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A Study of VHF Absorbers and Anechoic Rooms

by

R. E. Hiatt, E. F. Knott and T. B. A. Senior

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National Aeronautics and Space Administration
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INTRODUCTION

This is the final report under NASA Contract No. NASr-54(L-1) and covers the period 23 September 1962 through 1 March 1963. The purpose of the contract was to provide assistance to personnel at NASA Langley Research Center with the design and specification of two anechoic chambers which they plan to build. The first of these rooms is intended as a research facility to operate at frequencies above 1000 Mc and since the required performance is not exceptional the design poses no severe problems. Only passing attention has been given to this. The second room will be used largely as an antenna pattern range for space vehicle antennas operating at frequencies from 200 Mc to the microwave range. It is anticipated that most of the antennas will be low in gain with patterns comparable to that of a dipole and this is one of the main factors that makes feasible the construction of such a UHF-VHF anechoic room. In many cases the tests will involve the full scale vehicle. As presently conceived the room will be 35 feet wide, 30 feet high and 100 feet long, but the operating space will be smaller due to the application of radar absorbing materials (RAM) to the walls.

This second room will be referred to as the low frequency anechoic chamber, and since it is the one whose performance requirements are more difficult to achieve, the present contract has been concerned primarily with problems related to it. As part of the work, a limited investigation of the following topics has been made: (i) methods of testing radar absorbing materials at frequencies as low as 200 Mc, and (ii) ways of evaluating the performance of anechoic chambers which are designed to operate at 200 Mc and above. In addition, however, the Radiation Laboratory has acted in a consultative capacity on matters relating to the general layout and specifications of the proposed room.

The first of these topics is considered in Section II. Possible methods for testing absorbers are listed and those which are commonly used are described in more detail. Each method, of course, has its own limitations, and these may differ according as the testing is for research purposes or production checking. Emphasis is placed on the latter type with particular reference to VHF frequencies, and the analysis which is given in support of this critique is believed new in many regards. Experimental data obtained from tests made on typical absorbers is presented. Test recommendations are given, along with some precautions which should be taken to ensure an accurate assessment of the 'free-space reflectivity'.

The next section is concerned with methods for evaluating room performance. These obviously depend on the purpose for which the room is to be used, and it is therefore appropriate to summarize the generally accepted procedures. One of these has been applied to a scale model of the NASA-Langley low frequency room constructed by the Radiation Laboratory and the results of this experimental investigation are given. Some recommendations as to testing methods are made in the light of the intended application of the NASA room, but of interest in this connection is the discussion in Appendix C. With joint support from the present contract and one from the Conductron Corporation, a method has been developed for the separate determination of either the radar cross section of a target or the background return from the room under conditions when the unwanted one may even exceed the other. The actual technique also specified the return from the target support, and is believed new in this regard. Its practical applicability has been verified by the successful measurement of the nose-on cross section of small cone-spheres, and in the course of this study values were obtained for the 'cross section' of the Radiation Laboratory's anechoic room at X-band frequencies.

II

RADAR ABSORBING MATERIALS

Although our interest is chiefly in the testing of high performance VHF materials, it is convenient to begin with a brief description of the methods available for the evaluation of radar absorbers in general. After a discussion of the probable form of absorber necessary for the present application, the main difficulties associated with each type of measurement are considered, and based on this examination a testing procedure is recommended.

2.1 Standard Methods of Evaluation

Several methods for evaluating the performance of radar absorbing materials have been developed and the most widely accepted ones are based on the following:

(i) the NRL arch,
(ii) 'free space' (using 'plane' waves),
(iii) Doppler shift,
(iv) waveguides
and (v) coaxial transmission lines.

Only two or three of these have received any extensive use, and probably the best known of all is the first. This has been aptly referred to (Clark et al, 1961) as the time-honored NRL Arch Method. As its name indicates, it was pioneered by the Naval Research Laboratory and though no actual date has been determined, the development would appear to have taken place in the years immediately after World War II. Montgomery (1947) gives a brief discussion of the general concept.

The type of equipment employed in the arch method is shown in Fig. 1. Separate transmitting and receiving horns are mounted on a semi-circular arc placed above the absorbing sample to be tested. With both horns directed at the sample, the signal which is received is compared with that obtained when the absorber is replaced by a metal plate of equal size, leading immediately to an estimate

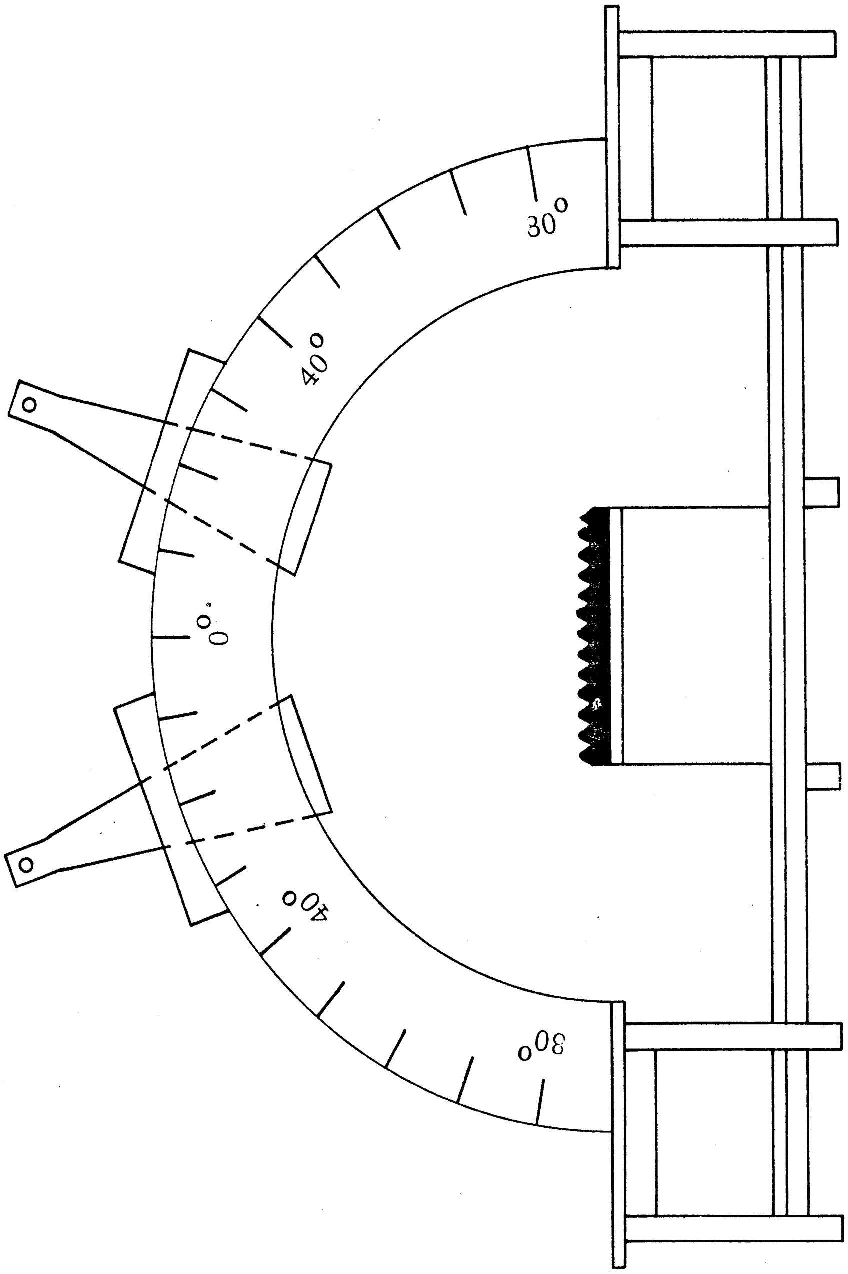

FIG. 1: NRL ARCH EQUIPMENT

of the reflection coefficient. The polarizations of the transmitted and received signals can be varied independently, and by changing the positions of the horns on the arch, the reflection coefficient can be determined for a range of incidence angles and for different bistatic angles in a plane normal to the surface of the absorber. An even greater variety is possible with the modified arch system used by the McMillan Industrial Corporation (see Clark et al, 1961). Here the receiving horn is mounted on a second 90° arc whose upper end slides on the main arc supporting the other horn and this system gives the receiver a second degree of freedom with respect to the transmitter. This type of flexibility is particularly desirable when measuring absorbers with irregular surfaces (composed, for example, of pyramids or cones).

The arch method is commonly employed at frequencies above 2.5 Gc although there are cases in which it has been used at frequencies as low as 1 Gc. At such low frequencies it may be more convenient to mount the system on its side so that the absorber is vertical and the direction of propagation is more or less horizontal, but the large physical size of the equipment is then a severe handicap. Although the horns can be (and almost certainly are) in the near field of the absorber sample, they should be in the far field of each other's 'image' (i.e. when distance is measured via the reflection point). In addition, the sample size must be so large that all, or nearly all, the incident radiation impinges on the surface. Clearly, therefore, the size can be reduced by having more directive antennas (see Section 2.2.2, however) and this will in turn decrease the direct coupling between transmitter and receiver, but it implies a larger size of horn and a consequent increase in range to satisfy the above far-field condition. It is obvious that at very oblique angles of incidence the accuracy will diminish as a result of the increasing failure of the optics approximation to the scattered field on which the method is based, but not quite so obvious is the fact (Clark et al, 1961) that a reflection coefficient which varies smoothly with angle of incidence is also necessary if the measured values are to be reliable. In spite of all these hazards, however, the arch method is still the most dependable and well suited for production control purposes for L-band and higher frequencies.

Perhaps the most natural way of measuring the reflection coefficient is the 'free space' or 'plane wave' method, but this also is by no means devoid of possible errors. The set-up is similar to that used for measuring the radar cross sections of aircraft or missile models and the only difference in experimental procedure is that the absorber patterns are calibrated with reference to the patterns for a metallic sheet of the same size and shape (often mounted on the rear of the absorber sample) rather than by using a sphere or corner reflector as standard. The transmitted signal is generally obtained from a cw stabilized oscillator,[+] and either a single antenna or separate antennas may be employed. A combined transmit/receive antenna restricts the measurements to the back scattering direction as a function of angle of incidence on the absorber, and the transmitted and received signals are isolated using a balanced hybrid tee system. This last can be adjusted so as to minimize the effect of the target support and the background prior to placing the sample in the field. With two antennas measurements as a function of the bistatic angle can be carried out. If necessary, the inherent isolation between the transmitting and receiving antennas can be improved by feeding a cancelling signal from the oscillator to the receiver, with the signal adjusted in amplitude and phase to minimize the leak-through.

Although free space nominally implies outdoor tests, it is possible to make equivalent measurements in an anechoic room providing the background contribution is not too large in comparison with the return from the sample. This requires that the room has better material than the sample or else the room must be so large that the background is diminished by the r^{-4} law.

[+] A pulsed system is an equally acceptable alternative in which the effect of the background (but not the target support) is separated from the required signal by range gating.

Whether the tests are performed indoors or out, there are certain restrictions on range and sample size which must be fulfilled to obtain a valid measure of the reflection coefficient. As the alternative title for these tests suggests, the absorber must be in the far field of the transmitting antenna and has, therefore, little or no illumination taper over its surface. This is in marked distinction to the situation with the arch method, and increases the relative magnitude of the contribution from the edges of the sample, but the validity of the method is based on the assumption that the ratio of the return from the sample to that from an equivalent metallic plate is equal to the free space reflection coefficient of the material. Since the theoretical edge contribution is roughly proportional to the area of the sample, whereas the normal incidence return from the 'body' of the sample is proportional to the square of the area, it would appear that the accuracy of the method will increase with increasing area of the sample, and that the error can be held to a tolerable value by choosing a sample whose dimensions are sufficiently large in comparison with the wavelength. This is discussed in more detail in Appendix A.

Having selected a sample of appropriate size depending of the magnitude of the reflection coefficient to be measured, there is the final requirement that the receiving antenna must be in the far zone of the sample. This is usually the factor which specifies the minimum range that can be used and makes difficult any attempt to test VHF absorbers within an anechoic chamber.

In order to achieve a complete separation between the return from the sample and the reflections from the background, a practical method has been devised by the McMillan Industrial Corporation in which the wanted signal is shifted in frequency through a motion of the sample relative to the background. This alternative 'free space' approach has been called the Doppler Method, and a full description has been given by McMillan and Schmitt (1960). The differential motion is provided by a rotating metal disc 62 in. in diameter with an offset counter-rotating disc 1 ft. in diameter. The whole is embedded in a ground plane on which are placed two half-horns, one for transmission and one for reception. All the surfaces are co-planar, and especial care is taken with the edges of the discs so as to minimize the scattering from them.

The sample to be tested is mounted vertically on the smaller disc whose speed of rotation is chosen so that for a small but finite time the sample preserves the same aspect relative to the antennas whilst moving with a sensibly uniform velocity towards them. The waveguide and receiver circuits associated with the horns are then designed to receive only a signal having a Doppler-shifted frequency corresponding to this velocity.

Using this system, measurements have been made at S- to X-band frequencies, but because of the size of the smaller disc the maximum horizontal dimension of the sample is limited to 1 ft. Though the equivalent vertical dimension is doubled through the use of a ground plane, the edge effect will be significant at frequencies lower than S-band, and it is difficult to conceive of a practical magnification of the physical set-up sufficient to permit VHF measurements.

