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WL-TR-93-7027

Millimeter Wave Reflectivity Measurement System

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SEPTEMBER 1993

FINAL REPORT FOR PERIOD OCTOBER 1991 - JANUARY 1993

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 1993	3. REPORT TYPE AND DATES COVERED Final October 1991 - January 1993		
4. TITLE AND SUBTITLE Millimeter Wave Reflectivity Measurement System		5. FUNDING NUMBERS PE: 62602F PR: 2068 TA: 20 WU: 14		
6. AUTHOR(S) Keith D. Trott John R. Walker, Jr.		8. PERFORMING ORGANIZATION REPORT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Wright Laboratory, Armament Directorate Advanced Guidance Division Seeker Technology Branch (WL/MNGS) 101 W. Eglin Blvd., Ste 231 Eglin AFB FL 32542-6810		9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) WL/MNGS 101 W. Eglin Blvd., Ste 231 Eglin AFB FL 32542-6810		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) WL/MNGS 101 W. Eglin Blvd., Ste 231 Eglin AFB FL 32542-6810		10. SPONSORING / MONITORING AGENCY REPORT NUMBER WL-TR-93-7027		
11. SUPPLEMENTARY NOTES Availability of report is specified on verso of front cover.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE A		
13. ABSTRACT (Maximum 200 words) The RF Technology Section of WL/MNGS is developing an in-house capability for modeling and measurement of target scattering and material characteristics at millimeter wave (MMW) frequencies. The goal of the modeling effort is to understand the basic mechanisms that contribute to the target scattering (coated and uncoated) at MMW frequencies. The measurement effort is two-fold: verify theoretical models (target and materials) and assess the effectiveness of actual countermeasures. The MMW Reflectivity Measurement System (MRMS) is capable of bistatic swept frequency measurements for copolarized (COPOL) transmit and receive signals, and it gives a quick-look capability useful in evaluating countermeasures. The primary goal is the understanding of the various mechanisms that contribute to the scattering in order to develop the algorithms and technology necessary to exploit these effects and improve seeker guidance techniques. This paper discusses the current hardware configuration and planned upgrades and outlines the modeling effort. Examples of the MRMS measurements are compared to theoretical predictions.				
14. SUBJECT TERMS Millimeter Wave Target Scattering Countermeasures, Material Characteristics Bistatic		15. NUMBER OF PAGES 21		
		16. PRICE CODE		
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR	

SUMMARY

The RF Technology Section of WL/MNGS is developing an in-house capability for modeling and measurement of target scattering and material characteristics at millimeter wave (MMW) frequencies. The Phenomenology, Analysis, and Modeling (PAM) program has been established to address these issues and their impact on MMW applications to autonomous seeker guidance for smart munitions. The goal of the modeling effort is to understand the basic mechanisms that contribute to the target scattering (coated and uncoated) at MMW frequencies. Surface variations can be a significant portion of a wavelength at MMW; therefore, surface roughness must be included in the derivations. Theoretical target models are being developed for canonical shapes such as plates and spheroids. These models will be bistatic, fully polarimetric (to account for depolarization), and include surface roughness. In a parallel effort, we are developing models for the material parameters ($\mu(\omega)$ and $\epsilon(\omega)$) that are valid in the MMW region. The measurement effort is two-fold: verify theoretical models (target and materials) and assess the effectiveness of actual countermeasures. The MMW Reflectivity Measurement System (MRMS) provides a quick-look capability useful in evaluating countermeasures. The MRMS is capable of bistatic swept frequency measurements for copolarized (COPOL) transmit and receive signals. The plan to upgrade this capability to allow for measurement of the full polarization scattering matrix (PSM), measuring COPOL and cross-polarized (XPOL) receive signals for both vertical and horizontal transmitted signals. The primary goal is the understanding of the various mechanisms that contribute to the scattering in order to develop the algorithms and technology necessary to exploit these effects and improve seeker guidance techniques. This paper discusses the current hardware configuration and planned upgrades and outlines the modeling effort. Examples of the MRMS measurements are shown.

