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A PROPOSED SCATTERING RANGE FOR SIMULATED ECHO AREA MEASUREMENTS OF PLASMA-COATED OBJECTS

BY

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ANTENNA LABORATORY
DEPARTMENT OF ELECTRICAL ENGINEERING
THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION
COLUMBUS 12, OHIO

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Research
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UNITED STATES AIR FORCE
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ABSTRACT

A scattering range is proposed for use in experimentally simulating echo area measurements of dielectric bodies and dielectric-coated bodies with dielectric constant less than one. These investigations were initiated due to interest in plasma coatings of satellites in the ionosphere. The optimum parameters of the scattering range and the liquid to be used as the ambient medium are discussed.

While no conventional dielectric has the required properties, a mixture of Rutile (42% by volume) in transil oil was found to have the required properties for use as the ambient medium. Settling problems can be greatly alleviated with little change in electrical properties by adding petrolatum to the mixture.

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I. INTRODUCTION

Recently a program has been initiated to study the radar cross sections of dielectric-clad bodies.[1,2,3,4] This program includes exact calculations for the sphere and for the infinite cylinder, and investigations of approximate techniques for other shapes.

Experimental confirmation of these approximations is possible for relative dielectric constants greater than unity, but dielectrics with relative dielectric constants less than unity, such as exist in the ionosphere, are not available in the laboratory. It was therefore proposed to simulate this situation in order to obtain experimental confirmation of calculations and approximations in this region.

The general method would be to employ a tank filled with a high dielectric constant liquid to serve as the ambient medium. Then a body with a dielectric coating of dielectric constant less than that of the ambient liquid would simulate a body with a coating of relative dielectric constant less than unity. Measurements of radar cross section could then be made.

Previously the exact solution for the echo area has been used to verify the approximate techniques that have been developed. Experimental methods would be of interest for those bodies for which no exact boundary value solution can be obtained for the echo area. However, the approximate methods have been so highly successful that the priority for such a scattering range is very low. While this scattering range is not to be constructed, the parameters of the range are discussed in this report for the benefit of those involved in similar problems.

II. SCATTERING RANGE PARAMETERS

The basic radar scattering range would consist of a tank filled with liquid into which a small body would be immersed and its echo properties measured.

Bodies in the resonance region are of major interest since these are the targets for which the approximate calculations are most likely to be in error. Also the size of the tank required for targets much larger than one wavelength in radius would make cost of the medium excessive, and would increase construction and maintenance problems considerably. Hence the bodies of interest would have a small echo area. It was therefore decided that the antennas should also be enclosed in the tank in order to minimize nulling problems which already are severe. Except for the tank containing the antennas and the model, the scattering range would be similar to the X-band CW range presently in use at the Antenna Laboratory of The Ohio State University.[14]

Data on amplitude and phase across a square aperture has been given by R. B. Green.[5] Investigations of Green's work show that the minimum range from antenna to target at which a phase deviation of less than $\pi/8$ radians can be obtained over a 1 wavelength cross section is about 10 wavelengths. This is the usual definition of the far field. Amplitude variation over the target is less than 3 db. Since the target should be placed near the center of the tank to minimize interaction with the walls, the minimum tank dimensions should be approximately 20 wavelengths. At S-band (3 kmc) with a liquid of relative dielectric constant $\epsilon_r = 4.0$, the tank dimensions would be

$$20\lambda = 1 \text{ meter.}$$

At X-band (10 kmc) with $\epsilon_r = 4.0$, the tank dimensions would be

$$20\lambda = 0.3 \text{ meters.}$$

From above, the S-band tank would require about 1 cubic meter of liquid, which is about 250 gallons. Cost of the liquid must therefore be considered a factor. In view of this and because of the mere physical size of the necessary tank, it would be inadvisable to operate below S-band.

