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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE 91-32

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Electronic Warfare Division

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ABSTRACT

Testing the performance of Radar Absorbing Materials (RAM) is often a difficult task and in most cases the manufacturer's specifications are the only source of performance data. This paper presents a method of measuring the normal reflection coefficient of planar RAM using a Hewlett-Packard 8510A Vector Network Analyzer and a small horn antenna. The Vector Network Analyzer is used to cancel the reflections from discontinuities in the signal path from the source to the RAM sample leaving only the reflections from the RAM sample. Using this approach, information can be gathered over a wide bandwidth very quickly and comparisons between RAM samples done easily.

RÉSUMÉ

Vérifier la performance d'un Matériel absorbant d'ondes radar (MAR) est une tâche difficile et les spécifications fournies par le manufacturier sont la seule source valable d'information de données. Ce rapport décrit une méthode qui permet de mesurer le coefficient de réflexion normal des échantillons en utilisant un 'Vector Network Analyzer' (VNA) modèle 8510A fabriqué par Hewlett-Packard et une antenne micro-onde. Le 'VNA' est employé pour éliminer les réflexions provenant de discontinuités dans les trajectoires entre la source et le MAR, laissant seulement les réflections directes provenant du matériel absorbant. En utilisant cette technique, il est possible d'obtenir rapidement de l'information sur une grande bande de fréquence et de comparer facilement différents échantillons de matériel absorbant.

EXECUTIVE SUMMARY

Radar Absorbing Material (RAM) can be used to reduce the radar echo from military platforms by partially absorbing incident radar signals. Several manufacturers are now supplying RAM to Canadian and other forces for application to ships and aircraft. A need for a method of testing the performance of RAM supplied to the Canadian Forces has arisen.

To solve this problem a novel method for measuring the absorption of RAM which uses a vector network analyzer was tested. This technique is an improvement of a previously reported technique which used a scalar network analyzer.

A discussion of computational techniques for analyzing RAM is provided to introduce the idea of equivalent surface impedance at the air-dielectric interface.

Examples of measurements are included for three types of RAM and for a metal plate. Anomolies in the metal plate measurements are due to multiple reflections between the metal plate and the signal path discontinuities. The measurements display the same characteristics as the typical curves provided by the RAM manufacturers for each type of RAM. For the first two RAM samples, which rely on some phase cancellation to work, a null is found at a specific frequency dependent on the type of material and its thickness. For electrically thick absorbers the attenuation curve is more constant with frequency as shown in the measurements of the third absorber.

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1.0 INTRODUCTION

There are two methods commonly used to reduce the RCS of radar targets; changing the shape of the target so energy is scattered away from the radar receiver and adding RAM to the scattering surfaces to partially absorb the incident energy. RAM is available commercially in several forms for varied applications. In all applications, the amount of attenuation afforded by the RAM and the performance of the RAM over a specified bandwidth are of prime importance. Other issues involved when making decisions about fitting RAM are initial cost, resistance to weather, weight/performance degradation, and expected usable lifespan. This paper will not cover the various types of RAM or the principles behind their design but will introduce analytical methods for calculating reflection coefficients of RAM and outline a method of measuring the performance characteristics of planar RAM; interested readers are referred to [2] and [7] for more complete studies of RAM design. The main advantage of the proposed measurement method is that it can be performed quickly and easily and data is collected over a wide bandwidth almost simultaneously.

2.0 ANALYTICAL TECHNIQUES

There are various methods of characterizing dielectric materials. They may be specified by their permittivity and permeability, the equivalent surface impedance, or a reflection coefficient. This section will describe the concept of surface impedance and reflection coefficient in terms of basic dielectric properties. This background is useful in discussing the measurement procedure described in the next section.