For a waveguide measurement a rectangular guide is appropriate because of the square cell structure of most high performance absorbers, and typical of the systems is that developed by the U. S. Naval Research Laboratory (Emerson et al, 1954). Over a distance of some 7 ft. a rectangular guide is slowly flared into a square section whose inner dimensions are 2 ft. by 2 ft. and which therefore allows the measurement of commercially available samples without cutting. When under test the sample is backed by a metal shorting plate. The input to the tapered section is a slotted waveguide whose size depends on the frequency of operation. For the frequency range 500 - 900 Mc, NRL use a 7 in. by 14 in. guide, and standard slotted lines for the ranges 1.1 to 2.0 Gc and 2.3 to 4.5 Gc. Carefully tapered waveguide adaptors provide coupling of the higher frequency guides to the large horn, and NRL report that the VSWR resulting from flanges and discontinuities in taper is no more than 1.05 over the above frequency bands.

The main reason for flaring the guide is to convert the fundamental waveguide mode into a field whose structure is comparable to that of a plane wave, but to do so makes possible the generation of higher order modes. In general the presence of such modes will tend to make the absorber look better than it really is since the cut-off limitation prevents them from re-entering the slotted section where the VSWR is measured. Note that if the absorber is uniform in properties in the plane normal to the guide axis, the sample cannot of itself introduce any higher-order modes in spite of any variation of its properties in the longitudinal direction, but it can obviously reflect any modes which are generated by the taper. In most cases, however, the absorber will almost certainly vary in the transverse direction as well as the longitudinal (as, for example, due to a pyramidal structure), and Haddenhorst (1955) has suggested that the sample should then contain at least two cells in order that the higher order modes will be below cut-off. It would appear that this argument is based on the assumption of an unflared guide of minimum (or near minimum) dimensions, and as indicated above the presence of such modes in even the flared out section can be a source of error.

On the other hand, it has come to our attention that some organizations are testing absorbers in unflared systems. For example, L-band guides have been used for measurements at frequencies near 1 Gc, and a specially designed waveguide 1 ft. by 3 ft. in cross section and approximately 15 ft. in length has been constructed for operation in the 250 to 400 Mc range. One of the disadvantages attendant upon the use of such guides is discussed in Appendix B.

Because of the higher order modes which may be generated by a flared waveguide and the fact that the field does not entirely simulate free space conditions, NRL have developed (Emerson et al, 1954) an alternative type of closed system for testing absorbers. This employs a coaxial line whose inner and outer conductors are slowly flared to maintain a constant impedance. The maximum diameter of the outer conductor is 18 in. and the input to the taper is provided by either of two smaller coaxial lines: a 2 in. diameter slotted section for 600 - 3000 Mc and a 5.75 in. section for the 100 - 1000 Mc range. Unfortunately, a system of this type is only suited to absorbers which are sensibly uniform in the transverse direction, and even then is entirely inappropriate for production testing because of the necessity for mutilating the samples to fit the line.

2.2 Discussion

Having summarized the various methods available for the testing of absorbing material, we shall now consider them further to see how well suited they are to the evaluation of high performance absorbers in the VHF range. Since the difficulties inherent in most of the methods increase in proportion to the wavelength employed, attention will be focussed on the lowest frequency of interest, namely 200 Mc.

2.2.1 VHF Absorbers

Commercial absorbers which are effective at these frequencies are typically foam rubber or plastic materials whose input side is shaped in the form of cones or pyramids which may or may not be hollow. The absorbing property is usually achieved by a coating of lossy material on the exterior surface, although in some cases the foam is composed of small particles which have themselves been coated with a lossy substance. Examples of such absorbers designed for VHF applications are:

CV-B 18 to CV-B 54	(Emerson and Cuming, Inc.)
VHP-26 to VHP-70	(The B. F. Goodrich Company)
AP-24 to AP-96	(McMillan Industrial Corporation)

For the NASA-Langley low frequency room, the absorber is required to have a reflection coefficient of -30 db or better for frequencies 200 Mc and higher. To meet these specifications, most manufacturers would recommend a material three or four feet thick, and the shape and thickness are factors which influence the choice of testing methods. On the other hand, a material whose characteristics differ markedly from the above is the multi-layered ferrite dielectric absorber developed by Conductron Corporation. Preliminary data (Grimes, 1963) on two absorbers of this type is shown in Figs. 2 and 3. The 'L-band' material (Fig. 2) has a thickness of about 1.5 in. but the material designed for the range 140 to 4200 Mc (Fig. 3) is even thinner (2/3 in. approximately). In both cases, the absorber weighs about 7 lbs per square foot and tends to be homogeneous in planes parallel to its surface. A small coaxial line could consitiute an appropriate test facility for this material, but since it would not be at all satisfactory for the large pyramidal type of absorber, the rest of the discussion is concerned mainly with evaluation procedures for foam-like substances.

2.2.2 Free Space Testing Methods

The five methods described in Section 2.1 can be divided into two groups: open and closed systems. The arch, free space and Doppler techniques all fall into the first category and all suffer to a varying degree from the disadvantage associated with the edge contribution from the absorber. The first two of these are comparable in that the sample is (or should be) in the far zone of the transmitter. The incident field then resembles a plane wave and provides little or no illumination taper over the surface. A theoretical treatment of the edge effect for this case is given in Appendix A. Not unreasonably, the relative magnitude of the edge contribution is found to decrease with increasing size of sample and with increasing reflectivity of the material. Unfortunately, it also depends on the nature of the absorber (smooth, pyramidal, etc.) and though no values are available for 'edge reflectivities' per se, experience with using absorbers for camouflage purposes suggests that the edges may appear almost as intensive as those of a metal plate. To measure a 30 db absorber to within 3 db would then require a sample at least 10λ in size.

In many cases, however, this result may be overly pessimistic, and if the edge of a 30 db absorber had only a -10 db reflectivity associated with it, a sample

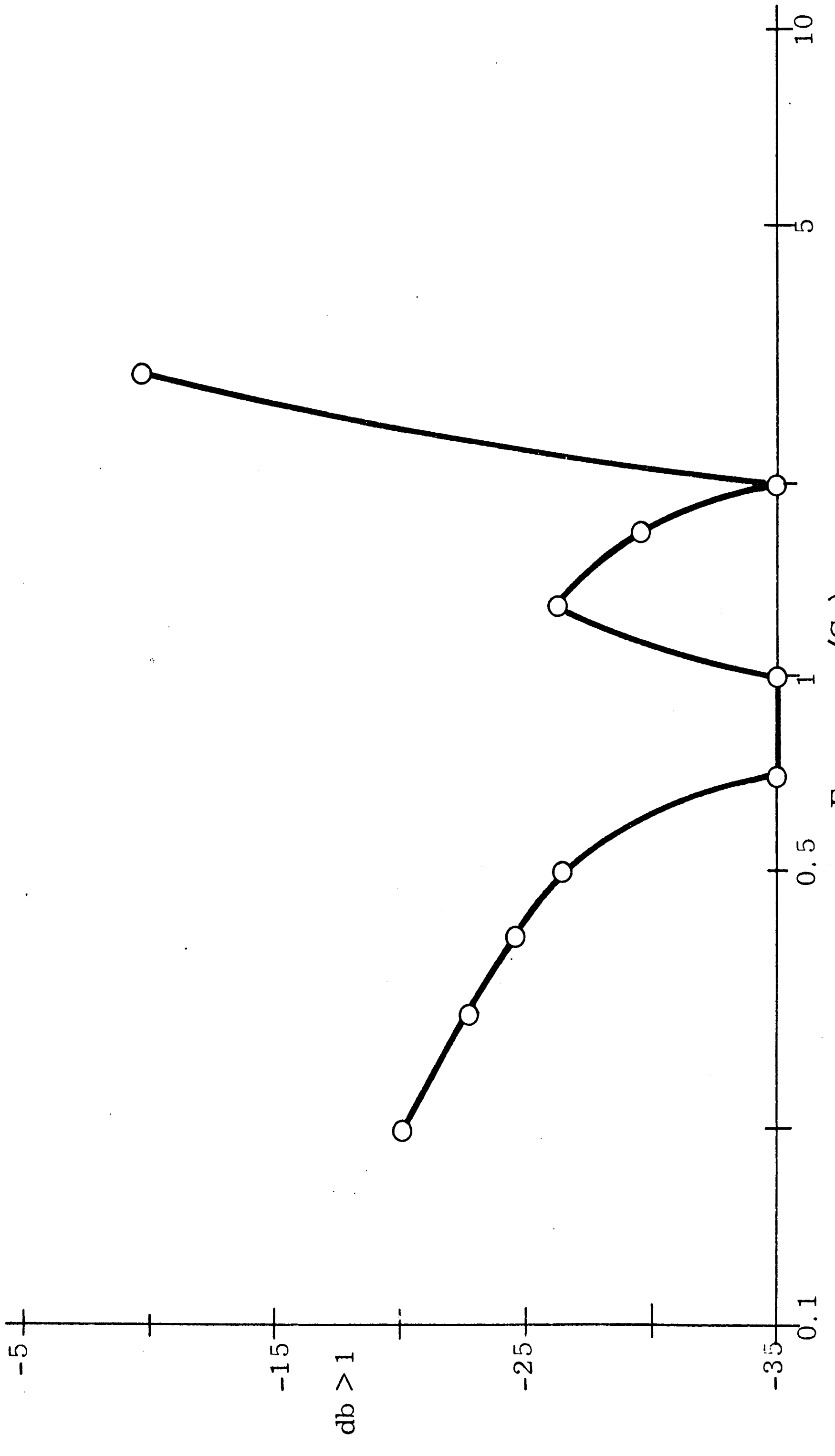

FIG. 2: REFLECTION COEFFICIENT OF 1-1/2 IN. THICK MULTI-LAYERED FERRITE DIELECTRIC ABSORBER (GRIMES, 1963).

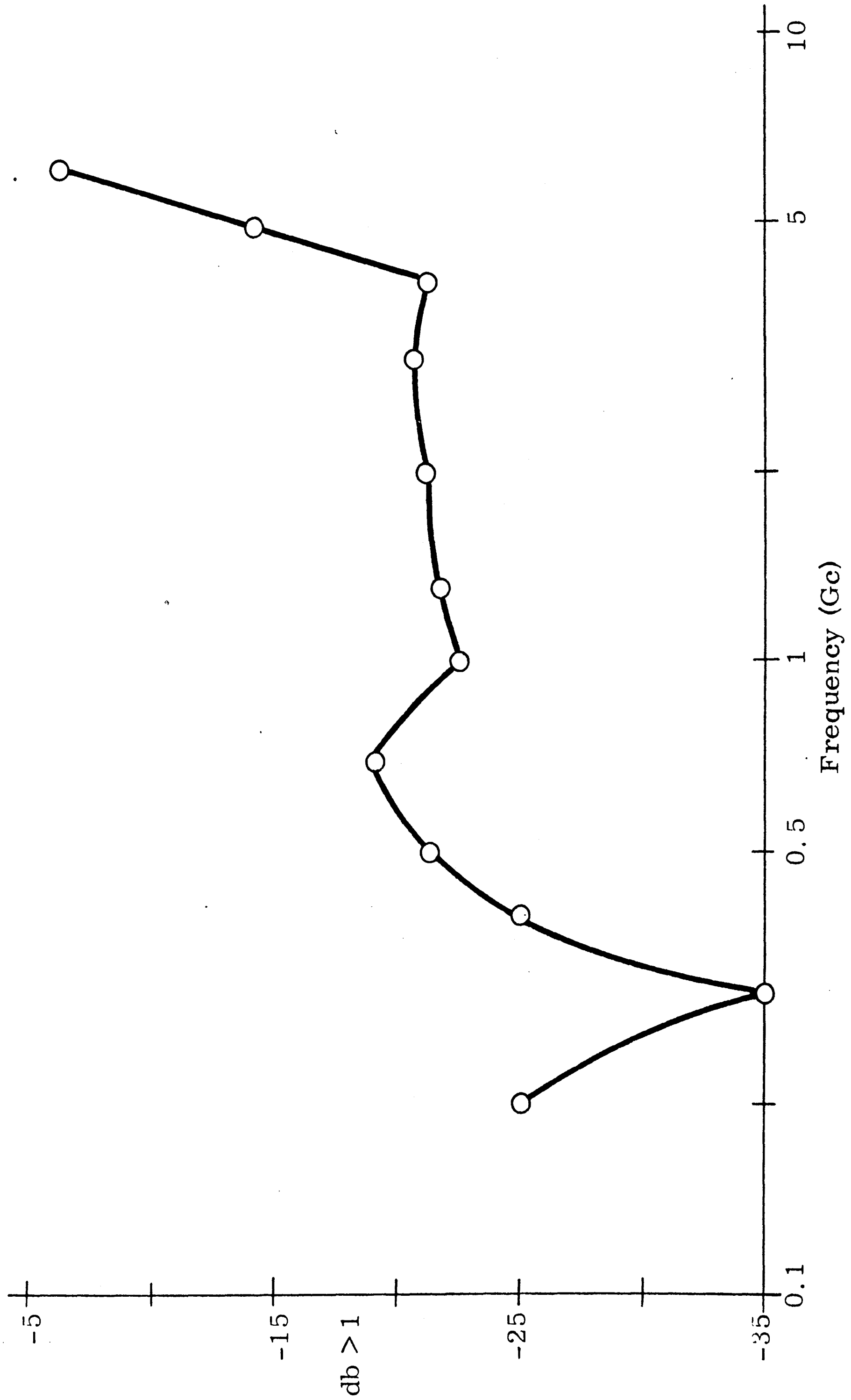

FIG. 3: REFLECTION COEFFICIENT OF 2/3 IN. THICK MULTI-LAYERED FERRITE DIELECTRIC ABSORBER (GRIMES, 1963)

of dimension 3 λ would now suffice for a 3 db accuracy of measurement. Clark et al (1961), in a qualitative discussion of edge effects for a disc-like sample, conclude that a diameter of 5 λ is adequate for testing 20 db absorbers, but also remark that in practice a plate of this size appears to be satisfactory even for absorbers with reflectivities as small as -26 db.

