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A K-Band Microwave Measuring System for the Analysis of Tree Stems

Pekka Eskelinen and Harri Eskelinen

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The internal structure of growing trees and freshly cut logs can be characterized in real time by analysing the transmission and reflection of Ku- or K-band microwave energy injected with a horizontal polarization towards the material. Information about the moisture content, material bends, number and location of knots and sections of spoiled wood e.g. due to insects can be gathered in real time. Most sensitive test parameters are attenuation, group delay and the rotation of a linearly polarized wavefront. A simultaneous recording of reflection reduces errors caused by non-significant surface deformations. The spatial resolution, humidity equalization and noise immunity can be improved by applying a wideband frequency modulation. Commercial building blocks supplemented with a special antenna arrangement give possibilities also for the rough harvester environment.

Keywords microwave measurements, wood analysis, knot detection, stem quality evaluation
Authors' address Lappeenranta University of Technology, Department of Electrical Engineering, P.O. Box 20, FIN-53851 Lappeenranta, Finland
Phone +358 5 62 111 **E-mail** ari.eskelinen@pp.inet.fi
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1 Introduction

The requirement for improved efficiency and at the same time wishes to conserve natural resources within forest industries has expanded to the actual gathering of raw material. In practice this implies a fast, accurate and sorting harvester system which prior to cutting a tree already knows what will come out of it – could the wood be used for making paper, for general logs or perhaps for high quality furniture material. In marginal situations the tree may be left growing there as it is due to severe deteriorations.

Current mechanical harvester machines are very efficient and fast. The actual cutting of a tree takes 3–5 seconds and after that a heavy stem moves at a speed of about 4–5 m/s while special blades cut the branches and the stem is further cut to pieces according to a preliminary acquisition plan, e.g. every 5 meters for sawn timber but at about 3–5 meters for paper and pulp. According to the industry, the largest diameter of Scandinavian logs of spruce or pine is about 70 centimeters, the average value 27 centimeters and the smallest economically usable 6–8 centimeters for pulpwood. Most harvesters operate round the year which means lively, wet trees in the summertime and frozen, dry trees in the winter. Also the temperature extremes fluctuate substantially.

Typical parameters which influence the value of a log and its coming use include, besides the dimensions, the size, number and quality of knots, the density and the annoying internal bends. Bad, often invisible internal deteriorations can be classified as damages caused by fungi or as insect attacks which both totally spoil at least a portion of a log. Many of these cannot be figured out by conventional external inspection. Initial attempts have been made to use X-rays for the analysis, but putting such a device in a harvester systems is quite impossible and even dangerous. Also microwave techniques were tried in the late 1970's and early 1980's but these projects were not commercially succesful due to the – at that time – apparently too costly electronics, an unfortunate frequency selection and a more theoretical approach.

The system (Tiuri et al. 1978) was not based on pure microwave radiation either but required a supplementing gamma source and an infrared detector, too, and the complicated system was only applicable in a steady saw-plant type installation. The method in Jakkula (1983) was also targeted to quality estimation of sawn goods and utilizes a special polarization arrangement for knot detection only thus putting a severe restriction on wider applications where the relative stem alignment is not easily controlled.

The main goal in this project was to evaluate the usability of commercial low-cost microwave components and associated mechanical modules for practical stem analysis – possibly already as a configuration thinkable also for the field environment – and to make measurements at previously untried carrier frequencies.

2 Description of the Test Arrangement

The prototype system, developed at the Lappeenranta University of Technology, Finland, utilizes basically the common vector network analyzer concept and measures simultaneously the microwave transmission and reflection observable in a growing tree before it is cut by the harvester or in a complete log just after cutting prior to sorting for the coming use. The operating principle is illustrated in Fig. 1 for the laboratory version which was based on commercial expensive test equipment first documented in (Eskelinen P. 1998).

