Detection of Moisture Accumulation in Wall Assemblies Using Ultra-Wideband Radio Signals

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Reprinted from the Proceedings of Performance of Exterior Envelopes of Whole Buildings IX International Conference, December 5-10, 2004, Clearwater Beach, FL

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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ABSTRACT

This paper discusses the use of ultra-wideband radio signals near 5 GHz to detect moisture problems within building assemblies. Ultra-wideband signals are made up of a large spectrum of electromagnetic waves, and hardware is available to temporally resolve the signals to a time scale on the order of picoseconds. By emitting these signals toward a wall assembly and analyzing the reflected signal, information can be obtained on the wall. Most notably, because water reflects these waves more significantly than dry building materials, the magnitude of the reflections can be correlated to moisture levels. This principle has been incorporated into a synthetic aperture imaging technique to create images of the moisture state of building assemblies. The pictures can help identify locations of unwanted moisture intrusion in a nondestructive manner. Advantages of using ultra-wideband compared to conventional radio frequency techniques include the improved spatial resolution and the ability to penetrate a wide range of materials.

INTRODUCTION

As moisture issues in buildings continue to draw significant attention, tools for diagnosing excess moisture within the building envelope are needed by practitioners and researchers. Ideally, such a tool would be nondestructive, though anecdotal evidence seems to indicate that one of the most common methods used to find moisture problems involves tearing apart walls. Better alternatives are available, though, and should be used in place of more primitive techniques. Instruments such as electrical resistance pin probes, capacitance meters, and relative humidity sensors are frequently used to estimate the moisture content of building materials. Each of these instruments has positives and negatives, as described by several authors (Ten Wolde and Courville 1985; Derome et al. 2001; Healy 2003). One of the drawbacks of probes, such as a pin probe, is the fact that contact is needed with the moist specimen to diagnose excess moisture. Tools that do not require contact to locate moisture problems in walls would greatly aid in finding problems in a nondestructive fashion. Furthermore, techniques that can scan larger areas of the building envelope would assist in isolating areas of excessive moisture compared to the more laborious task of examining individual areas with localized meters and sensors.

A number of different methods proposed could complement the instruments previously mentioned in isolating moisture problems in buildings. Infrared cameras have been used to locate moisture because of the lag in temperature changes of materials laden with water compared with dry materials (Tobiasson et al. 1977; Korhonen and Tobiasson 1978). Such temperature differences can be observed with infrared cameras and can provide a simple-to-use tool for investigators. One drawback of such a method is the fact that the infrared emission is a surface phenomenon that can be affected by such surface properties as emissivity and roughness. Other drawbacks include the fact that temperature gradients from features other than moisture can create false identification of wet areas and that information regarding the condition inside the wall may not be attainable using this surface-dependent technique. Other methods that may provide noncontact determination of the moisture level within walls include gamma-ray attenuation

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and neutron scattering (Knab et al. 1981). Such devices can accurately determine the presence of water within a wall, yet the transportation of the radioactive sources used in such devices causes concern.

An emerging technique for nonintrusively detecting the moisture condition within a wall is the use of ultra-wideband (UWB) radio waves. Healy and van Doorn (2004) recently discussed preliminary work that shows the potential of this technique. In this work, ultra-wideband radar was first used to determine the moisture content of gypsum board, pine, and oriented strand board. The technique was then used on a simulated wall to independently determine the moisture content of the individual layers. Results were then shown in which a three-dimensional map of the wall located a moist patch within the wall. The technique has the ability of locating not only the location on the face of the wall but also the depth of the water within the wall.

This paper describes techniques that have been developed to create images of the moisture state of a wall. New hardware will be described that complies with recent regulations passed by the Federal Communications Commission (FCC) and that eases the acquisition of moisture images of a wall. A brief discussion will be made concerning issues that are currently being investigated that will complicate acquisition of images in actual buildings. The next section will describe UWB radio technology in more detail and will discuss some of the advantages and disadvantages of the method. Experiments that were performed on a sample wall section will then be described to demonstrate the performance of the equipment and software.

ULTRA-WIDEBAND RADIO OVERVIEW

Ultra-wideband radio signals are electromagnetic transmissions that comprise a broad range of frequencies. 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

$$\eta = \frac{f_h - f_l}{f_h + f_l}, \qquad (1)$$

where

f_h = highest frequency contained in signal, and
f_l = lowest frequency contained in signal.

