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MEASUREMENT TECHNIQUES FOR DETERMINING THE REFLECTION COEFFICIENT AND COMPLEX PERMITTIVITY FOR PYRAMID CONE ABSORBERS

by
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Abstract

In previous work, a mathematical model to predict the performance of pyramid cone absorbers that line anechoic electromagnetic measurement chambers has been developed. In this report, we will report on experimental techniques used to test the validity of the absorber pyramid cone model.

1 Introduction

In earlier work [1], a theoretical model was developed to predict the low-frequency (30-300 MHz) reflection coefficient for arrays of pyramid cones that line the wallsof anechoic electromagnetic measurement chambers. This model has been used to compute the fields produced by sources in the chamber in [2], under the assumption that the walls are good enough absorbers that more than one reflection from them can be ignored. However, before the model for the absorbing cones can be used with confidence, one needs to examine how the theoretical reflection coefficient correlates with measured values.

To compare measured and theoretical reflection coefficients, accurate values for the material properties of the absorber are needed for use in in the theoretical model. There is a large body of literature dealing with the determination of bulk permittivity, conductivity and permeability of materials from reflection and transmission measurements [3]-[14]. Techniques for measuring the reflection coeffecients of absorbing materials have also been discussed [14]-[31]. Among the latter, techniques range from time-domain methods [13], [25], and free-space measurements [27], [28], [29], to waveguide methods [27], [16], [29]. One technique that was useful in our measurements that is beginning to appear in the literature uses a TEM cell [13], [14], [29] and [30]. In our study, many techniques for determining absorber properties were assessed, and the techniques presented here appeared to perform most reliably.

In this analysis, it was necessary to perform two types of experiments: the first to determine the bulk material properties of the absorber cones, and the second to determine the bulk material reflection coefficient for an array of such cones. The chamber wall model of [1] uses a plane wave as the incident wave. One way of measuring the reflection coefficient experimentally is to have a wall mounted with absorber cones such that the dimensions of the wall are large compared to a wavelength. However, this type of experiment requires a very large test area and introduces edge effects due to the finite wall size. We thus decided to use a TEM cell. If the cell is loaded with an integer number of cones, then the reflection coefficient of a TEM wave in this cell should be the same as that of a normally incident plane wave from an infinite array of cones.

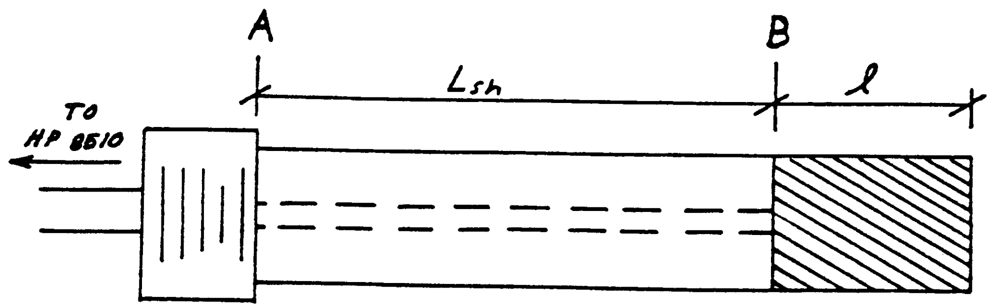


Figure 1: Experimental set-up for coaxial line.

2 Material Properties Measurement

The first experiment was performed in order to obtain the bulk material properties for the cones and for the backing layer. Once the material properties were obtained, they were used in the theoretical model to obtain the reflection coefficient for the frequency range of interest (here between 200-300 MHz due to limitations of the experimental configuration).

For this experiment we used a HP-8510 network analyzer in conjunction with a coaxial transmission line as shown in Figure 1. In this setup a material sample of length $l = 3$ cm was placed just inside the end of the coax, which was left open-circuited, and the HP-8510 was connected to the other end of the coax. The distance L_{sh} was physically measured in order to shift the reference plane of the HP-8510 (at point A in Figure 1) to the interface of the material sample (at point B in Figure 1). With the reference plane shifted, the reflection coefficient Γ_{int} at the interface can be directly measured using the network analyzer. Alternatively, we can characterize this reflection in terms of the impedance $Z(l)$ presented to the air line section of coax as:

$$Z(l) = \eta_0 \frac{1 + \Gamma_{\text{int}}}{1 - \Gamma_{\text{int}}} \tag{1}$$

where $\eta_0 = \sqrt{\mu_0/\epsilon_0}$ is the wave impedance of free space.

