# Microwave Method for In-kiln Moisture Content Measurement

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**ABSTRACT**

A technique based on microwave sensing technologies has been developed which provides a means of estimating the average moisture content across a stack of timber during kiln drying. The microwave sensor, which comprises of a linear array of slots excited from both ends, was developed and trialed under a range of standard commercial kiln drying schedules using 100mm x 50mm *Pinus radiata* sample boards.

Discrete power measurements in the frequency range from 5.3 to 5.5 GHz were performed and then summed to produce a gradient response. This gradient response is a measurement of the frequency shift of the resonant peak of the array with respect to the moisture content of the material covering the slot. Using this measured gradient response a linear model was developed and then inverted to produce an estimate of the average moisture content across the stack.

Analysis of the relationship between the estimated and actual average moisture contents showed a significant correlation . Moisture contents of less than approximately 15% (by dry basis) gave an error of less than 3% in moisture content for confidence levels of 99%. The error increased as moisture content increased and for moisture contents below 50% an error of 10% at the 99% confidence levels was found. Further work is being performed to enhance this technique.

## INTRODUCTION

The inability to remotely determine in situ the moisture content of a stack of timber during drying is a major deficiency in the efficient drying of timber. As well as the economic loss of reprocessing or downgrading wet material, there is an increasing trend towards quality assurance. Modern developments in drying for minimising stress and brownstain all rely on knowledge of moisture content during drying. Present techniques either depend on operator skill at interpreting a range of qualitative and quantitative factors, or are expensive and require continual calibration and customisation for individual types of material and for each chamber. A system is yet to emerge that can reliably and simply measure stack moisture content.

The drying of softwoods especially radiata pine can be performed very quickly at elevated temperatures (>100°C). However this means that the need to predict the endpoint of drying is very important under such conditions. Radiata pine can have a very high initial moisture content (>200% by dry basis for sapwood) with heartwood at 40 to 50%. In practice the initial moisture content can be very variable. Timber is dried in batches with stack widths up to 2.4 m wide and since the air flows laterally though the stack and cools, variability is introduced during drying as well. Softwood drying sites tend to have banks of kilns and long chambers with many packets of timber and may operate at 150 to 200°C, although there is a trend towards drying material for high quality use at lower temperatures such as 90 to 70°C.

In order to overcome these difficulties a probe will need to be able to handle temperatures of up to 200°C, accurately assess average moisture across a stack, and be cheap and rugged enough to allow multiple sensors. The ability to measure moisture content from green to dry is an advantage, but this is secondary to the ability to accurately determine the final end point which is paramount.

## SENSOR DESIGN

The kiln environment exhibits high temperature and humidity and the potential for physical damage to a sensor when the stack is placed in or out of the kiln makes many forms of modern electronic componentry unsuitable. The sensor and associated apparatus are required to withstand these environmental factors. The simplest of the microwave structures that meets these requirements is rectangular waveguide.

The fundamental concept embodied in the construction of this sensor structure is that microwave energy propagating along the interior of a waveguide will radiate when presented with a resonant length aperture in the broadwall. The microwave energy will partially radiate from the aperture and due to the presence of the covering material, partially undergo reflection back into the waveguide and hence the energy will propagate back to the measurement plane where these reflections can be measured directly. A previous study showed that the permittivity ( a physical quantity which relates electric field intensity to electric field density in a material) of timber is directly related to the moisture content (mc) and thus as the timber is dried the permittivity change will influence the amount of microwave energy reflected by the slot. For the current design the slot was chosen to be a resonant length in air at 5.3 GHz. The slot is centred in the broadwall and for minimum reflection in the air covered case a slot angle was determined. A slot in this configuration is analogous to a series of lumped admittances at intervals along the waveguide.

The admittance of an individual slot can be found by calculating the reflection coefficient (ratio of reflected energy to incident energy) ρ of the slot which is governed by the slot angle and length. An analytical solution for this has been given by Wolff and by Rengarajan for the general case of thin slots in rectangular waveguide. Then using the general transmission line expression the input admittance of the slot can be found from the reflection coefficient.

In order to sample the average moisture content across the stack a linear array of slots was constructed in the waveguide using the slot design described in the previous section. Since the slots may be considered as lumped parallel admittance elements we can assume that if we have a linear array of admittance elements the overall input admittance measured at the measurement plane will be the algebraic sum of these admittance elements. This is subject to the condition that the admittance's are spaced at multiples of half wavelengths so that negative reinforcement does not occur at the slots. Figure 1 shows the magnitude of reflection coefficient for both measured data and modelled for a 26 slot array in 35mm x 20mm waveguide with slots spaced at half wavelength spacings (in air) at 5.2 GHz.

