FREQUENCY DOMAIN MEASUREMENTS OF MICROWAVE ABSORBER DESIGN AND TESTING

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Frequency domain measurements of microwave absorber design materials.

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APR 17 1983

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FREQUENCY DOMAIN MEASUREMENTS

OF

MICROWAVE ABSORBER DESIGN MATERIALS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
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Master of Science

by

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Approved for Public Release; Distribution Unlimited.
Measurements of the intrinsic properties, complex permittivity and permeability of radar absorber design materials whose properties change relatively slowly with frequency can presently be made over two or even three decades of frequency using a time domain system. Such a system was developed for the Air Force Avionics Laboratory by the Sperry Corporate Research Center. However, this time domain technique is limited to frequency measurements below 16 gigahertz (GHz).

This thesis is the documentation of a final automated experimental setup for measurement in the Ku band (12.4 - 18 GHz) used to demonstrate the feasibility of a possible frequency domain measurement technique to extend intrinsic property measurements up to 100 GHz.

The prospect of experimental work in the Air Force Avionics Laboratory, coupled with a project in the area of electrodynamics, presented a thesis topic ideally suited to my desires. The application of Maxwell's equations to the study of microwave absorber materials used to reduce the radar cross section of aircraft is a logical extension of my education in electronic warfare.
Acknowledgements

I wish to express my appreciation to all of the kind and helpful personnel at the Air Force Avionics Laboratory in the Passive Electronic Countermeasures Branch. In particular, I owe a special debt of gratitude to Dr. Pelton and Dr. Kentzer. Also, I wish to express thanks to my thesis advisor, Dr. Rustan, and to my readers, Dr. Fontana and Dr. Golden. Their positive feedback and words of encouragement provided the impetus for my work.

Finally, I would like to thank my lovely wife, Cathy, and my daughters, Ami and Heather, for their encouragement and understanding when I really needed it.

Donald G. Aguirre

(This thesis was typed by Sharon A. Gabriel)
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Roman letter Symbols

- B: Magnetic flux density (webers/m²)
- c: Velocity of light in vacuum (≈ 3×10⁸ m/sec)
- D: Electric flux density (coulombs/m²)
- d: Distance (mils)
- E: Electric field (volts/m)
- H: Magnetic field (amp/m)
- J: Current density (amp/m²)
- K_m: Hankel function
- S_11: Reflection scattering coefficient
- S_21: Transmission scattering coefficient
- V_A: Reflected wave
- V_A^+: Transmitted wave at interface
- V_{inc}^+: Incident wave at interface
- V_B: Transmitted wave through sample
- Z_0: Characteristic impedance of free space (ohms)
- Z: Impedance of medium (ohms)
- z: A transmission coefficient (exp(yd))

Greek letter Symbols

- α: Attenuation constant
- β: Phase constant
- ε_0: Permittivity for vacuum
- ε_r: Relative permittivity
- γ: Complex propagation constant
\[ \begin{align*} 
\tau & \quad \text{Reflection coefficient} \\
\lambda & \quad \text{Wavelength} \\
\mu_0 & \quad \text{Permeability for vacuum} \\
\mu_r & \quad \text{Relative permeability} \\
p & \quad \text{Reflection coefficient} \\
\tau & \quad \text{Transmission coefficient} \\
\omega & \quad \text{Angular frequency} 
\end{align*} \]
Abstract

Using frequency domain techniques, a system was developed to measure the complex permittivity and permeability of different materials in the Ku band (12.4 to 18 GHz). A sample of fiberglass, teflon, FGM-40, and two different plexiglas configurations were chosen for this experiment. The newly developed measuring system consisted of a two horizontal-plane sectoral horn and a sample holder assembly. A 9.5 x 0.8 cm piece of the sample material was cut and fitted into the sample holder assembly. The reflection and transmission coefficients for the sample were measured, using a network analyzer and frequency synthesizer as the swept frequency signal source. A dedicated computer calculated the complex permittivity and permeability and plotted the output data. The measurements were performed automatically by having the computer control the frequency synthesizer while running the experiment.

The two configurations of plexiglas and the fiberglass sample were tested ten times to obtain a statistical representation of the results. In all cases good repeatability was obtained. The standard deviation of the real part of the permittivity and permeability for the two cases of plexiglas was within ± 4% of the mean. The fiberglass had a typical standard deviation within ± 7% of the mean for the real part of the permittivity and permeability.

The permittivity and permeability obtained for the selected samples using the frequency domain measurement technique were compared with the results obtained in a previously developed system which used time domain techniques. The data comparison between the two systems was good for teflon, plexiglas, and fiberglass in the frequency range from 12.4 to—
16 GHz. Some variations were noted for the ICM-40. Since the results obtained were generally consistent between both techniques, it is claimed that the newly implemented frequency domain system is a viable alternative for the rapid measurement of intrinsic properties in the Ku band.
INTRODUCTION

The application of radar absorber design material to the concealment of aircraft and missiles hinges on a knowledge of the intrinsic properties of complex permittivity (epsilon) and permeability (mu) of the microwave absorber design materials over a wide frequency range (Rock and Barrick, 1970; Crispin, 1970). These two properties are a measure of the ability of materials to conduct electric and magnetic fields which are present in the radar environments (Hayt, 1974; Allen, 1976).

Background

The ability to design and test radar absorber design materials depends on the capability to accurately measure the intrinsic properties of complex mu and epsilon of the material over a wide frequency range. The Air Force Avionics Laboratory contracted the Sperry Rand Research Corporation to build a time domain measurement system that could measure complex mu and epsilon parameters of design materials over a frequency range from 0.1 to 16 GHz (Nicolson, 1971; Nicolson, 1974). Traditionally, such measurements have been made at fixed frequencies below 10 GHz using slotted-line and impedance-bridge configurations (Hippel, 1958).

Essentially, the time domain measurement system consists of a sub-nanosecond pulse generator and coaxial line system to hold samples of materials, a wideband sampling oscilloscope, and an electronic
system which scans and digitizes the transient response of microwave materials (Nicolson, 1970; Nicolson, 1971; Nicolson, 1974). The transient response is then Fourier transformed on a Hewlett-Packard 21MX computer to provide frequency domain scattering coefficients. Further computation provides printouts and graphs of complex \( \mu \) and complex \( \epsilon \) as a function of frequency. Although the time domain system works well, the Air Force Avionics Laboratory has a need for a measurement capability of complex permittivity and permeability of candidate design materials at frequencies higher than 16 GHz.

The National Bureau of Standards published a report dealing with radar absorber design material measurement techniques at frequencies above 20 GHz (Nahman, 1979). One area of the report reviews the existing time domain measurement system in use at AFAL and recommended a frequency domain approach as one possible way to extend the \( \mu \) and \( \epsilon \) measurement capability into the millimeter frequency range. This would involve the development and verification of a frequency domain technique that can be integrated into the present time domain measurement system with the minimum equipment modification possible. The time domain system uses two specialized generators. One of these generators produces a very narrow and sharp impulse-like signal, whose spectral content is primarily in the frequency range from 0.1 to 10 GHz (Nicolson, 1971). The second generator emits a radio frequency burst, whose spectral content is between 9 and 16 GHz (Nicolson, 1974). Utilizing these two generators, two measurements then characterize the permeability and permittivity of a sample from 0.1 to 16 GHz. A sampling oscilloscope is used to sample the transient response for digitizing, so that scattering parameters can be computed at discrete frequencies.
The technological limitations of the sampling oscilloscope provides the impetus to develop a frequency domain measurement system (Baker, 1979). The frequency domain approach would delete the requirement for the two special radio frequency generators and instead utilize a continuous wave generator, frequency synthesizer, tuned from discrete frequency to discrete frequency. The continuous wave radio frequency signals would also negate the requirement for sampling the transient signal response. Instead, the reflected and transmitted signals would be at a set frequency and could be digitized and processed using analog-to-digital (A/D) techniques.

**Problem and Scope**

The problem addressed in this thesis is that of experimentally developing a millimeter frequency domain measurement system, and demonstrating the system capabilities by measuring the intrinsic properties of several common materials at the Ku band (12.4 to 18 GHz). Existing material properties obtained from the time domain system can be used for comparison. The computer code should be modified to automate the measurement process by putting the frequency synthesizer under computer control and reading the network analyzer phase and amplitude outputs with the computer's A/D converter.

After demonstration of the concept feasibility, the Air Force Avionics Laboratory personnel would later modify the measurement setup to apply the technique at frequencies between 20 and 100 GHz.

This thesis contains a description of the fully automated frequency domain measurement system and data comparisons for fiberglass, two thicknesses of plexiglas, teflon, and FGM-40 absorber materials measured.
in both the time domain and the frequency domain systems. The frequency domain measurement system is depicted in Figure 1. The frequency domain setup consists of two H-plane sectoral horns (Barrow and Chu, 1939) which are placed mouth to mouth. The system is used to measure the reflection and transmission coefficients from a single rectangular sample of the design material.

Five specific samples were evaluated, fiberglass, two thicknesses of plexiglas, teflon, and an FGM-40 absorber. To show concept feasibility, data were compared for the five samples tested on both the time domain system and the frequency domain system. The samples prepared for use in the time domain system were of such small dimension that a good uniformity of thickness could be expected; however, samples used in the frequency domain system were larger (7.60 sq cm) and were subject to slight nonuniformity of thickness. Therefore, the thickness value used for the computation of relative mu and epsilon in the frequency domain system is the average thickness across the sample.

The H-plane sectoral horn assembly is assumed to produce a transverse electromagnetic plane wavefront at the sample interface (Jasik, 1961). The plane wavefront approximation was sought because it provides a means to calculate mu and epsilon values using relatively uncomplicated mathematics.

Assumptions

In the frequency domain measurement setup, it will be assumed that the electromagnetic fields normally incident on the sample material interface approximate a plane wave. This assumption is discussed in the theory section. The theoretical phase variation in the mouth of the
Figure 1. Frequency Domain Measurement System
H-plane sectoral horn ranges from 11.8° at 12.4 GHz to 16.24° at 18 GHz, using the dimensions of $L_h = 150$ cm and $a = 9.5$ cm in the equation $\angle \phi = \left[ \frac{a^2}{8\lambda_h} \right] 360^\circ$ (Jasik, 1961).

General Approach

The research reported in this thesis involved eight major areas:

1. We studied the existing time domain measurement system.

2. We analyzed literature material associated with the sample holder, network analyzer, frequency synthesizer, and waveguide components used in the measurement system.

3. We performed an initial determination of the test setup and the actual assembly of the test system.

4. We modified the existing time domain computer program to delete portions of code associated with the Fourier Transform and added computer code to accept the frequency domain measured values as input.

5. We automated the test setup, putting the frequency synthesizer under computer control and reading the network analyzer's phase and amplitude outputs through the computer's A/D converter.

6. We measured the sample materials and compared $\mu$ and $\varepsilon$ from both the time domain and frequency domain systems.

7. We extended the ideas developed in building the test system and designed and built a final frequency domain system that could measure reflection and transmission coefficients from a single, small sample.
8. We took the measured values of mu and epsilon from the final frequency domain system and compared it to data obtained from the time domain system.

Sequence of Presentation

The material in the thesis is presented in the following manner:

1. The theory underlying the measurement technique is presented in Section II.

2. A description of the equipment used in the frequency domain setup is given in Section III.

3. The sample measurement procedures are presented in Section IV.

4. The results are given in Section V.

5. Finally, the conclusions and recommendations are presented in Section VI.
II. Theory

As an introduction to the theory used in developing the frequency domain measurement system for the intrinsic property measurements of radar absorber design materials, let's look first at a brief description of the properties themselves.

Dielectric Materials and Permittivity

A dielectric is a substance in which the electrons are so well bound or held near their equilibrium positions that they cannot be detached by the application of ordinary electric fields. The important characteristic in a dielectric is its permittivity $\varepsilon$. The permittivity (Dielectric Constant) relates the electric field intensity $E$ to the electric flux density $D$ by the equation $D = \varepsilon E$. As $\varepsilon$ increases for a material, the material will have an increased electric flux density present within (Ramo, 1965).

Because the permittivity of a dielectric is always greater than the permittivity of vacuum $\varepsilon_0$, it is convenient to use the relative permittivity $\varepsilon_r$ of the dielectric, that is to say $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$, where $\varepsilon_0$ is the permittivity of space $\varepsilon_0 = (1/36\pi) \times 10^{-9}$ farads per meter and $\varepsilon_r$ characterizes the effect of the atomic and molecular dipoles in the material. This relative permittivity is a dimensionless quantity (Ramo, 1965; Kraus, 1953). At higher frequencies, typically above 0.1 GHz, the dielectric material
experiences energy losses. The relative permittivity can be expressed as a complex number to account for such losses,

\[ e^* = e_r - j\varepsilon_r' \] (Nippel, 1958).

**Magnetic Materials and Permeability**

All materials show some magnetic effects. Depending on their magnetic behavior, substances can be classified as diamagnetic, paramagnetic, and ferromagnetic. In diamagnetic materials, the magnetization is opposed to the applied field, while in paramagnetic materials the magnetization is in the same direction as the field. The materials in these two groups, however, show only weak magnetic effects. Materials in the ferromagnetic group, on the other hand, show very strong magnetic effects. Magnetization occurs in the same direction as the field, as it does in paramagnetic materials.

The level of magnetization of materials can be quantized by referring to the relative permeability \( \mu_r \) defined as \( \mu_r = \frac{\mu}{\mu_0} \). By definition, the relative permeability of free space is unity. The relative permeability of ferromagnetic materials is generally much greater than one. The magnetic flux density \( \mathbf{B} \) is related to the magnetic intensity \( \mathbf{H} \) by \( \mathbf{B} = \mu\mathbf{H} = \mu_r\mu_0\mathbf{H} \) where \( \mu_0 \) is the permeability of space = \( 4\pi \times 10^{-7} \) henrys per meter and \( \mu_r \) measures the effect of the magnetic dipole moments of the atoms comprising the medium (Ramo, 1965).

In extending the concept of permeability to frequency dependent magnetization in ferromagnetic materials, it is convenient to
introduce the idea of a complex permeability. As frequency increases, the following effects can be accounted for by a complex relative permeability $\mu_r^* = \mu_r - j\mu_r''$. This physical fact is that in a sinusoidally varying magnetic field a phase angle $\theta$ arises between $B$ and $H$ due to energy losses associated with magnetic resonance and relaxation phenomena. Such losses arise physically from reorientation of the magnetic moments.

**Theoretical Development**

The theoretical development presented here is an extension of theory from the standpoint of classical boundary value solution techniques for plane waves (Kraus, 1953; Hayt, 1974) and subsequent relationship to the scattering coefficients $S_{11}$ and $S_{21}$ (Ramo, 1965) for reflection and transmission parameters respectively. The theory of the H-plane sectoral horn will be given by presenting a few key points from the work of Barrow and Chu (1939).

The scattering coefficients $S_{21}$ and $S_{11}$ are a measure of the forward- and back-scattered energy respectively (Nicolson, 1970). These scattering coefficients are used to calculate the complex permeability $\mu_r^* = \mu_r - j\mu_r''$ and permittivity $\varepsilon_r^* = \varepsilon_r - j\varepsilon_r''$ of the test sample. The sample will be examined under the assumption of plane waves normally incident at the interface.

Consider a slab of homogenous, isotropic, nonconducting material with permittivity $\varepsilon_r^* = \varepsilon_0 \varepsilon_r^*$ and permeability $\mu_r^* = \mu_0 \mu_r^*$ and thickness $d$ positioned in a free space medium with characteristic impedance $Z_0$ with region three infinite in extent, as shown in Figure 2. Within the region $0 \leq x \leq d$ the impedance of the slab
Figure 2. Plane wave at sample

REGION 1

\[ z_1 = z_2 = z_0 = \sqrt{v_0/e_0} \]

REGION 2

\[ z_2 = z_0 = \sqrt{v_0/e_0} \]

REGION 3

\[ z_3 = z_0 = \sqrt{v_0/e_0} \]
will be \( Z = \sqrt{\frac{\mu^*}{\epsilon^*}} \sqrt{\mu_0} = \sqrt{\frac{\mu^*}{\epsilon^*}} Z_0 \). If \( d \) are infinite, then the reflection coefficient of a plane wave normally incident on the interface would simply be (Nicolson, 1970)

\[
\Gamma = \frac{Z - Z_0}{Z + Z_0} = \frac{\sqrt{\frac{\mu^*}{\epsilon^*}} - 1}{\sqrt{\frac{\mu^*}{\epsilon^*}} + 1}
\]

According to Maxwell's curl equations,

\[
\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}
\]

(2)

\[
\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

(3)

and since a nonconducting media is assumed, \( \mathbf{J} = 0 \) in Eq (2). Taking the curl operation of Eq (3) and substituting Eq (2), the wave equation is obtained,

\[
\nabla \cdot \mathbf{E} = \mu_0 \epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}
\]

(4)

For a linearly polarized plane wave traveling in the \( x \) direction, the solution of the wave equation reduces to a term that is a function of position multiplied by the time variation term \( \exp(j\omega t) \) (Hayt, 1974). Defining the complex propagation constant as \( \gamma = \alpha + j\beta \),
the position term of the electric field in region one is

\[ E_1 = E_1 \left[ e^{-i\gamma_1 x} + e^{i\gamma_1 x} \right] \]  

(5)

where \( E_1 \) is the incident field and \( E_1 \) is the total field made up of the incident and reflected components of the fields. In region two (within the sample), the corresponding electric field term is

\[ E_2 = A e^{-i\gamma_2 x} + B e^{i\gamma_2 x} \]  

(6)

And, in region three we obtain

\[ E_3 = iE_1 e^{-i\gamma_3 x} \]  

(7)

The magnetic field in region one expressed in terms of the incident electric field is

\[ H_1 = j \frac{1}{\omega} \left[ -\gamma_1 e^{-i\gamma_1 x} + \gamma_1 e^{i\gamma_1 x} \right] \]  

(8)

In region two (within the sample) the magnetic field is

\[ H_2 = j \frac{1}{\omega} \left[ -A e^{-i\gamma_2 x} + B e^{i\gamma_2 x} \right] \]  

(9)

And, in region three the magnetic field is

\[ H_3 = -j \frac{E_1}{\omega} \gamma_3 e^{-i\gamma_3 x} \]  

(10)
The components $E_1$, $E_2$, $E_3$, $H_1$, $H_2$, and $H_3$ of the electric fields $E$ and magnetic fields $H$, respectively, in these expressions are complex quantities independent of time and depend on the space variables only. The actual field is the real part of $E e^{j\omega t}$ and of $H e^{j\omega t}$.