One way to achieve a signal with such a large frequency spectrum is to emit pulses that are inherently composed of waves of various frequencies. For example, by taking the Fourier transform of an impulse, one can observe that such an ideal pulse consists of an infinite frequency bandwidth. On the other hand, the Fourier transform of a sinusoidal signal shows that the signal is composed of a single frequency. Such a signal is characteristic of conventional radio or radar. A good overview of ultra-wideband technology is given by Taylor (1995).

The hardware used in the present study is designed to emit pulses having the idealized shape of a Gaussian monocycle, as shown in Figure 1. The Fourier transform of this pulse (Figure 1) displays the broad range of frequencies that make up this signal. The center frequency for this particular design is 4.7 GHz and the bandwidth is 3.2 GHz. This large bandwidth allows one to term the signal an ultra-wideband signal. One might imagine that such a signal would interfere with many different devices. One of the characteristics of UWB systems, however, is that the signal is emitted at a very low power. The hardware used in the current study emits pulses at an effective isotropically radiated power of 0.33 mW (-11 dBm). This power level is considered to be below the electromagnetic noise floor in most situations. The question is then logically raised as to how an antenna picks up the signal if it is below the noise floor. The key to this problem is the fact that the hardware is capable of generating and detecting pulses at an extremely rapid rate (up to 9.6 million pulses per second). By emitting many identical pulses and averaging the received

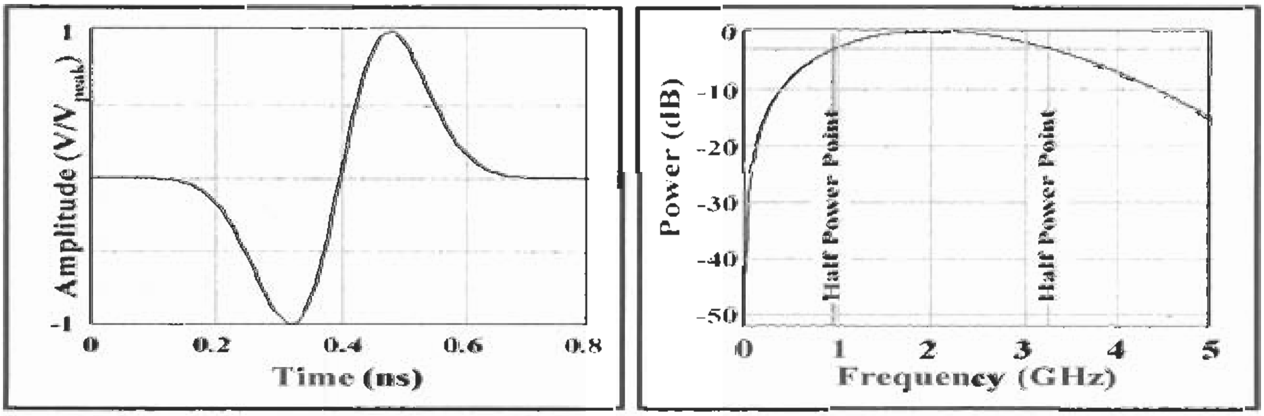


Figure 1 A Gaussian monocycle pulse and its spectrum.

pulses, the presumably random noise is averaged to zero and the underlying signal is recovered. This series of pulses is termed a pulse train. The spacing between pulses is approximately 100 ns, while each pulse width is on the order of 1 ns.

Uses of Ultra-Wideband Signals

One application of UWB signals lies in wireless communications (Taylor 1995). Once a transmitter and receiver set up contact, binary digits can be transmitted by altering the timing of the pulse. For example, a pulse that is sent 10 ns before an expected time can be considered as a 0, while a pulse sent 10 ns after a prescribed time can be interpreted as a 1. An example of the bandwidth capability can be obtained when considering the hardware used in the present study. Since the hardware is capable of transmitting up to 9.6 million pulses per second, it is conceivable that 9.6 megabits can be transmitted per second. Maxing out in such a way would not allow for any error correction but, in principle, such large communication bandwidth could be attained. One advantage for using UWB signals for such communications is the fact that the signals are very low power. This characteristic will minimize interference with other components in buildings that operate on radio frequencies. The fact that the signal is composed of a large frequency range increases the robustness of the transmission since it is likely that some frequency component will be able to travel from the transmitter to the receiver without being attenuated. Entry of UWB technology into the communications market was aided in 2002 by a decision from the FCC that permitted its use in a wide array of applications (FCC 2002). Hopes are high that such FCC authorization will speed the technology to market and decrease the cost of the equipment needed to generate and receive UWB signals. The hardware used in this study complies with these regulations.