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PREFACE

This report covers research done during the period Oct 91-Jan 93 under project 20682009 and 20682014. Project 20682009, MMW Phenomenology, Analysis, and Modeling, is directed by Major Keith Trott, WL/MNGS. Project 20682014, MMW Laboratory, is directed by John R. Walker, Jr., WL/MNGS.

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SECTION I

MRMS HARDWARE AND SOFTWARE

1. BACKGROUND

The goal of the modeling effort is to understand the basic phenomenology for target scattering (coated and uncoated) at MMW frequencies. The measurement effort is two-fold: verify the theoretical models and assess the effectiveness of actual countermeasures. Currently the MMW Reflectivity Measurement System (MRMS) is capable of performing monostatic and bistatic swept frequency measurements for copolarized (COPOL) transmit and receive signals. The MRMS will be used to verify the target and material models and to improve our understanding of how various scattering mechanisms contribute to the target signature. In addition, the MRMS will be useful in determining the effectiveness of RCS reduction techniques at MMW. This report is the initial description of this in-house capability. It describes the genesis of the MRMS and plans for its use. The following chapters will discuss the current hardware/software configuration, planned upgrades, and the modeling effort.

2. HARDWARE

Several basic goals drove the design of the MRMS test stand:

- Target/RAM in the far field of the antennas
- Target/RAM size such that edge effects could be minimized
- Capable of both monostatic and bistatic measurements
- Incident angle range of ± 45 degrees
- Swept frequency measurements
- Relative measurements to reduce calibration requirements
- Data available for quick-look and retrieval for indepth analysis.

The MRMS test stand is shown in Figure 1. This apparatus was designed and built in-house. It consists of antenna arms that rotate on a semicircular arc with adjustable antenna-mounting shelves for the transmit and receive antennas. The location of the antennas is adjustable to allow control of the illumination footprint on the target/RAM sample, which is placed beneath the antennas on a bed of anechoic material. Due to the pivoting motion of the arms, the same spot is always illuminated on the sample. These components are constructed of laminated bakelite and fiberglass. The movement of the arms generates the various incidence and observation angles relative to the sample.

The hardware configuration is shown in Figure 2 and the component descriptions are detailed in Table 1. The transmit and receive antennas are positioned by the controller and a baseline sweep of a 30 cm X 30 cm metallic (aluminum) plate is made. This baseline sweep