The permittivity and permeability are material properties of the test sample at a microscopic level. They determine the interaction between the material and an incident electromagnetic field. Permittivity and permeability are usually given relative to the free space values, *ie*,

$$\begin{aligned} \epsilon &= \epsilon_r \, \epsilon_o \\ \mu &= \mu_r \, \mu_o \end{aligned} \tag{1}$$

where ϵ_o and μ_o are, respectively, the permittivity (8.854×10^{-13}F/M) and permeability ($4\pi \times 10^{-7}$H/M) of free space.

The relative permeability and permittivity are, in general, complex and can be written in terms of real and imaginary parts. The real parts account for the lossless dielectric properties of the substance and the imaginary parts account for the lossy properties.

They can be written as [2]

$$\begin{aligned} \epsilon_r &= \epsilon_r' + i\epsilon_r'' \\ \mu_r &= \mu_r' + i\mu_r''. \end{aligned} \tag{2}$$

The complex permittivity and permeability can also be expressed as a complex exponential, for example:

$$\begin{aligned} \epsilon_r &= |\epsilon_r| e^{i\delta_e} \\ \mu_r &= |\mu_r| e^{i\delta_m}. \end{aligned} \tag{3}$$

The phase angles of the above expressions are termed the loss tangents and are often quoted as a measure of the loss characteristics of a material.

The lossy (imaginary) part of the permittivity is made up largely of conductive losses. It can be written in terms of σ, the conductivity of the material, as

$$\epsilon_r'' = \frac{\sigma}{\omega \epsilon_o} \tag{4}$$

where ω is the radial frequency of the excitation. A table of permittivity values for some common materials is shown in Table 1 [1]. These values can only be related to the macroscopic or overall scattering properties of the surface if the material is homogeneous.

In the case of heterogeneous dielectric mixtures, if the inclusions are randomly oriented and placed, the equivalent permittivity can be estimated by the formula [6]

$$\epsilon_a \approx \epsilon_h + v_i(\epsilon_i - \epsilon_h) \tag{5}$$

where ϵ_a is the equivalent permittivity of the mixture, ϵ_h is the permittivity of the filler material, v_i is the percent volume of the inclusion, and ϵ_i is the permittivity of the inclusion.

Figure 1 shows the analytical model used for evaluating backscatter from RAM. The dielectric slab is characterized by its permittivity, permeability and thickness and the metal surface is assumed to be a perfect conductor. The intrinsic impedance, Z, of a homogeneous material can be calculated in terms of the permittivity and permeability as

$$Z = Z_o \sqrt{\frac{\mu_r}{\epsilon_r}} \tag{6}$$

where $Z_o = \sqrt{\frac{\mu_0}{\epsilon_0}}$ is the impedance of free space ($\approx 377\ \Omega$). This impedance is the ratio

Material	f(GHz)	ϵ'	ϵ''
amber (fossil resin)	3	2.60	0.23
fiberglass BK-174	3	4.40	0.13
	10	4.37	0.16
glass, phosphate	3	5.17	0.024
	10	5.00	0.021
Lucite HM-199	3	2.57	0.0126
	10	2.57	0.0082
Neoprene Compound	3	4.00	0.135
	10	4.00	0.105
Plexiglass	3	2.60	0.015
	10	2.59	0.175
Polystyrene	3	2.55	0.00085
	10	2.54	0.0011
Teflon	3	2.10	0.0003
	10	2.08	0.0008
Water	3	80.5	25.0
	10	38.0	39.0

Table 1: Values of Permittivity of some Common Materials.

