Ultra-Wideband Radar "Seeing" Through Walls

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Abstract

Using ultra-wideband radar's capabilities of propagating through walls, this project will develop a blue-print image of a building by flying over or driving around the desired target. This project is sponsored by the Micro-Power Impulse Radar Group (MIR) at Lawrence Livermore National Laboratories. Ultra-wideband radar signals have a bandwidth of 500 MHz to several gigahertz and have properties that allow the signals to penetrate everything but solid sheets of metal and water. The purpose of this project is to increase the precision of this blue-print image by determining the penetrated wall thicknesses. The accuracy of penetrated wall thickness is useful in an urban warfare environment to see the blue-print image of the building and the location of all armed and non-hostile personnel.

In order to determine the penetrated wall thicknesses, the first step is to determine the frequency response of the wall. Two models are used to calculate frequency response, a single and dual antenna model. Using the frequency response equations for each model, the calculated received signal is analyzed to determine a relationship between reflections and wall thickness. This relationship is linear. By May 2007, the mathematical model (frequency response) and mathematical algorithms are completed and will be tested by the MIR group.

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Introduction

Lawrence Livermore National Laboratories (LLNL) is a Department of Energy (DOE) research facility whose primary purpose is the research and development of science and technology pertaining to national security. The Micro-Impulse Radar Group (MIR) at LLNL researches and implements technologies involving ultra-wideband (UWB) radar for a myriad of purposes. In May 2006, MIR was tasked by the Defense Advanced Research Projects Agency (DARPA) to create an ultra-wideband radar device that will be able to create an accurate visual "blue-print" image of any building by flying over or driving around that building. The reflected UWB radar signals will be used to create this blue-print image and may eventually include additional information regarding the infrastructure building materials.

Ultra-wideband radar signals have an extremely large frequency spectrum, usually including frequencies from 500 MHz to several gigahertz. The wide frequency spectrum and extremely short pulses allow the radar signals to penetrate everything except solid sheets of metal and water. The current stage of development of ultra-wideband radar includes the ability to detect motion behind walls. The UWB radar requires further research to understand how the signals are altered by propagating through walls, in order to determine wall thickness. A useful blue-print image will be represented with the exact thickness and composition of the walls.

Prior research on finding wall thicknesses includes data taken in May-June 2006 during a summer internship at LLNL. The data taken involves simulating walls by using concrete and wooden blocks. The UWB radar was used to take several data tests at various distances away from the blocks. Further testing also included changing the thickness of the "wall." There has been only minor research in determining how a wall will affect the UWB signal through

deconvolution methods. Further research on signal propagation modeling and the frequency response of the penetrated wall is still required.

Upon examination of ultra-wideband radar, the primary goals and objectives for this project are to understand how the UWB radar signals propagate, to model the ultra-wideband radar signal propagation, and to create mathematical algorithms to determine wall thickness so MIR can use this information to create an accurate depiction of any building without having any knowledge of the building material.

Background

Ultra-Wideband History

Ultra-wideband frequency spectrum was discovered in the 1960s and technologies using ultra-wideband frequencies were further utilized in the 1970s and 1980s [1]. This frequency band's primary purpose was for covert military operations [1]. Ultra-wideband is defined to have a low energy spectrum evenly spread over several gigahertz of bandwidth (Figure 1). As compared to common communication devices, ultra-wideband pulses spread their energy evenly across all its frequencies, which make the signals appear like white noise in comparison to narrowband and even wideband signals [2].

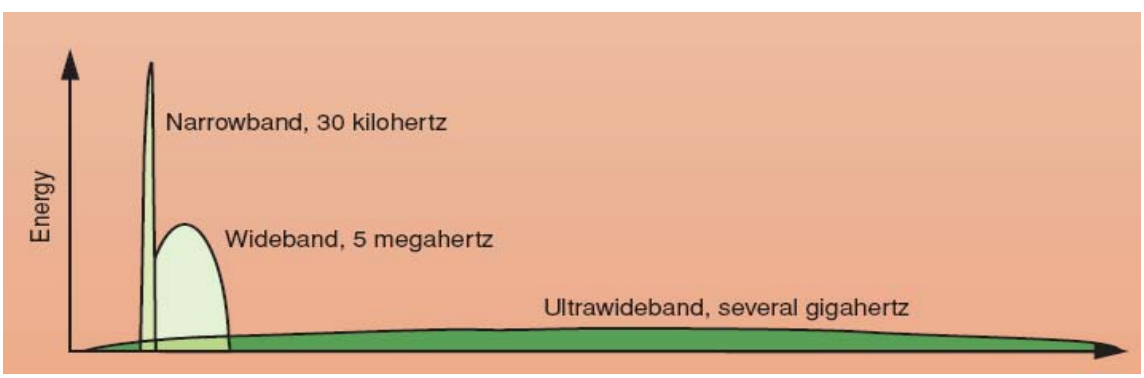

Figure 1: Bandwidth Comparison [2]

When contrasting narrowband, wideband, and ultra-wideband signals the primary difference is how energy is distributed over their unique bandwidths. Narrowband signals, such as radio communications, are modulated using a sinusoidal carrier signal [3]. Narrowband signals limit the information capability of radio systems because the amount of information transmitted in time is proportional to its specific bandwidth [3]. Increasing this system's information capacity requires expanding its frequency band, or alternatively increasing the amount of time to transmit the information [3]. For example, traditional cellular phones and GPS usually operate in the wideband frequency spectrum [1]. On the contrary, UWB-based signals operate in the baseband using a series of short pulses that spread the energy of the signal from near DC to a few gigahertz. Figure 2 shows an example of such a pulse [5].

This unique signal's benefits include a high information rate, anti-interference capabilities, and anti-interception capabilities [5]. The UWB signal is difficult to detect and intercept due to low power spectral density of the ultra-wideband signal, being mistaken for white noise.

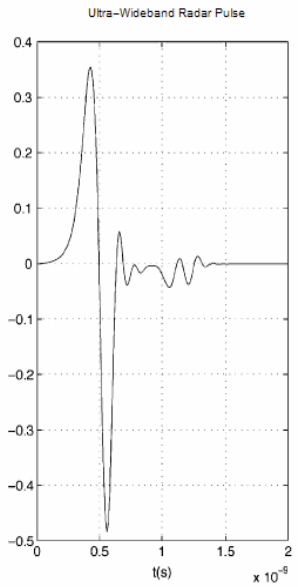

Figure 2: Example of Ultra-Wideband Pulse [6]

Capabilities of Ultra-Wideband Radar

Due to its unique signal qualities, UWB radar has a myriad of capabilities implemented in current technologies such as search and rescue radar (SARDAR), intrusion detection, through-wall detection, and heart and respiration detection [2]. The search and rescue radar involves using the ultra-wideband radar to sense movement in a collapsed building structure. SARDAR has been successfully tested after 9/11, Hurricane Katrina, and at NASA Ames [7]. NASA Ames is an annual exercise designed for the training of first responders in an urban emergency such as hurricane or terrorist attack [7]. The first responders participating in NASA Ames used the SARDAR as a tool to locate possible victims within a collapsed building [7].

The intrusion detection capability of the ultra-wideband radar involves the detection of any movement through an invisible boundary created by the radar (Figure 3).

Figure 3: Intrusion Detection [2]

Through-wall detection is an important military capability of the ultra-wideband radar. The ultra-wideband radar can detect movement through walls to eventually have the capability to map the structure of a building including the location of all personnel (Figure 4). Through-wall propagation is the primary capability used in this project.

Figure 4: Through-wall Detection [2]

More sensitive ultra-wideband radar systems can detect movement as slight as a heart beat or breathing rate. The ultra-wideband radar is responsive enough to accurately depict a heart rate as compared to an EKG (Figure 5). The top plot is the heart pulses measured using the MIR radar, while the bottom plot is the heart pulses using an EKG. The sensitivity of the radar requires less power resulting in a small functioning range.

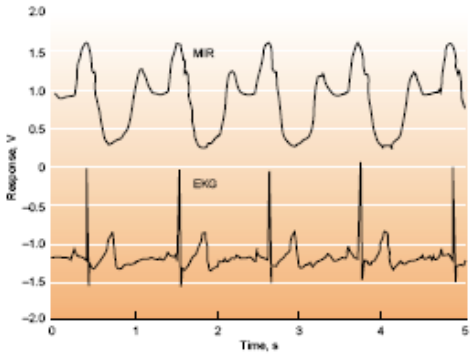

Figure 5: Heart Rate Comparison [2]

UWB Criteria

DARPA defined the standard for a signal to be classified as UWB in 1991 as electromagnetic signal waveforms that have an instantaneous fractional bandwidth greater than 0.25 with respect to the center frequency [3]. Fractional bandwidth is defined as a ratio of the high and low

frequencies, or known as the percentage of the center frequency (eq. 1). The variables f_h, f_l, f_c are the high, low, and center frequencies respectively. The fractional bandwidth can also be defined as the total bandwidth the signal uses over the center frequency. The ultra-wideband criterion is important in order to classify signals bandwidths, for instance narrowband, wideband, and ultra-wideband. Without this criterion, there is no quantitative measure to classify this type of signal.

$$\text{Fractional Bandwidth} = \frac{2\left(f_h - f_l\right)}{f_h + f_l} = \frac{f_h - f_l}{f_c} = \frac{\text{BW}}{f_c} \qquad \text{(eq. 1)}$$

Project Description

The MIR group is currently contributing to a DARPA sponsored project using the ultra-wideband radar, which commenced in June 2006. DARPA tasked LLNL to visually generate a blue-print image of any building using the ultra-wideband radar. This is a multi-year endeavor and will be accomplished in several partitions, such as determining wall thickness, the height and width of a room, and the floor plans of each level of the building.

The specific concentration for this Capstone project is to use the ultra-wideband radar signals to determine the thickness of a wall. The Project Plan details the purpose and main objectives required to be completed (Appendix A). Determining wall thickness is important, because it allows for a true-scale blue-print image of the building. Without this information the blue-print image would not be accurate, defeating the purpose of this project. The prior research for this portion of the project was accomplished during the summer internship at LLNL, where a preliminary understanding of UWB radar systems was gained.

Prior Research

During May through June 2006, a summer internship at LLNL, the MIR group tasked 1/c Kirsten Ambors to commence research by gaining background information on ultra-wideband radar and deconvolution. The emphasis was to concentrate on using real data to create algorithms to determine wall thickness. Most of the preliminary data analysis completed during this time period involved deconvolution, to determine the frequency response of the penetrated wall. Theoretically, by analyzing the frequency response of the wall, the differences between wall thicknesses would be visually and quantitatively evaluated, providing suggestions of how to find wall thickness.

In addition to deconvolution, the power spectrum density is a quantitative method of determining wall thickness. Another aspect examined during this time period, besides determining methods of finding the wall's frequency response, was the process of taking experimental data. The experimental data setup involved using concrete blocks and wooden blocks to simulate a wall while the radar oscillated back and forth and increased its distance away from the wall (Figure 6). This data was repeated multiple times in order to minimize outliers and any error while taking data.

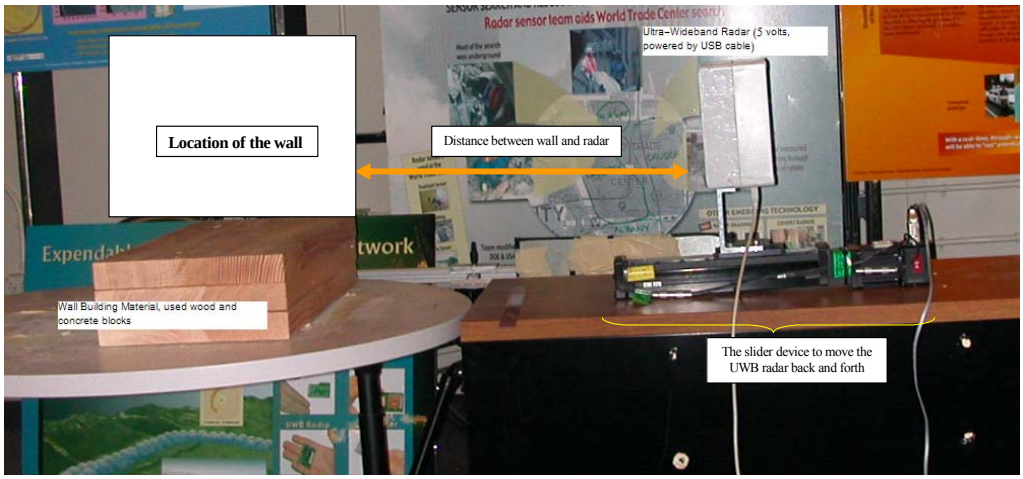

Figure 6: LLNL Experimental Setup

Wall Characteristics

In order to determine how various walls affect the propagation of the UWB radar signals, the wall characteristics need to be identified. Different materials are measured by their permeability and permittivity describing how signals are affected as they propagate through the material. Permeability is the degree of magnetization of a material that responds to a magnetic field [9]. Permittivity describes how an electric field affects and is affected by a dielectric medium, relating to a material's ability to transmit an electric field [9]. Characteristic impedance, η, is measured in Ohms (eq. 2). The characteristic impedance depends upon the magnetic permeability Henry/meter (μ) and the electric permeability or dielectric constant Farad/meter (ε).

$$\eta = \sqrt{\frac{\mu}{\varepsilon}} \qquad \text{(eq. 2)}$$

For example, the permittivity, permeability, and intrinsic impedance for free space are shown in (eq. 3).

$$\begin{aligned} &\varepsilon_o = 8.85x10^{-12} \text{ F/m (permittivity)} \\ &\mu_o = 4\pi x10^{-7} \text{ H/m (permeability)} \\ &\eta = 376.7\ \Omega \text{ (impedance)} \end{aligned} \qquad \text{(eq. 3)}$$

Wall materials differ in terms of permeability and permittivity as shown in Figure 7. A myriad of wall building materials and their corresponding dimensions, permeability, as well as their loss (in decibels) at 5 GHz. These characteristics describe how the signal will be attenuated, distorted, and delayed as it propagates through these various building materials.

Material	Dimensions (cm)	ε_r	Loss at 5 *GHz (dB)*
Wallboard (drywall)	**1.16992** x 121.8 x 196.9	2.44	0.45
Cloth Partition	**5.9309** x 140.7 x 153.1	1.23	2.55
Structure Wood	**2.06781** x 121.5 x 197.8	2.11	1.35
Sample door	**4.44754** x 90.70 x 211.8	2.08	2.0
Ply Wood	**1.52146** x 121.9 x 197.51	2.49	1.75
Glass	**0.235661** x 1.44 x 111.76	6.40	1.25
Styrofoam	**9.90702** x 121.8 x 197.7	1.11	0.10
Bricks (single)	**8.71474** x 5.82676 x 19.8	4.22	6.45
Concrete Block	**19.45** x 39.7 x 19.5	2.22	13.60
Reinforced Concrete (TDL)	**60.96** x 121.92 x …	-	-

Figure 7: Wall Material Characteristics [8]

Signal Propagation

It is vital to understand how the basic signals propagate through different materials. The signal will reflect whenever there is a change in material in each region (Figure 8). Figure 8 displays the simple model of signal reflection, illustrating the reflection off of the end of region II. Technically, the signal will reflect after reaching region II, again after reaching the end of region II, and the process continually repeats until the energy of the reflected signal may be considered negligible.

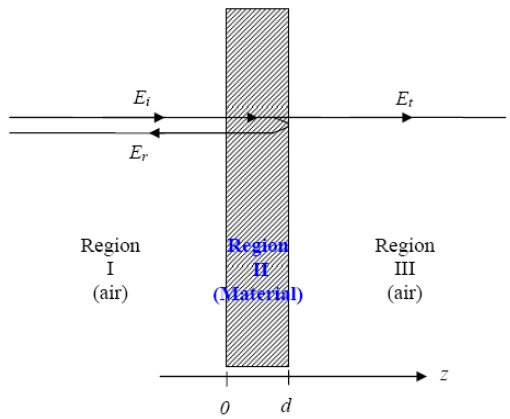

Figure 8: Basic Wall Thickness Diagram [8]

Another important concept in the basic propagation is the understanding that the total received signal is the addition of all the reflected signals. The reflection of an electromagnetic wave occurs when a wave meets a discontinuity in the characteristic impedance of the propagation medium [9], meaning that the wave is reflected if it encounters a material different than the one it is currently traveling through. The overall reflection from a complex target depends on the electrical size of all reflectors, spatial relationships among reflectors, and the angle of reflection of the re-radiated signal [9]. The angle of incident also affects the perceived reflectivity. From the received signal, it will be visually apparent when the first reflection arrives. This information can easily determine the distance from the antenna to the wall. However, to finding the wall thickness, *d* as shown in Figure 8, is complicated because there is no clear visual solution from the received signal.

When a signal propagates through one material, as shown in Figure 9, the signal is altered by the characteristic impedance of the material.

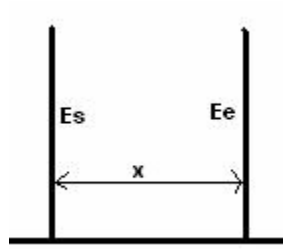

Figure 9: Signal Propagation through One Region

The start signal, E_s, is affected by the thickness of the region, x, as well as the characteristic impedance, γ, (eq. 4). Gamma, γ, is defined in terms of the attenuation constant, α, and the phase constant, β, (eq. 5) [8].

$$E_E = E_S e^{-\gamma x} \qquad \text{(eq. 4)}$$

$$\gamma = \alpha + j\beta \qquad \text{(eq. 5)}$$

When a signal reaches a change in region characteristics, there is a reflected signal and the transmitted signal, Figure 10.

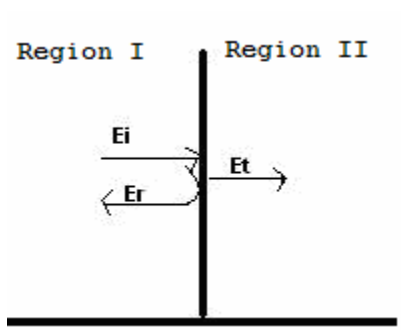

Figure 10: Signal Propagation through Different Regions

The transmitted signal, E_t, is multiplied by a ratio of the different region impedance characteristics, τ, (eq. 6). The ratio of the impedance characteristics affecting the transmitted signal is defined by τ, (eq. 8). The reflected signal, E_r, is also multiplied by a ratio of region

impedance characteristics, Γ, (eq. 7). The ratio of characteristic impedance affecting the reflected signal is defined by Γ, (eq. 9) [10].

$$E_t = \tau E_i \qquad \text{(eq. 6)}$$

$$E_r = \Gamma E_i \qquad \text{(eq. 7)}$$

$$\tau = \frac{2\eta_2}{\eta_2 + \eta_1} \qquad \text{(eq. 8)}$$

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \qquad \text{(eq. 9)}$$

Ultra-Wideband Radar Specifications

Another name for the ultra-wideband radar system is micro-power impulse radar. The specifications for the MIR are approximately uniform across all systems, with variations due to the differences in building the device, parts used, and the design purpose for the system. The specifications of the micro-power impulse radar includes the antenna pattern, center frequency, emission bandwidth, average emission power, duty cycle, detection range, motion pass band, analog output, receiver gain, power, and size (Table 1) [3].