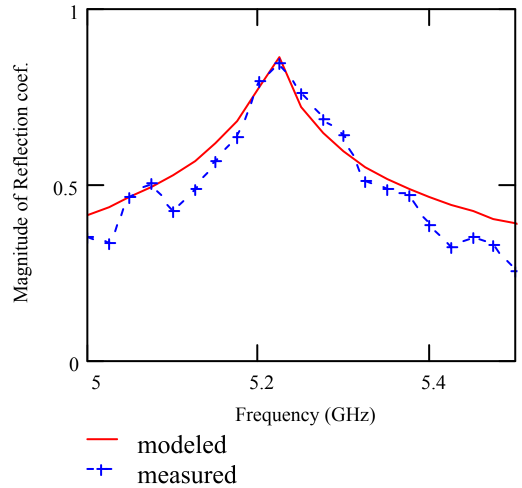


Figure 1, modelled aperture array vs measured for 26 slot array

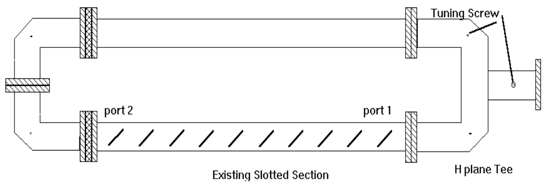


Figure 2 waveguide aperture array.

To improve the performance of the array and to compensate for mechanical tolerances the linear aperture array was driven from travelling waves incident from both ends. This has the affect of setting up a standing wave inside the waveguide which excited the slots, which at certain frequencies forces all the slots to be in phase and add constructively. Figure 2 shows one possible implementation of the sensor structure.

## EXPERIMENTAL TRIALS

A series of experimental trials were performed in a wood drying tunnel with the waveguide sensor orientated with the sensor beneath the sample boards with the slots facing upwards. In each series 600mm long radiata pine sample boards were stacked in 1.5 m wide layers suspended on a load cell, and then dried using a range of commercial schedules. Air flow could be directed from either direction and inlet dry bulb and wet bulb temperatures were controlled as in a commercial drier. The waveguide sensor was inverted and attached to the load cell frame. This removed taring problems and since all samples rested on the array, there was no air gap. In all cases compressed air was fed through the sensor to expel the high temperature and humid air from the interior of the sensor and to avoid condensation occurring in the cold waveguide outside the kiln. Samples were weighed initially and at the end of each run. In some kiln charges weighings were conducted during the run to allow more accurate average moisture content assessment and as well assess uniformity.

The microwave reflection coefficient measurements were performed using a Hewlett Packard 8720B vector network analyser. The HP8720B was configured to measure frequency points from 5 to 5.8 GHz. The system was calibrated using a standard algorithm which placed the measurement reference plane in the waveguide, hence the reflection coefficients measured were within the waveguide structure and reflections due to the input coax and waveguide to coax transitions were removed. A simple software programme was written to control the HP8720B remotely and allowed for measurements to be performed and data stored at predetermined intervals during the drying runs. This interval was chosen based on the anticipated length of the drying run such that a total of approximately 150 measurements would be performed.

## ANALYSIS AND RESULTS

For each of the kiln drying charges the magnitude of the reflection coefficient was calculated for all frequency points covering the range of 5.3 to 5.55 GHz which where then summed to produce a measure of the frequency response gradient. It can be shown that this measured response gradient is related to the power spectral density. This had the additional effect of reducing measurement noise.

In addition to this the average moisture content of the stack at the time of measurement was calculated using the final oven dried weight and the kiln load cell measurements. Figure 3 shows a graph of response gradient as a function of the average moisture content across the stack for a 130°C drybulb /80°C wetbulb schedule charge determined using the procedure described above. The shape of this response gradient is typical of all the charges measured.

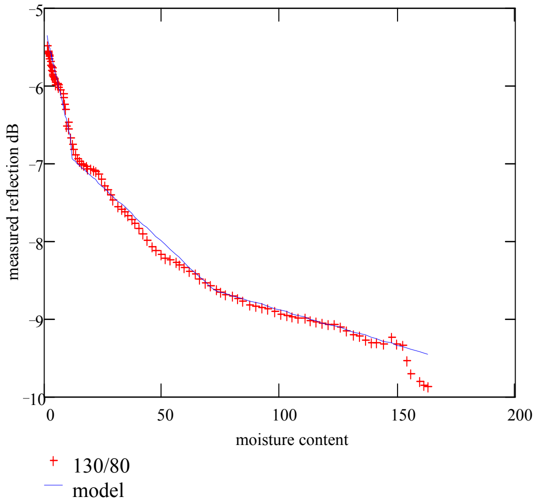


Figure 3 Typical response gradient vs average moisture content for 130/80 schedule

Examination of the response of the microwave measurements with average moisture content showed that the measured results can be considered as three distinct regions each exhibiting an approximately linear response to moisture content but each having a different gradient. It is possible to link the behavoiur between each region with changes in drying behavoiur. In the first region, at high moisture content, drying is dominated by mass liquid flow and most board surfaces are at the wet bulb temperature. At about 70% average mc all boards have finінshed this stage and vapour movement through the boards begins to have increasing influence on drying. Finally at about 10-12% stack average all boards will have reached fibre stauration and only bound water is being removed.