With the arch method the edge effect is less severe because of the illumination taper over the sample. Thus, for example, the S-band arch facility of the B. F. Goodrich Company produces a 15 db reduction in illumination at the edge of a 2 ft. sample compared with the center when the transmitting horn is directed at the center, and because of this the reflection coefficient can be measured using a smaller[+] size of sample than is possible with the other open systems. Even with the arch method, however, the measurement of a high performance absorber still demands a relatively large sample size. This is apparent from the results obtained with the B. F. Goodrich arch equipment on the variation of apparent reflectivity with dimension for VHP-4 and VHP-8 absorbers (Emerson, 1963). The measured power return and reflection coefficient are plotted in Fig. 4 as functions of a/λ, where a is the sample size. In spite of the reduced illumination of the edges, reflection coefficients approximating those for the full 2 ft. sample (a/λ = 6.1) were not attained until the sample size was 4 to 5 λ "and/or was large enough to cover the first Fresnel zone" (Emerson, 1963). The results for the VHP-8 material suggests that even larger sizes may be necessary.

[+] In part, however, the advantage gained by a reduction in the illumination of the edges is lost by a reduction in the optics return from the metal plate due to the illumination taper. This is apparent from Fig. 4. Most of the variation in reflection coefficient as a function of size is produced by the variation in the return from the equivalent metal plate. In short, the illumination taper means that a larger metal plate is necessary before the optics approximation (which is the basis for the measurement procedure) becomes valid.

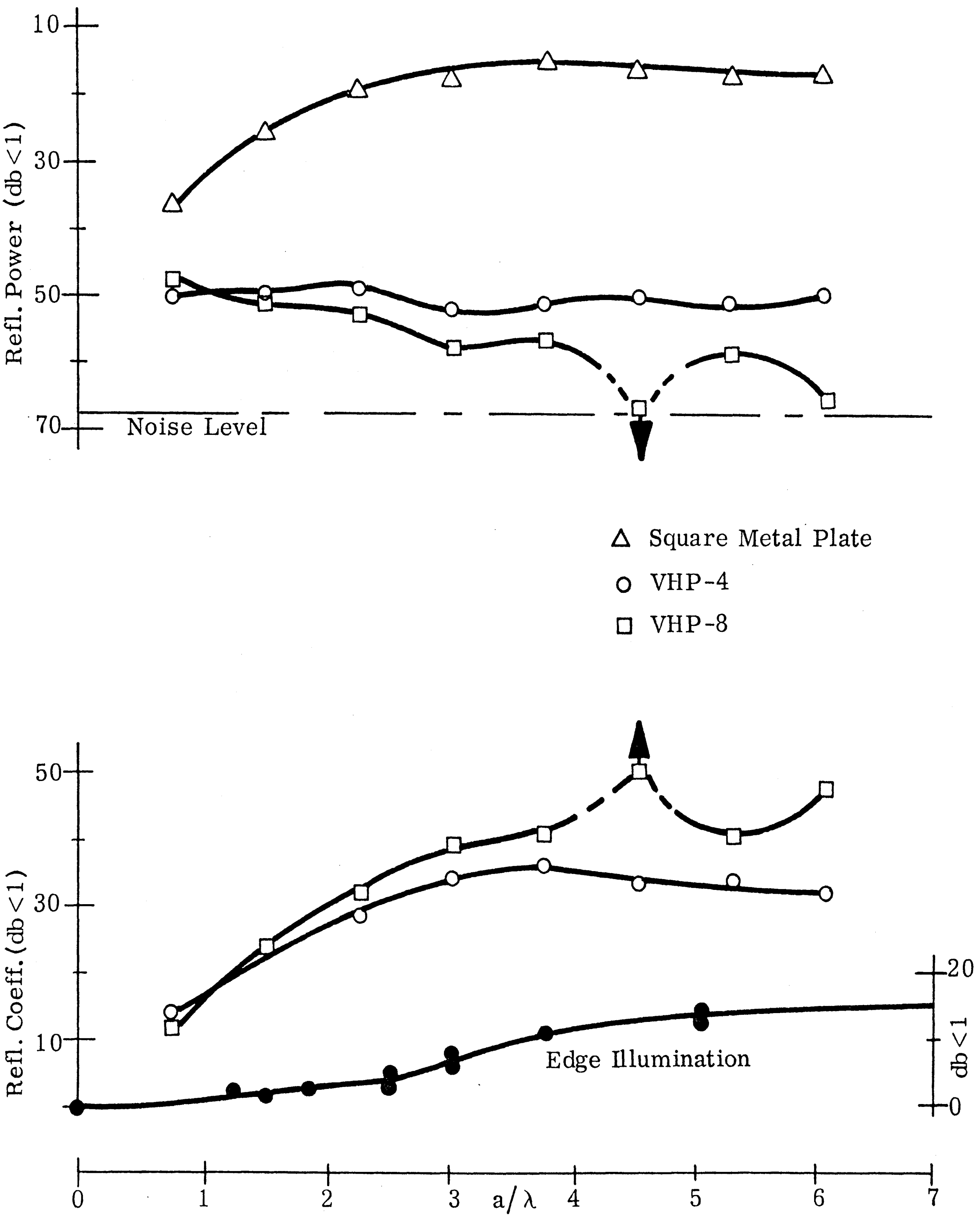

FIG. 4: EFFECT OF SAMPLE SIZE IN ARCH MEASUREMENTS AT 3 Gc. (Emerson, 1963)

During the last year there has been some discussion about the discrepancies which have appeared between data obtained with the arch and free space methods. The recent investigation of edge effects has shown how important these contributions can be particularly with high performance absorbers, and it now seems probable that many of the discrepancies are attributable to using samples of insufficient size. Even so, however, there is still no way of calculating the minimum size which is really necessary for an accurate measurement of the reflection coefficient, and it may therefore be of interest to describe some of the free space experiments carried out in the Radiation Laboratory.

The fundamental validity of free space tests has frequently been demonstrated and our own measurements have shown good agreement with data obtained by the arch method for S-band and higher frequencies. This statement, however, requires some qualification. In testing S-band material which was specified to have a reflection coefficient of -45 db, we found only -40.5 db. For lower performance material, the agreement was in general excellent, as it was at the higher frequencies. Thus, for example, a -50 db material at X-band registered at -50.3 db. The trend which is indicated here has been found by others and is supported by analysis, namely, that free space and arch data are in good accord when the material has only a low or average performance and/or the sample is large in terms of wavelengths. Some illustrative data for the VHP-18 material is shown in Table 1. The measurements

TABLE 1

Freq. (Mc)	Edge Size (in λ)	Refl. Coeff. (db < 1)	Std. Dev.	Specified Refl. Coeff.
9350	19	50.3 (48)	2.80	50
2870	5.8	40.5 (12)	2.03	45
1335	2.7	27.1 (16)	3.09	40
1300	2.6	29.6 (39)	1.50	40

at the first three frequencies were carried out in the anechoic room of the Radiation Laboratory, whilst the fourth measurement was performed by the Conductron Corporation on its own outdoor range. The figures in parentheses indicate the number of individual samples tested.

To provide a more complete set of data on the effect of sample size, a series of free space measurements was undertaken using three different types of absorbers: VHP-2, a pyramidal foam material designed to operate at X-band and higher frequencies, and manufactured by the B. F. Goodrich Company; H-2, a hairflex material designed for S-band and above, also manufactured by the B. F. Goodrich Company; and AN-72, a loaded foam absorber made by Emerson and Cuming, Inc. This last is intended for use at K-band and higher frequencies, and was chosen so as to simulate a poor material at X-band. No information about its expected performance at X-band was available in advance of the tests, but the manufacturer's specifications indicate a reflection coefficient of -20 db at K-band and above. The rated value for VHP-2 at X-band is -40 db, and for H-2 the manufacturer guarantees -20 db at 2.5 Gc, rising to -30 to -40 db at frequencies ten times this.

The initial tests on the VHP-2 absorber were made at 8.7, 9.3 and 9.9 Gc to verify that no resonant effects were apparent, and having confirmed this fact the subsequent work was carried out at 8.7 Gc only. The samples were first measured in the standard 24 in. size. After these tests were completed, samples with average performance were selected and quartered to give four times the number of 12 in. samples. A selection of these were used for the 12 in. tests and so on down to samples 3 in. in dimension. In each case, the sample under test was backed by a metal plate of dimension 23.5, 11, 75, 5.75 or 2.75 in. as appropriate. The results are shown in Fig. 5. Each point is the average for the number of samples indicated by the figure adjacent to it, with the vertical lines representing the standard deviations of the measured values. Of the four sample sizes treated, it is felt that the 12 in. size produced the more reliable data. The patterns for the 24 in. samples had such

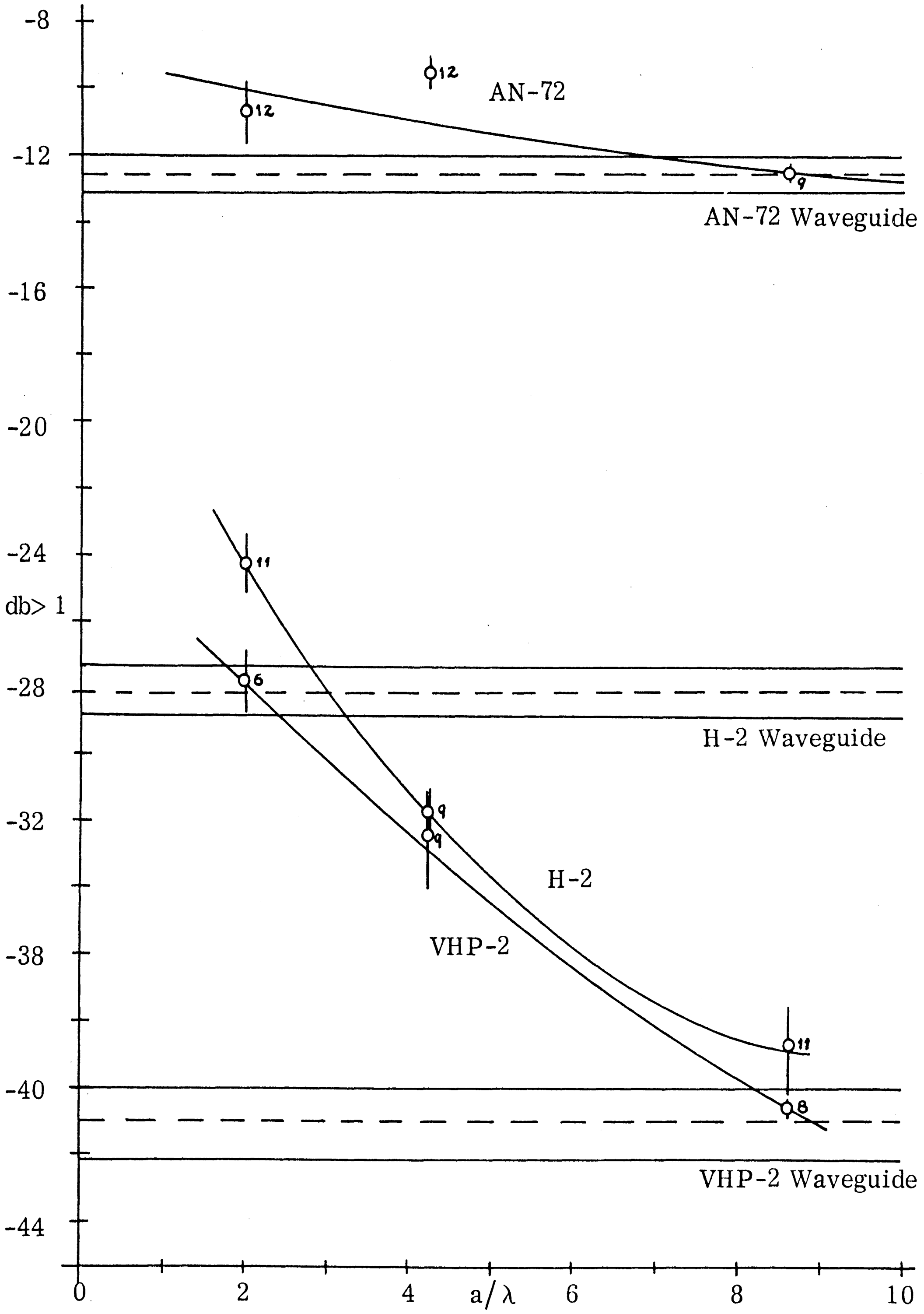

FIG. 5: APPARENT REFLECTION COEFFICIENT VS SAMPLE SIZE

fine structure and narrow lobes that slight changes in angle of look could cause uncertainties as large as 5 db, and for this reason the data has been omitted from Fig. 5.

