Characterization of the dielectric properties of various fiberglass/epoxy composite layups

Marcotte, Laurissa (University of Kansas); Arnold, Emily
Center for Remote Sensing of Ice Sheets, University of Kansas
Lawrence, KS
laurissa@ku.edu

Abstract— **The Center for Remotes Sensing of Ice Sheets (CReSIS) utilizes aircraft equipped with multiple radar antenna arrays to image and sound polar ice sheets. The structures required to integrate these antenna arrays on to the airborne platform must consider both structural and RF performance. Fiberglass/epoxy composites are common materials used for the construction of antenna radomes and other support structures.**

Structural properties of fiberglass/epoxy composite materials can be tailored for specific applications, and the material's high strength-to-weight ratio make it ideal for aircraft applications. In addition, the non-conductive, low-loss nature of fiberglass/epoxy composites are necessary characteristics for materials used for antenna radomes and support structures.

This study proposes to investigate the effects of stacking sequence (order and orientation of the individual plies in a composite laminate) on the dielectric properties of fiberglass/epoxy composite materials similar to those utilized by CReSIS.

Key words—Composite materials, dielectric constant, stacking sequence, non-isotropic dielectrics

I. INTRODUCTION

A. Background – Composite materials

Fiberglass/epoxy composite materials consist of glass fibers embedded in an epoxy resin. Structural components comprised of composite materials mainly carry applied loads in the direction of the fibers. Because structural properties of composite materials can be easily manipulated and because they have a high strength-to-weight ratio, these materials are widely used in the design and fabrication of modern aircraft.

B. Stacking sequence

Composite materials consist of many layers of zero/ninety degree plies and forty-five/negative forty-five degree plies. The order in which these plies appear in the layup is called the layup's stacking sequence. Stacking sequence is specific to the structural requirements of the component being built.

C. Dielectric materials

Because fiberglass materials are used in the construction of antenna radomes/fairings developed by the Center for Remote Sensing of Ice Sheets (CReSIS) for remote sensing applications, it is important to understand the effects of stacking sequence on their dielectric properties. A material's dielectric constant (or permittivity), ϵ_r, governs a lossless, non-conductive, non-magnetic material's impedance via the relationship:

$$\eta = \frac{\eta_0}{\sqrt{\epsilon_r}} \qquad \text{(Equation 1)[1]}$$

where η_0 is the impedance of free space (377 Ω). When an electromagnetic wave propagates through a material with a dielectric constant greater than one, part of the signal is reflected and the rest is transmitted at each interface between the material and free space. Figure 1 illustrates the behavior of an electromagnetic wave as it passes through a dielectric.
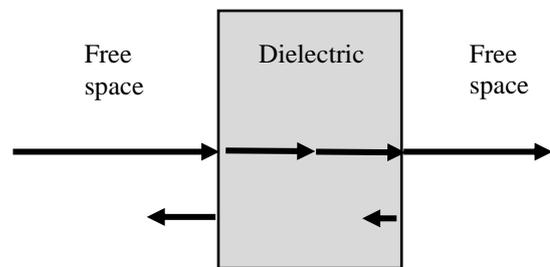

Figure 1: Behavior of light as it passes through a dielectric

The total reflected field over the total incident field, called the reflection coefficient Γ, can be calculated via the equation:

$$\Gamma = \frac{\eta - \eta_0}{\eta + \eta_0} \qquad \text{(Equation 2)[1]}$$

A dielectric constant which matches that of free space will results in a reflection coefficient of zero. The transmission coefficient T is given by:

$$T = \frac{2\eta}{\eta + \eta_0} \text{(Equation 3)[1]}$$

In airborne remote sensing applications, it is important to maximize the transmission coefficient of an antenna's signal toward the object of interest below. Hence, characterizing the dielectric properties of fiberglass/epoxy materials—which appear on many CReSIS aircraft—will help researchers improve antenna performance in airborne remote sensing systems.

