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ENGINEERING AND GINNING

Multipath Interference Investigation for Cotton Bale Microwave Moisture Sensing

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ABSTRACT

Since more cotton gins are installing cotton moisture restoration systems, it is becoming increasingly important to accurately determine the moisture content of cotton bales. Recent research at the USDA has shown that bales with too high of a moisture content will undergo a grade change when in storage for as little as 6 months. In order to address these issues, research has been undertaken to develop a microwave based cotton bale moisture sensor. To further this research, the effects of multipath interference on this type of measurement was explored. A finite-difference time-domain model (FDTD) was prepared to aid in the development of a microwave moisture sensor. The prediction of cotton bale, microwaves, antennas, and structure interactions were investigated using this model. The model was shown to have a good correlation to the closed form solution of Maxwell's equations for free-space microwave propagation. When used to determine the effects of a surrounding metal structure typical of a cotton gin, the model indicated that multipath reflections severely affect the transmitted signal. It also indicated that this affect could be calibrated out of the system to yield an accurate prediction of the moisture content of cotton bales within a metal-clad structure.

Moisture content of cotton bales is an important characteristic for both the operation of the cotton gin bale press, as well as for maintaining cotton quality. Further attention to this feature is becoming more prevalent with the recent proliferation of cotton moisture restoration systems that are now being used in cotton gins. It has been recognized that added moisture reduces wear and tear on the bale press, and that the semipermeable or nonpermeable packaging retains the moisture added to the bale for long periods of time. Adding moisture to the bale provides a further economic incentive, because cotton is sold on a wet-weight basis that is irrespective of the moisture content. It is also well known that if too much moisture is added to the bale, mold growth and color and quality degradation can occur. For these reasons, it becomes important to have good control over the moisture restoration process. This study is a continuation of current research into the development of a low cost microwave bale moisture sensor that can be used to control these types of systems.

This research is focused on the sensing of cotton bale moisture by measuring the microwave propagation characteristics as microwave energy is transmitted through the cotton bale. In the process of conducting this research, it was desirable to obtain a generalized measurement of the electrical characteristics of cotton that will yield a fixture and geometry independent measurement. Knowledge of these fundamental parameters will permit the development of a wide variety of sensors that can use different antenna geometries, cotton volume geometries, and varying densities. This generalized measurement can then be applied by measuring the electrical permittivity of the cotton bale using a free-space non-contact microwave transmission measurement.

In order to obtain this measurement, a microwave horn is placed on either side of the cotton bale and microwave energy is transmitted through the bale. By measuring the received signal and comparing it with the transmitted signal and taking into account the transmission path length, it is possible to determine the permittivity of the cotton bale. In previous research, the permittivity of a low-loss dielectric material had a high correlation to the moisture content of the material (Meyer and Schilz, 1982; Kraszewski et al., 1989; Nelson et al., 1990; Kraszewski and Nelson, 1992).

In pursuit of this goal, all of the laboratory work has been conducted with anechoic shielding in place. Since this material is very expensive and large, the commercial cooperator has attempted to deploy the proto-type microwave system without the shield. When practicing this technique inside metal buildings during these initial field tests, it was noticed that the measurement is dependant upon the placement of the antenna. This led to the requirement that the antenna be bolted in place in a solid configuration to avoid any movement of the antennas

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that would alter the measurement and destroy any previously obtained calibration. Due to the time consuming nature of obtaining calibration data, the majority of the research has been conducted in a laboratory environment and limited field data has been obtained. The results of these initial field tests and observations has led to the development of a theory that perhaps the placement of the antenna is required due to some of the signals propagating around the bale rather than propagating through the bale as designed. If this is the case, then there is also a concern about the effects of neighboring metallic reflectors on the accuracy of this measurement. Since microwaves are invisible, it is difficult to fully understand exactly what is being measured in this type of environment. The primary goal of this research was to obtain a better understanding of the propagation of microwaves through cotton bales in multipath rich environments. A further goal was to determine if this type of sensing system can be expected to provide a reasonable measure of moisture across the entire range of moisture content of interest, when the system is subjected to a high degree of multipath interference that is typical of modern commercial cotton gins.