A second large application area for UWB is in sensing. Most sensing applications rely on the fact that electromagnetic pulses are reflected differently from objects depending upon their physical makeup. These reflections can be analyzed to determine the location of objects and possibly the composition of the product. The excellent temporal resolution of the equipment can be used to make precise estimations of the locations of objects that reflect the pulses. The added feature that UWB brings to remote sensing applications compared to single frequency signals is the likelihood that some component of the signal will be capable of penetrating most materials so that information can be obtained regarding objects behind an obstruction. With narrowband signals, the chances that one can find a signal that passes through obstructions yet is sensitive to the constituent of interest are much less. This property of ultra-wideband has led to sensing applications related to object location for military purposes and identification of people within buildings or rubble.

Sensing Technique

The basis for the sensitivity of radio waves to moisture lies in the large difference between the dielectric constant of water ($\varepsilon_r = 81$) and that of porous building materials such as wood ($\varepsilon_r \approx 5$). The dielectric constant affects the propagation of radio waves in several ways. First, the speed of propagation of electromagnetic waves, c, through a solid is dependent upon the dielectric constant, as described by Equation 2.

$$c = \sqrt{\mu_0 \mu_r / (\varepsilon_0 \varepsilon_r)} \qquad (2)$$

where

μ_o = the magnetic permeability of free space

μ_r = the relative magnetic permeability of the medium to that of free space

ε_o = the permittivity of free space

ε_r = the dielectric constant of the medium

The second way in which moisture affects the propagation of radio waves through a solid is through reflection at the interface between the surface of the solid and the adjacent material. The reflection at the interface between materials 1 and 2 is governed by the reflection coefficient, Γ_{12}.

$$\Gamma_{12} = \frac{c_1 - c_2}{c_1 + c_2} \qquad (3)$$

where c_1 and c_2 are the speed of light in materials 1 and 2, respectively, as described by Equation 2. This number provides the ratio of the amplitude of the reflected waves to that of the incoming waves. Since the speeds of light, c_1 and c_2, depend upon the dielectric constants, the reflection coefficient also depends upon the dielectric constants. The dielectric constant affects attenuation of the electromagnetic waves as well, though this trait will not be used in this sensing application. It should also be noted that the dielectric constant is a function of frequency and temperature. Adjustments may be needed to any measurements made at temperatures differing greatly from that at which a material is calibrated. The present studies were carried out in a laboratory in which the temperature was held at approximately 20°C ± 2°C, so no effect of temperature has been investigated here. The fact that the dielectric constant varies with frequency may actually be an advantage in the use of ultra-wideband signals considering the large frequency spectrum contained in the pulses.

SYNTHETIC APERTURE IMAGING

The UWB signals have been used in two related methods for investigating the moisture state of building materials. The aim of the first method was to obtain quantitative estimates of the in-situ moisture content of materials that are below the saturation level. Preliminary results are discussed in Healy and van Doorn (2004), and work is ongoing to better determine the relationship between the reflected signals and the moisture content of building materials such as oriented strand board (OSB), plywood, gypsum board, and fiberglass insulation. This investigation is not the focus of this paper.

The second method of using UWB signals for detecting moisture in buildings is aimed at locating bulk water intrusion and materials that are close to saturation. To make this task simpler, UWB can be used to create three-dimensional images of the moisture state of the wall. Because the incident pulses should theoretically be able to penetrate several layers of a wall, water intrusion that is not visible should be detectable by the technique. Such images are obtained by taking scans of the reflected radio waves at different locations in front of the wall. These techniques are the focus of this paper.

