In-Situ Measurement of the Moisture Content of Building Materials Using Ultra-Wideband Radio Waves

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ABSTRACT: A study was carried out to determine the feasibility of commercial, off-the-shelf, and potentially low-cost ultra-wideband radio hardware to serve as a measurement tool for the moisture content of building materials. The study examined both reflections from and transmission through an envelope assembly when pulses with a center frequency of 4.7 GHz were emitted towards the materials. The reflected energy was found to be the best measure of moisture content. Tests on oriented strand board, plywood, and gypsum board showed that a linear trend was found between the reflected energy and moisture content of the two wood products, but the range of moisture contents in the gypsum boards was insufficient to have any appreciable effect on the signal returned. The ability to independently measure the moisture content of several layers with a single scan was also examined, but the data suggest that more work is needed to accomplish this goal.

1 INTRODUCTION

1.1 *In-situ moisture detection*

Measurement of the in-situ moisture content of the materials making up the building envelope is a complicated endeavor. Several reviews have discussed the various methods that are currently available (TenWolde & Courville 1985, Derome et al. 2001, Healy 2003), and the general consensus is that significant improvements could be made to provide more accurate measurements. Electrical pin probes are currently the most popular method of making such measurements since the sensitivity of electrical resistance to moisture is high and the equipment can be built or purchased at a relatively low cost. These sensors, however, rely on contact with the material and are difficult to install in existing walls or roofs without damaging them. In contrast, non-contact in-situ measurements permit moisture measurement without disturbing the wall or roof.

A number of such techniques have been tested previously. Several investigators have used infrared techniques to determine areas of wetness in roofs (Tobiasson et al. 1977, Korhonen & Tobiasson 1978). Using such a technique, however, does not provide quantitative data on the moisture content, and it is difficult to get data on layers that are hidden from view. Other researchers have taken advantage of gamma-ray attenuation and neutron scattering (Knab et al. 1981) to identify the amount of water in the building materials. This technique has proven effective, but the use of radioactive materials is a concern for those who operate the equipment.

A technique that has received recent attention is the use of ultra-wideband radio signals (Healy & van Doorn 2004a, 2004b). This paper will discuss further attempts to characterize the ability of commercial off-the-shelf hardware to provide non-destructive in-situ measurements of the moisture content in building materials.

1.2 *Ultra-wideband*

Ultra-wideband signals are radiofrequency transmissions that consist of a large spectrum of frequencies. A good discussion of this topic is given by Taylor (1995). By definition, a signal is considered to be ultra-wideband if its relative bandwidth, η, is greater than 0.25. The relative bandwidth is defined as:

$$\eta = \frac{f_h - f_l}{f_h + f_l} \tag{1}$$

where:
f_h = highest frequency contained in signal
f_l = lowest frequency contained in signal

One technique for creating such signals is to emit extremely short pulses in the time domain that, through the Fourier Transform, can be shown to be comprised of a large spectrum in the frequency domain. The key advantage of these signals is their ability to penetrate a variety of wall constructions. Since a signal consists of a large range of frequencies, the likelihood that all those frequencies would be attenuated by a particular building material is small. Therefore, this technology could potentially provide information on a variety of materials in a building envelope, including those that are hidden from view.

While ultra-wideband technology has been used in communications because of its ability to transmit data through a range of constructions, another potential application is that of sensing. The significant difference between the dielectric constant of water (approximately 81) and that of dry building materials (approximately 5) indicates that the reflections of signals can be correlated with the moisture content of the material since electromagnetic waves reflect more significantly from materials with high dielectric constants than from those with low dielectric constants. It should be noted that the dielectric constant is both frequency dependent and comprised of real and imaginary parts, but those features were not investigated in this study. In this analysis, an averaged dielectric constant across all frequencies will be considered and only the magnitude of the reflected signals (corresponding to the real part of the dielectric constant) will be examined. All tests performed here were carried out at 21°C ± 1°C (70°F ± 2°F).