Figure 1. MRMS Test Stand

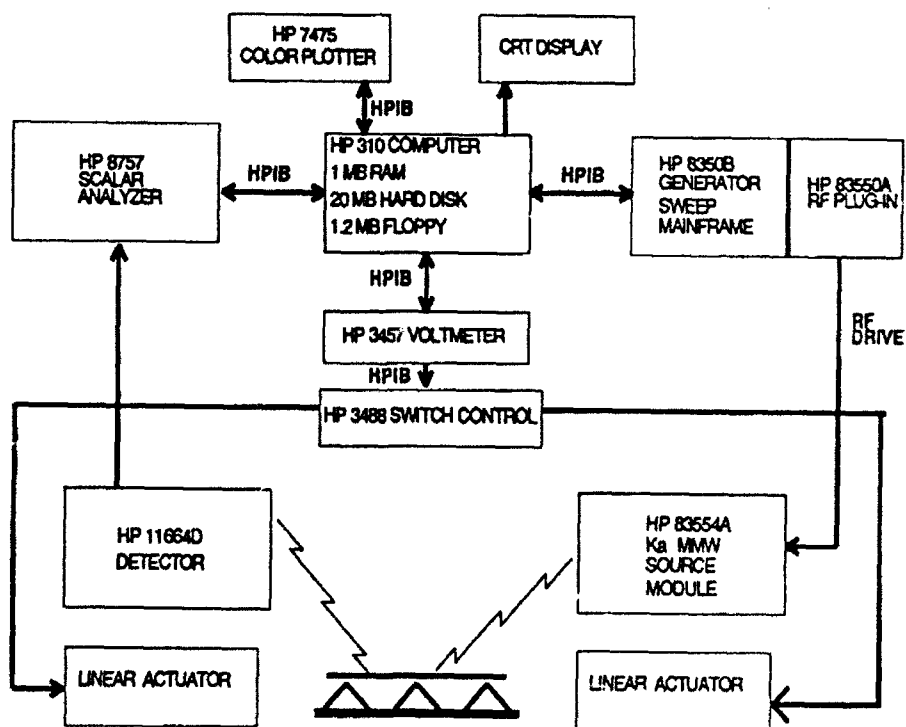


Figure 2. MRMS Block Diagram

TABLE 1. SOFTWARE SUBROUTINES

EQUIPMENT	FUNCTION
Hewlett Packard (HP) 310	Integrator and system controller
HP 8350B	Sweep generator with HP 83550A RF plug-in that generates 13.25-20 GHz of swept frequency energy at 15 mW. (Modulated with 27 kHz square wave for AC detection)
HP 83554A	Upconverts signal with X2 multiplier to produce 26.5-40 GHz output. Levels power at + 7 dBm.
Antennas	Linear standard gain horns providing 25 dB gain and 7.5° beamwidth.
HP 11664D	Detector for AC modulated signal. Sensitivity of -50 dBm. Overall dynamic range of 40 dB.
HP 8757 scalar analyzer	401 point amplitude vs frequency plot. Normalizes the data and stores returns in memory. Also sends data to the HP 310 computer.
HP 7475 Color Plotter	Provides for color hardcopies of the data.
HP 3488 Relay Control Box	Through an interface with the computer, controls the movement of the antenna arms.
Linear Actuators	Driven by DC motors to move the antenna arms. Voltage applied across potentiometer to determine position of the arms.
HP 3457	Voltmeter measures the position voltage and sends a digital reading to the computer.

provides a reference measurement to determine the relative change once the RAM sample is placed over the plate. A second sweep is then made that shows the total effect of the coating on the scattered field at particular incidence and observation angles. The entire band, or only a portion of the band, may be swept. Basically, the measured quantity is the reflection coefficient for a coated conductor or material slab. This varies as a function of incidence angle and frequency. Taking into account depolarization, it also varies as a function of observation angle. The measured data can be stored on disk, retrieved from disk, or displayed on the CRT or a plotter. In the manual mode, there is a real-time display capability that allows for quick comparisons between different materials, material thicknesses, and material placement.

3. SOFTWARE

The software executes HP Basic version 5.0 on the HP 310 computer, with the basic flowchart shown in Figure 3. There are two main measurement programs called MSR1 and MSR5. MSR1 is used with materials not subject to change due to movement or placement. It takes only one measurement. MSR5 is designed for flexible materials. It takes five measurements, with time allowed between measurements to reposition the sample. This gives

the average effect of the material under test. The eight major subroutines are discussed in Table 2. The current software is rudimentary; however, the plan is to upgrade to a 486-based computer that will also have dedicated data analysis software. This, and other planned upgrades, is discussed in the next section.