The reflection coefficient $\rho$ and transmission coefficient $\tau$ will now be found using boundary value solution techniques (Kraus, 1953; Hayt, 1974; Hippel, 1951). Since the tangential components of the electric field in Eqs (5) and (6) are continuous at the boundaries, then at $x = 0$

$$E_1 [1 + \rho] = A + B$$  \hspace{1cm} (11)

and from Eqs (6) and (7), at $x = d$

$$A e^{-\gamma_d d} + B e^{\gamma_d d} = \tau E_1 e^{\gamma_d d}$$  \hspace{1cm} (12)

The tangential components of the magnetic fields are continuous at the boundaries, thus at $x = 0$

$$j \frac{\gamma_1 E_1}{\omega \mu_1} [\rho - 1] = j \frac{\gamma_2}{\omega \mu_2} [B - A]$$  \hspace{1cm} (13a)

Using the substitution $Z = j \frac{\omega \mu}{\sigma}$ where $j \frac{\omega \mu}{\sigma} = j \frac{1}{\sigma} \frac{1}{1 + j \omega \sigma}$ and since the slab is a nonconductor $\sigma = 0$, then

$$Z = j \frac{\omega \mu}{\varepsilon} = \sqrt{\frac{\mu}{\varepsilon}}$$ which represents the impedance of the medium.
For the system being described in Figure 2, \( Z_1 = Z_3 = Z_0 \), where \( Z_0 \) is the characteristic impedance of free space; however, this derivation is for the general case, hence

\[
\frac{E_i}{Z_1} [\rho - 1] = \frac{1}{Z_2} [B - A] \tag{13b}
\]

And at \( x = d \)

\[
\frac{1}{Z_2} [A e^{-\gamma_2 d} - B e^{\gamma_2 d}] = \frac{r E_i}{Z_3} e^{-\gamma_3 d} \tag{14}
\]

The variables \( A \) and \( B \) are eliminated from these equations by multiplying Eq (13b) by \( Z_2 \) and then adding Eq (11) to get

\[
2B = E_i [(1 + \rho) - \frac{Z_2}{Z_1} (1 - \rho)] \tag{15}
\]

Equation (14) is multiplied by \( Z_2 \) and added to Eq (12) to get

\[
2A = \frac{r E_i}{Z_3} e^{(\gamma_2 - \gamma_3) d} \frac{Z_2}{Z_3} \tag{16}
\]

Equation (13b) is multiplied by \( Z_2 \) and Eq (11) is subtracted off to get

\[
2A = E_i [(1 + \rho) + \frac{Z_2}{Z_1} (1 - \rho)] \tag{17}
\]
Equation (14) is multiplied by $Z_2$ and subtracted off Eq (12) to get

$$2B = \tau E_1 e^{-(\gamma_2 + \gamma_3)d \left[ 1 - \frac{Z_2}{Z_3} \right]} \quad (18)$$

Equating Eqs (16) and (17) gives

$$\tau e^{(\gamma_2 + \gamma_3)d \left[ 1 + \frac{Z_2}{Z_3} \right]} = \left[ (1 + \rho) + \frac{Z_2}{Z_1} (1 - \rho) \right] \quad (19)$$

And, equating Eqs (15) and (18) gives

$$\tau e^{-(\gamma_2 + \gamma_3)d \left[ 1 - \frac{Z_2}{Z_3} \right]} = \left[ (1 + \rho) - \frac{Z_2}{Z_1} (1 - \rho) \right] \quad (20)$$

Equation (20) is solved for the transmission coefficient $\tau$ and it is substituted into Eq (19) to yield the reflection coefficient $\rho$.

$$\tau e^{-(\gamma_2 + \gamma_3)d \frac{Z_3 - Z_2}{Z_3}} = \left[ \frac{Z_1(1+\rho) - Z_2(1-\rho)}{Z_1} \right] \quad (21a)$$

$$\tau = e^{(\gamma_2 + \gamma_3)d \left[ \frac{Z_3}{Z_1} \right]} \left[ \frac{Z_1(1+\rho) - Z_2(1-\rho)}{Z_3 - Z_2} \right] \quad (21b)$$

$$\tau e^{-(\gamma_2 - \gamma_3)d \frac{Z_3 + Z_2}{Z_3}} = \left[ \frac{Z_1(1+\rho) + Z_2(1-\rho)}{Z_1} \right] \quad (22a)$$
\[
\begin{align*}
& \quad \quad e^{(\gamma_2 + \gamma_3) d Z_2} \left[ \begin{array}{c}
\gamma_1(1+i) - \gamma_2(1-i)
\end{array} \right] \quad e^{(\gamma_2 - \gamma_3) d Z_2} \left[ \begin{array}{c}
Z_3 + Z_2
\end{array} \right] = \left[ \begin{array}{c}
Z_1(1+i) + Z_2(1-i)
\end{array} \right] \\
& \quad \quad e^{2\gamma_2 d} \left[ \begin{array}{c}
Z_1(1+i) - Z_2(1-i)
\end{array} \right] \left[ \begin{array}{c}
Z_3 + Z_2
\end{array} \right] = \left[ \begin{array}{c}
Z_1(1+i) + Z_2(1-i)
\end{array} \right] \\
& \quad \quad e^{2\gamma_2 d} \left[ \begin{array}{c}
Z_1 - Z_2
\end{array} \right] + \rho(Z_1 + Z_2) \left[ \begin{array}{c}
Z_3 + Z_2
\end{array} \right] = \left[ \begin{array}{c}
(Z_1 + Z_2) + \rho(Z_1 - Z_2)
\end{array} \right] \\
& \rho \left[ e^{2\gamma_2 d} \left( \begin{array}{c}
Z_3 + Z_2
\end{array} \right) \left( \begin{array}{c}
Z_1 + Z_2
\end{array} \right) \right] - (Z_1 - Z_2) = \left[ \begin{array}{c}
(Z_1 + Z_2) - e^{2\gamma_2 d} \left( \begin{array}{c}
Z_3 + Z_2
\end{array} \right) (Z_1 - Z_2)
\end{array} \right] \\
& \quad \quad \rho = \left[ \begin{array}{c}
(Z_1 + Z_2) - e^{2\gamma_2 d} \left( \begin{array}{c}
Z_3 + Z_2
\end{array} \right) (Z_1 - Z_2)
\end{array} \right] \left[ \begin{array}{c}
\begin{array}{c}
\gamma_2 (1+i)
\end{array}
\end{array} \right] \\
& \quad \quad e^{2\gamma_2 d} \left( \begin{array}{c}
Z_3 + Z_2
\end{array} \right) (Z_1 + Z_2) \\
& \quad \quad e^{2\gamma_2 d} \left( \begin{array}{c}
Z_3 + Z_2
\end{array} \right) (Z_1 - Z_2)
\end{align*}
\]

Defining

\[
\begin{align*}
\gamma_{1,2} &= \frac{Z_2 - Z_1}{Z_2 + Z_1} \\
\gamma_{2,3} &= \frac{Z_3 - Z_2}{Z_3 + Z_2}
\end{align*}
\]
\[
\begin{align*}
\rho &= \left[ e^{-2\gamma_2 d \left( \frac{Z_3-Z_2}{Z_2+Z_3} \right)} \left( \frac{Z_1-Z_2}{Z_1+Z_2} \right) \right] = \left[ e^{-2\gamma_2 d \left( \frac{\Gamma_{2,3}}{\Gamma_{1,2}} \right)} - \left( \frac{\Gamma_{1,2}}{\Gamma_{1,2}} \right) \right] \\
&\quad \left[ 1-e^{-2\gamma_2 d \left( \frac{Z_3-Z_2}{Z_3+Z_2} \right)} \left( \frac{Z_1-Z_2}{Z_1+Z_2} \right) \right]
\end{align*}
\] (22i)

Since regions one and three are free space, the following is true

\[
\Gamma_{2,3} = -\Gamma_{1,2}
\] (22j)

and Eq (22i) reduces to

\[
\rho = \Gamma_{1,2} \left[ 1 - \frac{1 - e^{-2\gamma_2 d}}{1 - e^{-2\gamma_2 d}} \right] = \Gamma_{1,2} \left[ 1 - \frac{1 - \gamma^2}{1 - \gamma^2 \Gamma_{1,2}} \right]
\] (22k)

The solution for the transmission coefficient \( \tau \) follows from Eq (19)

\[
\begin{align*}
\tau &= e^{(\gamma_2 - \gamma_3) d} \left[ \frac{Z_2 + Z_3}{Z_3} \right] \left[ \frac{Z_1(1+\rho) + Z_2(1-\rho)}{Z_1} \right] \\
&= e^{\gamma_2 d} e^{-\gamma_2 d} \left[ \frac{Z_3}{Z_2 + Z_3} \right] \left[ \frac{1}{Z_3} \right] \left[ (Z_1 + Z_2) + \pi(Z_1 - Z_2) \right] \\
&= e^{\gamma_2 d} e^{-\gamma_2 d} \left[ \frac{Z_1 + Z_2}{Z_2 - Z_3} \right] \left[ \frac{Z_3}{Z_1} \right] \left[ 1 + \pi(Z_1 - Z_2) \right]
\end{align*}
\] (23a, 23b, 23c)
For the system being studied, \( Z_1 = Z_3 \) and \( \tau = \Gamma_{1,2} \)

\[
\tau = e^{\gamma_3d} e^{-\gamma_2d} [1 - \rho \Gamma]
\]  

(23d)

The expression for the reflection coefficient \( \rho \) in Eq (22k) is substituted into Eq (23d) to give

\[
\tau = e^{\gamma_3d} e^{-\gamma_2d} \left[ 1 - \Gamma \left( \frac{1-e^{-2\gamma_2d}}{1-\Gamma^2 e^{-2\gamma_2d}} \right) \right]
\]  

(23e)

\[
\tau = e^{\gamma_3d} e^{-\gamma_2d} \left[ \frac{1-\Gamma^2}{1-\Gamma^2 e^{-2\gamma_2d}} \right] = e^{\gamma_3d} Z \left[ \frac{1-\Gamma^2}{1-\Gamma^2 Z^2} \right]
\]  

(23f)

In order to use scattering coefficients \( S_{11} \) and \( S_{21} \) to calculate the complex permittivity and permeability of radar absorber design material, they must be extracted from the measured reflection coefficient \( \rho \) and transmission coefficient \( \tau \). The relationship between \( \rho \), \( \tau \), \( S_{11} \) and \( S_{21} \) becomes apparent when the signal flow graph in Figure 3 is used to evaluate closed form expressions for the scattering coefficients \( S_{11} \) and \( S_{21} \).

The development of closed form expressions for \( S_{11} \) and \( S_{21} \) will follow that which was presented in a technical memorandum published for the Air Force Avionics Laboratory (Kent, 1979). This material is also an extension of the signal flow graph ideas presented by Nicolson (1970).
Figure 3. Signal Flow Graph for Sample
When the incident wave strikes the front face of the sample, part of the wave is transmitted and part is reflected. The amplitude of the reflected wave, in terms of the amplitude of the incident wave, denoted $V_A^-$, is easily calculated from the signal flow graph to be

$$|V_A^-| = \Gamma V^+_{\text{inc}} \quad (24)$$

where

$$\Gamma = \frac{Z_2 - Z_0}{Z + Z_0} \quad (25)$$

The amplitude of the transmitted wave, at $x = 0$, is found to be

$$|V_A^+| = (1 + \Gamma) V^+_{\text{inc}} \quad (26)$$

where

$$(1 + \Gamma) = \frac{2Z_2}{Z_2 + Z_0} \quad (27)$$

Once the transmitted wave strikes the far face of the sample ($x = d$, or point B), part of this wave is reflected back and part is transmitted out the end. Since our substance of interest is electrically and magnetically lossy, complex $\mu$ and $\epsilon$, the wave amplitude will suffer some attenuation as it travels through the sample with a propagation constant $\gamma = \alpha + j\beta$. Therefore, the propagation constant

21
is \( \gamma = \alpha + j \beta = j \sqrt{\mu_{ec}} = j \frac{\omega}{c} \sqrt{\mu_r^{*} \epsilon_r^{*}} \). The magnitude of the incident wave at B will be reduced by the attenuation portion of

\[ \exp \left( -j \frac{\omega}{c} \sqrt{\mu_r^{*} \epsilon_r^{*}} d \right) \]

from that of its amplitude at \( x = 0 \) or point A. By defining \( z = \exp \left( j \frac{\omega}{c} \sqrt{\mu_r^{*} \epsilon_r^{*}} d \right) \) where \( \mu_r^{*} = \mu_r' - j \mu_r'' \) and \( \epsilon_r^{*} = \epsilon_r' - j \epsilon_r'' \), the incident wave at \( x = d \) is found to be

\[
|V_{Binc}^+| = z|V_A^+| = z(1 + \Gamma) V_{inc}^+
\]

(28)

The fraction of the incident wave transmitted out to the far end is

\[
V_B^+ = \left( \frac{2Z_0}{Z_L + Z_0} \right) zV_A^+ = (1 - \Gamma) zV_A^+ = (1 - \Gamma)(1 + \Gamma) zV_{inc}^+
\]

(29)

So, as a first approximation, the magnitude of the reflected and transmitted wave amplitudes through this sample can be found as follows:

(a) Incident wave amplitude: \( V_{inc}^+ \)

(b) Reflected wave amplitude: \( V_A^- = i V_{inc}^+ \)

(c) Transmitted wave amplitude: \( V_B^+ = z(1 - \Gamma)V_{inc}^+ \)

This approximation fails to consider second, third, and higher order internal reflections within the sample, which could make a significant contribution to the total reflected and transmitted wave amplitudes. If the measurement system is to work for any homogeneous unknown, how
many internal reflections must be taken into account? To precisely answer this question, consider the signal flow graph that simplifies the description of this system without loss of accuracy.

If one takes "n" interactions of the loop representing the internal reflections of the samples and allows the number n to approach infinity, then the amplitude of the transmitted wave can be expressed as an infinite series of the following form

\[ V_B^+ = V_{inc}^+ \left\{ (1 + \Gamma)(1 - \Gamma) z + (1 + \Gamma)(1 - \Gamma) z (\Gamma z)(\Gamma^2 z) \right\} \ldots \] (30a)

\[ V_B^+ = V_{inc}^+ \left\{ z(1 - \Gamma^2) + z^2 \Gamma^2 (1 - \Gamma^2) + z^5 \Gamma^4 (1 - \Gamma^2) + \ldots + z^{2n+1} \Gamma^{2n}(1 - \Gamma^2) \right\} \] (30b)

\[ V_B^+ = V_{inc}^+ (1 - \Gamma^2)(z)(1 + z^2 \Gamma^2 + z^4 \Gamma^4 + z^6 \Gamma^6 + \ldots + z^{2n} \Gamma^{2n}) \] (30c)

\[ V_B^+ = V_{inc}^+ \left( \frac{1 - \Gamma^2)(z)}{1 - \Gamma^2 z^2} \right) (1 + z^2 \Gamma^2 + z^4 \Gamma^4 + z^6 \Gamma^6 + \ldots + z^{2n} \Gamma^{2n})(1 - \Gamma^2 z^2) \] (30d)

\[ V_B^+ = V_{inc}^+ \left( \frac{1 - \Gamma^2)z}{1 - \Gamma^2 z^2} \right) \] (30e)

As one can see, the above is a very convenient closed form expression for the transmission scattering coefficient. Since this transmission scattering coefficient is, in general, a function of frequency, it follows that
which can be conveniently expressed as follows

\[ S_{21}(\omega) = \frac{V_B^+}{V_{\text{inc}}^+} \]  

(31)

Similarly, the amplitude of the reflected wave can be expressed as an infinite series. A closed form is also desired.

\[ V_A^- = V_{\text{inc}}^+ \frac{(\Gamma + (\Gamma) (1 - \Gamma) z (-\Gamma z) + (1 + \Gamma) (1 - \Gamma) z (-\Gamma z) (-\Gamma z)^2 + \ldots)}{1 - \Gamma^2 z^2} \]  

(33a)

\[ V_A^- = V_{\text{inc}}^+ \frac{(1 - (1 - \Gamma^2) z^2 - (1 - \Gamma^2) z^4 - (1 - \Gamma^2) z^6 - \ldots - (1 - \Gamma^2) z^{n+2} \Gamma^2 \Gamma^2 \Gamma^2 \ldots)}{1 - \Gamma^2 z^2} \]  

(33b)

\[ V_A^- = V_{\text{inc}}^+ \frac{(1 - \Gamma^2 z^2)}{(1 - \Gamma^2 z^2)} \frac{(1 - (1 - \Gamma^2) z^2 - (1 - \Gamma^2) z^4 - (1 - \Gamma^2) z^6 - \ldots - (1 - \Gamma^2) z^{n+1} \Gamma^2 \ldots)}{1 - \Gamma^2 z^2} \]  

(33c)

\[ V_A^- = V_{\text{inc}}^+ \frac{(1 - \Gamma^2 z^2) \Gamma \Gamma \Gamma \ldots}{(1 - \Gamma^2 z^2)} \frac{1 - z^2 + \Gamma^2 z^2 - \Gamma^2 z^2 - \Gamma^2 z^2 - \Gamma^2 z^6 - \ldots - z^{n+2} \Gamma^2 \Gamma^2 \Gamma^2 \Gamma^2 \ldots}{1 - \Gamma^2 z^2} \]  

(33d)

\[ V_A^- = V_{\text{inc}}^+ \frac{(1 - z^2) \Gamma \Gamma \Gamma \ldots}{(1 - \Gamma^2 z^2)} \frac{1 - z^2 + \Gamma^2 z^2 - \Gamma^2 z^2 - \Gamma^2 z^6 - \ldots - z^{n+2} \Gamma^2 \Gamma^2 \Gamma^2 \Gamma^2 \ldots}{1 - \Gamma^2 z^2} \]  

(33e)
A closed form relation between the incident wave amplitude and the reflected wave amplitude has been obtained. As with the transmission scattering coefficient, the reflection scattering coefficient can also be defined as a function of frequency.

\[
S_{11}(\omega) = \frac{V_r}{V_{inc}} = \frac{(1 - \frac{z^2}{\omega^2})\Gamma}{(1 - i^2 z^2)}
\]  