II. METHODS

A. Time delay method

One method for finding permittivity values of fiberglass panels utilized the time delay a transmit antenna's signal experiences as it passes through a dielectric. When a signal travels from one antenna to another in free space, it travels at approximately 3 x 10^8 m/s, or the speed of light, c, along the entire path. When a dielectric is placed between the two antennas, the signal slows down momentarily as it passes through the material. The velocity at which the signal propagates through a non-magnetic dielectric is given by:

$$V_p = \frac{c}{\sqrt{\epsilon_r}} \qquad \text{(Equation 4)[2]}$$

Figure 2 illustrates the passage of electromagnetic energy from a transmit antenna to a receive antenna through a dielectric material.
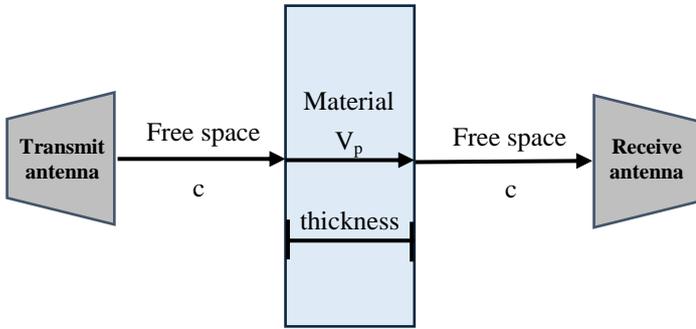

Figure 2: Slowing of an EM wave as it passes through a dielectric

If two transmission measurements are taken with a network analyzer—one with a panel in between and one without—the transmission of the signals can be plotted as a function of time. Because the signal's velocity decreases as it passes through the dielectric, the maximum transmission of the signal traveling through the panel will occur later than the maximum transmission of the signal traveling only in free space. Figure 3 shows an example of two S21 plots in the time domain.
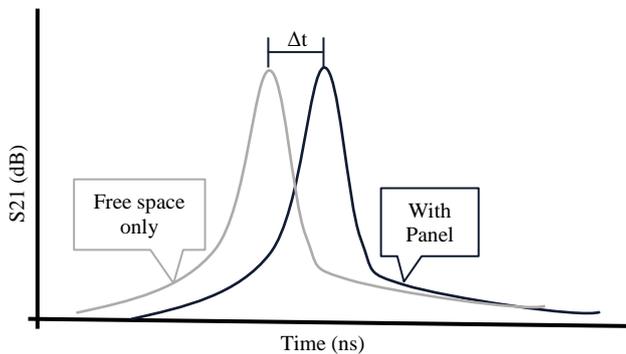

Figure 3: S21 measurements of two antennas in free space and with a dielectric

The difference between the times of maximum transmission of these two signals is the time delay, which can be used to find the dielectric constant of the material by subtracting the free space measurement's propagation time from the dielectric measurement's propagation time and substituting into Equation 4:

$$t_{dielectric} - t_{free\ space} = \frac{thickness}{V_p} - \frac{thickness}{c}$$
$$\rightarrow \Delta t = \frac{thickness}{c}(\sqrt{\epsilon_r} - 1) \text{ (Equation 5)}$$

The time delay caused by a thin dielectric panel is extremely small. Because the time step of the network analyzer is inversely proportional to the operating bandwidth of the transmit and receive antennas, antennas with a very wide bandwidth must be used in order to detect the slight time delay caused by a thin panel.

B. High Frequency Structure Simulator method

Another method used to find the dielectric constant of the fiberglass panels was to compare the shift in resonant frequency of a microstrip antenna mounted on a fiberglass substrate with computed values generated by a parametric analysis tool in ANSYS High Frequency Structure Simulator (HFSS). HFSS is a powerful modeling program designed to accurately predict the frequency response of high-frequency antennas such as microstrip antennas mounted on a substrate. [3] Figures 4 and 5 show an example of an antenna design and its calculated frequency response in HFSS, respectively.
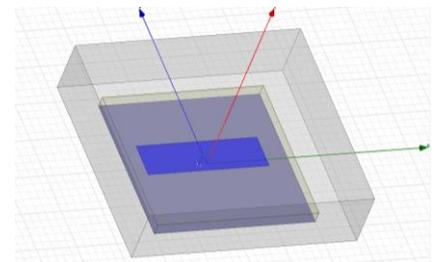

