PROJECT NUMBER: PR07.2041

LOCATING RESIN DEFECTS IN SLASH PINE BILLETS USING MICROWAVE IMAGING – A LABORATORY SCALE TRIAL
Locating resin defects in slash pine billets using microwave imaging – A laboratory scale trial

Prepared for

Forest & Wood Products Australia

by

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Publication: Locating resin defects in slash pine billets using microwave imaging – A laboratory scale trial

Project No: PN07.2041

This work is supported by funding provided to FWPA by the Australian Government Department of Agriculture, Fisheries and Forestry (DAFF).

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ISBN: 978-1-920883-59-1

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Final report received by FWPA in December, 2008

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EXECUTIVE SUMMARY

LOCATING RESIN DEFECTS IN SLASH PINE BILLETS USING MICROWAVE IMAGING – A LABORATORY SCALE TRIAL.

AIM

The aim of this study was to investigate the potential of (i) microwave imaging and (ii) acoustic tomography to detect the presence and location of resin shakes and/or resin streaks in Slash pine (P. elliottii) billets.

METHODS

Two approaches were made using microwave technology. One was to use transmission tomography (microwave source and the detector are on opposite sides of the log, so that the signal is transmitted through the log). The second was to use microwave reflection (the source and detector are on the same side, so that a reflected signal is detected). In addition, 2D acoustic tomography was undertaken. Reference images of the billets was provide via magnetic resonance imaging (MRI).

RESULTS

Locating resin streaks/shakes in freshly felled Slash pine logs with microwave sub-surface radar imaging has shown to be feasible in the instance where the resin defect breaches the heart/sapwood boundary. The detection of resin defects relies on observing discontinuities in the microwave reflection that normally results from the heart/sap boundary, therefore any breach of the boundary by resin results in a disruption to the reflected signal.

All the resin-affected samples collected showed this type of defect. No samples were available that had resin streaks contained totally within the heartwood. As such it is impossible to say whether it is possible to observe resin when contained solely in the heartwood.

A commercially available, portable, microwave sub-surface radar, the SIRO-Pulse, has been shown to possess many of the required features for detecting resin in logs. With some adaptations to this system it should be possible to differentiate between logs with and without resin inclusions and to locate the inclusions when only a few are present. This should be achievable both in real time on a stand off production line system and for a hand-held contact system for use in the field.
CONCLUSIONS

The results of this investigation show that resin streaks in logs can be clearly identified from the control sample. Some issues need to be addressed including the presence of multiple reflections and low sensitivity for the larger logs. In addition the lower limit of resolution needs to be investigated to determine whether resin shakes are observable in fresh logs.

Two potential end-use intervention points can be imagined. One is as a field tool to use on standing trees for either pre-harvest assessment or as a screening tool for field trials. The portable nature of the SIRO-Pulse lends itself to application in either of these areas.

The second implementation is at the log yard debarker. At this stage a decision can be made as to whether the log should be sawn to recover construction grade or merchant grade material (or even simply chipped). While the SIRO-Pulse tool would operate in such a situation given modification to allow non-contact measurement to be made, the current resolution and discrimination of resin streak detection, means it is not conceivable that it would aid optimised recovery via log rotation/saw pattern options.

RECOMMENDATIONS

In order to exploit the results of this study the following recommendations are proposed:

1. An in-forest trial of the SIRO-Pulse system to assess the potential for locating resin-containing trees by scanning at breast height, 2 m and ca. 3 m. It would be particularly useful for field trials investigating variation in resin defect susceptibility. In order to ground-truth the trial it would be essential to fell the trees and assess the resin incidence via cross-cutting the stem.

2. An in-mill trial using the SIRO-Pulse located at the log yard debarker. A simple recovery trial is envisaged, whereby scanned logs would be identified by painting the log ends with a colour pattern that would allow back-to-log recovery to be undertaken.

3. The antenna design for the SIRO-Pulse needs to be optimised to enable higher coupling of power into and out of the logs for the two cases of contact and non-contact measurement. For both cases significant gains could be made by matching the antennas to the log and for the stand off case a more appropriate antenna (eg a horn) for reducing multiple reflections is required. After choosing more appropriate hardware, preprocessing methods may also need to be investigated to do tasks such as reducing the effect of multiple reflections.

4. Image processing methods need to be thoroughly investigated. The feasibility of performing tomography with a larger transmitter to receiver separation or an array should be investigated. Following this an investigation should be taken into the best way to display the SIRO-Pulse data in order to provide user-
friendly and meaningful interpretation to be made by unskilled operators with little training required. An automated aid to provide either a quantitative or qualitative measure of resin defect would dramatically aid the ease of implementation.
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1. INTRODUCTION

The presence of resin streaks and resin shakes in *Pinus elliottii* (Slash pine) and *P. caribea* (Caribbean pine) in Queensland plantation logs is the cause of considerable downgrade of product (Figure 1). While Harding *et al.* (2006) were unable to determine any relationship between resin defects and grade recovery of MGP10 or above, there is considerable cost associated with visual downgrade and increased processing costs due to saw damage and machinery failure. Estimates of $4 – 5 million/annum to Queensland industry have been proposed (Harding *et al.* 2004).