Two sets of linearly polarized small specially configured antennas (Eskelinen H. 1998) are fixed to the harvester head and connected electrically to the TR-test (Transmission - Reflection) device currently operating in the K-band. The complex S_{12} is measured as a function of frequency and distance along the tree. An option exists for the simultaneous recording of S_{11} as well which can help in separating less important fluctuations caused by the very rough surface of e.g. old pines from the actual interesting internal deformations. The electrical block diagram is shown in Fig. 2 and the actual test arrangement utilized during the laboratory tests can be seen in Fig. 3.

Challenging measurement problems are encountered. The ability to detect small defects not only depends on the transducer´s two-dimen-

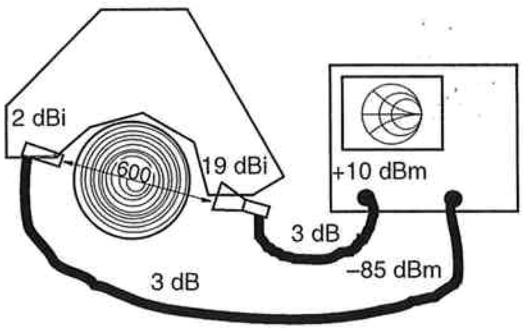

Fig. 1. The operating principle of the suggested method as implemented on a harvester head and based on a commercial microwave vector analyzer. Typical power levels and attenuation values are given.

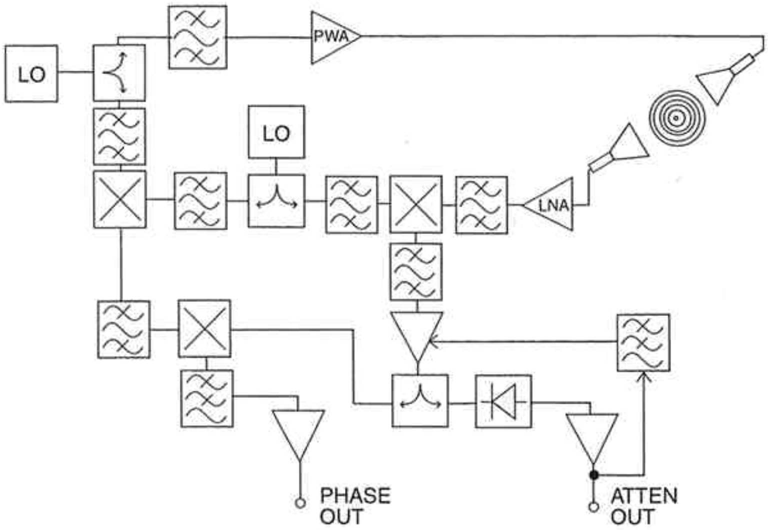

Fig. 2. The schematic presentation of the applied measuring instrumentation which presents both the amplitude and phase information of the transmitted or reflected microwave energy.

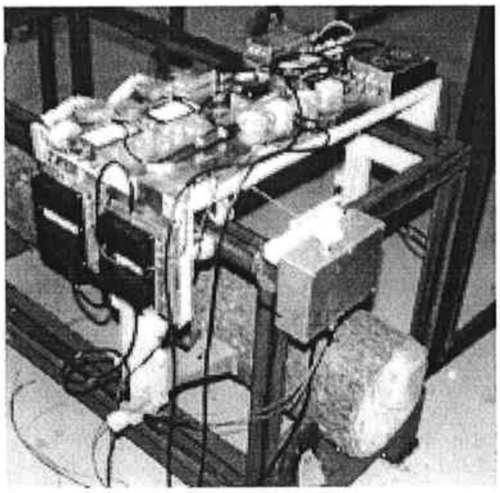

Fig. 3. Fresh logs were brought in to the laboratory and mounted inside the test track which is capable of handling diameters up to 500 mm.