2 EXPERIMENTAL OVERVIEW

2.1 *Radio hardware and software*

The ultrawideband equipment was a commercially available evaluation kit designed to comply with recent United States Federal Communications Commission regulations for the communications market (2002). Although the hardware was not optimized for remote sensing purposes, the aim was to investigate the sensing capabilities of this equipment since the anticipated market for these products may lead to low cost components that could be incorporated into sensing instruments. The kit consisted of two identical radios. One radio was set up as the transmitter of the ultrawideband signal, while the other was set up as the receiver. Both radios were connected to a computer via Ethernet cables, and software was written to control each box. The transmitter is set to emit gaussian monocycle pulses with a center frequency of 4.7 GHz and a bandwidth of 3.2 GHz. While significant absorption cross-sections lie in the infrared or terahertz region of the spectrum, this equipment was largely selected based on its potential for low cost. Pulses are emitted at an average frequency of 9.6 million pulses/s, each pulse having a width of approximately 5 ns and separated by approximately 100 ns. Precise timing circuits ensure that the receiver listens at the proper time to capture the signal coming from the transmitter. While each pulse lies below the ambient noise floor, the averaging of many pulses over time eliminates the random noise and leaves only the repetitive signal arising from the transmitted pulse. In these experiments, each waveform is created by integrating 1024 pulses. Magnitudes of the returned signal are collected in bins with a width of 12.7 ps. Therefore, the entire collected waveform is comprised of roughly 1000 data points, creating a waveform with an approximate length of 13 ns.

For each test specimen, a total of 29 waveforms were automatically scanned into the computer to provide more data for each specimen. These 29 waveforms were then averaged together to obtain a single waveform for each experimental setup. One of the challenges in averaging the waveforms was that the successive scans were occasionally out of alignment in time. An algorithm was developed to align these scans so that averaging did not result in destructive interference and so that the time of flight could be obtained. This process was performed by correlating the first scan with each of the successive scans. The subsequent scans were shifted in time until the best correlation was found.

2.2 *Building material samples*

Panels of gypsum board, oriented strand board (OSB), and plywood measuring 910 mm by 610 mm by 13 mm (3 ft × 2 ft × 0.5 in.) were first placed in ovens and weighed to estimate their dry mass. OSB and plywood were kept in the oven for about 1 week at a temperature of 103°C ± 1°C (217°F ± 2°F), while gypsum board samples were placed in an oven at 45°C ± 1°C (113°F ± 2°F) for approximately 2 weeks. After the mass of each sample was determined to have reached a steady-state value, the samples were placed in chambers of constant relative humidity to reach a variety of moisture contents. Five chambers were used, having relative humidities (RH) of (0, 33, 56, 84, and 97) %. The relative humidity of 0% was achieved by placing a pan of desiccant in the chamber, while saturated salt solutions (Greenspan 1977) were placed in the other chambers to achieve the desired relative humidity. RH sensors were placed in several of the chambers to verify the effectiveness of the conditioning method. With the large volume of air in the chambers and the large size of the samples, the equilibrium RH was achieved in about 1 week. Also, the equilibrium levels did not always reach their desired levels, owing largely to infiltration from the ambient air. The uncertainty in the relative humidity in each chamber is estimated as ±5% RH. The moisture contents of the test panels were determined gravimetrically. The uncertainty in the measured moisture contents (MC) is estimated to be ±0.6% MC, where MC is defined as the percentage of the mass of water in a substance divided by the dry mass of that substance.

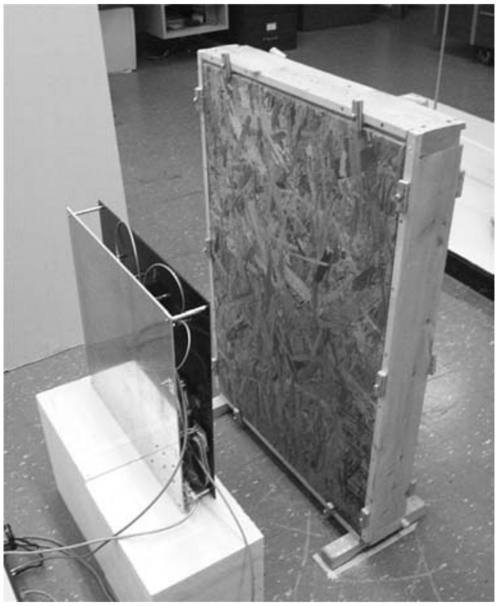

Figure 1. OSB specimen (right) and antenna holder (left).

Table 1. Test parameter levels and values for preliminary tests.