Table 1: MIR Specifications [3]

MICROPOWER IMPULSE RADAR (MIR) SPECIFICATIONS	
Item	**Specifications**
Antenna Patters (H-plane)	-360º with dipole antenna -160º with a cavity backed monopole -Narrower with horn/reflector/lens
Center Frequency	1.95 GHz or 6.5 GHz ± 10%
Emission Bandwidth	500 MHz @ 1.95 GHz center
Average emission power	~ 1μW (measured)
Duty cycle	<1%
PRF (average)	2 MHz ± 20%
PRF coding	-Gaussian noise -Low coherence swept FM -Psuedonoise
Receiver noise floor	< 1μV_{rms}
Receiver gate width	250 ps for 1.95 GHz system
Range delay	RC analog, pot/DAC controllable
Range delay stability	RC component limited over temperature (drift in range delay expands/shrinks shell)
Detection range	Adjustable from 2 in > 20ft
Motion passband	0.3-10 Hzm Doppler-like signature
Analog output	~ 0.1-2 V peak on motion sensing Hand motion at 6 ft vies ~ 300 mV peak
Receiver gain	70 dB
Power	5 V @ 8 mA, Normal power mode 2.5 V @ 20 μA, long battery life version
Size	1.5 in^2 SMT PCB w/ 1.5 ft long wire dipole elements
Semiconductors	74AC04 CMOS (1 ea.) Bipolar or CMOS opamps (2 ea., quads) Bipolar RF transister @ >4 GHz F_T (2 ea.)

The transmitted signal of the ultra-wideband radar is required to have particular characteristics: short in time length, a large recognizable main pulse in time domain, a large lobe in the frequency domain. The second derivative of the Gaussian pulse matches all of these requirements. Figure 11 shows a plot comparing the Gaussian function with its derivatives.

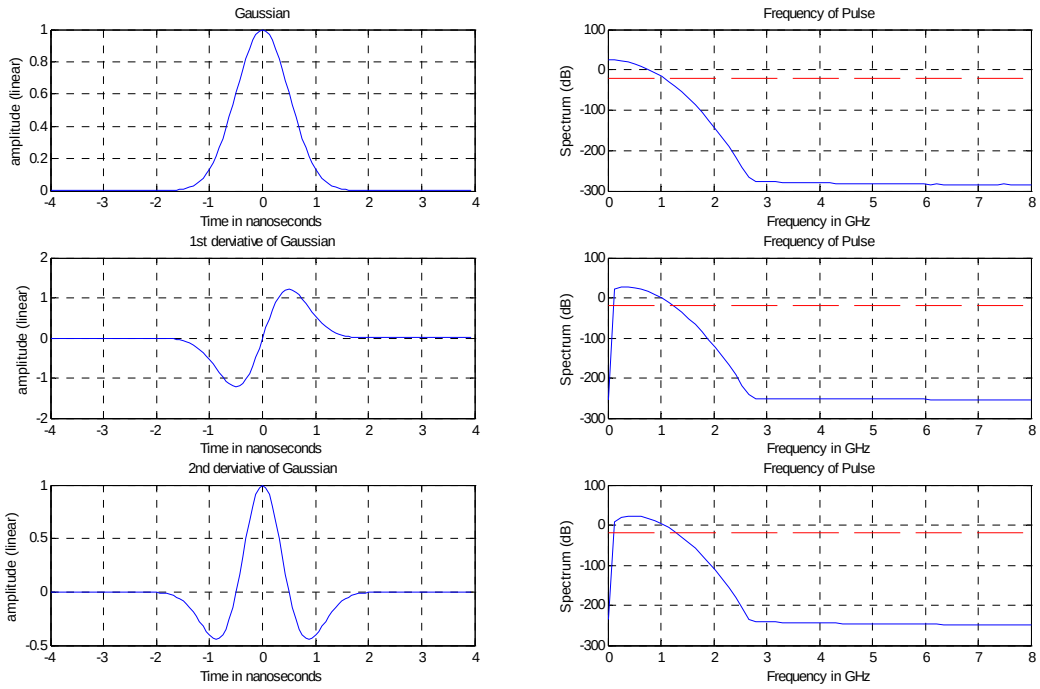

Figure 11: Gaussian Plot Comparison

The Gaussian function is smooth and continuous in the time domain, creating a single impulse-like pulse. The frequency domain plots show how the Gaussian functions have energy evenly distributed amongst its frequency spectrum. The second derivative optimizes the frequency spectrum by having the largest band of frequencies as well as the most evenly distributed energy amongst its frequencies. The ultra-wideband radar uses an extremely short pulse in the time domain. Figure 12 shows the second derivative of the Gaussian pulse with different widths in time domain as well as their corresponding frequency domains plots. As shown, when the pulse shape is shortened, the corresponding frequency domain plot does not change.

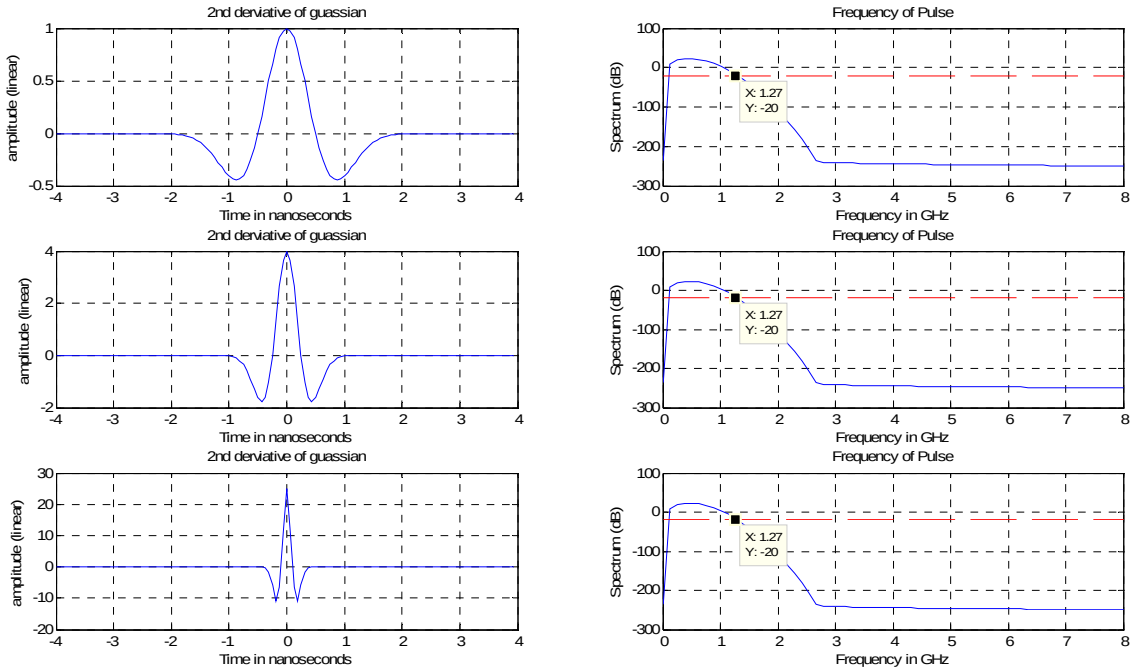

Figure 12: 2nd Derivative Gaussian Pulse Shapes

The second derivative of the Gaussian pulse has only one peak, easily noticed in the time domain and also has the longest lobe in the frequency domain, creating the large bandwidth of the signal. Another pulse would not fit these requirements since it would not have both the large single pulse in the time domain and cover a large spectrum in the frequency domain. Figure 13 shows a cosine defined over a specific period, a continuous cosine, sinc, and a periodic chirp in order to portray the important characteristics unique to the Gaussian function.

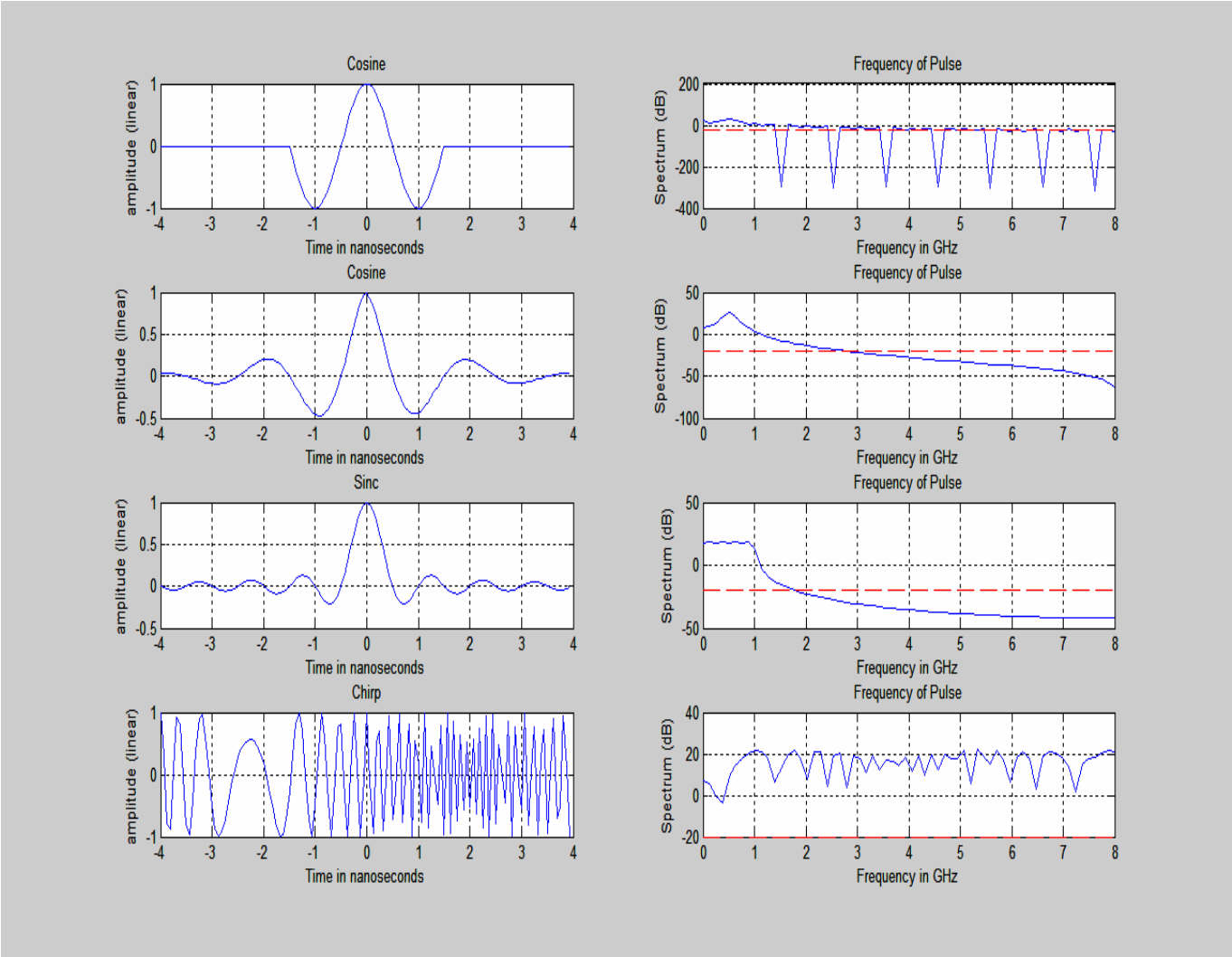

Figure 13: Comparison of Other Similar Pulses

As shown, the cosine function defined over a specific interval has the single large pulse in the time domain; however, the frequency domain is periodic and does not have the large lobe and decreases steadily containing a broad spectrum of frequencies. The manipulated continuous cosine function also matches the requirement in the time domain, but does contain a smooth lobe in the frequency domain. The frequency domain plot has a peak and decreases rapidly, not meeting the requirements for the transmitted pulse. The sinc function also meets the requirements in the time domain but does not in the frequency domain, although is the closest function to meet the requirements. The frequency spectrum does contain a large band of

frequencies; however, the magnitude of the frequencies decreases too rapidly, it needs to be a smooth decent. The periodic chirp does not meet any of the requirements as it is a periodic chirp in both the frequency and time domains, not containing a single large pulse in the time or a smooth lobe spectrum. These plots were generated using MATLAB and the code is attached in Appendix F1.

Objectives

The goal for this project was to view beyond what the human eye can see in order to create a blue-print image of a building using ultra-wideband radar. The specific purpose for this project was to determine the wall thickness to create a scaled representation. There were two primary objectives for this project: to model how ultra-wideband radar signals propagate through a wall and to create mathematical algorithms to ascertain the wall thickness. Each objective includes several requirements and necessary procedures to accomplish before the objective is satisfied. A further description of all the requirements are discussed in the Requirements Specification, included in Appendix B.

Modeling Objective

To model the propagation of ultra-wideband radar signals requires both a mathematical description and a software model to simulate the signal propagation. Before using modeling software to implement the mathematical understanding of UWB radar signal propagation, the proper modeling software needs to be chosen based on capabilities and the ability to be user-friendly, with an easy to use graphical user interface. User-friendly software was defined as software that the project advisors can determine the basic working principles of the software within one week, as stated in requirement 1.B.III (Appendix B). Important aspects to consider

when choosing the software are the program's ability to simulate propagation through different materials and the ability to create narrowband, wideband, and ultra-wideband signals. Accuracy of the software will be another deciding factor, measured by the software's ability to measure real-world environments including noise and multi-path simulation. The signal propagation modeling software, Wireless InSite, met the majority of the desired requirements. A 30-day free trial version of the software was received from Remcom at the end of February. The cost of the modeling software is approximately $4,000.

Requirements

According to the Requirements Specification, the modeling requirement would be satisfied upon the completion of a narrowband model. The models do not have to be complex in order to be useful. A simple model, such as a transmitting antenna on one side of a wall and the receiving antenna on the other, showed the user how the wall changes the transmitted signal, providing data to determine the frequency response of the wall. A complex model could illustrate how the ultra-wideband signals propagate through walls that use a variety of building materials or how the signals propagate around corners of a wall. This information is necessary for the MIR group's goal of creating a realistic blue-print image of a building. The sponsor required a simple model that simulates signal propagation through at least one wall of a uniform material.

The secondary objective was to create mathematical algorithms to solve for wall thickness. Mathematical wall thickness approximation algorithms needed to have the ability for implementation in MATLAB and the modeling software used, as dictated in requirement 2.A.III (Appendix B). In order for the algorithms to determine wall thickness to be successful, they all must approximately measure the wall thickness within 10% error and must complete the

algorithm in less than five minutes 95% of the time, as stated in requirement 3.A.III (Appendix B).

By May, the signal propagation model as well as wall thickness algorithms were delivered to LLNL. Dr. Farid Dowla is the point of contact with LLNL and will be testing the UWB radar signal propagation model and wall thickness algorithms using real data from the MIR ultra-wideband radar before May 2007, according to requirement 3.A.IV (Appendix B). The optimal method for finding wall thickness will be determined based upon its efficiency of correctly finding wall thickness, time to complete analysis, and the simplicity of the algorithm.

System Design

In order to complete a design that proves the understanding of UWB radar signal propagation, a visual model was required. A visual model provided a clear depiction of how the signals propagate through different building materials of walls of varying widths. This model allowed the ability for the user to change the building material, wall thickness, and location of the UWB radar antennas. Wireless InSite, a signal propagation modeling software, was the medium to create the visual models in order to visually depict how the signals propagate through a wall. The model, shown in Figure 14, represents a simplistic model where the green square represents the transmitting antenna and the red square represents the receiving antenna. The rectangle in the middle is representative of a wall. The modeling software the met the majority of the requirements for a signal propagation modeling software is Wireless InSite. Wireless InSite has the capability for modeling signal propagation through any environment, such as an urban or rural environment. This software can create simple or complex models with the capability of creating a movie animation showing how the signal is reflected in the process of propagating

through different materials. The program has a GUI interface with several drop-down menus to make selections. Wireless InSite also provided a variety of transmitted pulses to select and has the ability to create an ultra-wideband signal. The shortfalls of Wireless InSite included the output is difficult to understand, containing plots that describe the energy field over a frequency spectrum that do not necessarily change as expected when creating a known environment. Wireless InSite's output was also difficult to manipulate and to create the desired results. The user could not view the received signal in the time or frequency domain. The user also could not view the signal during various points of its propagation. Due to the economic considerations and difficulties understanding the output, Wireless InSite was not purchased, as reflected in the Decision Consideration section in the Design Specification, located in Appendix E.

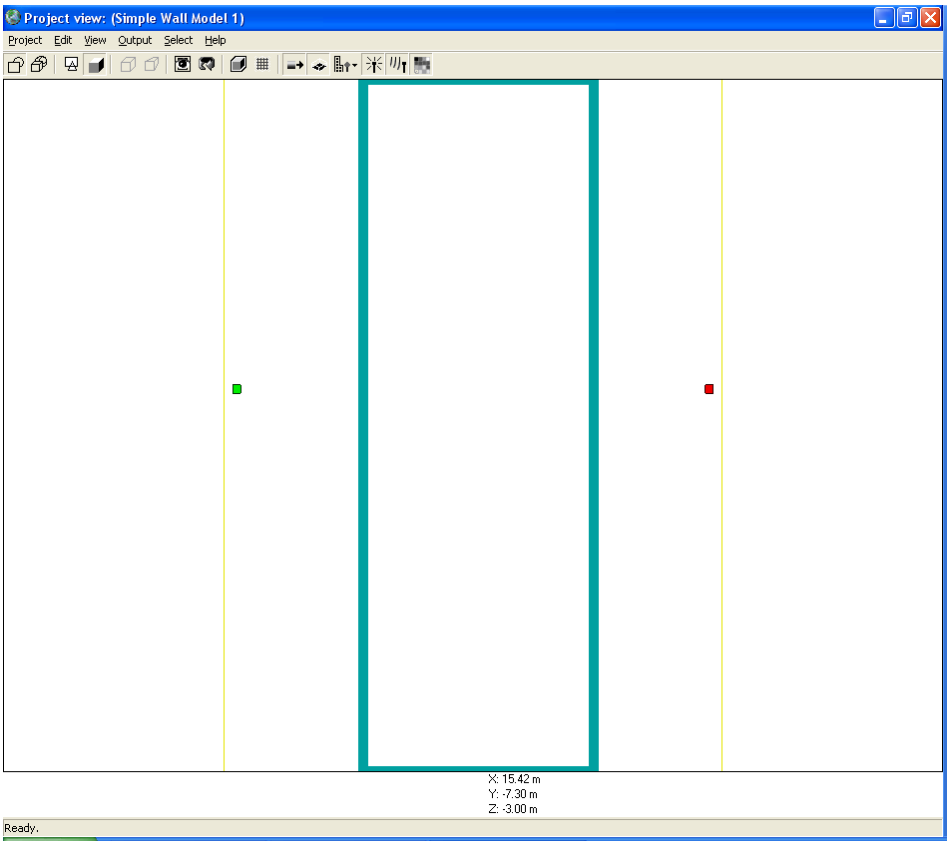

Figure 14: Wireless InSite Two Antenna Model

A more complicated model was also created using Wireless InSite using the same antenna for both transmitting and receiving the ultra-wideband radar signal, Figure 15. This was a three dimensional model showing a visual capability of Wireless InSite; the red and green antennas symbolize the transmitting and receiving antenna.

