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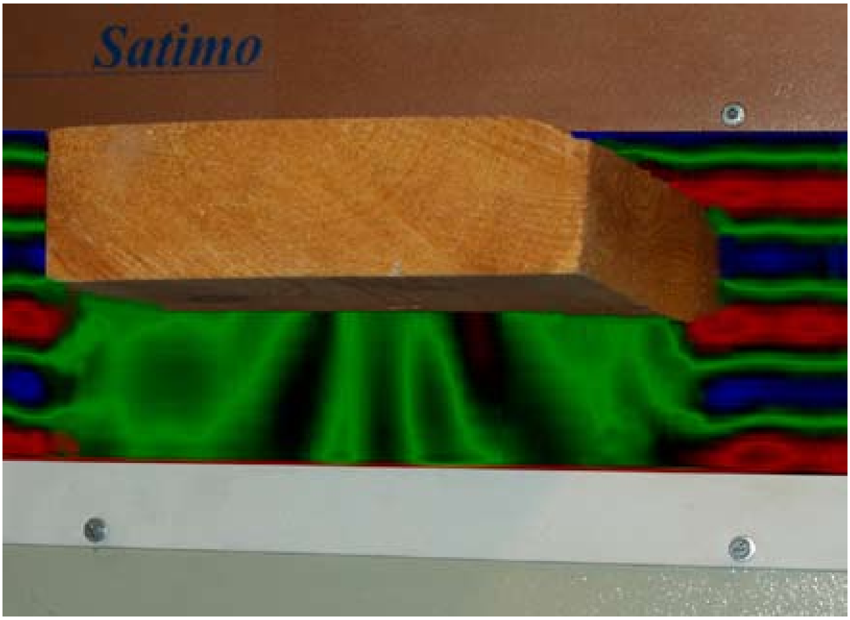
LICENTIATE THESIS

Modelling Microwave Measurements in Wood



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Modelling Microwave Measurements in Wood

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Abstract

The purpose of the present study was to evaluate a microwave sensor for prediction of wood properties and for strength grading of lumber. It was also the purpose to analyze the interaction between wood and microwaves in order to propose improvements to the sensor and to the methods of interpretation of the measurements. Finite element models have been developed in order to analyze how microwaves interact with the internal structure in wood. It is possible to simulate how the sensor responds to variations in different wood properties by making changes in the model. Simultaneous prediction of moisture content and density is possible, but requires careful calibration or modifications of the sensor. The correlations found when modulus of rupture was predicted from microwave measurements are promising, even if there was considerable uncertainty in the reference measurement.

Keywords: microwave scanning; density; moisture content; strength grading; finite element

Preface

For nearly three years, I have tried to understand the way different properties in wood will affect a microwave signal and the algorithms used to describe these effects. Stephen Hawking once wrote:

” If everything in the universe depends on everything else in a fundamental way, it might be impossible to get close to a full solution by investigating parts of the problem in isolation. Nevertheless, it is certainly the way that we have made progress in the past.”

The use of computers and multivariate analysis has made it possible to investigate (almost) everything at once and I have used this method to find out how different variables are related. However, if we want to explain the correlations that we find, there will still be need for the old fashioned way of breaking the problem into small parts.

The work presented in this thesis was carried out at Luleå University of Technology, Skellefteå Campus, under supervision of Professor Olle Hagman and Professor Anders Grönlund. The project was financed by the SkeWood program, through the Swedish Agency for Innovation Systems (Vinnova) and the Kempe foundation. Special thanks to: Olle for sharing his knowledge about microwaves, image processing and multivariate analysis; Jan Johansson who designed the scanner system and participated in my work during the first year; Lena Antti and Lars Hansson who have helped me to understand wood, microwaves and how they interact. Finally thanks to all my colleagues at Campus Skellefteå for the help I have received and for good company.

Skellefteå, September 2005

Nils Lundgren

List of papers

I. Hansson L, Lundgren N, Antti L, Hagman O. *Microwave penetration in wood using imaging sensor.* Accepted for publication in Journal of International Measurement Confederation (March 2005)

II. Hansson L, Lundgren N, Antti L, Hagman O. *FEM simulation of interactions between wood and microwaves*. Submitted to Journal of Wood Science (April 2005)

III. Lundgren N, Hagman O, Johansson J, *Predicting moisture content and density distribution of Scots pine by microwave scanning of sawn timber II: evaluation of models generated on a pixel level.* Accepted for publication in Journal of Wood Science (June 2005)

Contribution to the included papers

I and II	The work was done by the author in collaboration with Lars Hansson with supervision and comments by Hagman and Antti.
III	Most of the work was done by the author with supervision and comments by the co-authors of the paper.

Contents

1. Introduction

1.1 Background

The number of commercial applications for microwaves has been constantly increasing over a wide range of areas such as communication, heating and measurements. Sensors based on microwave technology provide several advantages for industrial applications:

- Microwave sensors are fast enough for online measurements.
- The sensors do not need mechanical contact with the material.
- The tested material is unaffected by the measurement.
- Microwaves penetrate all materials except for metals, which makes it possible to measure interior properties.
- Electromagnetic radiation at low power levels is safe in contrast with radioactive radiation.
- The multivariate character of the signal can be used to deduce more than one property of the measured object.

Microwave techniques that are suitable for prediction of wood properties have been recapitulated by Nyfors and Vainikainen.[1] More recently, different methods for nondestructive imaging of the internal structure of wood are provided by Bucur[2], with descriptions of microwave techniques that have been proposed for inspection of forests, logs, lumber and composites. An interesting application for microwaves that has been studied by Kaestner[3] is three-dimensional imaging. It has also been shown by, among others, Shen et al.[4] that microwaves can be used to measure the grain angle in wood. One disadvantage with images obtained from microwaves is the poor resolution compared to X-rays or IR imaging. The use of modulated scattering technique (MST) is one way to increase resolution at a low cost, and such applications have been developed by James et al.[5] and by Bolomey et al.[6]

It is possible to use microwave sensors for concurrent prediction of density, grain angle and moisture content (MC) since microwaves are affected by several properties in the wood. At the same time, the complex relations make it difficult to separate influences from different wood properties. One way of solving this problem is the use of multivariate models. This has been done by Johansson et al.[7] for prediction of density and MC. Since the properties in wood that affect microwaves are also related to strength, microwave sensors have been tested in stress-grading applications. These sensors have improved stress grading with bending machines.[8] It has also been shown by

Johansson[9] that strength grading of lumber with no other information than microwave measurements is possible.

The inhomogeneous structure of wood complicates calibration and interpretation of the measured signal. Thus the use of microwaves has not yet reached its breakthrough in the wood industry, while there is an increase in commercial applications for microwave measurement of homogeneous materials. The purpose of the present study was to evaluate the sensor used by Johansson[9] for prediction of wood properties and for grading of lumber. It was also the purpose to analyze the interaction between wood and microwaves in order to propose improvements to the sensor and to the methods of interpretation of the measurements.

1.2 Outline

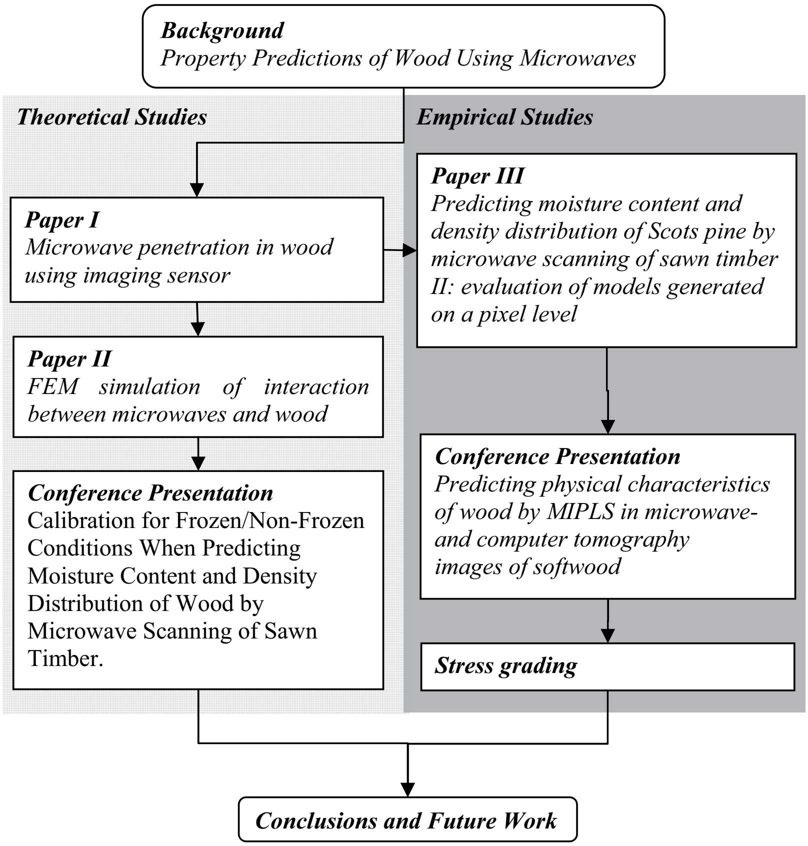

Figure 1: Working procedure for this thesis.

The work leading to this thesis consists of empirical studies in combination with theoretical calculations and simulations of how microwaves interact with wood. All microwave measurements were made with a scanner developed at Luleå University of Technology, Campus Skellefteå.[9] The working procedure is shown in figure 1, where the studies have been divided into two groups depending on whether the focus was set to calculate and verify theoretical models or to generate empirical models by using multivariate calibration. Paper I describes a calibration of the scanner in which measurements were compared to calculated values. This work is continued in Paper II, where simulations of the electromagnetic field within a cross section of wood are described. Finite element modelling is used to describe the variation of dielectric properties. A preliminary study of the response from scanning of frozen wood was made and presented at Forest Products Society's annual meeting in Grand Rapids.[10]

Paper III describes an experiment in which prediction models for MC and density were calibrated. The variables from the microwave scanner were used as predictors in a multivariate model. A multivariate image analysis based on measurements from paper III was presented at the Forestry Wood Chain conference in Edinburgh[11]. Finally, some of the boards that were measured in paper III were also graded by destructive four-point bending. Prediction models for strength and elasticity based on the microwave measurements were calibrated and evaluated.

1.3 Theory

1.3.1. Microwaves

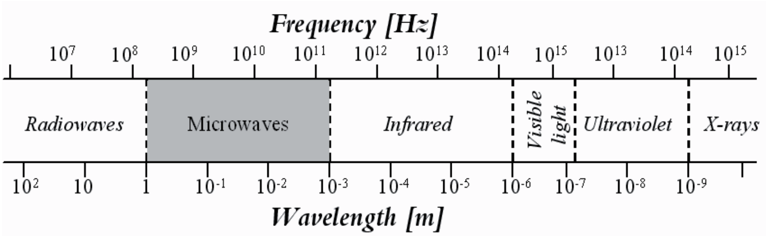

Figure 2: Electromagnetic spectrum with the wavelength in free space.