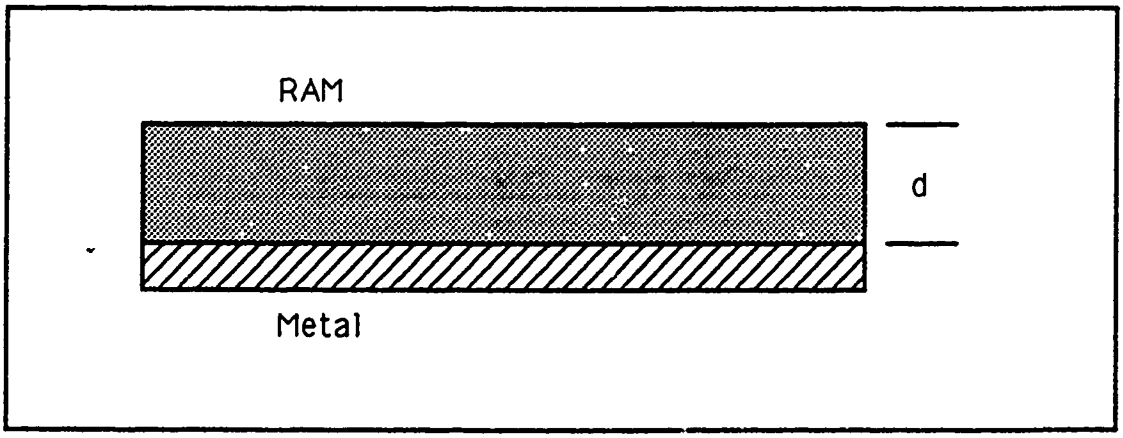

Figure 1: Model for Backscattering from RAM

between the magnitude of the electric and magnetic field vectors in free space. If the dielectric is thick enough or lossy enough to be considered infinite, the surface impedance presented to an impinging wave is the intrinsic impedance. Thus, the surface impedance can be written as

$$Z_s = Z_o\sqrt{\frac{\mu_r}{\epsilon_r}}. \tag{7}$$

From Eq. 7, a dielectric material with $\epsilon_r = \mu_r$ would be perfectly matched to free space and absorb all energy incident normal to the surface since it would present a free space impedance to an impinging wave. Both ϵ_r and μ_r are, however, frequency dependant so a broadband absorber is difficult to realize using this concept.

In the case where the material is not infinite and the incoming wave reflects from the metal surface behind the dielectric, the surface impedance is dependant on both the material properties and the thickness (in wavelengths) of the dielectric. For the case of a flat dielectric slab over a perfectly conducting sheet the surface impedance can be written:

$$Z_s = Z_o\sqrt{\frac{\mu_r}{\epsilon_r}}\ \tanh\left(-ik_o d\sqrt{\mu_r\epsilon_r}\right) \tag{8}$$

where d is the thickness of the dielectric slab and $k_o = \omega\sqrt{\mu_o\epsilon_o}$, the free space wavenumber.

Other types of surfaces can be characterized by their surface impedance. For example, a corrugated surface has an anisotropic surface impedance which is dependant on the depth of the corrugations. The concept of surface impedance is strictly valid only for flat structures but can be used for surfaces with a radius of curvature large compared to the wavelength [7].

The reflection coefficient is a measure of the wave reflected back from a surface normalized to the incident wave. It is an overall property of the geometry and material composition of the structure. To completely specify the reflection coefficient, both the magnitude and phase of the reflected wave must be known as compared to the magnitude and phase of the incident wave.

In cases where the surface impedance of the scattering structure is known, the reflection coefficient, R, for normal incidence from free space, can be calculated as

$$R = \frac{Z_s - Z_o}{Z_s + Z_o}. \tag{9}$$

Using an absorbing dielectric with a graduated permittivity or permeability profile is a popular method of making wide-band RAM. The profile can be produced by changing the amount of inclusion in a matrix material or by shaping of the material. The