Multipath interference. In the transmission of microwave energy, the ratio of the signal being transmitted forward as opposed to away from the target is known as the front to back ratio or the gain of the antenna. A typical microwave horn has a front to back ratio varying from 8dB to 22dB. In the application of measuring cotton bale moisture, it is expected that the most likely location of implementation will be inside a metal building. It is possible that a significant portion of the signal will not go directly through the bale, but instead will be reflected from the walls and ceiling. These alternative or multipath signals would then later be recombined with the direct-path transmission signal yielding a modified direct-path signal. This phenomenon, known as multipath interference, occurs when microwave energy received through a direct-path is being combined with microwave energy that has been delayed by reflecting off neighboring reflectors. Since this reflected energy takes a longer path to reach the antenna, it is out of phase and likely of a different amplitude than the direct-path energy, so it combines both destructively and constructively in a non-coherent and unpredictable manner.

The general combination of a multipath signal with the direct-path signal can be modeled by the combination of the original sinusoidal signal along with the convolution of a linear time-invariant system with the original sinusoidal signal (Viterbi, 1995; Lee and Miller, 1998). It has been shown that the convolution of a linear-time invariant system with a sinusoid produces a sinusoid of the same frequency but with an altered phase and magnitude (Strum and Kirk, 1988). This is based on the assumption that it does not interact with a moving reflector, which would impart a Doppler or frequency shift. This is a good assumption for detecting bale moisture, since there are typically no rapidly moving vehicles inside a cotton gin. This provides a model for multipath interference based on the simple combination of multiple sinusoids that vary only by phase and magnitude.

In combining of multiple sinusoids, which vary only by phase and magnitude, it can readily be shown that a single sinusoid is created. To illustrate, a simulation was setup that has multiple multipath signals that are combined with the original direct-path signal yielding the received signal. Figures 1 illustrates the relation between the unaltered direct-path signal and the received signal when influenced with a set of multipath interferers. Figure 2 details the same direct-path signal combined with a different multipath set. Examination of figures 1 and 2 illustrates that the received signal is dramatically altered when the direct signal is influenced by multipath signals. It is also evident that the final signal is dependant on the particular configuration of the multipath signal, which is a function on the location and size of the metal reflectors in the environment.

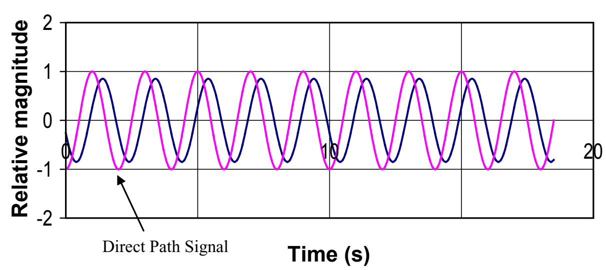

Figure 1: Comparison of a direct-path signal (pink signal with the peak to peak magnitude = 2) with the combination of the direct-path signal with two multipath delayed signals of differing amplitudes and phases.

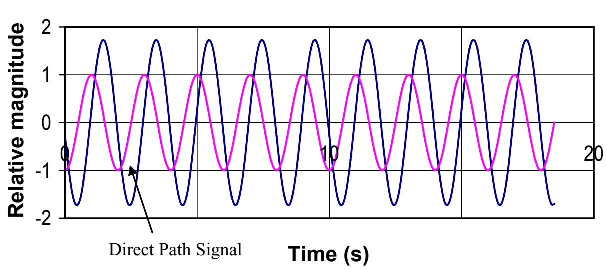

Figure 2: Comparison of a direct-path signal (pink signal with the peak to peak magnitude = 2) with the combination of the direct-path signal with a different set of two multipath delayed signals of differing amplitudes and phases.

The process of measuring the permittivity of the material consists of obtaining a free-space direct-path measurement of the signal without a cotton bale (the air reference) and then subsequently comparing both the phase and magnitude of the air reference with the measured phase and magnitude of the direct-path signal with a cotton bale. This comparison provides the required information for the calculation of the permittivity of material, and illustrates anything that alters either the phase or the magnitude of the direct-path transmitted signal for either the air reference or the bale being tested is cause for concern over the validity of the measurement. The previous model demonstrates the potential influence of multipath interference on both the amplitude, as well as the phase, of the received signal and raises concerns about the integrity of using free-space measurement to characterize the moisture measurement of cotton bales in a multipath rich environment.