Using a simple straight line approximation to the data in each of the three regions a model was developed and is shown in Figure 3 along with the actual measured response gradient.

This simple straight line approximation model agrees well with the measured response gradient . However it can also be noted that the value of moisture content at

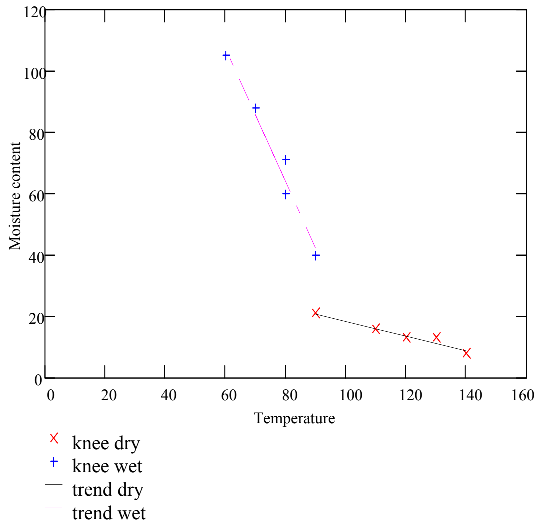


Figure 4: model points of inflection as a function

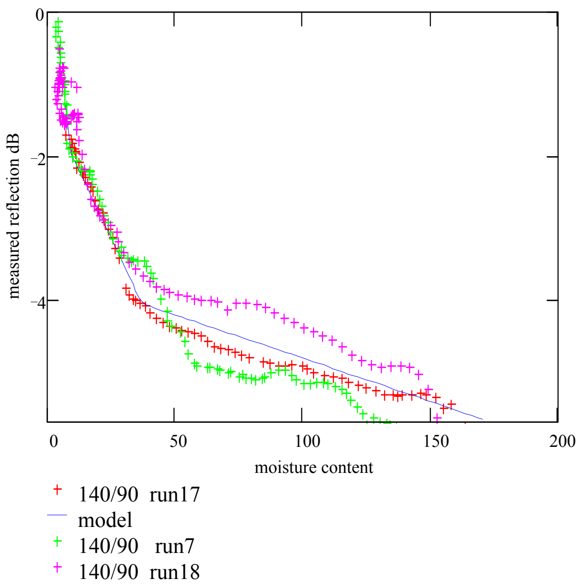


Figure 5: typical response curves for 140/90 drying of moisture content and temperature schedule

which the regions intersect varies somewhat. These two points of inflection "knees" in the model appear to be primarily determined by the wood temperature, as shown in Figure 4, and can be predicted using the kiln schedule or actual wetbulb/drybulb measurements.

It can be seen from Figure 4 that the first (high moisture content ) knee is determined by the wetbulb temperature and that the second ( low moisture content) knee is determined by the dry bulb temperature. In both cases these are simple linear functions and hence can be predicted.

Figure 5 shows a graph of the simple linear model and the response gradients for three separate 140/90 schedule charges as a function of average moisture content. It is easily seen that there is a large variation for high average moisture contents but the agreement between the model and the measured response gradient improves for moisture contents below the point were mass liquid transfer ceases. This variation is partially due to the fact that there is some interaction with the average moisture content from a volumetric measurement directly above the slots. This means that any variation in actual moisture content above the slot of the samples from the average will significantly influence the measurement. This variation could be attributed to the fact that compressed air from the slot may create a micro-climate above the sensor whose moisture content differs from that of the surrounding timber. This effect appears to be dominant in the high moisture content region of the drying run but does not occur after all the free water has been removed is highly correlated to moisture content.