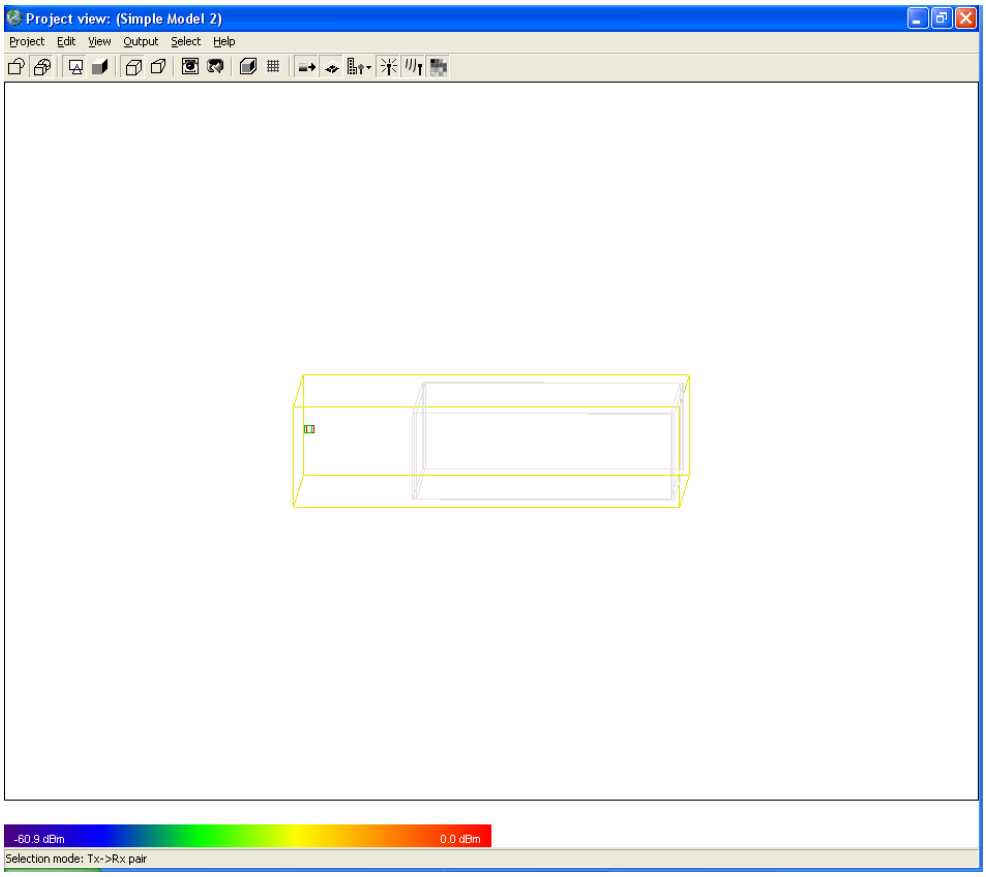

Figure 15: Wireless InSite Single Antenna Model

The location of the UWB radar antennas immediately affects the complexity of the model. The simpler version has a transmitting antenna on one side of a wall and a receiving antenna on the other side of the wall, the received signal is the summation of all the reflected signals (Figure 16). The UWB radar signal reflects when encountering any changes in permeability and permittivity. Figure 16 illustrates the reflected signals; not all reflected signals are shown

because their affect on the received signal is negligible. The thickness of the arrow symbolizes the energy of the signal.

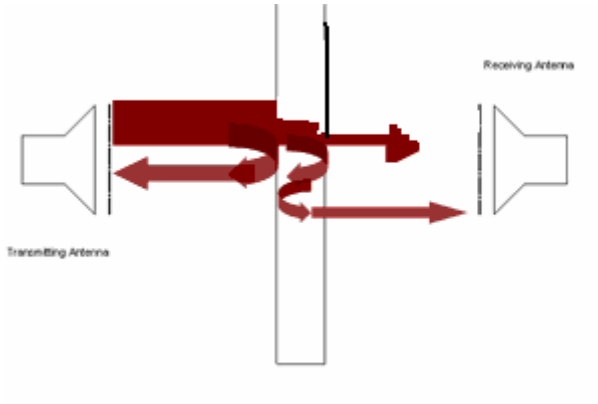

Figure 16: Two Antenna Desired Model

The more complex model that will use a single antenna for transmitting and receiving the UWB radar signal (Figure 17). This model is more realistic to prior experiments completed by the MIR group. In this model, the signal is propagated through one wall and is then stopped by a solid metal sheet. This solid metal sheet will ensure full reflectivity and no loss because the ultra-wideband signal cannot propagate through the material due to its density. The purpose of the solid metal sheet is to allow for the entire transmitted signal to be propagated and return to the receiving antenna. The thickness of the signal decreases as it propagates because energy is lost within the building material.

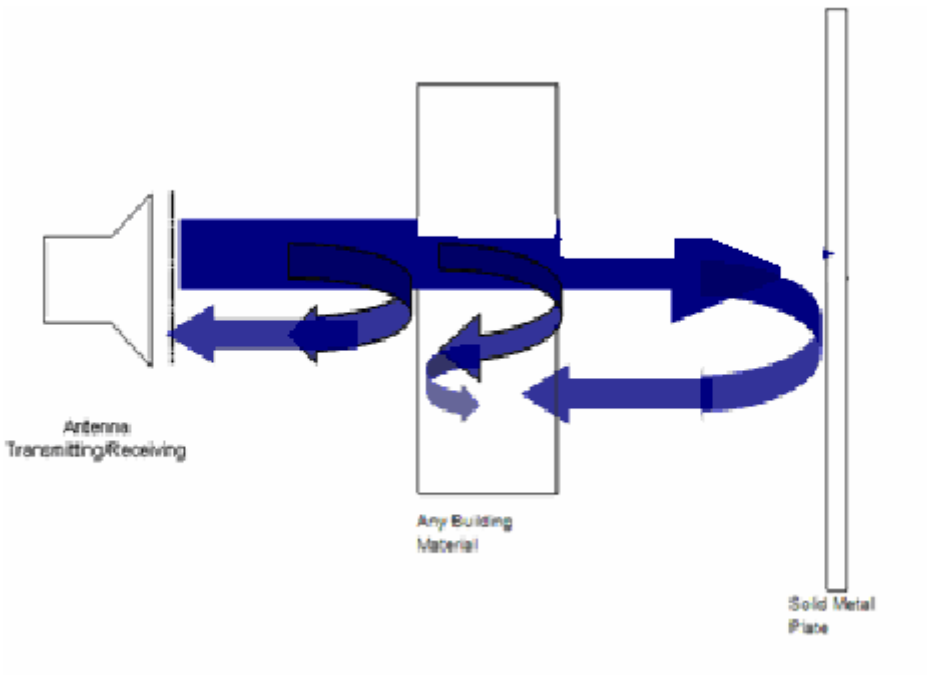

Figure 17: Single Antenna Desired Model

The focus, in order to determine wall thickness, is on calculating the frequency response of the wall. Through research, a frequency response equation was found for the model where there is an antenna placed on each side of the wall. However, this is not a realistic frequency response equation since in the actual scenario there will be one antenna that will both transmit and receive the ultra-wideband radar signal. Based on the signal propagation theory equations, described in the Background section, a frequency response for the one and two antenna models can be designed. The Design Specification, located in Appendix E, describes all design processes and decisions in further detail. Before determining the frequency response, the user needs to understand the different points along the propagation path and how they differ. Figure 18 visually depicts the important steps along the propagation path in the two antenna model.

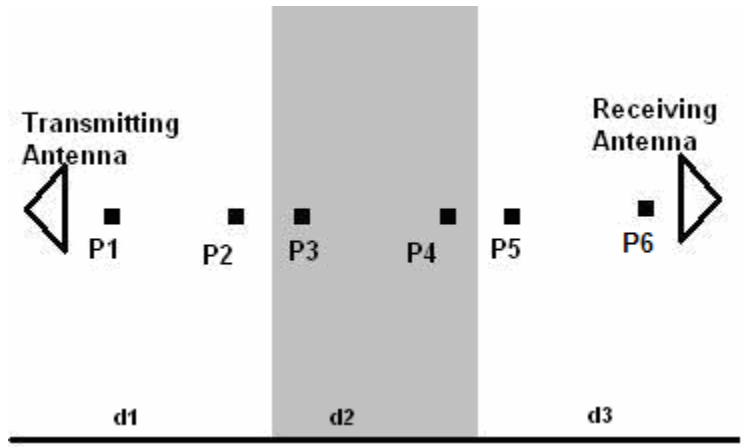

Figure 18: Significant Points along the UWB Signal Propagation Path in Two Antenna Model

The first region is considered air and has a thickness of d1. The wall thickness, denoted by region 2, has a thickness of d2. The third region is also considered air with a thickness of d3. Point 1 is the second derivative of the Gaussian pulse as transmitted from the antenna. Point 2 is the transmitted signal after it has propagated through region 1 of d1 thickness. Point 3 is the signal after it has been transmitted through the region boundary between region 1 and 2. The transmitted signal will be altered according to (eq. 6). Point 4 is the signal after it has been propagated through the wall material, (eq. 4). Point 5 describes the signal after it has been transmitted through the region change from the wall to air. Point 6 is the received signal after propagating through the entire system. The frequency response of the through the wall propagation model is calculated by taking the ratio of the signal at point 1 and point 6, (eq. 10) [8].

$$H(j\omega) = \frac{E_{P6}}{E_{P1}} \qquad \text{(eq. 10)}$$

The equation for the Gaussian second derivative is shown in (eq. 11), the transmitted pulse [8]. Time in the transmitted pulse is in terms of nano-seconds, ns. This also depicts the shortness of the pulse, appearing almost like an impulse in the time domain. The received signal appears like

several peaks differing in time and in magnitude. The short peak in the transmitted signal provides for the ability to see the difference between reflections in the received signal due to the time and magnitude variations.

$$p(t) = \left[1 - 4\pi\left(\frac{t - .75ns}{1.762ns}\right)^2\right] e^{\left(-2\pi\left(\frac{t-.75ns}{1.762ns}\right)^2\right)} \qquad \text{(eq. 11)}$$

Figure 19 is a flow chart describing the process of creating the through the wall (two antenna) model frequency response for the wall. The simple processes involve using the equations defining the incident signal and signal propagation theory in order to determine the frequency response equation. This frequency response process does not take into consideration any wall reflections, only considering the transmitted pulses while ignoring the reflected pulses. This is a simplistic frequency response equation since it is simply modeling how the ultra-wideband pulse is altered by going through a wall, rather than through and reflections of the wall. The processes for determining the frequency response for the two antenna model was outlined within reference 8.

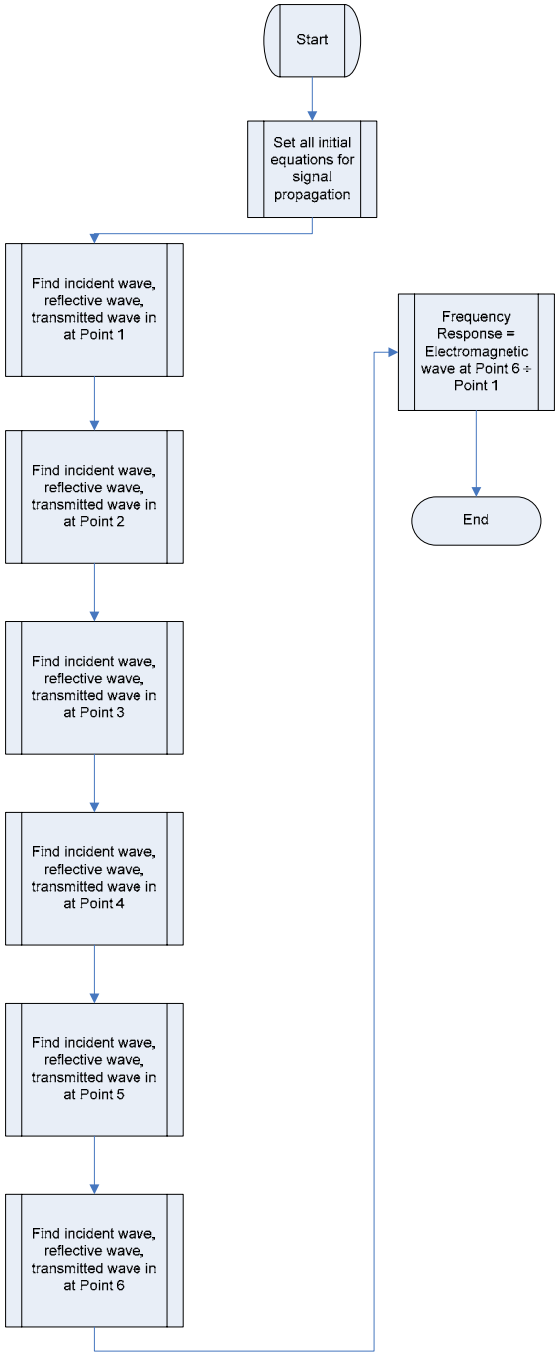

Figure 19: Determining Frequency Response for Two Antenna Model

The single antenna model, shown in Figure 20, illustrates the significant points of signal propagation. This model is equivalent to LLNL's experimental setup of their ultra-wideband radar system.

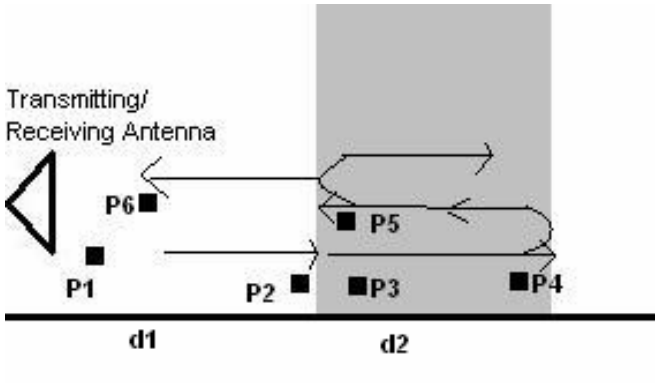

Figure 20: Single Antenna Propagation Model's Significant Points

In order to calculate the frequency response equation of the wall, the same ratio of point 1 and point 6 is used, (eq. 10). Point 1 is the transmitted signal, the second derivative of the Gaussian pulse. Point 2 is after the signal has propagated through region 1, air. Point 3 is the signal after it has transmitted through the boundary change into region 2. Point 4 is the signal after propagating through the wall as well as the reflection off of the back of the wall. Point 5 is the signal after the reflection off of the back of the wall propagation through the wall and reaches the boundary change, and another reflection occurs. Point 6 is the signal that is transmitted through the boundary change propagates back to the receiving antenna. The process for determining this frequency response also involves taking the first reflection off of the wall into consideration. The process is outlined in a flow chart depicted in Figure 21. The frequency response for the single antenna model uses the same theory as the two antenna model. No research was found that outlines the processes to determine a frequency response equation for this model.

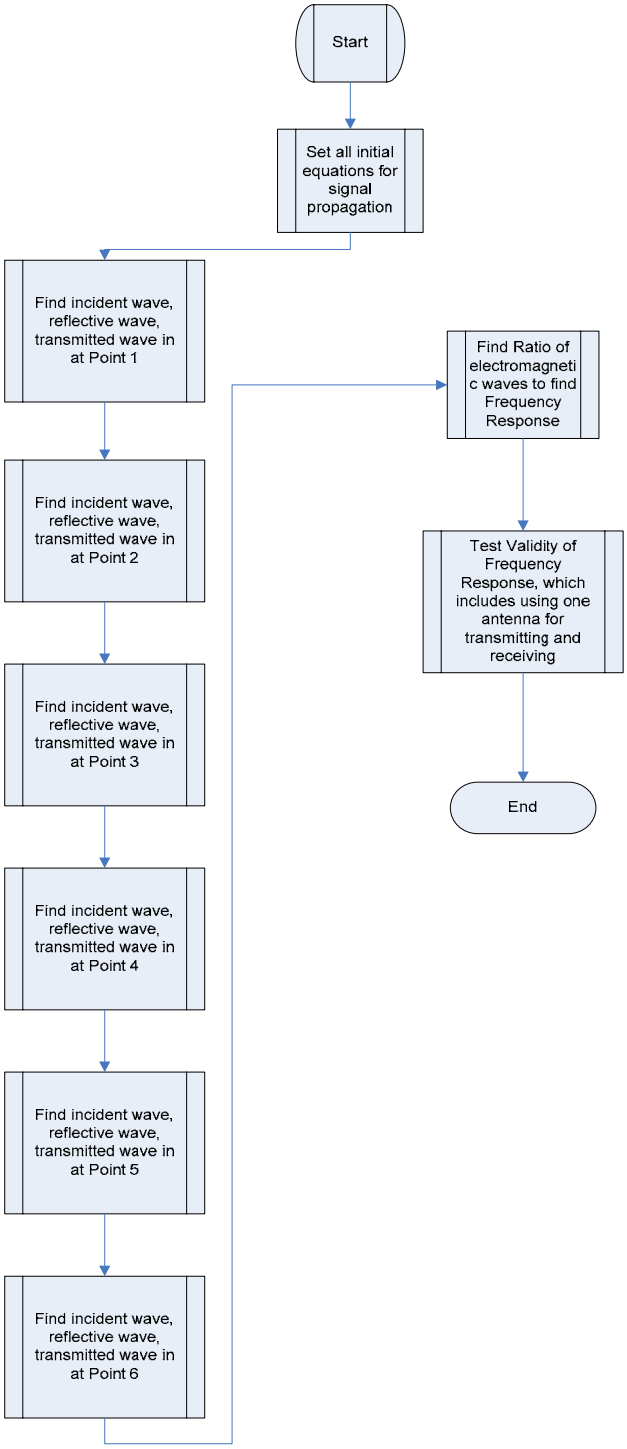

Figure 21: Process for Determining One Antenna Model Frequency Response

The validity and realistic modeling of the calculated one antenna model frequency response equation will be tested as outline in the Test Plan (Appendix D). The general procedure for

testing the wall's frequency response in this model is illustrated in Figure 22. Since no prior research has been found to calculate the frequency response of the wall in the single antenna model, the frequency response equation needs to be validated.