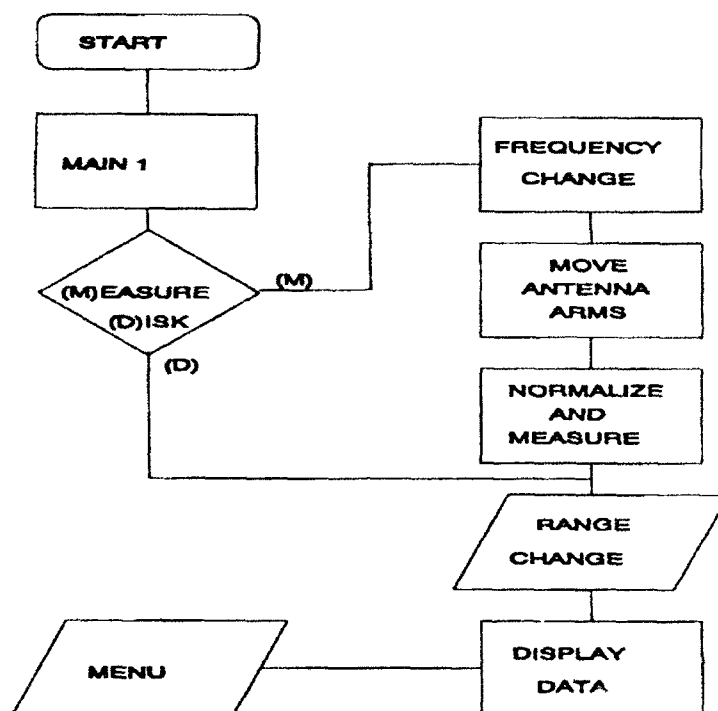


Figure 3. Measurement Flowchart

TABLE 2. SOFTWARE SUBROUTINES

SUBROUTINE	FUNCTION
Main 1	Initial execution. Presets instruments to initial settings.
Measure	Takes measurement or retrieves existing data.
Frequency Change	Allows change of the sweep range.
Test Arm Movement	Controls movement of the test arm.
Normalize and Measure	Prompts operator for reference sample, turns the RF on, makes measurement, and stores it in the analyzer. Prompts operator for test sample, turns the RF on, and makes measurement. This measurement is subtracted from the reference measurement. Subsequent measurements do not require the reference step unless something has changed.
Range Change	Changes default data display range.
Display Data	Sends data to the CRT.
Menu	Seven choices of operations: - See data again. - Plot data. - Store data on disk. - Make measurement. - Renormalize and measure. - Retrieve data from disk. - Exit.

4. FUTURE UPGRADES

The first upgrade planned is to include a vector network analyzer to allow phase measurements. There is currently a Wiltron Model 360 Analyzer that will be integrated into the MRMS. This will provide the capability to generate the polarization scattering matrix, measuring COPOL and cross-polarized receive signals for both vertical and horizontal transmit signals. Additional frequency coverage beyond 40 GHz is also planned. The equipment covering the 75-110 GHz range has been procured. The W-band setup will use DC detection as opposed to the AC detection used at Ka-band. This will require periodic calibration to compensate for drift and errors due to temperature variations. Also, the output power is 8-10 dB lower, which may decrease the dynamic range accordingly. These, and other problems, need to be evaluated to characterize the W-band system. A small positioner in the base, with a styrofoam target-mounting column, will allow the measurement of more complex targets at various aspect angles and tilt angles. The final hardware upgrade would be a pulsed measurement system, which would allow us to gate out unwanted returns from beyond the target/RAM sample. Software upgrades would include a dedicated 486-based controller with the necessary speed to do on-line data analysis.

SECTION II

MODELING

1. REFLECTION

Models of the reflection from a coated conductor and a material slab are needed. Similar derivations can be found in many texts (References 1, 2, and 3). Solving the boundary value problem for the coated conductor for $\parallel$ and $\perp$ to the plane of incidence yields

$$\begin{bmatrix} E_{\parallel}^r \\ E_{\perp}^r \end{bmatrix} = \begin{bmatrix} R_{\parallel} & 0 \\ 0 & R_{\perp} \end{bmatrix} \begin{bmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{bmatrix} \quad (1)$$

where, in decoupled form (Reference 3) we can isolate particular mechanisms, such as the front face and the transmitted wave or effect of the multiple-bounce terms. Decomposition takes the form

$$R_i = \Gamma_i - e^{-2jkd \cos \theta^i} \left[\frac{1 - \Gamma_i^2}{1 - \Gamma_i e^{-2jkd \cos \theta^i}} \right] \quad (i = \parallel, \perp) \quad (2)$$

where $\Gamma_{\parallel}$ and $\Gamma_{\perp}$ are the usual parallel and perpendicular reflection coefficients from a material half-space given by

$$\Gamma_{\parallel} = \frac{\eta \cos \theta^i - \cos \theta^t}{\eta \cos \theta^i + \cos \theta^t} \quad (3)$$

$$\Gamma_{\perp} = \frac{\eta \cos \theta^i - \cos \theta^t}{\eta \cos \theta^i + \cos \theta^t} \quad (4)$$