Overview of Synthetic Aperture Imaging

In a stationary system in which one antenna transmits a signal and a second antenna receives the reflections of that signal from various objects, the typical output scan shows the voltage received at the receiving antenna as a function of time. Reflections will be coming from many different surfaces, so reflected signals will be returning to the receiving antenna over a large time frame. To create an image from these multiple scans, a technique proposed by Lorenz et al. (1991) has been implemented in the present work. By noting that the waves travel at the speed of light, the path length of the reflected wave can be determined, and an educated guess can be made regarding the surface from which it has reflected. For a given time of flight, the exact point of reflection is not known exactly, but it is known that the reflection will have occurred on a hyperboloid, as shown in Figure 2 (all points on the surface have the same combined distance to the two foci of the shape). This estimate assumes that all responses received at the receiving antenna are from single reflections and that the speed of light changes little in the different materials through which the waves pass. A longer time of flight corresponds to a larger hyperbola, so information is gained about the surroundings at each set of antennae positions. There is still uncertainty, however, as to where a particular amplitude in the signal obtained at the receiver originates. To resolve this uncertainty, triangulation is used between multiple antenna positions to identify the source of the reflection source. While other radio frequency techniques could be used to locate moisture, the time resolution of the UWB hardware and the ability of the UWB waves to penetrate various forms of construction make it an attractive choice for carrying out such analyses.

To create an image of a building assembly, scans are taken at different locations in front of a wall, and the assembly is then discretized into an array of pixels. For each scan, the amplitude of the received signal is examined as a function of time after initial transmission of signal. At each time of flight, we add the amplitude of the signal to all pixels in the discretized wall section that may have contributed to that signal. The antennae are moved to different locations and the process is repeated. Pixels that represent an actual location of moisture within the wall will continue to be identified by all scans and will therefore get a higher amplitude tally as more scans are added to the map. A few examples will show this technique in action.

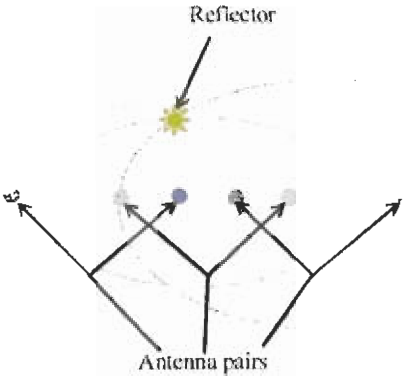


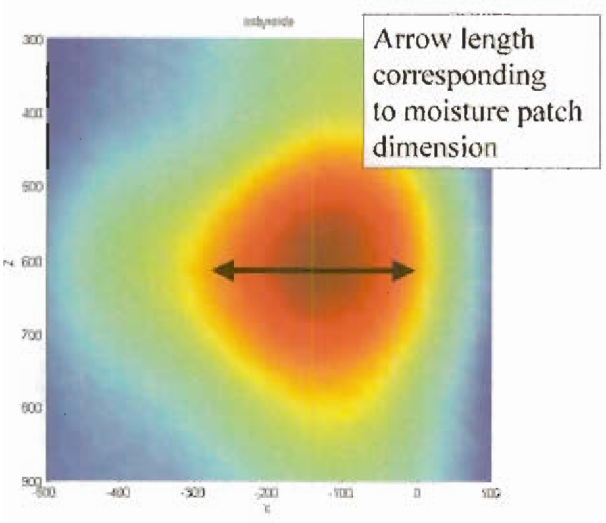
Figure 2 *Hyperbolic times of flight. With knowledge of only the time between the transmission of a signal and the reception at a second antenna, one can only pinpoint the location of the reflector on a hyperbolic shape. Inclusion of different antenna positions allows one to use triangulation to pinpoint the location of the reflector.*