Losses in the liquid ambient medium must also be considered. The attenuation factor is

$$\alpha \approx \frac{k}{2} (\tan \delta) = \frac{\pi}{\lambda} (\tan \delta)$$

where tan δ is the loss tangent of the liquid. The signal decay per wavelength in the ambient medium is given by

$$A = 27.3 \tan \delta \text{ db.}$$

Since the echos from the target may be very small, the losses due to the liquid medium must be kept low. Five db was estimated as an upper limit. The total path length will be about 20λ so that the total attenuation will be

$$(Ax) = (27.3)(20) \tan \delta \text{ db}, \quad \text{or}$$

$$(Ax) = 546 \tan \delta \text{ db.}$$

Hence for an attenuation less than 5 db we must have

$$\tan \delta < 0.01$$

in the liquid. For a loss tangent of this magnitude, attenuation over the region containing the body will be very small, so that changes in the echo area due to loss in the ambient medium will not be significant.

It was desirable to be able to model relative dielectric constants of $0.25 < \epsilon_r < 1$ and model sizes of $0.05\lambda < r < 1.0\lambda$. Hence the liquid must have a relative dielectric constant of at least $\epsilon_r = 4.0$ to satisfy the first requirement. Then if $\epsilon_r = 4.0$ and the frequency is X-band (10 kmc) the minimum size model would have a radius

$$r = 0.05\lambda = 0.75 \text{ mm} .$$

This is just about the minimum size which would be machineable, and thus X-band is about the highest usable frequency.

Thus the parameters of the scattering range include:

1. Enclosed antennas
2. A frequency of 3 kmc to 10 kmc
3. A liquid such that
    a. $\epsilon_r \sim 4.0$
    b. $\tan \delta < 0.01$
    c. reasonable cost
    d. usable physical properties
4. For $\epsilon_r = 4.0$
    a. At S-band, the tank volume would be about 1 cubic meter requiring about 250 gallons of liquid.
    b. At X-band, the tank volume would be about 0.04 cubic meters requiring about 10 gallons of liquid.

Scattering by the tank walls could be minimized by proper choice of the tank shape, by the use of absorber materials, and by constructing the tank walls to serve as a matching device between the liquid and the medium beyond the walls.

Considerable research was directed toward finding a suitable liquid. Tables of dielectric constant and loss tangent were examined thoroughly and various chemical companies were queried but no satisfactory liquid was found to meet the above requirements.

A letter[7] received from the Massachusetts Institute of Technology, Laboratory for Insulation Research explained the scientific reasons for the non-existence of such a liquid. However, it suggested a mixture of a low loss dielectric liquid with Rutile (TiO_2) as a possible solution to our problem. This had independently been considered here and investigations of its feasibility begun. A shorted-line system for measuring the dielectric constant and loss tangent was constructed, and mixtures as well as pure liquids were tested.

III. DIELECTRIC CONSTANT AND LOSS TANGENT MEASUREMENTS

A. Theoretical Considerations

The values of dielectric constant and loss tangent of materials considered for use as the ambient medium were measured using the shorted waveguide method described by von Hippel[12], in which the measured quantities are (1) the shift in null position of the standing wave when a dielectric sample is placed in the shorted section, and (2) the inverse standing-wave-ratio with the sample in the guide. The modifications to this method by Dakin and Works[10] and further simplifications by Bowie and Kelleher[8] were used. The relationships derived by Roberts and von Hippel[9] were simplified by Dakin and Works for the case of a relatively low-loss dielectric (viz., $\tan\delta < 0.1$). Bowie and Kelleher in turn rearranged Dakin and Works' approximate expressions such that two universal charts, or sets of curves, relating the measured quantities to the dielectric constant and loss tangent were obtained. These curves apply to rectangular waveguides in general, provided a specific frequency and specific sample lengths are used. The frequency is determined by the cutoff wavelength, as are the sample lengths for the chart relating dielectric constant and null shift.