The electromagnetic spectrum shown in figure 2 covers a wide range of waves with different properties depending on the frequency, f, of the wave. The wavelength, λ is related to frequency through the speed of propagation ($c = \lambda \cdot f$) where c equals the speed of light in free space.

Microwaves are usually defined as electromagnetic waves in the frequency region from 300 MHz to 30 GHz. This means that the wavelength in free space has the same order of size as the components used for generation and detection of microwaves.

1.3.2. Dielectric properties of wood

When an electromagnetic wave is transmitted through a dielectric, there will be attenuation and a delay in the signal compared to a wave travelling through free space. Descriptions of how microwaves are affected by the material are given by Nyfors and Vainikainen[1], among others.

Figure 3 shows propagation of microwaves in free space compared to propagation through a dielectric.

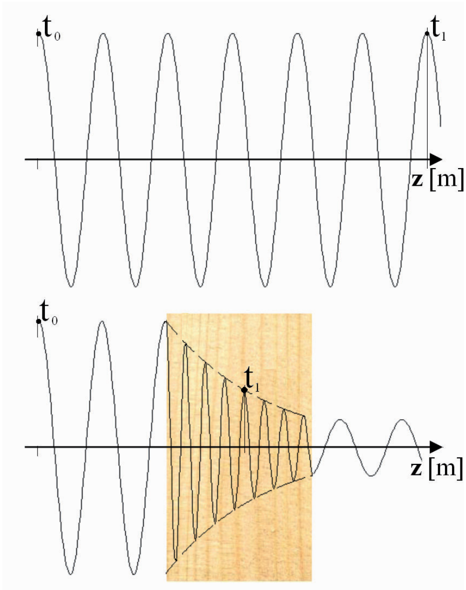

Figure 3: If a signal is initiated from a transmitter at time t_0 it will arrive later at the receiver if it must pass through a dielectric. There will also be an attenuation of the signal.

The electric field, **E**, from a wave moving in the z-direction at time *t* can be described mathematically by the equation:

$$\mathbf{E} = \mathbf{E}_0 e^{j\omega t - (\alpha + j\cdot\beta)z}, \qquad [1]$$

where the attenuation factor, α, and the phase factor, β, depend on the dielectric properties of the material in which the wave propagates. By measuring these factors it is possible to decide properties of the dielectric such as relative permittivity, ε', and relative dielectric loss factor, $\tan\delta$. Sometimes it is more convenient to use the index of refraction,

$$n = \sqrt{\varepsilon'}\,. \qquad [2]$$

In wood these properties will depend on density, MC, temperature and frequency of the electromagnetic wave. The influence on the electric field will be direction dependent, since the dielectric properties of wood are anisotropic. This makes it possible to calculate the grain angle by measuring the polarization of the transmitted or reflected field.

2. Calibration and Simulations

2.1. Microwave Scanner

The scanner system that was used in this study was developed at Luleå University of Technology, Campus Skellefteå, by Johansson[9]. The system is based on a sensor from Satimo[12] and modulated scattering technique as described by Bolomey and Gardiol.[13] During scanning, the wood is illuminated by a quasiplane wave, i.e., a wave where small deviations from the pure plane wave are tolerated. The real and imaginary parts of the transmitted electromagnetic field are measured in two orthogonal polarization angles at every 8th mm. By combining the sensor with a conveyer it is possible to obtain two-dimensional images. Paper I contains a thorough description of the microwave scanning system.

2.2 Calibration

Calibration of the sensor as described in paper I was done by comparing the measurements with theoretical values of attenuation and phase shift for microwaves transmitted through birch wood with varying thickness, dry density, MC and temperature. There was good agreement in measured and theoretical values, but the measured attenuation contained a lot of noise.

A preliminary study on how the response from the scanner depends on the temperature of the wood[10] was done for Scots pine (*Pinus* sylvestris). Figure 4 shows how the measured phase shift increases with temperature. The high moisture content in sapwood gives a steeper curve as compared to heartwood.

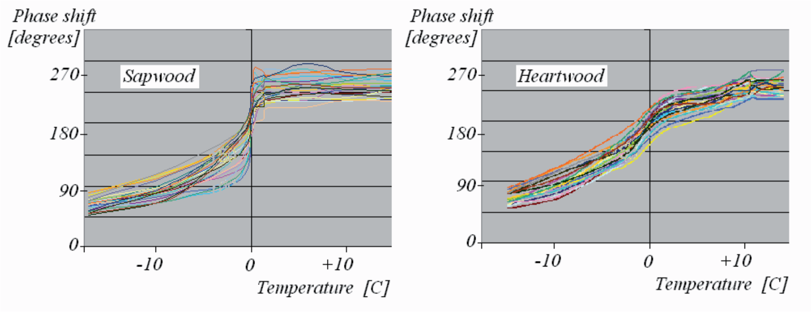

Figure 4: Variation in phase shift of a microwave signal transmitted through a piece of green pinewood at different temperatures. (Hagman et al.[10])

Figure 5 shows how the amplitude of the measured signal changes at different positions and temperatures. It is impossible to calibrate the scanner for measurements during thawing since a small change in the relations between frozen and nonfrozen wood will give a large change in the response from the sensor. Calibration for prediction of moisture and density can be done when the temperature is well below, or above, 0 C. The influence of water will be much less for measurements on frozen wood, which might be used to increase the penetration depth in green wood.

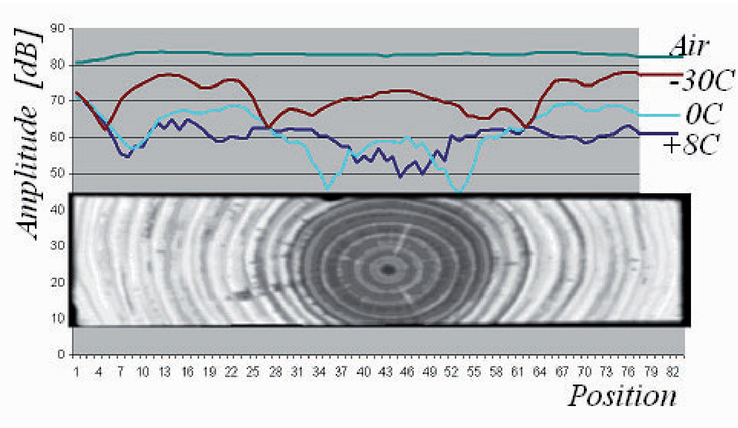

Figure 5: Variations in amplitude of a microwave signal transmitted through a piece of green pinewood at different temperatures. (Hagman et al.[10])

2.3 Simulations

Interactions between wood and microwaves were simulated in order to explain how the sensor responds to variations within the wood. The models, which were developed in paper II, were constructed with the finite element method as described by Jin[14], among others. Partial differential equations (PDEs) that describe the wave propagation were solved using the electromagnetic module in FEMLAB version 3.1 software from Comsol.[15] Density data from computed tomography (CT) scanning of Scots pine (*Pinus* sylvestris) was used to calculate variations in dry density of the wood and moisture distribution in green condition. The dielectric properties could then be interpolated from values given by Torgovnikov[16] at certain frequencies, densities and MCs. The variations in dielectric properties can be visualized by the index of refraction. Figure 6 shows how this index is affected by moisture and dry density in the wood.

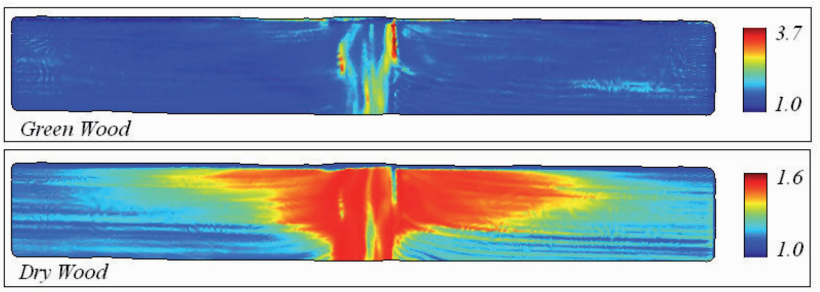

Figure 6: Index of refraction for a cross section of spruce wood containing a knot in green and dry condition.

It was possible to use finite element calculations to simulate the way microwaves interact with the internal structure of wood. The results from these simulations show how small variations in dielectric properties may have a large effect on the transmitted microwave signal if the scattering pattern is changed.

3. Moisture content and density

Paper III describes how models for prediction of MC and density were calibrated using multivariate methods. The variables obtained from microwave measurements were used as predictors, while MC and dry density was measured and calculated from weighing and CT scanning of the boards at different moisture levels.

3.1. Material

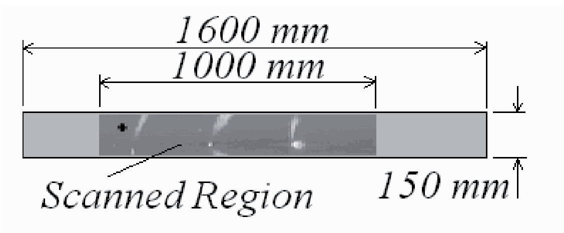

Figure 7: Scanned region of the boards.

96 boards of Scots Pine (*Pinus sylvestris)* were measured, 48 with a cross section 150 x 50 mm and 48 with a cross section 150 x 25 mm. The boards, originating from two different areas in Sweden, were scanned with microwaves and x-rays at three different moisture levels below fibre saturation point. Dimensions and scanned region of the boards are shown in figure 7.

3.2 Multivariate models

Models for prediction of MC and dry density were calibrated by projection to least square (PLS) regression as described by Martens and Næs[17] using the Simca P+ 10.0 software from Umetrics. Approximately 80% of the observations were used in a training set for calibration of each model, while the remaining 20% were used as a test set for verification.

3.3 Results

It was not possible to classify from which part of Sweden the boards originated by microwave measurements. The study presented in paper III shows that the average MC could be predicted with a correlation coefficient, R^2 = 0.72 for 25-mm boards and R^2 = 0.90 for 50-mm boards. The density could be predicted for each 8- x 8-mm pixel with R^2 = 0.71 for 25-mm boards and R^2 = 0.64 for 50-mm boards.

It has previously been shown by, among others, Johansson et al.[8] that this type of sensor can be used for simultaneous prediction of MC and dry density. Models for density in the present study where only calibrated at uniform moisture content after the last drying step. One reason for this was that variations in dry density could be predicted for each pixel while MC only could be predicted as averages over a region of the board.