Queensland wood processors are particularly interested in detecting resin streaks and shakes which form when cracks appear in the interior of the tree and subsequently fill with sap. This results in pockets of dry or wet resin that radiate from the core and terminate at a sharp point. Resin shakes and streaks significantly decrease the quality of the timber and often are not externally visible (Figure 1). Non-destructive detection of resin defects prior to log merchandising or milling would provide considerable savings to the timber industry.

![Figure 1. Examples of resin in logs and in processed boards (from Harding *et al.* 2004)](image)

When grading logs, only the external surfaces, and the log ends in particular, are available for visual detection of defects, such that any defects located in the log interior are unable to be detected. During the late 1990’s, New Zealand Forest Research (now Scion) undertook investigations into using ground-penetrating radar (GPR) to locate the defect-free pruned core in *P. radiata* (Radiata pine) (Parker and Visser 2000; Parker and Todoroki 2004).

The CSIRO Information and Communication Technologies (ICT) Centre in conjunction with CSIRO Materials Science and Engineering (CMSE) and CSIRO Forest Biosciences (CFB), has recently performed an investigation into the feasibility of detecting resin pockets in *P. elliottii* billets using microwave imaging. In addition CFB have undertaken 2D acoustic tomography on the same billets.

Two prior reports exist for this study; one of which deals with practical measurements of the dielectric constant of different regions in a log (Lewis, 2007),
and the other describes numerical modeling of the electromagnetic behavior of logs (Hislop, 2008).

The following report will describe the experimental approach taken in the non-destructive detection of resin defects in the trial billets. The report details results first from quantitative measurements of our ability to detect the presence of a metal drill bit inside a hole drilled in a log, then presents the results of scans of logs with and without resin inclusions before giving recommendations for future work.

2. DEVELOPMENT OF A MICROWAVE IMAGING SYSTEM

2.1 Dielectric Data

The acquisition of dielectric data was undertaken on samples of Slash pine heartwood, sapwood and resin to provide fundamental parameters in order to firstly model the problem and then optimise the equipment setup. The dielectric data obtained on was reported as Milestone 2 of this project (Lewis, 2007). The complete data set has been provided to FWPRDC/FWPA as a series of Excel files in Zip format.

An HP8714ES RF network analyser and an HP 85070B dielectric probe were used to collect data from the ten wood and resin samples. The dielectric measurement equipment was initially calibrated and checked against distilled water, air and Teflon.

The data collected consists of a sequence of 100 measurements at evenly spaced frequencies between 300 MHz and 3 GHz. Data was collected for \( e' \), the dielectric constant and \( e'' \), the dielectric loss (Figure 2). The dielectric constants used for simulation modelling are given in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Relative permittivity horizontally</th>
<th>conductivity horizontally (S/m)</th>
<th>Relative permittivity vertically</th>
<th>conductivity vertically (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin (isotropic)</td>
<td>5.2</td>
<td>0.122</td>
<td>5.2</td>
<td>0.122</td>
</tr>
<tr>
<td>Earlywood Sapwood</td>
<td>32.5</td>
<td>1.3</td>
<td>43</td>
<td>1.8</td>
</tr>
<tr>
<td>Latewood Sapwood</td>
<td>12.5</td>
<td>0.43</td>
<td>33</td>
<td>1.3</td>
</tr>
<tr>
<td>Heartwood</td>
<td>8</td>
<td>0.11</td>
<td>33</td>
<td>1.5</td>
</tr>
</tbody>
</table>

It should be noted that Lewis (2007) reports dielectric values only up to 3 GHz (measurements above that being difficult to make) while we were initially interested in operating from 4 – 10 GHz as suggested in Kaestner and Baath (2005).
Figure 2. Dielectric constant and loss as measured for *P. elliottii* in three orthogonal directions (Lewis 2007).
2.2 Microwave Transmission Tomography

Reports in the literature have demonstrated success in imaging knots in logs using microwave frequencies in the range 4 to 8 GHz (Kaestner and Baath, 2005). As a result the initial investigations in this study focused on this frequency range.

2.2.1 In-silico Modelling

Using the dielectric data obtained in Milestone 2 (Table 1), the system of sapwood, heartwood and resin was modelled (Hislop, 2008) using Microwave Studio (www.cst.com). Initially nine scenarios were simulated including three variations on the log itself and three frequency ranges. Figures 3-5 below demonstrate the three log shapes, these figures depict a log with no resin, resin in the sapwood and resin in the heartwood respectively (resin depicted as a black spot). The different values used were:

⇒ resin (small black circle): relative permittivity $\varepsilon_r = 5.2$, conductivity $\sigma = 0.122$ S/m,
⇒ earlywood (yellow rings): $\varepsilon_r = 32.5$, $\sigma = 1.3$ S/m,
⇒ latewood (brown rings): $\varepsilon_r = 12.5$, $\sigma = 0.43$ S/m,
⇒ heartwood (grey/pink central region): $\varepsilon_r = 8$, $\sigma = 0.11$ S/m,

To improve computational costs only the horizontal (perpendicular to log axis) polarization was considered. For each of these log scenarios three different sized open ended wave guides were used to excite the log. For each case a pulse was used as the excitation method and the three frequency ranges (corresponding to the three wave guide sources) were, 2.6 – 3.95 GHz, 3.95 – 5.85 GHz and 5.85 – 8.2 GHz. The logs are all 200 mm in diameter, the heartwood is 80 mm in diameter and the ring structure in the sapwood is of variable widths chosen to simulate a “real” log.