Observe that the H-2 and VHP-2 materials behave in similar fashion, with their apparent performance improving with sample size. The AN-72, however, is behaving almost the same independently of sample size, which would seem to confirm that for a material with relatively poor performance at the frequency of observation a fairly small sample is sufficient. For absorbers with much smaller reflection coefficients, however, a considerable increase in sample size is necessary, and the trends of the data in Fig. 5 suggest that even samples 9 λ in dimension may not be quite large enough to realize the true reflectivities of the H-2 and VHP-2 materials. With this size of sample the measured reflection coefficients for AN-72 and VHP-2 are in accordance with the manufacturers' specifications, but the H-2 material behaves far better than anticipated.

If the above results are compared with Emerson's data on the effect of sample size using the arch method, a reasonably consistent picture is apparent. Due to the illumination taper inherent in the latter method one would expect that a somewhat smaller size of sample would be sufficient there, with samples 4 or 5 λ in dimension being equivalent to 8 or 9 λ pieces in a far field measurement.

Before leaving this phase of the work, brief mention should be made of some free space measurements which were carried out at 200 and 500 Mc on an outdoor range. It was our original intention to use samples of materials which had been proposed as possibilities for the NASA Langley low frequency room, and to conduct a preliminary investigation to compare the free space estimates of reflection coefficient with the manufacturer's data obtained by waveguide or other methods. Unfortunately, the scheme proved impractical in the time available, but it was decided to go ahead with a small scale program using materials designed for application at higher frequencies.

Four pieces of VHP-26 absorbers, each 2 ft. square, were obtained from the B. F. Goodrich Company, and were attached to a foil-coated plywood panel with a fine dacron line. In addition, four pieces of CV-B 54 absorbers were provided by Emerson and Cuming, Inc., but in this case the greater rigidity of the material made possible the construction of a 4 ft by 4 ft. sample using mylar ribbons and masking tape. The experimental procedure[+] was similar to that commonly employed in making radar cross section measurements, and the only essential difference was that coaxial components were used in place of waveguides. A block diagram of the equipment is shown in Fig. 9, and the back scattering patterns obtained with the CV-B 54 absorber are reproduced in Figs. 6 and 7. The physical and performance data for both materials is presented in Table 2, along with our test results. Each of the values shown in the last two columns is the result of a single measurement only, and because of the small sample size (0.81 λ at 200 Mc and 2.03 λ at 500 Mc) these values should not be regarded as reliable estimates of the reflection coefficient of the material.

TABLE 2

Material	Physical Characteristics	Performance					
		Supplier's Data				Test Data	
		200 Mc	300 Mc	500 Mc	X-band	200 Mc	500 Mc
CV-B 54	Rigid Foam Pyramids	-40[++]	-	-	-	-23.7	-30.1
VHP-26	Foam Plastic Pyramids	-	-30	-35	-50	-14.7	-28.4

[+] Our thanks are due to the Conductron Corporation, for permitting us to use its outdoor range in the measurements.

[++] Manufacturer's extrapolated estimate from measured data on thinner CV-B material.

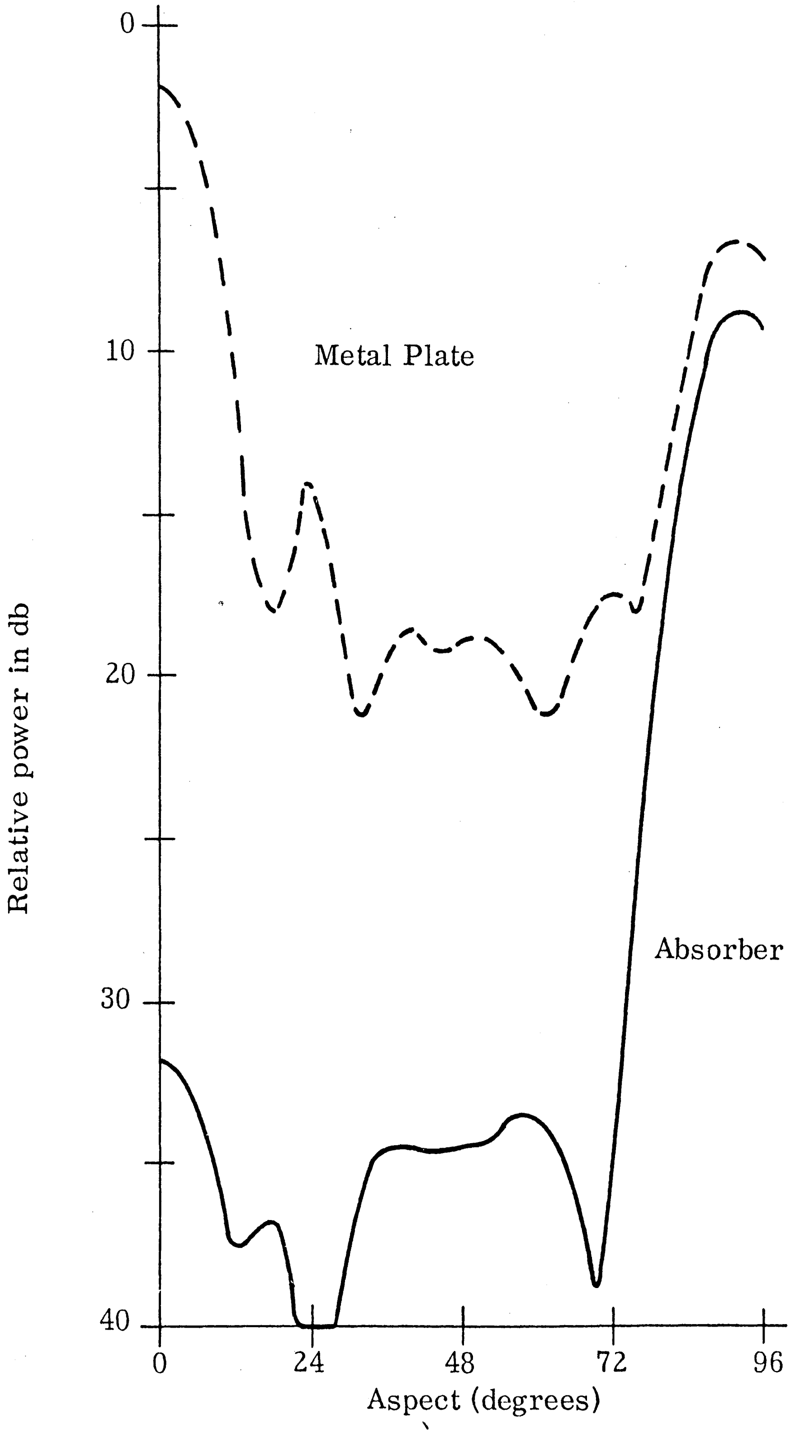

FIG. 6: BACK SCATTERING CROSS SECTION OF 4 FT SQUARE SAMPLE OF CV-B 54 ABSORBER, 500 Mc, VERTICAL POLARIZATION

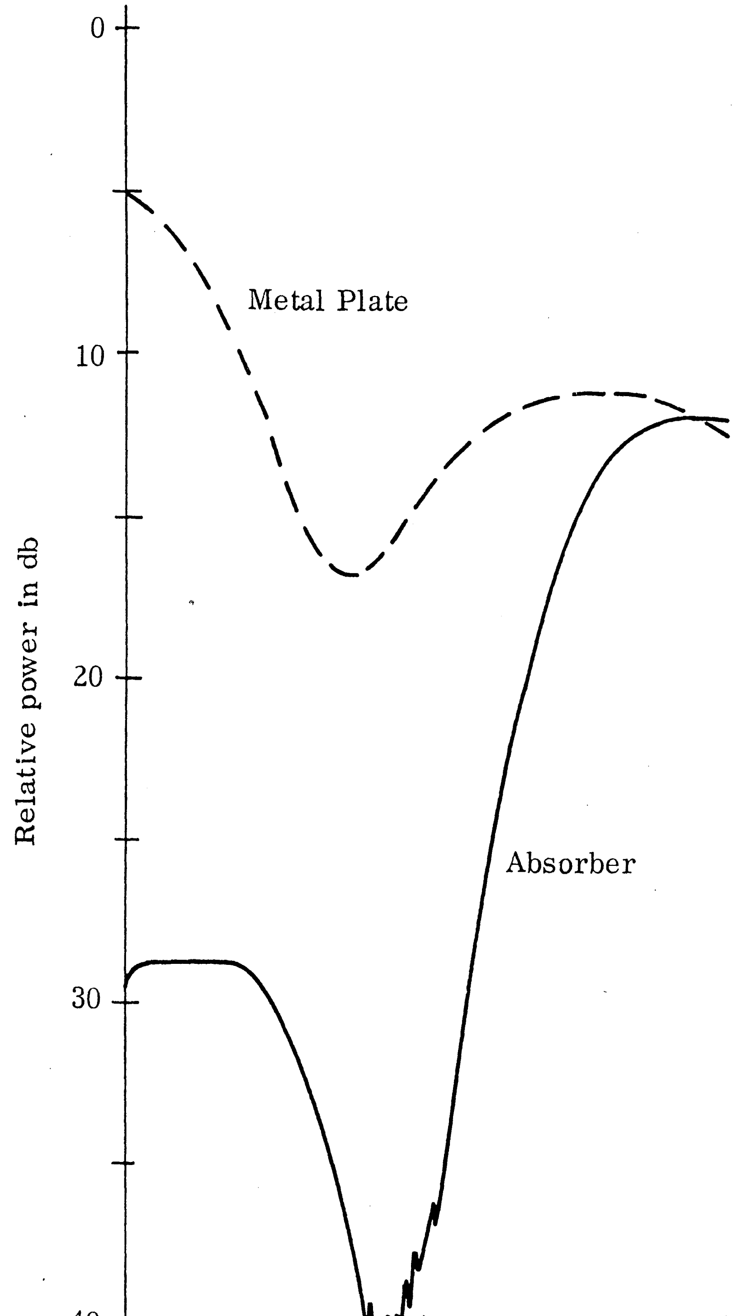

FIG. 7: BACK SCATTERING CROSS SECTION OF 4 FT SQUARE SAMPLE OF CV-B 54 ABSORBER, 200 Mc, VERTICAL POLARIZATION

From an examination of all of the free space data on reflection coefficients available to us, coupled with the analysis of edge effects given in Appendix A, we must conclude that samples at least 8λ in dimension are necessary for the adequate testing of high performance absorbers using a free space or far zone method where there is little or no illumination taper over the surface of the material. To carry out such measurements at 200 Mc would be quite difficult, and not least of the practical problems is the design of a support suitable for a sample 40 ft in size. Given enough time and money it is almost certain that the engineering problems entailed by a test procedure of this type could be solved, but we would still be faced with the undesirable fact that each test sample would involve no less than 400 pieces of the standard-sized 2 ft. square absorber.

The number of absorber pieces necessary for the test sample is probably the most damning feature of the plane wave method at low frequencies. The test objective should be to determine the performance of pieces one or two at a time, whereas to test in lots of 400 would be of little use in production control. In addition no manufacturer would wish to produce so much material before obtaining an evaluation of the material's performance, with the attendant risk that all of such a batch may have to be discarded. Even if one compromised to the limit and specified that the assembled sample need only be 5λ square, the number of unit pieces is still 150, and the above objections remain in force.

Some reduction in the sample size can be achieved by using the arch method. This is quite satisfactory, for example, at S-band frequencies where horn apertures 1.5λ square can be used to look at samples 4 to 5λ in dimension. With an arch radius 8 to 10λ, the horns are in the far field of each other measured over the path of the reflected energy, and their directivity is sufficient to provide an illumination taper of 10 db or so over the sample, thereby minimizing edge effects. But if we now scale this to a frequency of 200 Mc, the advantages gained by the slight decrease in sample size compared with the plane wave method is largely nullified by the more cumbersome nature of the physical equipment. The horns (or other type antennas) have 8 ft. square apertures and the arch radius is 40 ft. Moreover, the sample size is still 25 ft. in dimension, necessitating 150 pieces of absorber, and even if we compromised by taking samples 3λ square, the number of units falls only to around 50. In short, therefore, it would appear that no free space testing procedure is at all satisfactory at frequencies as low as 200 Mc, and there is no alternative but to advocate the use of an enclosed system.

2.2.3 Closed System Tests

The most common of the closed system methods is the waveguide technique, and this is widely used in both production and research testing. Early in 1962, however, we became aware of serious discrepancies between the reflectivities of absorbing materials measured in free space (plane wave or arch method) and in a waveguide. Measurements on a large number of samples of VHP-18 in free space produced a reflection coefficient averaging -27 db as compared with the specified -40 db obtained in a waveguide, and being uncertain as to the cause of this discrepancy we were led to question the validity of both procedures. As a result of experiments carried out since then, it is clear that the size of the samples was too small for the free space method to provide an accurate determination of the reflection coefficient, and some at least of the discrepancy is attributable to this fact. In this section of the report, however, attention will be directed at the waveguide method with particular reference to the errors and ambiguities which may accompany such a measurement.

The purpose of any test, waveguide or not, is to determine the effectiveness of the absorber in reducing the reflection of a plane wave from a surface on which the material is mounted, and if the test measures some quantity other than the free space reflection coefficient, it is of value only if this quantity can be related to the free space coefficient. Any waveguide mode differs from a plane wave in field structure, wave impedance, etc, and consequently the guide reflection coefficient is not necessarily a valid measure of the way in which the material will behave in free space. Moreover, the precise relationship between the two coefficients cannot be found except in certain idealized cases which may or may not have any relevance to a practical situation. It is therefore customary to choose a form of guide such that the field which is incident upon the absorber sample differs as little as possible from a plane wave, and then assume that the reflection coefficient measured in the guide can be identified with the reflection coefficient for normal incidence in free space.