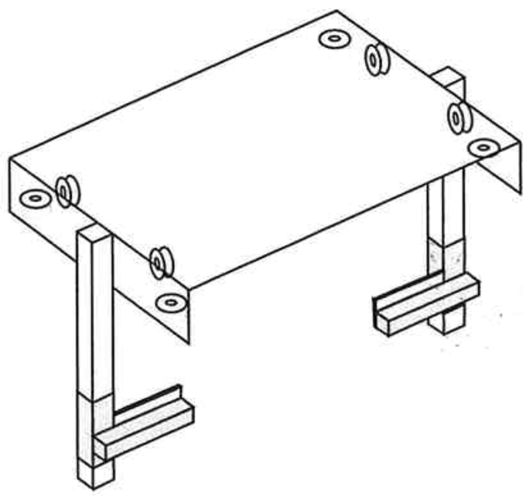

Fig. 4. During laboratory tests the logs were kept stationary and the instrumentation was moved along their axial direction by using a special eight-wheel trailer which was able to maintain the precise alignment of the opposing transducers mounted on the gray-shaded supports.

sional resolution but also on the signal processing speed. A 10 mm knot will be "visible" only for 2.5 milliseconds and we have to cover the whole circumference of a log. A typical attenuation in a fresh tree is more than 150 dB/m and thus the receiver noise figure must be kept below 1 dB in order to avoid exceeding a safe transmitter power density level. However, due to the noisy environment, some averaging of the raw detected signal should be done. The group delay measurement is even more difficult because it would require a stable reference power level and the AGC (Automatic Gain Control) attack time should be an order of magnitude shorter than the smallest impulse caused by a change in the wood´s internal structure. A quite tricky circuit design is used to accomplish this, originally developed for cellular coverage measurements.

3 Transducer Details

Much of the spatial resolution of the measuring arrangement and the mechanical reliability almost totally is defined by the performance of the small microwave transducer facing the wood material at the closest practical distance (10–20 mm). Their task is further complicated by the 4 GHz frequency sweep which indeed improves resolution and gives some coding gain but at the same time dictates the use of a fairly wideband front end and suitable antennas with a reasonable bandwidth (2–5 GHz) and polarization characteristics. Both conventional and corrugated (see Fig. 5) rectangular horns have been tested, the latter giving nearly optimum radiation patterns for the task. Due to the severe operating environment in a real-life application with shocks, dirt and snow the transducers must be completely sealed but still there is no room for additional attenuation of the wanted signal due to the protective measures.

The hard winter time produces some extra problems first by covering the lower portions of trees with ice and snow often as hard as the wood itself. Also the temperature may fall below –40 °C which will freeze all free water inside the tree and frost covers the transducer Duroid® windows. The multiple reflections occuring at both sides of the measuring path can be solved by using the information from the wide FM (Frequency Modulation) sweep. The reliable fastening of the radomes is carried out by laminating in a high remperature a special plastic shroud around their edges onto which conventional adhesives are readily applicable.

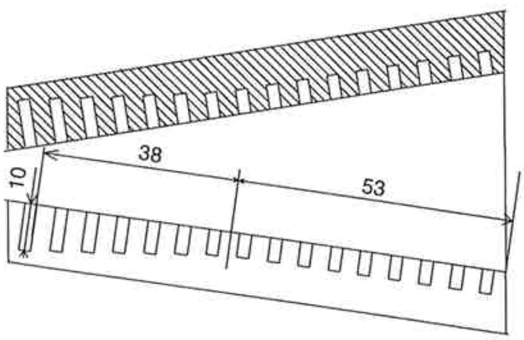

Fig. 5. Well-known in satellite communications and radar work, corrugated horns proved useful also for these measurements due to their radiation characteristics. The construction is laser processed from aluminium.