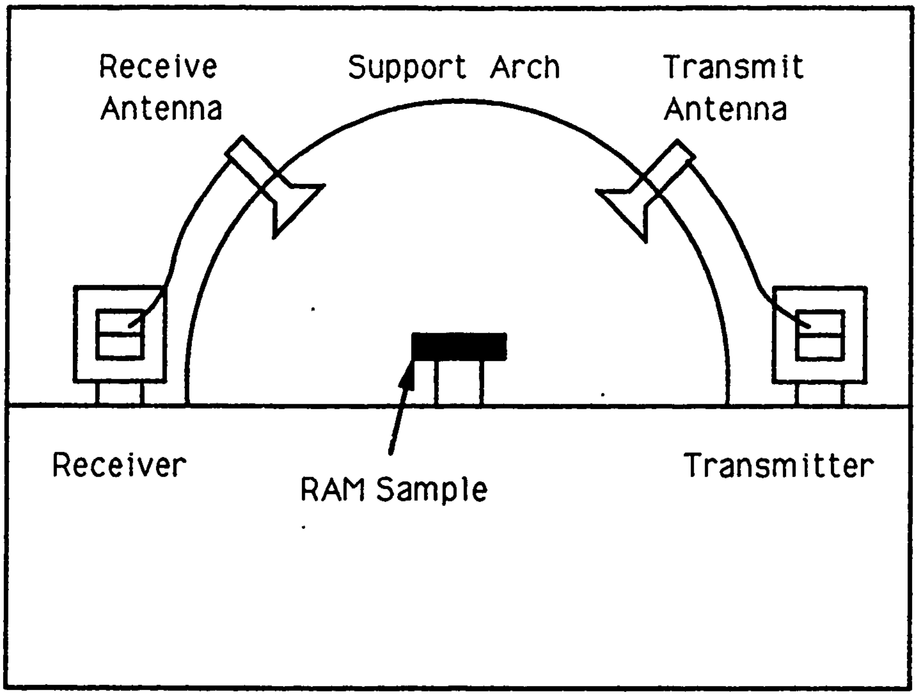

Figure 2: The NRL Arch

reflection from a material with a known permittivity profile can be approximated as [6]

$$R(z_o) \approx \int_{-\infty}^{z_o} \frac{\beta}{2\beta'} e^{2j\int_{z_o}^{z} \beta dz} dz \tag{10}$$

where $\beta = k_o\sqrt{\epsilon(z)}, \beta' = \frac{d\beta}{dz}$ and it is assumed that the dielectric is electrically thick.

Reflection from structures at oblique angles is an even more difficult problem to solve analytically and is beyond the scope of this report. The reader is referred to [4].

3.0 MEASUREMENT TECHNIQUES

The standard application of RAM is over top of a flat or nearly flat sheet of metal. This typical situation is shown in Fig. 1. The measurement procedure described here measures the reflection coefficient at the surface of the dielectric.

A common method of measuring the efficacy of RAM is to use an NRL arch as shown in Fig. 2 [2]. Separate transmit and receive horns are used to provide isolation and bistatic scattering measurements can be made. The measurements of the RAM are then referenced to those of a metal sheet in the same position. Thus, the effectiveness of the RAM relative to that of metal is measured.