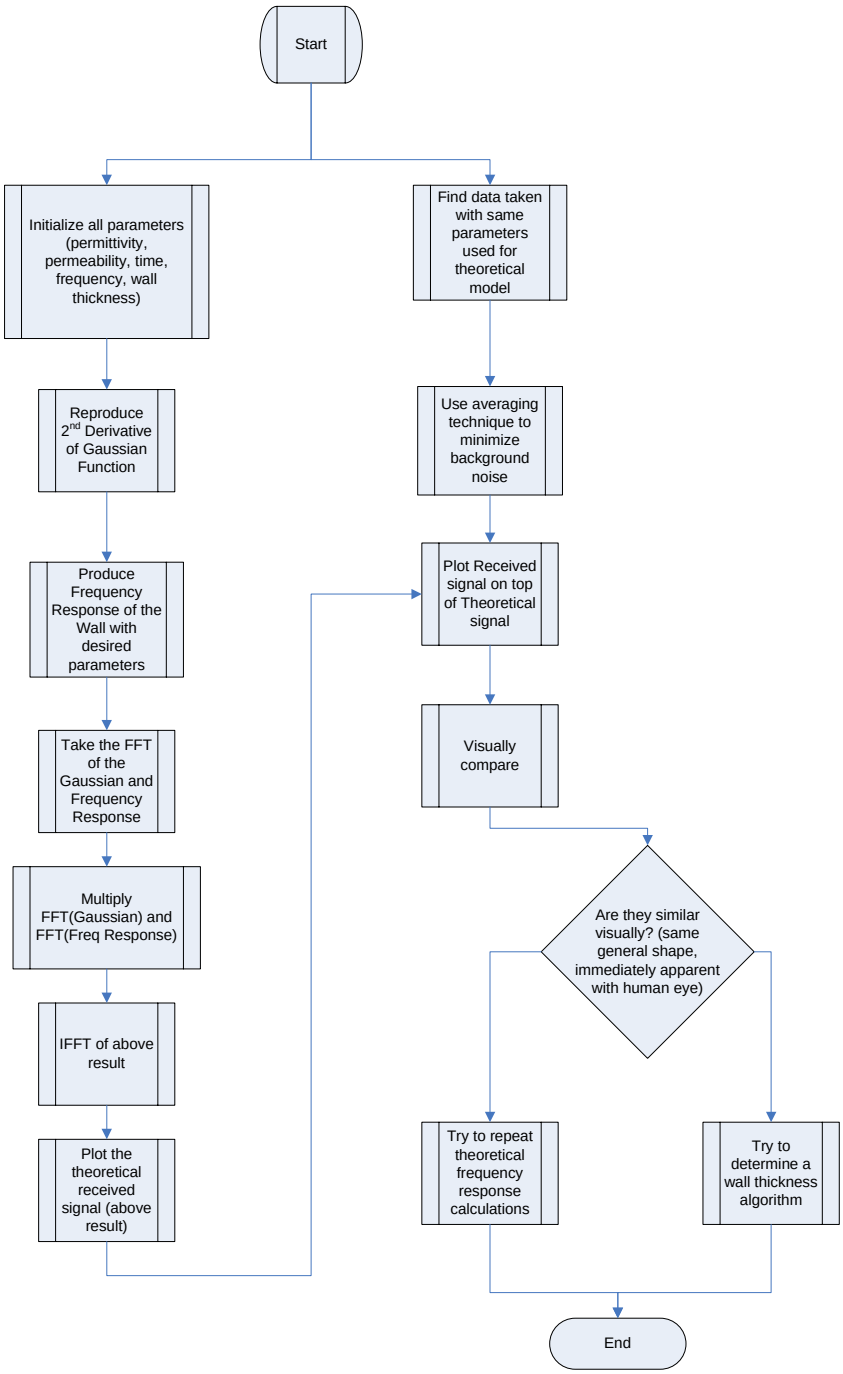

Figure 22: Frequency Response Validity Flow Chart

In order to determine a wall thickness algorithm based upon the frequency response of the wall, the relationship between wall thickness and the time to the first received signal is analyzed. The first received reflection is considered the peak impulse of the received signal, where the magnitude is the greatest. The magnitude will be the greatest on the first impulse reflection since it has attenuated over the least amount of distance. MATLAB was used to plot the received signal using our calculated frequency response of the wall in order to determine this relationship. The frequency response of the through-wall model is shown in (eq. 12) [8].

$$H(jw) = \frac{4e^{j\beta_o d}}{e^{\gamma d}\left(2 + \frac{\eta_1}{\eta_2} + \frac{\eta_2}{\eta_1}\right) + e^{-\gamma d}\left(2 - \frac{\eta_1}{\eta_2} - \frac{\eta_2}{\eta_1}\right)} \qquad \text{(eq. 12)}$$

The process to determine the relationship between wall thickness and time to the peak reflection is portrayed in the flow chart in Figure 23. The process uses the same wall characteristics for all calculations, except thickness. The frequency response equation is calculated using the given wall characteristics. The frequency response is then multiplied by the second derivative of the Gaussian, in the frequency domain. The inverse Fast Fourier Transform (IFFT), MATLAB command, is used in order to transform the received signal to the time domain. The point maximum magnitude of the received signal is recorded. Next, the same series of steps is repeated for a different wall thickness. The recorded values are inputted into linear regression software entitled MINITAB. The relationship is analyzed using MINITAB to determine the best linear fit, assuming the relationship is linear.

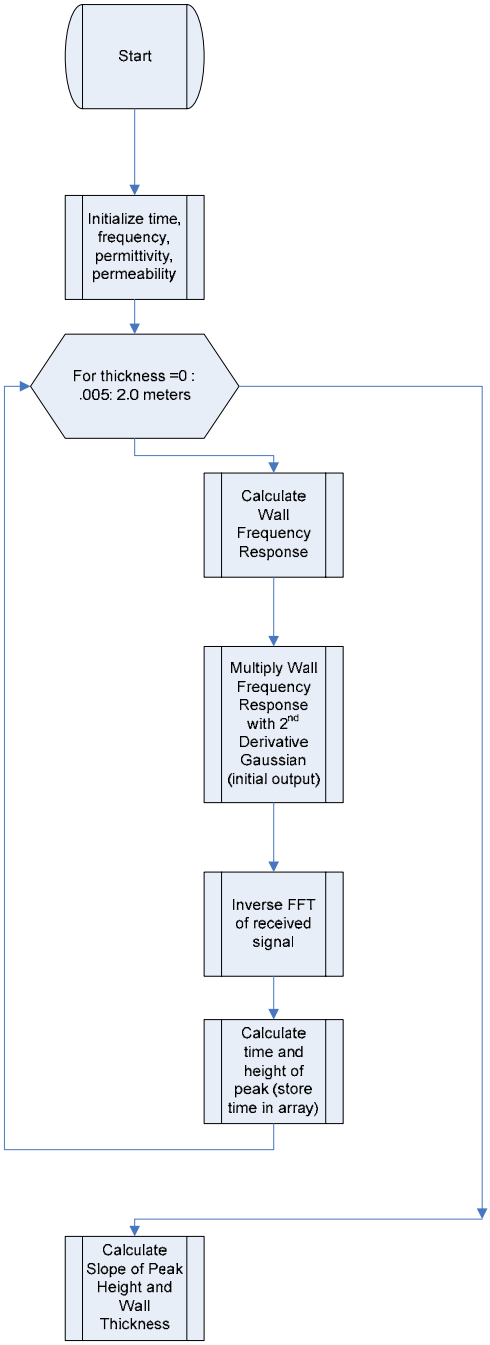

Figure 23: Flow Chart to Determine Relationship between Wall Thickness and Time to First Received Signal

The coefficient of determination is used to evaluate the linear relationship of the wall thickness and peak magnitude of the received UWB radar signal. The coefficient of determination, R^2, is the ratio of regression sum of squares (SSR) over the total sum of squares (SSTO), (eq. 13) [11]. The coefficient of determination is a tool in linear regression to determine if the relationship is a

good linear fit. SSTO measures the variation in the actual observations, Y_i, or the uncertainty in predicting Y, (eq. 15) [11]. Sum of squared errors (SSE) measures the variation in the actual response variable, Yi, when a regression model using the predictor variable (wall thickness), X, is employed, (eq. 14) [11]. SSR is the measure of the effect of X in reducing the uncertainty of predicting Y, (eq. 16).

$$R^2 = \frac{\text{SSR}}{\text{SSTO}} \qquad \text{(eq. 13)}$$

$$\text{SSE} = \sum_i \left(y_i - \hat{y} \right)^2 \qquad \text{(eq. 14)}$$

$$\text{SSTO} = \sum_i \left(y_i - \bar{y} \right)^2 \qquad \text{(eq. 15)}$$

$$\text{SSR} = \text{SSTO} - \text{SSE} \qquad \text{(eq. 16)}$$

The coefficient of determination varies between zero and one. R^2 is interpreted as the proportionate reduction of total variation associated with the use of the predictor variable, X (wall thickness) [11]. However, R^2 is limited in its capabilities of predicting the validity of a linear relationship. Other characteristics of the linear relationship, in addition to the R^2 value, need to be considered in order to effectively evaluate the linear relationship between wall thickness and time to peak magnitude. MINITAB generates information in order to effectively assess the relationship between two variables. In order for a relationship to be linear, the

regression function needs to be linear. Determining the nonlinearity of the regression function is accomplished by studying the residual plot against the fitted values [11]. If the relationship is an appropriately linear, then the residual values will be randomly distributed around zero. If there is any pattern associated with this plot the error variance is nonconstant. In order to have an appropriate linear relationship, the variance of the error terms (residuals) need to be constant [11]. Another characteristic of a linear relationship is the normality of error terms. This can be evaluated by analyzing the linearity the normal probability plot. If the normal probability plot has a linear fit, then the error terms are normal. If any of these characteristics insinuate that the relationship between two variables is not a good linear fit, a transformation can occur. A transformation affects the predictor variable by creating a better linear relationship to the predictor variable. For example, if the regression pattern of the initial relationship is inversely related, then the new predictor variable (X') would be transformed as shown in (eq. 17) [11].

$$X' = \frac{1}{X} \text{ or } X' = e^{-X} \qquad \text{(eq. 17)}$$

The linear relationship between wall thickness and time of peak magnitude will be used to approximate wall thickness in actual data. In order to have a valid linear relationship, the coefficient of determination needs to be at least 90%. The testing process to determine if the wall thickness algorithm is valid is briefly outlined in Figure 24. Further details regarding specific testing of the frequency response equations as well as wall thickness algorithms is outlined in the Test Plan, included in Appendix D.

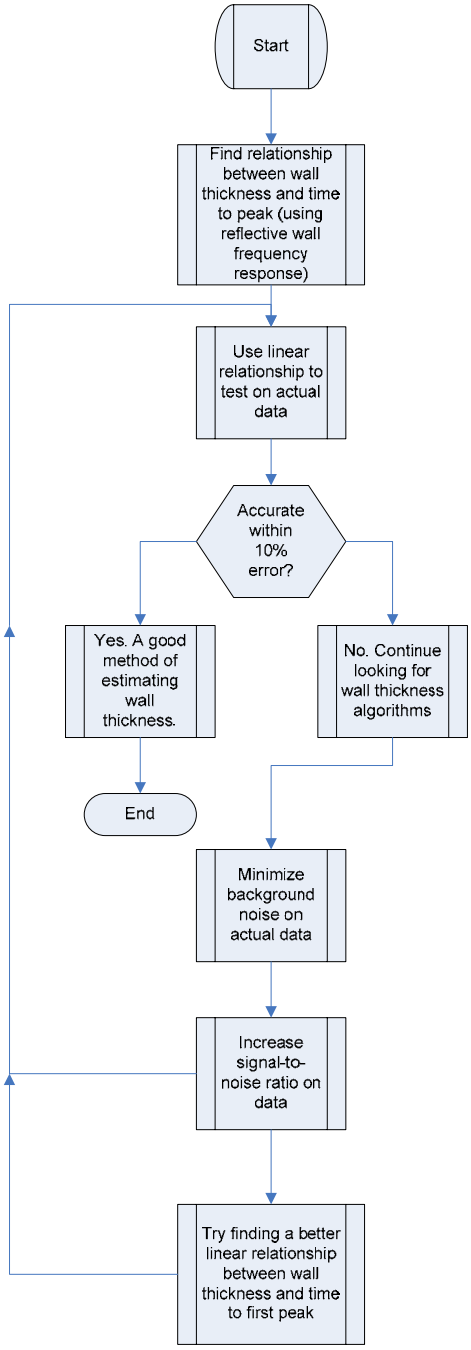

Figure 24: Testing Wall Thickness Algorithm

After completing all requirements, the models and algorithms will be tested by the project's advisors and sponsor. After reporting the results to the sponsor, there are no features in place to require future support according to the Support Plan, included in Appendix D. The Support Plan clearly outlines all logistical features relating to this project. Currently, this project does not

have any life-cycle costs or maintenance considerations. The mathematical algorithms will be able to function in both MATLAB and the chosen modeling software, according to Appendix B: Requirements Specification. The Support Plan also details that the sustainability of the project depends solely on the user having either MATLAB.

Results

The two antenna model, or through-wall, was primarily used as a basis for the single antenna model in order to understand how the ultra-wideband radar behaved without considering wall reflections. The two antenna frequency response equation was calculated using the ratio of the electric field at the receiving antenna over the electric field at the transmitting antenna, (eq. 10). The frequency response equation for the through wall model is shown in (eq. 12). The through-wall model's magnitude and frequency response was plotted to understand the expected affects upon the ultra-wideband radar signal, Figure 25. The magnitude response looks like an isosceles triangle centered at zero. The phase response is approximately linear.

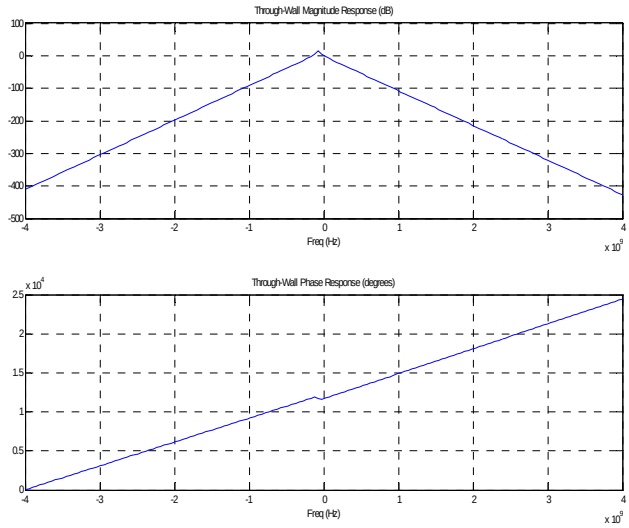

Figure 25: Magnitude and Phase Response of Through-Wall Model

Through experimentation of using the frequency response to create a received signal, using the second derivative of the Gaussian as the inputted signal, it was noticed there was a relationship between the delay of the pulse and wall thickness. As illustrated in Figure 26, the received signals was attenuated, distorted, and delayed based upon the wall thickness. As wall thickness increases, the delay to the received pulse increased. The pulse shape was attenuated and distorted more as wall thickness was increased.

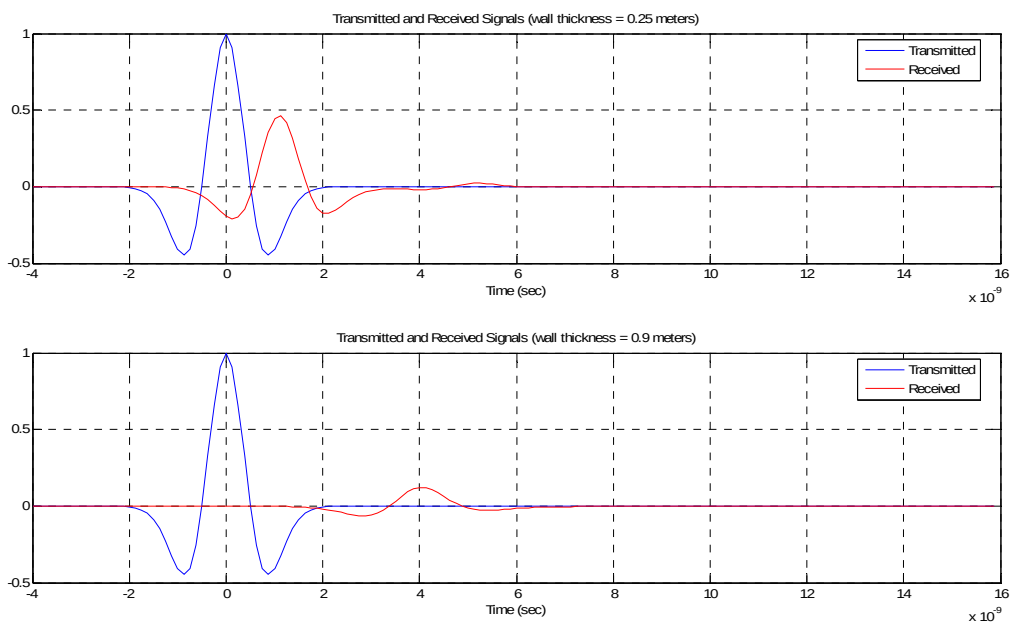

Figure 26: Affect of Wall Thickness on Through-Wall Model

The relationship between wall thickness and time delay to the received pulse was analyzed using MINITAB. The data was simulated using the defined frequency response and transmitted pulse (the second derivative of the Gaussian) and included within Appendix F. The linear regression model determined using MINITAB had a positive slope indicating that as wall thickness increased the time delay also increased, (eq. 18).

$$\text{Peak Time(ns)} = -0.121 + 4.67d \qquad \text{(eq. 18)}$$

The validity of this linear regression model can first be evaluated by analyzing the scatter plot of time to received pulse and wall thickness, Figure 27. The scatter plot shows a perfectly linear relationship indicating a positive slope.