Consider a rectangular waveguide bearing the dominant (TE_{10}) mode. To ensure that no higher modes are generated it is necessary that the width of the guide satisfies

$$\lambda/2 < a < \lambda$$

where λ is the free space wavelength and the lower limit exists to ensure that the dominant mode is above cut off. There is no limitation on the vertical dimension for this mode. Having generated a TE_{10} mode, the horizontal dimension of the guide can now be increased and providing that the flaring is carried out slowly, with care taken to avoid any discontinuities in curvature, etc, it is feasible that the field in the enlarged guide will still be substantially a TE_{10} mode, but the difference between its impedance and that of a plane wave will have been decreased as shown in equation (B-1). The sample of absorber is then placed in a uniform portion of the expanded guide.

One of the main disadvantages of a flared guide is the possibility of higher order modes being introduced by the flare. Since these will not re-enter the standard guide where the VSWR is measured, their presence will tend to make the absorber look better than it really is. In addition, reflections may occur from flanges and discontinuities in the taper and these could cause error unless steps are taken to eliminate them in the measurement procedure. The manner in which this is done is most conveniently described with reference to some preliminary waveguide tests of absorbing materials carried out in the Radiation Laboratory.

These tests were made to provide a direct comparison of far field and waveguide measurements for three selected absorbing materials. The absorbers were VHP-2, H-2 and AN-72, and the results of the free space tests are shown in Fig. 5. The waveguide evaluations were performed using the conventional moving probe technique of VSWR measurement in a waveguide terminated in a specially designed sample holder. The input to the holder consisted of a transition flaring out from standard RG 52/U X-band guide to a 3 in. square section of guide, some 6 in. long, in which the absorber was placed. The absorber, backed by a metal plate, was then moved in small increments over a distance of several wavelengths towards the generator. During this process the VSWR was recorded and was observed to vary between maximum and minimum values.

By this type of manipulation it is possible to separate the reflection coefficient attributable to the absorber from the reflections associated with discontinuities in the system. Let k_r and k_o denote the moduli of these two reflection coefficients. If both k_r and k_o are small compared with unity, the maximum and minimum values of the VSWR are

$$\rho_{max} = \frac{1+k_r+k_o}{1-k_r-k_o} , \qquad \rho_{min} = \frac{1+k_r-k_o}{1-k_r+k_o}$$

approximately. Hence

$$k_{max} = k_r + k_o , \qquad k_{min} = |k_r - k_o|$$

giving

$$k_r = \frac{1}{2}(k_{max} \pm k_{min}) , \qquad k_o = \frac{1}{2}(k_{max} \mp k_{min})$$

with the upper or lower signs according as $k_r \gtrless k_o$ respectively. Since it is not known a priori which of k_r, k_o is the larger, it is not immediately obvious which case we must choose, but the difficulty can be resolved by repeating the process with different samples of absorber. k_o, being a function of the guide only, should remain constant, and the coefficient which varies is then attributed to the absorber.

Eight samples of VHP-2, seven of H-2 and four of AN-72 were measured at each of the frequencies 8.7, 9.3 and 9.9 Gc using the above technique. The samples were nominally 3 in. square to effect a snug fit inside the holder, and the average values of the power reflection coefficient at 8.7 Gc are indicated by the broken lines in Fig. 5. The solid lines on either side show the standard deviations of the measured data.

The AN-72 material proved to be somewhat sensitive to orientation, suggesting that the composition possesses a definite grain, but nevertheless the waveguide value -12.5 db is in excellent agreement with the results of the free space measurement on the largest sample used. For VHP-2 the waveguide value -41 db is close to the free space reflection coefficient implied by the largest sample, though the direction of the curve indicates a potentially lower free space value than that which was obtained. The H-2 material did not, however, perform as expected. The wave waveguide value -28 db differs considerably from the -40 db level suggested by the free space test and it is probable that at least part of this discrepancy is due to poor electrical contact between the absorber and the walls of the guide (because of the hair construction of this material, the edges of the samples tended to be irregular). Nevertheless, another contributing factor is the fundamental difference between waveguide and free space tests, and it is now time to examine the commonly made assumption that a waveguide reflection coefficient can be treated as a valid estimate of the free space quantity.

Consider a rectangular waveguide of dimensions a and b supporting the dominant (TE_{10}) mode. The only non-zero component of the electric vector is in the vertical (or b) direction and is independent of the vertical coordinate y but varies sinusoidally as a function of x. This variation can be interpreted as the effect of two 'free space' waves travelling down the guide at angles $\pm \sin^{-1}(\lambda/2a)$ to the axis, and by imaging in the walls of the guide we now see that any waveguide measurement of a test object is equivalent to a free space measurement with an illumination consisting of two symmetrical plane waves at oblique incidence.

It is conceivable that for some objects the scattered field in the direction normal to the surface will be sensibly the same as it would be for plane wave illumination at normal incidence, but this will be the exception rather than the rule. In general, therefore, the reflection coefficient of an absorber measured in a waveguide will differ from the free space reflection coefficient. Since the incidence angle decreases with increasing a, it is expected that the difference between the measurements will also decrease if the guide is flared in such a manner that the field remains a TE_{10} mode, and it is certainly zero in the limit $a = \infty$. But in any practical case a discrepancy between the two measurements will exist and could be serious for any material whose reflection coefficient varies appreciably with angle of incidence.

An entirely equivalent way of looking at this problem is from a consideration of the impedances inside and outside the guide. This is the approach which is adopted in Appendix B. In two idealized cases a direct relationship between the waveguide and free space reflection coefficients (R_w and R respectively) is found. To know R_w then specifies R uniquely. In most production testing, however, no phase measurements are performed and a knowledge of the VSWR determines only $|R_w|$. An infinity of $|R|$ are then possible, and for one of the cases the extreme values of $|R|^2$ are plotted as a function of a/λ for four different choices of $|R_w|^2$. A study of Figs. B-1 through B-4 shows the tremendous errors which could occur if a measurement of $|R_w|$ in an unflared guide ($1/2 < a/\lambda < 1$) were regarded as an estimate of $|R|$, and for high performance materials ($|R_w| \ll 1$) the possibility of error persists even when the guide has a substantial flare. Thus, for example, a material (of the above idealized type) which registers -35 db in a guide which is flared to 3λ could have a free space performance as good as -39 db or as bad as -32 db (see Fig. B-3).

Any practical absorbing material will differ markedly from the idealized versions treated in Appendix B. It will probably not be homogeneous in the transverse direction (it may have a physical structure, such as cones or pyramids), and will certainly not have constant electrical properties in the normal direction. The relevance of our analysis is therefore questionable, but since there is now no feasible way of finding the theoretical relation between R and R_w, it would appear at least prudent to require that any waveguide measurement be carried out in a guide of such dimensions that even the extreme errors referred to above will not affect the acceptability or otherwise of the material. To judge from the cases treated, a 3λ flare for example, would ensure that any value of $|R_w|^2 > 10^{-3.5}$ did not overestimate the free space performance by more than 3 db.

If the absorber is non-uniform in shape and/or composition, the field which is reflected from a waveguide sample will include higher order modes. Such modes, whether they originate at the absorber or in the flare, cannot enter the measurement section of the guide, and therefore tend to make the absorber appear better than it is. The generation of these modes in the flare can be minimized by making the transition between the two parts of the guide as smooth and gentle as possible. Unfortunately, there is little that can be done to cut down their generation by the absorber, but for a discussion of this problem reference should be made to Haddenhorst (1955).

2.3 Recommendations

Owing to limitations of time and money, the investigations under this contract have been somewhat piecemeal and several of the topics mentioned in the preceeding paragraphs are worthy of more attention than we have been able to give. Thus, for example, a more detailed examination of free space data on absorbing materials as a function of sample size would provide valuable information about the actual magnitude of the edge contribution for practical materials, and would lead to a more precise specification of minimum sample size required by each of the free space methods. It must be admitted that there has been a tendency in the past to accept as valid free space measurements on samples whose size would now appear to have been insufficient. Equally, however, there are pitfalls associated with absorber tests performed in closed systems. The data obtained with the hairflex absorber suggests that care is necessary to ensure good electrical contact between the absorber and the walls of the guide, but much more important is the appreciation of how large a guide may be necessary for high performance materials before the waveguide reflection coefficient can be regarded as a valid estimate of the free space coefficient. In the time available all that we have been able to do in this connection is to demonstrate the type of error which could be incurred with waveguides of relatively small dimension, and because of the reliance which is placed on this type of test, an appreciation of its limiations is desirable. It is, perhaps, unfortunate that a critical comparison of testing methods is not readily available in the general literature, and the present investigation has no more than skimmed the surface.

At frequencies as low as 200 Mc, none of the standard methods are really satisfactory for practical purposes, and when those compromises are made which are necessary for expediency the validity of the tests can be held in question. Assuming that the material to be evaluated has a free space reflection coefficient of -30 db or better, a plane wave or a Doppler test would require a sample 8λ or more in dimension, and even with the arch method a sample 4 or 5λ in size appears called for. Any significant reduction in these dimensions would introduce the possibility of error, and since samples 3λ square are still too large for a satisfactory scheme of production checking, it would seem desirable to recommend the use of a closed system at VHF frequencies. A coaxial line has many attractions but the fact that the absorber must be mutilated to fit the line is an overwhelming disadvantage. We are therefore left with the waveguide method as the only possibility. Some of the major disadvantages associated with this method were discussed in Section 2.2.3, and though flaring of the guide may well introduce higher order modes and reflections from discontinuities, it is our feeling that as long as the waveguide reflection coefficient is to be identified with the free space coefficient, every effort should be made to flare the guide to a width of 3λ or so.

III

ANECHOIC CHAMBERS

The first known case of an anechoic room constructed specially for microwave antenna studies is the Naval Research Laboratory room which was completed in the early fifties. Prior to this, however, the MIT Radiation Laboratory had been making indoor measurements of antenna patterns. Resonant absorber screens were set up in the halls to minimize unwanted reflections, and a venetian blind arrangement of these same screens was used to form a partially enclosed room for measuring the primary patterns of antenna feeds. No published reference to this work is available, but for the NRL room a description has been provided by Simmons and Emerson (1953). For present purposes this paper is of particular interest since it also gives methods for the evaluation of anechoic rooms.

During the four or five years subsequent to the installation of the NRL room, the problem of room design received very little attention. Anechoic rooms were built at the Air Force Cambridge Research Center, The Ohio State University[+] (Upson and Hines, 1956), Lockheed Aircraft Corporation (Ihly, 1957) and Raytheon's Bedford Laboratories (Smith and Gagaro, 1958), but little was done about methods of evaluation. Since 1958 and through to the present time, each year has seen an increasing number of rooms constructed. Some particular examples have been described by Clapp and Angelakos (1959), Wolfe et al (1961) and Blackwell (1962), but apart from these publications there is only a small body of literature on the subject, and most of it has originated with the absorber manufacturers themselves. Credit is also due to them for the development and improvement of many of the evaluation techniques currently in use.

[+] who were probably the first in this country to make radar cross section measurements indoors.

3.1 Methods of Evaluating Room Performance

Although present day methods of room evaluation are superior to those originally used, they still leave something to be desired. In assessing the value of any product, one likes to be able to assign a number indicating the degree of excellence. In the early studies of room performance, no attempt was made to arrive at an overall rating, and the specification of such a figure has been one of the main objectives in the development and refinement of methods for room testing. Some of the methods discussed in Sections 3.1.1 and 3.1.2 do result in a performance figure or curves, but it is important to note that these are only meaningful when accompanied by a full description of the test conditions. It should also be pointed out that experience with room evaluation procedures has been largely restricted to UHF and higher frequencies.

The purpose of an anechoic room is to combine the advantage of operation in a controlled environment free from the difficulties associated with rain, wind, etc., with the achievement of plane wave illumination in the region of the antenna or scatterer under test. This type of illumination is possible only over a restricted portion of the chamber, and this is generally a cylindrical volume (sometimes called the 'quiet zone') which extends roughly along the longitudinal axis of the room from the transmitter to the receiver. The desired plane wave will exist within the transmitted beam once the range exceeds the near field distance providing that no reflected energy reaches the test region. The first objective of all test procedures is to determine if any reflected energy is present, and if so, to find the source and magnitude of the interfering signal.

The various methods proposed for room evaluation can be divided into two classes: those using one-way transmission, and those using scattering techniques or two-way transmission. It is convenient to consider each of these classes separately.

3.1.1 One-Way Transmission

One of the most simple and direct methods of room evaluation is to compare the radiation patterns of test antennas in the room with the corresponding patterns taken on a proven outdoor range. This method has been used extensively (for example, by Simmons and Emerson, 1953; Clapp and Angelakos, 1955), and the information obtained depends on the care taken and the variety of antennas and frequencies employed. If the test antenna has side lobes which are much lower than the returns from the walls, distortions present in the indoor patterns can help in finding the source and level of the room reflections. This type of evaluation procedure is satisfactory for determining the adequacy of the room for a specific test purpose. It does not provide a performance figure, but modifications in the method to be described later do fulfill this need.

