenna was a linearly polarized horn. The sample under test was positioned vertically in front of the lens antenna at the focal distance, so that vertical nominal polarization was aligned with the axial direction of the wood.

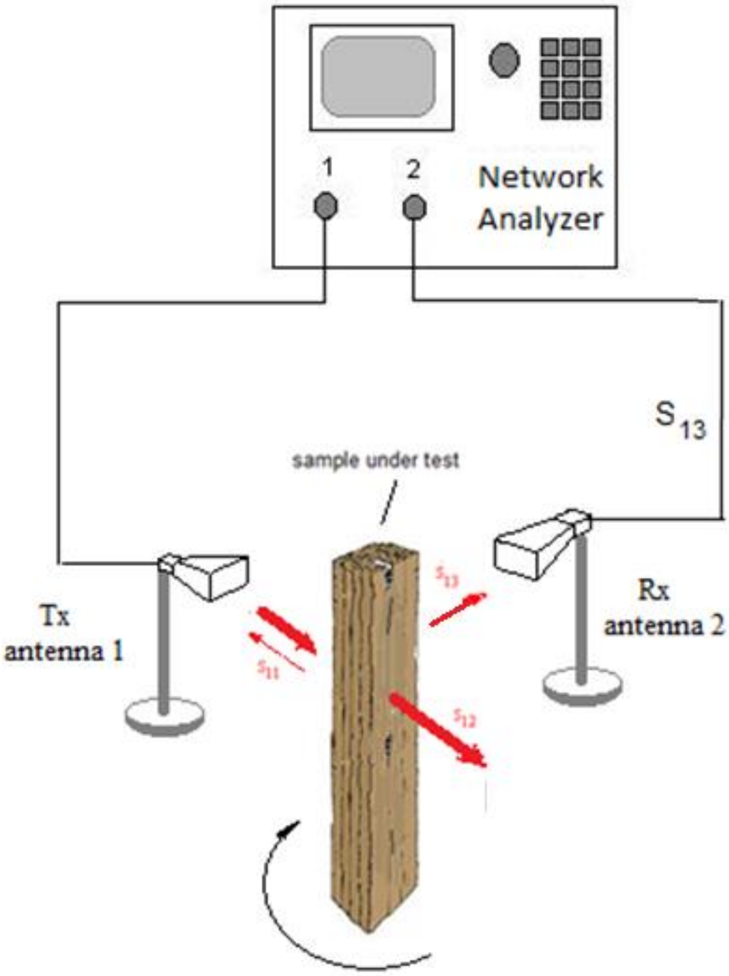

Figure 9. Measurement setup

In order to describe the wave transmission in the observed direction, a scatter transmission coefficient S_{13} was defined. S_{13} is considered as a coefficient, as it is a normalized value. It is measured as a transmission from antenna Tx to the receiving antenna Rx, when these are positioned at 90° to each other (Fig. 9). Microwave data werefurther processed by averaging measureddB values of scatter coefficient's magnitude over the frequency range, providing a single numerical value of S_{13} for each sample. As wood is an anisotropic material, this value changes for each observation direction. Thus each sample was rotated around the vertical axis, for transmission measurement from all four directions. In addition, its value changes with polarization, but,only nominal vertical polarization datawas presented here, as an initial study recommended itas the most indicative.

Measurements were performed on 22 Pinus Radiata samples, with dimensions 5x10x40 cm. Measured microwave scatter coefficient relates to the volume illuminated by the 6 cm wide Gaussian beam at 24 cm height on the sample under test. To get reference values for wood interior structure and density / density variation of wood in the observed volume, a CT scan was performed at ASCOT Radiology in Auckland, New Zealand. The results were saved in a Dicom 3 format and software for viewing the images was MxLiteView (Version 1.18), by Phillips Medical Systems Inc., Cleveland, USA.

B. *Measured Scatter Coefficient and Data Analysis*

Frequency response of the scatter coefficients $S_{13}$for 22 measured samples is plotted in Fig. 10. To determine a wood property which causes the noted variations in response, we investigate correlation between microwave measurements and each of the following four wood properties: bulk density, density variation (slow varying density), presence of defects (sharp varying density) and early wood/ late wood pattern.