While this simple model does illustrate that multipath is likely to be a problem, it does not provide any insight into whether this could be calibrated out of an installed system or if the dielectric properties, which are affected by the moisture content and density of the cotton bale, will alter the multipath signals. These issues are of critical interest to this research because the effect of the permittivity of the cotton bale and its interaction with multipath signals caused by nearby reflectors are potentially large sources of measurement errors. In order to study this issue further, a FDTD (finite difference time domain) electromagnetic model was developed. This model will then be used on a qualitative basis for examining the effects of multipath interference on the integrity of the free-space permittivity measurement, as well as to provide insights and direction for future research efforts into this type of measurement technology.

Finite difference time domain model. The FDTD method was first introduced by Yee (1966) in which Maxwell's equations are discritized on a staggered grid to provide a finite-difference solution that directly calculates the electric and magnetic field strengths at every node inside the model solution space. The method was later refined to produce a mathematical algorithm to provide a perfectly matched layer (PML) interface that removes reflections at the model boundaries that are otherwise present in the FDTD method introduced by Yee (Berenger,1994; 1996; 1997; Mittra and Pekel, 1995). The use of the perfectly matched boundary layer significantly improves the accuracy of the simulation and reduces the required model size. The FDTD method did not become a truly useful analytical tool that can be trusted to provide accurate and reliable simulations that agree well with physical experiments until this improvement was realized (Taflove, 1995). The FDTD method provides a direct time marching solution to Maxwell's electromagnetic equations (equations 1 and 2),

$$\frac{\partial \mathbf{H}}{\partial t} = -\frac{1}{\mu}\nabla \times \mathbf{E} \tag{1}$$

$$\frac{\partial \mathbf{E}}{\partial t} = \frac{1}{\varepsilon}\nabla \times \mathbf{H} - \frac{\sigma}{\varepsilon}\mathbf{E} \tag{2}$$

where ∇ = gradient operator; E = electric field (V/m); H = magnetic field (A/m); ε = permittivity of medium; μ = permeability of medium; σ = conductivity of medium.

Boldface type is used to indicate vectors.

The model was setup using Berenger's (1994; 1996; 1997) perfectly matched layer (PML) at all four solution space edge boundaries to remove any reflection off of the model domain's edges. This effectively makes the model treat the edges as infinite free-space extending beyond the model boundaries. In this configuration, any walls or ceilings will have to be provided inside the solution space.

In the interest of reducing the solution time, as well as simplifying the coding of the model, only the real portion of the complex permittivity can be used if the material of interest can be classified as either a lossless or with a minor error a very low loss material (Taflove, 1995). Since agricultural materials in prior research have satisfied the very low loss assumption (Kraszewski et al., 1989; Nelson et al., 1990; Kraszewski and Nelson, 1992), it is expected that cotton bales may also exhibit this behavior. Since commercial cotton bales are very dense and are also very thick, this assumption may not be valid and should be tested. To address these concerns a basis for using only the real portion of the complex permittivity was developed. The characteristics of the propagation of a plane wave in general lossy media are derived by Pozar (1998). This analysis details the solution for one-dimensional plane waves, which shows that the complex propagation constant for the medium is

$$\gamma = \alpha + j\beta \tag{3}$$

where γ = complex propagation constant; β = phase delay constant; α = attenuation constant.

By assuming an electric field with a single dimensional component, the analysis provides the positive traveling wave in the time domain of the form

$$E(z) = \mathbf{e}^{-\alpha z}\cos(\omega t - \beta z) \quad (4)$$

where t = time; β = phase delay constant; α: = attenuation constant; ω = frequency (rads/s); z = distance along propagation path (m); E(z) = electric field strength as a function of distance along propagation path.

In this form, the attenuation measurement of a propagating signal will characterize the attenuation constant of the material. This measurement will provide a method to quantify the propagation behavior of the material as being either lossy or low loss material. In the lossless or very low loss material, the propagation constants have the following properties (Pozar, 1998)

$$\alpha = \mathbf{0} \quad (5)$$

$$\beta = \omega\sqrt{\mu\varepsilon} \quad (6)$$

Because the model keeps track of both the magnetic and electric field strengths, the relation of these nodal field strength values to the impressed charge on the receiving antenna can be quantified as shown in equation 7 (Taflove, 1995).

$$Q = \varepsilon_{\mathbf{o}} \oiint \mathbf{E} \bullet ds = \varepsilon_{\mathbf{o}} \mathbf{dA^2} \sum_{4\,faces} E_{face} \quad (7)$$

where Q = charged enclosed by the nodal volume (C); dA = elemental area of the face of the node (m^2).