Parameter	Levels	Values
Material	3	OSB, Gypsum Board, Plywood
RH level	4	(0, 33, 58, 84) % RH
Sample	2	A, B

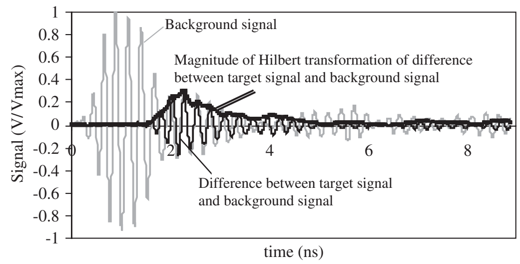

Figure 2. Typical set of waveforms used in analysis.

2.3 *Radio and wall setup*

The conditioned samples were placed in a pine wood frame shown in Figure 1. Either a single sample could be placed in the frame, or two panels could be placed with a separation of 8.9 cm (3.5 in.) to simulate typical layering present in residential construction. Clamps on each side of the frame ensured that samples were kept flush against the stud cavity.

3 SINGLE-PANEL EXPERIMENTS

3.1 *Preliminary screening*

Three parameters of interest were investigated in a preliminary study of the factors that affect the measurement of moisture content using ultra-wideband signals. In these screening tests, the primary interest was the signal reflected from the building material. Parameters that were changed included the distance between the antenna and the building material, the distance between each antenna, and the orientation of the antennae. Preliminary tests found that the signal was improved as the antennae approached the wall and that positioning the antennae closer to each other was better for this setup considering that the field of view of the specimen was limited. As for the antenna orientation, the hardware made it difficult to acquire a consistent signal when the antennae were aligned at an angle of 90° to each other as is typical of the dipole antennae used in this study. The signal was therefore much stronger when both antennae were positioned vertically. By doing so, it is acknowledged that some information in regards to polarization that may help differentiate building materials or moisture levels is not acquired.

Following these preliminary tests, an experiment was set up to focus on the issue of moisture measurement using the ultra-wideband radios. The antennae were fixed at 0.3 m (1 ft) from the walls and placed on polystyrene foam, while the distance between the antennae was maintained at 0.3 m (1 ft) throughout the tests. Scans were first made with no wall or building material in place to get a background waveform. This scan shows the effects of the direct coupling between the antennae and reflections from the environment. Specimens were then placed in the test stand and the experimental plan was carried out. A full factorial test plan was undertaken with the independent parameters given in Table 1. The "Sample" parameter refers to the fact that two specimens of each material were conditioned at each RH level to estimate differences in similar materials. The total number of tests in this full factorial run was 24. Additionally, the tests were repeated on a second day to get a sense of the repeatability.

3.2 *Data analysis*

To begin the data analysis, the waveforms were lined up as mentioned previously. This step allowed the subtraction of the background waveform from the waveform with the specimen (target) present, resulting in a waveform with only the effects of the material of interest. Figure 2 shows a typical background waveform and the difference between the background waveform and a waveform obtained with a specimen in place (not shown). The effect of the specimen can better be represented by taking the magnitude of the Hilbert transform of the signal difference. This transform places an envelope around the waveform; the peak in this envelope identifies a region of significant difference from the background and, therefore, provides the approximate location of the specimen.

A number of features of these scans were examined to determine which gave the most information. First, the energy reflected was determined by integrating the area under the target curve. Another output that was examined was obtained by performing a spectral analysis on the data. This step provided a plot of the power associated with each frequency in the scan. From this plot, both the location of the peak spectral power and the magnitude of the peak spectral power were examined.

To help determine which analysis technique performed best, a metric was developed that is akin to a signal-to-noise ratio. The desired signal is the change in the output variable with RH level. The noise is either the change due to material or that due to different samples. Noise created by material is less of a concern since it is conceivable that a technique using ultra-wideband reflections to determine moisture content could correct for the material, but it was of interest to find out if this technique could provide data that did not depend upon material. The more significant metric is that of the change in the output variable with RH compared to the change with sample. This measure will help determine the significance in the change in the signal due to changes in moisture level.