The various values of dielectric constant were determined using this chart. Bowie and Kelleher's second chart (relating loss tangent to the value of dielectric constant obtained from the first chart) was not used, since to do so would have involved an additional measurement of each sample (the curves of this chart were plotted for sample lengths determined by the dielectric constant). The various values of loss tangent were determined using Dakin and Works' approximate expression, as modified below.

Dakin and Works show that

$$(1) \qquad \tan\delta \approx \frac{\Delta x}{d}\left[\frac{\left(\frac{1}{\lambda_c^2}+\frac{1}{\lambda_g^2}\right)-\frac{1}{\epsilon_r\lambda_c^2}}{\frac{1}{\lambda_c^2}+\frac{1}{\lambda_g^2}}\right]\cdot\left[\frac{\beta_2 d\left\{1+\tan^2\left(\frac{2\pi x_o}{\lambda_g}\right)\right\}}{\beta_2 d\left\{1+\tan^2\beta_2 d\right\}-\tan\beta_2 d}\right]$$

where Δx = width of standing-wave minimum at twice minimum power value (3 db above minimum)

d = sample length

ϵ_r = dielectric constant of sample

λ_c = cutoff wavelength in air-filled portion of guide

λ_g = wavelength in air-filled portion of guide

β_2 = propagation constant in sample

x_o = distance on air side of air-sample interface to the first standing-wave minimum.

Roberts and von Hippel[9] have shown that for the shorted waveguide

(2) $$\frac{E_{min}}{E_{max}} = \frac{\sin \theta}{\left\{\left(\frac{E_x}{E_{min}}\right)^2 - \cos^2 \theta\right\}^{1/2}}$$

where $\theta = \dfrac{\pi \Delta x}{\lambda_g}$

$\dfrac{\Delta x}{2}$ = distance from the minimum to some point x, and

E_x = E-field at that point.

If E_x is chosen as the 3 db above minimum point, and if $\rho < 0.1$, then Eq. (2) reduces to

(3) $$\frac{E_{min}}{E_{max}} \approx \frac{\pi \Delta x}{\lambda_g}$$

where Δx = distance between the 3 db above minimum points.

This assumption is included in the derivation of Eq. (1), and since it is possible for $\pi \Delta x/\lambda_g > 0.1$ while simultaneously $\tan\delta < 0.1$, it is desirable to make Eq. (1) more general by re-inserting E_{min}/E_{max} explicitly. This may be done by solving Eq. (3) for Δx and substituting into Eq. (1) to obtain

$$\tan\delta \approx \frac{E_{min}}{E_{max}} \frac{\lambda_g}{\pi d} \left[\frac{\left(\frac{1}{\lambda_c^2} + \frac{1}{\lambda_g^2}\right) - \frac{1}{\epsilon_r \lambda_c^2}}{\frac{1}{\lambda_c^2} + \frac{1}{\lambda_g^2}} \right] \left[\frac{\beta_2 d \left\{1 + \tan^2\left(\frac{2\pi x_o}{\lambda_g}\right)\right\}}{\beta_2 d \{1 + \tan^2 \beta_2 d\} - \tan \beta_2 d} \right] \quad (4)$$

for $\tan\delta < 0.1$.

Equation (2) may then be used to determine E_{min}/E_{max}. The technique described by Westphal[11] was used for obtaining values of Δx corrected for guide-wall loss for use in Eq. (2)

B. Equipment

The measurements were made at X-band, and in order to use Bowie and Kelleher's chart, 10.37 kmc was the specific frequency used. A block diagram of the measuring system is given in Fig. 1. The klystron was immersed in a constant-temperature oil bath and the circuit was isolated as shown for purposes of frequency stability. The amount of loss varied in the samples measured, and it was therefore desirable to vary the power level in the system. A precision attenuator was used to so isolate the source in order to prevent fluctuations in the null positions with varying attenuation.