Figure 4: Example of an antenna design in HFSS

To test for permittivity frequency dependency, two microstrip antennas were designed using HFSS—one resonating at 4 GHz and another resonating at 6.7 GHz. To ensure that the results predicted by HFSS would be accurate, each antenna was first mounted on a Rohacell substrate with a dielectric constant of 1.1 and compared to reflection values predicted by HFSS. [4] The antennas were then mounted onto fiberglass/epoxy substrates and their resonant frequencies were recorded. A parametric analysis tool in HFSS was used to generate frequency response plots of the antennas on substrates with varying permittivity values. Permittivity values corresponding with the most similar

generated responses to the real, measured resonant frequencies of the antennas were recorded as representing the approximate permittivity values of the fiberglass.
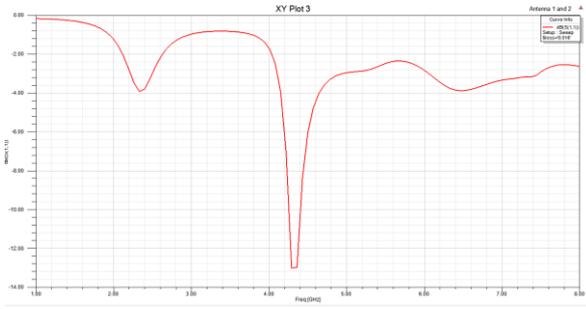

Figure 5: Example of a frequency response calculation in HFSS

III. EXPERIMENTAL SETUP

A. Materials tested

The stacking sequence families tested in this experiment were 10/80/10, 25/50/25, and 50/0/50 biaxial cloth. These families vary in the number and sequence of 0/90-degree and 45/-45 plies that appear in the layup. All panels were comprised of 24 layers of pre-impregnated S-glass/epoxy material. After curing, all panels were approximately 0.25 inches thick.

Family	0/90 degree plies	45 degree plies
10/80/10	20%	80%
25/50/25	50%	50%
50/0/50	100%	0%

The 10/80/10 and 25/50/25 families were chosen to be tested because these two families are common in aircraft component fabrication. [5] The 50/0/50 family was chosen to be tested because it allows investigation into the effect of 45-degree plies on material dielectric properties

B. Time delay method

A two antennas (one quad-ridged horn and another dual-ridged horn) were placed 3.5 feet apart in an anechoic antenna chamber. All wires that were to be used were connected to Ports 1 and 2 of an Agilent network analyzer, which was then calibrated with an electronic calibration unit. The two antennas were then connected to the transmission lines. The network analyzer was set to measure between 2 GHz and 18 GHz, and an inverse Fourier transform was subsequently applied to convert the collected data into the time domain. A free space S(21) measurement was taken. Each fiberglass panel was then carefully placed, one at a time, halfway between the antennas, and their corresponding S(21) responses were recorded.

The times at maximum transmission were extracted from the .s2p files using a simple MATLAB code and then substituted into Equation 3 to find the dielectric constant of each fiberglass panel.

C. HFSS method

Two high-frequency microstrip antennas were designed using HFSS, one resonating at 6.9 GHz and another resonating at 4.0 GHz. Each antenna's frequency response was calculated for a substrate with a dielectric constant of 1.1.