As an example of the calculation of these measures, the computation of the ratios will be discussed for the analysis in which mean energy was the output variable of interest. For the mean energy, the average signal increased from a fractional value of 0.374 to 0.525 (mean energy reflected divided by mean energy in background scan) over a change in RH from 0% to 84% for all materials and samples (uncertainties in these measurements will be discussed later). This difference is compared to the maximum difference among the materials, given in this case by the difference between the average reflection from all OSB samples and all gypsum samples (0.105). This first ratio, termed SMR for Signal-to-Material Ratio is 1.4, indicating that material effects cannot be ignored when attempting to determine the RH at which the sample has been conditioned. The second ratio, termed the Signal-to-Sample Ratio (SSR) is the ratio of the change in the average signal over the range of moisture levels to the difference between the average signal reflected from the two samples (0.0029). This ratio is 50.8, indicating that the signal change representing changes in RH is much larger than sample-to-sample variation. If we assume that the variation of the reflected mean energy with relative humidity is linear, we can estimate the change in signal as 0.0018 per 1% RH. The sample variation (0.0029) therefore corresponds to a change of approximately 1.6% RH, thereby providing a bound on the sensitivity of the technique.

Table 2. Signal ratios and sensitivity for three different analysis techniques.

Technique	SMR	SSR	Sensitivity % RH
Mean Energy	1.4	50.8	1.6
Magnitude of spectral peak	1.42	40.0	2.1
Location of spectral peak	0.72	2.94	28.5

Table 3. Test parameter levels and values.

Parameter	Levels	Values
Propagation path	2	Transmission, Reflection
RH level	4	(0, 33, 58, 98) % RH
Material	3	OSB, Gypsum Board, Plywood
Sample	2	A, B
Day	2	1, 2

Table 2 shows these results for each of the three analysis techniques. These results suggest that the mean energy has the best sensitivity, followed closely by the magnitude of the spectral peak. For the remainder of this discussion, the mean energy will be discussed as the pertinent output parameter from the radios.

3.3 *Moisture content relationships*

In the second set of experiments, similar issues were examined as done in the previous case, but an investigation of the transmission through the wall was added. Input parameters and their levels are given in Table 3. A full factorial test was carried out with each setting being repeated on a second day, resulting in a total of 96 tests. Before each day, a background scan was taken to estimate environmental effects.

3.3.1 *Reflected signal vs. moisture content*

Figure 3 shows the reflected signal vs. each of the parameters that were investigated. The amount of energy reflected divided by the amount of energy that was measured by the antenna at the wall position is plotted as the output variable. For these plots, values are averaged across all tests whenever that condition is met. For example, the plots at RH = 33% contain averages of all materials and samples conditioned at RH = 33%. As can be seen, the RH level at which the samples were conditioned has the most dramatic effect on the results, with the material having a lesser effect, and the sample and day showing the least effect.

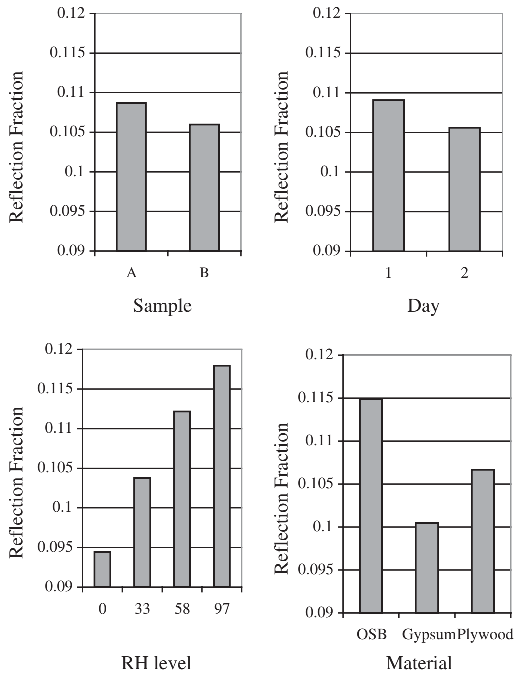

Figure 3. Parametric variation of reflection fraction.

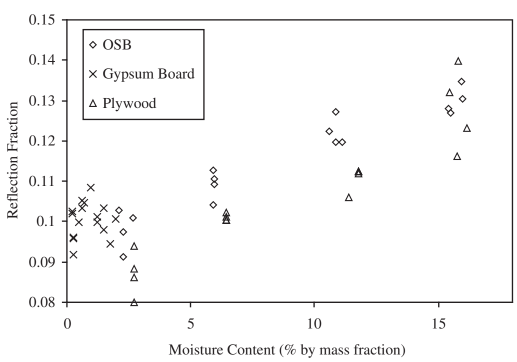

Figure 4. Reflection fraction vs. moisture content.