(34)

Therefore, it becomes apparent that the measured value of reflection coefficient \( \rho \) is equal to the reflection scattering coefficient and the transmission coefficient \( \tau \) differs from the transmission scattering coefficient by the phase term \( \exp (\gamma_0 d) \).

\[
S_{11} = \rho = \frac{(1 - \frac{z^2}{\omega^2})\Gamma}{(1 - i^2 z^2)}
\]  

(35)

\[
S_{21} = \frac{1}{\gamma_0 d} = \frac{e^{\gamma_0 d}}{(1 - i^2 z^2)} \frac{z(1 - i^2 z^2)}{(1 - i^2 z^2)} \frac{-1}{\gamma_0 d} = \frac{z(1 - i^2 z^2)}{(1 - i^2 z^2)}
\]  

(36)

where

\[
\gamma_0 = j\omega \sqrt{\mu_0 \varepsilon_0}
\]  

(37)

The reflection and transmission scattering coefficients can thus be determined. The following details show how they are used to calculate the complex \( \mu \) and \( \varepsilon \) values of a radar absorber design material.
A variable $x$ will be defined as the ratio of $1 - V_1 V_2$ and $V_1 - V_2$.

$$x = \frac{1 - V_1 V_2}{V_1 - V_2}$$  \hspace{1cm} (40)$$

By direct substitution of the defining expressions for the scattering coefficients into Eq (40) yields the following equation

$$x = \frac{(1 + z^2)(1 - z^2)}{2i(1 - z^2)} \cdot \frac{1}{2i} + 1$$  \hspace{1cm} (41)$$

This equation can be solved for $\Gamma$.

$$\Gamma = x \sqrt{x^2 - 1}$$  \hspace{1cm} (42)$$

where the plus or minus sign is chosen to restrict $\Gamma$'s magnitude to less than one in absolute value.
Again, direct substitution of the defining expressions for the scattering coefficients, in Eq (33), yields an equation for \( z \) in terms of \( V_1 \) and \( \Gamma \).

\[
z = \frac{V_1 - \Gamma}{1 - V_1 \Gamma}
\]

(43)

From Eq (1), define

\[
C_1 = \frac{V_1 - \Gamma}{1 - V_1 \Gamma} = \left( \frac{1 + j}{1 - j} \right)^2
\]

(44)

and from the definition of \( z = \exp(-j \frac{\omega}{c} \sqrt{u_r^* u_r} \cdot d) \), define

\[
C_2 = \frac{V_1 - \Gamma}{1 - V_1 \Gamma} = -i \frac{c}{d \omega} \ln \left( \frac{1}{z} \right)^2
\]

(45)

Then,

\[
\sqrt{C_1 C_2}
\]

(46)

\[
\sqrt{C_2 C_1}
\]

(47)

Thus, the complex permittivity and permeability are easily calculated from a knowledge of the reflection and transmission scattering coefficients. Because the reflection coefficient is measured using an H-plane sectoral horn, the theory that underlies this horn will be presented next.
The following theory on the H-plane sectoral horn was taken from a published article by W. L. Barrow and I. J. Chu (1939). It is presented here for the special case which was implemented as part of this thesis.

Using the geometry of the sectoral horn depicted in Figure 4, Maxwell's equations in a form suitable for our problem yield the following components of electric field \( E_y \) and magnetic field \( (H_\rho, H_\phi) \):

\[
E_y = B \cos(mv) K_{mv} \left(\frac{2\pi \rho}{\lambda}\right) \tag{48}
\]

\[
H_\rho = B \frac{mv}{j\omega\mu} \sin(mv) K_{mv} \left(\frac{2\pi \rho}{\lambda}\right) \tag{49}
\]

\[
H_\phi = -Bj\sqrt{\frac{\varepsilon}{\mu}} \cos(mv) K_{mv} \left(\frac{2\pi \rho}{\lambda}\right) \tag{50}
\]

In these expressions, the complex quantities are independent of the time and depend on the space variable only. The actual field is the real part of \( E e^{j\omega t} \) and \( H e^{j\omega t} \). Here \( K_{mv} \) is the derivative of \( K_{mv} \), the Hankel function, with respect to its argument \( (2\pi \frac{\rho}{\lambda}) \) and \( \lambda \) is the wavelength of a plane wave in an unbounded medium of constant \( \mu \) and \( \varepsilon \). The remaining components of field are zero, i.e.,

\[
H_y = E_\rho = E_\phi = 0 .
\]

The metal is assumed to have an infinitely high conductivity.

The boundary conditions require that the tangential component of the electric field vanish at the boundary. There is no electric field in our wave tangential to the top and bottom surfaces of the horn, hence
the boundary conditions are automatically satisfied for $y = 0, a$.

At the two sides, where $\xi = \pm \phi_0/2$, $E_y$ must vanish, so we must have

$$\cos \left( m \xi \phi_0/2 \right) = 0$$

This equation can be satisfied by letting the integer $m$ be odd $(1, 3, 5, \ldots)$ and

$$v = \frac{\pi}{\phi_0}$$

(52)

The integer $m$ specifies the order of the wave. Physically, it indicates the number of half-period sinusoidal variations between the two sides of any component of the field along an arc $\xi =$ constant. The constant $v$ depends only on the flare angle $\phi_0$, as specified by Eq (52). Since $m$ is always associated with $v$ as a product, the product

$$mv = \frac{nm}{\phi_0}$$

(53)

determines the behavior of the wave inside the horn. Only those $H_{m,0}$ waves which have an electric field of even symmetry about the center of the horn radiate beams with a central lobe.

Several advantages are gained by using the sectoral horn for the measurement of reflection and transmission coefficients. Near the
throat, the radial component of the magnetic field is still of considerable magnitude, but in the more distant parts of the horn, where \( \rho \) is large, the component \( H_\rho \) becomes negligible compared to the other two field components. Both the magnetic and electric field lines are normal to each other and to the direction of propagation, and the waves at the mouth of the horn behave very much as do transverse electromagnetic waves in free space. Thus, a sample placed at the mouth of a sectoral horn with a large radius \( (\rho) \) would experience a closely approximated normally incident plane wave condition.

Lower signal power requirements can be realized by using the sectoral horn to approximate a normally incident plane wave on the sample. The usual technique to obtain a plane wavefront is to remove the sample far from the transmitting source. In this case, power loss increases with separation. The sectoral horn allows the sample to be placed within the mouth area, as if inside a wave guide, where the power is reduced only by wall losses.

The total area of the sample used for measurements is typically greater than that of samples used in the time domain. This aspect would reduce some of the delicate machining needed to make small samples.
III. Equipment

During the course of this work, there were two operating systems developed. The first system was a test setup and used an anechoic chamber and a modified H-plane sectoral horn to measure the transmission and reflection coefficients, respectively. A full description of this setup is provided in Appendix B. The second system utilizes the two H-plane sectoral horns. It is this second system which is reported on in the main body of the thesis.

The major pieces of equipment used in the frequency domain measurement system will be described first. Then a full description of how these major pieces of equipment are assembled for intrinsic property measurements will be given.

The equipment used to support this thesis project consisted of a frequency synthesizer which served as the signal source, a network analyzer used for making relative decibel amplitude and phase measurements, a two sectoral horn assembly and sample holder used to measure reflection and transmission coefficient parameters, and a Hewlett-Packard 21MX RTE computer used to control the measurement setup. The complete measurement setup is diagrammed in Figure 1.

**Frequency Synthesizer**

The signal source is a Watkins and Johnson model 1204-1; rapidly tunable over a frequency range of 0.1 to 26 GHz. The following information was taken from the Watkins and Johnson 1204-1 specification sheet. The frequency resolution is 10 kHz from 100 MHz to 249.99 MHz,
100 kHz from 250 MHz to 1.9999 GHz, and 1 MHz from 2 - 26 GHz. The frequency is displayed with a five-digit LED, in GHz, with floating decimal. The frequency accuracy is ± 0.00035% for 180 days over a 0 - 50°C range. A single frequency can be selected on the keyboard with the enter, ENT, button and displayed on the LED. The frequency can be slewed up or down in 1, 10, and 100 MHz steps as selected on the INCREMENT controls. The synthesizer sweeps repetitively upward within the following bands: 0.1 - 1 GHz, 1 - 2 GHz, 2 - 8 GHz, 8 - 13 GHz, 13 - 18 GHz, and 18 - 26 GHz. The AF symmetrical sweep about phase-locked center frequency F which is displayed on the LED readout is 0 to ± 0.1% of F. The synthesizer provides 0 dBm (1 mw) minimum leveled output power. The variations in leveled power for the 0 dB attenuator setting is ± 1 dB over the range of 0.1 - 26 GHz. The output power can be attenuated over a range of 0 to 90 dB in 10 dB steps. The output power accuracy (meter reading plus attenuator setting) is: 0 dB attenuator setting, 0.1 - 18 GHz, ± 1 dB and 18 - 26 GHz, ± 1 dB; 10 dB - 90 dB attenuator setting, ± 2 dB and 18 - 26 GHz, ± 2.5 dB.

Network Analyzer

The network analyzer is a Hewlett-Packard Model 8410A with a phase-gain indicator. The 8413A phase-gain indicator uses a meter display. The 8411A harmonic frequency converter provides RF-to-IF conversion. The 8411A converter has been modified under Option 018 to work across the Ku band. The VSWR at the reference and test port under Option 018 increases to 10 at 18 GHz. Measurements are based
on the use of two wideband samplers to convert the input frequencies to a constant IF frequency. RF-to-IF conversion takes place entirely in the harmonic frequency converter, which converts frequencies over a range of 12.4 - 18 GHz to 20 MHz IF signals. The phase and amplitude of the two RF input signals are maintained in the IF signal. The network analyzer mainframe provides the phase-lock circuitry to maintain the 20 MHz IF frequency while frequency is being swept, takes the ratio of the reference and test channels by use of identical AGC amplifiers, and then converts down to a second IF at 278 kHz. It also has a precision 0 to 69 dB IF attenuator with 10 and 1 dB steps for accurate IF substitution measurements of gain or attenuation. The frequency domain measurement setup utilized the following piece of equipment during data measurements: a plug-in for the 8410A mainframe, the 8413A phase-gain indicator. It compares the amplitudes of the two IF signals and provides a meter readout of their ratio directly in dB with 0.1 dB resolution. It also compares phase in degrees over a 360° unambiguous range with 0.2° resolution on the meter. Phase difference is presented on the same meter when the appropriate function button is depressed. This plug-in has two analog output ports accessible from the front, one for dB amplitude, 20 mv/db, and one for phase, 50 mv/degree.

**Horn Assembly**

The H-plane sectoral horn assembly and sample holder is constructed from aluminum. There are three major parts comprising this assembly. The two horns, the sample holder/reference slide section, and the
sample holder itself. The individual pieces are depicted in Figure 5.

The two sectoral horns are placed mouth to mouth and form the central part of the measurement system. The full length of the horn section is 310.5 cm. The inner dimensions at the end flange region are 1.6 cm x 0.8 cm, and at the mouth 9.5 cm x 0.8 cm. The two horns are connected at the sample holder area.

The sample holder section is made up of a 6 cm x 5 cm x 15 cm solid block slider which fits inside the 10.5 cm x 11 cm x 15 cm rectangular housing. There are three windows cut along the length of the slider section. In the center window, the slider section has a shorting plate made of stainless steel used to obtain the reference for making reflection coefficient measurements. At one end of the slider, there is an open rectangular window measuring 9.5 cm x 0.8 cm which is used to obtain the reference for making transmission coefficient measurements. The third window is used to hold the sample during measurement.

The sample holder is removed from the slider section during sample installation. The overall dimensions of the sample holder are 11.3 cm x 5 cm x 3 cm. A 9.5 cm x 0.8 cm window in the sample holder serves to accommodate the sample. A set screw at one side is used to apply a small amount of pressure on the sample to hold it in place so it does not become misaligned during installation of the sample holder in the slider.

A gauge block is used when mounting the sample material into the sample holder. The gauge block provides a means to position the sample's front face at the same plane as the shorting plate for
reflection coefficient measurements. The sample holder is placed on the gauge block with the 1.119 cm raised section inserted in the sample window. The sample is placed in the sample window and forced firmly against the raised section as the set screw is tightened.

21MX Computer

The Hewlett-Packard 21MX computer is used to control the data measurement. The frequency synthesizer is commanded to a discrete frequency by the computer and a data measurement taken through the computer A/D converter connected to the outputs of the network analyzer. The disk subsystem and I/O devices are used to store, process, and display the results of a data run. The computer software is provided in Appendix A.

With some insight into the main parts of the frequency domain measurement system, the rest of this chapter will deal with describing the system as a whole and how it is interconnected. This description is an amplification of Figure 1.

Measurement System

The Watkins and Johnson 1204-1 Synthesizer serves as the signal source. It is commanded by the 21MX computer to discrete frequencies as part of the intrinsic property measurement routine. The RF signal is routed from the signal synthesizer to the Ku band wave guide by means of a six foot coaxial cable (C1803-72 HAW Associates, Inc., Burlington, MA). The cable connects into a Narda 4609, 12.4 to 18 GHz, coaxial to wave guide adapter. The Narda adapter is attached to a
20 dB Hewlett-Packard (HP) directional coupler, model number P7520. The 20 dB coupler couples a portion of the signal into the reference port of the HP 8411 Harmonic Frequency Converter (modified with Option 018 to extend its capability from 12.4 to 18 GHz). The main RF signal is fed into a second directional coupler. This second HP directional coupler, Model P752A, couples 3 dB of the signal into a third directional coupler and sends the rest of the signal into a matched load. The third HP coupler, model number P752A, is used to couple 3 dB of reflected signal from the sample or short into an FXR model Y641A switch and then into the test port of the harmonic frequency converter during reflection coefficient measurements. During transmission coefficient measurements, any reflected signal coupled through this 3 dB coupler is switched into a Waveline Type 754 matched load.

For transmission coefficient measurements, the RF signal which transmits through the sample is routed into the test port of the harmonic frequency converter through a PRD Electronics, Inc. Type 1208 Isolator and the switch. The transmitted signal through the sample is terminated in a matched load at the switch during reflection coefficient measurements.

The harmonic frequency converter provides the IF signal to the HP 8410B Network Analyzer. The analog amplitude and phase ports on the front of the HP 8413A Phase-Gain Indicator are read by the computer. An HP Plug-In 20 kHz Analog-to-Digital Interface Subsystem located in the 21MX computer, machine model HP2108A, converts the analog inputs to digital values used for computation. A Tektronix 4006-1 CRT
Terminal is the operator control center for sample measurements. Finally, the processed mu and epsilon data are routed from the computer to the HP 2635A Line Printer or, for plots of mu and epsilon, to the Tektronix 4631 Hard Copy Unit.
IV. Procedure

1. The sample is prepared by cutting a 9.5 x 0.8 cm rectangular piece from the material to be measured.
   1a. The sample is cut to fill the sample window completely.
   1b. The thickness of the sample in mils is determined for use in the computer program.

2. The frequency synthesizer and network analyzer are turned on for a half hour before any measurements are to be taken.

3. The frequency synthesizer and network analyzer are adjusted for making measurements. The slider section in the sample holder assembly is positioned with the shorting plate in the sectoral horn and the reflected signal line is switched to the test port of the harmonic frequency converter as shown in Figure 1.
   3a. The local/remote switch at the back of the frequency synthesizer is placed in local.
   3b. The Ku band midrange frequency of 15 GHz is entered at the frequency synthesizer keyboard and the output signal power level is set to +3 dbm.
   3c. The network analyzer is adjusted to read 0 dB on the 3 dB amplitude scale by means of the amplitude vernier and the amplitude gain amplifier.
   3d. The amplitude meter is switched to the 30 dB scale and an additional 30 dB is added to the test signal amplitude.
gain amplifier to insure an adequate operating range when making measurements.

3e. The phase offset dial on the network analyzer is placed at +20°. This value is arbitrary since the coefficient phase measurements are only difference values between a reference phase and the phase associated with reflections off and transmissions through the sample.

3f. The local/remote switch on the frequency synthesizer is set to remote. This mode enables communications between the computer and frequency synthesizer.

4. The computer program is initiated and a statement about the sample is typed in for use as a heading on the relative mu/epsilon output data at the line printer.

4a. The sample thickness in mils is entered for use in calculating the relative mu/epsilon data of the sample.

4b. The beginning and ending frequencies in GHz are entered next.

4c. The number of frequencies to be measured is entered. The frequency increment is determined in the computer routine by the equation

\[ \Delta F = \frac{\text{End Frequency} - \text{Start Frequency}}{\text{No. of Frequencies to be Measured} - 1} \]

This routine allows the first frequency measured to be the start frequency.
4d. The main command listing is displayed on the CRT and the characteristic of the system can now be measured.

5. Under ideal conditions, the relative mu and epsilon values are determined using the free space values $\mu_0$ and $\epsilon_0$. However, it is possible to measure a $\mu_0$ and $\epsilon_0$ value for the frequency domain system which has slight deviations from the free space values. These new measured values of $\mu_0$ and $\epsilon_0$ can be complex and characterize how well the frequency domain measurement system approximates free space. A typical plot of $\mu_0$ and $\epsilon_0$ characterizing the measurement system is given in Figure 6A and 6B. The system measured values of $\mu_0$ and $\epsilon_0$ are used to renormalize the relative mu and epsilon data calculated for the sample prior to output.

5a. The sample holder with no sample installed is used in the system characteristic measurement.

5b. The coding plate is placed at the center of the horn assembly and the reflection signal line is switched into the test port of the harmonic frequency converter.

5c. The reflection coefficient measurement routine is entered and the reference values are measured and stored.

5d. At the end of the reference measurement routine, the sample holder window is placed at the center of the horn assembly and the sample measurement routine entered.

5e. At the end of the sample measurement routine, the computer has calculated and stored the reflection coefficient values.
5f. At this time, the slider is repositioned with the open reference window at the center of the horn assembly and the transmission signal line is switched into the test port of the harmonic frequency converter.

5g. The transmission coefficient measurement routine is entered and the reference values through the open window are measured and stored.

5h. When the reference measurements are complete, the sample window is again slid to the center of the horn assembly and the sample measurement routine entered. The transmission coefficient is calculated and stored.