Once $Z(l)$ has been measured, the permittivity of the unknown material is obtained by applying the following equations [3]:

$$\Gamma(l) = \Gamma_o e^{-2\gamma l} \tag{2}$$

This is the equation for the reflection coefficient for a section of uniform line. For an ideal open-ended transmission line:

$$\Gamma_o = 1 \tag{3}$$

Therefore equation (2) becomes:

$$\Gamma(l) = e^{-2\gamma l} \tag{4}$$

where γ is the complex propagation constant of the section of line (here containing the material of unknown properties). Since

$$Z(l) = \eta \frac{1 + \Gamma(l)}{1 - \Gamma(l)} \tag{5}$$

where

$$\eta = \sqrt{\frac{\mu}{\hat{\epsilon}}} \tag{6}$$

then substituting equation (4) into equation (5), we get:

$$Z(l) = \eta \coth(\gamma l) \tag{7}$$

We rearrange equation (7) into the following form:

$$\sqrt{\hat{\epsilon}} = \frac{1}{j\omega\sqrt{\mu} l} \tanh^{-1}\left(\frac{\sqrt{\frac{\mu}{\hat{\epsilon}}}}{Z(l)}\right) \tag{8}$$

A certain arbitrariness is introduced because of the implied branch of the inverse hyperbolic tangent taken in (8). No difficulties are introduced by this if the sample is sufficiently small compared to a wavelength in the material. Equation (8) is a transcendental equation, but an iterative technique can be used to obtain the value of $\hat{\epsilon}$ if μ, l, ω and $Z(l)$ are known.

There were three different types of materials that were used; two different cone types and one kind of bulk backing layer; Sample A corresponds to 6.35 cm cones (Rantec EHP-3), Sample B to 12.7 cm cones (Rantec EHP-5), and Sample C to a slab absorber later used as a backing layer (Rantec EHP-5WW). Once the reflection coefficients were obtained, the permittivity of the samples was determined by equation (8). These results are given in Table 1.

Table 1: Bulk material properties obtained from the coax experiment.

Frequency (MHz)	SAMPLES					
	Sample A		Sample B		Sample C	
	ϵ_r'	ϵ_r''	ϵ_r'	ϵ_r''	ϵ_r'	ϵ_r''
200	4.71	9.66	3.07	5.64	16.31	28.30
210	4.56	9.29	2.98	5.43	15.95	27.35
220	4.45	8.96	2.89	5.23	15.45	26.28
230	4.30	8.67	2.82	5.03	15.30	25.58
240	4.19	8.75	2.75	4.89	14.90	24.79
250	4.09	8.12	2.72	4.76	14.64	24.03
260	3.90	7.87	2.64	4.59	14.39	23.21
270	3.90	7.64	2.58	4.45	14.17	22.76
280	3.83	7.42	2.53	4.33	13.82	21.97
290	3.73	7.25	2.47	4.21	13.56	21.37
300	3.67	7.04	2.44	4.09	13.36	21.02

3 Reflection Coefficient Measurements

It was desired to simulate a normally incident plane wave to check how our theory would correlate with measured values. In the second experiment, a TEM cell was used in conjunction with the HP-8510 network analyzer to determine the reflection coefficient. The TEM cell was used because the field distribution of the fundamental TEM mode inside the cell is merely a "warped" version of a plane wave normally incident onto whatever is inserted transverse to the cell's axis.

A metal plate was taped with metal tape (BORDEN: Mystik Tape) at one end of the segment of the TEM cell where the cross section is largest to establish a short circuit, while the other end of the cell was connected to the HP-8510. The array of cones was then loaded transversely into the cell, and between the base of the cones and the metal plate a layer of absorbing material was inserted into the cell (see Figure 2 for an illustration of the experimental set-up).