4. Stress grading

4.1 Four-point bending

After drying of the boards described in section 3.1, destructive four-point bending was used to measure the local modulus of elasticity (MOE) and modulus of rupture (MOR) for the 48 boards with a cross section of 150 x 50 mm. MOE and MOR were decided according to the European standard[18] in a setup shown in figure 8. The dimension of the pieces made it necessary to reduce the distance *L* and *L1* between supports. *L1* was set to 400 mm and *L* was set to 1200 mm. The deformation, *w*, was measured at the centre with *L1* taken as the gauge length while the load, *F*, was increased.

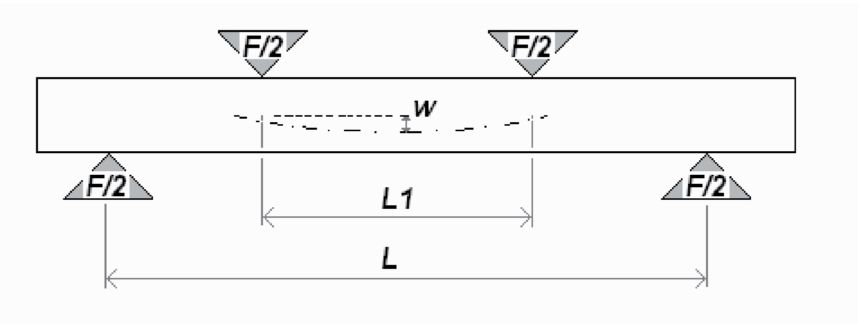

Figure 8: Test arrangement for measuring the local modulus of elasticity.

The local modulus of elasticity was calculated using the expression

$$MOE = \frac{aL1^2(F_3 - F_2)}{16I(w_3 - w_2)}, \qquad [3]$$

where *a* is the distance from a loading position to the nearest support and *I* is the second moment of area (b x h^3 / 12) where *b* is the width and h is the height of the board. F_3 and w_3 are the load and deformation at 40% of maximum load while F_2 and w_2 are the load and deformation at 10% of maximum load.

The modulus of rupture was calculated as

$$MOR = \frac{3F_4 \cdot L}{2bh^2}, \qquad [4]$$

where F_4 is equal to the maximum load before rupture.

4.2 Results

Models for prediction of modulus of rupture have a correlation coefficient $R^2 = 0.44$. Figure 9 shows observed MOR plotted versus MOR predicted from microwave scanning.

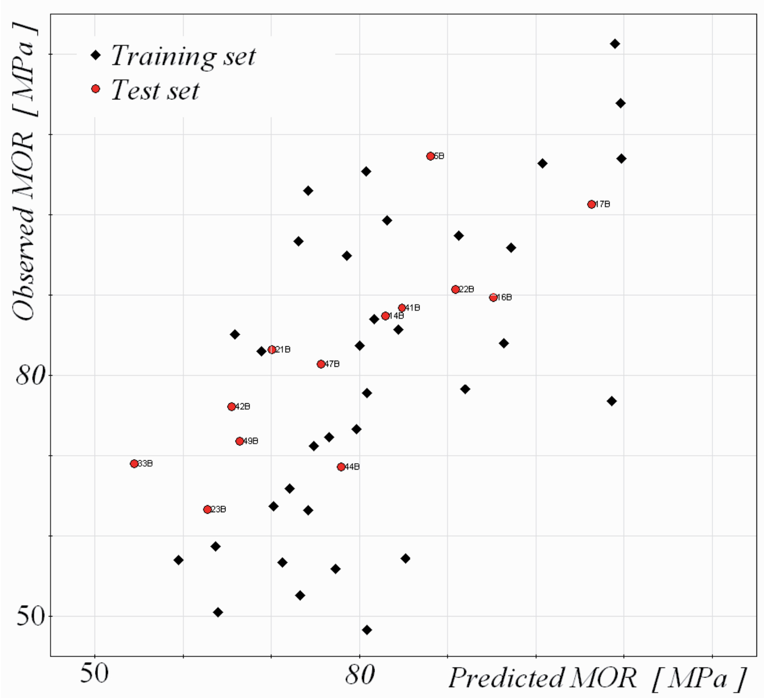

Figure 9: MOR predicted from mean values of microwave measurements at the breaking point.

When a model for prediction of MOR from dry density was calibrated, a value of $R^2 = 0.39$ was attained.

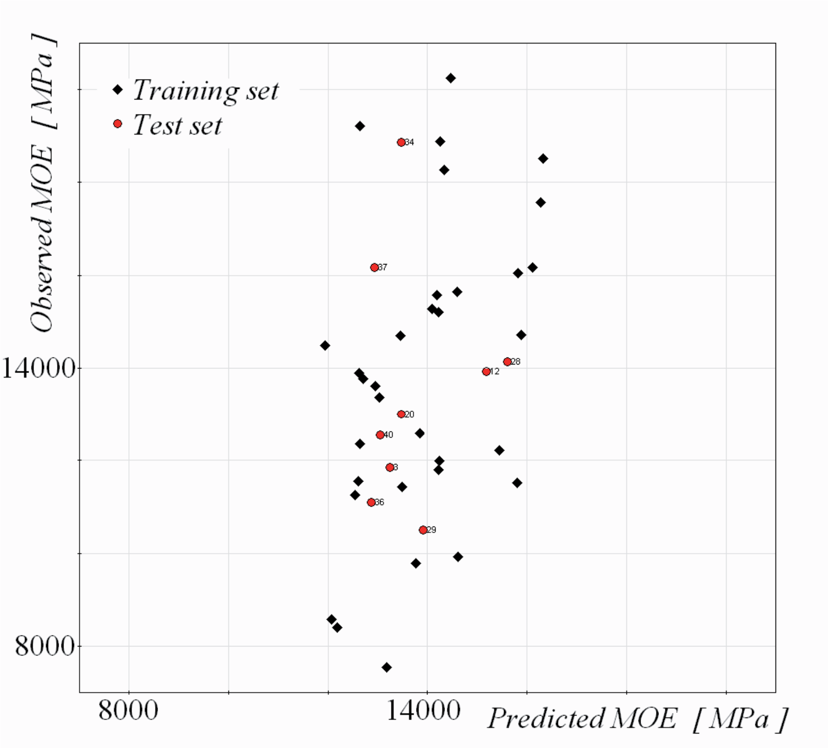

Figure 10: MOE predicted from mean values of microwave measurements over each board.

Figure 10 shows the observed and the predicted moduli of elasticity plotted against each other. As can be seen from the figure, there was no correlation in MOE and microwaves. Nor was any correlation in MOE and MOR found. This indicates some kind of error in the mechanical grading, since the correlation coefficient between bending strength and elasticity normally has a value of $R^2 \approx 0.5$.

5. Discussion

5.1 Calibration

There is a small drift over time in the measurements, but this will stabilize when the system has reached its working temperature. The main problem was how to handle the periodic character of variables describing phase shift. These variables could only be used in the models if the maximum phase shift between different measurements was less than one period. This was the case when dry density was predicted, but variations in phase shift between different moisture contents were larger. Hence these models were mainly based on the amplitude of the signal. All variables are needed for simultaneous prediction of moisture and density, which requires that the phase is unwrapped or that variations in moisture content are small.

Reflection and scattering at boundaries where the dielectric properties change caused large local variations in the amplitude of the transmitted signal. This could be seen as noise in the images. Measurements of phase shift produce less noise in the resulting images, since reflections at boundaries have a smaller effect on the phase shift.

5.2 Prediction of wood properties

Johansson et al.[7] reported a correlation coefficient, R^2 = 0.92 for prediction of average MC in boards with the cross section 125 x 25 mm. That is close to the result for 50-mm boards obtained from the present study (R^2 = 0.90). Several factors may have caused the lower correlation found for 25-mm boards (R^2 = 0.72). Variations in wood structure and moisture gradients could influence the models. Errors in the measurements caused by twist and deformation of the boards after drying had greater influence on models for 25-mm boards. The model calibrated for prediction of average density by Johansson et al.[7] had R^2 = 0.99. Noise will be added when each 8 x 8 mm pixel is treated as one observation, since the knots will cause both high and low values in the microwave variables. Hence there was a lower correlation found for density in the present study.

The results from four-point bending were affected by the dimensions of the pieces. The low correlation between MOE and other measurements may have been caused by deformation of the wood. The short distance between the supports during four-point bending gave a high load at each supporting point. There was also a short distance from the lower supports to the edges of the boards. This made it possible for cracks to start at the edges and follow the pith or the boundary between sap and heartwood from one side of the board to the other. Two of the boards cracked through the drilled reference hole. Some examples are shown in figure 11.

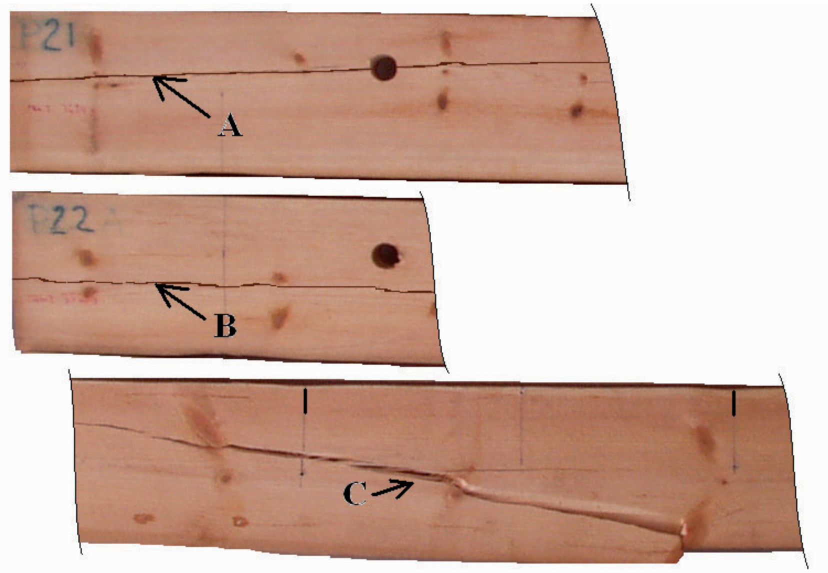

Figure 11: Examples of how the boards could crack through the reference hole (A), the pith (B) or knots (C).

The correlation coefficient found for prediction of MOR from microwaves ($R^2 = 0.44$) is of the same order of size as when dry density from x-ray scanning was used as a predictor ($R^2 = 0.39$). Johansson[9] reported R^2 values of about 0.70–0.90 from a preliminary study on prediction of MOR from microwaves. These values can be compared to results obtained by Schajer[19] from x-ray measurement. By combining information about clearwood density and knot distribution, he has presented models for prediction of strength at selected weak points with R^2 values around 0.70.

6. Conclusions

Microwaves can be used to predict average moisture content and dry density in wood. The sensor evaluated in this study needs modification so that phase shift can be measured over more than one period if simultaneous prediction of these two properties is required. If the moisture distribution is uniform, it is possible to predict dry density for every 8 x 8 mm pixel from images obtained by the sensor.