Once the charge on the surface element has been obtained the following relation provides the impressed voltage into the receiving circuit.

$$V = \frac{dQ}{dt} R \quad (8)$$

where V= impressed voltage (volts); R= resistance (ohms)

Once the received voltage signal has been obtained, equation 6 provides a means to obtain a direct measurement of the permittivity by quantifying the propagation phase delay constant β. It should be noted, that in this test a portion of the propagation path is air which needs to be removed from the measurement. Since it is also a goal of this technique to provide a measurement of material that is independent of geometry, the path length of the propagation also needs to be accounted for. One method that can remove the propagation phase delay of air is to take two separate measurements; one an air reference and then perform another with a bale in position. The air reference provides a zero reference point for the system thereby removing the effects of the signal propagating through the air. This is detailed in equations 8, 9 and 10.

$$\theta_{air} = \beta_{air} z - 2\pi n \quad (8)$$

$$\theta_{mat} = \theta_{bale} - \theta_{air} \quad (9)$$

$$\beta_{mat} = \frac{(\theta_{mat} + 2\pi n)}{z} \quad (10)$$

where θ_{air} = measured phase of the air reference (rads); β_{air} = phase constant of air (rads/m); θ_{bale} = measured phase of the material under test (rads); θ_{mat} = phase delay of the material under test (rads); β_{mat} = phase constant of material (rads/m); n = integer number of cycles.

Using the basic relations from equations 4, 6, and 8 through 10, a function that predicts the relative permittivity of material is provided (equation 11).

$$\varepsilon_r = \frac{\beta^2_{mat}}{\omega^2 \mu_o \varepsilon_o} \quad (11)$$

It should be noted that the permittivity of material is calculated from equations 8 through 11, as long as the relative phase delay between the air reference and the bale signals over the permittivity range of interest does not exceed 360°. If it exceeds 360°, then a range ambiguity occurs in the measurement, which would lead to a confusion between low moisture bales and high moisture bales. To avoid this issue, a specific frequency range was chosen in order to provide good resolution of the phase constant of the material, while maintaining the maximum phase delay of less than 360°.

In the interest of simplifying the model and testing the characterization of cotton bales as a low loss material, an experiment was conducted on commercial size and density cotton bales to determine if a low loss model would be sufficient or if it would be necessary to carry out the model using a complex permittivity representation for the dielectric constant. In conducting these tests, typical full density commercial cotton bales were obtained that were within the expected moisture content range for the majority of commercially produced cotton bales. The dry bales ranged from 3.5% to 4.8% moisture content, and the wet bales ranged from 7.8% to 8.2% moisture content (dry basis). In order to determine the assumption of low-loss, a test was conducted to determine the attenuation of a signal propagating through the bales. In this test, two microwave horn antennas that were configured so that the opening of each horn was pointed at the opposing antenna, and the bale was inserted between the two antennas.

In order to ensure that only the direct-path signal was measured, each antenna was placed inside an anechoic rf-absorbing tube. The center of the tube was omitted to allow for the insertion of the cotton bale in between the two antennas that were housed deep inside these anechoic tubes. The anechoic absorbing material was used to ensure that the energy from the antennas was propagated only through the bale, thereby reducing the effects of multipath interference by more than –20dB (anechoic material's attenuation ability at the frequency of the test). In conjunction with the anechoic material, the test was conducted with microwave horns that provided an additional 8dB of forward gain, so it was reasonable to assume that the multipath components had been significantly reduced.

To obtain the measurements, a microwave impedance analyzer was used to determine the magnitude of the attenuation and phase delay of the signal across the frequency range of interest (1.85GHz to 2.2GHz). In order to remove the effects of the cables and antennas from the measurement, an air reference was conducted to obtain a baseline reference before each bale was tested. Once the air reference had been established and removed from the measurement, the signal attenuation and phase delay was measured for both the wet and dry cotton bales.