Figure 3: Simulated log without resin inclusion and with a waveguide source.
A Microwave Studio probe was placed on the edge of the log in front of the open ended waveguide. The results (not presented (refer Hislop, 2008)) show no visible distinction between the returns from the rest of the log and from the resin pocket. Locating these returns within the return from the rest of the logs will be difficult. Table 2 summarises the power levels relative to the excitation pulse in each case. Due to the extremely low returns from the resin in heartwood these pulses were not plotted. The high frequency return from the resin in the sapwood shows two pulses the first being an artefact introduced by microwave studio in some very high dynamic range scenarios.

<table>
<thead>
<tr>
<th></th>
<th>2.6 – 3.95 GHz</th>
<th>3.95 – 5.85 GHz</th>
<th>5.85 – 8.2 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin in sapwood</td>
<td>-35.6 dB</td>
<td>-32.3 dB</td>
<td>-36.33 dB</td>
</tr>
<tr>
<td>Resin in heartwood</td>
<td>-77 dB</td>
<td>-80 dB</td>
<td>undetected</td>
</tr>
</tbody>
</table>

The cases presented at three different frequency ranges have very wide pulses due to narrow bandwidths. An attempt was made to combine the three data sets together to obtain a narrow pulse. When the resulting pulse was obtained a later return from the resin pocket could not be seen. It is difficult to distinguish the transmitted/direct reflected pulses from returns from the resin pocket and or ring structure. The presence of a ripple from the reconstruction procedure may also be responsible for concealing the different returns.

To further investigate whether the return from the resin pocket could be detected with a larger bandwidth and larger target the scenario was changed so that a plane
wave source with frequency range 2.6 – 8.2 GHz was used, the resin pocket's diameter was doubled and the solution domain decreased to only half a log so as to reduce computational complexity. A microwave studio probe was placed at the origin to measure the reflected waves. This repositioning of the probe allowed for the direct and reflected waves to be more easily subtracted from the raw data. A simple deconvolution technique, commonly used in processing Ground Penetrating Radar data to remove ground surface bounce and cross talk, was used to remove the corresponding factors in this simulation.

It should be noted that Lewis (2007) reports dielectric values only up to 3 GHz (measurements above that being difficult to make) while we are interested in operating from 4 – 10 GHz as suggested in Kaestner and Baath (2005). A significant variation was noted between different measurement samples and an average dielectric constant was picked for the simulations. As a probe was used to make the measurements they are spot measurements and no information is available on how gradually the permittivity changes between regions so it has been modelled as a sudden change. It should also be noted that the surface of the samples were not perfectly flat making probe contact difficult. These factors all place limitations on the accuracy of these simulations and thus the results should be taken as indicative but not definitive.

2.2.2 Preliminary Trial of Microwave Transmission Tomography

In this preliminary trial, a 200 mm diameter freshly cut Pinus eliottii log was sourced and used for the following experiments. The log was covered in plastic and periodically weighed to ensure minimal moisture loss during measurements. First transmission measurements were performed on the log using a vector network analyser and various open ended waveguide antennas across the 4 – 8 GHz range. Measurements were obtained across the full spectrum available to the various antenna pairs and an inverse Fourier transform used to obtain a time series. Despite the use of very large integration times a signal could not be detected after transmission through the log. The next step was to investigate the feasibility of reflection imaging using a wide band horn. This method was reported as successful in Kaestner and Baath (2005). In attempting to repeat this experiment a wide band horn antenna was mounted via a vector network analyzer and used to analyse the log between 4.5 and 8.5 GHz.

**High Dielectric Contrast Target**

Holes of 20 mm diameter were drilled in the end of the log both along the log's axis (ie centre) and 50 mm from the log’s surface (coinciding roughly with the heartwood boundary). Wide bandwidth measurements where taken and an inverse Fourier transform used to obtain the time domain response in all four possible polarization combinations (transmit horizontally/vertically and receive horizontally/vertically). This was done without the log, with the log present and finally with the log present and a metal drill bit in one of the two holes. The result without the log was subtracted from the other results thereby cancelling reflections from within the antenna and cables and leaving only the response from the log. The experimental apparatus is depicted in Figure 6. In Figure 7 the time series response is plotted both with and without the drill bit present in the hole closest to the log surface.
These two pulses cannot be distinguished indicating that penetration does not occur to the depth of the bolt. This experiment was then repeated with a wider frequency range of 2 – 10 GHz with similarly poor results. A third hole was drilled 25 mm from the edge of the log thereby leaving only 15 mm of wood mass between the antenna and the hole. Figure 8 shows the results for the drill bit present and absent in this new hole.