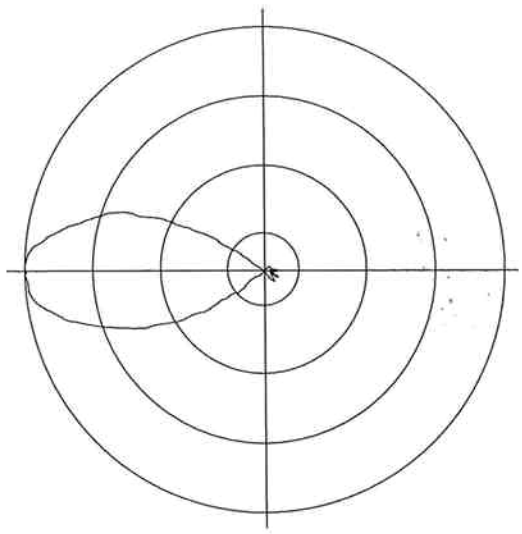

Fig. 6. The measured E-plane radiation pattern of a rectangular horn transducer shows a spatial resolution of 100 mm in the middle of a 600 mm log. Scaling is 10 dB/div.

4 Preliminary Results

Five logs (both spruce and pine) with diameters between 260 and 500 mm have been measured up to now with promising results. The plots collected here all have a relative recording of attenuation (arbitrary scale) and a track of the signal's phase, also with no specific reference value. The selected visualisation practise is based on the fact that only momentary deviations of either parameter have been found to be of significance. Attenuation as such could be used as a measure of wood's inherent density but this requires much background information currently unavailable to the authors. As anticipated, knots are generally very well observed but also defects originating from them, as is shown in the recording of Fig. 7 come clearly visible. The respective cuts of the log are illustrated in Fig. 8 and Fig. 9.

The second sample (log 2) was used to test the effects of illumination angle. The reference plot is in Fig. 10 and associated cuts of the log in Fig. 11. If the log is rotated by 45 degrees we notice that the phenomena at 400 mm are no more recorded (Fig. 12) and if rotated further (90 degrees from the original) we get totally new observations (Fig. 13), e.g. a partially dried knot at 1100 mm from the log´s end, illustrated as a cut in Fig. 14.

The third sample was a 260 mm pine log which was known to have had small brances at almost equal distances. The measurement proved to work here as well but due to the limited size of the targets also the observed phase and amplitude changes stay less prominent which is document-

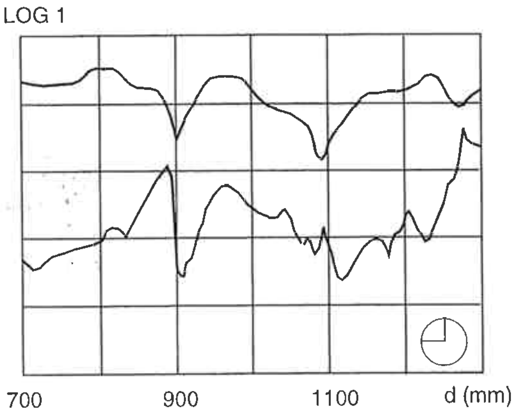

Fig. 7. Sample 1 shows a sharp phase reversal (lower trace) and an increase in attenuation (upper trace) at 900 mm from the end. The "clock" in the corner shows the relative attitude of the sample.

Fig. 8. At 920 mm from the log's end (sample 1, pine) we find an internal deformation, obviously initiated by a former knot which has been covered during the years.

Fig. 9. Starting at 1050 mm from the end of sample 1 (starting at the tip of the arrow and extending across the whole cut to 1 o'clock) we have another internal deformation.

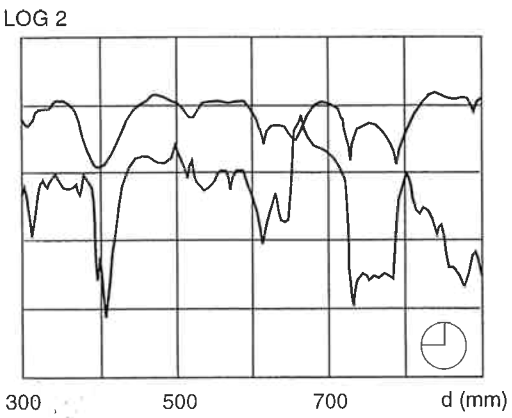

Fig. 10. The recording of the second pine sample shows e.g. a distinct dip at 400 mm from the log's end when the sample is illuminated from the direction indicated by the clock in the plot corner.