The angles are related by the usual Snell's Law given by

$$\theta^i = \theta^t \quad (5)$$

$$\sin \theta^t = \sqrt{\frac{\mu_0 \epsilon_0}{\mu}} \sin \theta^i. \quad (6)$$

Also, $\eta = \eta_t / \eta_i$, and since the incident field lies in free space, η_i is $\sqrt{\mu_0 / \epsilon_0}$; hence,

$$\eta = \frac{\eta_t}{\eta_i} = \sqrt{\frac{\mu' - j\mu''}{\epsilon' - j\epsilon''}}. \quad (7)$$

The first term in the decoupled form is due to the front face reflection, and the second term is related to the closed form of the geometric series formed by summing the multiple interactions between the front face and the conductor. This term is multiplied by an e^{-jkd} factor and as k'' increases (more loss), $e^{-k''d} \rightarrow 0$, which drives the multiple-bounce contribution to zero; therefore, $R_{\parallel} \rightarrow \Gamma_{\parallel}$ and $R_{\perp} \rightarrow \Gamma_{\perp}$. The reflection coefficient for normal

incidence ($\theta^i = \theta^r = 0$) is independent of polarization and given by

$$R = \frac{\eta - 1}{\eta + 1} - \frac{4\eta e^{-2jkd}}{(\eta + 1)^2} \left[\frac{1}{1 - \frac{\eta - 1}{\eta + 1} e^{-2jkd}} \right]. \quad (8)$$

The leading term is given by $(\eta - 1)/(\eta + 1)$; therefore, the obvious approach to reducing the reflection from the coated conductor is to choose $\eta = 1$. This is not usually realizable because it requires $\mu' - j\mu'' = \epsilon' - j\epsilon''$.

Solving the boundary value problem for the material slab, the reflection coefficient is given by

$$R_i = \Gamma_i - \Gamma_i e^{-2jkd \cos \theta^i} \left[\frac{1 - \Gamma_i^2}{1 - \Gamma_i^2 e^{-2jkd \cos \theta^i}} \right] \quad (i = \parallel, \perp). \quad (9)$$

As before, we have isolated the front face term. As $d \rightarrow 0$, the reflection goes to zero, and as $d \rightarrow \infty$ (assuming slightly lossy) the reflection approaches the front face or half-space term. Theoretical and measured values for the reflections from coated conductors and material slabs will be compared with the MRMS.

2. MATERIAL MODELING

In the reflection coefficient expressions, the complex material parameters play an important role and warrant further discussion. For the $e^{j\omega t}$ time convention, the complex permeability and the complex permittivity are written

$$\mu = \mu_0(\mu' - j\mu'') = |\mu| e^{-j\delta_m} \quad (10)$$

$$\epsilon = \epsilon_0(\epsilon' - j\epsilon'') = |\epsilon| e^{-j\delta_e} \quad (11)$$

where μ_0 and ϵ_0 are the permeability and permittivity of free space. In loss-tangent notation

$$\mu = \mu_0\mu'(1 - j \tan \delta_m) \quad (12)$$

$$\epsilon = \epsilon_0\epsilon'(1 - j \tan \delta_e) \quad (13)$$

where

$$\tan \delta_m = \frac{\mu''}{\mu'} \quad (14)$$

$$\tan \delta_e = \frac{\epsilon''}{\epsilon'}. \quad (15)$$

The complex wavenumber, $k = \omega\sqrt{\mu\epsilon}$, is given by $k = k' - jk''$. In general,

$$k = k' - jk'' = k_0 \sqrt{(\mu' - j\mu'')(\epsilon' - j\epsilon'')}; \quad (16)$$