EXPERIMENTS

Test Samples

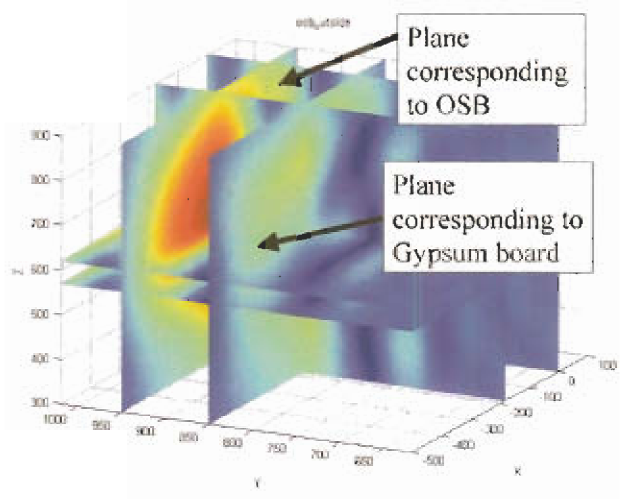
To test the scheme, two different test walls were constructed. The first wall section was composed of 7.6 cm (3 in.) of R-19 fiberglass insulation sandwiched between a 1.27 cm (0.5 in.) sheet of gypsum board and a 1.27 cm (0.5 in.) layer of oriented strand board. The insulation had kraft paper that faced the gypsum board. Panels of these materials measuring 0.61 m (2 ft) wide by 0.91 m (3 ft) tall were placed within a wooden frame constructed of 2-by-4s of sugar pine. The rig was constructed so that panels of varying moisture content could be interchanged to obtain a wide range of moisture conditions. To simulate water intrusion, a wet cloth wrapped in plastic was temporarily attached to different places of the wall. The dry cloth and plastic bags were also tested to ensure that they had no independent effect on the reflected radio signals.

The second test wall was larger and included three conventional stud cavities. It was constructed after the concept was proven with the smaller wall section. The width and height of the second wall were both 1.2 m (4 ft), while the sheathing layer and interior wall layer were separated by an 8.9 cm (3.5 in.) cavity made by four 2-by-4s spaced 40.6 cm (16 in.) apart (center-to-center). The main purpose of the second test rig was to develop techniques to handle the presence of nonparallel features such as studs and wires in the imaging techniques. As in the previous case, moisture intrusion was simulated by placing a wet cloth inside a plastic bag and attaching it in various positions within the wall section. A layer of OSB sheathing was clamped to the outer plane, while a panel of gypsum board was attached to the interior.



Arrow length corresponding to moisture patch dimension

Figure 3 *Synthetic aperture image of moisture patch on OSB panel (dimensions in mm).*



Plane corresponding to OSB

Plane corresponding to Gypsum board

Figure 4 *Three-dimensional synthetic aperture image showing moisture accumulation in plane corresponding to OSB panel location (dimensions in mm).*

Movable Antenna

To test the concept of synthetic aperture imaging to detect unwanted water in walls, the antenna was set up in front of the wall with the gypsum board facing the antenna to simulate the instrument being used on the interior side of the wall. For the first set of experiments, a single antenna was used that served as both the transmitter and receiver with a high-speed switch changing between modes. This antenna was then attached to a robotic arm that automated the task of moving the antenna in front of the wall to provide the multiple scans that are needed to develop a synthetic aperture image. The antenna was maintained at a distance of 1.4 m from the gypsum board in the model wall. This distance was somewhat arbitrarily selected; studies are ongoing to determine an optimal setting for this distance. The antenna position was modified along a square grid having 11 × 11 points and a resolution of 70 mm between adjacent grid lines. These 121 measurement locations created a square synthetic aperture having a length of 700 mm on each side.

To illustrate the potential of the synthetic aperture technique for visualizing the moisture condition of a wall, we will focus on one experiment in which the wet cloth was placed on the interior side of the OSB panel in the model wall. If this layer were wet, it would not be visible to an observer without modification to the structure such as pulling away siding or inserting pin probes through holes drilled in the envelope. Figure 3 shows an image of the radar return at the plane corresponding to the OSB location. The red section indicates a region of high radar reflection, and the arrow on the plot shows the width and location of the wet cloth that was attached to the wall. One can see that the location and size of the wet spot have been well identified by the technique. An apparent anomaly in the results is that the region of high reflection appears circular, but the cloth that has been inserted to simulate the wet area was rectangular. The reason for this behavior is the smearing nature of the algorithm. If better resolution of the sharp edges of the towel were desired, the antenna spacing could be decreased. Thus, one technique for finding moisture problems would be to carry out an inspection with widely spaced antenna positions and then to use finer spacing in questionable areas. A three-dimensional image (Figure 4) can also be created that provides another view of the wall to identify potential moisture accumulation. Here, the planes corresponding to the OSB and gypsum board are plotted along with images in the other two planes. Images in the planes of the building panels show the location of the moisture patch, while the images in the other planes show that moisture is not detected in the layers away from the OSB. This view clearly shows that the synthetic aperture imaging technique yields an image that can be studied to detect the location and size of potential moisture problems within a wall. An additional feature that is not clearly evident in this view is the fact that dry walls do show some reflection. It is therefore expected that a priori knowledge of the wall dimensions may not be necessary in using this technique. This theory will be tested further in the future on walls of different dimensions. The uncertainty in the depth resolution is approximately 5 mm, based on the timing accuracy of the units used in this study and the changes in the propagation speed through the wall. Further studies can be made to reduce the ambiguity of the moisture level at the gypsum board layer. The result, however, is a promising method for creating contour plots of the moisture levels at different layers within a wall.