5i. At this point, the mu/epsilon calculation routine is entered. During this calculation, the thickness value used for computation of mu and epsilon is 200 mils if this is the first measurement run after entering the program. If this is not the first measurement run after entering the program, the thickness value used for calculation is that thickness entered at the beginning of the program for the sample.

5j. The system characteristic values are stored for renormalization of sample relative mu and epsilon values.

6. The reflection coefficient measurement routine is re-entered and the sample to be measured is installed in the sample holder.

6a. The sample holder is removed from the slider section and placed on the gauge block with the raised section inserted.
in the sample window such that the set screw is to the right. The sample is inserted and pressed firmly against the raised section of the gauge block. The set screw is adjusted to hold the sample tightly.

6b. The sample holder is re-installed in the slider section with the set screw away from the shorting plate.

6c. The $\mu$ and $\epsilon$ values are determined by following the steps from 5b to 5i.

7. The relative $\mu$ and $\epsilon$ values calculated for the sample are renormalized and then routed as numeric data output to the line printer or as plots to the hard copy unit. When the plot option is used to display the output data, a statement about the sample must be entered to serve as a title for the plots.
V. Results

To demonstrate the feasibility of the frequency domain measurement system, fiberglass, two thicknesses of plexiglas, teflon, and an FGM-40 absorber were measured and their relative permittivity and permeability values calculated. These values were compared to the relative permittivity and permeability for the same fiberglass, plexiglas, teflon, and FGM-40 absorber materials measured on the time domain system. Because the frequency domain system was designed to operate in the Ku band, 12.4 to 18 GHz, and the time domain data were valid below 16 GHz (Nicolson, 1974), the data were compared between the two systems only from 12.4 to 16 GHz.

Expected Results

The relative permittivity values measured for fiberglass, plexiglas, and teflon materials are provided in the table of dielectric materials given below (Hippel, 1953).

<table>
<thead>
<tr>
<th>Dielectric Material</th>
<th>T °C</th>
<th>.1 GHz</th>
<th>.3 GHz</th>
<th>3 GHz</th>
<th>10 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated Fiberglass</td>
<td>24</td>
<td>4.8</td>
<td>4.54</td>
<td>4.40</td>
<td>4.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tan δ</td>
<td>260</td>
<td>240</td>
<td>230</td>
</tr>
<tr>
<td>Plexiglas</td>
<td>27</td>
<td>2.66</td>
<td></td>
<td>2.60</td>
<td>2.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tan δ</td>
<td>--</td>
<td>62</td>
<td>57</td>
</tr>
<tr>
<td>Teflon</td>
<td>22</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tan δ</td>
<td>&lt; 2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Values for tan δ are multiplied by 10^4.
The permeability value for these dielectrics is, of course, 
\[ \mu = \mu_r \mu_0 \text{ where } \mu_r = 1. \]

It is not known whether the laminated fiberglass listed in the table above was the same type of fiberglass material used in the thesis work. However, the permittivity value given above compares extremely well with that value obtained on the time domain system at 10 GHz.

**Fiberglass Sample**

The time domain data for the fiberglass sample are given in Figure 7A and 7B. The plot of the time domain data is for a single measurement run. The frequency domain data for the fiberglass sample are presented graphically in Figure 8A and 8B. The frequency domain data are the statistically averaged relative epsilon and mu values from ten separate measurement runs. It is assumed that the data values at any given frequency are normally distributed. The standard deviation is depicted on the plot as a vertical line above and below the mean. A complete listing of the average values of relative permittivity and permeability, along with the standard deviation, is presented in Table 1. The complex permittivity and permeability values calculated for the fiberglass sample are compared for the frequency range of 12.4 to 16 GHz in Table II.

**First Plexiglas Sample**

The complex permittivity and permeability values measured on the time domain for the 64.5 mil plexiglas sample are plotted in Figure 9A and 9B. Again, these data are for a single measurement run. The
Figure 24. Time Domain (Real) Data for 134.5 mil Fiberglass Sample
SAMPLE: 41: FIBERGLASS THICKNESS = 135 MILS.

Figure 33. Frequency Domain (Imaginary) Data for 135 mil Fiberglass Sample
<table>
<thead>
<tr>
<th>FREQUENCY (MHz)</th>
<th>$\epsilon'$</th>
<th>$\epsilon''$</th>
<th>$\mu'$</th>
<th>$\mu''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2</td>
<td>1.25</td>
<td>0.26</td>
<td>1.39</td>
<td>0.04</td>
</tr>
<tr>
<td>9.6</td>
<td>2.17</td>
<td>0.30</td>
<td>1.44</td>
<td>0.04</td>
</tr>
<tr>
<td>10.0</td>
<td>3.07</td>
<td>-0.11</td>
<td>1.48</td>
<td>0.01</td>
</tr>
<tr>
<td>10.4</td>
<td>3.96</td>
<td>-0.38</td>
<td>1.21</td>
<td>-0.06</td>
</tr>
<tr>
<td>10.8</td>
<td>4.13</td>
<td>-0.19</td>
<td>1.00</td>
<td>-0.00</td>
</tr>
<tr>
<td>11.2</td>
<td>4.07</td>
<td>-0.18</td>
<td>1.02</td>
<td>0.04</td>
</tr>
<tr>
<td>11.6</td>
<td>4.08</td>
<td>0.48</td>
<td>1.01</td>
<td>-0.12</td>
</tr>
<tr>
<td>12.0</td>
<td>4.60</td>
<td>0.54</td>
<td>0.94</td>
<td>-0.08</td>
</tr>
<tr>
<td>12.4</td>
<td>5.01</td>
<td>0.47</td>
<td>0.88</td>
<td>-0.07</td>
</tr>
<tr>
<td>12.8</td>
<td>4.83</td>
<td>0.36</td>
<td>0.92</td>
<td>-0.06</td>
</tr>
<tr>
<td>13.2</td>
<td>4.46</td>
<td>0.68</td>
<td>1.00</td>
<td>-0.14</td>
</tr>
<tr>
<td>13.6</td>
<td>4.26</td>
<td>0.57</td>
<td>1.05</td>
<td>-0.07</td>
</tr>
<tr>
<td>14.0</td>
<td>4.48</td>
<td>0.42</td>
<td>1.05</td>
<td>0.01</td>
</tr>
<tr>
<td>14.4</td>
<td>4.69</td>
<td>0.32</td>
<td>0.98</td>
<td>0.01</td>
</tr>
<tr>
<td>14.8</td>
<td>4.74</td>
<td>0.16</td>
<td>0.96</td>
<td>-0.03</td>
</tr>
<tr>
<td>15.2</td>
<td>4.63</td>
<td>0.37</td>
<td>0.99</td>
<td>0.01</td>
</tr>
<tr>
<td>15.6</td>
<td>4.27</td>
<td>0.76</td>
<td>1.03</td>
<td>0.01</td>
</tr>
<tr>
<td>16.0</td>
<td>3.97</td>
<td>0.61</td>
<td>1.09</td>
<td>0.01</td>
</tr>
<tr>
<td>16.4</td>
<td>4.14</td>
<td>0.13</td>
<td>1.05</td>
<td>0.01</td>
</tr>
<tr>
<td>16.8</td>
<td>4.88</td>
<td>-0.60</td>
<td>0.91</td>
<td>0.01</td>
</tr>
<tr>
<td>17.2</td>
<td>5.72</td>
<td>-0.94</td>
<td>0.78</td>
<td>0.10</td>
</tr>
<tr>
<td>17.6</td>
<td>6.78</td>
<td>-0.04</td>
<td>0.67</td>
<td>0.06</td>
</tr>
<tr>
<td>18.0</td>
<td>6.70</td>
<td>0.68</td>
<td>0.65</td>
<td>0.08</td>
</tr>
<tr>
<td>18.4</td>
<td>6.56</td>
<td>1.16</td>
<td>0.91</td>
<td>0.11</td>
</tr>
<tr>
<td>18.8</td>
<td>4.45</td>
<td>1.44</td>
<td>0.92</td>
<td>0.09</td>
</tr>
<tr>
<td>19.2</td>
<td>2.67</td>
<td>1.09</td>
<td>1.37</td>
<td>0.06</td>
</tr>
</tbody>
</table>

TABLE I

SAMPLE: FIBERGLASS

FREQUENCY DOMAIN DATA

THICKNESS = 134.5 MILS

53
<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>4.25+0.25</td>
<td>1.07-0.01</td>
<td>12.4</td>
<td>5.91+0.47</td>
<td>1.88-0.07</td>
</tr>
<tr>
<td>12.8</td>
<td>4.19+0.25</td>
<td>1.99-0.01</td>
<td>12.8</td>
<td>6.83+0.36</td>
<td>1.32-0.08</td>
</tr>
<tr>
<td>13.2</td>
<td>4.18+0.27</td>
<td>1.60-0.01</td>
<td>13.2</td>
<td>6.46+0.66</td>
<td>1.92-0.14</td>
</tr>
<tr>
<td>13.6</td>
<td>4.19+0.23</td>
<td>1.00-0.01</td>
<td>13.6</td>
<td>4.26+0.51</td>
<td>1.65-0.17</td>
</tr>
<tr>
<td>14.0</td>
<td>4.12+0.17</td>
<td>1.00-0.00</td>
<td>14.0</td>
<td>4.47+0.42</td>
<td>1.15-0.04</td>
</tr>
<tr>
<td>14.4</td>
<td>4.37+0.31</td>
<td>0.55+0.00</td>
<td>14.4</td>
<td>6.69+0.03</td>
<td>1.92-0.03</td>
</tr>
<tr>
<td>14.8</td>
<td>4.62+0.15</td>
<td>0.90+0.02</td>
<td>14.8</td>
<td>6.74+0.16</td>
<td>1.78-0.03</td>
</tr>
<tr>
<td>15.2</td>
<td>4.64+0.12</td>
<td>0.99+0.02</td>
<td>15.2</td>
<td>6.63+0.37</td>
<td>1.10-0.09</td>
</tr>
<tr>
<td>15.6</td>
<td>4.36+0.77</td>
<td>0.02+0.04</td>
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<td>4.27+0.76</td>
<td>1.03-0.11</td>
</tr>
<tr>
<td>16.0</td>
<td>4.20+0.01</td>
<td>0.94+0.07</td>
<td>16.0</td>
<td>3.97+0.61</td>
<td>1.09-0.11</td>
</tr>
</tbody>
</table>

**TABLE II**

**SAMPLE: FIBERGLASS**

**TIME DOMAIN SYSTEM**

THICKNESS = 134.5 MILS

**FREQUENCY DOMAIN SYSTEM**

THICKNESS = 135 MILS
Figure 5A. Time Domain (Real) Data for 64.5 mil Plexiglas Sample
SAMPLE: PLEXIGLAS 64.5 MILS 10-1-80

Figure 90. Time Domain (Imaginary) Data for 64.5 mil Plexiglas Sample
frequency domain data for a 65.5 mil plexiglas sample is shown in Figure 10A and 10B. As before, this frequency domain data is the mean and standard deviation for ten data runs. The mean and standard deviation calculated for the mu and epsilon values are presented in Table III. The comparison for the time domain and frequency domain data is presented in Table IV for the frequency range from 12.4 to 16 GHz.

Second Plexiglas Sample

The time domain data obtained for the 174 mil plexiglas sample are presented graphically in Figure 11A and 11B for a single measurement run. The frequency domain data for the 174 mil plexiglas sample are presented in Figure 12A and 12B. As before, the frequency domain data are the mean values of ten runs and the standard deviations are presented in Table V. The comparison of the 174 mil plexiglas data for the time and frequency domain systems from 12.4 to 16 GHz are given in Table VI.

Repeatability

The statistics developed for the frequency domain data measurements show the repeatability of the measurement technique. During each of the data runs the network analyzer was turned off and on, or the sample was removed from the sample holder and re-installed. The system configuration did not allow for power removal from the computer or the frequency synthesizer.
Figure 113.  Frequency Domain (Imaginary) Data for 65.5 mil Plexiglas Sample
<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>$e'_1$</th>
<th>$e''_1$</th>
<th>$s_1$</th>
<th>$e'_2$</th>
<th>$e''_2$</th>
<th>$s_2$</th>
<th>$e'_3$</th>
<th>$e''_3$</th>
<th>$s_3$</th>
<th>$e'_4$</th>
<th>$e''_4$</th>
<th>$s_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2</td>
<td>1.57</td>
<td>.12</td>
<td>1.22</td>
<td>.05</td>
<td>1.65</td>
<td>.02</td>
<td>-1.15</td>
<td>.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.6</td>
<td>2.10</td>
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### TABLE IV
SAMPLE: PLEXIGLAS

**TIME DOMAIN SYSTEM**
THICKNESS = 64.5 MILS

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**FREQUENCY DOMAIN SYSTEM**
THICKNESS = 65.5 MILS

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Figure 11A. Time Domain (Real) Data for 174 mil Plexiglas Sample
Figure 113. The Domain (Imaginary) Data for 174 mil Plexiglas Sample
SAMPLE: #3: PLEXIGLAS THICKNESS = 174 MILS.

REAL PART

Figure 12A. Frequency Domain (Real) Data for 174 mil Plexiglas Sample
### Table V

**Sample: Plexiglas**

**Frequency Domain Data**

**Thickness = 1/4 Mil**

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<td></td>
</tr>
<tr>
<td>14.7</td>
<td>2.54 + j0.14</td>
<td>0.99 - j0.94</td>
<td>14.7</td>
<td>2.72 + j0.05</td>
<td>0.98 - j0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.2</td>
<td>2.41 + j0.17</td>
<td>1.00 - j0.35</td>
<td>15.2</td>
<td>2.67 + j0.10</td>
<td>1.00 - j0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.3</td>
<td>2.32 + j0.25</td>
<td>1.06 - j0.06</td>
<td>15.3</td>
<td>2.67 + j0.20</td>
<td>1.03 - j0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16.0</td>
<td>2.30 + j0.35</td>
<td>1.05 - j0.16</td>
<td>16.0</td>
<td>2.39 + j0.17</td>
<td>1.07 - j0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The time domain data for the teflon sample are given in Figure 13A and 13B. The plot of the time domain data is for a single measurement run. The frequency domain data for the teflon sample is presented graphically in Figure 14A and 14B. The frequency domain data plots are for a single measurement run. A complete listing of the frequency domain data is given in Table VII. The comparison of time and frequency domain data is presented in Table VIII for the frequency range from 12.4 to 16 GHz.

**FGM-40 Absorber Sample**

The FGM-40 absorber is composed of ferrites in silicon rubber. It is an Fcosorb high-loss microwave absorber. The relative mu and epsilon values calculated for the FGM-40 absorber on the time domain system are presented graphically in Figure 15A and 15B. The frequency domain data of relative mu and epsilon are graphically presented in Figure 16A and 16B. Both the time domain and frequency domain plots are for a single measurement run. The complete listing of relative mu and epsilon values measured with the frequency domain system is given in Table IX. The comparison for the time domain and frequency domain data from 12.4 to 16 GHz is given in Table X.

Comparison of time and frequency domain data points up a problem in the frequency domain data. Although the permittivity follows a similar trend as that from the time domain, it is seen that the real part of the permittivity was approximately 25% below the values.
Figure 130. Time Domain (Imaginary) Data for 181 mil Teflon Sample
Figure 14B. Frequency Domain (Imaginary) Data for 100 mil Teflon Sample
### TABLE VII

**SAMPLE: TEFION**

**FREQUENCY DOMAIN DATA**  
**THICKNESS = 160 MILS**

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2</td>
<td>1.08+J.04</td>
<td>1.05+J.01</td>
</tr>
<tr>
<td>9.6</td>
<td>1.32+J.03</td>
<td>1.20+J.01</td>
</tr>
<tr>
<td>10.0</td>
<td>1.59+J.12</td>
<td>1.24+J.03</td>
</tr>
<tr>
<td>10.4</td>
<td>1.90+J.19</td>
<td>1.14+J.05</td>
</tr>
<tr>
<td>10.8</td>
<td>1.98+J.09</td>
<td>1.01+J.01</td>
</tr>
<tr>
<td>11.2</td>
<td>1.94+J.11</td>
<td>1.04+J.02</td>
</tr>
<tr>
<td>11.6</td>
<td>1.91+J.10</td>
<td>1.03+J.11</td>
</tr>
<tr>
<td>12.0</td>
<td>2.03+J.13</td>
<td>0.96+J.08</td>
</tr>
<tr>
<td>12.4</td>
<td>2.19+J.21</td>
<td>0.95+J.05</td>
</tr>
<tr>
<td>12.8</td>
<td>2.12+J.17</td>
<td>0.97+J.05</td>
</tr>
<tr>
<td>13.2</td>
<td>1.98+J.22</td>
<td>1.01+J.10</td>
</tr>
<tr>
<td>13.6</td>
<td>1.95+J.21</td>
<td>1.01+J.08</td>
</tr>
<tr>
<td>14.0</td>
<td>2.04+J.16</td>
<td>1.01+J.05</td>
</tr>
<tr>
<td>14.4</td>
<td>2.11+J.05</td>
<td>0.98+J.02</td>
</tr>
<tr>
<td>14.8</td>
<td>2.08+J.06</td>
<td>0.98+J.04</td>
</tr>
<tr>
<td>15.2</td>
<td>2.07+J.06</td>
<td>1.02+J.03</td>
</tr>
<tr>
<td>15.6</td>
<td>1.99+J.11</td>
<td>1.05+J.07</td>
</tr>
<tr>
<td>16.0</td>
<td>1.90+J.14</td>
<td>1.06+J.07</td>
</tr>
<tr>
<td>16.4</td>
<td>1.92+J.09</td>
<td>1.03+J.05</td>
</tr>
<tr>
<td>16.8</td>
<td>2.07+J.01</td>
<td>1.01+J.01</td>
</tr>
<tr>
<td>17.2</td>
<td>2.20+J.10</td>
<td>0.97+J.03</td>
</tr>
<tr>
<td>17.6</td>
<td>2.26+J.00</td>
<td>0.91+J.02</td>
</tr>
<tr>
<td>18.0</td>
<td>2.36+J.07</td>
<td>0.88+J.04</td>
</tr>
<tr>
<td>18.4</td>
<td>2.34+J.16</td>
<td>0.78+J.07</td>
</tr>
<tr>
<td>18.8</td>
<td>2.14+J.32</td>
<td>0.74+J.14</td>
</tr>
<tr>
<td>19.2</td>
<td>1.87+J.44</td>
<td>1.07+J.24</td>
</tr>
<tr>
<td>FREQUENCY (GHz)</td>
<td>EPSILON</td>
<td>MU</td>
</tr>
<tr>
<td>----------------</td>
<td>----------</td>
<td>---------</td>
</tr>
<tr>
<td>12.4</td>
<td>2.03+J.05</td>
<td>.98+J.00</td>
</tr>
<tr>
<td>12.8</td>
<td>2.04+J.06</td>
<td>.99+J.00</td>
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<td>.97+J.00</td>
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<td>2.07+J.03</td>
<td>.98+J.00</td>
</tr>
<tr>
<td>14.4</td>
<td>1.95+J.01</td>
<td>1.00+J.00</td>
</tr>
<tr>
<td>14.8</td>
<td>1.96+J.00</td>
<td>.99+J.02</td>
</tr>
<tr>
<td>15.2</td>
<td>1.97+J.02</td>
<td>1.01+J.01</td>
</tr>
<tr>
<td>15.6</td>
<td>1.99+J.04</td>
<td>1.00+J.05</td>
</tr>
<tr>
<td>16.0</td>
<td>1.90+J.07</td>
<td>1.03+J.06</td>
</tr>
</tbody>
</table>
Figure 75A. Time Domain (Real) Data for 37 mil FGM-40 Sample
Figure 183. Time Domain (Imaginary) Data for 37 Mil FGM-40 Sample
SAMPLE: FGM 40 ABSORBER THICKNESS = 38.5 MILS.