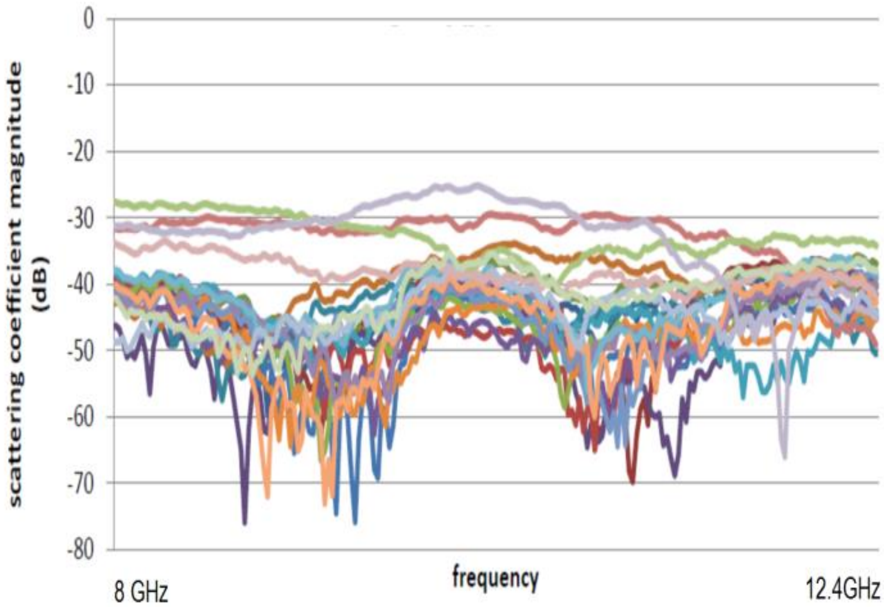

Figure 10. Scatter coefficient S_{13} magnitudes vs. frequency (8 to 12.4 GHz range) for twenty two samples, measured in nominal vertical polarization

a) *Scatter Coefficient and BulkDensity*

A mean value of density related quantity was obtained from CT scans using the Dicom viewer. The density of samples was correlated with four scatter coefficient values obtained by rotating the sample by 90° after each measurement. A very poor correlation was obtained, with R^2 values for front, back, left and right observation direction being: $S_{13front}$=0.158, S_{13back}=0.193, S_{13left}=0.084 and $S_{13right}$= 0.004. It can be thus concluded that variation in the measured scatter coefficient is not caused by the change in sample density.

b) Scatter Coefficient and Density Variation

The scatter coefficient $S_{13}$was correlated to a slow variation in density within the volume of the sample illuminated by the microwave beam. In this hypothesis, the transmission S_{13} is considered as a consequence of scattering from the boundaries within the sample. The maximum and minimum brightness value, indicating change in density within the sample, are obtained from CT scans using Dicom viewer. Then, a difference between minimum and maximum readout values was calculatedas a parameter showing density variation. This value was then correlated with measured microwave scatter coefficientS_{13}. The correlation is very poor and R^2 values for four direction of observation are: $S_{13\ front}$ =0.0383, S_{13back}= 0.0565, S_{13left} =0.0597 and $S_{13right}$ = 0.0765. Thus small variations in density within the sample do not contribute to the sideways scatter.

c) Scatter coefficient and defects

Based on the visual inspection and CT scans, defects and variations in wood structure were detected within the observed volume and samples were categorized into four groups: (1) clear samples, (2) samples with variation in annual rings, (3) samples with pins and (4) samples with knots. In the following step, it was observed how well measured microwave data fits within these groups. Measured values were sorted in ascending order, presented in a bar graph (Fig.10) and sample category was written in the base of each bar. In addition, a color coding was introduces, with green color for clear samples (1), orange for samples with variation in annual rings (2), blue for samples with pins (3) and red for samples with knots (4). Measured S_{13} values for 22 samples observed from the front side in VV polarization are presented in Fig. 8.

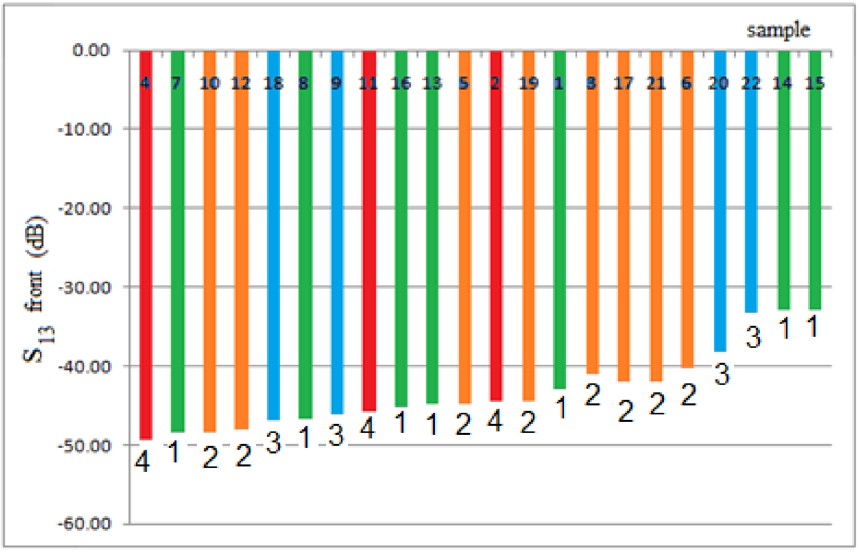

Figure 11. Scatter coefficient in descending order with noted sample categories

We have expected to see clusters of the samples with the same color / category number. Unfortunately, none of the four observation directions shows clustering. It is clear that defects do not determine the level of scattering in the sideways direction.