To verify multipath rejection, measurements of the propagation phase delay constant of the material were obtained using the anechoic shielding at several different antenna-separation distances. The results of the tests provided essentially the same propagation delay constant within a reasonable degree of noise tolerance. Conversely, when the same test was conducted without the anechoic material, the results between the different antenna spacings were highly uncorrelated and provided little confidence in the obtained propagation delay constant. It was concluded from these results that the anechoic material setup was performing adequately in the prescribed configuration.

The test results determined the average attenuation for the dry bales was –2.45 dB, and the average attenuation for the wet bales was –5.43 dB. Based on the range of the obtained measurements, it became apparent that the attenuation measurement would provide a very poor indicator of moisture because the noise in the measurement covers a large portion of the span, but the phase delay constant provided a suitable range and noise tolerance. In conclusion, the choice of frequencies was suitable and based on the attenuation values, the cotton bales can be safely classified as a low loss material for these wavelengths over this limited range of moisture at these commercial densities.

Based on these results, a formulation of the FDTD model was developed that allowed for each node in the domain to carry separate values for the permittivity, complex permeability (for implementation of the PML), and conductivity. This formulation allowed for the definition of multiple domains within the solution space and for the model to simulate the microwave radiation propagating through free-space (air), dielectrics, such as cotton, and anechoic materials. Additional flexibility of this method allows for insertion of metallic structures, such as microwave horns, metal walls, and a metal roof, into the solution space. The solution domain was conducted on a rectilinear coordinate system because most of the objects of interest are not curved. This choice eases the coding, as well as improving the convergence time. The model's transmitter and receiver was modeled as an electromagnetic radiation point source located within a metal horn. Taflove (1995) suggests the best method to achieve this is to assign a desired time function directly to one of the components, either H or E, at a desired node preferably in the near vicinity of a metallic reflector. In this manner, the metallic reflector is excited to effectively provide a zero impedance generator. In order to obtain a wave propagating in the x direction, the H_z component at the source node was excited with a 1.85GHz signal. During the course of the transient analysis, monitoring of both the electric and magnetic field strengths at a point interior to the receiving horn was performed at a node where a typical horn excitation probe would be located. This data was logged as the solution progressed from time (t) 0 to t final. The transmission frequency investigated was 1.85GHz and the model discretization was setup for 0.1 times the wavelength of the source to ensure both accuracy, as well as timely model convergence. The cotton bale and microwave horns were introduced into the model domain with the bale thickness being calculated with a cell spacing of + ½ cell width on each side of the bale boundary. The solution time was started after the simulation came to a steady state solution, which was estimated by examining a plot of the electric and magnetic field strength versus time at the receiver's location (Fig. 3). Both the phase and magnitude of the received signal were logged at this location. To obtain meaningful results, the model was first run without the cotton bale to obtain an air reference. This air reference was used in conjunction with each of the test simulations to obtain the phase delay constant of the material and to calculate the permittivity of the material. This allowed the simulation experiment to compare the known permittivity of the model's cotton bale with the receiver's predicted permittivity of the cotton.

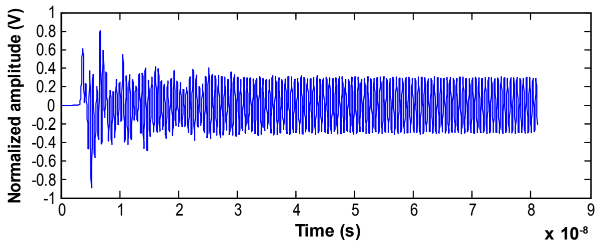

Figure 3: All of the finite-difference time-domain (FDTD) simulations were run until steady state conditions were observed. The y axis is relative magnitude of the received signal strength and the x axis is time in seconds. The permittivity was calculated for all of the simulations by using only data that was obtained after steady state conditions were achieved. In this case, the signal was assumed to be stable after 4e-8 seconds.