REAL PART

Figure 16a. Frequency Domain (Real) Data for 38.5 mil FGM-40 Sample
Figure 108. Frequency Domain (Imaginary) Data for 38.5 mil FGM-40 Sample
<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.2</td>
<td>2.78+0.83i</td>
<td>1.42+1.57i</td>
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<tr>
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<td>2.43+1.98i</td>
</tr>
<tr>
<td>10.0</td>
<td>12.73+1.71i</td>
<td>2.02+1.53i</td>
</tr>
<tr>
<td>10.4</td>
<td>18.63+2.21i</td>
<td>1.47+2.40i</td>
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<tr>
<td>10.8</td>
<td>20.27+2.21i</td>
<td>1.02+2.06i</td>
</tr>
<tr>
<td>11.2</td>
<td>20.57+1.15i</td>
<td>0.85+2.05i</td>
</tr>
<tr>
<td>11.6</td>
<td>22.38+2.17i</td>
<td>0.91+1.98i</td>
</tr>
<tr>
<td>12.0</td>
<td>24.26+3.07i</td>
<td>1.00+1.78i</td>
</tr>
<tr>
<td>12.4</td>
<td>24.29+3.95i</td>
<td>1.07+1.79i</td>
</tr>
<tr>
<td>12.8</td>
<td>22.64+2.02i</td>
<td>1.03+1.77i</td>
</tr>
<tr>
<td>13.2</td>
<td>21.60+1.63i</td>
<td>0.96+1.69i</td>
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<tr>
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<td>21.77+1.93i</td>
<td>0.84+1.67i</td>
</tr>
<tr>
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<td>23.15+1.54i</td>
<td>0.90+1.52i</td>
</tr>
<tr>
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<td>24.76+1.57i</td>
<td>0.91+1.52i</td>
</tr>
<tr>
<td>14.8</td>
<td>26.07+1.39i</td>
<td>1.10+1.48i</td>
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<td>1.17+1.68i</td>
</tr>
<tr>
<td>15.6</td>
<td>22.34+5.27i</td>
<td>0.94+1.77i</td>
</tr>
<tr>
<td>16.0</td>
<td>20.99+3.55i</td>
<td>0.65+1.71i</td>
</tr>
<tr>
<td>16.4</td>
<td>24.83-1.88i</td>
<td>0.48+1.43i</td>
</tr>
<tr>
<td>16.8</td>
<td>27.31-2.77i</td>
<td>0.35+1.27i</td>
</tr>
<tr>
<td>17.2</td>
<td>30.15+1.26i</td>
<td>0.44+1.17i</td>
</tr>
<tr>
<td>17.6</td>
<td>26.52+4.60i</td>
<td>0.62+1.24i</td>
</tr>
<tr>
<td>18.0</td>
<td>24.03+3.91i</td>
<td>0.71+1.24i</td>
</tr>
<tr>
<td>18.4</td>
<td>22.23+1.48i</td>
<td>0.52+1.22i</td>
</tr>
<tr>
<td>19.2</td>
<td>20.94+3.87i</td>
<td>0.49+1.31i</td>
</tr>
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</table>

SAMPLE: 1CM-40 ABSORBER

THICKNESS = 38.5 MILS
### TABLE X
SAMPLE: FGM-40 ABSORBER

<table>
<thead>
<tr>
<th>TIME DOMAIN SYSTEM</th>
<th>FREQUENCY DOMAIN SYSTEM</th>
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<tbody>
<tr>
<td>THICKNESS = 37.0 MILS</td>
<td>THICKNESS = 38.5 MILS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.4</td>
<td>27.20+31.20</td>
<td>1.00+31.24</td>
<td>12.4</td>
<td>24.29+32.95</td>
<td>1.07+31.79</td>
</tr>
<tr>
<td>12.6</td>
<td>27.20+31.20</td>
<td>0.80+31.92</td>
<td>12.8</td>
<td>22.64+32.92</td>
<td>1.13+31.77</td>
</tr>
<tr>
<td>13.2</td>
<td>27.20+31.20</td>
<td>0.80+31.92</td>
<td>13.2</td>
<td>21.60+31.63</td>
<td>0.68+31.53</td>
</tr>
<tr>
<td>13.4</td>
<td>26.72+30.88</td>
<td>0.80+31.92</td>
<td>13.6</td>
<td>21.77+30.93</td>
<td>0.73+31.67</td>
</tr>
<tr>
<td>14.0</td>
<td>27.20+30.96</td>
<td>0.60+31.68</td>
<td>14.0</td>
<td>23.13+31.54</td>
<td>0.50+31.61</td>
</tr>
<tr>
<td>14.4</td>
<td>32.20+30.36</td>
<td>0.40+31.66</td>
<td>14.4</td>
<td>24.76+31.54</td>
<td>0.51+31.52</td>
</tr>
<tr>
<td>14.6</td>
<td>34.50+30.88</td>
<td>0.72+31.20</td>
<td>14.6</td>
<td>25.57+31.39</td>
<td>0.70+31.45</td>
</tr>
<tr>
<td>15.2</td>
<td>34.00+30.40</td>
<td>0.96+31.25</td>
<td>15.2</td>
<td>24.34+31.70</td>
<td>1.17+31.55</td>
</tr>
<tr>
<td>15.6</td>
<td>33.20+32.60</td>
<td>1.20+32.72</td>
<td>15.6</td>
<td>22.34+35.27</td>
<td>0.94+31.77</td>
</tr>
<tr>
<td>16.0</td>
<td>32.60+32.00</td>
<td>1.20+32.00</td>
<td>16.0</td>
<td>20.99+32.55</td>
<td>0.65+31.71</td>
</tr>
</tbody>
</table>
measured on the time domain and the imaginary part of the permittivity from the frequency domain measurement could not be compared. During tests of the placement of the sample relative to the shorting plate, it was seen that the imaginary permittivity parameter was very sensitive to position within the sample holder. Also, the ICM-40 sample was seen to deform slightly when it was inserted into the sample window. This effect could not occur on the other harder samples of plexiglas, fiberglass and teflon. These factors may give a clue to the poor comparison of data for this sample. Unfortunately, time did not permit extensive investigation in this area.
VI. Conclusions and Recommendations

Conclusions

A frequency domain measurement system was developed. The intrinsic properties of fiberglass, two thicknesses of plexiglas, teflon, and an ICM-40 absorber were measured on the frequency domain and time domain systems and compared. On the basis of the results obtained from the frequency domain system, the following conclusions are drawn:

1. The feasibility of measuring intrinsic properties of materials using a frequency domain technique has been shown.

2. Repeatability was investigated for the two thicknesses of plexiglas and fiberglass. Repeatability of measurement was extremely good in the case of the two thicknesses of plexiglass, but began to show a problem in the imaginary part of the permittivity of fiberglass.

3. The comparison of data between the time domain and frequency domain system was good for the plexiglas and teflon. The fiberglass data began to show some error, especially in the area of the imaginary permittivity.

4. The greatest error was seen when measuring the ICM-40 absorber. Although the permitivity compared well for both the time domain and frequency domain data, the real part of the permittivity was approximately 25% below that of the time domain and the imaginary
FREQUENCY DOMAIN MEASUREMENTS OF MICROWAVE ABSORBER DESIGN

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part of the permittivity was not comparable.

5. The refinement of the sample holder and slider section may result in smaller errors than those seen in this study. This observation is drawn from experience gained during trouble-shooting problems in the sample holder area.

6. A possible cause of error in the frequency domain data of the FGM-40 absorber material may have been distortion of the sample during insertion into the sample window. Unlike the other materials tested, the FGM-40 absorber was rubbery and easily compressed.

Recommendations

Based on the assumptions stated initially and observations made during the investigation, the following recommendations are proposed for further study:

1. The high VSWR, which ranged up to 10 at 18 GHz, at the test and reference ports of the frequency converter, could be investigated as a source of error.

2. The sensitivity of reflection coefficients to the reference shorting plate and sample position within the sample holder could be investigated.

3. A computer model could be developed to investigate the H-plane sectoral horn plane wave approximations to TEM waves used in
this thesis and how this approximation relates to the samples' intrinsic property measurements.

4. A system characteristic was used to renormalize the relative mu and epsilon values. An investigation could be done to determine if a better technique were possible for removing inherent system error.
Bibliography


Appendix A

Control Software

The operating system controls the Hewlett-Packard network analyzer and Watkins and Johnson frequency synthesizer during parameter measurements. The software and system relationship is diagrammed below.

Figure 17. Software Control Diagram
PROGRAM CPLN3
DIMENSION IFREQ(120), IEPR(120), IEPI(120), MUR(120), MUI(1120), RMOD(120), RPHA(120), TMOD(120), TPHA(120), LU(5), IWD(32), INAME(3), IDATA(1024), J1(120), J2(120), J3(120), J4(120)

EXECUTABLE STATEMENTS FOLLOW

ZERO PRINCIPLE ARRAYS

CALL RMPAR(LU)
INAME(1)=2HWNJ
INAME(2)=2HSE
INAME(3)=1HT
SEND=EXEC(9,INAME,1)
GO TO 2 II=1,120
IFREQ(II)=0.
IEPR(II)=0.
IEPI(II)=0.
MUR(II)=0.
MUI(II)=0.
RMOD(II)=0.
RPHA(II)=0.
TMOD(II)=0.
TPHA(II)=0.
2 CONTINUE

READ IN SAMPLE NAME AND THICKNESS

WRITE(LU,10)
READ (LU,11) (IWD(I),I=1,32)
READ (LU,11) (IWQ(I),I=1,32)
11 FORMAT (32A2)
10 FORMAT("INPUT COMMENT ABOUT SAMPLE AND PRESS RETURN."
WRITE(LU,22)
23 FORMAT("PLEASE ENTER SAMPLE THICKNESS IN MILS AND PRESS RETURN."
READ(LU,4) THT

ESTABLISH START AND END FREQ AND NUMBER
OF STEP INCREMENTS.

WRITE(LU,4)
4 FORMAT("INPUT BEGINNING FREQ IN GHZ AND PRESS RETURN."
READ(LU,4) XMIN
WRITE(LU,5)
5 FORMAT("INPUT END FREQUENCY IN GHZ AND PRESS RETURN."
READ(LU,4) XMAX
WRITE(LU,6)
6 FORMAT("INPUT NUMBER OF FREQUENCY STEPS DESIRED."
READ(LU,*) M
IV=23
DELF=(XMAX-XMIN)/(M-1)

INITIAL COMMANDS FOR SYSTEM CONTROL

7 WRITE(LU,30)
30 FORMAT("MEASUREMENT/OUTPUT COMMANDS",/,"0=END",/,
1="I=REFLECTION MEASUREMENTS",/,"2=TRANSMISSION MEASUREMENTS",/,
2="3=MU,EP CALCULATION",/,
3="4=THE PRINT OF MU,EP DATA",/,"5=PLOT OF MU,EP DATA"
READ(LU,*) NCW
M=NCW+1
L30
N=NCH+1
GO TO (100, 110, 120, 130, 140, 150), N
100 WRITE (LU, 40)
40 FORMAT ("PROGRAM COMPLEX END")
INAME(1)=2HNJ
INAME(2)=2HSE
INAME(3)=1HT
PEG=EXEC(9, INAME, 0)
STOP
110 CALL REFCL (LU, RMOD, RPHA, M, XMIN, DELF)
WRITE (LU, 50)
50 FORMAT ("REFLECTION MEASUREMENT COMPLETED.")
GO TO 7
120 CALL TRANS (LU, TMOD, TPHA, M, XMIN, DELF)
WRITE (LU, 60)
60 FORMAT ("TRANSMISSION MEASUREMENT COMPLETED.")
GO TO 7
130 CONTINUE
THK=200
*IF (KY.EQ.0) THK=THT
*CALL CDATA (LU, RMOD, RPHA, TMOD, TPHA, IEPR, IEPI, MUR, MUI,
1THK, XMIN, DELF, M, IFREQ)
*IF (KY.EQ.0) GO TO 65
KY=0
GO 61 I=1, M
J1(I)=IEPR(I)
J2(I)=IEPI(I)
J3(I)=MUR(I)
J4(I)=MUI(I)
61 CONTINUE
WRITE (LU, 62)
L30
WRITE (LU, 62)
62 FORMAT ("THE CHARACTERISTIC OF THE SYSTEM HAS BEEN RECORDED.")
65 CONTINUE
WRITE (LU, 600)
600 FORMAT("ENTER '99' TO NORMALIZE DATA.")
READ(LU, *) HM
IF (HM.NE.99) GO TO 655
55 CONTINUE
DO 665 I = 1, M
665 AEP1 = FLOAT(IEPR(I))/100.
AEP2 = FLOAT(IEP1(I))/100.
CM1 = FLOAT(MUR(I))/100.
CM2 = FLOAT(MUI(I))/100.
CJ1 = FLOAT(J1(I))/100.
CJ2 = FLOAT(J2(I))/100.
CJ3 = FLOAT(J3(I))/100.
CJ4 = FLOAT(J4(I))/100.
CALL CPLEX (AEP1, AEP2, CJ1, CJ2, ANR, ANI, 2)
IEPR(I) = ANP+100.
IEP1(I) = AN1+100.
CALL CPLEX (CM1, CM2, CJ3, CJ4, AR, AI, 2)
MUR(I) = AR+100.
MUI(I) = AI+100.
CONTINUE
WRITE (LU, 66)
66 FORMAT ("MU, EP CALCULATION COMPLETED.")
GO TO 7
CONTINUE
WRITE (LU, 141)
141 FORMAT("ENTER '88' TO ENTER NORMALIZE ROUTINE.")
READ(LU, *) PN
IF (RN.EQ.88) GO TO 65
L30
IF (RN EQ. 88) GO TO 65
CALL LIST (1, M, IFREQ, IEPR, IEPI, MUR, MUI, IND)
WRITE (LU, 80)
80 FORMAT ("HARD COPY OF MU, EP COMPLETED.")
GO TO 7
150 CONTINUE
BUILD IDATA ARRAY THAT GOES ON DISC
DO 1 I=1, 120
IDATA(I) = IFREQ(I)
IDATA(I+120) = IEPR(I)
IDATA(I+240) = IEPI(I)
IDATA(I+360) = MUR(I)
IDATA(I+480) = MUI(I)
1 CONTINUE
IDATA(601) = M
DO 3 I = 1, 423
IDATA(601+I) = 0
3 CONTINUE
DISC TRACK ALLOCATION (1 TRACK)
IEEE = 0
ISET = 0
ISTREK = 0
CALL EXEC(15, 1, ISTRK, IEEE, ISET)
WRITE ARRAY DATA ON TRACKS
CALL EXEC(2, 2, IDATA, 1024, ISTRK, 0)
INAME(1) = 2MPL
INAME(2) = 2HT
L10

INAME(2)=2HT
INAME(3)=1H
LL=LU(1)
C
SCHEDULE PLOT PROGRAM (PLT)
REG=EXEC(9,INAME,ISTRK,0,0,0,LL)
C
RELEASE DISC TRACKS
CALL EXEC(16,1,ISTRK,IDISC)
WRITE(LU,90)
90 FORMAT ('"PLOT COMPLETED."')
GO TO 7
END
L30

FTN4

PROGRAM WIJSET
DIMENSION IPRAM(S)
WRITE(12,1)
1 FORMAT ("WIJSET PROGRAM ENTERED.")
C THIS PROGRAM ALLOWS THE LOCAL AND REMOTE COMMANDS
C TO BE SENT TO THE FREQUENCY SYNTHESIZER AT THE
C START AND TERMINATION OF THE MAIN PROGRAM....
CALL RMTR(IPRAM)
IF (IPRAM(1).LE.1) CALL RMO TC(23)
IF (IPRAM(1).EQ.0) CALL LOC L(13)
END

EGF
L30

CNO
SUBROUTINE RECL(LU,RMOD,RPHA,M,XMIN,DELF)
DIMENSION RMOD(1),RPHA(1),A(200),B(200)
1 WRITE (LU,2)
2 FORMAT ("REFLECTION MEASUREMENT COMMANDS",/,
1 "1=RETURN TO MAIN PROGRAM",/,"2=MEASURE SHORT",
2/,"3=MEASURE SAMPLE")
READ (LU,*) NN
GO TO (100,110,120),NN
100 RETURN
110 WRITE (LU,3)
3 FORMAT ("WOUULD YOU LIKE TO CONTROL SWEEP RANGE?",/,
1 ":=YES",/,"2=NO")
READ (LU,*) KK
GO TO (111,112),KK
111 N1=0.
K=1
AK1=0.
AK2=0.
4 WRITE (LU,5)
5 FORMAT ("ENTER START AND STOP FREQ.")
READ (LU,*) AK1,AK2
J=(AK2-AK1)/DELF
DO 7 I=N1+1,J+N1+K
FR=AK1+(FLOAT(I)*DELF)-(DELF*FLOAT(N1+K))
WRITE (23,6) FR
7 WRITE (F5.3,"e")
CALL WAIT(S00)
A(I)=0.
B(I)=0.
CALL READ(LU,A,B,I)
/
L30