Another insightful plot is that of reflected energy vs. moisture content. Figure 4 shows a plot of the measured reflected energy for all samples. Note that this plot shows all three materials along with the different samples of each material. The following trends emerge when examining the data in Figure 4.

For OSB and plywood, the reflected energy increases with moisture content. Further, there does appear to be a material effect, as the reflections from OSB tend to be higher than those from the plywood. Reflections from gypsum board show little dependence on moisture content, but this result can be attributed to the small differences in moisture content between "dry" samples and those conditioned at high humidity levels. The sensitivity of the results for gypsum board is not sufficient to resolve these small differences in moisture content.

For the OSB and plywood, trends that appear linear between the reflected energy and moisture content can be seen. The difference between alternative samples of each material does not appear significant, but there is a fair amount of variation found upon repeats of the same sample, especially at higher moisture contents.

From these data, linear fits were attempted so that one could predict the moisture content given the reflected energy. No attempts were made to develop a regression line for the gypsum board data, but the following lines were developed for the OSB and the plywood, respectively:

$$\text{OSB:} \quad \text{ReflectionFraction} = 0.092 + 0.00264 * \text{MC} \tag{2}$$

$$\text{Plywood:} \quad \text{ReflectionFraction} = 0.076 + 0.00339 * \text{MC} \tag{3}$$

Since the desired output from such a technique would be a prediction of the moisture content, the independent and dependent variables in the previous equations can be switched to provide a prediction of the moisture content:

$$\text{OSB:} \quad \text{MC} = 379 * \text{ReflectionFraction} - 34.9 \tag{4}$$

$$\text{Plywood:} \quad \text{MC} = 295 * \text{ReflectionFraction} - 22.3 \tag{5}$$

The average absolute error between the predictions and the experimental results for the OSB is 1.50% MC while the average absolute error for the plywood is 1.32% MC.

The general conclusions that can be made from the data in Figure 4:

(a) the resolution is not great enough to distinguish moisture content of gypsum board below the saturation level.
(b) some degree of material effects exist, though these effects are not as great as the effect of moisture content.
(c) trend appears to be linear.
(d) significant scatter exists in data.

At this point, a note about the uncertainty in the measurements is warranted. Each one of these data points was created by averaging the energy contained in over 400 scans obtained from the equipment. To estimate the uncertainty in the measurement of the reflection fraction, the standard deviation of the integrated energy in each of those scans was compared to the mean of the integrated energy across all scans. It was found that the standard deviation was consistently at a value of approximately 15% of the average

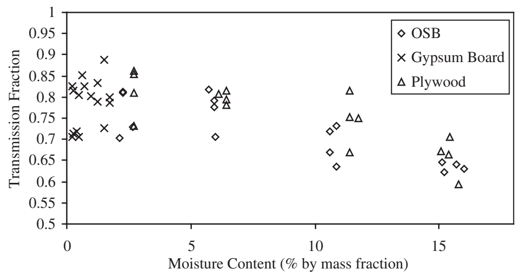

Figure 5. Transmission fraction vs. moisture content.

energy for each scan. The fact that so many scans are used in calculating the averages brings the uncertainty in reflection fractions down to ± 0.002 ($k = 2$), but the large variation between scans raises concerns regarding the repeatability of the hardware and signal processing system.

3.3.2 *Transmitted signal vs. moisture content*

Experiments were also performed in which the transmitter was placed on one side of the sample while the receiver was placed on the other side. In these experiments, both the transmitter and the receiver were placed 0.3 m (1 ft) from the closest surface of the specimen. In this case, it is expected that the signal transmitted through the sample will decrease with an increase in the moisture content of the sample. Figure 5 shows the fraction of energy transmitted with specimens in place compared to the energy transmitted with no specimens as a function of material moisture content. Uncertainties for these values are the same as that for the reflection fraction (± 0.002).

Transmission data show a tremendous amount of scatter. While it is evident that the transmission decreases with an increase in moisture content, the large scatter in the data indicate that this equipment would be less useful in this mode than in reflection mode. One theory for why transmission data are scattered compared with the reflection data is that the consistency of the radios is dependent upon the receiver locking on to a particular part of the signal from the transmitter. With the radios positioned on the same side of the sample, the process of locking on to the signal is simpler because the radios are closer than if the transmitter and receiver are on opposite sides of the panel. Considering the large scatter in the data, no further analysis is presented.