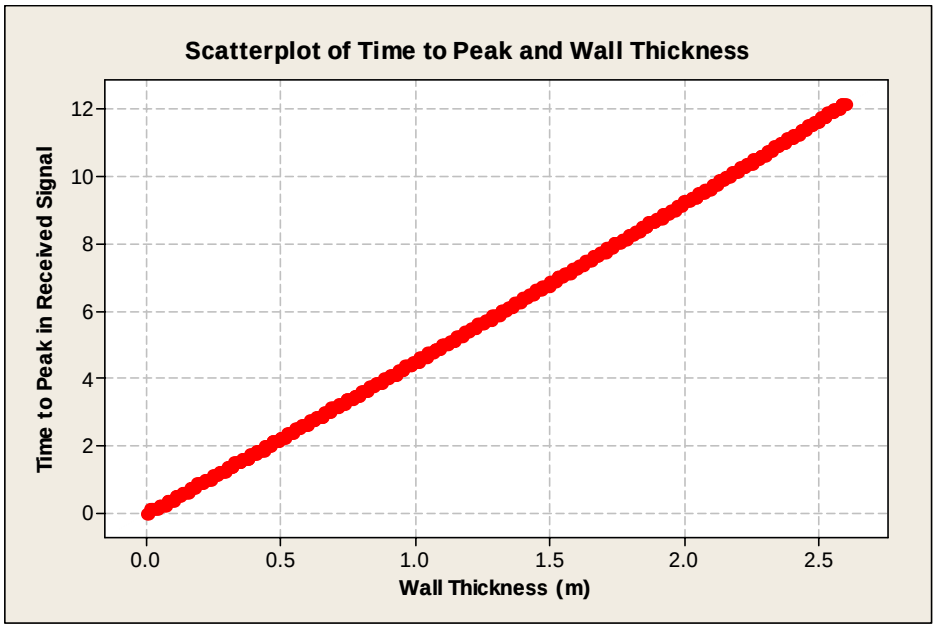

Figure 27: Scatter Plot of Time to Peak and Wall Thickness in Two Antenna Model

The residual plots, shown in Figure 28, were used to evaluate the suitability of the linear regression model to the set of data. In an ideal linear model, the error terms are normally distributed. By evaluating the normal probability plot of the residuals it can be inferred that the error terms in our model are approximately linear, since the points are approximately linear. The linearity of the regression function is evaluated by evaluating the residuals versus fitted values plot. In the ideal model, the points would be randomly distributed and centered at zero. The curve in the residual versus fitted values plot indicates that a curvilinear regression model may be more appropriate to model the data. Furthermore, the error terms are independent in an ideal linear model. The independence of the error terms is indicated in the residual versus order of the data plot. If the data points are randomly distributed and centered on zero, then the error terms

are independent. However, in the given plot, the error terms are not independent, which is indicative that a curvilinear plot may be more suitable.

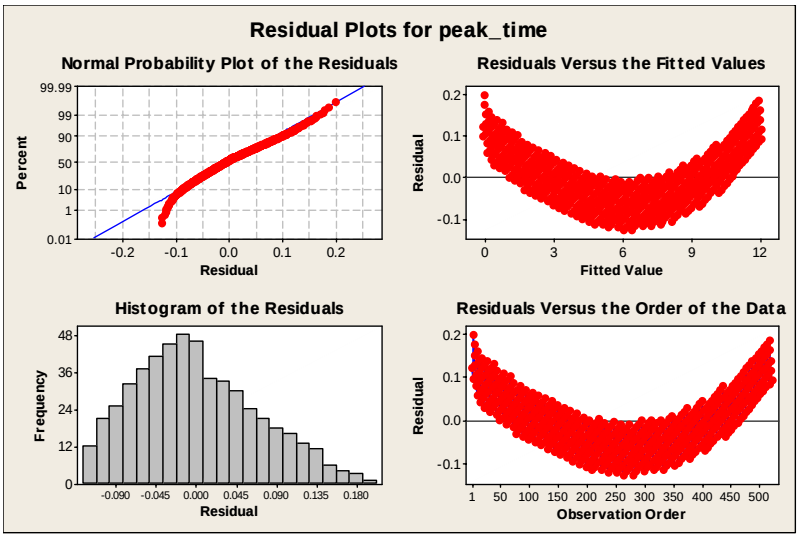

Figure 28: MINITAB Plots for Through-wall Linear Relationship

Since the residuals versus fitted values and residuals versus order of the data plots indicate a curvilinear plot is more appropriate, various curvilinear models were evaluated to see if the residual plots improve. In Figure 29 the curvilinear model used was the square root of the delayed times. As shown, all the residual plots indicate that this model is not an appropriate model for the data. The error terms are not normal or independent and the model is nonlinear.

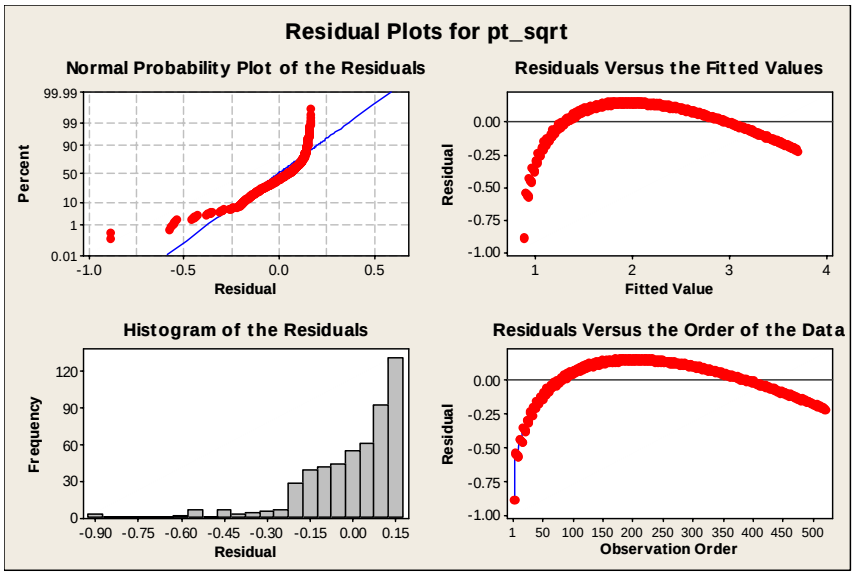

Figure 29: Curvilinear Regression Model Using $Y' = \sqrt{y}$

Another curvilinear model was also used to prove the validity of the initial linear regression model, Figure 30. The curvilinear model residual plots shown are for the inverse of the delay times. Similar to the square root curvilinear model, the error terms are not normally distributed or independent. The model is also nonlinear.

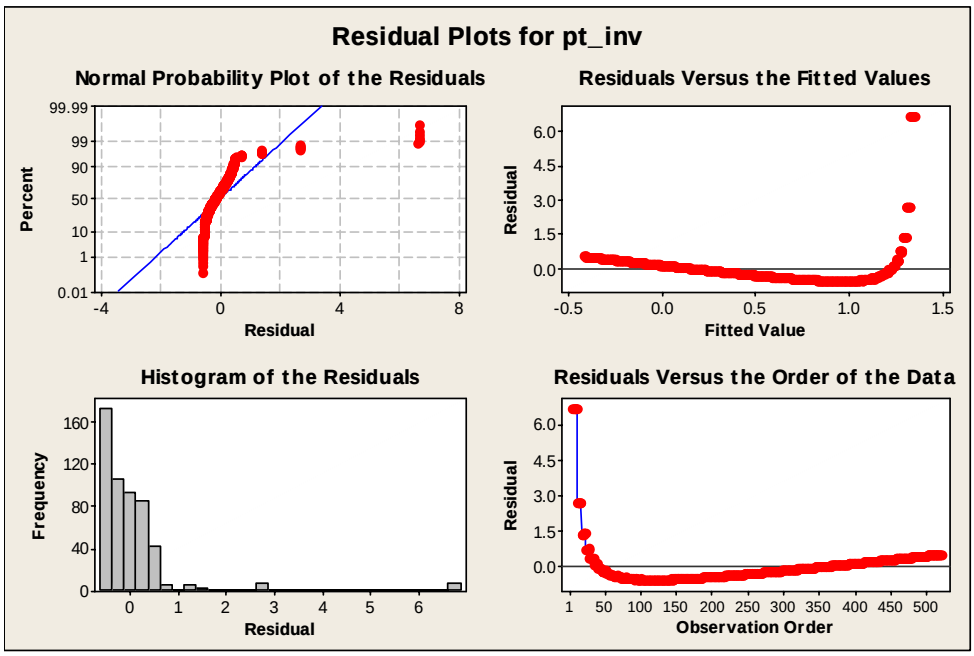

Figure 30: Curvilinear Regression Model Using Y' = 1/y

Since the curvilinear plots are not improving the residual characteristic plots, the first linear model was valid. Furthermore, the coefficient of determination was 1.0, confirming the validity of the linear regression model. This regression model can be used to determine wall thickness by calculating the time to the maximum point of the received pulse and solving for wall thickness. The realistic model, using a single antenna for both transmitting and receiving, used the same principles for defining a frequency response equation as the through-wall model, (eq. 19).

$$H(jw) = \frac{E_r}{E_i} = e^{-2\gamma_1 d_{\text{air}}} \left(\Gamma_{12} + \tau_{12} e^{-2\gamma_2 d_{\text{wall}}} \Gamma_{23} \tau_{21} \right) \qquad \text{(eq. 19)}$$

The magnitude and phase response of the frequency response is shown in Figure 31. Similarly to the through-wall model, the phase response is linear. Also the magnitude has a similar shape, where the largest magnitudes are centered on zero and decrease to approach -9 dB.

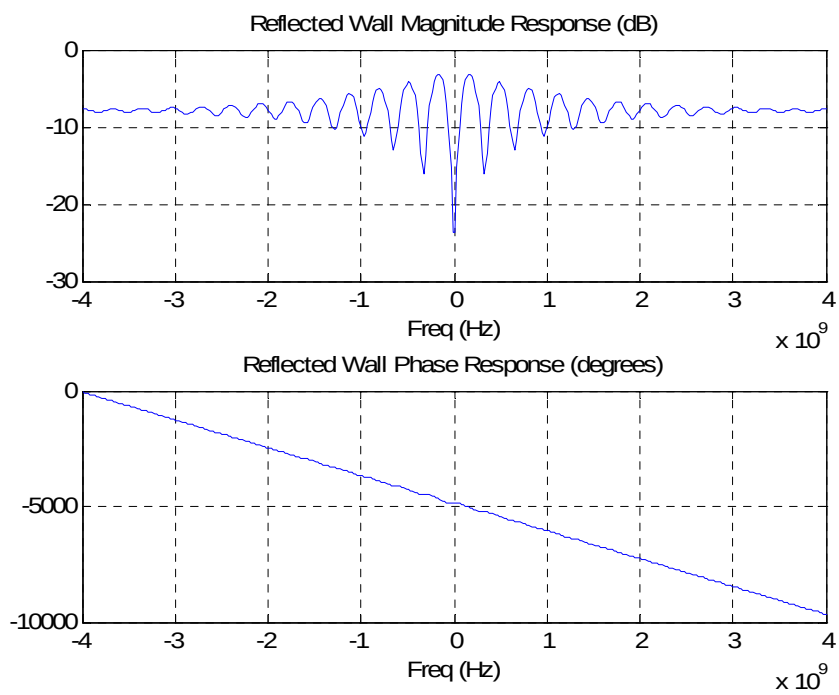

Figure 31: Magnitude and Phase Response of Single Antenna Wall Frequency Response

Distance from the antenna to the wall is d_{air}. The thickness of the wall is d_{wall}. As defined in the background section on signal propagation, (eq. 8) and (eq. 9) define Gamma (Γ) and Tao (τ). Figure 32 shows the various regions the UWB radar signal would propagate through.

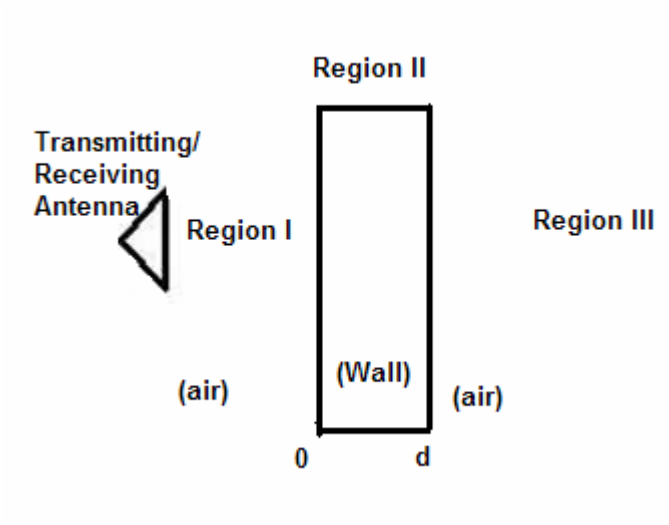

Figure 32: Regions of Propagation for Single Antenna Model

It was detected that the incident pulse off of the front of region II (the wall) will not change in time received, regardless of wall thickness, permeability, or permittivity. The first reflection, therefore, cannot be analyzed to determine a wall thickness algorithm, similarly to the through-wall model. Although, the time to the second reflection which is propagated off of the back of region II (the wall) varies according to wall thickness, Figure 33.

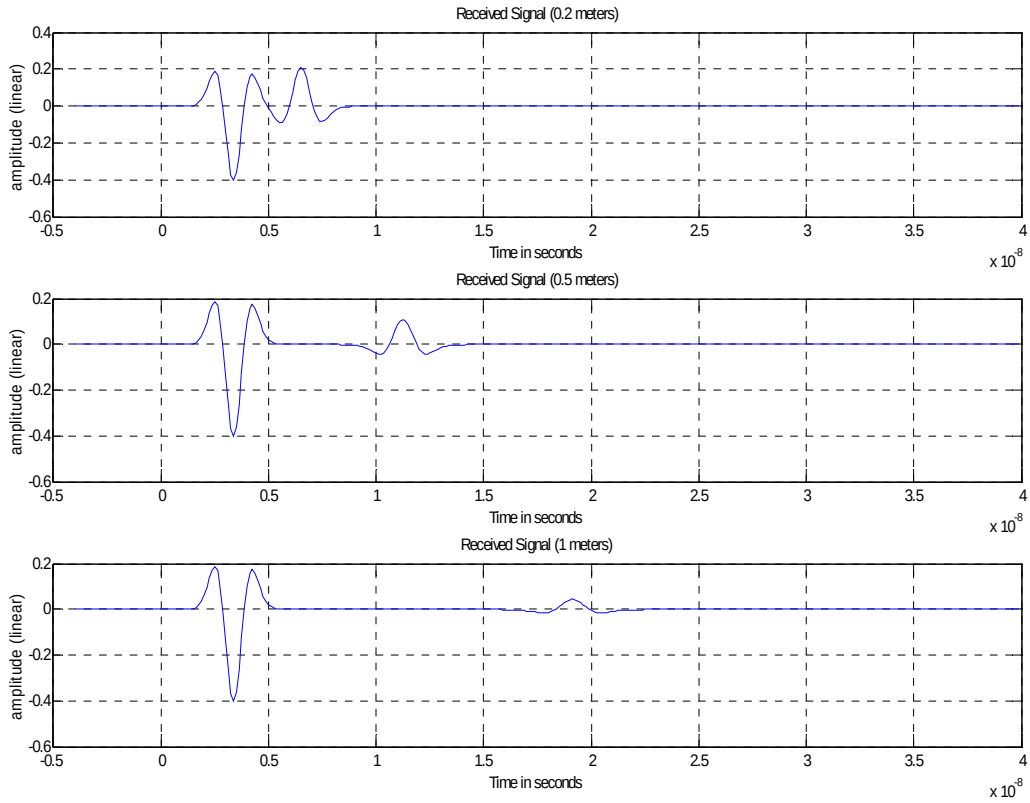

Figure 33: Varied Wall Thickness in Single Antenna Received Signal

Also apparent is that as wall thickness is small, the second reflection is received near the same point in time as the first incident reflection is received. This causes one pulse like shape to be in the received signal that is further distorted due to the combined reflections. In order for a relationship to be examined, there needed to be two distinct reflections. The time between reflections and wall thickness was analyzed in MINITAB. Data collection was completed using MATLAB, files are attached in Appendix F. The relationship of time between reflections and wall thickness was approximately linear as observed in the scatter plot of the data, Figure 34.

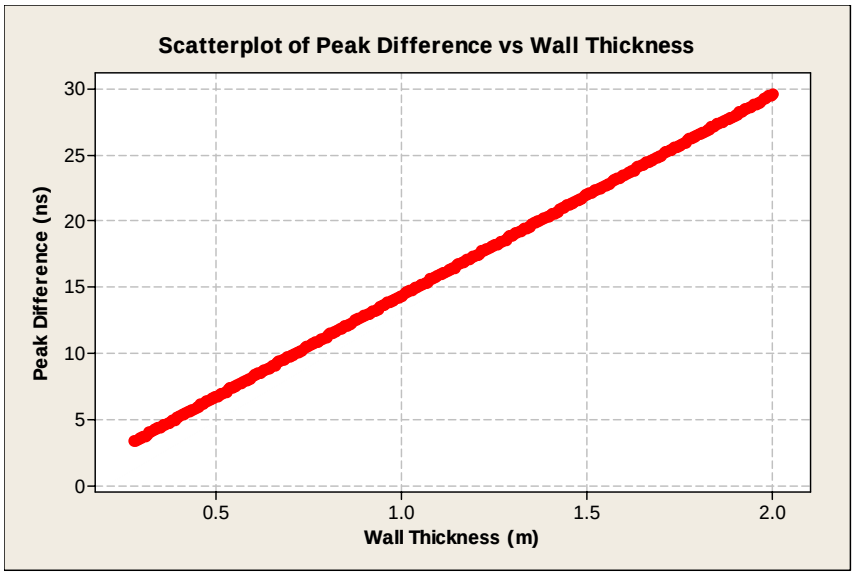

Figure 34: Scatter Plot of Peak Difference and Wall Thickness

The data was analyzed using MINITAB and the linear regression model is shown in (eq. 20).

$$\text{Peak Difference (ns)} = -0.801 + 15.2d \qquad \text{(eq. 20)}$$

The validity of this linear regression model was also evaluated using the residual plot produced by MINITAB, Figure 35. The error terms are approximately normally distributed as shown with the near linear fit in the normal probability plot. The regression model is linear as portrayed in the residuals versus fitted values plot by having the terms approximately equally distributed and centered on zero. The error terms are also independent as illustrated in the residuals versus order of the data plot. The points are approximately randomly and equally distributed around zero.