The reflection coefficients for two different sizes of cones (10 cm and 6 cm) were obtained for three different backing layers; 6 cm, 3 cm, and 0 cm (the cone structures themselves have a small amount of backing already, for mechanical stability). It should also be noted here that the two different sizes of cones are composed of different materials (see next section). The data for the six different experiments are given in Tables 2 and 3.

For this experiment, the measured frequency range was between 200 and 300 MHz. The lower frequency limit was chosen because a portion of the test system available at the Electromagnetics Laboratory at the time (the HP-8514A,

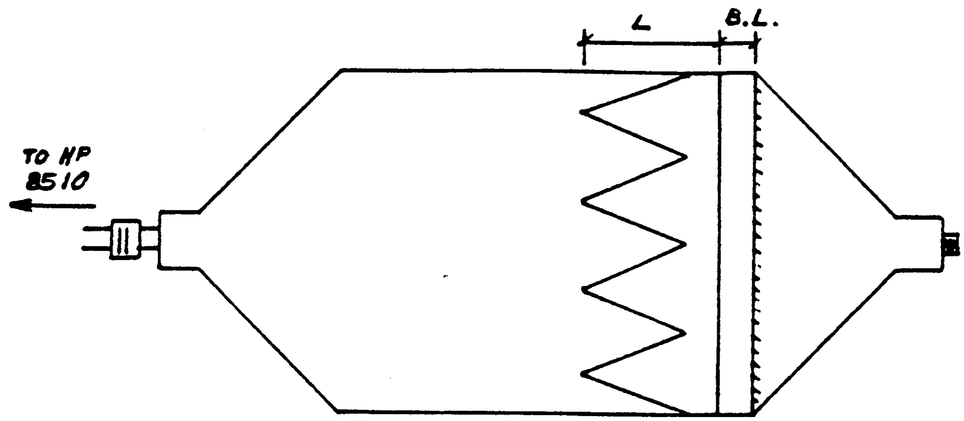


Figure 2: Experimental set-up for the TEM cell.

Table 2: Measured reflection coefficient for 6.35 cm cones.

Frequency (MHz)	6.35 cm cones		
	0.0 cm Backing	3 cm Backing	6 cm Backing
	$\|\Gamma\|$	$\|\Gamma\|$	$\|\Gamma\|$
200	0.933	0.812	.760
210	0.931	0.793	.752
220	0.926	0.776	.744
230	0.920	0.758	.734
240	0.913	0.742	.723
250	0.905	0.729	.713
260	0.903	0.712	.706
270	0.891	0.701	.702
280	0.881	0.689	.696
290	0.873	0.679	.691
300	0.868	0.671	.684

Table 3: Measured reflection coefficient for 12.7 cm cones.

Frequency (MHz)	12.7 cm cones 0.0 cm Backing	3 cm Backing	6 cm Backing
	$\|\Gamma\|$	$\|\Gamma\|$	$\|\Gamma\|$
200	0.874	0.721	0.708
210	0.863	0.699	0.694
220	0.848	0.681	0.682
230	0.833	0.661	0.669
240	0.816	0.648	0.657
250	0.803	0.633	0.643
260	0.775	0.612	0.636
270	0.765	0.606	0.626
280	0.753	0.596	0.614
290	0.739	0.588	0.605
300	0.726	0.578	0.596

S-Parameter Test Set on the HP-8510) was limited to 200 MHz and above. The upper frequency limit was due to the geometry of the TEM cell. Above about 300-350 MHz higher-order modes begin to develop in the cell, which is to be avoided because the assumption of a pure TEM wave would no longer be valid.

4 Theoretical and Experimental Comparison

Once the values of the permittivities of the cones and the backing layer are known, the differential equation for the reflection coefficient for the array of cones was used to obtain theoretical plots of the frequency response [1]. This equation was solved numerically for the same geometry that was used in the second experiment and the results are shown in Tables 4 and 5.

Once the measured and theoretical values have been determined, they were plotted on the same graphs for comparison. Six such plots were obtained and are shown in Figures 3-8. On these curves, the magnitude of the reflection coefficient in dB has been plotted as a function of frequency, over the range from 200 to 300 MHz. From the plots it is clear that the theoretical and the measured values differ from one another by 0.2 dB to 1.9 dB or from 2 to 20 percent. A discussion of the possible sources of errors is therefore in order.