4 DOUBLE-PANEL EXPERIMENTS

A distinctive feature of ultra-wideband technology is its ability to precisely locate features that are reflecting signals because of the fine time resolution. The received signal is resolved in increments of 12.7 ps by the hardware, thereby providing a theoretical spatial resolution of 3.8 mm (0.15 in.) when the waves are traveling at the speed of light. Ideally, one could find the spots in the scan corresponding to the times of flight from transmitter to each panel in a wall construction and back to the receiver, and analysis of that particular area of the waveform would give information on the moisture level at that layer. In reality, however, the fact that the emitted pulse lasts on the order of 1 ns complicates the analysis since reflections from multiple panels will overlap. Further, as seen in the results for the single panel, the imprecision in the radios also makes the analysis difficult. Nevertheless, attempts were made to determine the possibilities of separately detecting the moisture levels in a wall assembly consisting of 2 panels separated by 8.9 cm (3.5 in.) of air.

For these tests, gypsum board was maintained as the material on the interior side of the wall, while plywood and OSB were used as the exterior sheathing material. Tests were performed with the antennae on either the interior side of the assembly or the exterior side. Only reflection data were collected. Samples were conditioned at one of 4 RH levels (0, 33, 58, 97), and all tests were repeated a second day. Overall, 128 tests were run along with background scans for each setup. The moisture content of each sample was obtained gravimetrically before each test.

Several analysis techniques were attempted to develop relationships between the reflected signal and the moisture content of the samples. As done by Healy & van Doorn (2004a), an attempt was made to use principal components analysis to blindly pull out relevant parameters from the scans. In this analysis, this approach did not lead to meaningful results. We then focused on analyzing data in parts of the waveforms that correspond to the locations of each wall panel. To start, the waveform obtained with the sample present is lined up with the waveform obtained with no sample present. The background waveform is subtracted from the waveform with the sample present, and the magnitude of the Hilbert transform of the difference is used for analysis. The reference point is considered to be the maximum value of the scans and is assumed to correspond to the point at which the pulse travels directly from the transmitter to the receiver. By knowing the distance between the transmitter and receiver, an estimate of the time of emission of the signal is obtained.

After the time of emission is determined, the time estimated to travel from the transmitter to each wall panel and back to the receiver is determined. These times are identified in the waveform and were investigated to determine if the reflection amplitude correlates with the moisture content of the corresponding layer.

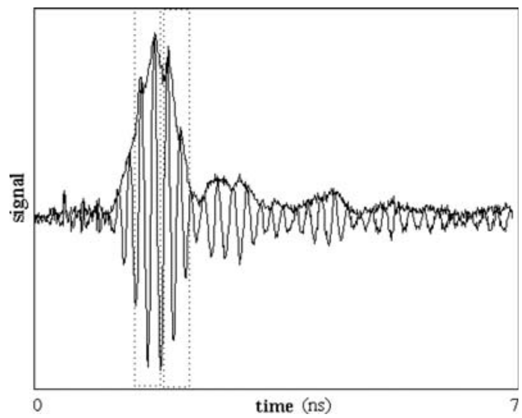

Figure 6. Sample waveform with the magnitude of its Hilbert transform and sample time frames used to compute reflections from each panel.

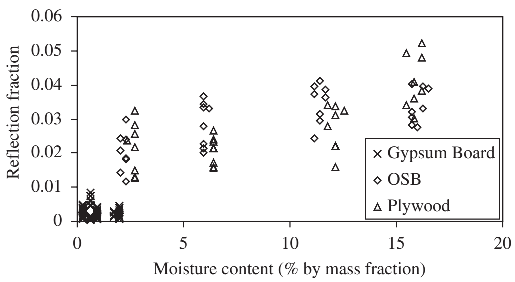

Figure 7. Reflection fractions for 3 different materials. Antenna placed on interior (gypsum) side of assembly.

This approach would be very effective if the emitted signal were extremely short. Unfortunately, real signals have some temporal width, so reflections are obtained over an extended time frame. Additionally, other information may be obtained from signals that bounce off other parts of the wall in addition to those lying in the shortest path. Because of these complications, analysis of time frames in the scans that surround the theoretical time of flight was used. For this analysis, frames containing 50 points of the waveform and lasting 0.64 ns are examined. Figure 6 shows a waveform and a sample of the frames used to examine reflections from each sample. The magnitude of the Hilbert transform of the waveform in each frame is integrated to estimate the reflected energy and is compiled for each test run.