The NRL arch is usable only if a sample of RAM is available to be placed under

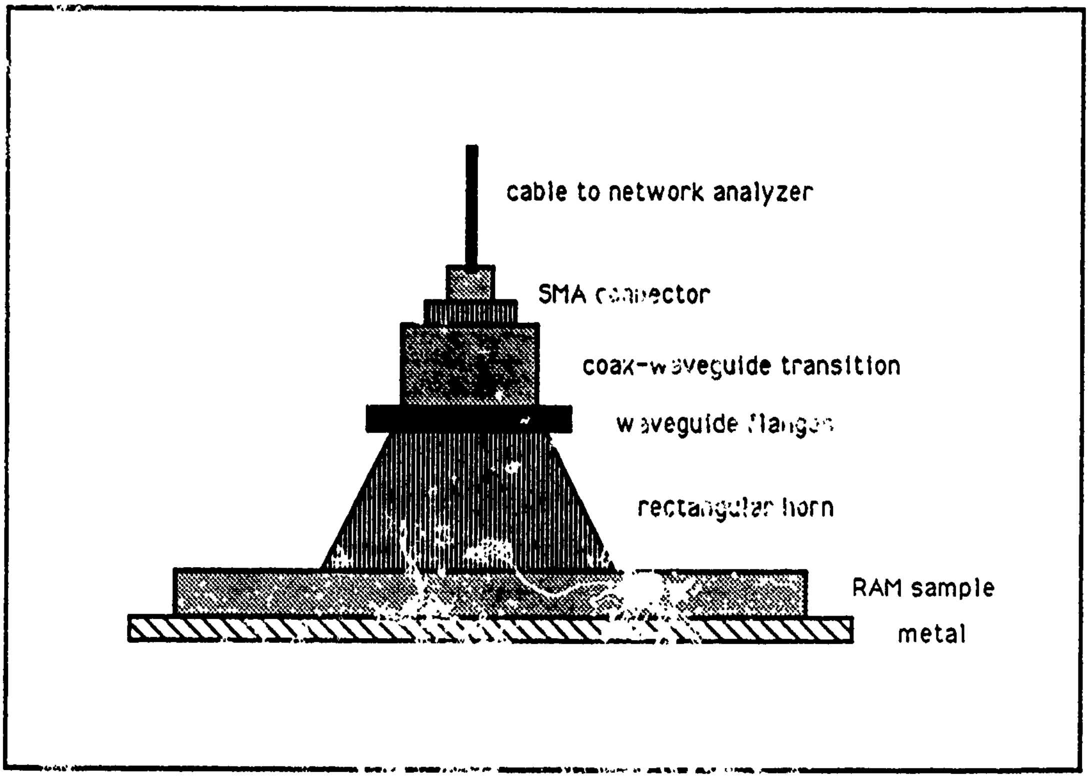

Figure 3: A RAM measurement System

the arch. It is difficult to use this type of measurement system on an operational target such as an aircraft fuselage.

A more appropriate method for measuring RAM *in situ* would be to use a single microwave applicator right at the surface of the RAM and to measure the power reflected into the applicator. This method can be used to compare the reflections from different surfaces but the measured results will not be the same as with the NRL arch since the sample is not in the far field of the antenna. A possible applicator is a horn antenna placed directly onto the surface of the RAM as shown in Fig. 3.

A schematic drawing of the equipment used for reflection measurements with a scalar network analyzer is shown in Fig. 4. If measurements are taken with a scalar network analyzer the reflections from the coax-waveguide junction and the horn aperture are large and mask the return from the material under test. The transmission line model of the discontinuities is shown in Fig. 5. It was found that the dynamic measurement range of this type of apparatus was less than 15 dB. This could be improved by using better quality components but it was felt that better results could be obtained using the vector network analyzer.