5 Sources of Error

The error may be due either to that of the experiments or to approximations inherent in the theory. In the experiment utilizing the TEM cell we can identify

Table 4: Calculated reflection coefficient for 6.35 cm cones.

Frequency (MHz)	6.35 cm cones 0.0 cm Backing $\|\Gamma\|$	3 cm Backing $\|\Gamma\|$	6 cm Backing $\|\Gamma\|$
200	0.993	0.882	.638
210	0.992	0.867	.624
220	0.991	0.852	.612
230	0.989	0.835	.603
240	0.988	0.819	.596
250	0.987	0.801	.591
260	0.985	0.783	.585
270	0.984	0.764	.584
280	0.982	0.746	.580
290	0.980	0.727	.579
300	0.978	0.708	.580

Table 5: Calculated reflection coefficient for 12.7 cm cones.

Frequency (MHz)	12.7 cm cones 0.0 cm Backing $\|\Gamma\|$	3 cm Backing $\|\Gamma\|$	6 cm Backing $\|\Gamma\|$
200	0.972	0.833	0.584
210	0.968	0.811	0.567
220	0.963	0.789	0.552
230	0.957	0.765	0.540
240	0.952	0.741	0.531
250	0.946	0.716	0.522
260	0.939	0.691	0.514
270	0.932	0.666	0.511
280	0.924	0.641	0.504
290	0.917	0.616	0.499
300	0.908	0.590	0.498

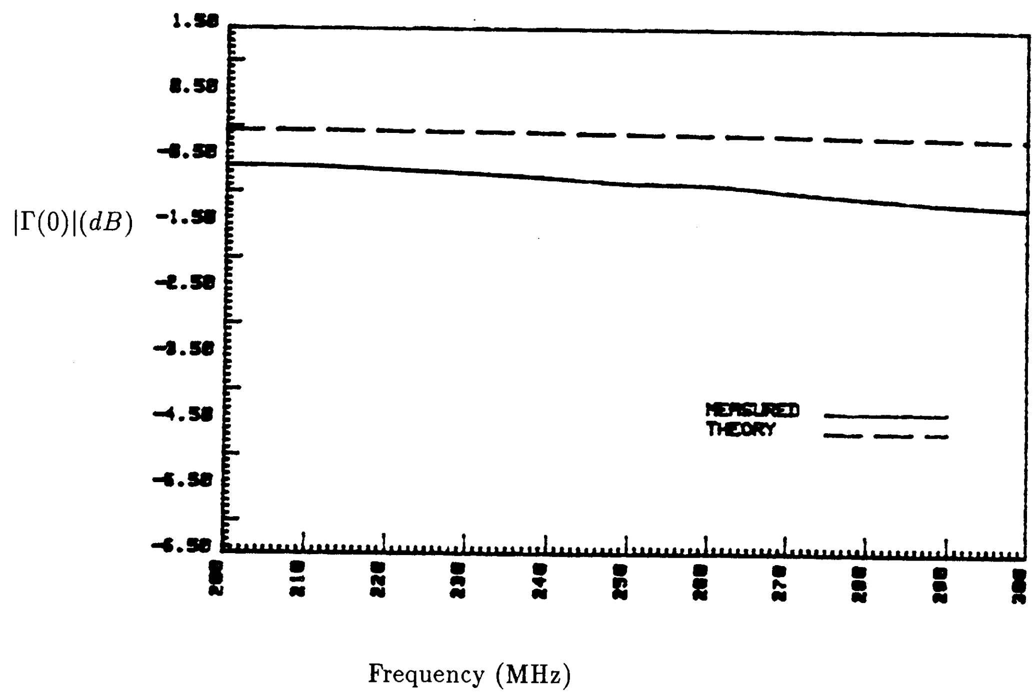


Figure 3: Comparison of measured and theoretical values of Γ for the small cones with $d = 0.0$ cm.