To see whether or not a plane wave does exist in the quiet zone, an obvious method is to probe this volume with a small pick-up device. Clark et al (1961) refer to this as the pick-up probe method, and as described by them the procedure involves an electric dipole or loop antenna which is small compared with the wavelength and which is used to map the field to detect standing waves produced by side and back wall reflections. The method is simple and essentially accurate, but may be difficult to carry out in practice owing to the necessity for many measurements and the errors which can result from (i) the probe support, (ii) probe misalignment and (iii) disturbances caused by the cables leading to the probe. Clark et al do not recommend this method for high performance rooms.

In a somewhat more sophisticated version of this scheme, NRL (Simmons and Emerson, 1953) have used a transmitting monopole antenna mounted on a ground plane and swung in an arc about a similar receiving antenna located near the center of the room. The standing wave pattern of the signal picked up by the latter is due to reflections from the walls adding in and out of phase with the direct signal, and from the magnitude of the standing wave ratio the level of the room reflections can be determined. Tests made on the original NRL room gave a level which varied from 1 percent for λ = 3 cm. to 5 percent when λ = 30 cm.

Another room evaluation procedure employed by Simmons and Emerson is a type of wall reflectivity measurement, and uses two directive antennas. The transmitting antenna is directed at various points on the side wall, and the patterns of the other antenna are recorded to show the change in the apparent side lobes. In tests on the NRL room the maximum change occurred at times of specular reflection, from which it was concluded that diffuse reflection was relatively unimportant in this room. The values for the wall reflectivity were in good agreement with the results obtained from individual samples of absorber prior to their installation.

Two variations of this method have been described by Clark et al (1961). They have called the first 'the directional antenna' method, and it is quite similar to the NRL procedure. The receiving antenna is located at the test point and is directed initially at the transmitter, and then at different reflection points. The direct and reflected signals are compared for orientations of the receiving antenna varying from the angle of specular reflection of the side wall to the normal to the back wall (180° aspect). From the ratio of these signals, curves of reflection coefficient versus receiver orientation are obtained. The importance of the receiving antenna having low side lobes and high front-to-back ratio is emphasized. In the second variation (the 'quasi-omnidirectional antenna' method) the high gain transmitting antenna is replaced by a dipole or other antenna having an azimuthal pattern which is omnidirectional. The measurement procedure is the same as before, but since the illumination is now more uniform, the room should appear inferior to what it would be in a typical operating situation. For a complete evaluation the tests are repeated for various positions of transmitter and receiver.

In the frequency shift method of Clark et al, separate transmitting and receiving antennas having the desired patterns are located at their operational positions. As the transmitted frequency is changed, the phase changes in the (unequal) path lengths of the direct and reflected rays produce an effective VSWR output at the receiver. Note that this assumes all components have broadband characteristics. There is also a modified form of the method in which two receiving antennas are used. One is directed at the transmitter and the other at a portion of the wall. Their output is summed in a common receiver, and from the variation in level as a function of frequency, the reflection coefficient is determined for that portion of the wall.

To the present authors the frequency shift method does not appear to be an attractive evaluation procedure. The data obtained would be difficult to interpret since one would not know how much of the change as a function of frequency was due not to the phase but to some frequency sensitive characteristic of the system. The phase changes necessary to differentiate between the direct and reflected signals can be obtained easily, and alternatively, by movement of the antennas.

The above methods of room evaluation only lead to partial information about performance, but nevertheless one or other of them may be adequate for a particular application. The methods which we shall now consider still involve one-way transmission, but are considered more satisfactory since the data which they provide can be analyzed to give numbers or curves to designate the performance.

The first method is the 'antenna pattern comparison technique' described by Buckley (1960) and Emerson and Cuming (1962). The latter give additional details of the scheme with illustrative curves. The tests are made with the transmitting antenna situated near the middle of an end wall (probably in its normal operating position) and directed at the center of the opposite wall. The receiving antenna is placed at the selected test location in the quiet zone, with provision for taking azimuthal or elevation patterns at various positions to left and right, above and below, the central position. Transmitting and receiving horns with gains of order 15 db are recommended.

For the frequency and polarization of interest, the receiving antenna is moved in discrete steps along a horizontal or vertical traverse and the pattern is recorded at each. The total distance moved should be sufficient to ensure that a complete cycle of interference between the direct and reflected signals is experienced, and when this is accomplished a new (and different) traverse is commenced. The group of patterns obtained from a single traverse are now compared with a reference pattern (usually the one corresponding to the central location) by successively superimposing each pattern on the standard so that their peak levels coincide. In each case the differences that occur at levels of (say) -10, -15, -20, -25 and -30 db are measured and tabulated. These are then expressed as voltage ratios R from which the magnitude E_2 of the reflected field is determined using the formula

$$R = \frac{E_1 + E_2}{E_1 - E_2} , \qquad (1)$$

where E_1 is the amplitude of the direct signal reduced by the number of db appropriate to the pattern level considered. In practice it is convenient to work entirely in db and to obtain E_2 from R and E_1 using prepared curves. The 3 to 5 values of E_2 resulting from a particular set of patterns are now averaged to give one mean value corresponding to the E_1 for that traverse, and so on for every E_1 level of the group. These are further averaged to provide values typical of one traverse, and the final step is to take the results from a series of horizontal and vertical traverses, and to average (or otherwise analyze) them to yield a number (or numbers) characterizing the room performance. If all of the data is taken with a receiver located at the maximum possible range consistent with normal operation, Emerson and Cuming regard the number obtained as representing the minimum room performance, since shorter ranges are less subject to interference. They further suggest that to characterize a room adequately it is sufficient to use a single frequency within the highest frequency range at which the room must operate, and to make one horizontal and one vertical traverse, recording either azimuthal or elevation patterns with any desired polarization.

The second method described by Buckley (1960) is the 'null-balance technique'. In this system two receiving antennas are placed in the test region and are directed towards the transmitter. The first antenna remains fixed and provides a comparison signal for the other antenna, which is moved horizontally or vertically. The two signals are compared by feeding them into a detection system. As the probe antenna is displaced from its central position, a curve is plotted whose variation is a consequence of the interference between the direct and reflected rays, and from the max. to min. ratio R the level of the reflected field is determined as

$$E_2 = E_1 \frac{R-1}{R+1} , \qquad (2)$$

where E_1 is unity since the peak value experienced by the moving antenna is always used.

The advantages claimed for the null-balance technique are the increased precision provided by the circuitry and the simplification of the data reduction problem. The information obtained, however, is less than that found by the preceding method. Each traverse gives only one value for the reflectivity, whereas about five would have resulted from a comparison of antenna patterns. Moreover, this one value would appear to correspond to that for a near-peak reading in the first method.

The B.F.Goodrich method (Emerson, 1962) is somewhat similar to the two discussed above. Transmitting and receiving horns are set up as they would be for an antenna pattern test, and as illustrated in Fig. 8. Room reflectivity data is obtained as a function of the aspect ϕ of the receiving horn, with ϕ varied in discrete

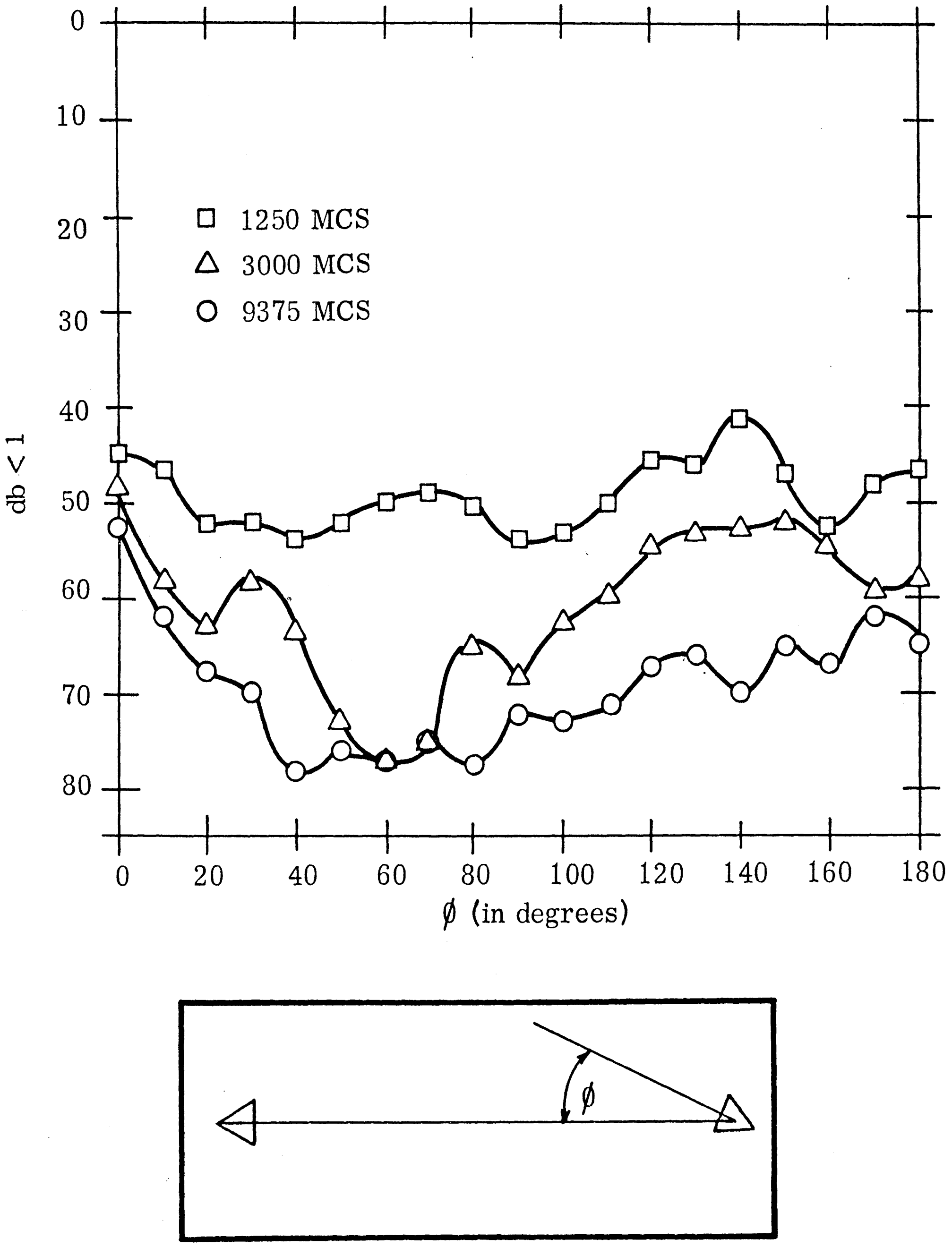

FIG. 8: UNIVERSITY OF MICHIGAN ROOM, COUNTERMEASURES LABORATORY (data and analysis by the B.F.Goodrich Co., 1962).

steps (for example, 10^o) from $\phi = 0^o$ (looking at the transmitter) to $\phi = 180^o$. At each aspect, the horn is moved back and forth along its axis to produce a change in the received signal from a maximum to a minimum. It is assumed that this results from the in and out-of-phase addition of the direct signal E_1 and the reflected signal E_2, the ratio of which can be obtained from the max. to min. ratio R using equation (2). The value used for E_1 depends on the orientation of the horn, and is found from the average signal received as the horn is moved along its axis by normalizing this relative to the peak value observed when $\phi = 0^o$.

Since it is not possible to cite a readily available reference for this method, it may be helpful to include some samples of the performance curves which it produces. Fig. 8 shows the way in which the data is presented, and is the result of an evaluation made by the B. F. Goodrich Co., of an anechoic room installed by them at The University of Michigan. Typical measured values to account for two points on the 1250 Mc curve might be as follows: at $\phi = 0^o$, E_1 would be 0 db or (say) 1 volt, and R might be 0.1 db (=0.9886), giving a value 0.57×10^{-2} or -45 db for E_2; at $\phi = 30^o$, E_1 might be -20 db or 0.1, whereas R may have increased to 0.45 db (=0.95) leading to a value 0.26×10^{-2} or -52 db for E_2 .

It is our opinion that the first and last of the three methods described above produce essentially the same information. Both are concerned with the ratio of the reflected to the direct fields. The antenna pattern comparison technique presents this as a function of the off-center position of the receiving antenna for what is really a number of orientations of this same antenna (see Fig. 2 of Emerson and Cuming, 1962). On the other hand, the B.F.Goodrich method provides the ratio for one antenna location as a function of the receiver orientation (see Fig. 8). The measurement would be repeated for the desired number of locations within the quiet zone to give a complete picture of the room performance.

Nevertheless, there is one difference between the methods which should be pointed out. In the antenna pattern comparison technique, the maximum variation observed at a certain level for a set of patterns is taken as the largest variation that has occured, and it is possible that the maximum and minimum conditions will not be experienced unless the discrete positions occupied by the receiving antenna are much less than one wavelength in separation. In the B.F.Goodrich method, the continuous movement of the horn for a particular orientation ensures a true maximum ratio providing, of course, that the horn is moved sufficiently.

3.1.2 Two-way Transmission

Any measurement of an antenna VSWR or a radar cross section involves two-way transmission, and the experimental procedure can be adapted to provide general information about the room performance.