MATERIALS AND METHODS

The first phase of this investigation was to ascertain the accuracy of the FDTD model. This was accomplished by comparing the measured phase delay of the signal at the receiving antenna with the closed form solution prediction obtained by the solution of Maxwell's equations for free-space propagation (Pozar, 1998). To determine the accuracy of the code, the model was run with a PML absorbing boundary for three levels of bale transmission lengths (bale width) at 16 levels of permittivity. Based on the physical measurements described previously, the expected range for the permittivites for cotton bales at standard density over the range from 5% to 8% should be within the range of 1.45 to 1.52. The test was focused across this range but run from 1 to 2.25 to provide a wider scope of results for reference. After these initial model tests were successful, the simulations were run at 8 levels of cotton bale permittivity that were selected to cover the expected levels of permittivity due to the bale moisture range at a bale density that corresponds to a 226.8 kg (500 lb.) UD bale. The full experiment consisted of four sets of simulations. The first set consisted of free space propagation with only the bale, antennas, and the PML inside the solution space. This configuration yields the perfect case with no reflectors to create multipath interference. The next three cases were setup with metal walls and a metal roof to form metal clad enclosures around the antennas and cotton bale. This was done in order to simulate operation in a typical cotton gin where multipath interference is expected to be significant. The only difference between these three cases was that the size of the metal room was modified, because cotton gins vary in size and it also provides a different multipath environment by which to examine the technique.

The experimental configuration (Fig. 4) for this model places a hard EM source on the left side of the bale inside of a metal open-ended cup to simulate a horn transmission antenna (Taflove, 1995). The cup is oriented so that the opening is facing the dielectric region (cotton bale) that is placed 0.23 meters to the right of the antenna. To the right of the antenna is a 1 meter high by 0.533 meters wide cotton bale. To the right of the bale is the receiving antenna located 0.23 meters away from the bale. The sizes of the antennas were constructed so that the waveguide of the microwave horn will exhibit a lower cutoff frequency than the test stimulus frequency. For the simulation where metal reflectors were used, they were given the permittivity, permeability, and conductivity values that are typical for steel.

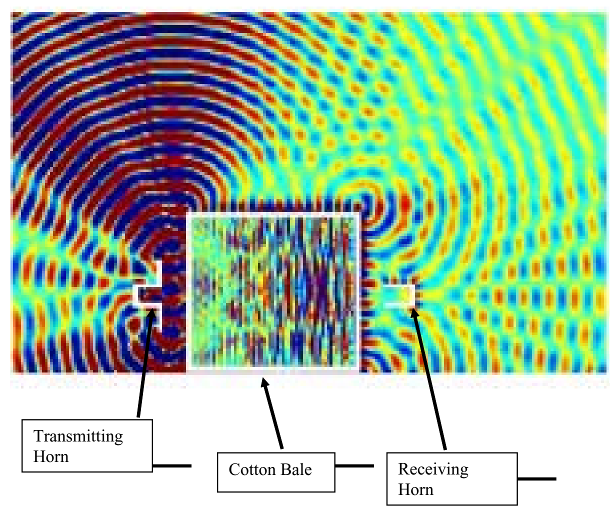

Figure 4: This figure details the simulation's structural geometry, as an overlay on top of the transient solution to the magnetic field strength (H/m) for a wet bale in free space. The darker colors represent the stronger field strengths, and notice the compression of the waves inside the cotton bale. The model provides a graphical display of the change in wave velocity as the signal travels in free-space and then through the bale. It is this measurement of the signal's propagation velocity through the bale which provides a direct measure of the permittivity of the cotton bale, which is known to have a strong correlation to the moisture-density of the bale.

RESULTS AND DISCUSSION

The model simulation was set up to predict the permittivity of the cotton bale based on the monitored electric and magnetic fields at the receiver location. The model predicts the permittivity of the cotton bale by transmitting microwave energy through the cotton bale and analyzing the received signal on the other side of the cotton bale. The field strengths were monitored at the receiving antenna for use in quantifying the model's prediction of the permittivity of the cotton bale. This prediction was also compared with the closed form solution for plane waves, such as a cotton bale, where a positive traveling wave has the propagation factor of the form of equations 4 and 6 (repeated here for convenience).

$$E(z) = \mathbf{e}^{-\alpha z}\cos(\omega t - \beta z) \tag{4}$$

$$\beta = \omega\sqrt{\mu\varepsilon} \tag{6}$$

Using equation 4 along with the values obtained in the simulation, as well as the previously obtained experimental values for the propagation phase delay, provides a measure of the accuracy of the model to simulate free-space propagation with no reflectors. The prediction of permittivity indicates that the model is able to predict the permittivity of the cotton bale with a standard error less than 1.0 % with a coefficient of determination of r^2 = 0.99 when configured in a transmission mode with no external metallic reflectors over a wide range of permittivities (Fig. 5).