Antenna Array

It should be noted that a robotic arm was used in the previous study, but that device was simply used for the convenience of carrying out the study. Any technique can be used for locating the radar at appropriate points in the viewing field. As an alternative to moving the antenna, it was surmised that a stationary system would be easier to use and would decrease the chance of user error in creating the images. An array of antennae was built that allows for several combinations of antenna positions without requiring motion of the antenna. By switching between different transmission and receiving antennae, one can create a synthetic aperture with no movement. A picture of the antenna array is given in Figure 5 (the target in this case is a military helmet instead of the wall envisioned for this application). The array consists of four rows of four antennae in a square pattern for a total of 16 antennae. The top row and the third row from the top consist of transmitting antennae, while the other two rows consist of receiving antennae. Two radios are connected to the antenna array to generate the signal and to analyze the received signal. Switches on the array change the connection between the radios and the appropriate antenna.

This array contains 64 different antenna combinations that can be used to construct a synthetic aperture. The resolution that can be attained using this array is a function of the bandwidth of the signal, the spacing of the antennae, the distance between the wall and the array, the antenna size, and spacing between antennae (the array is placed parallel to the surface of the wall). With the array placed close to the wall at a distance of approximately 1 cm, it is estimated that features of the wall can be resolved to within 3 mm. The drawback of being so close is that the field of view is limited to the approximate size of the array. By pulling the array farther away from the wall, one can obtain a larger field of view at the expense of resolution. It is expected that fields of view on the order of a single-story wall can be coarsely examined using this technique. At this point, work is ongoing to investigate the effectiveness of this technique in making such measurements and to determine the resolution that is capable for locating moisture.

The Effect of Studs and Wires

The results from the smaller wall having no studs shows the ability of this technique to detect moisture in a wall consisting of planar layers of building materials. The effect of nonparallel features, such as studs and wires, has not been addressed in these studies. It is expected that the synthetic aperture images will show the presence of those features very prevalently, especially wires owing to the fact that metal reflects radio waves very well. The antenna array is currently being used to determine if there is an easy way to differentiate between reflections due to nonplanar features and those due to moisture.

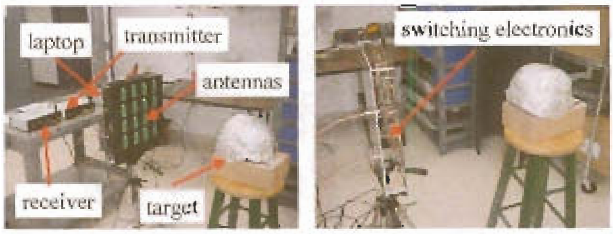


Figure 5 *Picture of antenna array used for synthetic aperture imaging.*

SUMMARY AND DISCUSSION

The use of ultra-wideband signals holds promise for helping determine the presence of unwanted water within walls in a nondestructive manner. UWB signals have the advantage over other radio-frequency techniques in that the time resolution is fine enough to pinpoint the location of moisture and that the signals penetrate a wide range of materials. While the technique can be used to obtain quantitative numbers that indicate the moisture level of different layers within a building assembly, qualitative detection of bulk water intrusion may prove to be the most useful application for this type of instrument. Much work needs to be done, however. For example, the detection of studs, nails, pipes, and other nonplanar features is currently being investigated to see if it affects the detection of moisture within a wall. Other building assemblies should also be examined, including the effect of siding layers and masonry products. Images that have been created have already shown the potential for this product to serve its purpose as a nondestructive technique for locating moisture intrusion within a wall. Work is continuing to examine the effectiveness of an antenna array for real-time creation of synthetic aperture images that indicate the hygrothermal state of a wall assembly.

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