An improvement on the measurement method using a scalar network analyzer

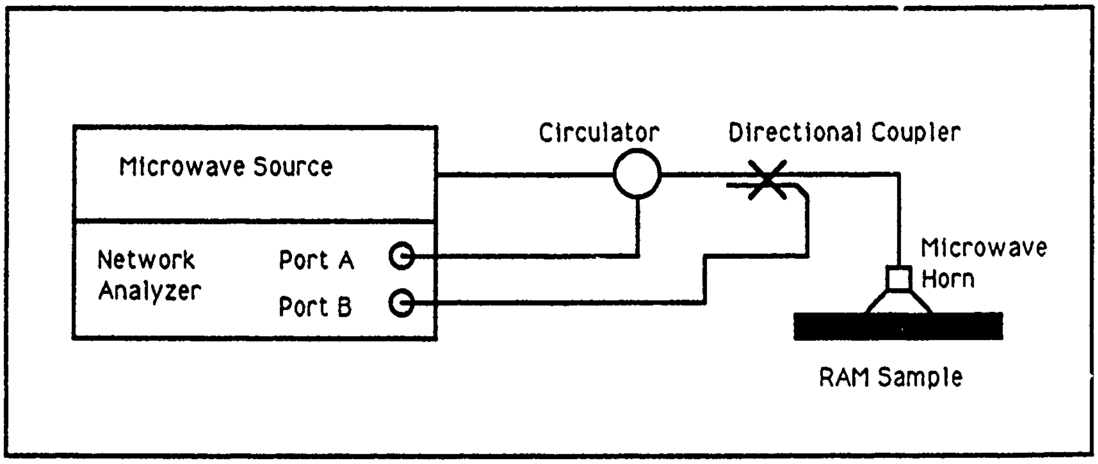

Figure 4: A Scalar Network Analyzer used for Reflection Measurements

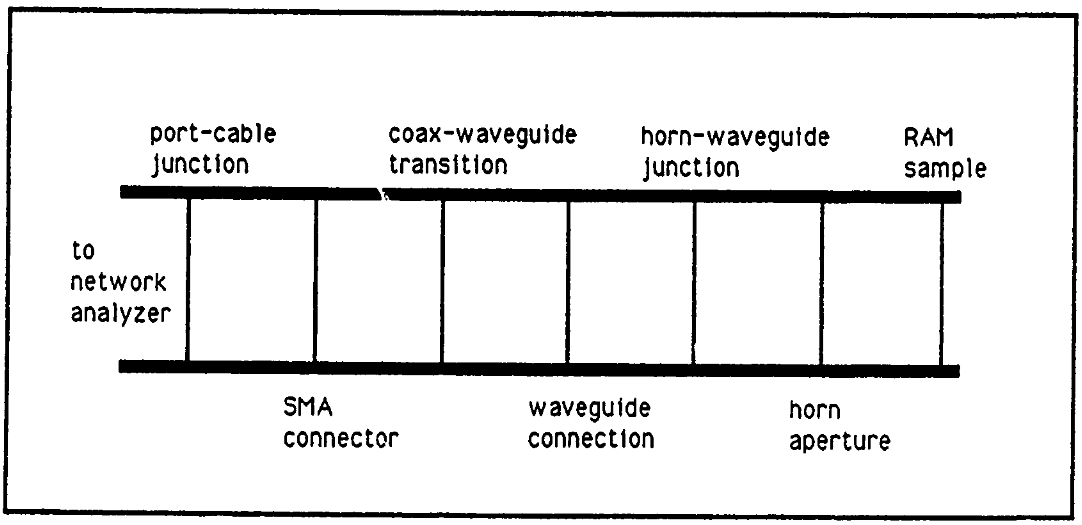

Figure 5: A Transmission Line Model of Discontinuities

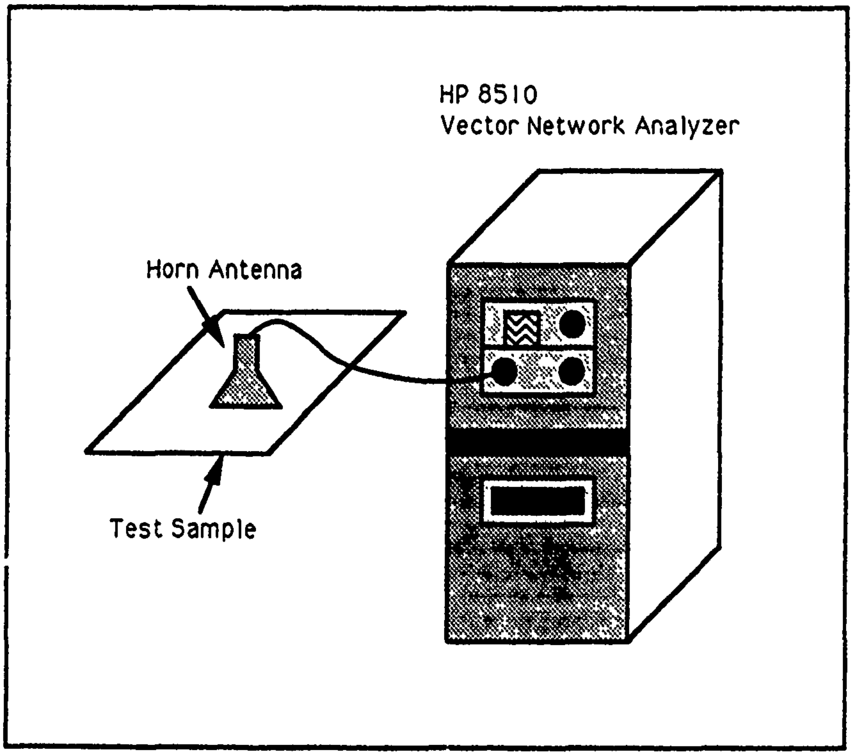

Figure 6: RAM Measurement Using A Vector Network Analyzer

has been reported by Baker and van der Neut. It uses an exponential horn with rolled edges at the aperture to provide better aperture matching to the RAM sample [8]. With this technique the authors claim a dynamic range of 30-35 dB.

This problem of reflections from junctions can be avoided by placing the sample under test inside a coaxial waveguide and using a slotted line to make voltage standing wave ratio measurements from which the reflection coefficient can be computed. This method, however, is not convenient for many RAM samples and certainly could not be used to measure vehicle surfaces.

The technique used for this study uses a single horn and a vector network analyzer to make the measurements. The test set-up is shown in Fig. 6. The vector network analyzer records both the magnitude and phase of the signal reflected back from the measurement applicator and the sample under test. This measured data is sampled at multiple frequencies across a wide frequency range and digital representations of the samples are stored in memory. Vector calculations can be done using both the stored data and the measurement data as it is collected. For example, as the measurements are taken they can be added to points in memory and the point-by-point summation of the two signals displayed on the screen. This feature is important for the measurement of the reflection coefficient since it can be used to cancel the reflections from the interfaces between the cable and horn.