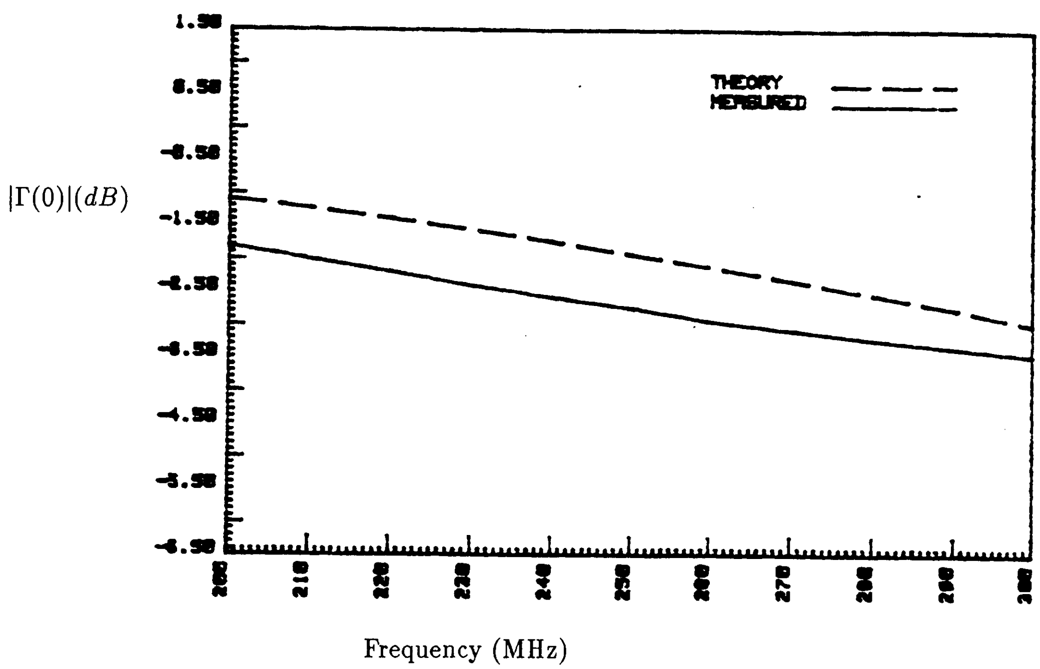


Figure 4: Comparison of measured and theoretical values of Γ for the small cones with $d = 3.0$ cm.

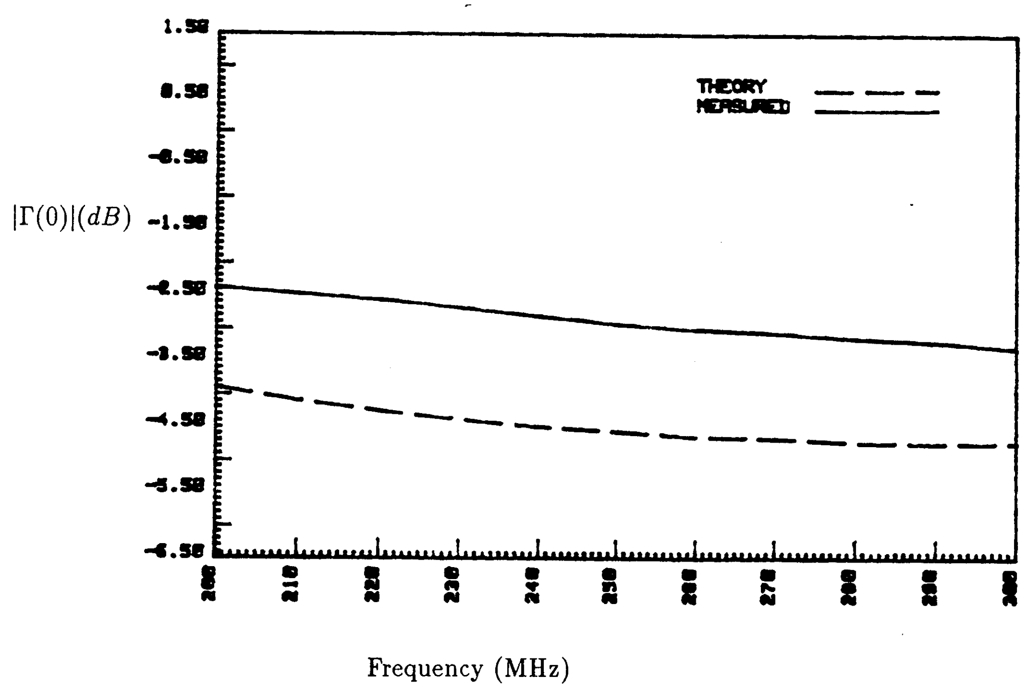


Figure 5: Comparison of measured and theoretical values of Γ for the small cones with $d = 6.0$ cm.