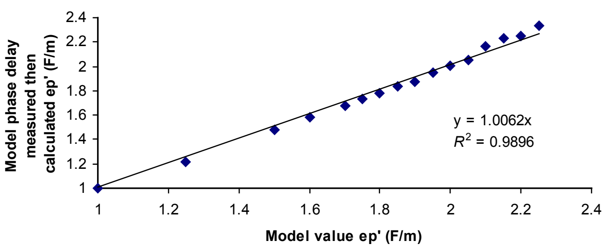

Figure 5: Results of the correlation analysis between the closed form solution to Maxwell's equations for a plane-wave and successful prediction of the permittivity (ep') of a dielectric absorber by the finite-difference time-domain (FDTD) model.

Qualitatively we can visualize what is happening by observing the various models. Figure 6 shows the transient response for the signal propagating inside a closed cavity, or metal building, with a wet bale. This transient response shows that there is a significant amount of energy emitting from the back of the horn along with a significant amount of energy that is being reflected backward from the front face of the wet cotton bale. This is significance because a large portion of the transmitting energy is not being transmitted through the bale to the receiving antenna and results in a significant amount of the energy being propagated around the bale rather than through the bale. This stray energy that propagates around the bale is then later received by the receiving antenna, which then recombines with the direct-path energy that was transmitted through the bale. Figure 7 shows the steady-state response for a dry bale in free space. There is very little phase delay in the signal propagating along-side the direct-path signal. Figure 8 shows the steady-state response for a wet bale in free space. In the wetter bales, the increased phase delay between the signal propagating alongside the bale and the direct-path signal is much more pronounced. In figures 9 and 10, the steady-state solutions are shown for the dry and wet bales inside a metal room. These steady-state cavity responses highlight the magnitude of the standing waves that are set up inside the metal structure, and show that it is acting very effectively as a resonant cavity. Again, the large magnitude of the amount of energy that is impinging upon the receiving antenna that was not propagated through the bale is apparent. All of these models detail the significant differences between propagation through the bale in free-space versus the propagation inside a metallic structure. Given the magnitude of the multipath components, it seems doubtful that equation 4 will remain valid; however, since this model allows for the inspection of the both the electric and magnetic field strengths at any point within the solution space, equation 4 can be readily tested for validity even with this significant amount of spurious radiation impinging upon the receiving antenna.

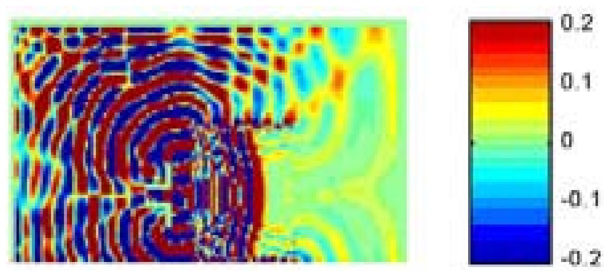

Figure 6: Transient response of a wet bale inside a metal structure. The colors are the relative range of signal strength (H/m).

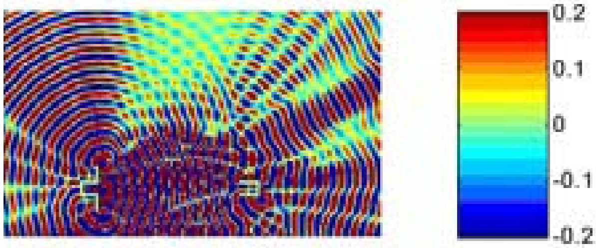

Figure 7: Transient response of a dry bale in free space. The colors are the relative range of signal strength (H/m).

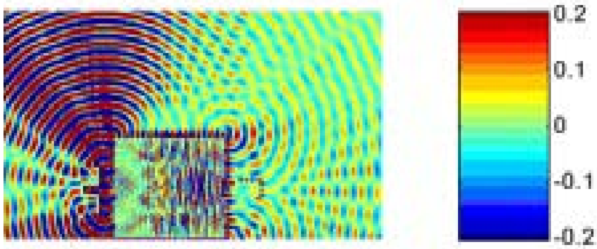

Figure 8: Steady state solution of a wet bale in free space. The colors are the relative range of signal strength (H/m).