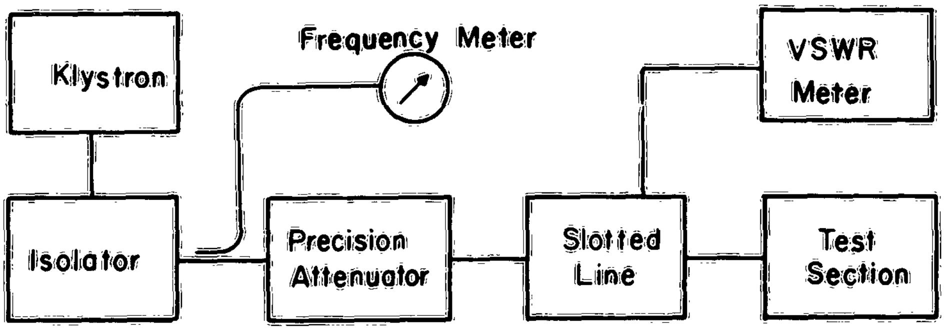

Fig. 1. Block diagram of equipment used to measure dielectric constant and loss tangent.

IV. RESULTS OF THE MEASUREMENTS

The required electrical properties of the (preferably liquid) material for use as the ambient medium were

$$\epsilon_r \sim 4.0$$
$$\tan \delta < 0.01$$

at X-band.

A literature search was conducted and various samples were measured; however no satisfactory material was found. The measured data are given in Table I. The values listed are, in general, averaged from several measurements, and wherever possible, the data are compared with those of von Hippel.[6]

Further investigations were performed by "doping" low-loss liquids (castor oil and transil oil*) with a high-dielectric-constant additive (TiO_2). The castor oil mixtures (Figs. 2-3) were too lossy, however the transil oil mixtures (Figs. 4 and 5) appear satisfactory. The loss tangent (Fig. 5) is somewhat erratic, and it is felt that this results from the random electrical lengths of the samples. A study of Eq. (4) has shown that the accuracy of the extreme points is lowest.

* Transil oil = 10-C insulating oil (G. E.)

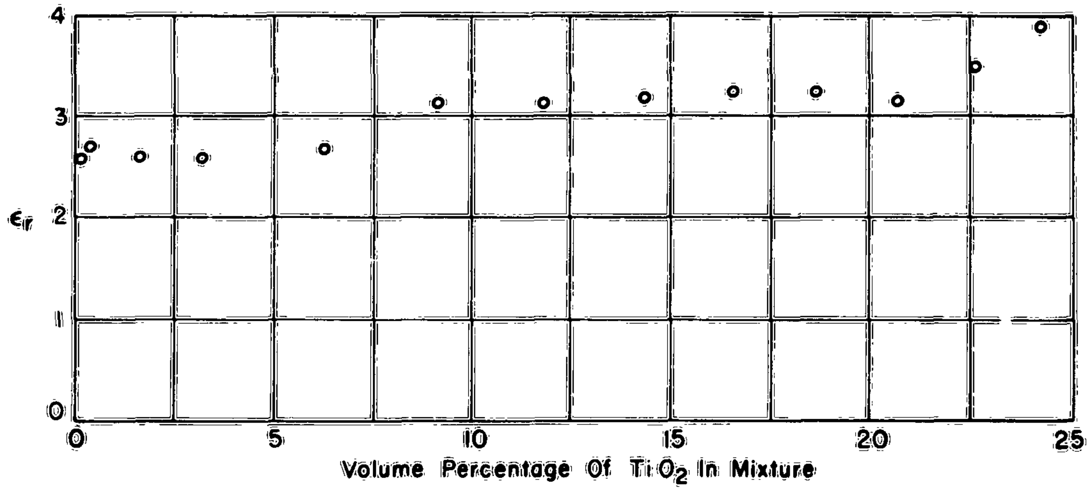

Fig. 2. Relative dielectric constant versus TiO_2 concentration for a castor oil — TiO_2 mixture at a frequency of 10.37 kmc.