d) Scatter CoefficientandAnnual Ring Arrangement

Finally, the samples are grouped based on the pattern made by annual rings (i.e. layers of early and late wood) in the sample cross section. Fig. 12 shows five sample categories, starting from category A (color code navy blue) with annual ring in vertical position and going gradually towards red which is category E with horizontal early wood / late wood pattern. Images of representative samples are given in Figure 11, while the bar graph above shows frequency-averaged scatter coefficient S_{13} in dB measured in front direction. Sample 21 is an odd one out as it does not fit in any of the categories due to a twist in grains along the sample.

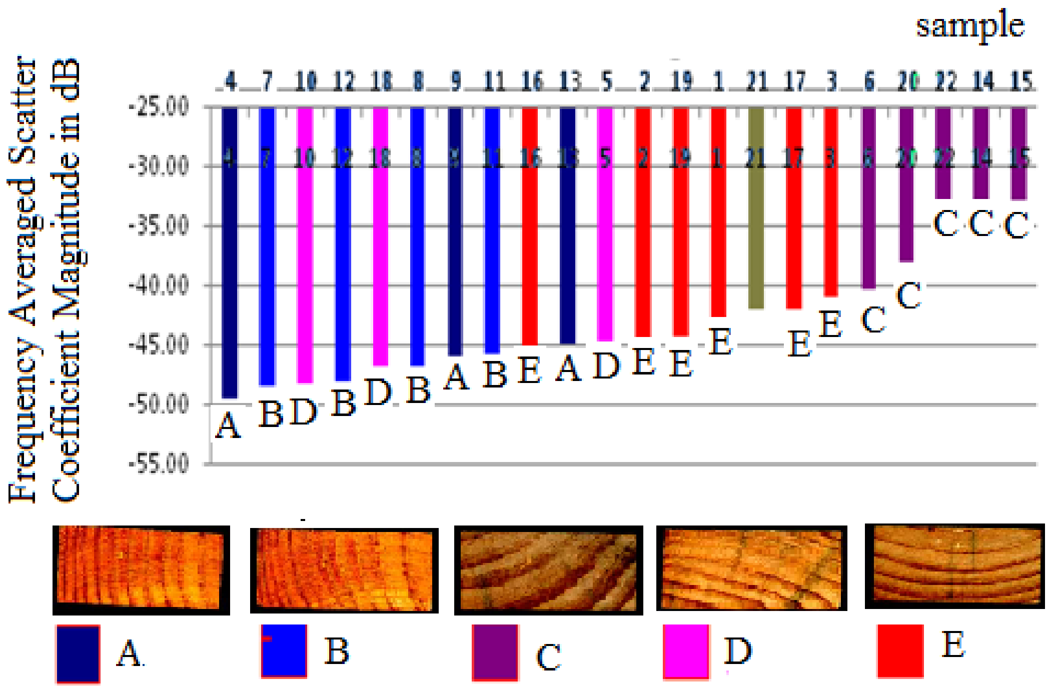

Figure 12. Frequency Averaged Scatter Coefficient Magnitudes and samples grouped by the annual ring pattern

Observing the bar graph for mean values of scatter coefficient S_{13} , it can be noted that samples in Category C have much higher level of scatter: samples 6, 20, 22, 14 and 15. These samples have the arrangement of the early wood and late wood layers positioned in such way that they look like guiding structures, guiding the waves towards the antenna in the S_{13} position, as the image of sample in Category C (in the middle) illustrates.

IV. CONCLUSION

Overall this paper has demonstrated the significance of the EW/LW layering on microwave measurements made on low moisture content lumber.

The result of this permittivity survey showed that the percentage of latewood has a large effect on the permittivity of low moisture content wood samples, and that the effect is comparable to that of basic density. It has also shown that these two factors are substantially independent variables.

For the Scattering experiment, contrary to expectations, the variation in density does not cause a scatter. A possible explanation for the obtained results is to consider wood as a layered dielectric media and the propagation of modes excited in such structure to be the cause of higher value of measured Scatter Coefficient. Schinker et al. [11] report the variation in effective permittivity in early wood and late wood layers. Effective permittivity depends on the volume portion of dry matter and higher percentage of dry matter means higher permittivity of the observed volume.

This Study has shown that the addition of the ratio of latewood, as an important parameter for microwave sensing systems for wood, should greatly improve the accuracy of these techniques.Further work is required in developing techniques to assess this ratio before it can be realized in a wood measurement system.

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