It is also possible to use the sensor in combination with other techniques for prediction of modulus of rupture. If strength grading is done from microwave measurements only, it is necessary to have control of all factors that influence the measurement, such as moisture, thickness and type of wood. Elasticity could not be predicted in this study. However, that is most likely due to measurement errors during the destructive bending.

Finite element modelling is useful when microwave scattering in wood is analyzed. One possible application is the simulation of varying conditions when models for prediction of wood properties are evaluated.

7. Future Work

The development of electronic components will make it possible to produce cheap equipment that can process microwave signals in real time. This can be suitable to produce sensors for the wood industry, but variations in dielectric properties between heartwood, sapwood, compression wood, knots, etc., will influence the prediction of wood properties such as MC, density and strength. Further investigation of the dielectric properties in wood at microwave frequencies would improve the prediction models. More studies are also needed on how the dielectric properties of the wood are related to strength. Finite element models of the interaction between microwaves and wood will give a deeper understanding of how the energy is scattered within the wood. By adding thermal properties in the models it is possible to simulate microwave heating. This can be used to develop equipment for wood drying or for high frequency hardening of glue.

An improved sensor for online measurements, e.g., in sawmills, should be able to measure phase shift over several periods. One way to accomplish this is by taking measurements at two slightly different frequencies.

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Paper I

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Microwave penetration in wood using imaging sensor

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Abstract

It is possible to determine properties of wood using microwave scanning techniques. The purpose of this study was to verify the measured values from a microwave imaging sensor. Attenuation and phase shift of an electromagnetic wave transmitted through birch wood were measured and compared with theoretical calculated values. A test piece with varying thickness was measured with a scanner based on a microwave sensor (Satimo 9.375 GHz) at different temperatures and moisture contents. The density distribution of the test piece was determined by computer tomography scanning. The result showed good correspondence between measured and theoretical values. The proportion of noise was higher at low moisture content due to lower attenuation. There is more noise in attenuation measurement than in measurement of phase shift. A reason for this could be that wood is an inhomogeneous material in which reflections and scattering affect attenuation more than phase shift. The microwave scanner has to be calibrated to a known dielectric to quantify the error in the measurement.

Keywords: Microwave scanning; Wood; Dielectric properties; Modulated scattering technique

1. Introduction

It is known that the dielectric properties of wood are affected by density, moisture content (mc), temperature and frequency [1]. For many applications, such as drying, sorting and strength grading, it is necessary to detect mc or density distribution in wood. These parameters can be detected by nondestructive testing using microwaves. This technique has been investigated by Portala [2] among others. The scanner used in the present work is based on the same microwave sensor (Satimo 9.375 GHz) as in Portala's study [2] where several types of sensors for measurements on wood were investigated. The sensor uses modulated scattering technique [3] with 128 fixed probes. The frequency corresponds to a wavelength of 32 mm in vacuum and gives an acceptable ratio between resolution and

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penetration. A similar technique has been used by James et al. [4]. The main difference in his method is frequency and probe construction. Johansson [5] has shown that simultaneous prediction of moisture content and density is possible using a scanner system based on the sensor from Satimo where scanner data was used as input for calibration of a multivariate model. These models have to be compensated for variations in temperature and thickness of the wood. Johanssons [5] study does not compare the multivariate model with a physical model.

The present study was carried out in order to examine how measurements from the microwave sensor vary at different mc, thickness and temperatures for birch wood. This provides a more detailed study of the sensor in comparison to Portala's [2]. The experimental scanner data was compared to theoretical values of phase shift and attenuation of the signal.

2. Theory

Electromagnetic waves have an electric field strength (***E***) and a magnetic field strength (***H***) that oscillate perpendicular to each other. When the wave is moving in the z-direction it can be described mathematically with the harmonic wave equation as:

$$\boldsymbol{E}(x,y,z,t) = \boldsymbol{E}_0 \cdot \mathrm{e}^{-\mathrm{j}\cdot\omega\cdot t-\gamma\cdot z}, \tag{1}$$

$$\boldsymbol{H}(x,y,z,t) = \boldsymbol{H}_0 \cdot \mathrm{e}^{-\mathrm{j}\cdot\omega\cdot t-\gamma\cdot z}, \tag{2}$$

where $\boldsymbol{E}_0$ and $\boldsymbol{H}_0$ are the amplitudes of the electric field and the magnetic field strength. They are transverse to the z-direction and move through space with a complex distribution factor:

$$\gamma = \mathrm{j}\cdot\omega\cdot\sqrt{\varepsilon\cdot\mu} = \alpha + \mathrm{j}\cdot\beta, \tag{3}$$

where ω is angular frequency and μ is the complex permeability, which is equal to the permeability μ_0 of the free space, since wood is not a magnetic material. Furthermore, α is the attenuation factor and β is the phase factor of the wave. ε is the relative complex permittivity defined as:

$$\varepsilon = \varepsilon_0 \cdot (\varepsilon' - \mathrm{j}\cdot\varepsilon''), \tag{4}$$

where ε_0 is the absolute permittivity for vacuum, ε' is the relative permittivity and ε'' is the relative loss factor. The absolute permittivity and the relative loss factor have been thoroughly investigated by Torgovnikov [1]. These investigations have shown that the absolute permittivity and the relative loss factor of wood depend on moisture content (mc), density, material temperature, direction of electric field relative to the fibre direction and wave frequency.

If the real and imaginary parts of Eq. (3) are equated, the expression for the attenuation factor and phase factor will be:

$$\alpha = \omega\cdot\sqrt{\varepsilon_0\cdot\mu_0}\cdot\left(\frac{\varepsilon'}{2}\cdot\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)\right)^{1/2}, \tag{5}$$

$$\beta = \omega\cdot\sqrt{\varepsilon_0\cdot\mu_0}\cdot\left(\frac{\varepsilon'}{2}\cdot\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right)\right)^{1/2}. \tag{6}$$

Insertion of Eq. (3) into wave Eq. (1) shows that the wave amplitude is attenuated exponentially with the factor $\mathrm{e}^{-\alpha\cdot z}$ as the wave penetrates the dielectric wood material (Fig. 1).

If the electric field strength decreases from $\boldsymbol{E}(0)$ to $\boldsymbol{E}(z)$, over the length Δz of wood (Fig. 1), the attenuation expressed in decibel is defined as:

$$\log\left(\frac{\boldsymbol{E}(0)}{\boldsymbol{E}(z)}\right) = \log(\mathrm{e})\cdot\alpha\cdot\Delta z \ [\mathrm{dB}], \tag{7}$$

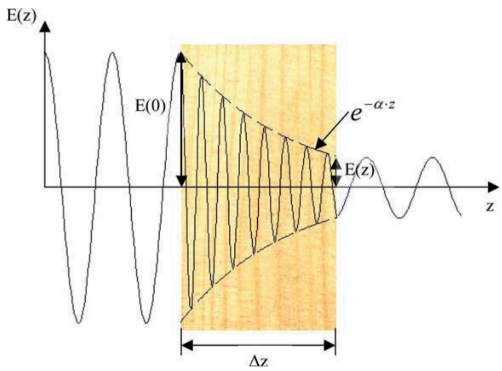

Fig. 1. An electromagnetic wave transmitted into wood.

and the phase shift ϕ over a length Δz as it penetrates wood instead of empty space is defined as:

$$\phi = \beta \cdot \Delta z \text{ [rad]}. \quad (8)$$

3. Material and methods

The study was based on one piece of birch wood with dimensions as shown in Fig. 2. The thickness increases linearly from 0 to 31 mm over a length of 248 mm. This will give a theoretical maximum attenuation of about 12 dB at 25% mc, which is within the dynamic range for the scanner system, which is stated to be about 40 dB. Measurements were excluded within 24 mm from the wood edges to reduce boundary effects on the field. The region of interest is inside the dotted line in Fig. 2.

The values of measured attenuation and phase shift over a width of 64 mm were compared with theoretical values calculated from Eqs. (7) and (8). For each moisture level the object was held at equilibrium mc in a climate chamber until the calculated target weight was reached. Initially the object was dried to 5% mc. By placing the piece in the climate chamber, the mc could be raised to a maximum of 21%. An intermediate measurement was taken at 13% mc. At each of these three levels, the object was scanned at room temperature using both the microwave and Computer Tomograph (CT) scanner. Then the object was dried to zero mc and scanned. Finally, the mc was raised once more to 21% and then the object was kept in a refrigerator for 48 h. Then a microwave scan was done with the object frozen to −20 °C.

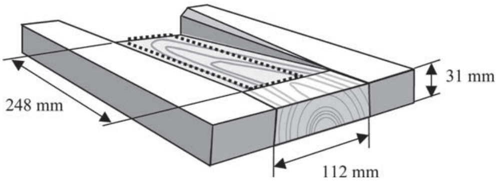

Fig. 2. Test object with birch pieces glued to the edges.

4. CT scanner

A CT scanner (Siemens Somatom AR.T.) was used to measure the density distribution in the test object. A scan was taken at every 8 mm with a 5 mm-wide X-ray beam. The 3D images from the CT scanner were transformed to 2D images with a pixel size of 8 mm × 8 mm.

5. Microwave scanner

Fig. 3 shows a schematic drawing on the main part of the microwave scanning system. The sensor (Satimo 9.375 GHz) is based on modulated scattering technique, MST, which makes it possible to measure the field at many points without a moving probe or microwave multiplexer [3]. The wood is illuminated by a quasi plane wave generated by a slotted waveguide that acts as a transmitting antenna. The transmitted wave is locally perturbed in the retina by a low frequency signal applied sequentially to 128 dual-polarised nonlinear dipoles loaded by PIN diodes. This will cause a modulation of the radio frequency (RF) signal that is proportional to the electromagnetic field. The modulated signal is collected by another slotted waveguide. The signal that reaches the RF receiver consists of a carrier wave modulated at the diode switching frequency. Down-conversion of the RF signal is done in a homodyne receiver that produces the real and imaginary parts of the electromagnetic field at the position of the dipoles. The

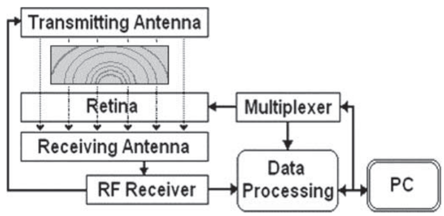

Fig. 3. Sensor system for the microwave scanner. The microwave signal is modulated by a low frequency signal at 128 probes in the retina. The electromagnetic field at each probe is then extracted from the signal.