therefore, as alluded to earlier,

$$e^{-jk r} = e^{-j(k' - jk'')r} = e^{-k''r} e^{-jk'r}. \quad (17)$$

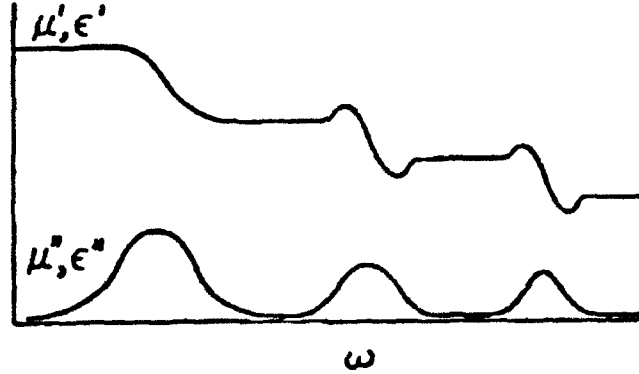


Figure 4. Material Resonances

The k' term is the propagation factor, and the k'' term is the attenuation factor. After manipulation, we can write

$$\begin{Bmatrix} k' \\ k'' \end{Bmatrix} = k_0 \sqrt{\frac{\mu' \epsilon'}{2}} \sqrt{(1 + \tan^2 \delta_e)^{\frac{1}{2}} (1 + \tan^2 \delta_m)^{\frac{1}{2}} \pm [1 - \tan \delta_e \tan \delta_m]}. \quad (18)$$

Material parameters can be frequency dependent $\mu(\omega)$ and $\epsilon(\omega)$. Figure 4 shows typical curves for the frequency dependence. We have several dispersion models for the frequency behavior and are working on the derivation of others. They may display resonances characterized by well-known material models such as the Debye model (relaxation time τ) and the Lorentz model (plasma freq ω_p and collision freq ν).

For composites, there are various mixing formulas such as the Maxwell-Garnett formula. The mixing formulas are functions of the parameters for the binder material, the fill factor, particle depolarization factors, and the μ and ϵ of the particle. The plan is to compare measurement and theory using the MRMS.

3. DEPOLARIZATION

The phenomenon of depolarization is associated with tilting plates. The reflected and incident field for a tilted half-plane (References 4 and 5) are related by

$$\begin{bmatrix} E_{\parallel}^r \\ E_{\perp}^r \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} E_{\parallel}^i \\ E_{\perp}^i \end{bmatrix} \quad (19)$$

where

$$R_{11} = \Gamma_{\parallel} \cos \beta_2 \cos \beta_1 + \Gamma_{\perp} \sin \beta_2 \sin \beta_1 \quad (20)$$

$$R_{12} = -\Gamma_{\parallel} \sin \beta_1 \cos \beta_2 + \Gamma_{\perp} \cos \beta_1 \sin \beta_2 \quad (21)$$

$$R_{21} = -\Gamma_{\parallel} \sin \beta_2 \cos \beta_1 + \Gamma_{\perp} \cos \beta_2 \sin \beta_1 \quad (22)$$

$$R_{22} = \Gamma_{\parallel} \sin \beta_2 \sin \beta_1 + \Gamma_{\perp} \cos \beta_2 \cos \beta_1. \quad (23)$$

These describe the depolarization and reduce to the uncoupled Fresnel reflection coefficients when β_1 and β_2 are zero. For the tilted coated conductor or material slab, $\Gamma_{\parallel}$ and $\Gamma_{\perp}$ are replaced by the appropriate $R_{\parallel}$ and $R_{\perp}$. The angles β_1 and β_2 are functions of the incident and observation angle given by

$$\cos \beta_1 = \frac{\sin \theta^i \cos \theta^r + \cos \theta^i \sin \theta^r \cos \phi^r}{\sin \beta} \quad (24)$$

$$\cos \beta_2 = \frac{\cos \theta^i \sin \theta^r + \sin \theta^i \cos \theta^r \cos \phi^r}{\sin \beta} \quad (25)$$

$$\sin \beta_1 = \frac{\sin \theta^r \sin \phi^r}{\sin \beta} \quad (26)$$

$$\sin \beta_2 = -\frac{\sin \theta^i \sin \phi^r}{\sin \beta} \quad (27)$$

where

$$\cos \beta = \cos \theta^i \cos \theta^r - \sin \theta^i \sin \theta^r \cos \phi^r \quad (28)$$

$$\sin \beta = \sqrt{\sin^2 \theta^r \sin^2 \phi^r + [\sin \theta^i \cos \theta^r + \cos \theta^i \sin \theta^r \cos \phi^r]^2}. \quad (29)$$