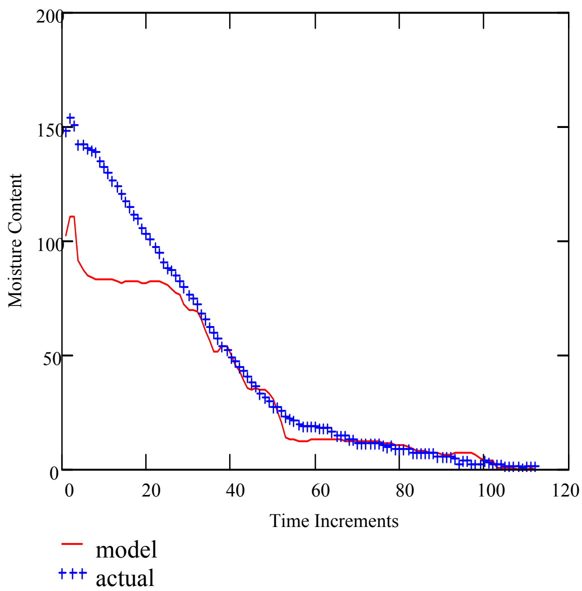


Figure 6: actual vs modelled (mc) for 140/90 schedule

The straight line approximations in the model can be simply inverted to yield a estimated moisture content based upon the measured response gradient, as is shown in Figure 6 for a 140/90 °C drying schedule. As can be seen in figure 6 there is good agreement between the

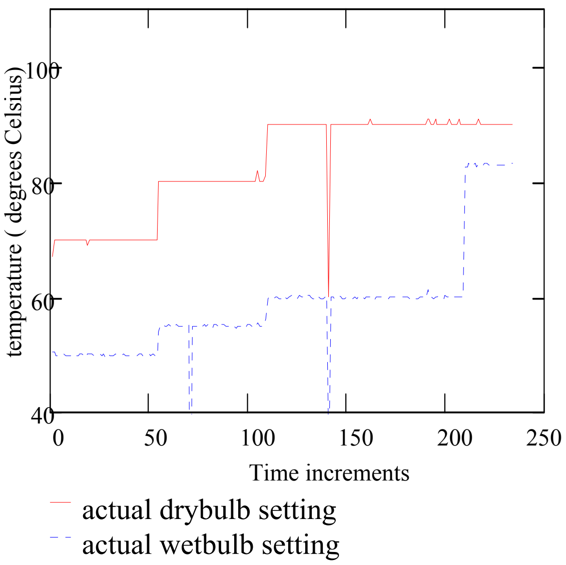


Figure 7: actual measured wet/drybulb Temperature

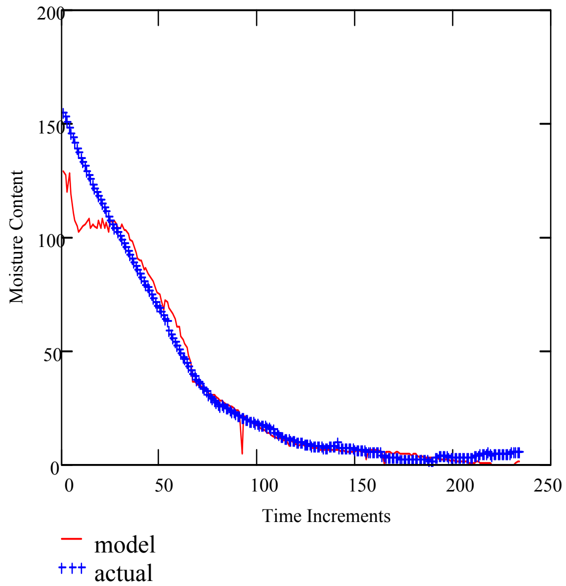


Figure 8: mixed schedule with actual wb/db imputed to model

estimate from the model and the actual average moisture content for moisture contents below 40%.

From the trial shown in figure 6 it can be seen that when reconditioning of the stack is performed the measurement does not track the average moisture content. This again is due to the volumetric measurement above the slots where the timbers moisture content above slot, due to its contact with the sensor, is not representitive of the average moisture content.

To test the variability of this technique to change in wood temperature several charges were performed using a mixed temperature schedule. The actual dry bulb and wet bulb settings were fed into the model for estimating the average moisture content in the stack (Figure 7), producing the graph of estimate from microwave sensor vs actual moisture content which is shown (Figure 8)

The drying charges to date have shown that for moisture contents in the three regions the error between the model and actual are typically; <3% for 99% confidence levels for moisture content less than 15%, and <10% for 99% confidence levels for moisture content less than 40%.

## CONCLUSION

The use of a waveguide aperture array has shown to be an accurate method of measuring the average moisture content of a timber stack in the harsh kiln drying environment. Accuracies of better then 1% rms are achievable at moisture contents below 15% and hence the technique has shown to be useful for determining the endpoint of drying, whilst still providing useful moisture content estimates throughout the drying process. The method described is currently patent pending and further work is being performed to enhance the technique

## REFERENCES

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Rengarajan S R, Josefsson L G ,”Slotted Waveguide Array Antenna Technology” Short Course Notes, 1995 IEEE AP-S / URSI Symposium June 1995.