Figure 6. Equipment setup for the high frequency experiment.

Figure 7. Time series response across 4.5 – 8.5 GHz without the drill bit present (blue line) and with the drill bit present in the hole 50 mm from the log’s surface (green dots).
The results presented in Figure 7 and Figure 8 clearly demonstrate that the attenuation of the moist timber is too large in the frequency range used to allow for detection of a large metal drill bit. As the difference between a metal target being present and absent is the largest contrast achievable for microwave radiation it is clear that the detection of resin in freshly cut pine logs is not feasible at these frequencies. This is in contradiction to Kaestner and Baath (2005) where they report success using this technique. After contacting the authors of this work it became apparent that their logs had been partially dried prior to imaging (Kaestner pers comm. 2008). This drying significantly decreases the signal attenuation effect of the log but also significantly defeats the aim of detecting resin defects in green logs and hence the economic gain in detecting resin early in the value chain is minimised.

**Low Frequency**

The next step was to investigate lower frequencies where higher penetration depths could be achieved. This was done by utilising a waveguide as the transmitting antenna and operating it across the 1.4 – 2.7 GHz range. The resulting signals in the time domain are given in Figure 9 for the cases without the drill bit and with the drill bit in the central and 50 mm from the surface holes. The results clearly show that this lower frequency is more suitable for the problem with the bolt clearly detected in the hole 50 mm away and noticeable when in the central hole.

As a result it was concluded that attenuation of signal is too great for even medium diameter logs and so a reflection imaging approach was adopted.
2.2.3 Preliminary Trial of Microwave Reflection Imaging

At this point it was decided to source a surface penetrating radar (SPR) unit, the CSIRO-developed SIRO-Pulse from CSIRO Materials Science and Engineering. This is a commercially available unit with many useful features for the problem at hand. It is an impulse rather than step frequency unit allowing for easy separation of surface, heartwood and resin returns, and it possesses a very narrow pulse and thus wide equivalent bandwidth and unlike our laboratory apparatus collects data and displays it in real time.

The first test involved using the 1.4 GHz (centre frequency) SIRO-Pulse radar with a small standoff distance from the log. Measurements were taken continually as the metal drill bit was placed and then removed from the central hole. Figure 10 depicts the power spectral density of the return from the log as well as the difference between the returns with and without the drill in the central hole. This figure clearly shows that the high frequency radiation is heavily attenuated by the wood thus further verifying the choice of using the SIRO-Pulse rather than a higher frequency system.
The heartwood region of a log has a significantly lower dielectric constant than the sapwood (Lewis, 2007) and as a result this region significantly interferes with microwave radiation. In reflection mode the sapwood region may be treated as homogenous, simplifying the imaging process, however, in transmission mode the heartwood’s presence makes for a very inhomogeneous medium. Table 3 shows the microwave signal attenuation for resin in heartwood and sapwood at varying frequency.

Table 3. Attenuation of microwave signal through log.

<table>
<thead>
<tr>
<th></th>
<th>2.6-3.95GHz</th>
<th>3.95-5.85GHz</th>
<th>5.85-8.2GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin in heartwood</td>
<td>-62dB</td>
<td>-73dB</td>
<td>-80dB</td>
</tr>
<tr>
<td>Resin in sapwood</td>
<td>-72dB</td>
<td>-73dB</td>
<td>-81dB</td>
</tr>
<tr>
<td>No resin</td>
<td>-61dB</td>
<td>-67dB</td>
<td>-71dB</td>
</tr>
</tbody>
</table>

Given these preliminary results and that the SIROPulse was designed and configured for reflection operation, it was decided to concentrate on reflection imaging and not to attempt transmission imaging at these frequencies.

A fresh log was sourced, approximately 200 mm in diameter and 500 mm in length. Once again it was covered in plastic to maintain moisture content and various scans were done around the log at different distances along its length. All these scans
gave similar returns suggesting an approximately constant cross section. After the log was imaged it was cross-cut to reveal its internal structure. Figure 11 shows a photograph of the cross-cut region showing a resin streak located halfway through quadrant C. The microwave data is displayed in Figure 12. As the scans were performed by hand it was easiest to do so in four quadrants and the data is displayed as such. This figure shows a clear return from the sapwood/heartwood boundary. The only break in this return occurs in the middle of quadrant C. This is a clear indication that resin exists in the sapwood and is obscuring the heartwood return.

Figure 11. Photograph of scanned region after the log was cut. Note the markings showing a clockwise scan through four quadrants A-D with a resin streak in quadrant C.