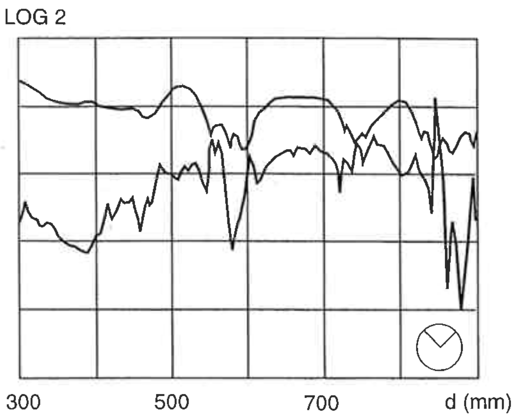

Fig. 12. If the direction of microwave illumination is changed we no more get information about the knot at 400 mm. However, new deformations which were not visible in Fig. 10 come up.

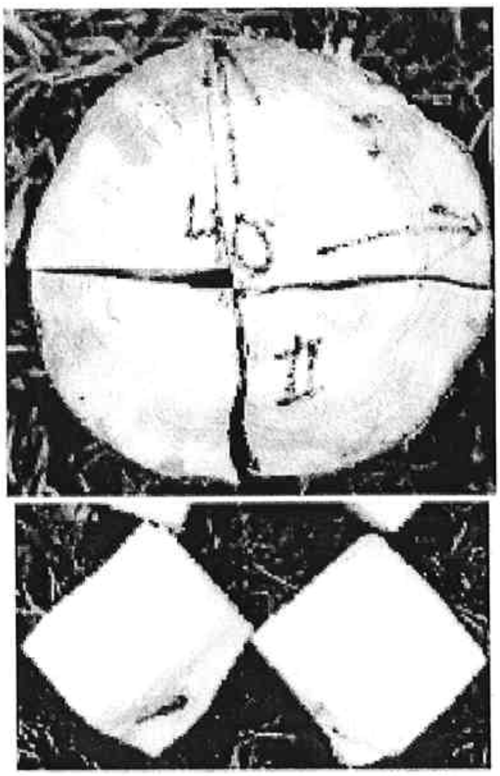

Fig. 11. The measured phenomenon at 400 mm comes visible when the log is first cut and then split into four pieces.The covered knot between the lower halves has been nearest to the receiving transducer.

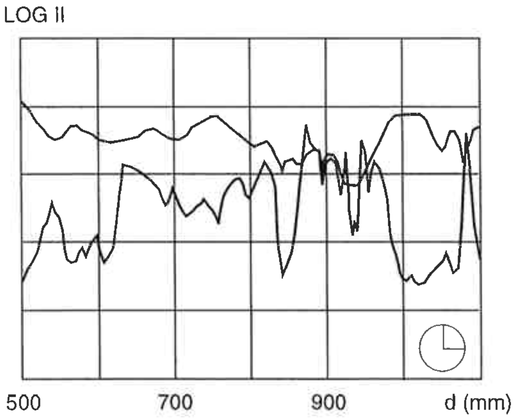

Fig. 13. A third illumination perspective shows a very sharp peak in the phase curve at 1080 mm.

ed in Fig. 15. The log was cut along its centerline (Fig. 16) to reveal the accurate position of knots. For an unknown reason the spatial accuracy shows an error of about 100 mm. Sample number 5 was the smallest of all which causes a by-pass effect of the propagation path and thus any phase or attenuation changes tend to vanish. However, a sharp yet tiny sign reversal at 200 mm, shown in the plot of Fig. 17 proved to be caused by a hidden knot which was just in the middle of the wanted signal path as can be seen in Fig. 18.