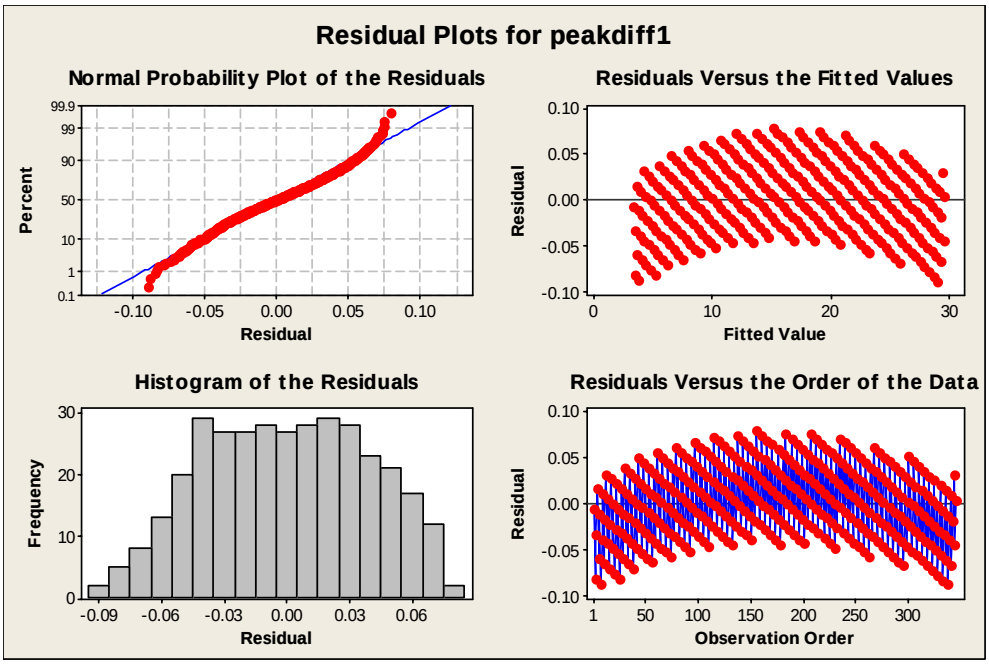

Figure 35: Residual Plots for Single Antenna Algorithm

In addition to the residual plots, the coefficient of determination (found using MINITAB) was 1.0. This also confirms the validity of the linear regression model.

Two wall thickness algorithms have been defined that are independent of wall permeability and permittivity. The through-wall algorithm can be used to find wall thickness by measuring the time to maximum point in the received signal, and then solving for wall thickness. The single antenna algorithm can be used to approximate wall thickness by determining the difference in time between the reflected pulses and solving for the predictor variable, wall thickness. The percent error and efficiency of these wall thickness algorithms cannot be evaluated until tested on ultra-wideband radar received signals in a controlled environment. MIR will be testing the effectiveness of the algorithms on data.

Conclusions

The Micro-Power Impulse Radar Group (MIR) at Lawrence Livermore National Laboratories was tasked by DARPA, in May 2006, to use ultra-wideband radar to a create blue-print image of

a building by flying over or driving around the specific building. Ultra-wideband radar signals have a large bandwidth with a spread energy level across the bandwidth. Ultra-wideband radar has very short pulses in combination with the large bandwidth provide a high information rate, and anti-interference capabilities. The pulse shape of the UWB radar signal reflects whenever there is a change in permeability and permittivity in its traveling space, second derivative of the Gaussian pulse. The received signal is the sum of all reflected signals. In order to gain a deeper understanding of how the signal reflects and propagates through various materials, a GUI modeling software will be used to create simple models to simulate a signal propagating through a wall.

After a basic understanding is attained, there were two desired models, which provided the necessary information in order to find wall thickness. The first model used different antennas for transmitting and receiving information, while the second model used the same antenna. In the second model, a solid metal plate is necessary so the entire transmitted signal is reflected and received with minimum loss. There is no loss when a UWB radar signal reflects off of metal. The modeling of the received signals will result in the formulation for mathematical algorithms to determine wall thickness. The received signal, calculated through the use of the frequency response equation of the wall, was analyzed to determine if a relationship existed between wall thickness and time to peak delay. In the through-wall propagation model, the delay time to the received pulse was directly correlated with the wall thickness. This relationship was analyzed using MINITAB to determine a linear regression model. This model is the first wall thickness algorithm. The second wall thickness algorithm was created from the difference between peak time delays and wall thickness in the single antenna model. The relationship between wall thickness and time between reflections was also linear and directly correlated. The linear

regression model for this relationship was also created using MINITAB. However, the second wall thickness algorithm is only valid when there are two distinct wall reflections. In order to determine wall thickness from having the received UWB radar signal, calculate the time between reflections and solve for wall thickness using the linear regression model.

By May 2007, this Capstone project has successfully modeled ultra-wideband radar signal propagation using Wireless InSite and created two wall thickness algorithms based upon derived frequency response equations modeling the single antenna and dual antenna models. Wall thickness algorithms were derived using relationships between reflections and wall thickness in the received signal. These methods for determining wall thickness will be tested using actual data by MIR. The goal for this project is to assist Lawrence Livermore National Laboratories to create an accurate depiction of the blue-print image by being able to calculate wall thickness and have a strong understanding of ultra-wideband radar and how its signals propagate through walls.

Appendices

Appendix A: Project Plan

Appendix B: Requirements Specification

Appendix C: Support Plan

Appendix D: Test Plan

Appendix E: Design Specifications

Appendix F: MATLAB Code

- Appendix F1: Transmitted Pulse
- Appendix F2: Determining Wall Thickness/Time to Peak Relationship
- Appendix F3: Determining Time Between Reflections

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Appendix A: Project Plan

28 January 2007

Purpose:

The Micro-power impulse radar group (MIR) at Lawrence Livermore National Laboratories is sponsored by DARPA to use ultra-wideband radar to map blue-prints of a building. Ultra-wideband radar signals have a bandwidth of 500 MHz to 1 GHz and have the properties that allow it to penetrate everything but solid sheets of metal and water. The purpose of my project is to increase the precision of this system by finding an accurate method to determine the wall thicknesses being penetrated.

Organization:

Project Sponsor: Dr. Farid Dowla, Lawrence Livermore National Laboratories
Project Advisor: CAPT Hartnett, CAPT Case, Dr. Gross, and LT Teixeira
Team Member: 1/c Kirsten Ambors

Goal:

By May 2007, I plan to present to my sponsor at Lawrence Livermore National Laboratories a myriad of methods to find the thickness of a wall penetrated with ultra-wideband signals. Furthermore, I will be able to describe the frequency responses of the wall based on wall thickness and building material.

Technical Challenges:

Challenge 1: To effectively model ultra-wideband signal propagation through walls.
Challenge 2: To find mathematical algorithms to determine the wall thickness.

Action Items/Responsibilities:

Below outlines the action items for me to complete in order to solve the wall thickness problem. Along the way, assistance from my project advisor and my project sponsor will be actively sought.

1. Research modeling software for signal propagation simulation.
2. Create a mathematical model to simulate propagation of ultra-wideband radar signal.
3. Learn how to use modeling software.
4. Create simplistic models using software to simulate signal propagation through walls.
5. Make simplistic models more complicated and continue to simulate receiving signal.
6. Brainstorm methods for finding wall thickness through signal processing.
7. Create mathematical algorithms for finding wall thickness.
8. Test algorithms on simulated data.
9. Test algorithms on actual data.
10. Compare results from tests and determine optimal algorithm.
11. Present results and findings to advisor and sponsor.

Below are the required class submissions, in order.

1. Updated Project Plan
2. Preliminary Design Report
3. Project Poster
4. Project Website
5. Test Plan
6. Design Specification
7. Final Design Report
8. Project Notebook
9. Project Binder

Timeline:

Below outlines my goal of progress on action items.

1. Research modeling software for signal propagation simulation. JAN2007
2. Create a mathematical model to simulate propagation of ultra-wideband radar signal. FEB2007
3. Learn how to use modeling software. FEB2007
    a. Determine whether or not to purchase software. FEB2007
4. Create simplistic models using software to simulate signal propagation through walls. FEB2007
5. Make simplistic models more complicated and continue to simulate receiving signal. FEB2007-MAR2007
6. Brainstorm methods for finding wall thickness through signal processing. FEB2007
7. Create mathematical algorithms for finding wall thickness. FEB2007-MAR2007
8. Test algorithms on simulated data. MAR2007
9. Test algorithms on actual data. MAR2007
10. Compare results from tests and determine optimal algorithm. APR2007
11. Present results and findings to advisor and sponsor. APR2007-MAY2007

Below outlines the exact dates that required class submissions are due.

1. Updated Project Plan, 29JAN2007
2. Preliminary Design Report, 29JAN2007
3. Project Poster, 22FEB2007
4. Project Website, 05MAR2007
5. Test Plan, 05MAR2007
6. Design Specification, 26MAR2007
7. Final Design Report, 02MAY2007
8. Project Notebook, 02MAY2007
9. Project Binder, 02MAY2007

Appendix B: Requirements Specification

15 December 2006

Background:

The Micro-power impulse radar group (MIR) at Lawrence Livermore National Laboratories is sponsored by DARPA to use ultra-wideband radar to map blue-prints of a building. Ultra-wideband is a classification of bandwidth that has low energy dispersed over a large number of frequencies. Ultra-wideband radar signals have a bandwidth of 500 MHz to several gigahertz and have the properties that allow it to penetrate everything but solid sheets of metal and water. The purpose of my project is to help to increase the precision of this system by finding an accurate method to determine the thickness of the walls being penetrated.

Problem Statement:

By May 2007, I plan to present to my sponsor at Lawrence Livermore National Laboratories (LLNL) a myriad of methods to find the thickness of a wall penetrated with ultra-wideband signals. Furthermore, I will be able to describe the frequency responses of the wall based on wall thickness and building material. This is a part of a larger project with LLNL in sponsored by DARPA to use ultra-wideband radar to determine a "blue-print" image of a building.

Requirements:

Level	Sponsor Need	Engineering Requirement	Justification
1	**Background Knowledge**		
1A	A detailed description of the ultra-wideband radar signal as they propagate through free space and common building materials such as brick, concrete, dry wall, and wood through the creation of a MATLAB and theoretical model.	I. Plot of pulse shape in the time domain II. Plot of pulse in the frequency domain III. Develop a mathematical model that describes how the ultra-wideband signal is transmitted and received and how it is affected by attenuating through free space and other materials, model needs implemented theoretically and practically using MATLAB and chosen modeling software.	This requirement was developed to provide background information on the theoretical signal processing concept regarding pulse shape and the movement of signals in free space and other materials.
1B	Selecting modeling software with the capabilities of modeling at signal propagation through various materials. Knowledge of the capabilities of the software	I. Must have a GUI interface. II. Must be able to model narrowband signals. III. Must be user-friendly,	User-friendly modeling software is a necessity in order to be able

	and how to create simple models using it.	determined if the project advisors can determine how to create a simple model within a week. IV. Must have the capabilities to model signal propagation through a variety of common building materials.	to create both simple and complex models to test the validity of wall thickness algorithms.
2	**Wall Thickness Algorithms**		
2A	A detailed description to discern what characteristics of the model can be used to determine the thickness of a wall.	I. Use created theoretical model to create mathematical equations describing the movement of the signals. II. Based on these mathematical equations, create a theory regarding an equation to find the thickness of the wall based on the designed theoretical model. III. Implement wall thickness estimation equations into a model created by the chosen modeling software.	In order to start finding possible algorithms, find the thickness of a wall through examining theoretical mathematics of signal attenuation.
2B	Develop algorithms using linear regression techniques to find the thickness of the wall.	I. Determine the relationship between wall thickness and time to the highest peak in the received signal. II. Create mathematical algorithms based upon the relationship between wall thickness and time to the received signal's peak.	Another way to develop algorithms for wall thickness is by using the basic concept of signal processing.
3	**Testing**		
3A	Determine which designed algorithms are the most effective and reliable for wall thickness determination.	I. Test designed algorithms using given data to determine the percent error of wall thickness detection as well as time to completion and reliability.	This requirement tests the validity of the algorithms to determine the optimal algorithm for this specific problem.

		II. Effective algorithms are those with less than or equal to 10% error in wall thickness detection III. Effective algorithms calculate the thickness of the wall within 5 minutes 95% of the time. IV. Completion by end 30 March 2007 and deliver results to Dr. Farid Dowla and co-workers on project.	

Appendix C: Support Plan

15 December 2006

Purpose:

The Micro-power impulse radar group (MIR) at Lawrence Livermore National Laboratories is sponsored by DARPA to use ultra-wideband radar to map blue-prints of a building. Ultra-wideband radar signals have a bandwidth of 500 MHz to several gigahertz and have the properties that allow it to penetrate everything but solid sheets of metal and water. The purpose of my project is to help to increase the precision of this system by finding an accurate method to determine the thickness of the walls being penetrated.

Design Solution:

The solution involves the creation of a model using modeling software to simulate the through-wall propagation of narrowband and ultra-wideband signals through walls. The project also involves the creation of several algorithms to determine wall thickness. Manufacturability criteria factored the most into the decision for deciding on which modeling software to use, considering user-friendly capabilities as well as ability to simulate propagation through various building materials.

Support Considerations:

Economic:

1. The project's funding source is LLNL MIR group, which is sponsored by DARPA.
    a. Specific funding for this Capstone project will be from the USCGA Electrical Engineering Department. No costs are predicted.
2. The whole DARPA project has a multi-million dollar budget.
3. There is no timeline for when the money must be spent.
4. There is no competition for the project's funding.

Manufacturability:

1. The design will be modeled using Microsoft Visio.
    a. The actual model will be using modeling software such as MATLAB.
2. There will be at least one system built. The first system built will be to model through-wall propagation for narrow band signals. The second system built will be to model through-wall propagation for ultra-wideband signals.
3. Special considerations are having an easy to use GUI model for the user to model signal propagation through walls using various building materials. The model should include the different permittivities and permeabilities of various building materials.

Sustainability and Reliability:

1. The sponsor does not have a sustainability or reliability specifically for the algorithms or the model.
    a. The sponsor simply requires a model that works showing how signals propagate through various materials.
2. The chosen modeling software will be required.
3. The extra copies of the modeling software will have to be purchased legally according to licensing rules for that particular manufacturer.

Life-Cycle Costs:

1. As long as the computer using the modeling software can properly execute the model, the model will continue working. There is no specific life cycle for this design.
2. Additional Life-Cycle Costs are denoted below.
    a. Maintenance: none needed
    b. Support: Provided by the software manufacturer if there are errors in the modeling software.
    c. Training: Provided by project leader.
    d. Spare Parts: none required.
    e. Upgrades: Optional, not required. If desired, cost will lie upon the use of the model.
    f. Disposal: No disposal costs exist for using modeling software.

External Considerations:

Environmental:

1. This project has no impact upon the environment since it is only using software to implement algorithms and to create functional models.
2. In order to dispose of the project, the user can simply delete the desired files or uninstall the used programs, causing no environmental damage.
3. Federal and State environmental regulations do not apply to this project.

Health and Safety:

1. There is no impact on the user's health and safety unless the user sits too close to the computer screen causing eye strain. Any possible health or safety side affects are not due to the nature of this project but rather ergonomics of the workplace causing excess strain while completing computer work.
2. This project does not affect the public's health and safety.
3. Federal and state legislation does not directly apply to this project.
4. No additional training is required in order to understand the safety concerns of this project. Additional ergonomics training must be provided by the company using this project due to requirements to take of personnel excessively using computers.

Ethical, Social & Political:

There are no specific ethnical, social, or political considerations went into the design solution.

Software Considerations:

Privacy:

1. No user data will be collected.

Security

1. The algorithms for finding wall thickness will store the experimental ultra-wideband signals as well as the frequency response of the wall and the estimated wall thickness. The model of signal propagation through walls will store what the expected received signal should look like.
2. As of this point, the senior design project aspects are not classified. Upon further examination, DARPA or LLNL may decided to make this project have an “L” or “Q” classification (using DOE Classification System: L = Secret, Q = Top Secret).
3. As of this point, the data does not need protection. Upon receiving a classification, the project will only be used and viewed on classified computers protecting the information from tampering.

Appendix E: Design Specification

Purpose: The Micro-power impulse radar group (MIR) at Lawrence Livermore National Laboratories is tasked by DARPA to use ultra-wideband radar to map blue-prints of a building. Ultra-wideband radar signals have a bandwidth of 500 MHz to 1 GHz and have properties that allow it to penetrate everything but solid sheets of metal and water. The purpose of my project is to help to increase the precision of this system by finding an accurate method to determine the penetrated wall thicknesses.

Design Solution:

Signal Propagation through Walls

Signal propagation through various materials is explained with how the signal behaves when it reaches a region of different characteristics and how it changes throughout the current region of propagation. Figure 36 clarifies how a signal reacts when it reaches a material of different characteristics. The incident signal (E_i) causes a transmitted signal that propagated through the material (E_t) and a reflected signal (E_r) that travels in the opposing direction as E_i.

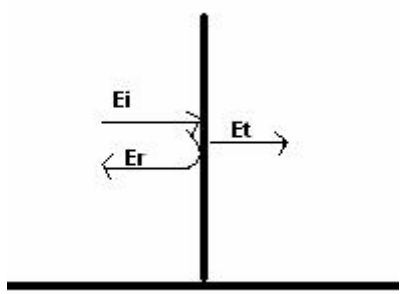

Figure 36: Definition of E_i, E_r, and E_t

Equations 1.1, 1.2, 1.3, and 1.4 define the received and transmitted signals in terms of the incident signal (Ei), τ, and Γ. Gamma (Γ) and τ is defined in using the intrinsic impedance of the different regions, η.

$$E_r = \Gamma E_i \tag{0.1}$$

$$E_t = \tau E_i \tag{0.2}$$

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2} \tag{0.3}$$

$$\tau = \frac{2\eta_2}{\eta_1 + \eta_2} \tag{0.4}$$

Figure 37 describes how the signal is altered by the current region when propagating over a specified distance, x.

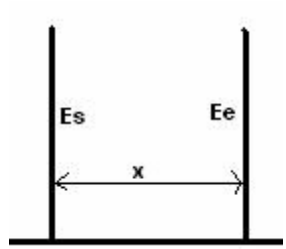

Figure 37: Signal Propagation through Same Region

Equation 1.5 states how a signal changes as it propagates through a region of a specified distance and characteristics. E_s is the starting signal and E_e is the signal at the end of the region. The attenuation constant, α, and the phase constant, β, are combined to define γ.

$$E_e = E_s e^{-\gamma x} \tag{0.5}$$

$$\gamma = \alpha + j\beta \tag{0.6}$$

Using these mathematical equations, the frequency response of the wall can be calculated as described in the next section.