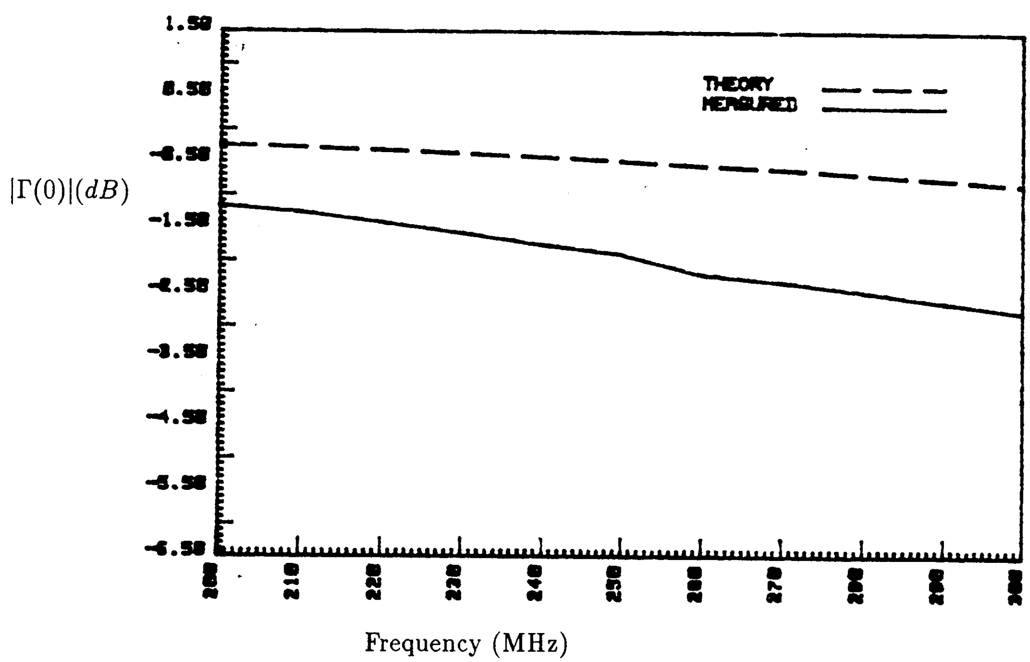
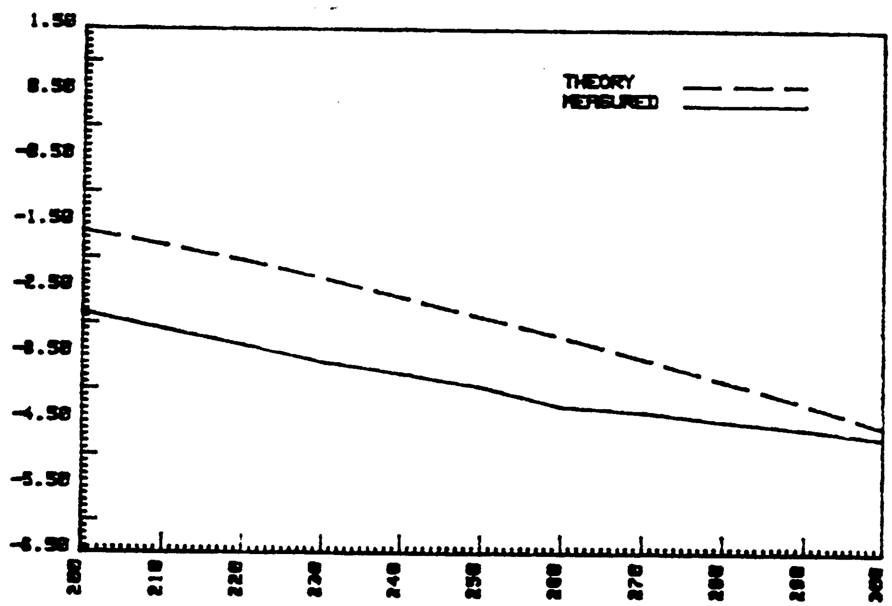


Figure 6: Comparison of measured and theoretical values of Γ for the large cones with $d = 0.0$ cm.