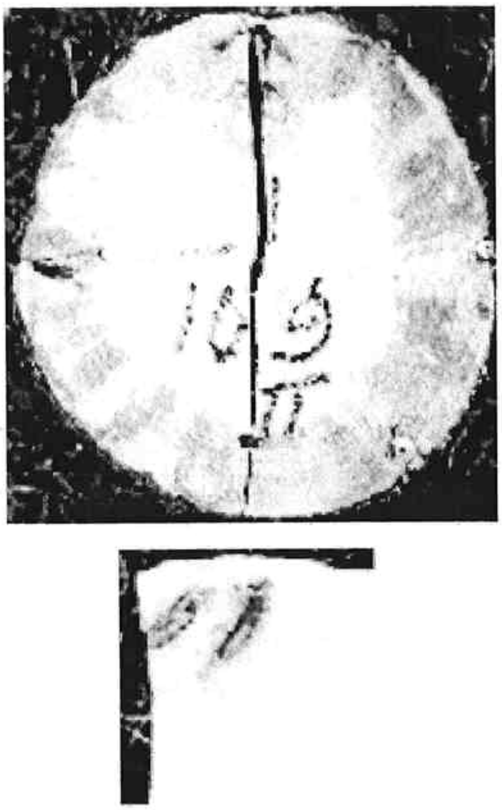

Fig. 14. Starting at 1090 mm from the log's end (sample 2) we have a dead knot which already has been totally covered with new wood material as shown in the lower cut.

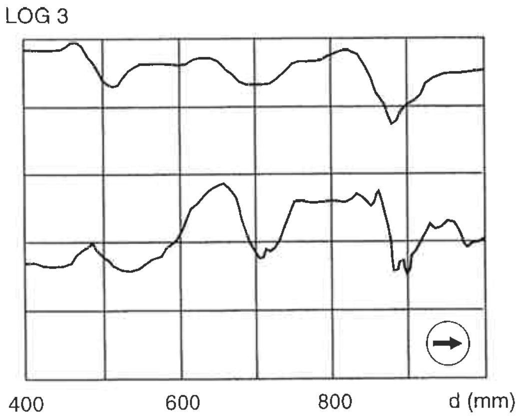

Fig. 15. A 260 mm spruce sample (number 3) shows quite low attenuation and two rather sluggish phase reversal at about 700 and 900 mm.

Fig. 16. The log sample number 3 was cut from the middle into two halves. Two groups of small knots are visible at 590 mm and at 940 mm.

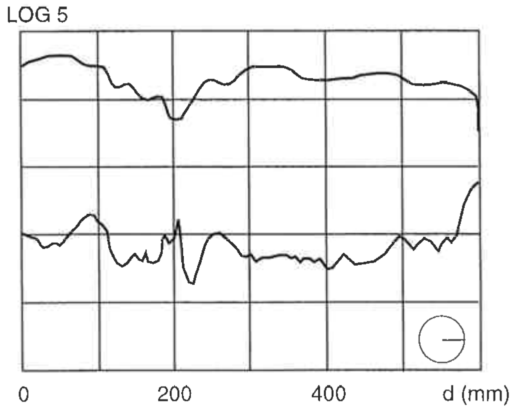

Fig. 17. The fifth sample (spruce) had very little deformations but one questionable peak at 200 mm.

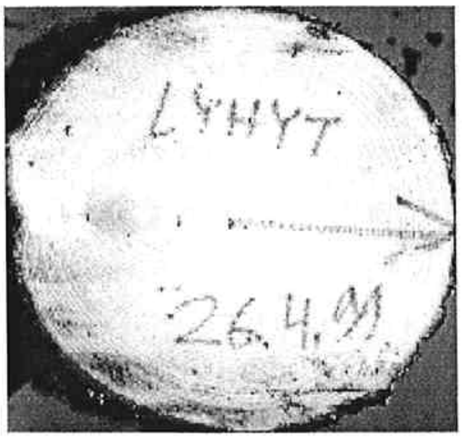

Fig. 18. Sample 5 showed a covered knot aligned along the measuring line at 200 mm.