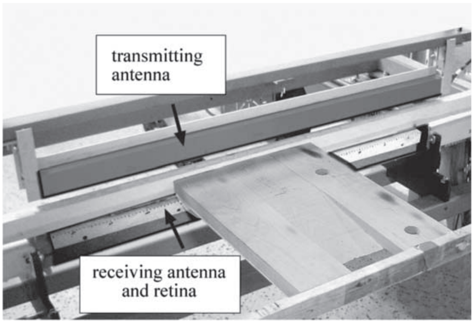

Fig. 4. Conveyer for the microwave scanner with antennas.

antennas are mounted on opposite sides of a conveyer shown in Fig. 4.

The conveyer position is controlled by programmable logic connected to the PC [5]. The distance between dipoles in the retina is 8 mm, which corresponds to one quarter of a wavelength. Since there are 128 dipoles, the resulting image covers a width of one meter. By setting the conveyer to stop for scanning every 8 mm, the same resolution is attained in both directions. From the collected data two images are extracted. One image describes the phase shift of the electromagnetic wave, and the other image describes the attenuation of the signal in dB after passing through the wood. There is a difference in level between sensors and also a small variation between measurements. These errors were minimized by setting the level in air to zero at every measurement.

6. Results and discussion

Fig. 5 shows the distribution of experimental and theoretical values for attenuation over the test object at 0% mc. The theoretical values are calculated with Eq. (7) using empirical values from Torgovnikov [1] and the density distribution obtained from CT scanning. Here the noise is about half of the maximum attenuation.

The measured surface has the same shape at 21% mc in Fig. 6, and the noise level is the same. The maximum attenuation has increased, which gives a better signal to noise ratio.

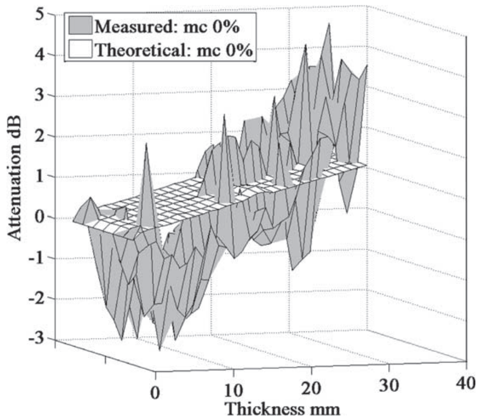

Fig. 5. Distribution of attenuation over a width of 64 mm in birch at 0% mc as thickness increases from 0 to 31 mm.

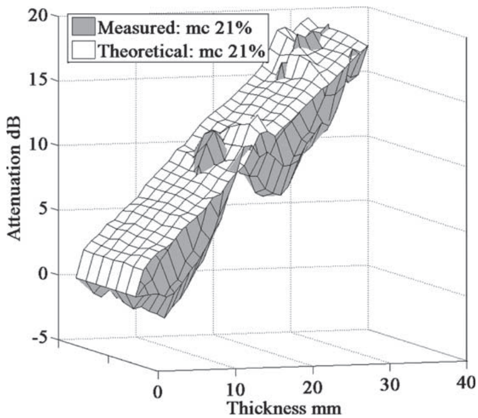

Fig. 6. Distribution of attenuation over a width of 64 mm in birch at 21% mc as thickness increases from 0 to 31 mm.

Figs. 7 and 8 show the corresponding distribution of phase shift at 0 and 21% mc where theoretical values have been calculated with Eq. (8) using empirical values from Torgovnikov [1] and the density distribution obtained from CT scanning.

Variations from the plane in Figs. 5–8 correspond to density variations as shown in Fig. 9. Different annual ring patterns or small regions with high density may cause reflections at bound-

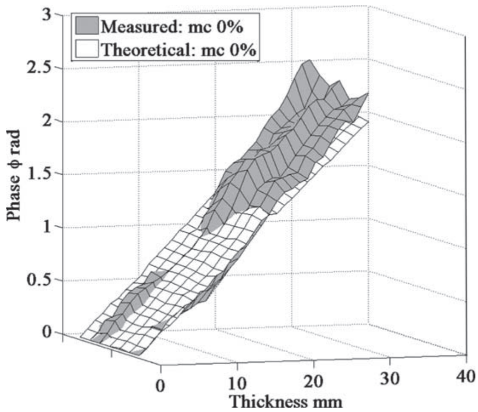

Fig. 7. Distribution of phase shift over a width of 64 mm in birch at 0% mc as thickness increases from 0 to 31 mm.

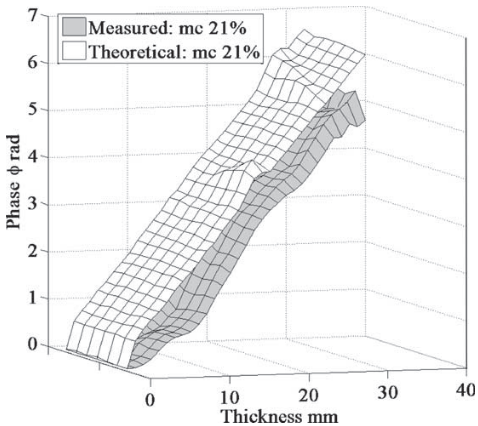

Fig. 8. Distribution of phase shift over a width of 64 mm in birch at 21% mc as thickness increases from 0 to 31 mm.

aries because of different dielectric properties. This will give deviations in attenuation from theoretical values, since theoretical values do not include effects from reflections. Attenuation is more affected by multiple reflections and mismatch losses than is the phase shift [6], and hence the deviations from theoretical values are smaller in phase shift than for attenuation. Another factor which may influence attenuation and phase shift is the variation of grain angle.

Fig. 10 shows the average over the area inside the dotted line in Fig. 2 of theoretical and measured values of attenuation versus thickness at mc 13% at room temperature and frozen at mc 21%. The water molecules in the frozen wood will not oscillate with the field, and the influence of water is decreased. This means that the attenuation in

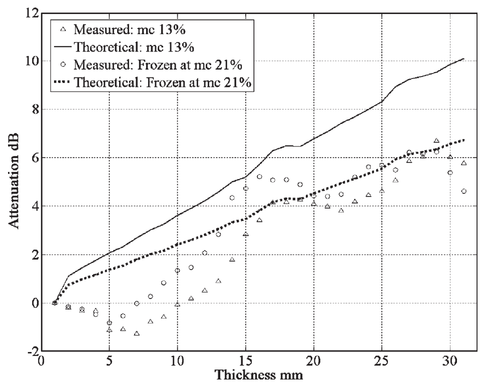

Fig. 10. Average values of attenuation versus thickness for microwaves at 9.375 GHz in birch wood. Measured and theoretical values.

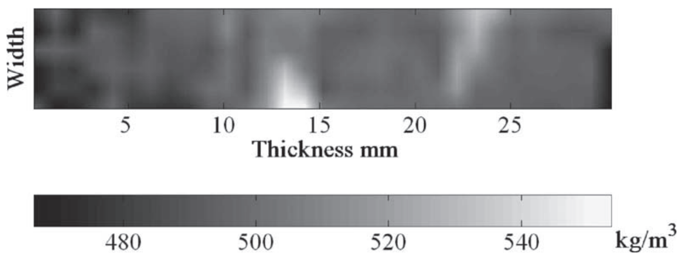

Fig. 9. Density distribution over the measured region. Two small regions have about 10% higher density.

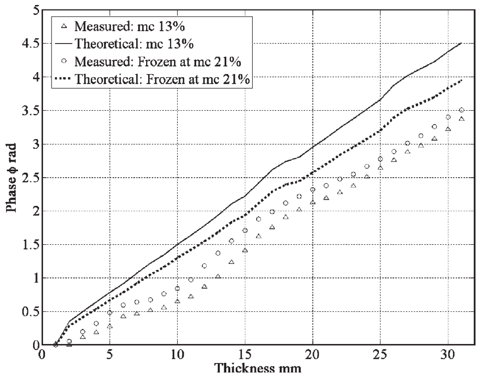

Fig. 11. Average values of phase shift versus thickness for microwaves at 9.375 GHz in birch wood. Measured and theoretical values.

frozen birch with mc 21% is almost the same as in room temperature with mc 13%. The same goes for phase shift in Fig. 11.

The influence of thickness on measured values is lower than on theoretical values, which may be caused by systematic errors in the microwave scanner. There could be gradients in the moisture distribution that cause deviations from theoretical values at some moisture levels. Another possible error is that theoretical values do not involve effects from reflections and scattering. These errors increase in dry wood.

7. Conclusions

- Good correspondence in measured and theoretical values of phase shift.
- The microwave scanner has to be calibrated with a known dielectric to quantify the error in the measurement.
- Reflections and scattering create more noise in attenuation measurement than in measurement of phase shift.
- The proportion of noise is higher at lower moisture content due to lower attenuation.

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Paper II

FEM simulation of interactions between wood and microwaves

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Keywords: microwave scanning, wood, dielectric properties, modulated scattering technique, finite element modelling

Abstract
The aim of this study was to use finite element modelling (FEM) as a tool to analyze microwave scattering in wood and to verify the model by measurements with a microwave scanner. A medical computed tomography scanner was used to measure distribution of density and moisture content in a piece of Scots pine (*Pinus sylvestris*). Dielectric properties were calculated from measured values for cross sections from the piece and used in the model. The models were verified by measurements with a scanner based on a microwave sensor. Images describing the distribution of the electric field and phase shift were obtained from the FEM simulation. The results show that simulated values correspond well to measured values. Furthermore, discontinuities in the material caused scattering in both the measured and the simulated values. The greater the discontinuity in the material, the greater was the need for computational power in the simulation.

Introduction
Microwave scanning is a fast and nondestructive method of measuring internal properties, such as density and moisture content (MC), of wood. This method has been studied, for example, by Johansson et al.[1] The aim of the present study was to use finite element modelling (FEM) as a tool to analyze microwave scattering in wood and to verify the model by measurement with a microwave scanner. Values of phase shift and attenuation from the measurements were compared to the FEM model.
By transforming the Maxwell equations into 2nd-order partial differential equations (PDEs) it is possible to solve electromagnetic wave propagation problems. As wood is an inhomogeneous and anisotropic dielectric material, the wave scatters in different directions as it propagates. Moisture and heat flow during microwave drying of wood have been modelled by Antti,[2] Perre and Turner[3] and Zhao and Turner.[4] No previous models have been made of electromagnetic wave propagation inside wood because of difficulties in ascertaining the internal structure and because of the need of computational power. In the present analysis, the internal structure of density and moisture content in wood was determined by computed tomography (CT) scanning, described by Lindgren.[5] Furthermore, from these density and moisture content values the distribution of dielectric properties was determined. The finite element modelling electromagnetic module in FEMLAB[6] version 3.1 software was used to solve PDEs that describe the wave propagation.

Theory

Microwaves in wood

The dielectric properties of wood depend on moisture content, density, frequency, grain angle and temperature. The real and imaginary part of the dielectric permittivity, ε′ and ε′′, perpendicular to the grain versus moisture content and density are shown in figures 1 and 2.