If the room is to be used only for studying antenna impedance characteristics, the room requirements are much less restrictive than for scattering or antenna pattern measurements, and to estimate the performance in the first case, Emerson and Cuming (1962) suggest a determination of the room VSWR. The equipment is similar to what is normally used in measuring the VSWR of an antenna except for the additional provision that it be possible to move the antenna and the slotted line axially over a distance of one wavelength or so. The information desired is the effective reflection coefficient of the room as 'seen' by the test antenna, and to measure this by moving the probe in the slotted line would necessitate a means for separating the reflection coefficient of the waveguide and antenna from that of the room. To avoid this problem, Emerson and Cuming suggest moving the entire assembly axially, reading the resulting VSWR from the fixed probe. The reflection coefficient thus obtained depends, of course, on the antenna pattern, the direction of pointing, and the distance to the walls being illuminated. If the quoted room VSWR is to be meaningful, this information must be included.

It is believed that the VSWR obtained by the method will be sufficiently accurate if the antenna system is well matched. Nevertheless, the results obtained by moving the antenna assembly are not independent of discontinuities between the detecting probe and the antenna aperture. Ginzton (1957), in his discussion of the sliding termination technique, requires that the VSWR in the slotted line be measured for the two positions of the load that give maximum and minimum VSWR. From these two values and a Smith chart transfer of impedance, the maximum and minimum values of the corresponding resistance is obtained. The VSWR of the sliding termination is then the square root of the ratio of the two resistances. An alternative to this is discussed in Section 2.2.3, and both of these procedures enable us to find not only the reflection coefficient of the sliding termination, but also that of the discontinuities in the measurement system.

Clark et al (1961) suggest a more novel method of room evaluation in which a millimicrosecond radar pulse is used to locate the sources of room reflections. The range discrimination provided by 10 ft long pulses would separate the returns from the end and side walls, and would point out areas needing improvement. In a variation of this method, the transmitting antenna is made omnidirectional. Instead of discrete pulse returns, the received signal would now tend to be continuous with a fast fall-off, since all parts of the room would have been illuminated. It is proposed that the decay time (e.g. the time required for a drop in intensity of 20 or 40 db) be used as a measure of the room performance.

Both of these short pulse ideas are attractive and warrant further investigation. It would appear that the pulse decay time will depend quite closely on the overall room performance, and though it may be difficult to relate it to the performance figures generally quoted, this is not necessarily a disadvantage. Nevertheless, it is doubtful if the method will be used extensively for room evaluation in the near future because of the cost and complexity of the equipment, particularly at VHF.

The final methods which we shall consider involve the use of CW radar scattering equipment, and as such represent an obvious choice when this is the purpose for which the room is intended. The necessary equipment (which would then be available) includes a frequency-stabilized oscillator, transmitting and receiving antennas, and a sensitive receiver. Both antennas are directed at the target support pedestal located in the test region to be investigated. Suitable attenuators and phase shifter provide a coupling signal which may be fed into the receiver to cancel out unwanted effects due to cross coupling and background reflections. An alternate system which is generally used in the Radiation Laboratory has only a single antenna for both transmission and reception, and the necessary isolation is obtained through a balanced hybrid tee. A block diagram of this equipment is shown in Fig. 9.

A few simple tests have long been standard in radar scattering studies to get qualitative information on room interference for use in particular measurements (see for example, Clark et al, 1961). A sphere rotated off-center gives almost constant return when in the far field since the variation in range is small enough to make insignificant any change due to the r^{-4} law. A large variation in the return then shows that reflections from the room are illuminating the sphere. In a similar test with non-spherical shapes, the pedestal and target are rocked back and forth to determine the importance of the room contributions. A change in the received signal of less than one or two db would generally imply that the room return was not intolerable for the shape and aspect considered.

Another test which is frequently used is to compare experimental and theoretical data for one or more of the shapes for which an accurate theoretical solution is available. Although good agreement indicates a good room performance for the particular scatterer(s) involved, poor results might be due to any one of several causes such as faulty equipment or bad technique, rather than to poor room behavior.

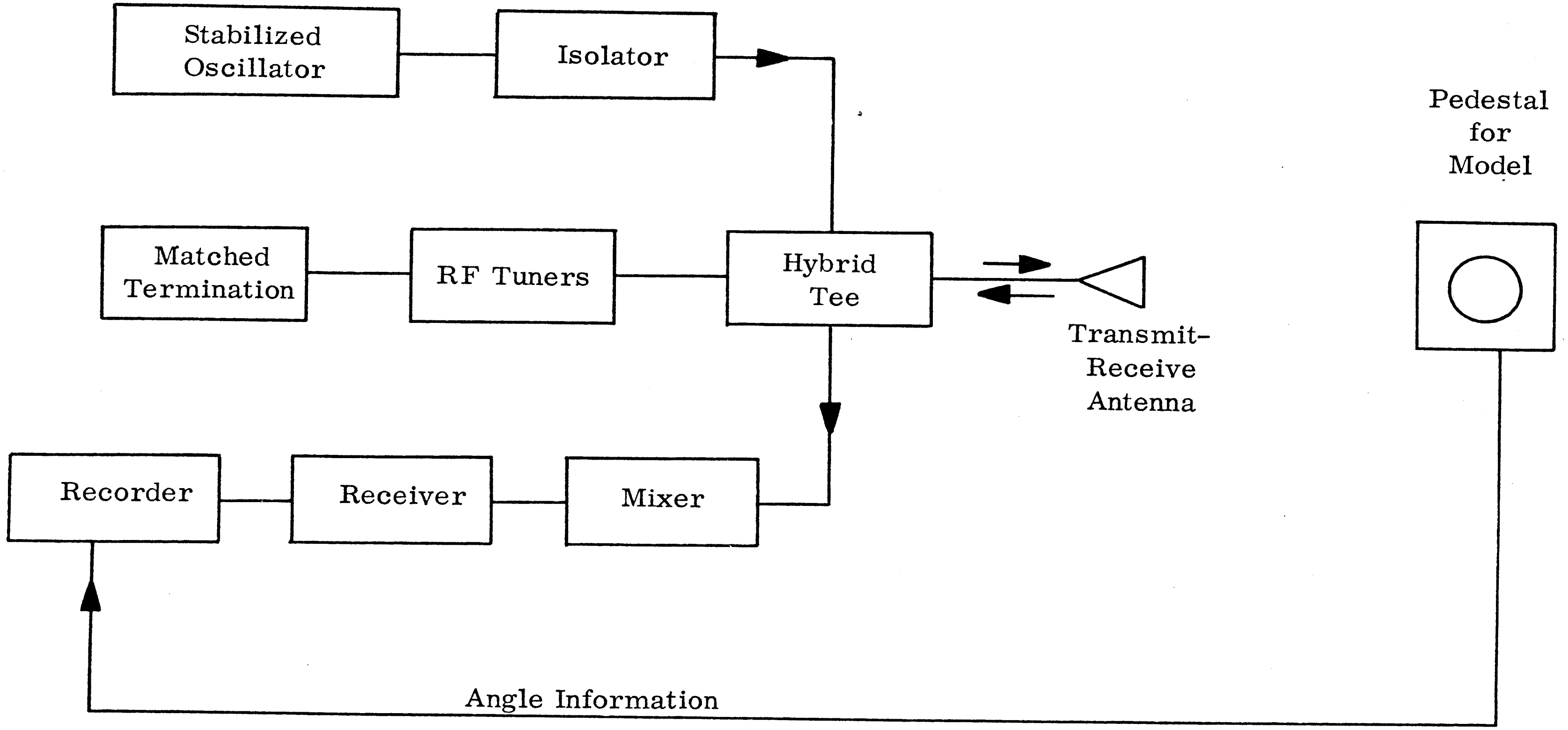

FIG. 9: BLOCK DIAGRAM OF EQUIPMENT

To obtain a performance figure for a room which is to be used in radar cross section studies, Upson and Hines (1956) and Buckley (1960) devised procedures for measuring its radar cross section. The former authors employ a single horn hybrid tee CW equipment, but Buckley's method, which is also discussed by Emerson and Cuming (1962), employs the two horn system described above, with the horns positioned for minimum bistatic angle and directed towards the pedestal at the desired range. Although the following remarks apply specifically to Buckley's method, the two procedures do not appear to differ in any essential way.

With no target in position the received signal is due partly to the room and partly to a leak-through or coupling signal from the transmitter. The entire antenna waveguide system is moved transversely until a minimum signal is received corresponding to an out-of-phase relationship between the room return $\sqrt{\sigma_r}\angle r$ and the coupling signal $\sqrt{\sigma_c}\angle c$. The latter is then adjusted in phase and amplitude to produce a null at the receiver, so that $\sqrt{\sigma_r}\angle r = -\sqrt{\sigma_c}\angle c$. The antenna-waveguide system is again moved a fraction of a wavelength, during which only $\angle r$ changes, until the received signal is a maximum equal to $2\sqrt{\sigma_r}$.

To determine the value of $\sqrt{\sigma_r}$ in wavelengths or meters, a target of known cross section σ_m is placed on the pedestal and caused to change in range so as to vary the phase with a no-change in its 'back scattering' cross section. The amplitude of the resulting interference pattern is

$$\left|\frac{2\sqrt{\sigma_r}+\sqrt{\sigma_m}}{2\sqrt{\sigma_r}-\sqrt{\sigma_m}}\right|,$$

from which two values of the room cross section are obtained depending on whether $\sigma_r \gtrless \sigma_m$. The ambiguity can be resolved by employing a second target with a cross section different from the first, so that two further possibilities for the room cross section result. The true value of σ_r should then be evident, since one value from the first measurement should be equal (or nearly equal) to one from the second.

The radar cross section found by this method is equivalent to assuming that the entire contribution of the room originates at the test model. It should be noted that this can be in error to the extent that shadowing by the model changes the effective room return. As is pointed out by Buckley, once the equivalent room cross section has been determined for the range r, it can be computed for other ranges using the r^{-4} law.

In radar cross section measurements, the return σ_r due to the room is cancelled or nulled-out by the waveguide tuning system. The room interference is not then σ_r , but the amount of unbalance due to the changes in σ_r resulting from shadowing by the model, and in Appendix C a method is described for measuring the magitude of this unbalance.

3.2 The Equivalent Cross Section of the Radiation Laboratory Anechoic Room

Since radar cross section measurements are one of the possible applications of the NASA Langley research room, a determination of its equivalent radar cross section is a desirable form of test. It is realized, however, that this may not be feasible unless CW scattering equipment is already on hand.

In order to evaluate the usefulness of this method, we have made several measurements of our own anechoic room in Hangar 2 (Willow Run Airport) during the present program. This room should not be confused with a smaller one installed by the B.F.Goodrich Company for The University of Michigan early in 1962, and discussed in Section 3.1.1. The Hangar 2 room is 100 ft long, 15 ft high and 30 ft wide. The sides, ceiling and floor are lined with B.F.Goodrich H-2 hairflex absorber having a reflectivity of about -20 db at S-band. Most of the end wall nearest the target (or receiver) is covered with VHP-18 absorber, having a specified performance of -50 db at S-band.

The tests were made at a frequency of 2.69 Gc using conventional CW single-antenna scattering equipment. The antenna had an aperture 3.4λ by 4.6λ with a gain of about 21 db, and the polarization was horizontal. The method differed from that described by Buckley (1960) only in that (i) a single antenna was employed and its motion was longitudinal rather than transverse with respect to the axis of the room, and (ii) the motion of the test model was longitudinal rather than the off-center rotation. At each of several ranges three values for the room cross section were determined to check repeatability, and these are presented in Table 3. It will be observed that the data is relatively consistent. The extent to which the cross section varies as r^4, where r is the distance between the antenna and the model, depends on the amount of shadowing by the model, and the cross sections σ_{14} shown in the last column of the table have been obtained from the r^4 law using the measured value at a range of 14 ft. The agreement with the measured data is quite good, with the possible exception of that for the longest range.

TABLE 3: EQUIVALENT CROSS SECTION OF HANGAR 2 ROOM, 2.69 Gc

Range r (ft)	Equivalent Room Cross Section, db < m^2			
	σ_1	σ_2	σ_3	σ_{14}
4	46.1	47.5	46.5	49.3
9.5	33.4	33.2	33.4	34.5
14	27.7	27.7	27.6	27.7
24.5	16.4	18.1	16.8	18.1
30	13.5	13.1	13.2	14.5
57	6.8	8.8	6.0	3.7

On the assumption that the equivalent room cross section is attributable to a signal originating at the back wall, a value can be found for the reflection coefficient of the absorber mounted there. A cross section of 27.7 db<1 m^2 at 14 ft is equivalent to one 6 db$>$ 1 m^2 at 100 ft. Since part of the wall is inclined at an angle to the beam, it would appear justified to neglect this in the calculation of a theoretical cross section, and if the remainder were a metal surface the flat plate formula leads to a cross section 62 db$>$ 1 m^2. The absorber would therefore appear to have an effective reflection coefficient 56 db<1, which is 6 db better than its nominal rating.

As noted earlier, however, the room cross section can be cancelled out in a CW scattering measurement. The room interference is therefore much smaller than the above, and is the result of changes in the cross section produced by shadowing.

3.3 Measurements on a Scale Model of the NASA Langley Low Frequency Room

Some data which has a direct bearing on the NASA Langley low frequency room has been obtained using a 1: 40 scale model of the room itself. This experimental study had two main objectives. Firstly, to investigate the variation of room performance as a function of the absorbing material lining the walls, with the hope that this information could be applied to effect economies in the room design by locating the absorber in the best positions. Because of the prohibitive costs in experimenting with full sized rooms, a scaled down version was selected as a working medium. The second objective was a practical evaluation of one of the antenna pattern comparison techniques as a means of determining room performance at VHF frequencies, and the method which was chosen was that described by Buckley (1960).