$|\Gamma(0)|(dB)$

Frequency (MHz)

Figure 7: Comparison of measured and theoretical values of Γ for the large cones with $d = 3.0$ cm.

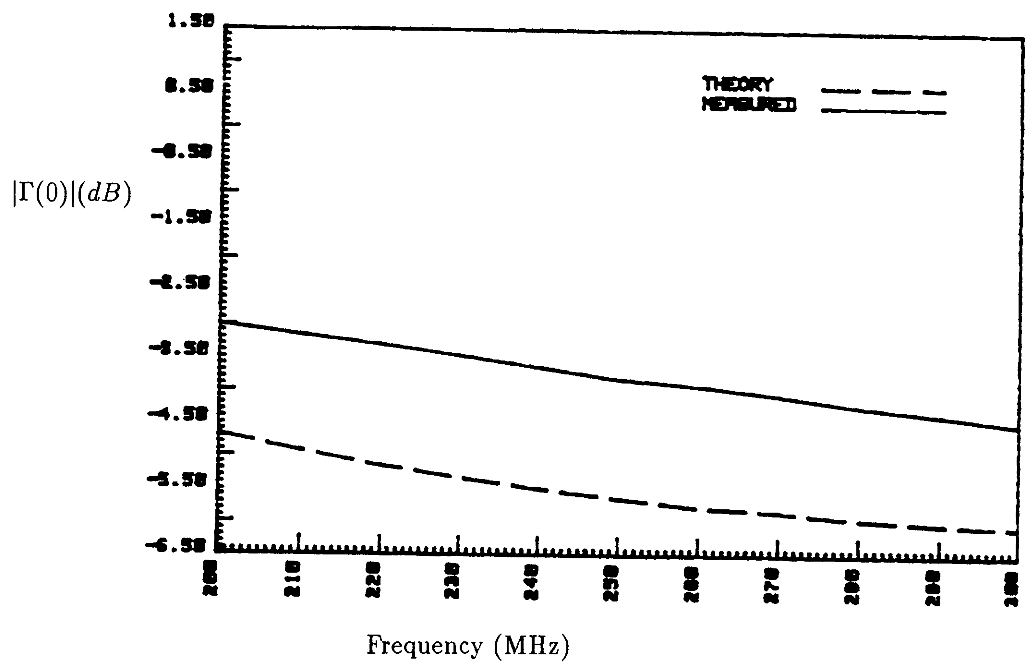


Figure 8: Comparison of measured and theoretical values of Γ for the large cones with $d = 6.0$ cm.

at least three sources of error:

1) In the TEM cell, it is necessary that a pure TEM wave be incident upon the samples. As a result, care needed to be taken in order not to allow higher order (waveguide) modes to develop in the cell. As mentioned before, this was controlled by the upper frequency limit of 300 MHz which is approximately the cutoff frequency of the next higher order mode.

2) One problem with the TEM cell was that of positioning the samples in the cell properly and avoiding the possibility of air gaps or non-vertical positioning of the samples.

3) In the TEM cell it was important to ensure that resonance (cavity) modes did not develop, that is, standing waves between the two ports of the cell.

In the experiment utilizing open-ended coax, the following may be sources of error:

1) When the samples were inserted into the coax, they became compressed. The original samples were 3 cm long, but once they were inserted into the coax fixture they tended to be compressed by about 10%. Since the properties of the sample are sensitive to such compression (this foam absorber is mostly air by volume), this change altered the value of the permittivity from its uncompressed state.