Ultra-Wideband Radar through-wall Frequency Response

Figure 38 shows the basic through-the-wall propagation model. There is a transmitting antenna that will be transmitting the second derivative of the Gaussian ("Mexican Hat Pulse") and the receiving antenna will receive the impulse after it propagates through all the regions. The various points will describe the signal at that point in the propagation model. The various distances of each region are described by d1, d2, and d3.

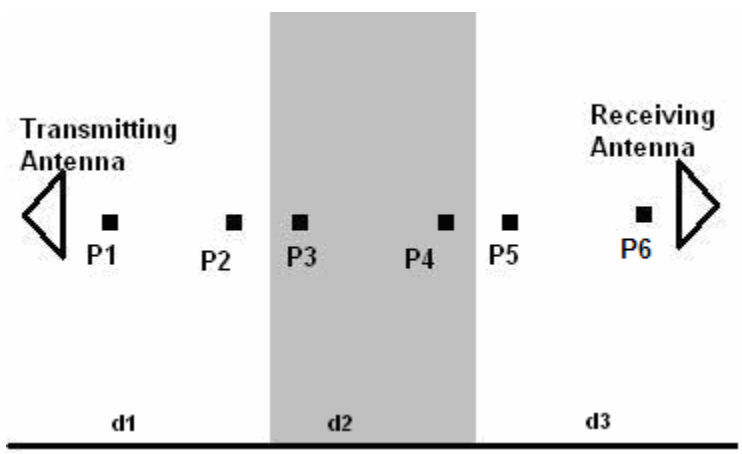

Figure 38: UWB through-the-wall Propagation Model

Equation 1.6 describes how to find the frequency response of this through-wall propagation model, being a ratio of the received signal and the original transmitted signal.

$$H(j\omega) = \frac{E_{P6}}{E_{P1}} \tag{0.7}$$

Equation 1.7 describes the transmitted pulse, which is the second derivative of the Gaussian pulse.

$$p(t) = \left[1 - 4\pi\left(\frac{t - .75ns}{1.762ns}\right)^2\right] e^{\left(-2\pi\left(\frac{t-.75ns}{1.762ns}\right)^2\right)} \tag{0.8}$$

In order to calculate the through-wall frequency response, several preliminary calculations are necessary and outlined in the flow chart below, Figure 39.

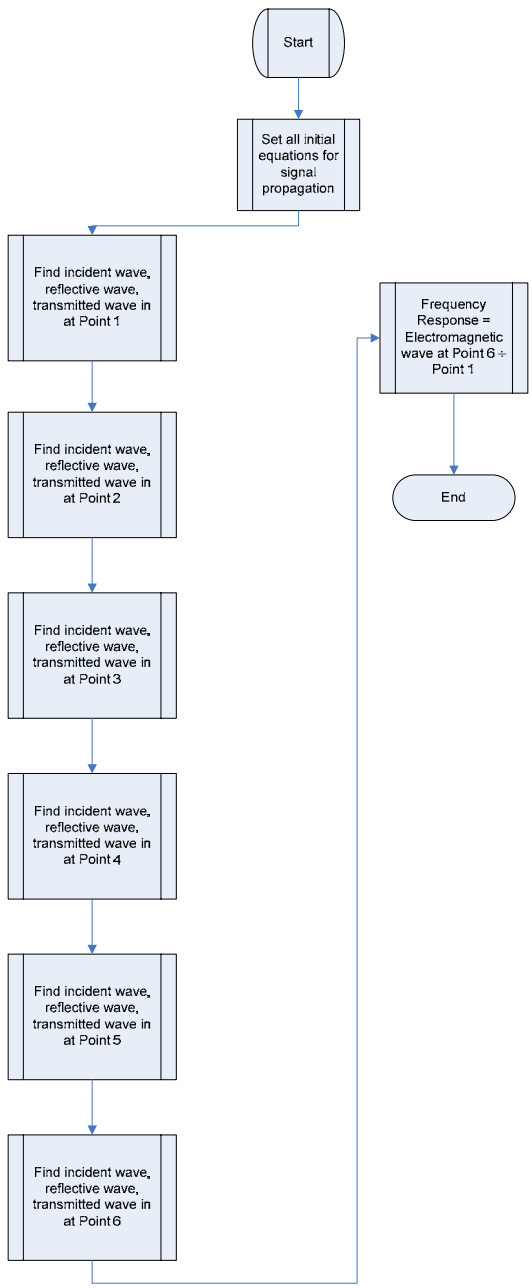

Figure 39: Wall Frequency Response for Through-Wall Propagation

The frequency response describes how the ultra-wideband radar signal propagates through the wall is helpful in understanding how the signal behaves when it reaches a region of different characteristics. Equation 1.8 is the through-the-wall frequency response equation describing how the wall affects the ultra-wideband signal. This frequency response equation is dependent on the wall thickness, d, as well the wall impedances η_1, η_2, and the complex constant, γ. Equations 1.9, 1.10, and 1.11 identify η_1, η_2, and γ. The wall characteristics of permittivity and permeability are represented by ε and μ.

$$H(jw) = \frac{4e^{j\beta_o d}}{e^{\gamma d}\left(2 + \frac{\eta_1}{\eta_2} + \frac{\eta_2}{\eta_1}\right) + e^{-\gamma d}\left(2 - \frac{\eta_1}{\eta_2} - \frac{\eta_2}{\eta_1}\right)} \tag{0.9}$$

$$\gamma = jw\sqrt{\mu_o \varepsilon_o \left(\varepsilon_r^{'} - j\varepsilon_r^{''}\right)} \tag{0.10}$$

$$\eta_1 = \sqrt{\frac{\mu_1}{\varepsilon_1}} \tag{0.11}$$

$$\eta_2 = \sqrt{\frac{\mu}{\varepsilon_o \left(\varepsilon_r^{'} - j\varepsilon_r^{''}\right)}} \cong \frac{\eta_1}{\sqrt{\varepsilon_r^{'}}} \tag{0.12}$$

However, the more realistic model (similar to the LLNL setup) involves using one antenna for transmitting and receiving the signals. The next section describes how to calculate the more realistic frequency response, including reflections.

Ultra-Wideband Radar Wall Frequency Response with Reflections

The more realistic model of analyzing the wall's frequency response is shown in Figure 40. There is one antenna used for both transmitting the Gaussian pulse and for receiving the propagated signal. The distances of each region are annotated by d1 and d2. Each point represents a different point in the propagation. Point 1 is when the signal is first transmitted. Point 2 is after the signal reaches the end of region 1. Point 3 is after the signal propagated through the region change into the wall. Point 4 describes when the signal reaches the end of the wall and reflects at the end of the wall. Point 5 is after the end of wall reflection reaches the first wall edge and part reflects back and part transmits into region 1. Point 6 illustrates the received signal.

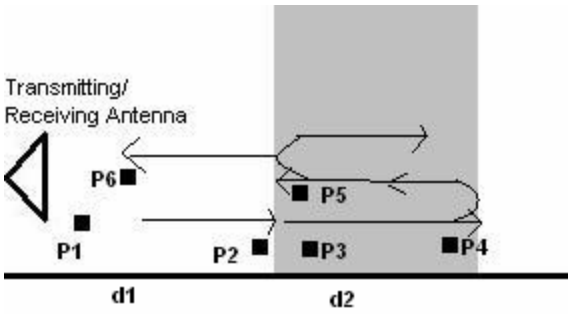

Figure 40: Single Antenna with Reflections Model

In order to calculate this frequency response including wall reflections, the flow chart depicted in Figure 41 describes the basic steps in calculation.

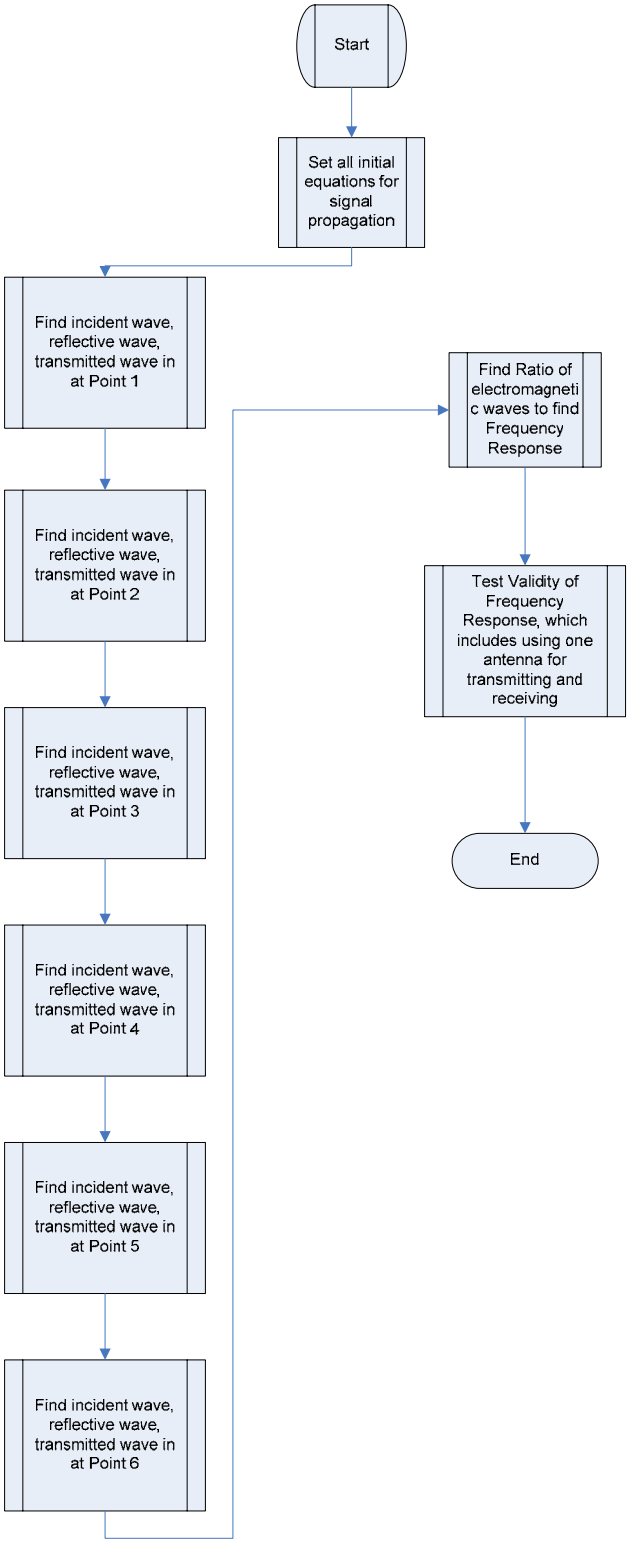

Figure 41: Wall Frequency Response for One Antenna

In order to understand how wall thickness affects the total received signal, the relationship between wall thickness and time to the maximum peak needs to be analyzed. Through

preliminary examination, it has been shown that the thicker the wall, the longer the maximum peak time. If this relationship is linear, then a wall thickness algorithm could be created in order to approximate wall thickness if the received signal is known.

Relationship between Wall Thickness and Time to Peak in Received Signal

Figure 42 describes the basic steps necessary in order to analyze the relationship between wall thickness and time to peak in the received signal. This flow chart calculates the slope of time to peak signal versus wall thickness, assuming a linear relationship. Preliminary modeling illustrates the relationship between wall thickness and time to peak in the received signal is a linear fit.

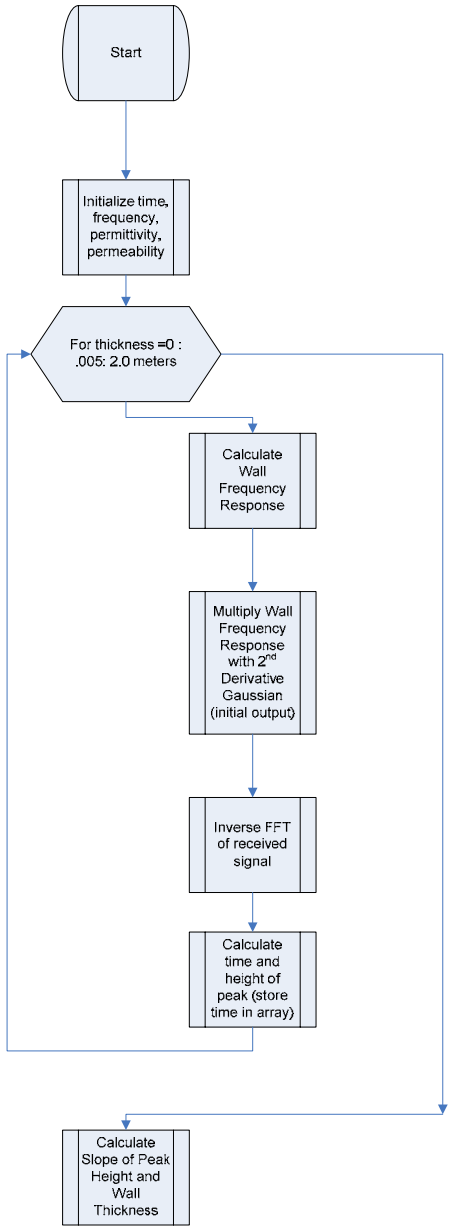

Figure 42: Relationship between Time to Peak and Wall Thickness

However, if wall characteristics affect the time to peak in received signal, then the wall characteristics may be a determining factor to estimating wall thickness.

Relationship between Wall Permittivity and Time to Peak in Received Signal

In order to understand how wall permittivity affects the slope of time to peak versus wall thickness, the following flow chart displays how to determine this relationship, estimated to be linear in Figure 43.

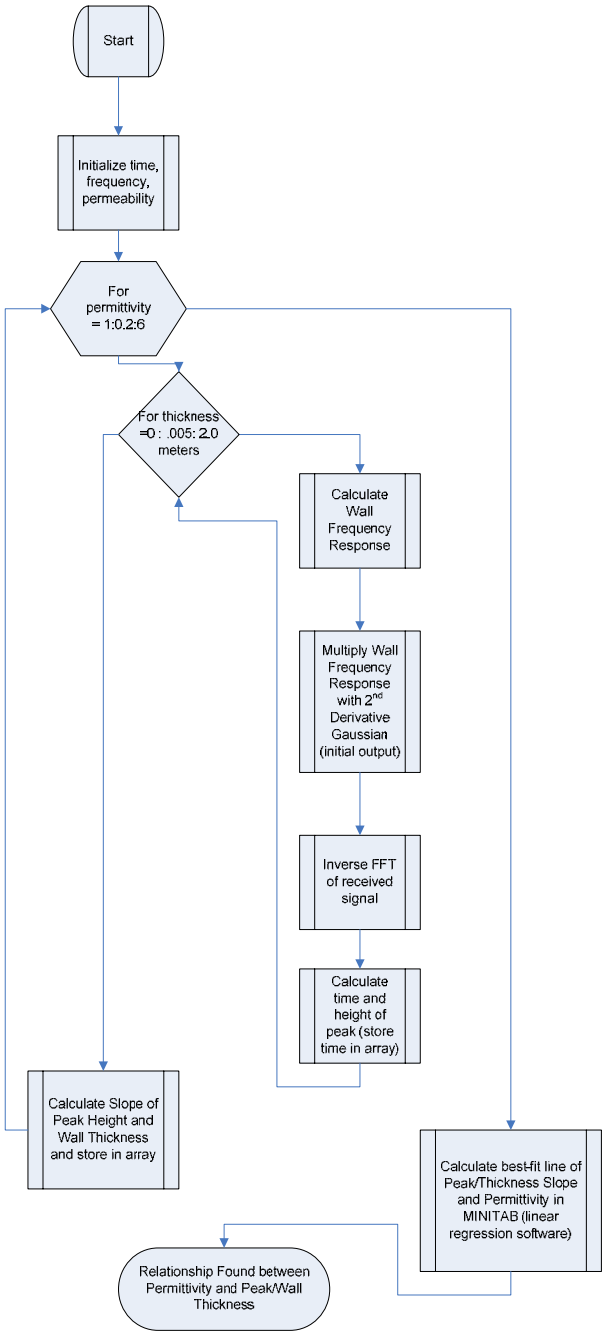

Figure 43: Relationship between Permittivity and Time to Peak/Wall Thickness

However, the validity of the calculated frequency response of the wall needs to be evaluated. In the next section, the validity of the wall's frequency response is evaluated.

Validity of Theoretical Wall Frequency Response with Reflections

Testing is necessary in order to determine if the calculated wall's frequency response is a good model to actual data with the same parameters set for each. Figure 44 depicts a flow chart outlining how the theoretical wall's frequency response will be used and compared against actual data taken using the UWB radar at LLNL in June 2006.