Figure 13 shows the radar data remapped to a polar coordinate by patching the four quadrant images from Figure 12 together, applying a quadratic depth dependant gain and then interpolating to a polar grid. For comparison the cross-sectional image of the log is also shown. The discontinuity in the heartwood/sapwood boundary reflection (red) is coincident with the location of the resin streak.
Figure 12. Radar return from (top to bottom left to right): quadrants a, b, c and d of the log, with the horizontal axis representing rotation around the log and the vertical axis depth into the log. The return from the log surface has been truncated to emphasize the sapwood/heartwood boundary and resin returns. The red circle in quadrant C highlights the gap in the sap/heartwood boundary due to scattering from the resin streak.

Figure 13. Figure 12, remapped to polar coordinates (left) and rotated image of log section showing resin shake in quadrant C. The discontinuity in the heart/sapwood boundary (red) in the radar image shows the location of the resin streak.
3. LAB TRIAL OF RESIN DETECTION IMAGING SYSTEMS

3.1 Billet Selection

This project was supported by the Weyerhaeuser sawmill at Caboolture (ca. 40 km north of Brisbane). Contrary to anecdotal evidence, during the trial it was difficult to find logs with suitable resin defects for the trial. Maurie Carfoot of the Weyerhaeuser Caboolture mill was able to source suitable material from a harvesting operation. Billets (~250 mm in diameter and 300 – 500 mm in length) were collected and wrapped in heavy-duty polyethylene wrap to minimise drying. Four billets were collected to contain resin defects and one billet was assessed as being free of defects.

3.2 Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) was performed on the billets to provide baseline images for comparison with the trial imaging techniques.

3.2.1 MRI Parameters

MRI was conducted at the University of Queensland Centre for Magnetic Resonance (CMR) at St Lucia in Brisbane. The system utilised was a Bruker S200 whole body MRI system with a body coil. A nominal “head” and “foot” (butt) were identified on each billet along with an “anterior” and “posterior” direction (Figure 14). This allowed consistent registration between the three imaging modalities to be achieved. Samples were arranged in the MRI with the top (Anterior - A) uppermost and the bottom (Posterior – P) lowermost and the sample number assigned as the foot. The images are viewed with the patient’s (sample’s) left (L) on the right of the image.

Initial tri-axial scout images were obtained to align the billets in the MRI. Additional preliminary images were obtained on log 1 in order to optimise image acquisition. The acquisition parameters used are as follows: RARE_512; 20 mm slice thickness; contiguous slices; TE (echo time) 20 ms, TR (repetition time) 3,000 ms; RARE Factor 4; NS (number of scans) 2; 90° Hermite pulse length 3.8 ms; 180° Hermite pulse length 6 ms; FOV (Field of View) 400 mm; MTX (Matrix size) 256 x 256 providing an in-plane spatial resolution of 1.6 x 1.6 mm.

The full length of each billet was imaged using 20 mm slices and the images are presented in Appendix 9.2. The image series are read from the head to the foot (butt) of the sample.

3.2.2 MR Images

A representative MR image of log 3 is shown in Figure 14. This shows the orientation of the billet with the Anterior uppermost and the Left of the log being presented on the right of the image. The resin streak is clearly visible in the log
core along with loss of image signal in the periphery due to fungal attack of the log after only one day post harvest.

Figure 14. MR image of log 3.

3.3 Microwave Imaging

3.3.1 Microwave Transmission

The preliminary trial showed microwave transmission to suffer from severe signal attenuation and hence was not continued in the final trial.

3.3.2 Microwave Reflection – SIRO-Pulse

The SIRO-Pulse is a hand-held sub-surface penetrating radar system that transmits ultra wide band microwave pulses (from 100 MHz - 4 GHz) into the area being investigated. The transmitted power is only a few milliwatts (far less than the
average mobile phone). It detects echoes reflected either by objects buried within the background material or from the interface between different layers.

The log dimensions and distances from the nominal foot/bottom of the log to each SIRO-Pulse scan are given in Table 4.

Table 4. Log dimensions and SIRO-Pulse scan positions

<table>
<thead>
<tr>
<th></th>
<th>Maximum Diameter (mm)</th>
<th>Approximate Length (mm)</th>
<th>Distance from log butt to scan locations (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Log</td>
<td>230</td>
<td>330</td>
<td>100, 150, 200</td>
</tr>
<tr>
<td>Log 1</td>
<td>300</td>
<td>450</td>
<td>80, 180, 280, 380</td>
</tr>
<tr>
<td>Log 2</td>
<td>310</td>
<td>490</td>
<td>100, 200, 300</td>
</tr>
<tr>
<td>Log 3</td>
<td>320</td>
<td>570</td>
<td>100, 200, 300, 400</td>
</tr>
<tr>
<td>Log 4</td>
<td>265</td>
<td>500</td>
<td>100, 200, 300</td>
</tr>
</tbody>
</table>