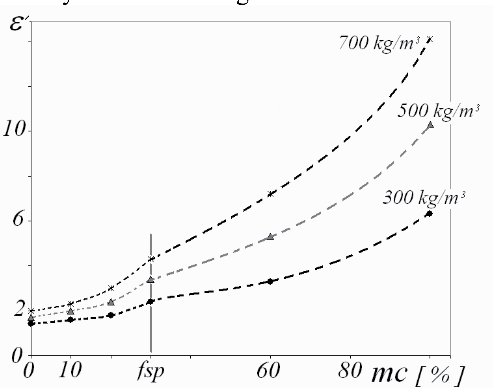

Figure 1: The relative permittivity, ε′, perpendicular to the grain versus moisture content and density (Torgovnikov[7]).

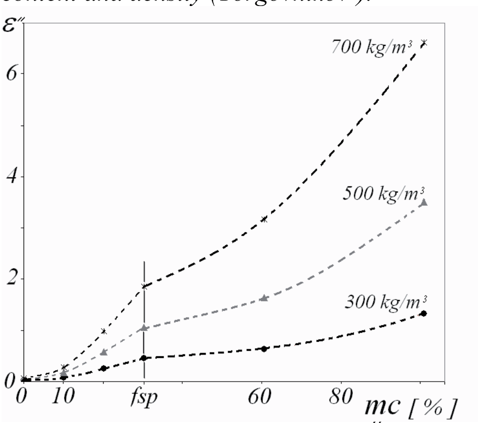

Figure 2: The relative loss factor, ε′′, perpendicular to the grain versus moisture content and density (Torgovnikov[7]).

The free water in the cell cavity seems to affect permittivity values somewhat differently above the fibre saturation point (fsp). Parallel to the grain the values are 1.2–2 times higher (Torgovnikov[7]).

Finite element analysis

Simulation models were constructed with the finite element method as described by, among others, Jin[8] using FEMLAB[6] 3.1. A transverse electric (TE) wave is propagated in the x direction through a piece of wood surrounded by air (figure 3).

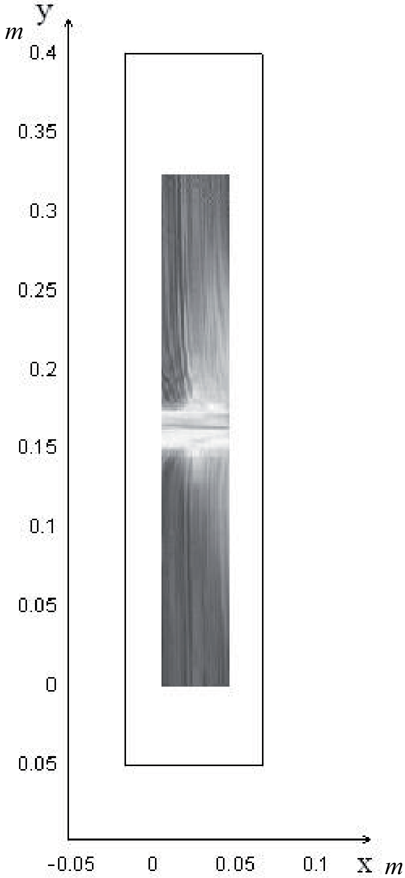

Figure 3. The computational domain in the x-y plane.

The simulation was done in two dimensions. Variations of dielectric properties in the z direction were neglected. In the model domain, the z component of the ***E*** field is solved by the following equation:

$$\nabla \times \left(\frac{1}{\mu_r} \nabla \times E_z \right) -$$
$$- \left(\varepsilon^* - j \cdot \frac{\sigma}{\omega} \cdot \varepsilon_0 \right) \cdot k_0^2 \cdot E_z = 0 , \qquad (1)$$

where μ_r is the relative permeability, which is equal to the permeability μ_0 of the free space in the total model domain, since wood is not a magnetic material. Furthermore, ω is the angular frequency, σ is the conductivity and $\boldsymbol{k}_0$ is the wave number in free space. ε^* is the dielectric permittivity defined as:

$$\varepsilon^* = (\varepsilon' - \boldsymbol{j} \cdot \varepsilon'') , \qquad (2)$$

where ε' is the relative permittivity and ε'' is the relative loss factor. The model uses a low-reflectance boundary condition on the left and right side, with electric field $E_z = 1$ on the left side and with a source field of zero on the right side (figure 3). The low-reflectance boundary is defined as:

$$\sqrt{\mu}_r \cdot (\boldsymbol{n} \times \boldsymbol{H})_z + \sqrt{\varepsilon^*} \cdot E_z =$$
$$= 2 \cdot \sqrt{\varepsilon^*} \cdot E_{0z} , \qquad (3)$$

where $\boldsymbol{H}$ is the magnetic field and μ_r is the permeability.
Since the incoming wave to the domain is propagated parallel to the horizontal boundaries (figure 3), and the magnetic field is perpendicular to these boundaries, a perfect magnetic conductor (PMC) boundary condition is used. PMC is defined as:

$$(\boldsymbol{n} \times \boldsymbol{H}) = 0 , \qquad (4)$$

where $\boldsymbol{n}$ is a unit vector normal to the boundary.

Material and methods

The material chosen for the study was one piece of Scots pine (*Pinus sylvestris*) shown in figure 4 with dimensions 40 x 150 x 320 mm. Close to the centre of the piece was a cone shaped knot with a diameter varying from 18 to 25 mm. Cross sections of the piece, as shown in figure 5, were scanned with microwaves and CT both parallel and perpendicular to the grain in green and dry condition.

Figure 4: The piece of Scots pine that was used in the study.

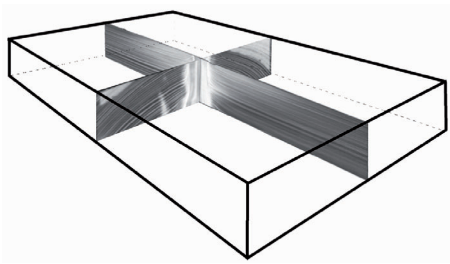

Figure 5: Two cross sections from the object were scanned. One section was parallel to the grain and the other section was perpendicular to the grain. Regions with low density are darker in the CT images.

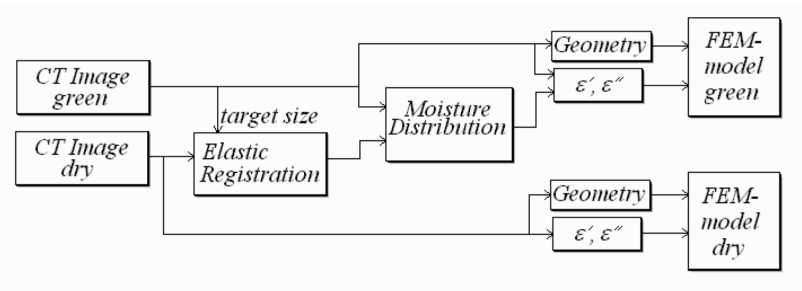

Figure 6: Brief description of the working procedure in the generation of FEM models.

The measured values of attenuation and phase shift in the microwave signal after passing through the wood were compared to finite element simulations in two dimensions. The moisture distribution in green condition has to be known in order to calculate the dielectric properties. Density data from CT scanning was used to calculate variations in the dielectric properties of the wood and of moisture distribution in green condition. A matrix with values of the dielectric properties over each cross section and moisture content generated using density images in green and dry condition.was estimated from CT scanning using empirical data from Torgovnikov.[7] Figure 6 shows how the FEM model was
The moisture content was calculated from the CT images after compensating the image of dry wood for shrinkage and deformation. Transformation of the CT image of dry wood to the shape of green wood was done by using elastic registration as described by Sorzano et al.[9]

CT scanner
A CT scanner (Siemens Somatom AR.T.) was used to measure the density in the cross sections. The geometric shape, dielectric properties and moisture distribution in green condition for each cross section were calculated from the measured density.

Microwave scanner
A scanning system described by Johansson[1] that measures attenuation and phase shift of the transmitted electromagnetic field every eight millimetres was used. The wood is illuminated by a quasi-plane wave generated by a slotted waveguide that acts as a transmitting antenna where the electrical field is perpendicular to the sensor[10] (9.375 GHz) that is based on modulated scattering technique (MST) as described by Bolomey.[11]

Results
The results show that simulated values correspond well to measured values. Figures 7 and 8 show the attenuation when the E-field is oriented perpendicular and parallel to the grain. There is a narrow peak indicating the knot in the model, but it is not detected in the measurement.

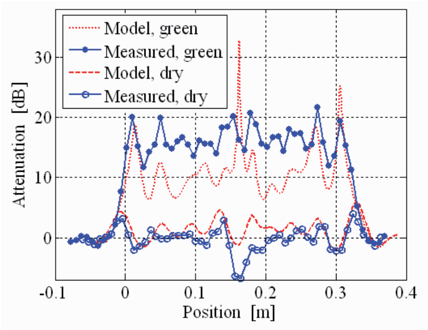

Figure 7: Simulated and measured attenuation of EM wave with the E-field oriented perpendicular to the grain after transmittance through green and dry wood.

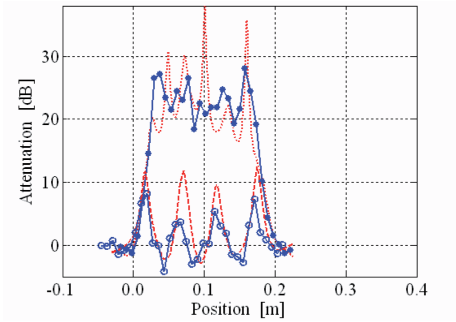

Figure 8: Simulated and measured attenuation of EM wave with the E-field oriented parallel to the grain after transmittance through green and dry wood.

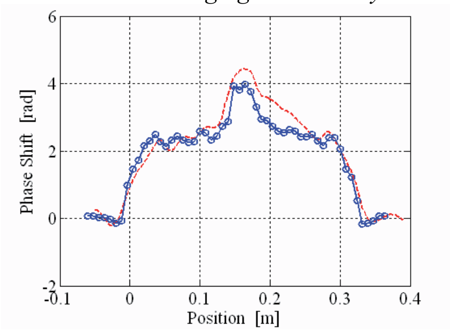

Figure 9: Simulated and measured phase shift of EM wave with the E-field oriented perpendicular to the grain after transmittance through dry wood.

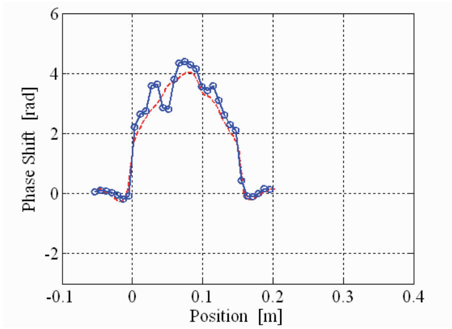

Figure 10: Simulated and measured phase shift of EM wave with the E-field oriented parallel to the grain after transmittance through dry wood.