The two antennas were then built by hand using adhesive copper tape as the ground plane and microstrip. For each antenna, a port was soldered to the ground plane and its feed was soldered to the microstrip. The feed ran from the port to the antenna via a feed line that passed through the material. Figure 6 illustrates the dimensions and setup of all microstrip antennas.
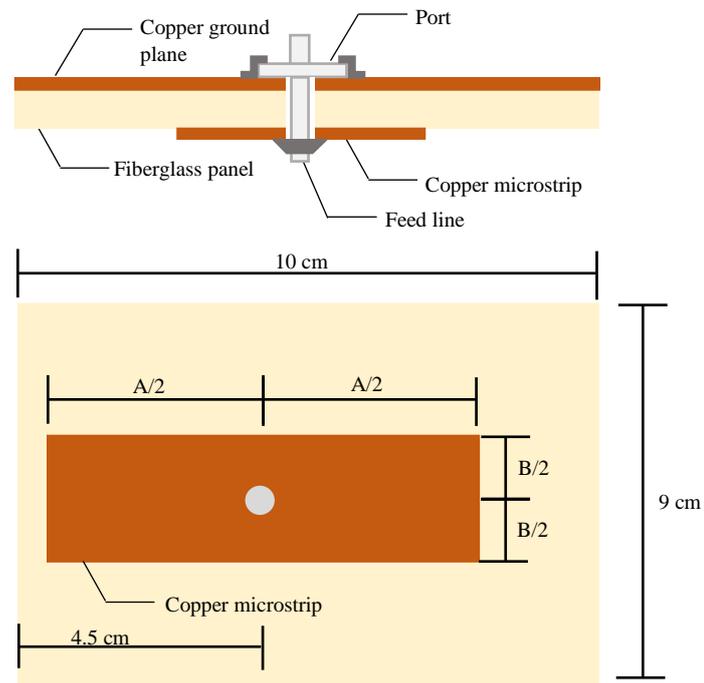

Figure 6: *Top:* Cross-section of microstrip antenna setup *Bottom:* Dimensions of microstrip on the substrate

Figure 7 shows one of the test antennas connected to a transmission line in the anechoic chamber. The ratio of the reflected energy to the incident energy at the port (denoted as S_{11}) was measured in the frequency domain. The Rohacell dielectric measurements were compared to HFSS's predicted results for a substrate with a dielectric constant of 1.1.

Each antenna type was then mounted onto each fiberglass panel, making six test panels total.

Figure 7: Microstrip antenna setup in anechoic chamber

A parametric analysis was then performed in HFSS for each antenna type, varying the substrate's dielectric constant with each iteration. The measured frequency response of each antenna was then compared to the parametric analysis results and matched to the closest calculated response from HFSS to pinpoint the dielectric constant of each substrate.

## IV. RESULTS

A. Time delay method

Because the transmit and receive antennas were limited to a bandwidth of 16 GHz, the smallest measureable time delay using the network analyzer was 62.5 picoseconds. A time delay of 62.5 picoseconds using panels 0.25 inches thick would indicate a permittivity value of 15.6. The permittivity of S-glass is 5.2 and the permittivity of epoxy is 3.6, therefore a dielectric constant of 15.6 is unrealistic. [6] In order to detect a permittivity value close to those of S-glass and epoxy, antennas operating at a bandwidth of over 30 GHz must be used with panels that are 0.25 inches thick. Because the antennas available operated at a narrower bandwidth than was necessary, the permittivity values calculated during a test run of this method were imprecise; thicker panels were necessary in order to produce accurate results. Because access to composite material was limited, this method was abandoned early in the investigation.

B. HFSS Method

The dimensions and calculated resonant frequency of the microstrip antennas are tabulated below.