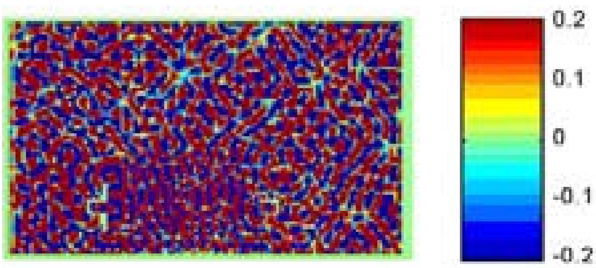

Figure 9: Steady state solution of a dry bale in a metal clad building. The colors are the relative range of signal strength (H/m).

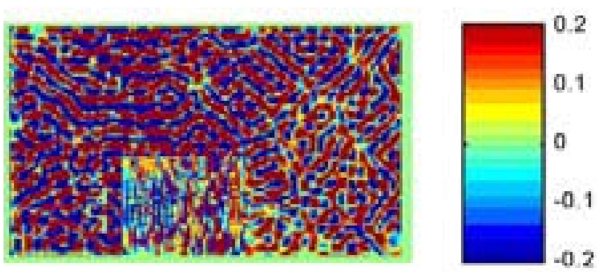

Figure 10: Steady state solution of a wet bale in a metal clad building. The colors are the relative range of signal strength (H/m).

After the simulations were all performed, the measured permittivity from the receiving antenna was compared with the known permittivity of the cotton bale. The measured response varies across the dielectric range that cotton bales will exhibit in both free-space, as well as in three different sized rooms (Fig. 11). Surprisingly, even the cavity tests indicate that the received signal varies in a linear relation to that of the bale's permittivity. It also shows that in each case this linear relation will vary in both slope and intercept from that of free-space propagation depending upon the size and shape of the surrounding metallic reflectors. In conclusion, it is apparent that the true permittivity of bales cannot be measured in a multipath rich environment, but there is a linear relation to increasing permittivity that could be exploited for use in moisture sensing.

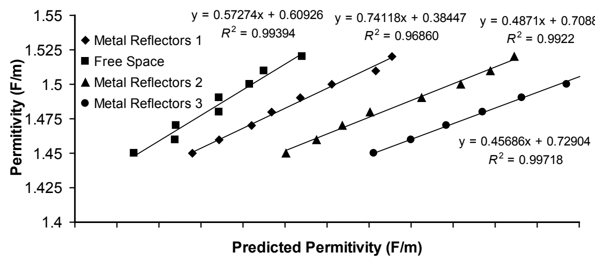

Figure 11: Regression analysis of the relationship between the measured permittivity and the predicted permittivity in free space and in three different-sized, metal buildings. This analysis shows that the strong multipath interference that occurs in metal buildings alters the measured permittivity. It also shows that while the measured permittivity is altered, this measured permittivity, while incorrect, does provides a linear relationship that can be used for moisture sensing as long as a site-specific calibration is performed for each metal building.

CONCLUSIONS

Once the model had been validated to perform to within reasonable tolerances to the closed form solution of the free-space propagation equation, the simulations looked at the signal degradation due to multipath interference, which are a direct result of the presence of external metal reflectors. The simulations revealed two main affects that should be expected when operating inside a metal clad structure; (1) the slope and intercept of the system is not going to behave in accordance to the closed form solution, and (2) even though the multipath interference will unpredictably alter the permittivity measurement, the system will provide a linear response to increasing permittivity and could be used for a moisture sensor as long as the system was calibrated for that particular installation. It also means that if the system is moved or a large metal piece of equipment is added in view of the sensor, that the calibration will have to be redone.

In all of the cavity simulations, the signal quality and accuracy was degraded by the multipath propagation, but not to an extent that would render the system useless. These results indicate that the system could provide an accurate prediction of the permittivity and therefore the moisture content of the cotton bale. The downside of this is that it also precludes a calibration based upon the permittivities of material as the wide range of deviation due to multipath interference is much larger than the entire range of expected permittivities for use in cotton bale moisture sensing.

In summary, the simulations reveal that multipath interference is extremely significant, but it also indicates that there is promise that an onsite calibration of the system could provide a working solution. The results from these simulations indicate that the system should provide an accurate measure of moisture even in a multipath rich environment once the system has been field calibrated, which warrants further research efforts that would explore the deployment of this sensor into commercial gins without the expensive anechoic multipath shielding that has been the mainstay of the laboratory protocols used in this research program.

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