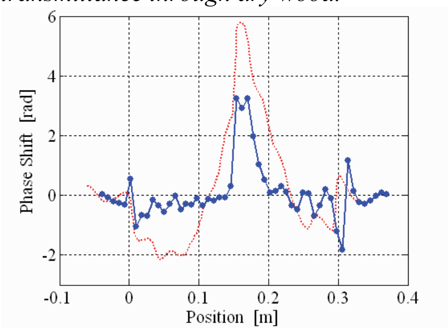

Figure 11: Simulated and measured phase shift of EM wave with the E-field oriented perpendicular to the grain after transmittance through green wood.

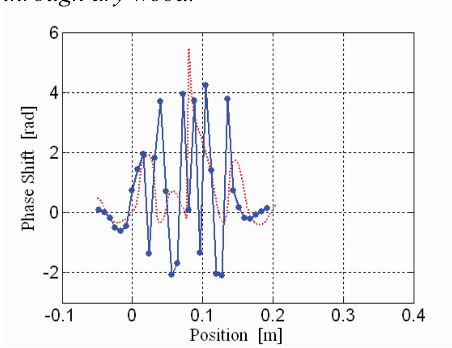

Figure 12: Simulated and measured phase shift of EM wave with the E-field oriented parallel to the grain after transmittance through green wood.

A clear pattern from the knot in the phase shift for dry wood is shown in figures 9 and 10. The phase shift perpendicular to the grain for green wood in figure 11 also shows a pattern caused by the knot. The knot is visible in simulated data for green wood parallel to the grain, but not in measured data (figure 12).

Discussion

The phase shift is periodic and can only be measured and simulated in the interval (-π, π). The vectors were unwrapped by changing absolute jumps greater than π to their 2π complement. This only works when the phase shift is less than 2π. The phase shift increases with moisture content. Thus the phase shift shown in figure 10 should be larger than the phase shift shown in figure 9. The measured and simulated values for phase shift in green clearwood shown in figure 11 are close to zero, but figure 13 shows that the real phase shift in clearwood is close to 2π. Figure 14 shows the simulated E-field in green wood.

The resolution in the microwave scanner is too low to measure the simulated peaks at the knot in figures 7 and 8. The model assumes that there is no variation in the z direction, which may cause errors close to the knot where variations are large in the z direction.

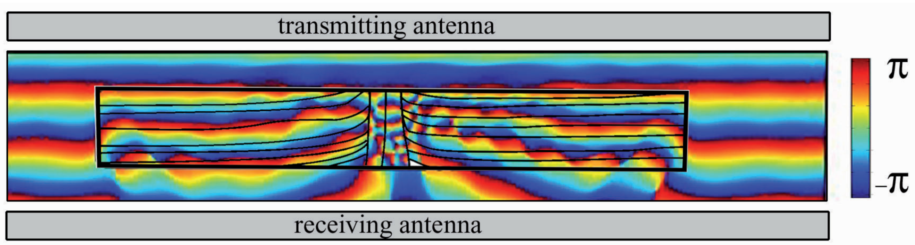

Figure 13: Simulated phase shift in green wood.

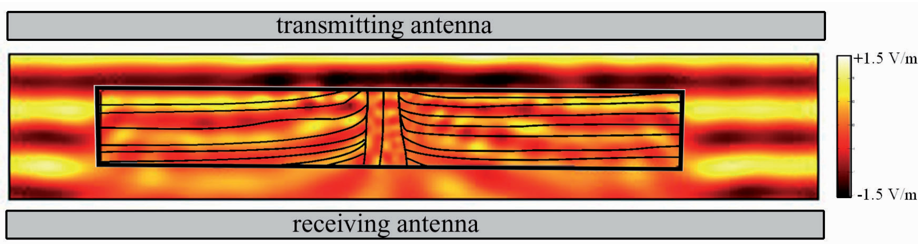

Figure 14: Simulated E-field in green wood.

Conclusions

The model corresponds well to the measured values, which show that the FEM simulation could be a useful tool for analyzing microwave scattering in wood. As wood is an inhomogeneous material, there can be discontinuities in density and moisture content in the wood pieces. Discontinuities in the material result in a huge scattering in the measured and the simulated values. The greater the discontinuities, the greater is the need for computational power in the simulation.

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Paper III

Predicting moisture content and density distribution of Scots pine by microwave scanning of sawn timber II: evaluation of models generated on a pixel level

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Abstract
The purpose of this study was to use images from a microwave sensor (Satimo 9.375 GHz) on a pixel level for simultaneous prediction of moisture content and density of wood. The microwave sensor functions as a line-scan camera with a pixel size of 8 mm. Boards of Scots pine (*Pinus sylvestris*) 25 and 50 mm thick were scanned at three different moisture contents. Dry density and moisture content for each pixel were calculated from measurements with a CT scanner. It was possible to create models for prediction of density on a pixel level. Models for prediction of moisture content had to be based on average values over homogeneous regions. Accuracy will be improved if it is possible to make a classification of knots, heartwood, sapwood, etc., and calibrate different models for different types of wood. The limitations of the sensor used are high noise in amplitude measurements and the restriction to one period for phase measurements.

Key words *microwave scanning, wood, density, moisture content*

Introduction
There is an increasing need in the wood industry for precision on-line measurement of moisture content (MC) and density. This information could be used for individual drying of the boards or for quality and stress grading. A microwave signal will be affected by several properties such as density, MC, temperature and grain angle when it is transmitted through wood. These properties have influence on attenuation, phase shift and polarisation of the signal. Moisture measurements can be improved by combining measurements of both attenuation and phase shift (Kraszewski[1]) or measurements of phase shift at two frequencies (Zhang and Okamura[2]). Another possibility is to use measurements of different microwave parameters for concurrent prediction of several wood properties from one noninvasive measurement. This has for example been done by Bolomey et al.[3] and Choffel et al.[4]

The present study is based on work by Johansson et al.[5] in which multivariate models to predict MC and density for boards of Scots pine (*Pinus sylvestris*) were calibrated using average values over the boards. The purpose of the present work was to evaluate and develop this method with models generated on a pixel level wherein each pixel was treated as one observation.

Theory

Consider a plane electromagnetic wave propagating through wood in the **z-**direction. If losses due to conductance and reflections are ignored, the attenuation and wavelength is governed by the factor $e^{-\gamma z}$ (von Hippel[6]), with the complex propagation constant,

$$\gamma = j\omega\sqrt{\varepsilon^{*}\varepsilon_0\mu'\mu_0} = \alpha + j\beta \ , \qquad [1]$$

where

ω is the angular frequency of the wave,
$\varepsilon^{*} = \varepsilon' - j\varepsilon''$ is the complex dielectric constant.
$\mu' \approx 1$ is the relative permeability of wood and
$\varepsilon_0 = 1/(\mu_0 c_0^2)$ is the permittivity of free space where
c_0 is the speed of light in free space,

The real part of γ can be defined as an attenuation constant,

$$\alpha = \frac{\omega}{c_0}\left[\frac{\varepsilon'}{2}\left(\sqrt{1+\tan^2\delta}-1\right)\right]^{\frac{1}{2}} \qquad [2]$$

and the imaginary part of γ as a phase constant,

$$\beta = \frac{\omega}{c_0}\left[\frac{\varepsilon'}{2}\left(\sqrt{1+\tan^2\delta}+1\right)\right]^{\frac{1}{2}} \qquad [3]$$

where $\tan\delta = \varepsilon'/\varepsilon''$ is defined as the loss tangent.

For low moisture content ($\tan\delta \ll 1$) it has been shown by King[7] that these expressions for α and β can be simplified from binomial expansion of equation 1:

$$\gamma = j\beta_0\sqrt{\varepsilon'(1-j\tan\delta)} = j\beta_0\sqrt{\varepsilon'}\left[1 - j\frac{\tan\delta}{2} + \frac{\tan^2\delta}{8} + \dots\right] \qquad [5]$$

where $\beta_0 = 2\pi/\lambda_0$ is the phase constant of air and λ_0 is the wavelength of the electromagnetic wave in air. Thus equation 3 and 4 can be approximated as

$$\alpha = \frac{1}{2}\beta_0\sqrt{\varepsilon'}\tan\delta \qquad [6]$$

and

$$\beta = \beta_0\sqrt{\varepsilon'}(1+\frac{1}{8}\tan^2\delta). \qquad [7]$$

King[7] suggested that α should be used for prediction of MC and β should be used for prediction of density. However tabulated values from Torgovnikov[8] plotted in figure 1 and 2 show that both ε' and $\tan\delta$ are correlated to wood density and moisture content. The complex relation between microwaves and wood properties indicates that multivariate methods are beneficial for simultaneous prediction of moisture content and dry density.

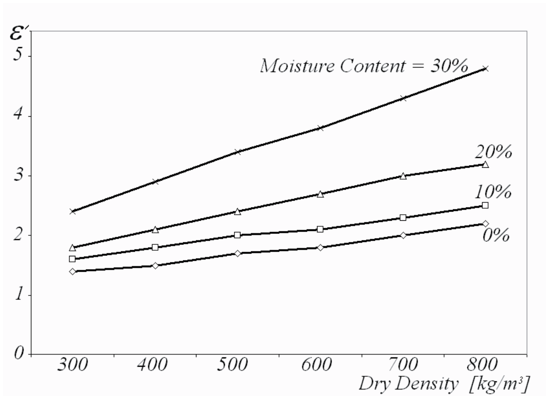

Figure 1: Real part of the dielectric constant (ε′) perpendicular to the grain as a function of dry density and moisture content at 10 GHz (Torgovnikov[6]).

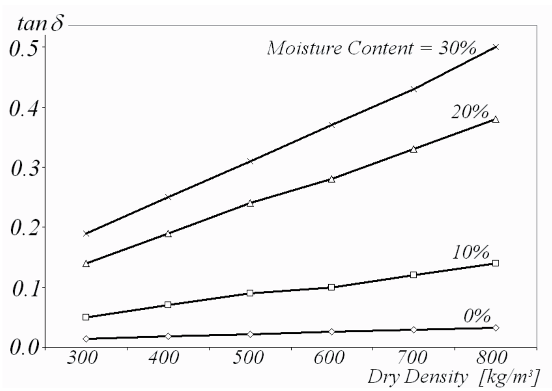

Figure 2: Loss tangent (tanδ) perpendicular to the grain as a function of dry density and moisture content at 10 GHz (Torgovnikov[6]).

Material and methods

The study was based on 96 boards of Scots Pine (*Pinus sylvestris)*, 48 with a cross section 150 x 50 mm and 48 with a cross section 150 x 25 mm. The 48 boards with a thickness of 50 mm consisted mainly of heartwood, while the amount of heartwood in the boards with a thickness of 25 mm varied from 0% to 100%. Examples of these variations are shown in figure 3.