The cancellation is done by first pointing the horn into free space and measuring the reflection coefficient. This measurement will include reflections from cable junctions and from the various discontinuities in the horn but will not include any reflections from beyond the aperture of the horn. This measurement is then stored in memory. Next, the RAM sample is placed against the aperture of the horn and the same reflection measurement is performed. This measurement will include the reflection from the RAM sample as well as the reflections from the discontinuities in the coax cable, the junction and the horn. Thirdly, the measurement of free space (held in memory) is subtracted from the RAM measurement and the difference displayed on the screen. The display will be only the reflection from the RAM as all of the other reflections will have cancelled out in the subtraction. Subtracting a measurement of free space from a previous free space measurement gives an indication of the dynamic range of the system. It was found that the return is 45 to 50 dB down from that of a metal plate.

4.0 RESULTS

The results of experiments are shown in Figs. 7 and 8. Figure 7 is a comparison of the return from a metal plate with those from two tuned absorbers. Figure 8 is a comparison of a metal plate with a broad-band absorber. In both cases, the spikes on the flat metal plate response shifted when the coax cable between the network analyzer and the horn was moved. These spikes are likely due to multiple reflections between the metal surface and the feed horn. Since the RAM attenuates the reflected wave these spikes do not appear on the measurements of RAM.

In Fig. 7, the measurements of the absorbers compare favourably with typical curves for this type of absorber. Over the bandwidth from 8-12 GHz each of the absorbers displayed a minimum reflection of approximately -30 dB compared with the return from a metal plate. This point of minimum reflection is at resonance when the thickness of the RAM is one-quarter of a wavelength of the incident signal and phase cancellation is the primary cause for the high attenuation. Away from resonance the attenuation is due to a combination of phase cancellation and absorptive losses in the material.

In Fig. 8, an electrically thick absorber was tested. As expected, this absorber does not display any resonances and the reflection coefficient steadily decreases with frequency. The absorption over the displayed bandwidth is between -5 and -10 dB.