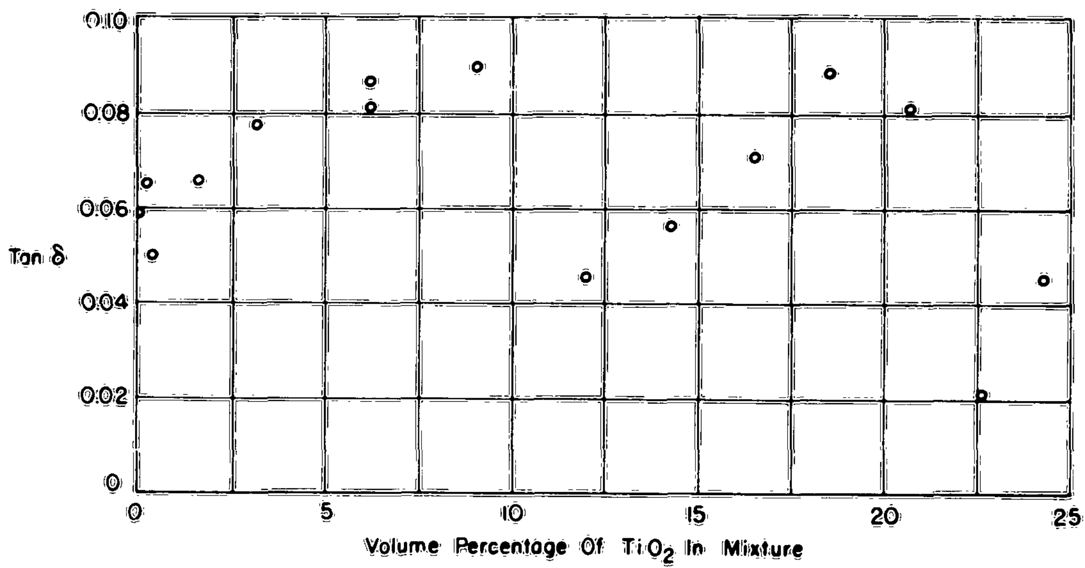

Fig. 3. Loss tangent versus TiO_2 concentration for a castor oil — TiO_2 mixture at a frequency of 10.37 kmc.

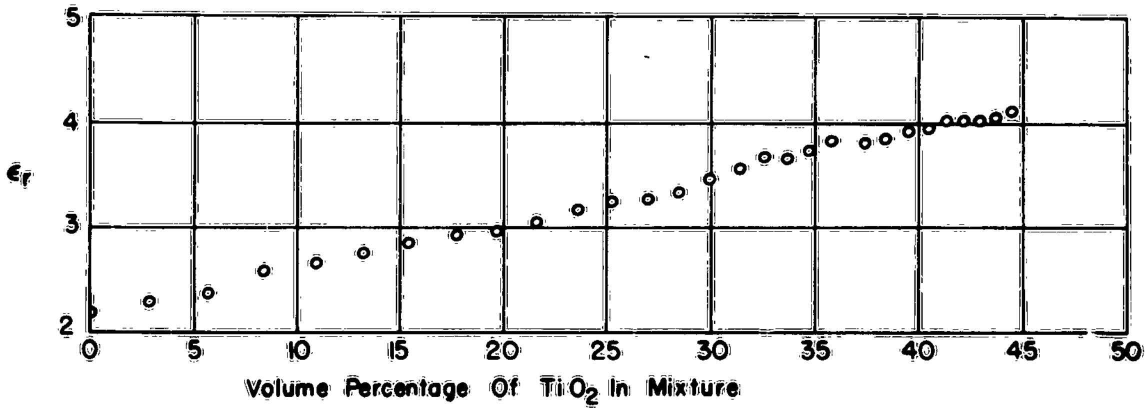

Fig. 4. Relative dielectric constant versus TiO_2 concentration for a transil oil — TiO_2 mixture at a frequency of 10.37 kmc.