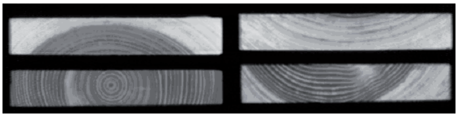

Figure 3: Cross sections from CT scanning of four different boards in green condition. The high MC gives high density in the sapwood compared to heartwood.

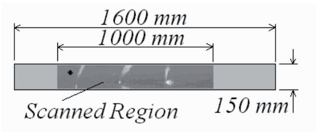

Figure 4: Image of one board from the CT scanner after transformation to two dimensions. A length of 1 m from each board was scanned.

The boards originate from two different parts of Sweden. Half of the boards of each dimension were sawn at a mill in Skellefteå (Wallmarks) situated in the northern part of Sweden. The other 48 boards were sawn at a mill in Ljungby (Vida), situated in the southern part of Sweden. Before scanning, each board was cut to a length of 1600 mm, and a 25-mm hole was drilled as a reference point.

The moisture content (MC) in some of the freshly sawn boards exceeded the dynamic measurement range of the microwave scanner. There was also a large variation in the moisture distribution at higher moisture contents. Therefore this study is limited to measurements below fibre saturation point (fsp), which corresponds to a MC of approximately 30%. The boards were dried from green condition to 7% MC. At three different moisture levels the boards were removed from the kiln and scanned with microwaves and X rays. Figure 4 shows an X-ray image of the scanned region from one board. The light regions in the image represent areas with high density.

Drying

The freshly sawn boards were dried in a small kiln. In order to decide average moisture content for the boards, they were weighed after each drying step. The target moisture content at each drying step was set to 20%, 12% and 7%. After the last scanning the dry weight of each board was estimated from five samples taken at even intervals from the board. The moisture content was assumed to be evenly distributed in the boards after the last drying to 7% MC. From that assumption the dry density in each pixel was calculated using the density measured in the CT scanner. The dry density was used to calculate MC in each pixel from measured density in the remaining observations. No corrections were made for shrinkage, since the maximum shrinkage was less than one pixel.

X-ray scanner

A computer tomography (CT) scanner (Siemens Somatom AR.T.) was used to scan the boards every 8 mm with a 5 mm wide X-ray beam. The scanner measures density in three dimensions with high accuracy (Lindgren[9]). The images from the CT scanner were transformed to two dimensions by taking mean values of density variations through the boards.

Microwave scanner
Using transverse feeding direction, the boards were scanned with a microwave sensor (Satimo 9.375 GHz) in combination with a computer and a conveyer described by Johansson[10]. The system produces images with a pixel size of 8 x 8 mm. The sensor is based on electromagnetic transmission through the wood and modulated scattering technique, which is described by Bolomey[11]. The sensor measures the real and imaginary part of the electromagnetic field in two orthogonal polarization angles. From these variables the linear and decibel amplitude and the phase shift were calculated. All of these five variables were measured and calculated in four different polarization angles: horizontal, vertical, plus 45 degrees and minus 45 degrees. This gives a total of 20 variables describing attenuation, phase shift and polarization of the transmitted field. Figure 5 shows an example of attenuation and phase shift measured in one direction with the microwave sensor compared to density measured with X rays.

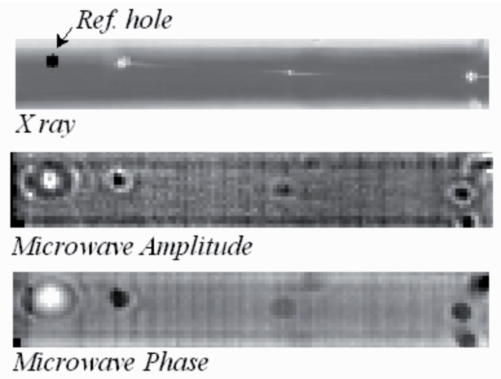

Figure 5: Example of images from X-ray scanning and microwave measurements on phase shift and amplitude of one board. Several knots are visible in the images.

Multivariate models
Models for prediction of dry density and moisture content were calibrated using PLS regression as described by Martens and Næs[12] using the Simca P+ 10.0 software from Umetrics. Average dry density and MC of the wood was calculated from CT images for each pixel in the microwave image and used as response variables. The variables from the microwave scanner were used as predictors. Each variable was centred and scaled to unit variance. Using the PLS algorithm means that uncorrelated principal components (PC) are formed as linear combinations of the correlated variables from the microwave scanner. The numbers of PCs were optimized by the software to two or three depending on response variable. The available amount of memory restricted the number of observations to 200 randomly selected pixels from each board. No distinction was made as to whether the points came from heartwood, sapwood or knots. About 80% of the observations were used as a training set for calibrating the models. The remaining, randomly selected observations were used as a test set for verification of the models. This gave about 23000 observations in the training set and 5700 observations in the test set for each thickness.

Result

Moisture content

Models based on values from randomly selected pixels turned out to be weak and noisy with a correlation coefficient of approximately $R^2 = 0.20$. To avoid this problem the models for MC shown in figure 6 and 7 are based on average values over five homogeneous regions from each board with sizes varying from 0.0025 to 0.015 m^2. This reduces the number of observations for each thickness to about 550 in the training set and 130 in the test set used for verification that is shown in the figures. The model for prediction of MC for 25-mm boards has a correlation coefficient of $R^2 = 0.72$ and estimated root mean square error RMSEP = 1.8% MC. The model for 50-mm boards has $R^2 = 0.90$ and RMSEP = 2.0% MC.

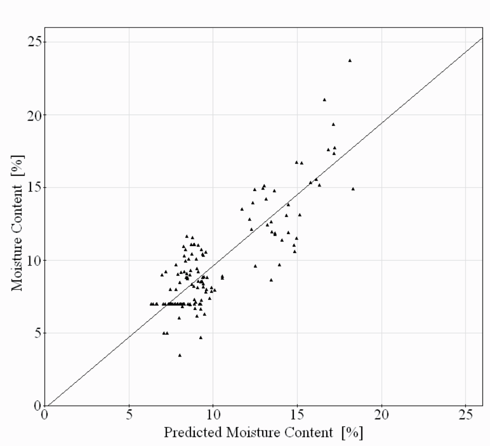

Figure 6: Measured versus predicted moisture content for 25-mm boards based on mean values over 5 regions from each board.

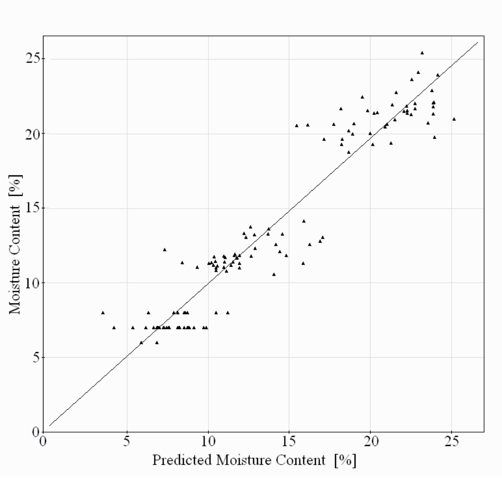

Figure 7: Measured versus predicted moisture content for 50-mm boards based on mean values over 5 regions from each board.

Density

The models for prediction of dry density shown in figures 8 and 9 are based on values from 200 pixels in each board. The model for prediction of dry density for 25-mm boards has a correlation coefficient of $R^2 = 0.71$ and estimated root mean square error RMSEP = 38 kg/m^3. The model for 50-mm boards has $R^2 = 0.64$ and RMSEP = 32 kg/m^3. The randomly selected pixels also contain some high-density values from knots that the model is not able to describe properly.

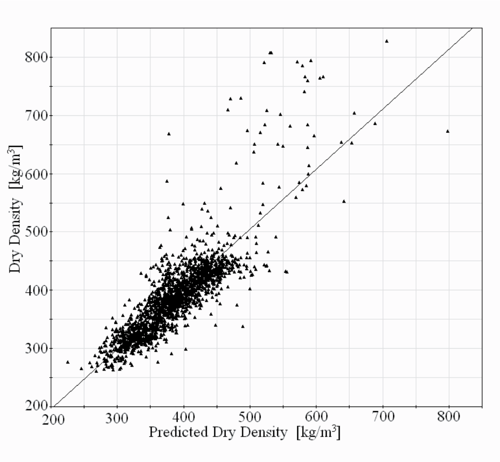

Figure 8: Measured versus predicted dry density for 25-mm boards based on values from randomly selected pictures.

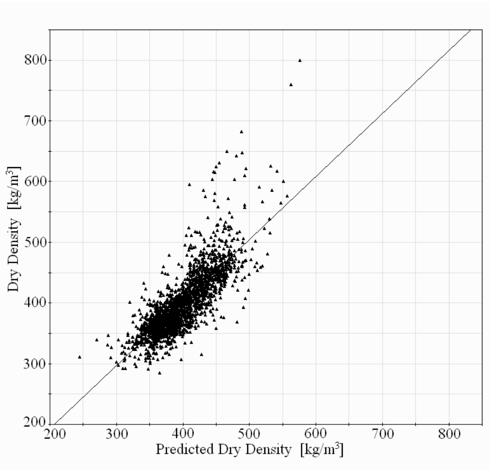

Figure 9: Measured versus predicted dry density for 50-mm boards based on values from randomly selected pixels.

Discussion

The 50-mm boards consisted mainly of heartwood, with the exception of three boards that showed up as outliers in the model and were excluded from the dataset. One board was also excluded because of rot. It would have been desirable to classify the amount of sapwood in the 25-mm boards in order to find correlations. This was not done, but five boards consisting mainly of heartwood were identified as outliers in the dataset and excluded. There was no significant difference between the two groups of boards originating from different parts of Sweden.

The variables describing phase shift are periodic and the variation was more than one period between measurements at different MC. This made it impossible to compare these measurements without calibration to a known reference. Therefore models for MC were mainly based on variables describing amplitude. It can be deduced from equation 6 in combination with figure 2 that MC should have a strong influence on amplitude. However reflection and scattering at boundaries where the changes in dielectric properties are large caused large local variations in amplitude. This explains why models for MC could not be based on pixel values. Variations in phase shift caused by differences in dry density were less than one period. Therefore the variables describing phase shift could be used as strong predictors for dry density.

Conclusions

This investigation can be concluded as follows:
A good model for prediction of density can be calibrated from pixel values. It is possible to calibrate a satisfactory model for moisture content from average values over homogenous regions, but not from pixel values. Edges, knots and other regions where properties change will cause errors in the models. These errors can be reduced by taking the average over a large area. If algorithms that classify the regions could be created, it would be possible to use different prediction models for different regions. An improved microwave sensor for wood scanning should measure phase shift over several periods, for example, by using two frequencies. It should also produce less noise in the amplitude measurements.

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