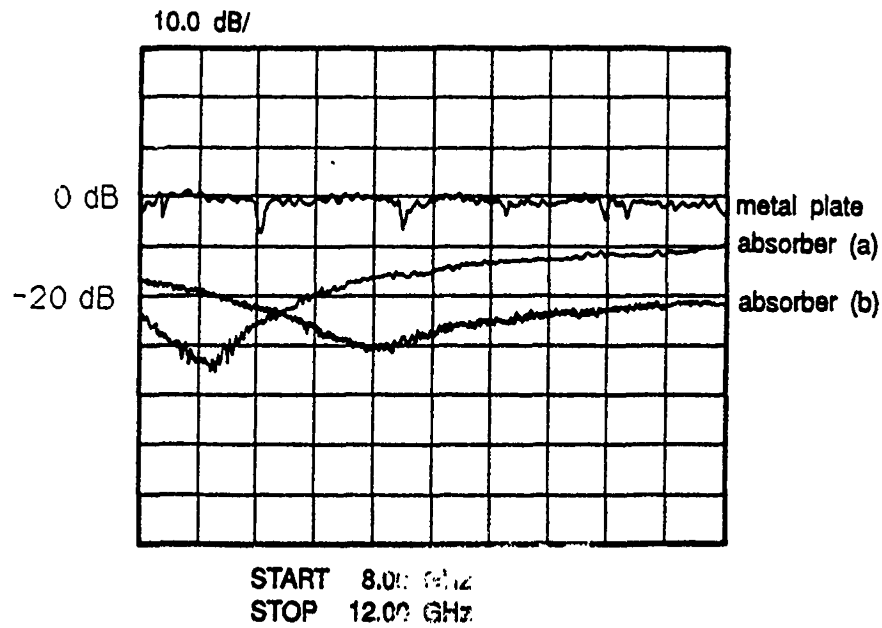

Figure 7: Comparison of reflected power from two RAM panels and a Metal Plate *vs.* Frequency

5.0 CONCLUSIONS

This method of using a vector network analyzer to compare the performance of radar absorbing materials was found to be easy, quick and accurate. It offered better dynamic range than previously reported techniques due to cancellation of the spurious reflections from discontinuities in the signal path.

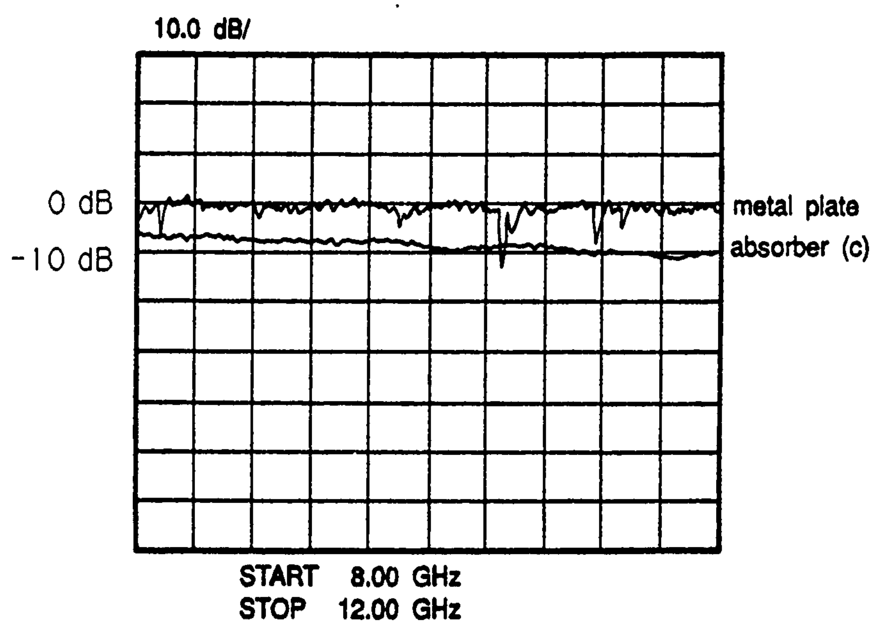

Figure 8: Comparison of reflected power from a Broadband Absorber and a Metal Plate *vs.* Frequency

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