To enable accurate positioning of the radar unit, a rotator was screwed to the end of each log in turn and the SIRO-Pulse antenna attached via a connecting arm as shown in Figure 15. Figure 16-Figure 20 display the MRI images of the various logs at the same distance along the log as the SIRO-Pulse measurements were taken. Some artefacts are present in these images appearing as a blur approaching from the outside of the log but the resin locations remain clearly defined. Unfortunately it is not clear from these images where the heartwood/sapwood boundary lies. The lower images in Figure 16 – Figure 20 also show the corresponding SIRO-Pulse images (in full in Appendix 9.3). These images consist of the raw data with a threshold and a quadratic depth dependant gain applied to ensure that the return from the log’s surface does not swamp the resin/heartwood returns. For ease of interpretation the raw data has then been interpolated onto a polar grid, so that the position around the polar grid gives the radar’s location while the distance in from the perimeter gives the time delay which is roughly equivalent to depth into the log. Note that despite the use of a polar grid these images are still only the raw data and do not represent a migrated image. The 2 GHz antenna head was used; however note that its centre frequency is roughly 1 GHz when in contact with the high dielectric logs. The log has the same orientation in the SIRO-Pulse images as in the MRI images.

In the results of Figure 12 the discontinuity in the heartwood’s return has been used as an indicator of the presence of resin crossing the heart/sapwood boundary. This argument is based on the assumption that resin pockets form due to fractures occurring which fill with resin and that such cracks typically point outward from the core and come to a point at their extremity. The MR images of Figure 16-Figure 20 verify that this is the case. Electromagnetically the disappearance of the heartwood’s return may be explained by the point of the resin streak randomly scattering the incident radiation and thus not allowing radiation to return to the receiver. Thus no return is expected from resin or heartwood when the radar is above a resin streak, however returns may be received from the side of another resin streak at this point. The results from imaging each of the five logs shall now be discussed separately.
The MRI images of the control log (Figure 16 - top) verify that it is free of resin. The corresponding SPR image (Figure 16 - bottom) clearly show an uninterrupted return from the log’s heartwood boundary in all three slices of the log. A slight fading of this return occurs in the top right of slice one but it remains unbroken. As the heartwood boundary is continuous there can not be resin between it and the log’s surface, verifying that the control is free of resin.

**NB** In support of this observation two additional defect-free billets have subsequently been imaged (to investigate the non-contact effect with bark on and off) and show exactly the same signal return as that shown in Figure 16.
The MRI images of log 1 (Figure 17 - top) clearly show a large amount of resin to be present. Figure 17 (bottom) gives the SIRO-Pulse images of the log. In these images an intermittent return is present running roughly parallel to the log's perimeter at an appropriate depth for the heartwood return in a log of this size. The intermittent nature of this return is a clear indication that the sapwood contains resin. Several of the gaps in the heartwood's returns line up with the resin locations in the MR image while several do not.

Figure 17. Axial MR images (Top) and SIRO-Pulse radar images (Bottom) of log 1 at (left to right) 80, 180, 280 and 380 mm from the log’s butt.

The MRI images of log 2 (Figure 18 - top) show a large resin streak with a predominately left to right nature. The SIRO-Pulse images in Figure 18 (bottom) show an intermittent return at a depth suitable for the heartwood boundary. Once again the absence of a continuous return form the heartwood indicates the presence of resin. However the gaps in this return do not line up with the resin streak locations. Note that this is the second largest log, and the penetration depth may be an issue.
The MR image in Figure 19 (top) shows significant resin in log 3 while the SPR image (bottom) displays some very faint returns from deep in the log which may be from the remains of the heartwood or from resin streaks. The returns are very faint, to the extent where one might argue that even if there were no resin, and thus an intact heartwood boundary, a continuous return may not be found.

The MR image in Figure 20 (top) gives the resin streak location within log 4 and (bottom) the SIRO-Pulse returns which clearly show an intermittent return at an appropriate depth for the heartwood. This is clear indication of the presence of resin.
in the sap wood. Some gaps in the heartwood’s return line up with resin streak locations while others do not.

Figure 20. Axial MR images (Top) and SIRO-Pulse radar images (Bottom) of log 4 at (left to right) 100, 200 and 300 mm from the log’s butt.

Further discussion on these results is given in the discussion section below. The next step was to investigate the feasibility of using the radar in non-contact mode as would be the case to facilitate production line scanning.

All the data thus far presented was taken with the 2 GHz SIRO-Pulse system in contact with the log where the bow tie antennas couple with the high dielectric log shifting the centre frequency down to approximately 1 GHz (see Figure 10). To maintain approximately the same frequency range with a slight stand off the 1.4 GHz SIRO-Pulse antennas were used with a 20 mm spacer of dielectric constant approximating that of air. Figure 21 gives the SIRO-Pulse return at slice 2 of log 4 in stand off and contact modes. As the heartwood/resin features proved harder to differentiate on a polar plot this data is given in its raw Cartesian nature with time delay as the vertical axis and position around the log as the horizontal. The stand off mode data is significantly obscured by multiple reflections between the bow tie antennas and the log, however the intermittent return between 2 – 4 ns in the contact data remains visible in the stand off data verifying that significant power penetrates the log even in standoff mode.