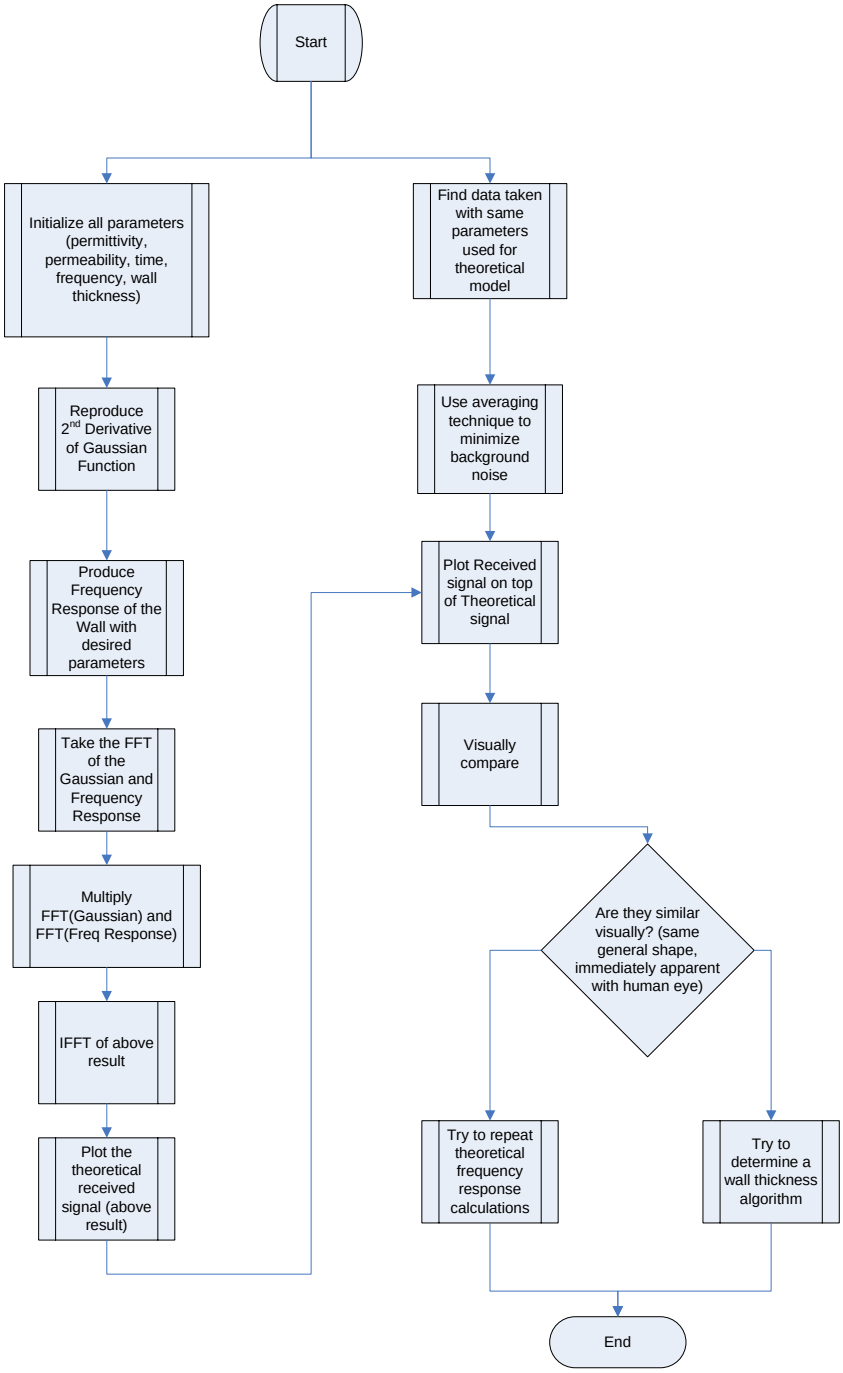

Figure 44: Validity Test of Theoretical Wall Frequency Response

If the frequency response can reproduce the actual data, then the frequency response can be considered a valid depiction of how the wall affects a UWB signal. The next section outlines how to find wall thickness algorithms from the given relationships regarding wall thickness and time to peak in the received signal.

Wall Thickness Algorithms

Figure 45 outlines the basic steps to use the assumed linear relationship between wall thickness and time to peak to estimate wall thickness. If this technique is proven effective, within 10% error, then it will be considered a valid wall thickness estimating algorithm.

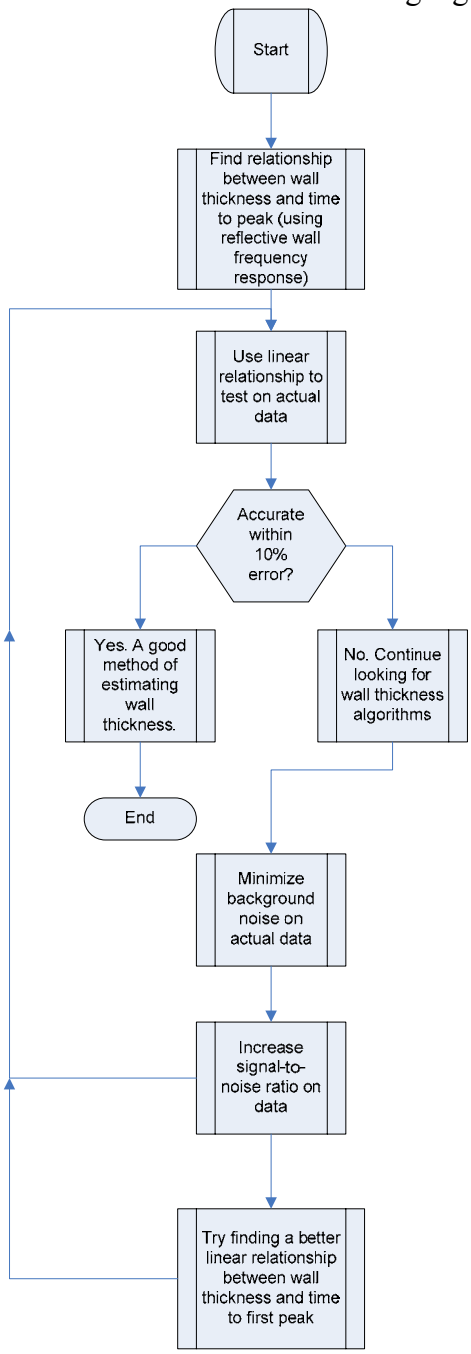

Figure 45: Wall Thickness Algorithm Formulation/Validity Model

Design Decisions:

1.) **Background Knowledge**: In addition to understanding how the wall affects the ultra-wideband radar signal, background knowledge was necessary regarding the ultra-wideband radar itself. Except for the LLNL summer internship in 2006, the Coast Guard Academy has

had no experience with ultra-wideband radar. In order to fully understand the problem of determining wall thickness, a strong understanding of how the ultra-wideband radar works was required. Due to the lack of knowledge in the ultra-wideband technical area, a strong emphasis was placed upon gaining technical background knowledge of ultra-wideband radar.

2.) **Frequency Response**: There is a strong emphasis on determining the frequency response of the wall in order to understand how the ultra-wideband radar signal propagates through any material. The strong emphasis is because of the knowledge considerations since the MIR group has not yet analyzed how the wall affects the signal in the frequency domain. This need for the frequency response is also due to economic consideration since the MIR group has had several problems gaining funding for further research and this experimentation and calculation to find the frequency response has no initial cost and no life-cycle costs.

3.) **Signal Propagation Modeling Software**: Wireless InSite is a type of signal propagation modeling software that can modeling ultra-wideband signals through a variety of conditions and through different building materials. Wireless InSite was not purchased due to economic conditions, considering the academic purchase price of approximately $4,000. No other uses could be found for this software, including incorporating it in the Antenna's modeling class. Since there is a high probability of this project ending in May, there was no use for the software within the next year. Therefore, due to economic and life-cycle costs the use of signal propagation modeling software was not developed further.

Requirements:

Level	Sponsor Need	Engineering Requirement	Requirement Satisfied
1	**Background Knowledge**		Yes
1A	A detailed description of the ultra-wideband radar signal as they propagate through free space and common building materials such as brick, concrete, dry wall, and wood through the creation of a MATLAB and theoretical model.	IV. Plot of pulse shape in the time domain V. Plot of pulse in the frequency domain VI. Develop a mathematical model that describes how the ultra-wideband signal is transmitted and received and how it is affected by attenuating through free space and other materials, model needs implemented theoretically and practically using MATLAB.	I, II, III were met through detailed research of mathematical equations describing the transmitted pulse (2nd derivative of Gaussian) and through understanding how signals propagate through various materials. These equation models were all implemented within MATLAB and plotted.
2	**Wall Thickness Algorithms**		Partially met

2A	A detailed description to discern what characteristics of the model can be used to determine the thickness of a wall.	IV. Use created theoretical model to create mathematical equations describing the movement of the signals. V. Based on these mathematical equations, create a theory regarding an equation to find the thickness of the wall based on the designed theoretical model. VI. Implement wall thickness estimation equations into MATLAB model.	I was met in the mathematical description of how signals propagate through various materials and describing the frequency response of the wall. II was met in the design of finding the relationship between wall thickness and time to peak. III will be met when this relationship is tested within MATLAB.
2B	Develop algorithms using deconvolution techniques to find the thickness of the wall.	III. Determine appropriate deconvolution methods, able to be implemented using MATLAB, to find the frequency response of the wall. IV. Create mathematical algorithms based upon deconvolution techniques to find the thickness of the wall, implemented using MATLAB.	No. I and II were not met by this design because instead of using deconvolution to find the frequency response of the wall, the frequency response was derived from the theory of how signals propagate.
3	Testing		No
3A	Determine which designed algorithms are the most effective and reliable for wall thickness determination.	V. Test designed algorithms using given data to determine the percent error of wall thickness detection as well as time to completion and reliability. VI. Effective algorithms are	I will be met when the theoretical frequency response will be used to duplicate data taken at LLNL in 2006.

		those with less than or equal to 10% error in wall thickness detection VII. Effective algorithms calculate the thickness of the wall within 5 minutes 95% of the time. VIII. Completion by end 30 March 2007 and deliver results to Dr. Farid Dowla and co-workers on project.	If this is effective, use the relationship between wall thickness and peak height to estimate wall thickness on actual data. II was met when testing the validity of the calculated frequency response equation as well as when testing the relationship of wall thickness and peak time. III is met since this algorithm is a linear relationship and will not take close to 5 minutes to complete. IV was not met due to time constraints and a steep learning curve into antenna modeling and signal propagation.

Appendix F1: MATLAB Code for Transmitted Pulse

```
% % 1/c Kirsten Ambors
% % May 1, 2007
% % PECE
% % Ultra-Wideband Radar "Seeing" Through Walls
% %
% % Purpose: To visually display the Gaussian and its derivatives in both
% the frequency and time domain

% pulse_ex1.m

%% the following code defines all the functions used

clear all

fs=16; % in GHz
T=4;% in ns
t=-T:1/fs:(T-1/fs); % in nano seconds
N=length(t);
sigma=0.5;
x=exp(-1.*t.^2*.5./sigma.^2);
x_p=t./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2);
x_pp=0.25*(1-t.^2./sigma.^2)./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2);

tp=1.7262; %ns
x_paper=(1-4./tp.^2*pi*t.^2).*exp(-2*pi.*t.^2./tp^2);

ff=2/T;
p=N*5/T/4;
x_cos=[zeros(1,p) cos(2*pi*ff*t(p+1:N-p)) zeros(1,p)];

temp=exp(-t(N/2+1:end)/1.2);
env=[fliplr(temp) temp];
x_cos2=env.*cos(2*pi*ff*t);

x_sinc=sinc(2*t);
x_chirp=cos(2*pi*(linspace(.5,fs/2,length(t))).*t);

y=20*log10(abs(fft(x)));
y_p=20*log10(abs(fft(x_p)));
y_pp=20*log10(abs(fft(x_pp)));
y_paper=20*log10(abs(fft(x_paper)));
y_cos=20*log10(abs(fft(x_cos)));
y_cos2=20*log10(abs(fft(x_cos2)));
y_sinc=20*log10(abs(fft(x_sinc)));
y_chirp=20*log10(abs(fft(x_chirp)));

f=linspace(0,fs/2,N/2);
bandthresh=-20*ones(1,N/2);

%% The following code displays the Gaussian pulse, first derivative, and
%% second derivative of the Gaussian in both time and frequency domains.
```

```
%-----------------------------------------------------------------------
figure(1), subplot(321), plot(t,x), title('Gaussian'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(322), plot(f,y(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse');
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
grid;

%-----------------------------------------------------------------------
subplot(323), plot(t,x_p), title('1st derviative of Gaussian'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(324), plot(f,y_p(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse');
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
grid;

%-----------------------------------------------------------------------
subplot(325), plot(t,x_pp), title('2nd derviative of Gaussian'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(326), plot(f,y_pp(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse');
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
grid;

%-----------------------------------------------------------------------
%% The following code displays the 2nd Derivative of the Gaussian pulse
%% with different widths in the time domain and the corresponding frequency
%% domain plots

figure(3)

subplot(321), plot(t,x_pp), title('2nd derviative of Gaussian'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(322), plot(f,y_pp(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse');
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
grid;

sigma = .25
x_pp=0.25*(1-t.^2./sigma.^2)./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2);

subplot(323), plot(t,x_pp), title('2nd derviative of Gaussian'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(324), plot(f,y_pp(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse');
```

```
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
grid;

sigma = .1
x_pp=0.25*(1-t.^2./sigma.^2)./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2);

subplot(325), plot(t,x_pp), title('2nd derviative of Gaussian'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(326), plot(f,y_pp(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse');
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
grid;

% The following section of code displays a figure showing other common pulses
% in both the time and frequency domains.  This makes it possible to visualize
% the benefits of the Gaussian pulse over other pulses.

figure(2), subplot(421), plot(t,x_cos), title('Cosine'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(422), plot(f,y_cos(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse'), grid;
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');


%-----------------------------------------------------------------------

subplot(423), plot(t,x_cos2), title('Cosine'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(424), plot(f,y_cos2(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse'), grid;
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');

%-----------------------------------------------------------------------

subplot(425), plot(t,x_sinc), title('Sinc'), grid;
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(426), plot(f,y_sinc(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse'), grid;
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');



%-----------------------------------------------------------------------

subplot(427), plot(t,x_chirp), title('Chirp'), grid;
```

```
xlabel('Time in nanoseconds');
ylabel('amplitude (linear)')

subplot(428), plot(f,y_chirp(1:N/2),f,bandthresh,'--r'), title('Frequency of Pulse'), grid;
xlabel('Frequency in GHz');
ylabel('Spectrum (dB)');
```

Appendix F2: MATLAB Code for Determining Wall Thickness/Time to Peak Relationship

```
% % 1/c Kirsten Ambors
% % May 1, 2007
% % PECE
% % Ultra-Wideband Radar "Seeing" Through Walls
% %
% % Purpose: To determine how wall thickness affects the signal.  Will use this
% %        data to create a wall thickness algorithm.  This is used on the
% %        simplistic model using one antenna on each side of the wall.

clear all


fs=8e9; % in Hz
T=4e-9;% in sec
t=-T:1/fs:(4*T-1/fs); % in nano seconds
N=length(t);
sigma=0.5e-9;

f2=linspace(-fs/2,fs/2,N);
w=2*pi*f2;

mu0=pi*4e-7; % permeability of free space
eps0=8.854e-12; % permittivity of free space
eps_p_r=5.1;
eps_pp_r=eps_p_r/5;

beta0=w*sqrt(mu0*eps0);
gamma=j*beta0*sqrt(eps_p_r);%simplified gamma
gamma2=j*w.*sqrt(mu0*eps0*(eps_p_r-j*eps_pp_r));% real gamma

x_pp=0.25e-18*(1-t.^2./sigma.^2)./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2);%

y_pp=fft(x_pp);

% defines the wall thickness array, and the arrays to store the peak times
peakshift=[];
peakshift1=[];
thickness=0:0.005:2.6;

% this for loop iterates the processes to determine the received signal
% based on the different wall thicknesses.  The loop then calculates the
% time to the peak value in the received signal and stores it in the array
% peakshift and peakshift1.

for ind=1:length(thickness),


TF_ideal=4*exp(j*beta0*thickness(ind))./(exp(gamma*thickness(ind)).*(2+(eps_p_r+1)./sqrt(eps_p_r))+...
```

```
    exp(-1*gamma.*thickness(ind)).*(2-(eps_p_r+1)./sqrt(eps_p_r)));

  n1=sqrt(mu0/eps0);
  n2=sqrt(mu0./(eps0*(eps_p_r-j*eps_pp_r)));
  TF=4*exp(j*beta0*thickness(ind))./(exp(gamma2*thickness(ind)).*(2+n1./n2+n2./n1)+...
    exp(-1*gamma2.*thickness(ind)).*(2-n1./n2-n2./n1));

  z_w=y_pp.*fftshift(TF);
  z=ifft(z_w,'symmetric');

  z_w_ideal=y_pp.*fftshift(TF_ideal);
  z_ideal=ifft(z_w_ideal,'symmetric');

  [y,index]=max(z);
  peakshift(ind)=t(index);

  [y1, index1] = max(z_ideal);
  peakshift1(ind) = t(index);

end


% plots the transmitted signal (2nd derivative of the Gaussian) and one of
% the received signals

figure(1), plot(t, x_pp, 'b', t,z_ideal,'r');
xlabel('Time (sec)');
legend('Transmitted','Received')
grid on;
```

Appendix F3: MATLAB Code for Determining Time Between Reflections

```
% % 1/c Kirsten Ambors
% % May 1, 2007
% % PECE
% % Ultra-Wideband Radar "Seeing" Through Walls
% %
% % Purpose: To determine how wall thickness affects the signal.  Will use this
% %        data to create a wall thickness algorithm.

clear all

% repeat process for wall thickness varying between 0 and 2.0 meters
dwall = 0:.005:2.0;
refdiff=[];

for ind = 1:1:length(dwall)
  fs=8e9; % in Hz
  T=4e-9;% in sec
  t=-T:1/fs:(10*T-1/fs); % in nano seconds
  N=length(t);
  sigma=0.5e-9;
```

```
f=linspace(0,fs/2,N/2);
f2=linspace(-fs/2,fs/2,N);
w=2*pi*f;

mu0=pi*4e-7; % permeability of free space
eps0=8.854e-12; % permittivity of free space

eps_p_r=5.5;
eps_pp_r=eps_p_r/10;

beta0=w*sqrt(mu0*eps0);
gamma_air=j*beta0;
gamma2=j*w*sqrt(mu0*eps0*(eps_p_r-j*eps_pp_r));% actual gamma

n1=sqrt(mu0/eps0);
n2=sqrt(mu0/(eps0*(eps_p_r-j*eps_pp_r)));
G12=(n2-n1)./(n2+n1);
G23=(n1-n2)./(n2+n1);
Tao12=2*n2./(n2+n1);
Tao21=2*n1./(n2+n1);

dair=0.5;
%dwall = .5;

TFp=exp(-2*gamma_air*dair).*(G12+G23*Tao12*Tao21.*exp(-2*gamma2*dwall(ind)));
TF=[fliplr(conj(TFp)) TFp];



%-----------------------------------------------------------------------

x_pp=0.25e-18*(1-t.^2./sigma.^2)./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2); %2nd deriv of gaus
%x_pp=0.5e-9.*t./sigma.^2.*exp(-1.*t.^2*.5./sigma.^2);  %1st deriv of gaus
y_pp=fft(x_pp);

z_w=y_pp.*fftshift(TF);
z=ifft(z_w,'symmetric');
plot(t.*10^9, z)
grid on;
xlabel ('time (ns)');
ylabel ('magnitude');
%title(['Single Antenna Model Received Signal for wall thickness = 'dwall(ind)])

pause

[minP1, index] = min(z);
mintime = t(index);

l=length(z);
t2 = t(index+1: l);
z2 = z(index+1: l);
[maxp2, index3] = max(z2);
l = length(z2);
```

```
    t2n = t2(index3+1: l);
    z2n = z2(index3+1: l);
    [minP2, index2] = min(z2n);
    mintime2 = t2n(index2);
    refdiff(ind) = mintime2-mintime;
end

dwall = dwall.';
refdiff = refdiff.'*1e9;
```