| A (cm)	B (cm)	f_{res} (GHz)
7.5	2	4.0
8	1	6.9

The accuracy of the HFSS simulations was confirmed by the measurements with the Rohacell substrate. The resonant frequency for each antenna fell within 0.15 GHz of its predicted value. Figures 8 and 9 show the frequency response of the antennas mounted on Rohacell compared to the free space-substrate antennas in HFSS.
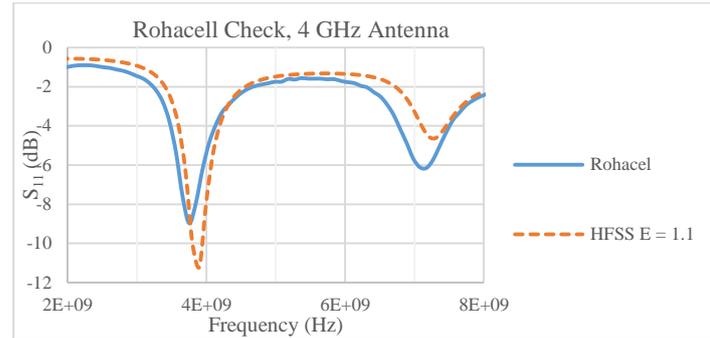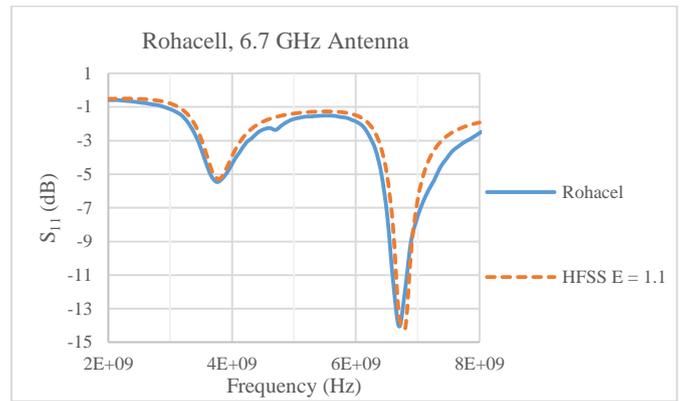
Figures 8 and 9: Calculated vs. measured responses of antennas mounted on Rohacell

The resonant frequency of the antennas mounted on fiberglass panels shifted downward with respect to measurements taken of antennas mounted on Rohacell. Figures 10 and 11 show the resonant frequency shifts of the measurements taken with fiberglass substrates.
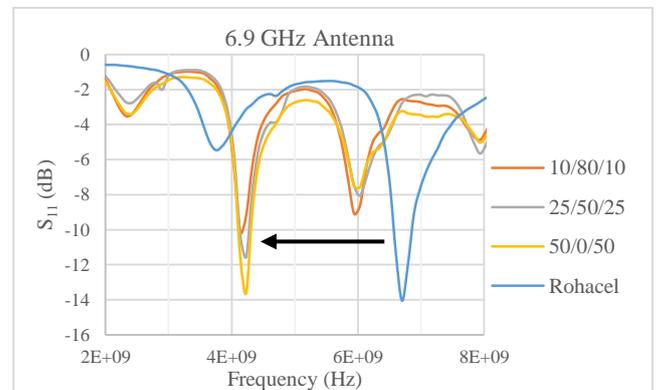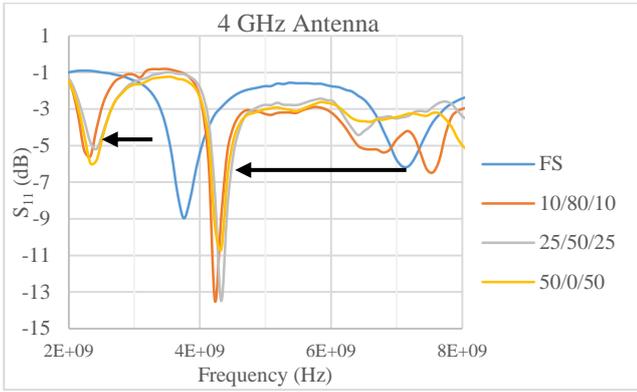
Figures 10 and 11: Downwards resonant frequency shift of antennas mounted on fiberglass substrates