Figures 7 and 8 plot the fractional reflected energy estimated from each panel as a function of its moisture content, with Figure 7 showing the data when the antennae are placed on the interior side (gypsum side) of the assembly and Figure 8 showing the data when the antennae are placed on the exterior side. For each test

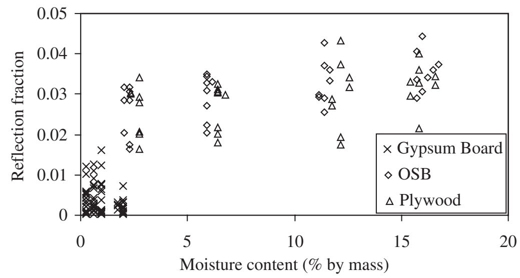

Figure 8. Reflection fractions for 3 different materials. Antenna placed on exterior (sheathing) side of assembly.

case, 2 data points are obtained since a single scan provides information on both the interior material and the exterior material. In both cases, the technique could not determine any difference among gypsum board panels conditioned at different relative humidities. As noted earlier, the small difference in moisture content is not sufficient to have any effect on the signal. For the OSB and the plywood, a slight trend in the reflected signal with increasing moisture content is noted, but the high imprecision in the data precludes further analysis. Quantifying moisture content in the hygroscopic regime would be difficult with this method, although indications of wet vs. dry appear to be possible. It should be noted that the trend is slightly more prominent when the antennae are on the exterior side of the assembly (Fig. 8) than when they are on the interior side (Fig. 7), indicating that some attenuation of the signal occurs as it passes through the interior layer.

Despite the poor results shown above, improvement may be possible with the following enhancements in the equipment and analysis. First, the size of the time frames could be further optimized to locate the best subsets of data to capture as much information as possible from the panels while minimizing overlap of signals from each layer. Improvements in hardware may still be needed in order to get adequate data. The off-the-shelf radio equipment used here did not generate pulses with a short enough width nor did they generate pulses of sufficient repeatability. Equipment made more specifically for sensing applications may improve the results, and several firms make research-grade equipment that may be more appropriate for this application. Antenna design can be tailored more for such an application as opposed to the communication applications for which the hardware was developed. One such study that used hardware more tailored for sensing applications is given by Johnk et al. (2004). Additionally, the work of Healy & van Doorn (2004a) demonstrated much better resolution in detecting moisture contents of building materials than observed in the present investigation. In that study, the radios emitted RF pulses with a center frequency of

1.8 GHz and a bandwidth of 1.2 GHz, and the antennae were tailored for transmitting signals towards a target as opposed to radiating equally in all directions. This research grade equipment provided more consistent signals and enabled finer discretization among the samples of varying moisture content. While that equipment may not achieve the market penetration and the subsequent price declines of the equipment used in the present study, it is worth examining the different frequency ranges and hardware designs should the technology be further explored for use in detecting moisture accumulation in building envelopes.

5 CONCLUSIONS

Experiments were performed to explore the ability of a commercial ultra-wideband system to determine the moisture content of materials in a building assembly. Initial tests on single panels of OSB, plywood, and gypsum board showed a general trend in which the energy reflected from the sample increased with the moisture content of the OSB and plywood. The small amount of moisture stored in gypsum board below the saturation point did not provide enough water to modify the signal appreciably. A slight material effect was observed between the OSB and the plywood, but the effect of moisture on the signal was evident. Data on transmission were less conclusive, and further investigation is warranted to determine the trends of transmitted energy versus moisture levels.

Tests were also performed to investigate whether ultra-wideband signals could be used to simultaneously measure the moisture content of 2 separate layers in a wall assembly. Differences were seen between the wet and dry extremes of OSB and plywood examined in this study, indicating that the method could potentially be used to tell whether a hidden material is dry or wet. Tests aimed at quantifying the moisture content below saturation, however, were inconclusive, as no precise data were evident after examining portions of the signal in which reflections from the samples were expected. It is believed that hardware that is more specially designed for the purpose of non-destructive sensing of walls would improve the chances of detecting the moisture level of separate panels using this technique. It is hoped that the disappointing results will not force people to abandon the possibilities of using ultra-wideband signals for moisture detection, but will rather spur researchers to develop improved hardware geared towards non-destructive evaluation of walls.

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