The resin has a low dielectric compared with the sap wood and when the radar is above the resin pocket’s point, the incident radiation is randomly scattered causing negligible returns to the radar. As a result no return at depth is found around the point of a resin streak. In the absence of resin the heartwood return should be visible from all angles.
3.4 Acoustic Tomography

Two-dimensional acoustic tomography was performed using a 16-channel Fakopp ultrasonic timer. The 16 transducers were arranged on a transverse plane at equidistant points around the billets. Three planes were assessed for each billet, namely 25%, 50% and 75% of the length (Figure 22).

Note that in this setup, transducer 9 corresponds to the Anterior position in the corresponding MR images (a 180° rotation). For direct comparison the MR images are rotated 180°.
Figure 22. Photograph showing arrangement and location of transducers and imaging planes.

Figure 23 – Figure 27 show the acoustic tomography images and corresponding MR images. While some images show considerable heterogeneity, this is not consistent with the presence, absence or location of resin streaks as determined by MRI.
Figure 23. 2D acoustic tomographic image and corresponding MR image of Log 1.
Figure 24. 2D acoustic tomographic image and corresponding MR image of Log 2.
Figure 25. 2D acoustic tomographic image and corresponding MR image of Log 3.
Figure 26. 2D acoustic tomographic image and corresponding MR image of Log 4.
Figure 27. 2D acoustic tomographic image and corresponding MR image of Log 5.
4. DISCUSSION

The high frequency microwave measurements have suffered significantly from attenuation of the signal by the log. The ideal frequency range which compromises penetration depth with respect to resolution was shown to be from a few 100 MHz to 2 GHz. This frequency range has in recent years seen considerable research for application to ground penetrating radar sensing. Thus with its ultra wide bandwidth, pulsed nature, high dynamic range, and ability to quickly recover from strong surface reflections, the SIRO-Pulse is an ideal system with which to investigate this problem.

The ability to detect resin streaks is dependent on the defect traversing the heartwood/sapwood boundary as the detection relies on identifying discontinuities in the reflection from the heart/sap boundary. Note however that none of the samples selected had resin defects fully contained within the heartwood and so it cannot be said that detection of resin within the heartwood is not possible.

The initial measurements made by the SIRO-Pulse system (Figure 12) accurately located the sole resin pocket in the log. The MRI images in Figure 16 – Figure 20 (top) support the assumption on resin pocket shape. The corresponding SIRO-Pulse returns in Figure 16 – Figure 20 (bottom) verify that an intermittent return from deep objects in the log signifies the presence of resin, while an uninterrupted return at depth signifies that the sapwood is free of resin. It was, however, difficult in these measurements to locate individual resin streaks within any of the logs using the SIRO-Pulse data. This is not surprising however considering the following:

1. All four logs with resin and especially the smaller two (logs 1 and 4) contained numerous resin pockets. One resin defect may affect the radar return a significant distance away. For example in Figure 12 the one resin defect present influences the heartwood’s return from just after halfway through quadrant B to nearly halfway through quadrant D. Thus with multiple resin defects present it is likely that interactions between them will effect the ability to locate each pocket individually.

2. The MRI images do not clearly differentiate between resin and heartwood and thus some smaller resin inclusions (resin shakes in particular) may exist in the logs that are not obvious from these images.

3. Much of the resin in this second experiment was bleeding sap and it is currently unknown to the authors the difference in the permittivity and thus the ability to detect hardened resin pockets versus bleeding ones.

The heartwood/resin returns in logs 2 and 3 ranged from weak to undetectable. These were the largest of the logs and Lewis (2007) showed a significant variability in the attenuation of different sapwood samples. It is likely that the heartwood and resin returns in these logs were weak and undetected due to insufficient sensitivity in the SIRO-Pulse system. This problem could be avoided by incorporating more sensitive receivers into the system and better/optimised coupling of the antennas to the log.

The stand off example given in Figure 21 showed that significant interference was present due to multiple reflections between the log and the bow tie antennas. Despite this interference similar returns to that of the contact case could be seen superimposed on the multiple reflections demonstrating that sufficient power was
coupling into the log. The SIRO-Pulse was designed for interfaces of a much lower contrast than that of wet wood where multiple reflections are less severe. In the case at hand a different choice of antenna (e.g. a horn) should significantly reduce the issue of multiple reflections.

No attempt has been made in this work to perform imaging through inverse scattering on the raw SIRO-Pulse data. The SIRO Pulse data presented is raw data with a quadratic depth gain applied and interpolated to a circular domain. True tomographic imaging was not applied because:

1. In the case of one resin defect or two well separated defects being present, the location of the defect is clearly identifiable by the absence of a heartwood return. A simpler and more readily implemented detection method would therefore use image processing to detect the discontinuities in the heartwood return.