DO 14 I = N1+1,J+N1+K
FR=AK1+(FLOAT(I)*DELF)-(DELF*FLOAT(N1+K))
WRITE (23,13) FR
13 FORMAT (F5.3,"E")
CALL WAIT(500)
CALL READ (LU,A,B,I)
RMOD(I)=A(I)
RPHA(I)=B(I)
WRITE (12,99) A(I),B(I),FR
99 FORMAT(F7.3,10X,F7.3,10X,F7.3)
14 CONTINUE
N1=I-1
K=0
IF (I-M) 11,1,1
140 DO 16 I=1,M
F1=(XMIN+FLOAT(I-1)*DELF)
WRITE(23,15) F1
15 FORMAT(F5.3,"E")
CALL WAIT(500)
CALL READ (LU,A,B,I)
RMOD(I)=A(I)
RPHA(I)=B(I)
16 CONTINUE
GO TO 1
END

SUBROUTINE READ (LU,A,B,I)
DIMENSION A(I),B(I),IQBUF(14),ICHAN(2),IAD(2)

C
C THIS SUBROUTINE READS DATA VALUES FROM THE
C NETWORK ANALYZER THROUGH THE A/D DEVICE.
C
L30
C
ICHAN(1)=2
ICHAN(2)=3
IRTN=0.
CALL R2313(IQ00F,14)
3 CALL SC313(9,IRTN)
IF(IRTN=1) 3,4,3
100 CONTINUE
4 CALL R2313(9,IRTN,0,2,ICHAN,2,IAD,0)
IF (IRTN) 110,110,120
110 WRITE (LU,5) IRIN
5 FORMAT ("RETURN CODE ERROR",15)
RETURN
120 V1=FLOAT(INTD(IAD(1),177760D))*.0003125
V2=FLOAT(INTD(IAD(2),177760D))*.0003125
A(I)=A(I)
B(I)=B(I)
A(I)=(V1*20.)-A(I)
B(I)=(V2*100.)-B(I)
RETURN
END
SUBROUTINE TRANS(LU,TMOD,TPHA,M,XMIN,DELF)
DIMENSION TMOD(1),TPHA(1),A(120),B(120),C(120),D(120)
1 WRITE(LU,2)
2 FORMAT("TRANSMISSION COMMANDS",/,"1=RETURN TO MAIN PROGRAM",/,
1"2=MEASURE OPEN REFERENCE WINDOW",/,
2"3=MEASURE SAMPLE")
READ (LU,x) N1
GO TO (100,110,120),N1
100 RETURN
110 DO 4 I=1,M
L30
110 DO 4 I=1,M
   F1=XMIN+(FLOAT(I-1)*DELF)
   WRITE (23,3) F1
3 FORMAT (F5.3, "E")
   CALL WAIT(500)
   A(I)=0.
   B(I)=0.
   CALL READ (LU,A,B,I)
4 CONTINUE
   GO TO 1
120 WRITE (L,U,5)
5 FORMAT ("SAMPLE MEASUREMENT COMMANDS",/,
       "1=END SAMPLE MEASUREMENT",/,
       "2=LEVEL SAMPLE RUN",/,
       "3=RAISED SAMPLE RUN")
   READ (L,U,X) KK
   GO TO (121,122,123),KK
121 CONTINUE
   GO TO 1
122 DO 7 I=1,M
   G(I)=A(I)
   D(I)=B(I)
   F1=XMIN+(FLOAT(I-1)*DELF)
   WRITE(23,6) F1
6 FORMAT (F5.3, "E")
   CALL WAIT(500)
   CALL READ (LU,A,B,I)
   TMD(I)=A(I)
   TPHA(I)=B(I)
7 CONTINUE
   GO TO 120
123 CONTINUE
L30 CONTINUE
N1=0.
K=1
AK1=0.
AK2=0.
WRITE(LU,9)
9 FORMAT("ENTER START AND STOP FREQ.")
READ(LU,X) AK1,AK2
J=(AK2-AK1)/DCLF
DO 11 I=N1+1,J+N1+K
FR=(AK1+FLOAT(I)*DCLF)-(DCLF*FLOAT(N1+K))
WRITE(23,10) FR
10 FORMAT(F5.3,"E")
CALL WAIT(500)
A(I)=C(I)
B(I)=D(I)
CALL READ(LU,A,B,I)
TMOD(I)=(TMOD(I)+A(I))/2.
TPHA(I)=(TPHA(I)+B(I))/2.
WRITE (12,99) TMOD(I),TPHA(I),FR
99 FORMAT (F5.2,10X,F5.2,10X,F5.2)
11 CONTINUE
N1=I-1
K=0
IF (I-M) 0,1,1
END
SUBROUTINE CRDATA(LU,RNOD,RPHA,TMOD,TPHA,IEPR,IEPI,MUR,MULT,TKN,DCLF,N2,IFREQ)
DIMENSION RNOD(1),RPHA(1),TMOD(1),TPHA(1),IEPR(1)
,IEPI(1),MUR(1),MULT(1),TKN(1),DCLF(1),N2(1),IFREQ(1)
,20021(120),CC2(120),CC2I(120),CC2R(120),
CC2I(120),CC2R(120),IFREQ(1)
L30 2:C2I(120),IFREQ(1)

C THE FOLLOWING SUBROUTINE CALCULATES MU AND EP.

C

FACB=1.0/THK
FACA=1.0/FACB
M=1
F=XM$1000.
DEL=DELX1000.

C BIG LOOP FOR PROCESSING MU AND EP

DO 400 I=1,N2
  REFR=0.
  REFI=0.
  DR=0.
  DI=0.
  AR=0.
  AT=0.
  TR=0.
  TA=0.
  D=0.
  XI=0.
  XR=0.
  DI=0.
  Z=0.
  D=0.
  RPHA(I)=RPHA(I)/57.3
  TPHA(I)=TPHA(I)/57.3
  REFR=(-1.)*(10.*RMD(I)/20.)*COS(RPHA(I))
  REFI=(-1.)*(10.*RMD(I)/20.)*SIN(RPHA(I))
  BR=(10.*TMD(I)/20.)*COS(TPHA(I))
L30
BR=(10.*X(TMOD(I)/20.))*COS(TPHA(I))
DI=(10.*X(TMOD(I)/20.))*SIN(TPHA(I))
PHI=PI/4*C
CALL CPLEX(BR,DI,COS(PHI),-SIN(PHI),TRAR,TRAI,1)
V1R=TRAR+RFR
V1I=TRAI+RFL1
V2R=TRAR-RFR
V2I=TRAI-RFL1
CALL CPLEX(V1R,V1I,V2R,V2I,AR,DI,1)
AR=1.0-DR
DI=-DI
CALL CPLEX(AR,DI,V1R-V2R,V1I-V2I,XR,XI,2)
CALL CPLEX(XR,XI,XR,XI,DR,BI,1)
BR=BR-1.0
CALL CPLEX(BR,BI,DUM,DUM,AR,AL,3)
GR=XR+AR
GI=XI+AI
IF(SQRT((GR*GR+GI*GI)).GT.1.0) GR=XR-AR
IF(SQRT((GR*GR+GI*GI)).GT.1.0) GI=XI-AI
CALL CPLEX(V1R,V1I,GR,GI,AR,AL,1)
CALL CPLEX(V1R-V1I,GR,GI,1.0-AR,-AI,ZR,ZI,2)
CALL CPLEX(1.0-GR,GR,GI,1.0-GR,-GI,CI,CI,2)
CALL CPLEX(ZR,ZI,DUM,DUM,AR,AL,4)
C2R=AR*FACB/F
C2I=AL*FACB/F
CC2I(M)=C2I
CC2R(M)=C2R
CC1I(M)=CI
CC1R(M)=CR
MM=M
L40
M=M+1
IF (M-N2) 365,370,370
365 CONTINUE
F=F+DEL
400 CONTINUE
370 CONTINUE
CALL SMOOTH(CC1R,MM)
CALL SMOOTH(CC1I,MM)
CALL SMOOTH(CC2R,MM)
CALL SMOOTH(CC2I,MM)

C
C COMPUTE MU AND EPSILON
C
DO 450 IJ=1,MM
C1R=CC1R(IJ)
C1I=CC1I(IJ)
C2R=CC2R(IJ)
C2I=CC2I(IJ)
CALL CPLEX(C1R,C1I,-C2I,C2R,XMR,XMI,1)
CALL CPLEX(-C2I,C2R,C1R,C1I,EPR,EPI,2)
XMI=XMI*X(-1.0)
XMI=IF(XMI.LT.-1.0) XMI=-1.0
EPI=EPI*X(-1.0)
EPI=IF (EPI.LT.-1.0) EPI=-1.0
M1R(IJ)=100*XMR
M1I(IJ)=100*XMI
450 CONTINUE
RETURN
END
L30
FTN4,L

SUBROUTINE CPLEX(A,B,C,D,ANR,ANI,N)

THIS IS A COMPLEX ARITHMETIC ROUTINE

THAT DOES ONE OF FOUR OPERATIONS DEPENDING

ON THE VALUE OF 'N'

N=1: (A+JB)*(C+JD)
N=2: (A+JB)/(C+JD)
N=3: SQRT(A+JB)
N=4: LN(A+JB)

GO TO (1,3,4,4),N
1 AR=A*C-B*D
   AI=A*D+B*C
2 ANR=AR
   ANI=AI
   RETURN
3 DIV=C*X+D
   AR=(A*C+B*D)/DIV
   AI=(B*C-A*D)/DIV
   GO TO 2
4 R=SQRT(A*A+B*B)
   TH=ATAN2(B,A)
   IF (TH.GT.0.0) TH=TH-6.28318
   IF (N.GT.3) GO TO 5
   R=SQRT(R)
   TH=TH/2
7 AR=R*COS(TH)
   AI=R*SIN(TH)
   GO TO 2
5 AR=ALOG(R)
   AI=TH
L30
A1=TH
C IF(A1.GT.0.0) GOTO 6
C 6 A1=A1-6.28318
EOF
END$
SUBROUTINE LIST(LU,N,IFR,IER,IEI,IMR,IMI,IC)
C
C THIS SUBROUTINE LISTS 30 LINES OF MU/EP DATA, MAKES A HARD COPY, ERASES THE SCREEN
C AND REPLACES THE PROCESS UNTIL THE N DATA POINTS ARE LISTED.
C
DIMENSION IFR(1),IMK(1),IMI(1),IER(1),IEI(1),IC(1)
NEWPG=2
C
CALL WAIT(100)
CALL MODE(NEWPG)
CALL WAIT(200)
KK=N/30+1
DO 1 J=1,KK
WRITE(LU,4) (IC(II),II=1,32)
DO 2 I=1,30
K=I+((J-1)*30)
IF(K.GT.N) GO TO 5
WRITE(LU,3) K,IFR(K),IER(K),IEI(K),IMR(K),IMI(K)
2 CONTINUE
5 CONTINUE
C
CALL WAIT(3500)
CALL HDCOPY
CALL WAIT(100)
CALL MODE(NEWPG)
IF(K.GE.N) RETURN
CONTINUE
4 FORMAT(32A2)
CALL WAIT(200)
RETURN
END
THE ABOVE PARAMETERS ARE USED AS
FOLLOWING POINTS TO PLOT
#1 FIRST POINT
#2 LAST POINT
#3 REAL (REAL PART)
#4 IMAGINARY (IMAG PART)
#5 REAL (REAL PART)
#6 IMAGINARY (IMAG PART)
#7 REAL (REAL PART)
#8 IMAGINARY (IMAG PART)
#9 COMMENT LINE
CALL PCIRX1(1)
CALL PCIRX2(1,2)
READ DATA ARRAY FROM DISC
CALL XG(1,2,1,DATA,1,DATA,1,DATA,0)
CALL XG(1,2,DATA,10,DATA,10,DATA,0)
CALL XG(1,2,DATA,10,DATA,0)
CALL XG(1,2,DATA,10,DATA,0)
L30
LU=IPRAM(5)
DO 100 I=1,120
IRYS(I)=IDATA(I)
IRY1(I)=IDATA(I+120)
IRY2(I)=IDATA(I+240)
IRY3(I)=IDATA(I+360)
IRY4(I)=IDATA(I+480)
100 CONTINUE
NGP=IDATA(601)
NN1=2
NN2=NGP
WRITE(LU,101)
101 FORMAT("PLEASE ENTER STATEMENT ABOUT SAMPLE."
READ(LU,102) (IRY6(I), I=1,32)
102 FORMAT(32F4.2)
A=FLOAT(IRYS(1))/1000.
B=FLOAT(IRYS(NGP))/1000.
IXMIN=INT(A)
IXMAX=INT(D)+1
IF((FLOAT(IXMAX)-B).EQ.1.) IXMAX=IXMAX-1
LARGE=0
YMIN=0.
NEWPG=2
NPL=1
10 CONTINUE
CALL WAIT (200)
CALL MODE(NEWPG)
CALL WAIT(200)
C WRITE THE HADR COMMENT LINE
CALL READ(LU,IRY6)
C DRAW THE GRID
L30
C
CALL WAIT(2000)
CALL IGRD
C
IF(NPL.EQ.1) CALL YMAXI(IRY1,IRY3,NSP,LARGE)
C
SET FLAG FOR 'REAL PART' GRAPH
JJ=1
IF(NPL.EQ.1) LG1=LARGE/100
CALL TGE(LG1,YMIN,JJ,IXMAX,IXMIN)
C
LABEL THE GRAPH
C
SAVE THE FREQ IN IRY7
DO 1 LLL=1,NSP
1 IRY7(LLL)=IRY5(LLL)
C
SCALE EP' AND FREQ TO ABSOLUTE
TETRONIX COORDINATES.
C
IF(NPL.EQ.1) CALL SCL(LARGE,NSP,IRY1,IRY5)
DO 2 LLL=1,NSP
2 IRY5(LLL)=IRY7(LLL)
C
SCALE MU' AND FREQ INTO ABSOLUTE
TETRONIX COORDINATES.
C
IF(NPL.EQ.1) CALL SCL(LARGE,NSP,IRY3,IRY5)
C
PLOT EP' AS A DASH LINE
CALL BLINI(NN1,NN2,IRY5,IRY1)
C
PLOT MU' AS A LINE
CALL LINI(NN1,NN2,IRY5,IRY3)
CALL HQCPY
CALL WAIT(2000)
L30
CALL WAIT(200)
CALL MODE(NEWPG)
LU=IPRAM(5)
CALL HEADK(LU,IRY6)
C
WRITE HEADER LINE FOR IMAGINARY
C
PART OF GRAPH.
C
CALL WAIT(500)
C
DRAW THE GRID
CALL WAIT(1000)
CALL HGRID
C
SET FLAG FOR IMAG PART OF GRAPH
JJ=2
YMIN=0.
LARGE=0
DO 3 LLL=1,NSP
  IRY5(LLL)=IRY7(LLL)
3  FIND THE MAXIMUM OF EP' AND MU'
   IF (NPL.EQ.1) CALL YMXI(IRY2,IRY4,NSP,LARGE)
   IF (NPL.EQ.1) LG2=LARGE/100
C
LABEL THE SECOND GRAPH
CALL FLDL(NSP,LD2,YMIN,JJ,IXMAX,IXMIN)
C
SCALE THE EP' AND FREQ DATA
C
INTO ABSOLUTE TETRONIX COORDINATES.
   IF(NPL.EQ.1) CALL SCL(LARGE,NSP,IRY2,IRY5)
C
SCALE THE MU' AND FREQ DATA
C
INTO ABSOLUTE TETRONIX COORDINATES.
   DO 4 LLL=1,NSP
4  IRY5(LLL)=IRY7(LLL)
   IF (NPL.EQ.1) CALL SCL(LARGE,NSP,IRY4,IRY5)
L30 IF (NPL.EQ.1) CALL SCL(LARGE,NSP,IRY4,IRY5)
       CALL DLINE (NN1,NN2,IRY5,IRY2)
       CALL LINE (NN1,NN2,IRY5,IRY4)
       CALL HDOCY
       CALL MODE (NEWPG)
       WRITE(LU,6)
       WRITE(LU,6)
    6 FORMAT("ENTER IPL TO REPLOT.")
       READ(LU,7) IANS
       CALL WAIT(500)
       IF (IANS.EQ.IPL) GO TO 10
       END
       EDF
       /ER
L30
FTN4,L

SUBROUTINE HEADR(LU,IPARM)

C THIS SUBROUTINE PRINTS AN ASCII HEADER STATEMENT OR COMMENT STATEMENT STORED IN THE ARRAY IPARM. IT BELONGS TO THE LOW FREQUENCY PLOT PACKAGE

C

DIMENSION IPARM(1)

WRITE(LU,20) (IPARM(I),I=1,32)

20 FORMAT(" .SAMPLE:",3X,32A2)

CALL WAIT(50)

RETURN

END

END$
L30 FTN4,L

SUBROUTINE SMOOTH(DATA,N)
DIMENSION DATA(1),WORK(120)

C THIS SUBROUTINE PERFORMS A 4TH ORDER DATA SMOOTHING
OF THE 'N' ELEMENTS OF THE DATA ARRAY.