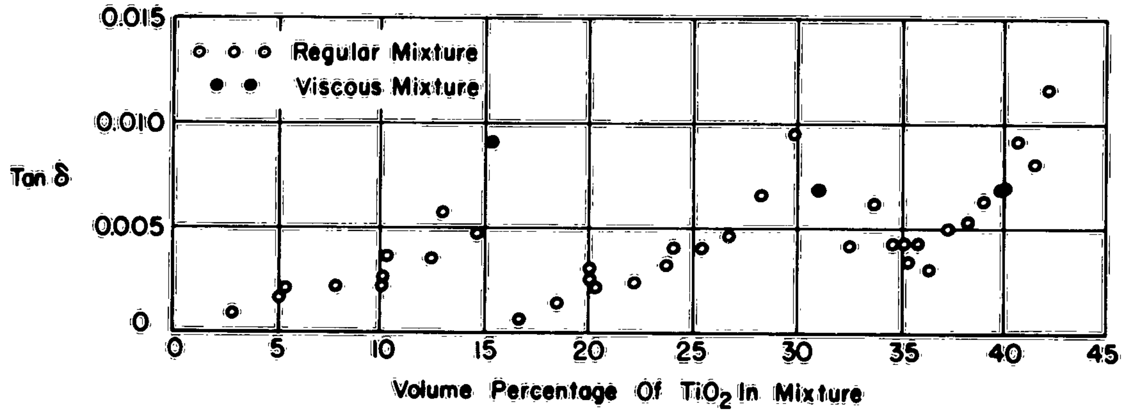

Fig. 5. Loss tangent versus TiO_2 concentration for a transil oil — TiO_2 mixture at a frequency of 10.37 kmc.

TABLE I

Material	Measured Data (f = 10.37 kmc)		From von Hippel (f = 10.00 kmc)	
	ϵ_r	tan δ	ϵ_r	tan δ
Polystyrene (Commercial sheet stock)	2.52	0.000628	2.535	0.000480
Pyranol 1467	2.63	0.0621	2.62	0.0740
Pyranol 1470	2.75	0.0776	----	------
Aroclor 1242	2.77	0.0234	2.69	0.0223
Castor oil	2.61	0.0610	----	------
Transil oil	2.18	0.002149	2.10	0.002000
Vaseline	----	------	2.16	0.001000

Due to Transil oil's low viscosity, the mixtures settled visibly in a matter of five to ten minutes, thus causing the electrical properties to vary with time. In order to increase the viscosity, petrolatum (vaseline) was added.* The effect of adding petrolatum (dielectric constant and loss tangent very similar to that of transil oil — see Chart I) was merely to reduce the TiO_2 concentration. Two such trial mixtures were measured, and the loss tangent values are plotted in Fig. 5. The values of TiO_2 concentration were determined approximately by noting from Fig. 4 at what concentration the respective dielectric constants occurred. In the resultant transil oil — TiO_2 — petrolatum mixture, appreciable settling did not occur for approximately an hour.

*The viscosity was increased to approximately that of castor oil, since the rate of settling had been relatively low in castor oil.

V. CONCLUSIONS

The basic parameters of a scattering range for simulating echo area measurements of plasma coated bodies have been determined.

The requirements for the ambient liquid are satisfied by a transil oil — TiO_2 — petrolatum mixture.

It is believed that the system is feasible; however numerous problems would undoubtedly be encountered in constructing and interpreting the data from such a system. Among these would be the small model size, and hence the extreme accuracy and system sensitivity required at X-band, or the construction and maintenance of the large tank of liquid required at S-band; difficulties in eliminating background reflection; and difficulties in accurately locating the models because of the optically opaque liquid.

While these problems are by no means insurmountable, it is felt that in regard to the present project the expected results do not justify construction of the system at this time. However, it is believed that the information contained herein may be of use to others who may wish to pursue the subject further.

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