4. SURFACE ROUGHNESS

The final modeling aspect we will eventually incorporate is that of surface roughness. At MMW frequencies, the surface irregularities can be a significant portion of a wavelength; therefore, they will impact the scattering from that surface (Reference 6). When the roughness is on the order of a wavelength, the usual scattering solutions must be modified to account for the effect of the roughness. Roughness of this order is very common in the MMW region.

SECTION III

MEASUREMENT COMPARISONS

In this section, examples of the measurements and theoretical predictions are compared. We opted for a material with known parameters for ease of comparison. Plexiglass slabs of various thicknesses, resting directly on the anechoic base of the MRMS, were measured. The plots of Figure 5 through Figure 7 show the raw measurements and the theoretical predictions for the samples. Good qualitative agreement is observed. The general resonant structure, i.e. the location and number of the nulls, is accurately measured by the MRMS. This is the first validation of the MRMS by a theoretical model. If the material were more lossy, even better agreement could be expected. Various materials will be measured to compare the reflection and material model predictions to the MRMS measurements.

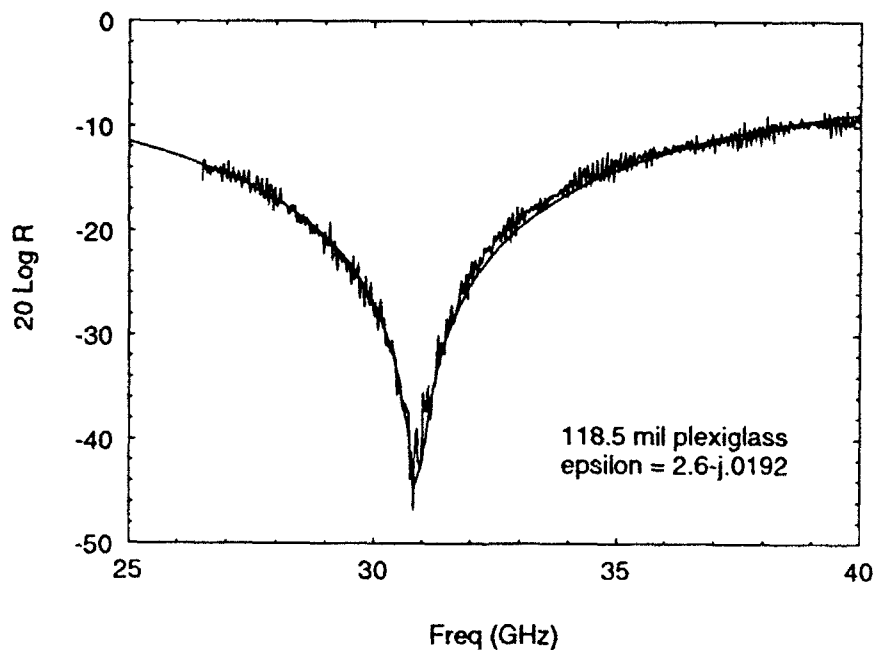


Figure 5. Measured and Predicted Data: 118.5 mil plexiglass

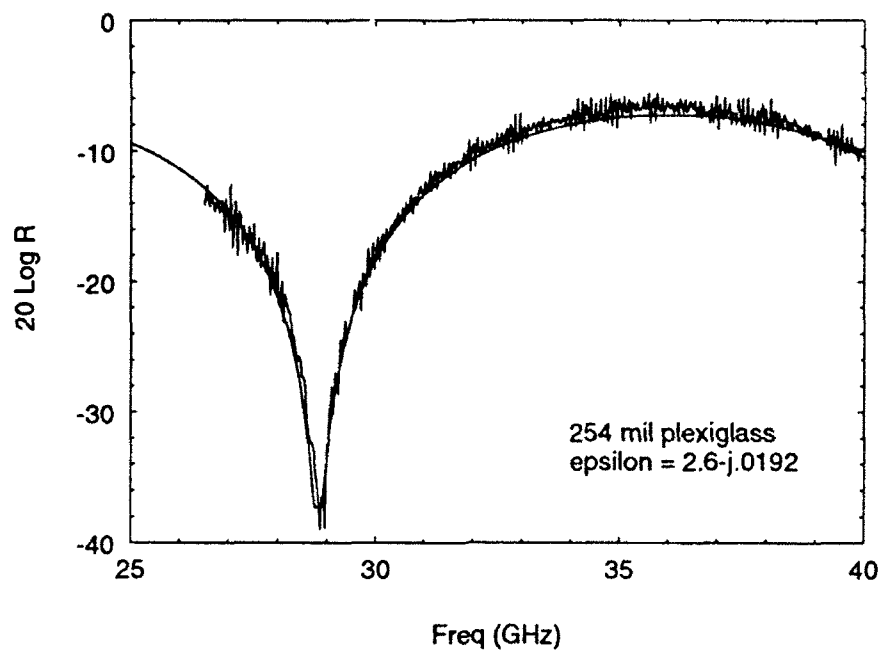


Figure 6. Measured and Predicted Data: 254 mil plexiglass

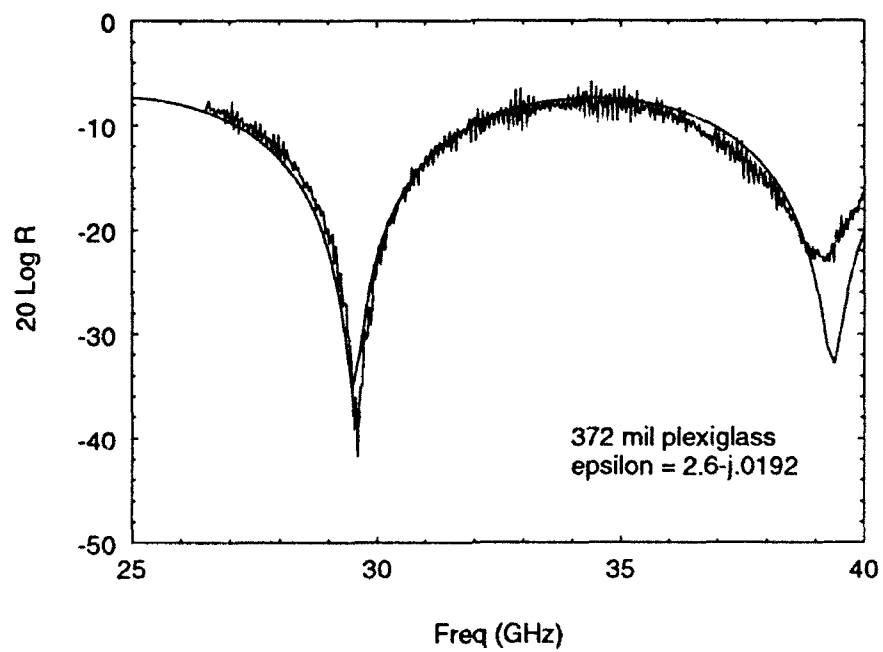


Figure 7. Measured and Predicted Data: 372 mil plexiglass

SECTION IV

CONCLUSIONS

The success in measuring the reflection from these materials with known parameters clearly suggests the ability to measure unknown materials and calculate the unknown material parameters. These parameters could then be substituted into the reflection prediction (material slab or coated conductor) programs and compared to the original measurements. This capability would enhance the material and target modeling efforts for the determination of exploitable phenomena to improve seeker guidance techniques.

In the preceeding sections, the configuration and current capabilities of the MRMS were described. We have also outlined planned hardware and software upgrades as well as phenomenology we plan to theoretically model and verify using the MRMS. The MRMS provides a unique capability to understand MMW scattering mechanisms and to verify the effectiveness of MMW countermeasures.

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