2) In developing the equations to obtain the permittivity of the samples, it was assumed that an ideal open-end existed, and the fringing field or end capacitance was neglected.

3) The non-uniformity of the material; the samples were assumed to be uniform, however in actuality, they are not. Samples were cut out of four sides of a larger cone sample, and the permittivities of the samples were obtained. The results showed that the imaginary part of the permittivity varied about 8-12% causing the theoretical reflection coefficient to vary 8-12% (see Figure 9). This non-uniformity will induce error in both the experimental and the theoretical results.

One of the major limitations of the theoretical model is the approximation used for the transverse permittivity of the cone structure [1]. However, evidence has been presented [32] that the expression used for the permittivity is accurate to within 5%. Furthermore, this expression gave the permittivity only for an array of square rods and not square cross section pyramid cones; the effect of the taper was also accounted for approximately. Finally, the whole concept of an average or effective permittivity for the pyramid cone array is all based on the technique of homogenization, in which the values of the permittivity were obtained by assuming the fields to be quasi-static. However, these cones were analyzed at 200-300 MHz, where the quasi-static assumption may begin

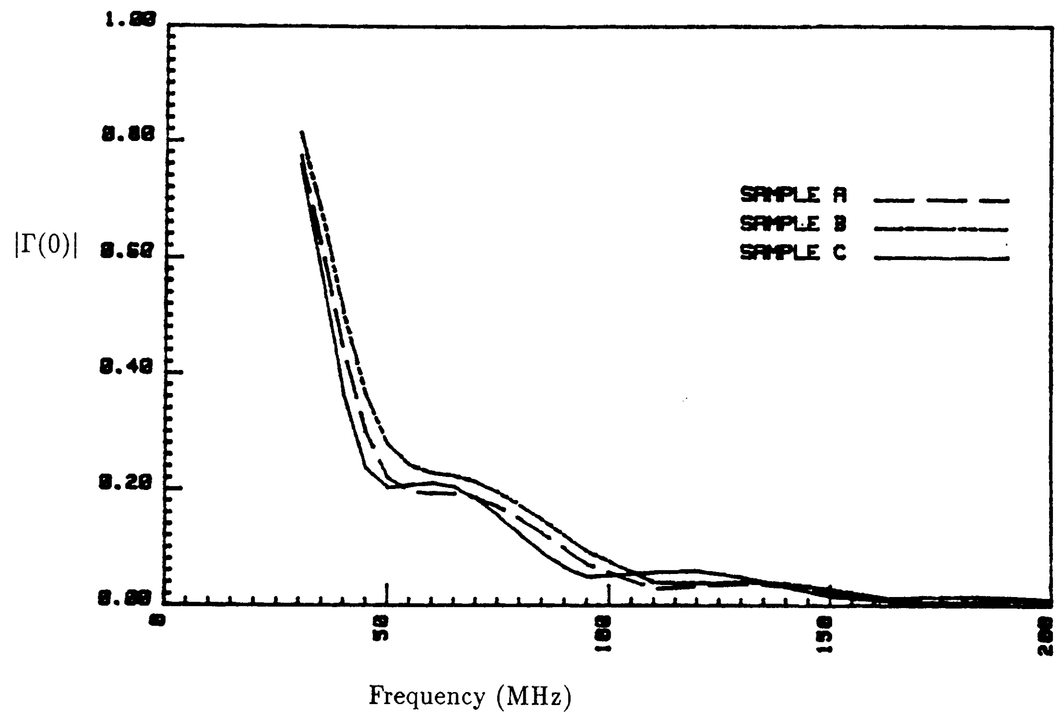


Figure 9: Variations in Γ due to the nonuniformity in material properties of the cones (the three samples are from different sides of the cone).

to become inaccurate. That is, we have not found the correction that is needed when the cone dimensions are not infinitesimally small.

6 Conclusion

When looking at the correlation between the theoretical and the measured values, the 2 to 20% difference might seem large. But once the stated errors have been considered, we judge that the low-frequency theoretical model of the cones correlates quite well with the measured values. As a consequence, we believe that the techniques reported here for measuring both the reflection coefficient and bulk permittivity for absorbing cones are viable and accurate, and should be useful in future studies of this kind.

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