5 Reliability Issues

All log samples were measured several (3–10) consecutive times in order to get a view on the repeatability of the suggested principle. Fig. 19 shows a very typical result with attenuation uncertainties below 0.5 dB and phase reversal positioning better than 10 mm which is actually much better than expected with just a 80 mm transducer width. In practise we can thus estimate that major changes in the electrical recording are either based on a different viewing angle (the direction of microwave illumination) or altered sample characteristics but not on e.g. random noise of the microwave instrumentation. The uncertainty of knot positioning seems to stay below 20 mm. In a practical field application the repeatability will be affected by mechanical vibration and temperature extremes unless proper shielding arrangements for the microwave head are used.

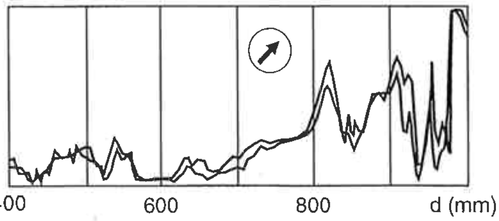

Fig. 19. The repeatability of the measurements was tested frequently. Here a sample plot of log 3 phase is shown as 5X magnified.

LOG 4, ϕ 450 mm horizontal polarization

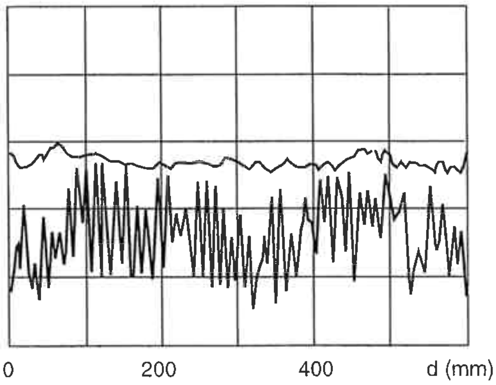

Fig. 20. With horizontal polarization the attenuation is high and prevents phase recordings indicated by the noise on the lower trace.

6 Choosing the Polarization

The transducer mounting configuration was chosen arbitrarily but it turned out to be a wise guess because, as we note from the plot of Fig. 20, horizontal polarization has no chances of getting through the wood. If elliptical polarization is utilized as suggested by earlier studies we are able to define the alignment of the test sample at the cost of more complicated electronics.

LOG 3 moisture test 11/98–2/99

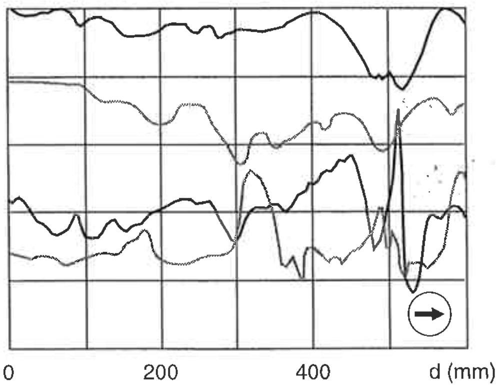

Fig. 21. The effects of decreasing moisture content come out as decreasing microwave attenuation and a loss of structural information. Note the absence of phase jumps initially found (lower red curve) at 330 mm.

7 Estimating the Effects of Water

Possibilities of the suggested principle for moisture content measurements were evaluated with log sample number three. Unfortunately a reliable reference instrument was not available and would anyhow have been highly problematic to use due to the probe cavities caused by it to the test sample's internal structure. Anyhow, the observations illustrated in Fig. 21 and taken as two extremes of the time scale (four months drying in the laboratory) seem to confirm that if scalable tests are to be conducted the amount of bound and free water must be analyzed e.g. by a frequency modulation technique. An accurate evaluation of the water content would need a further supplement of the system with a special "pilot tone" transmitted at the H_2O absorption frequency. This is particularly important because a fairly dry wood does not produce significant phase reversals of the transmitted microwave signal (look at the curves near 330 mm) even though the deformations are still there.

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