2. The SIRO-Pulse in its current form consists of a bistatic radar with transmitter and receiver located next to each other. In this scenario the dominant effect of the resin pockets on the SIRO-Pulse data is to interrupt the otherwise continuous heartwood return. Some returns are obtained from the resin defects themselves but these are unreliable being from interaction of the antenna side lobes or the extremity of the main lobe with the side of a resin defect and not from direct measurement. As limited returns are obtained from the resin defects themselves, tomographic imaging will not reconstruct the resin defects reliably. It may be feasible to perform tomographic inversion if the transmitter to receiver offset is varied or an array used.

3. An index would need to be developed in conjunction with processors to classify resin defects according to their own particular end-use. For example it may be a simple %area or if more than one quadrant is affected or the observance of a single resin shake extending the length of the log.

Attempts to detect the location of resin defects using 2D acoustic tomography have shown that there is insufficient resolution to achieve this level of detection. At best it could be said that an irregular tomographic image would indicate the presence of resin defect(s) somewhere in the stem.

5. CONCLUSIONS

Locating resin defects (shakes and streaks) in freshly felled logs with microwave imaging has shown to be feasible in the instance where the resin defect breaches the heart/sapwood boundary. A commercially available microwave sub-surface radar, the SIRO-Pulse, has been shown to possess many of the required features for this problem. With some adaptations to this system it should be possible to differentiate between logs with and without resin inclusions and to locate the inclusions when only a few are present. This should be achievable both in real time on a stand off production line system and for a hand held contact system. Recommendations have been given to help achieve these products.
6. RECOMMENDATIONS

The results of this investigation show that resin defects in logs can be clearly identified from the control sample. Some issues need to be addressed including multiple reflections and low sensitivity for the larger logs. As a result of this the following recommendations are proposed:

1. An in-forest trial of the SIRO-Pulse system to assess the potential for locating resin-free and resin-containing trees by scanning at breast height and up to 3-4 m in height. The trial may use targeted field trials deployed to investigate variation in resin defect susceptibility. In order to ground-truth the trial it would be essential to fell the trees and assess the resin incidence via cross-cutting the stem.

2. An in-mill trial using the SIRO-Pulse located at the log yard debarker. A simple recovery trial is envisaged, whereby scanned logs would be identified by painting the log ends with a colour pattern that would allow back-to-log recovery to be undertaken and correlating predicted versus measured out-turn.

3. The antenna design for the SIRO-Pulse needs to be optimised to enable higher coupling of power into and out of the logs for the two cases of contact and non-contact measurement. For both cases significant gains could be made by matching the antennas to the log and for the stand-off case a more appropriate antenna (e.g. a horn) for reducing multiple reflections is required.

4. After choosing more appropriate hardware, preprocessing methods may also need to be investigated to do tasks such as reducing the effect of multiple reflections.

5. Image processing methods need to be thoroughly investigated. The feasibility of performing tomography with a larger transmitter to receiver separation or an array should be investigated. Following this an investigation should be taken into the best way to display the SIRO-Pulse data to allow automated (or semi-automated) quantitative or qualitative segregation to be performed.

Following on from the development work reported in MS 3 (Hislop 2008), several practical experiments are recommended as follows:

1. Using a dual polarised horn antenna and a vector network analyser (VNA) reflection measurements in all four possible polarisations may be taken at frequencies ranging from 2-10 GHz and an inverse Fourier transform used to obtain the time domain return from the log.

2. If experiment 1 proceeds well the log may be attached to a rotator allowing for reflection measurements from different orientations of the log. Migration methods such as Synthetic Aperture Radar may then be used to image the log’s structure.

3. Experiment 1 should also be repeated in transmission mode where two waveguides are used as transmitter and receiver on opposite sides of the log.

4. If experiment 3 shows success the log should be rotated as in 2 and transmission tomography methods used to image the structure.
7. ACKNOWLEDGMENTS

The authors would like to thank FWPA for partial funding of the project and to Weyerhaeuser Australia, particularly Andy McNaught, Maurie Carfoot and Greg Levinge of the Caboolture Mill for support and supply of material. Thanks are also extended to Ian Last (FPQ), Geoff Stringer (Hyne and Son) and Andy McNaught for valuable feedback on the final report.

8. REFERENCES


9. APPENDICES
9.1 Magnetic Resonance Imaging

LOG 1
9.2 Microwave Images

Log 1

Log 1 slice 1

Log 1 slice 2

Log 1 slice 3

Log 1 slice 4
Log 2

Log 2 slice 1

Log 2 slice 2

Log 2 slice 3
Log 3

Log 3 slice 1

Log 3 slice 2

Log 3 slice 3

Log 3 slice 4
Log 4

Log 4 slice 1

Log 4 slice 2

Log 4 slice 3
Log 5 – Control

Control log slice 1

Control log slice 2

Control log slice 3
9.3. Acoustic Tomography Images

Log 1 – Top (75% height), Middle (50% height) and Bottom (25% height)
Log 2 – Top (75% height), Middle (50% height) and Bottom (25% height)
Log 3 – Top (75% height), Middle (50% height) and Bottom (25% height)
Log 4 – Top (75% height), Middle (50% height) and Bottom (25% height)
Log 5 (Control) – Top (75% height), Middle (50% height) and Bottom (25% height)
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