For all substrates, the HFSS result that most closely matched the measurements taken using the network analyzer was that of an antenna mounted on a substrate with a dielectric constant of 3.4. Figures 12 and 13 compare the measured frequency responses of both antennas mounted on the various composite layups as substrates.
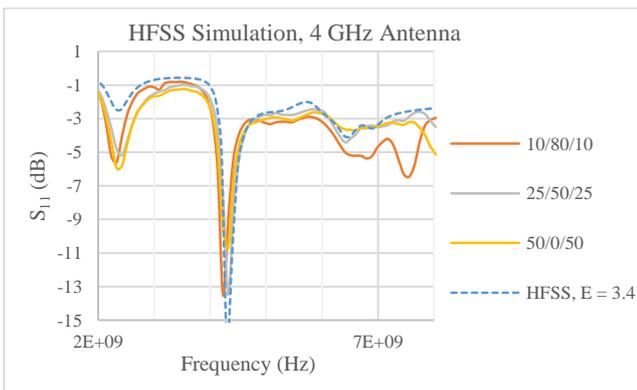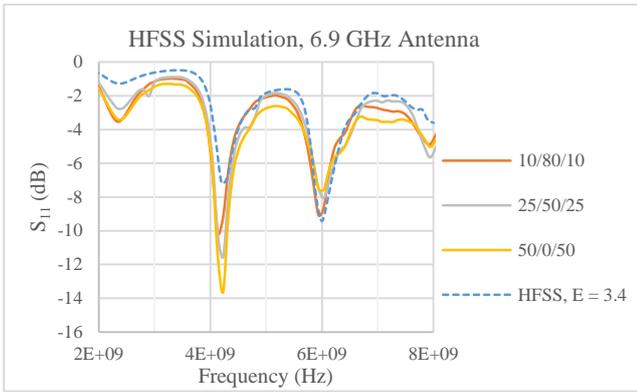
Figures 12 and 13: Measured results of antennas mounted on fiberglass vs. calculated results of a substrate with a permittivity of 3.4

Because a loss tangent of zero was assumed for all substrates in HFSS, discrepancies in the Q factor between measurement results and HFSS predictions may be attributed to losses in the material.

V. ANALYSIS AND CONCLUSIONS

To use the time delay method to find the dielectric constant of a thin material sample, antennas operating at a very wide bandwidth must be used in order to accommodate the fine time resolution required to detect a small time delay, as in the case of a material with a small dielectric constant. Alternatively, the antenna operating at a bandwidth of 16 GHz would need to be used with very thick material samples. Because access to pre-impregnated composite material was limited and there were no antennas available with a wide enough bandwidth to measure a small time step, the time delay method did not produce accurate results.

Using the HFSS method, it was possible to approximate the dielectric constant of S-glass/epoxy composite materials to be around 3.4. Because the same approximate dielectric constant fit well with the results of both antennas and for all stacking sequences, it can be concluded that permittivity does not heavily rely on stacking sequence or frequency in the tested frequency range. Differences in the Q factor of each resonance from the projected results in HFSS imply that fiberglass/epoxy composite materials may be lossy. Figure 14 shows the HFSS analysis results for antenna 1 mounted on two substrates, both with a permittivity of 3.4 but two different loss tangents:
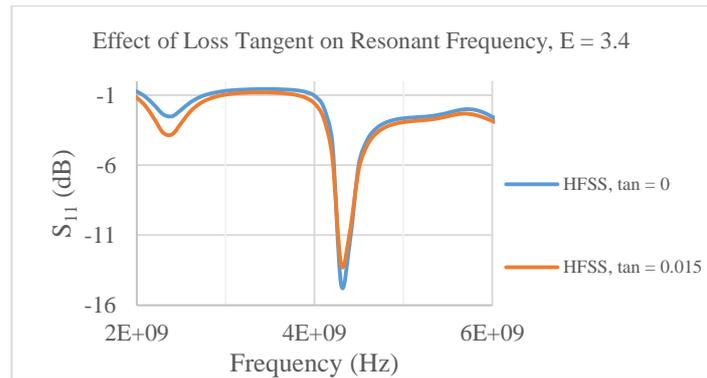

Figure 14: Comparison of two loss tangent values for a given relative permittivity

In this experiment, all measured permittivity values were compared to HFSS-predicted values with a loss tangent of zero. Further investigation into the dielectric properties of composite materials should explore the effects of stacking sequence and frequency on the material's loss tangent as these materials may exhibit non-isotropic loss.

My work on the time delay method was based on previous research conducted by Dr. Stephen Yan. He also provided helpful advice throughout this project regarding antennas and working in the anechoic chamber.

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