FACTR=3./35.
MAXI=N-1
DO 10 I=1,MAXI
   WORK(I)=DATA(I+1)-DATA(I)
10 CONTINUE
DO 20 J=1,3
   TOP=WORK(1)
   MAXI=MAXI-1
   DO 20 I=1,MAXI
20 WORK(I)=WORK(I+1)-WORK(I)
MAXI=N-2
DO 30 I=3,MAXI
30 DATA(I)=DATA(I)-WORK(I)*FACTR
DATA(1)=DATA(1)+TOP/5.0+WORK(1)*FACTR
DATA(2)=DATA(2)-TOP*0.4-WORK(1)/7.0
DATA(N)=DATA(N)-WORK(N-3)/5.0+WORK(N-4)*FACTR
DATA(N-1)=DATA(N-1)+WORK(N-3)*0.4-WORK(N-4)/7.0
RETURN
END
END$
SUBROUTINE HFGRD

THIS PLOTTING SUBROUTINE, WHICH BELONGS
TO THE (MU-EI') HIGH FREQ PLOTTING
PACKAGE, PLOTS A GRID ON THE CRT.
ALL CONSTANTS ARE IN THE TETRONIX
ABSOLUTE COORDINATES.
WRITTEN 2-07-79 BY CAM

DRAW THE VERTICAL GRID LINES

L40  FTN4,L

C

IX1=100
DX=82.90909
DO 25 I=1,12
   IY=75
   IDX=DX*(I-1)
   IX=IX1+IDX
   CALL PLOT(IX,IY,3)
   IY=600
   CALL PLOT(IX,IY,2)
25 CONTINUE

C

IY1=40
IDY=50
DO 100 N=1,13
   IY=IY1+N*IDY
   IX=95
   CALL PLOT(IX,IY,3)
   IX=1012
   CALL PLOT(IX,IY,2)
100 CONTINUE
RETURN
END
END$
SUBROUTINE FLBL(NN,MAX,YMIN,JJ,IXMAX,IXMIN)
DIMENSION LA(20),LY(23),LS(15),LX(20)

THIS SUBROUTINE, WHICH IS PART OF THE
SPERRY PLOTTING PACKAGE, LABELS THE
MU AND EP GRAPH THAT IS PLOTTED ON THE
TETRONIXS CRT. THE PARAMETERS PASSED TO
THE SUBROUTINE ARE USED TO SCALE THE AXIS
PROPERLY. THE 'JJ' SWITCH SPECIFIES THE
"REAL" OR "IMAG" PORTIONS OF MU AND
EPSILON TO BE PLOTTED.

DATA LX/2HF,2HER,2H(Q,2HMG,2H)Z,2H ,2H ,2H ,2H ,
C 2H ,2H ,2H ,2H ,2HER,2HLA,2H ,2HAP,2HTR,2HMI,
C 2HGA/
DATA LY/2H R,2H E,2H L,2H A,2H T,2H I,2H V,2H E,2H
2,2H L,2H 0,2H N/

THE FOLLOWING ROUTINE SCALES THE
VERTICAL AXIS ACCORDING TO THE
LARGEST VALUE OF THE MU OR EP SENT
TO THIS SUBROUTINE, AND THEN ROUNDS
OFF TO THE NEAREST FACTOR OF 5.

NGCT=60B
MY=MAX
L30
MY=MAX
MY=1+MY/5
C LIMIT MAX SCALE TO 95 (I.E. 5X19)
IF(MY.GT.19) MY=19
NDEC=MY
YMIN=-1.0*FLOAT(NDEC)
MY=5*MY
DO 25 N=1,11,2
NY=MY
NY=NY/10
IF(NY) 10,10,5
5 CONTINUE
NOINY=NOCT+NY
LS(N)=NOINY
GO TO 15
10 CONTINUE
LS(N)=26040B
15 CONTINUE
NY1=NY-(NY*10)
LS(N+1)=NOCT+NY1
MY=MY-NDEC
25 CONTINUE
C BEGIN LABELING THE AXIS
CALL SYMB(500,5,1,LX)
C LABELS "FREQ(1GHZ)"
DEL=FLOAT(IXMAX-IXMIN)/11.
AMY1=IXMIN
AMY2=FLOAT(IXMIN)+(6*DEL)
AMY3=IXMAX
CALL SYMB(5,650,23,2,LY)
/ C LABELS "RELATIVE MU AND EP"
L30 C LABELS "RELATIVE MU AND EP"
   IF(JJ-1) 60,60,70
60 CONTINUE
   CALL SYMB(480,710,5,1,LX(14))
   LABELS "REAL" PART
   GO TO 75
70 CONTINUE
   CALL SYMB(480,710,2,1,LX(19))
   LABELS "IMAG"
   CALL SYMB(535,710,3,1,LX(16))
   LABELS "PART"
   GO TO 75
75 CONTINUE
DO 32 J=1,11,5
   IF(J.EQ.1) AMY4=AMY1
   IF(J.EQ.6) AMY4=AMY2
   IF(J.EQ.11) AMY4=AMY3
DO 31 N=1,5
   F=N=FLOAT(N)
   NY1=AMY4*(10.**F)/1000.
   IF(NY1) 26,26,27
26 IF(N.EQ.1) LA(J+N-1)=20040B
   IF(LA(J+N-1).EQ.20040B) GO TO 28
   IF(N.GT.2) GO TO 30
   IF(LA(J+N-2).EQ.20040B) LA(J+N-1)=20040B
   IF(LA(J+N-2).NE.20040B) GO TO 30
   GO TO 28
27 CONTINUE
   NOINT=NOCT+NY1
   LA(J+N-1)=NOINT
28 CONTINUE
L30 20 CONTINUE
   AMY4=AMY4-FLOAT(NY1)*1000./(10.*FN)
   GO TO 31
30 CONTINUE
   NOINY=NOCT
   LA(J+N-1)=NOINY
   GO TO 28
31 CONTINUE
32 CONTINUE.

THE FOLLOWING PORTION OF THIS SUBROUTINE
PRINTS THE SCALED VERTICAL AXIS LABELS.

LS(13)=24440
LL=674
DU 100 I=1,11,2
   CALL SYMB(50,LL,1,1,LS(I))
   CALL SYMB(63,LL,1,1,LS(I+1))
   LL=LL-100
100 CONTINUE
   CALL SYMB(27,74,1,1,LS(13))
   CALL SYMB(50,74,1,1,LS(9))
   CALL SYMB(63,74,1,1,LS(10))
   LA(16)=56B
   CONTINUE LABELING THE AXIS

THE FOLLOWING PORTION OF THIS SUBROUTINE
PRINTS THE SCALED HORIZONTAL AXIS LABELS.

CALL SYMB(71,58,1,1,LA(1))
   CALL SYMB(84,58,1,1,LA(2))
L30
CALL SYMB(84,50,1,1,LA(2))
CALL SYMB(97,50,1,1,LA(3))
CALL SYMB(110,50,1,1,LA(16))
CALL SYMB(123,50,1,1,LA(4))
CALL SYMB(136,50,1,1,LA(5))
CALL SYMB(152,50,1,1,LA(6))
CALL SYMB(165,50,1,1,LA(7))
CALL SYMB(178,50,1,1,LA(8))
CALL SYMB(191,50,1,1,LA(16))
CALL SYMB(604,50,1,1,LA(9))
CALL SYMB(617,50,1,1,LA(10))
CALL SYMB(949,50,1,1,LA(11))
CALL SYMB(962,50,1,1,LA(12))
CALL SYMB(975,50,1,1,LA(13))
CALL SYMB(988,50,1,1,LA(16))
CALL SYMB(1001,50,1,1,LA(14))
CALL SYMB(1012,50,1,1,LA(15))
RETURN
END
L30
FTN4,L

SUBROUTINE POINT(IX,IY)
DIMENSION ID(4)

THIS SUBROUTINE CHANGES THE TETRONIX CRT TO THE
GRAPHICS MODE, AND MOVES WITH A DARK VECTOR TO
THE POINT (IX,IY)

N=IX/32
ID(3)=N+32
ID(4)=IX-32*N+64
N=IY/32
ID(1)=N+32
ID(2)=IY-N*32+96
M=-4
CALL OUT2(M,ID)
RETURN
END

COF
/ER
SUBROUTINE DLINE(JXX,JXY,NXPT,NYPT)
DIMENSION NYPT(1),NXPT(1)

CALL MODEC(3)
DO 1 I=JXX,JXY,2
   IF(I.EQ.JXX.AND.JXX.GT.1) CALL PLOT(NXPT(I-1),NYPT(I-1),3)
   CALL PLOT(NXPT(I),NYPT(I),2)
   CALL PLOT(NXPT(I+1),NYPT(I+1),3)
1 CONTINUE
RETURN
END

THIS SUBROUTINE PERFORMS THE SAME
OPERATION AS SUBROUTINE 'LINE' EXCEPT
IT PLOTS A DASH LINE INSTEAD.
SUBROUTINE LINE(JXX,JXY,NXPT,NYPT)
DIMENSION NYPT(1),NXPT(1)

THIS PROGRAM PLOTS THE LINE FOR THE
MU AND EPSILON CURVES.
ONLY MINOR CHANGES TO ACCOMMODATE
INDIRECT ADDRESSING DISCERNS THIS
PROGRAM FROM THE RCS 'LINE' SUBROUTINE

CALL MODE(3)
DO 1 I=JXX,JXY
   CALL PLOT(NXPT(I),NYPT(I),2)
   CONTINUE
1 CONTINUE
RETURN
END

END
L30
FTN4, L
    SUBROUTINE PLOT(IX, IY, IPEN)
    C
    C    THIS SUBROUTINE MOVES FROM TETRONIX CURRENT
    C    (X,Y) COORDINATE TO THE COORDINATE (IX, IY)
    C    WITH EITHER A LIGHT VECTOR (IPEN=2) OR A
    C    DARK VECTOR (IPEN=3)
    N=IABS(IPEN)
    IF(N-2) 2,2,3
    C......IPEN-2, MOVE WITH LINE
    2     CALL POINT(IX, IY)
         RETURN
    C......IPEN=3, MOVE WITH NO LINE
    3     CALL MODE(3)
         CALL POINT(IX, IY)
         RETURN
    END
END
L30
FTN4,L
SUBROUTINE HDCPY
C.....MAKES A HARD COPY FROM EITHER THE A/N OR THE GRAPHICS MODE
C.....TERMINAL REMAINS IN THE MODE PRIOR TO THE HARD COPY COMMAND
DIMENSION L(2)
   L(1)=27
   L(2)=23
   CALL OUT2(-2,L)
C.....WAIT FOR HARD COPY
   CALL WAIT(4000)
   RETURN
   END
SUBROUTINE YMAXI(IY1,IY2,N,NDIG)

DIMENSION IY1(1),IY2(1)

C THIS SUBROUTINE SEARCHES FROM NL TO NU TO FIND
C THE BIGGEST ELEMENT IN THE TWO ARRAYS HY1(N)
C AND HY2(N) AND SENDS THIS VALUE BACK TO THE
C CALLING PROGRAM THROUGH 'NDIG'
C SUBROUTINE MODIFIED 3 APR 79 BY CAM
C SUBROUTINE WRITTEN FOR LOW-FREQ PLOTTING PKG.

NL=4
NU=N-3
NDIG=0
DO 5 L=NL,NU
     IF(IY1(L)-NDIG) 3,3,2
      CONTINUE
      NDIG=IY1(L)
   3 CONTINUE
     CONTINUE
   5 CONTINUE
     NDIG=0
   6 CONTINUE
   10 L=NL,NU
     IF(IY2(L)-NDIG1) 6,6,7
      CONTINUE
      NDIG1=IY2(L)
   7 CONTINUE
     CONTINUE
   10 CONTINUE
     IF(NDIG-NDIG1) 15,15,20
   15 CONTINUE
   20 CONTINUE
RETURN
END

END
L30
ASMB,R,L,T
NAM OUT2
ENT OUT2
EXT .ENTR
N
NOP
IO
NOP
OUT2
NOP
JSP .ENTR
DEF N
DLE IO
LOC
BSS 1
OUTPT EQU 21B

21B IS THE I/O SLOT OF THE GRAPHICS CRT

* ATTN OCT 120000
 CLF 00
*
 LDA N, I
 STA LOC
 LDA IO, I
 JSP OUTCH
 LSR B
 SRA
 JSP OUTCH
 ISZ IO
 NOP
 ISZ LOC
 JMP *-B
 STR 0
 JMP OUT2, I
*
OUTCH NOP
L30
OUTCH NOP
LDB ATTN
QTB OUTPT
OTA OUTPT
STC OUTPT,C
SFS OUTPT
JMP X-1
JMP OUTCH,I

* END

EOF
/
L30
      FTN4,L
      SUBROUTINE MODE(I)
      DIMENSION IO(4)
      C.....SUBROUTINE TO CHANGE TEKTRONIX MODE
         IF(I-2)1,2,3
         C.....MODE I=1 IS ALPHANUMERIC
            1  IO(1)=31
               M=-1
               CALL OUT2(M,IO)
               RETURN
         C.....MODE I=2 GIVE NEW PAGE
            2  IO(1)=27
               IO(2)=12
               M=-2
               CALL OUT2(M,IO)
         C.....WAIT FOR PAGE ERASE
            CALL WAIT(750)
               RETURN
         C.....MODE I=3 IS GRAPHICS MODE
            3  IO(1)=29
               M=-1
               CALL OUT2(M,IO)
               RETURN
      END
      END$
SUBROUTINE SYM(IX, IY, N, IHV, IO)

DIMENSION IO(30)

C THIS PROGRAM OUTPUTS A SYMBOL (IN ASCII)
C FOR A STRING OF SYMBOLS STORED SEQUEN-
C TIONALLY IN AN ARRAY.
C TO A LOCATION (IX, IY), POINTING EITHER
C HORIZONTALLY OR VERTICALLY DEPENDING
C ON THE VALUE OF IHV.
C
C MOVE TO X,Y; CHANGE MODE
CALL MODE(3)
CALL POINT(IX, IY)
CALL MODE(1)
IF (IHV=1) I, 1, 2

C SYMBOLS ALONG HORIZONTAL LINE (IHV=1)
1 M=-N
CALL OUT2(M, IO)
RETURN

C SYMBOLS ALONG VERTICAL (Y) AXIS (IHV=2)
2 JY=IY
DO 3 I=1, N
M=-1
IT=IO(I)
CALL OUT2(M, IT)
CALL MODE(3)
JY=JY-20
CALL POINT(IX, JY)
3 CALL MODE(1)
RETURN
END

EOF
L30
FTN4,L

SUBROUTINE WAIT(N)

C.....WAIT IS A SUBROUTINE THAT DOES NOTHING BUT WASTE TIME
C.....N DETERMINES THE AMOUNT OF TIME TO BE WASTED
DO 1 I=1,N
   Y=I
   1 X=SQRT(Y)
RETURN
END

EOF
/
APPENDIX B

First Test Setup of Frequency Domain Measurement System

The equipment used in the first test setup of the frequency domain measurement system will be described. Then the procedures used to measure fiberglass and two thicknesses of plexiglas will be discussed. Finally, the relative complex mu and epsilon values measured for the fiberglass and two thicknesses of plexiglas will be presented.

Equipment

The equipment used to support this thesis test setup consisted of a frequency synthesizer which served as the signal source, a network analyzer used for making relative decibel amplitude and phase measurements, an anechoic chamber used for the transmission coefficient measurements, a sectoral horn assembly used to make the reflection coefficient measurements, and a Hewlett-Packard 21MX RTE computer used to control the measurement setup. The complete measurement setup is diagramed in Figure 18.

The power source was a Watkins and Johnson model 1204-1; rapidly tunable over a frequency range of 0.1 - 26 GHz. The following information was taken from the Watkins and Johnson 1204-1 specification sheet. The frequency resolution was 10 kHz from 100 MHz to 249.99 MHz, 100 kHz from 250 MHz to 1.9999 GHz, and 1 MHz from 2 - 26 GHz. The frequency was displayed with a five-digit LED, in GHz, with floating decimal. The frequency accuracy was ±0.00035% for 180 days over a
0 - 50° C range. A single frequency could be selected on the keyboard with the enter, ENT, button and displayed on the LED. The frequency could be slewed up or down in 1, 10, and 100 MHz steps as selected on the INCREMENT controls. The synthesizer sweeps repetitively upward within the following bands: 0.1 - 1 GHz, 1 - 2 GHz, 2 - 8 GHz, 8 - 13 GHz, 13 - 18 GHz, and 18 - 26 GHz. The AF symmetrical sweep about phase-locked center frequency \( F \) which was displayed on the LED readout was 0 to \( \pm 0.1\% \) of \( F \). The synthesizer provides 0 dBm (1 mw) minimum leveled output power. The variations in leveled power for the 0 dB attenuator setting was \( \pm 1 \) dB over the range of 0.1 - 26 GHz. The output power could be attenuated over a range of 0 to 90 dB in 10 dB steps. The output power accuracy (meter reading plus attenuator setting) was: \( \pm 0 \) dB attenuator setting, 0.1 - 18 GHz, \( \pm 1 \) dB and 18 - 26 GHz, \( \pm 1 \) dB; 10 dB - 90 dB attenuator setting, \( \pm 2 \) dB and 18 - 26 GHz, \( \pm 2.5 \) dB.

The network analyzer was a Hewlett-Packard Model 8410A with a phase-gain indicator. The 8413A phase-gain indicator used a meter display. The 8411A harmonic frequency converter provided RF-to-IF conversion. Measurements were based on the use of two wideband samplers to convert the input frequencies to a constant IF frequency. RF-to-IF conversion took place entirely in the harmonic frequency converter, which converted frequencies over a range of 12.4 - 18 GHz to 20 MHz IF signals. The phase and amplitude of the two RF input signals were maintained in the IF signal. The network analyzer mainframe provided the phase-lock circuitry to maintain the 20 MHz IF frequency while frequency was being swept, took the ratio of the
reference and test channels by use of identical AGC amplifiers, and then converted down to a second IF of 2/8 kHz. It also had a precision 0 to 69 dB IF attenuator with 10 and 1 dB steps for accurate IF substitution measurements of gain or attenuation.

The frequency domain measurement setup utilized the following piece of equipment during data measurements: a plug-in for the 8410A mainframe, the 8413A phase-gain indicator. It compared the amplitudes of the two IF signals and provided a meter readout of their ratio directly in dB with 0.1 dB resolution. It also compared phase in degrees over a 360° unambiguous range with 0.2° resolution on the meter. Phase difference was presented on the same meter when the appropriate function button was depressed. This plug-in had two analog output ports accessible from the front, one for dB amplitude, 20 mv/dB, and one for phase, 50 mv/degree.

The anechoic chamber was a 9.5 ft x 3 ft x 3 ft upright box structure as shown in Figure 19. The outer structure was made of 2 in x 6 in boards covered with 1/2 inch plywood. The inner structure was 1/2 inch plywood supported by 2 inch x 4 inch boards. The 1/2 inch plywood inside of the chamber was covered with 4 inch thick CV-4 radar absorbing material (RAM). At the middle of the chamber, a 2 inch thick styrofoam square and AN-74 RAM square provided a table top support area for the test sample. An 8 inch square hole was cut in the table top to provide a window for signal transmission. At the top and bottom of the anechoic chamber, there were 3 square inch holes cut to allow access for horn antennae. A hinged door was located at one side of the chamber to allow easy insertion and removal of samples to be tested.

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Figure 19. Anechoic Chamber Used in Frequency Domain Measurement Test Setup
An H-plane sectoral horn was designed and built for this project using formulae from Jasik, pages 10-8 and 10-9. An improved free space match was obtained by introducing a set of parallel plates coupled with a set of curved cylinders at the mouth of the horn. The horn is depicted in Figure 20. The theoretically computed phase variations across the aperture were 49.1° at 12.4 GHz to 71.7° at 18 GHz.

The Hewlett-Packard 21MX computer was used to control the data measurement. The frequency synthesizer was commanded to a discrete frequency by the computer and a data measurement was taken through the computer A/D converted, connected to the network analyzer. The disk subsystem and I/O devices were used to store, process, and display the results of a data run. The software used in the computer for the test setup was an earlier version of that given in Appendix A.

Procedures

The procedure followed in measuring the complex mu and epsilon values of a test sample involved the preparation of the sample, initialization of the computer program, setup and measurement of the reflection coefficient values, setup and measurement of the transmission coefficient values, data calculation to obtain mu and epsilon, and data output to present the mu and epsilon values.

In preparing the sample, a one square foot piece of test material was used. From the one square foot piece of material, a small strip 0.8 inches in width was cut from one side. The 0.8 inch wide piece of test material was used in the sectoral horn for reflection.
Figure 20. Modified H-Plane Sectoral Horn
During reflection coefficient measurements, the sample piece was placed directly on the mouth of the horn where the parallel plates were attached. The larger piece of the sample was placed inside the anechoic chamber during transmission coefficient measurements.

Once the sample pieces were prepared, the computer program was initialized. The operator entered a comment statement that identified the sample. This statement was printed as the heading for the line printer output of the mu and epsilon values. The thickness of the sample was entered next. Then, the start and stop frequencies were entered and the number of discrete frequencies at which measurements occurred were entered. At this point, the operator entered the portion of the program that makes reflection coefficient measurements.

For the reflection coefficient measurements, the sectoral horn was switched into the network by manually setting switch number one (the switch feeding power to the horn) to the right, and switch number two (the switch connected to the test signal port of the converter unit) to the left. The shorting plate was placed on the horn at the location previously described for the sample. The network analyzer gain amplifier was set to 13 dB. The frequency synthesizer power output was set to zero dB. The operator commanded the computer to step the frequency synthesizer across the frequency range to obtain a background reference for the short. Next, the sample was placed in the horn and the operator allowed the computer to step through the frequencies again. The computer determined the difference between the two sets of values and stored these differences as the reflection
coefficients. Now, the operator entered the portion of the program to obtain transmission coefficients.

The large sample piece was used for determining the transmission coefficients. The gain amplifier on the network analyzer was set to 41 dB. The anechoic chamber was switched into the network by placing switch one to the left and switch two to the right. The anechoic chamber was set up first with nothing over the 4 inch square window on the table assembly. The operator allowed the computer to measure the open window across the frequency range for a reference background measurement. Next, the sample was placed flush against the table surface, centered on the 4 inch square window. The first set of values for the sample transmission coefficients was determined and stored in the computer. Next, the sample was offset with two shims that were 0.5 cm thick and a second set of transmission coefficients was measured. The two sets of values were averaged to obtain a single set of values as the transmission coefficients. This procedure was performed to help compensate for the inherent VSWR within the anechoic chamber. At this point, the data needed to compute mu and epsilon had been obtained.

The data calculation to obtain the complex mu and epsilon values was now performed by the computer at the operator's request. The system was ready to output this data as hard copy at the line printer or as plots.

The output could be requested in the form of hard copy. This output gave the frequency in MHz and the mu and epsilon values scaled up by a factor of 100. A second program was loaded into memory at the request of the operator to produce plots.
The plot program was requested from the main program. It required a statement about the sample for use as a title on the plots. The output was produced on the CRT of the computer and automatically copied to a Tektronix hardcopy unit. At the direction of the operator, the main program was reentered and terminated.

**Fiberglass Sample**

The frequency domain data for the fiberglass sample is given in Figure 21A and 21B. The frequency domain values of relative mu and epsilon between 12 and 18 GHz are compared to the time domain data from Figure 7A and 7B in Table XI.

**First Plexiglas Sample**

The frequency domain data for the 64 mil plexiglas sample is given in Figure 22A and 22B. The frequency domain data between 12 and 18 GHz is compared to the time domain data from Figure 9A and 9B in Table XII.

**Second Plexiglas Sample**

The frequency domain data for the 172 mil plexiglas sample is given in Figure 23A and 23B. The frequency domain data between 12 and 18 GHz is compared to the time domain data from Figure 11A and 11B in Table XIII.
Figure 2iA. Frequency Domain (Re.1) Data for 142 mil Fiberglass Sample
### TABLE XI

**SAMPLE: FIBERGLASS**

<table>
<thead>
<tr>
<th>TIME DOMAIN SYSTEM</th>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>THICKNESS = 134.5 MILS</td>
<td>12.5</td>
<td>4.35+1.27</td>
<td>.95+0.00</td>
</tr>
<tr>
<td>12.4</td>
<td>4.25+1.25</td>
<td>.97+0.01</td>
<td></td>
</tr>
<tr>
<td>12.3</td>
<td>4.19+1.25</td>
<td>.99+0.01</td>
<td></td>
</tr>
<tr>
<td>12.2</td>
<td>4.19+1.27</td>
<td>1.00+0.01</td>
<td></td>
</tr>
<tr>
<td>12.1</td>
<td>4.19+1.23</td>
<td>1.00+0.01</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td>4.12+1.17</td>
<td>1.00+0.01</td>
<td></td>
</tr>
<tr>
<td>11.9</td>
<td>4.32+1.06</td>
<td>.96+0.00</td>
<td></td>
</tr>
<tr>
<td>11.8</td>
<td>4.62+1.09</td>
<td>.90+0.02</td>
<td></td>
</tr>
<tr>
<td>11.7</td>
<td>4.64+1.02</td>
<td>.89+0.02</td>
<td></td>
</tr>
<tr>
<td>11.6</td>
<td>4.36+1.07</td>
<td>.92+0.04</td>
<td></td>
</tr>
<tr>
<td>11.5</td>
<td>4.20+1.07</td>
<td>.94+0.07</td>
<td></td>
</tr>
<tr>
<td>11.4</td>
<td>4.26+1.07</td>
<td>.98+0.03</td>
<td></td>
</tr>
<tr>
<td>11.3</td>
<td>4.18+1.00</td>
<td>.98+0.03</td>
<td></td>
</tr>
<tr>
<td>11.2</td>
<td>3.74+1.04</td>
<td>.98+0.03</td>
<td></td>
</tr>
<tr>
<td>11.1</td>
<td>3.44+1.04</td>
<td>.98+0.03</td>
<td></td>
</tr>
<tr>
<td>11.0</td>
<td>3.58+1.02</td>
<td>.98+0.03</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>THICKNESS = 142 MILS</td>
<td>12.5</td>
<td>4.27+0.18</td>
</tr>
<tr>
<td>12.4</td>
<td>3.93+0.35</td>
<td>.95+0.00</td>
</tr>
<tr>
<td>12.3</td>
<td>3.89+0.44</td>
<td>1.04+0.14</td>
</tr>
<tr>
<td>12.2</td>
<td>4.54+0.60</td>
<td>1.07+0.05</td>
</tr>
<tr>
<td>12.1</td>
<td>3.68+0.81</td>
<td>1.08+0.07</td>
</tr>
<tr>
<td>12.0</td>
<td>3.78+1.24</td>
<td>1.04+0.14</td>
</tr>
<tr>
<td>11.9</td>
<td>3.37+0.37</td>
<td>1.16+0.15</td>
</tr>
<tr>
<td>11.8</td>
<td>3.72+0.66</td>
<td>1.02+0.15</td>
</tr>
<tr>
<td>11.7</td>
<td>4.35+0.26</td>
<td>1.01+0.00</td>
</tr>
<tr>
<td>11.6</td>
<td>4.32+0.03</td>
<td>1.00+0.01</td>
</tr>
<tr>
<td>11.5</td>
<td>3.54+0.26</td>
<td>1.15+0.12</td>
</tr>
<tr>
<td>11.4</td>
<td>4.60+0.87</td>
<td>1.94+0.12</td>
</tr>
<tr>
<td>11.3</td>
<td>5.59+0.06</td>
<td>1.62+0.12</td>
</tr>
<tr>
<td>11.2</td>
<td>6.40+0.63</td>
<td>1.75+0.16</td>
</tr>
<tr>
<td>11.1</td>
<td>4.54+1.60</td>
<td>1.65+0.12</td>
</tr>
<tr>
<td>11.0</td>
<td>4.63+0.47</td>
<td>1.80+0.35</td>
</tr>
</tbody>
</table>
Figure 22A. Frequency Domain (Real) Data for 64 mil Plexiglas Sample
Figure 22b. Frequency Domain (Imaginary) Data for 64 mil Plexiglas Sample
<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>2.51+J.09</td>
<td>.99-J.02</td>
<td>12.0</td>
<td>3.53+J.12</td>
<td>.55-J.10</td>
</tr>
<tr>
<td>12.4</td>
<td>2.47+J.04</td>
<td>.99-J.02</td>
<td>12.4</td>
<td>2.51-J.09</td>
<td>1.26-J.15</td>
</tr>
<tr>
<td>12.8</td>
<td>2.44+J.03</td>
<td>1.02-J.05</td>
<td>12.8</td>
<td>2.47-J.33</td>
<td>.69-J.25</td>
</tr>
<tr>
<td>13.2</td>
<td>2.43+J.00</td>
<td>1.05-J.09</td>
<td>13.2</td>
<td>2.37+J.10</td>
<td>1.01-J.16</td>
</tr>
<tr>
<td>13.6</td>
<td>2.47+J.06</td>
<td>1.09-J.10</td>
<td>13.6</td>
<td>2.99-J.27</td>
<td>.64-J.08</td>
</tr>
<tr>
<td>14.0</td>
<td>2.55+J.06</td>
<td>1.07-J.04</td>
<td>14.0</td>
<td>2.74-J.32</td>
<td>.71-J.08</td>
</tr>
<tr>
<td>14.4</td>
<td>2.64+J.14</td>
<td>1.07-J.02</td>
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<td>2.73-J.20</td>
<td>.64+J.08</td>
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<tr>
<td>14.8</td>
<td>2.69+J.14</td>
<td>1.06+J.02</td>
<td>14.8</td>
<td>2.75-J.03</td>
<td>.98-J.03</td>
</tr>
<tr>
<td>15.2</td>
<td>2.69+J.24</td>
<td>.16+J.33</td>
<td>15.2</td>
<td>2.52+J.12</td>
<td>1.11-J.01</td>
</tr>
<tr>
<td>15.6</td>
<td>2.58+J.17</td>
<td>.08+J.07</td>
<td>15.6</td>
<td>2.33+J.01</td>
<td>1.15+J.17</td>
</tr>
<tr>
<td>16.0</td>
<td>2.52+J.20</td>
<td>1.15+J.35</td>
<td>16.0</td>
<td>2.78-J.10</td>
<td>.86+J.00</td>
</tr>
<tr>
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<td>2.46+J.46</td>
<td>1.28+J.03</td>
<td>16.4</td>
<td>2.27-J.00</td>
<td>1.10-J.06</td>
</tr>
<tr>
<td>16.8</td>
<td>2.59+J.75</td>
<td>1.49+J.16</td>
<td>16.8</td>
<td>2.71+J.15</td>
<td>.99-J.02</td>
</tr>
<tr>
<td>17.2</td>
<td>2.74+J.70</td>
<td>.30+J.35</td>
<td>17.2</td>
<td>2.54-J.01</td>
<td>1.15+J.09</td>
</tr>
<tr>
<td>17.6</td>
<td>2.75+J.40</td>
<td>1.15+J.33</td>
<td>17.6</td>
<td>2.69-J.30</td>
<td>.99+J.14</td>
</tr>
<tr>
<td>18.0</td>
<td>2.56+J.15</td>
<td>1.05+J.17</td>
<td>18.0</td>
<td>2.61+J.12</td>
<td>1.06-J.05</td>
</tr>
</tbody>
</table>
Figure 73A. Frequency Domain (Real) Data for 172 mil Plexiglas Sample
Figure 233. Frequency Domain (Imaginary) Data for 172 mil Plexiglas Sample
### TABLE XIII

**SAMPLE: PLEXIGLAS**

**TIME DOMAIN SYSTEM**

THICKNESS = 174 MILS

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.0</td>
<td>2.42+0.60</td>
<td>1.00+0.00</td>
<td>12.0</td>
<td>2.37+0.47</td>
<td>1.06+0.07</td>
</tr>
<tr>
<td>12.4</td>
<td>2.43+0.61</td>
<td>1.00+0.00</td>
<td>12.4</td>
<td>2.43+0.22</td>
<td>1.06+0.05</td>
</tr>
<tr>
<td>12.8</td>
<td>2.49+0.65</td>
<td>0.99+0.03</td>
<td>12.8</td>
<td>2.24+0.43</td>
<td>1.03+0.26</td>
</tr>
<tr>
<td>13.2</td>
<td>2.44+0.64</td>
<td>0.99+0.05</td>
<td>13.2</td>
<td>2.64+0.25</td>
<td>1.95+0.04</td>
</tr>
<tr>
<td>13.6</td>
<td>2.49+0.68</td>
<td>0.98+0.04</td>
<td>13.6</td>
<td>2.10+0.49</td>
<td>1.00+0.33</td>
</tr>
<tr>
<td>14.0</td>
<td>2.55+0.04</td>
<td>0.97+0.03</td>
<td>14.0</td>
<td>2.05+0.60</td>
<td>1.04+0.47</td>
</tr>
<tr>
<td>14.4</td>
<td>2.54+0.05</td>
<td>0.96+0.03</td>
<td>14.4</td>
<td>2.22+0.47</td>
<td>1.05+0.22</td>
</tr>
<tr>
<td>14.8</td>
<td>2.54+0.14</td>
<td>0.96+0.04</td>
<td>14.8</td>
<td>2.34+0.42</td>
<td>0.98+0.18</td>
</tr>
<tr>
<td>15.2</td>
<td>2.61+0.17</td>
<td>1.01+0.05</td>
<td>15.2</td>
<td>2.44+0.23</td>
<td>1.02+0.10</td>
</tr>
<tr>
<td>15.6</td>
<td>2.32+0.25</td>
<td>1.06+0.09</td>
<td>15.6</td>
<td>2.52+0.34</td>
<td>1.08+0.09</td>
</tr>
<tr>
<td>16.0</td>
<td>2.35+0.35</td>
<td>1.05+0.16</td>
<td>16.0</td>
<td>2.74+0.49</td>
<td>1.07+0.26</td>
</tr>
<tr>
<td>16.4</td>
<td>2.33+0.58</td>
<td>1.02+0.24</td>
<td>16.4</td>
<td>2.55+0.37</td>
<td>0.99+0.15</td>
</tr>
<tr>
<td>16.8</td>
<td>2.53+0.81</td>
<td>0.88+0.26</td>
<td>16.8</td>
<td>2.86+0.24</td>
<td>0.96+0.07</td>
</tr>
<tr>
<td>17.2</td>
<td>2.73+0.47</td>
<td>0.83+0.13</td>
<td>17.2</td>
<td>2.21+0.26</td>
<td>1.02+0.03</td>
</tr>
<tr>
<td>17.6</td>
<td>2.46+0.12</td>
<td>0.92+0.04</td>
<td>17.6</td>
<td>2.36+0.78</td>
<td>1.01+0.27</td>
</tr>
<tr>
<td>18.0</td>
<td>1.87+0.00</td>
<td>1.16+0.08</td>
<td>18.0</td>
<td>2.68+0.36</td>
<td>0.94+0.00</td>
</tr>
</tbody>
</table>

**FREQUENCY DOMAIN SYSTEM**

THICKNESS = 172 MILS

<table>
<thead>
<tr>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
<th>FREQUENCY (GHz)</th>
<th>EPSILON</th>
<th>MU</th>
</tr>
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<td>12.0</td>
<td>2.37+0.47</td>
<td>1.06+0.07</td>
</tr>
<tr>
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<td>2.43+0.61</td>
<td>1.00+0.00</td>
<td>12.4</td>
<td>2.43+0.22</td>
<td>1.06+0.05</td>
</tr>
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</table>
VITA

Donald G. Aguirre was born on 12 March 1950 in Holdenville, Oklahoma. He graduated from high school in Holdenville, Oklahoma in 1969 and attended the University of Oklahoma from 1969 to 1971, at which time he enlisted in the Air Force. Through the Airmen Education and Commissioning Program, he attended the California State University in Sacramento, California, from which he received (with honors) the degree of Bachelor of Science in Electrical Engineering in January 1976. Upon graduation, he attended the Officer Training School and received his commission in April 1976. He served as a technical engineer with the 341st Strategic Missile Wing at Malmstrom AFB, Montana, until entering the School of Engineering of the Air Force Institute of Technology in June 1979.

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Holdenville, Oklahoma
74848
Using frequency domain techniques, a system was developed to measure the complex permittivity and permeability of different materials in the Ku band (12.4 to 18 GHz). A sample of fiberglass, teflon, ICM-50, and two different plexiglas configurations were chosen for this experiment. The newly developed measuring system consisted of a two horizontal-plane sectoral horn and a sample holder assembly. A 9.5 x 0.8 cm piece of the sample material was cut and fitted into the sample holder assembly. The reflection and transmission coefficients for the sample were measured, using a network analyzer and frequency synthesizer.
as the swept frequency signal source. A dedicated computer calculated the complex permittivity and permeability and plotted the output data. The measurements were performed automatically by having the computer control the frequency synthesizer while running the experiment.

The two configurations of plexiglas and the fiberglass sample were tested ten times to obtain a statistical representation of the results. In all cases good repeatability was obtained. The standard deviation of the real part of the permittivity and permeability for the two cases of plexiglas was within ±4% of the mean. The fiberglass had a typical standard deviation within ±7% of the mean for the real part of the permittivity and permeability.

The permittivity and permeability obtained for the selected samples using the frequency domain measurement technique were compared with the results obtained in a previously developed system which used time domain techniques. The data comparison between the two systems was good for teflon, plexiglas, and fiberglass in the frequency range from 12.4 to 16 GHz. Some variations were noted for the FGM-40. Since the results obtained were generally consistent between both techniques, it is claimed that the newly implemented frequency domain system is a viable alternative for the rapid measurement of intrinsic properties in the Ku band.
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