In constructing the room, the scale factor of 1: 40 was adopted since this put the operating frequency at X-band, which is a convenient place in the spectrum for measurements. 9.0 Gc with the model then corresponds to 225 Mc in the NASA room. In addition, the VHP-2 material corresponds roughly to a 6 ft absorber, which is about the thickness of VHP-70, one of the materials being considered. It was later realized, however, that VHP-2 is nearly 3 in. thick, not 2 in., so that the scaling was not dimensionally perfect for the two materials.

3.3.1 The Equipment

The scale model room was built of 1/2 in. plywood with inside dimensions 10 1/2 in. by 9 in. by 30 in. The interior was lined with foil and the absorbing material was attached with dacron line threaded through holes pierced in the walls. The roof of the model was removable. A port was cut in one end of the room to permit insertion of a 15 db X-band horn, and two traversing slots approximately 4 in. in length were cut in the floor to receive a half-wave dipole. In operation, the horn was used to transmit and the dipole to receive.

Fig. 10 illustrates the construction of the room and the dipole. It will be observed that the latter feeds into a section of RG 52/U waveguide which in turn delivers the signal to a superheterodyne receiver. The model was supported on a base straddling a turntable to which the waveguide was clamped. The dipole was passed up through the desired slot in the floor of the model to a position midway between the roof and the floor, and both the receiver output and azimuth information from the turntable were fed to a rectangular recorder.

The antenna patterns of the dipole were recorded at 1/2 in. intervals along the slots, yielding nine patterns for the comparison technique in each case.

3.3.2 The Measurements

The frequencies used in the tests were 8.5, 9.0 and 9.5 Gc. At all three, experimental dipole patterns compared well with the theoretical, and at 9.0 Gc the agreement was almost perfect. Five room conditions were considered, and in four of these the separation of the two antennas was 8 in. These four were obtained by lining the walls of the room with, (i) VHP-2, whose nominal rating at 9.0 Gc is -40 db, (ii) a combination of VHP-2 and AN-72 in which the former was used for the first 12 in. of the room, plus the rear wall, with the poorer (-10 db) material over

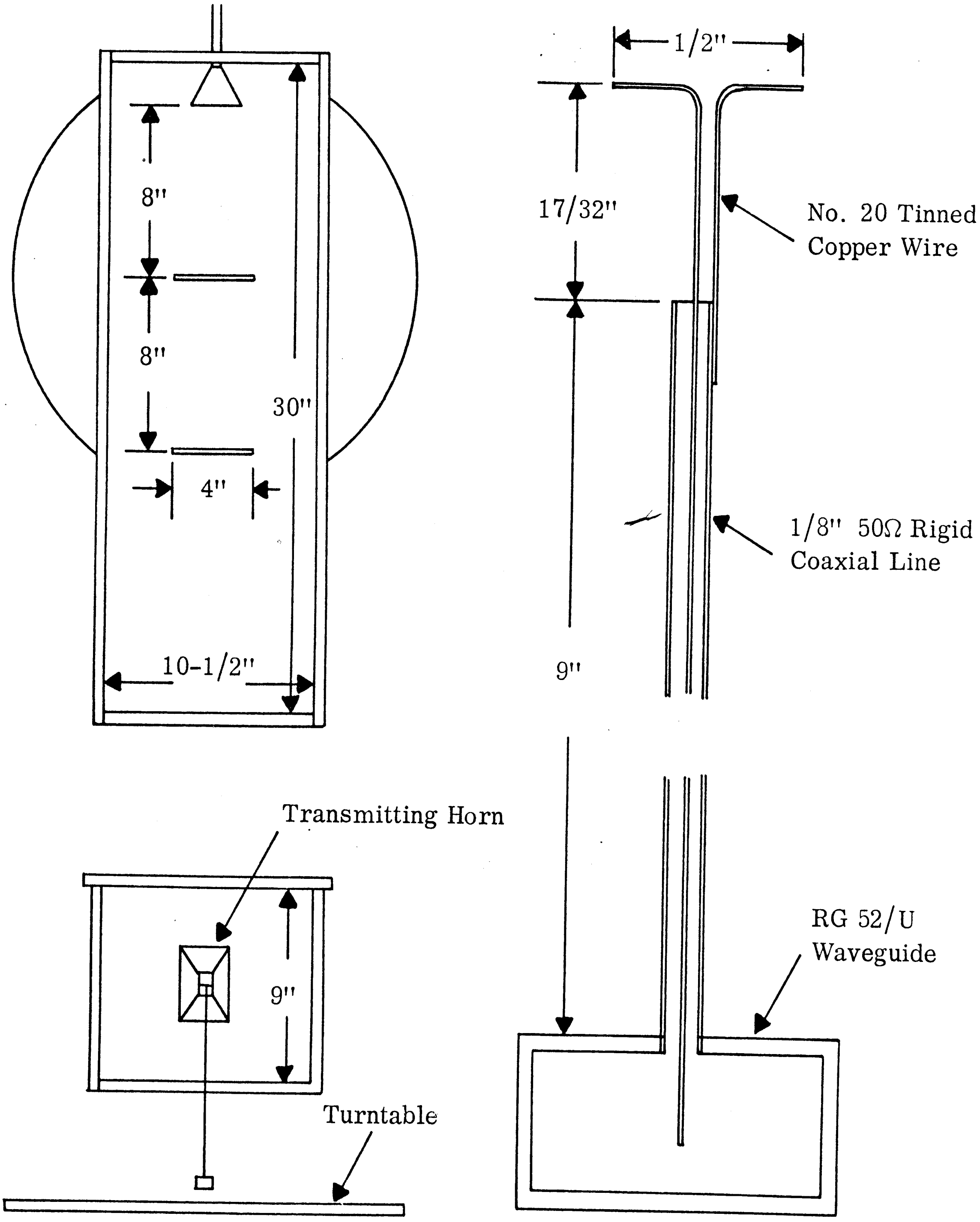

FIG. 10: THE SCALE MODEL ROOM
AND HALF WAVE DIPOLE CONSTRUCTION

the remainder, (iii) AN-72, and (iv) AN-73, which is rated at -20db at 9.0 Gc. The fifth condition was the same as the last named except that the antenna separation was now 16 in. All five conditions were investigated at each frequency, but most of the pattern comparisons were made with the 9.0 Gc data, and attention will be confined to this.

The pattern variations at -10, -15, -20, -25 and -30db levels were plotted as a function of the dipole placing for nine separate positions along the slots. The variation was assumed due to a reflected ray whose phase changes with respect to the direct ray as the slot is traversed, and the magnitude E_2 of the interfering signal was determined from the ratio R of the maximum to minimum signal using the procedure outlined in Section 3.1.1. The calculation was made for each of the five pattern levels listed above, leading to values for the performance figure P of the room and these were then averaged[+] to give a final performance figure for the corresponding room condition.

For the five room conditions tested, the data is summarized in Table 4, and the pattern variations are plotted in Figs. 11 through 15. The latter gives a somewhat exaggerated picture of the differences in the actual dipole patterns, and as a matter of fact the distortion at the upper level was always quite small. The shape never departed significantly from that typical of a dipole, and the large differences recorded usually occurred near the pattern null. The variations shown in the Figures have been corrected for the effects of reduced power level as the slot is traversed by adjusting the receiver gain. Since they were obtained by lining up the peaks of the right lobe of the patterns, the fluctuation of the absolute power level across the room (the level was observed to fall by 2 to 4db from the axis to the extremes of the traverse) does not affect the evaluation. It is understood that this is the practice followed by Emerson and Cuming, Inc. (Buckley, 1962). Note that

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[+] The averaging was carried out after conversion of the db values to power levels.

TABLE 4 : SUMMARY OF PATTERN COMPARISONS AT 9.0 Gc[+]

Material and Range	Average Pattern Level, E_1	Total Pattern Variation, R	Interference Level E_2	Room Performance, P	Average Room Performance
VHP-2 8 in.	-9.8	0.8	-26.5	-36.3	-32.2
	-14.6	1.9	-19.0	-33.4	
	-18.6	3.5	-14.0	-32.6	
	-21.8	6.1	-9.5	-31.3	
	-24.0	9.5	-6.0	-30.0	
VHP-2, AN-72 Comb. 8 in.	-9.7	0.8	-26.5	-36.2	-31.0
	-14.2	1.7	-20.0	-34.2	
	-18.0	3.2	-14.8	-32.8	
	-20.8	6.4	-9.0	-29.8	
	-22.5	11.0	-5.0	-27.5	
AN-72 8 in.	-10.0	1.3	-22.2	-32.2	-31.9
	-14.8	1.5	-21.0	-35.8	
	-19.0	3.6	-13.5	-32.5	
	-22.4	6.9	-8.5	-30.9	
	-24.7	10.6	-5.3	-30.0	
AN-73 8 in.	-9.2	1.9	-19.0	-28.2	-30.1
	-14.4	2.7	-16.0	-30.4	
	-19.2	4.2	-12.5	-31.7	
	-22.8	7.5	-7.8	-30.6	
	-36.0	12.5	-4.2	-30.2	
AN-73 16 in.	-9.6	0.6	-29.0	-38.6	-36.3
	-14.4	1.2	-23.0	-37.4	
	-19.0	2.2	-17.8	-36.8	
	-22.8	4.0	-12.8	-35.6	
	-25.8	6.9	-8.5	-34.3	

[+] (all values in db).

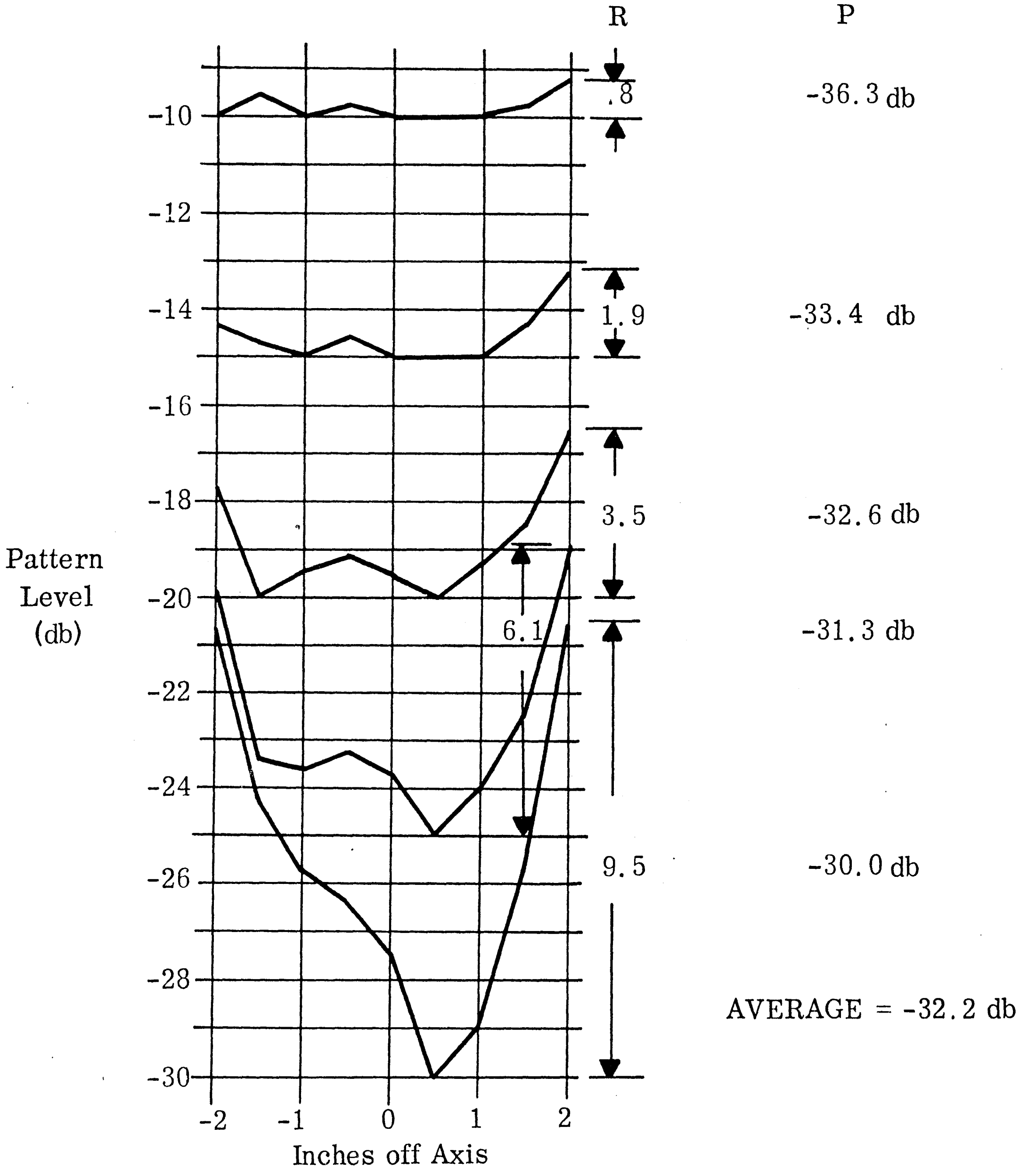


FIG. 11: SCALE MODEL TEST WITH VHP-2, 8 in. RANGE

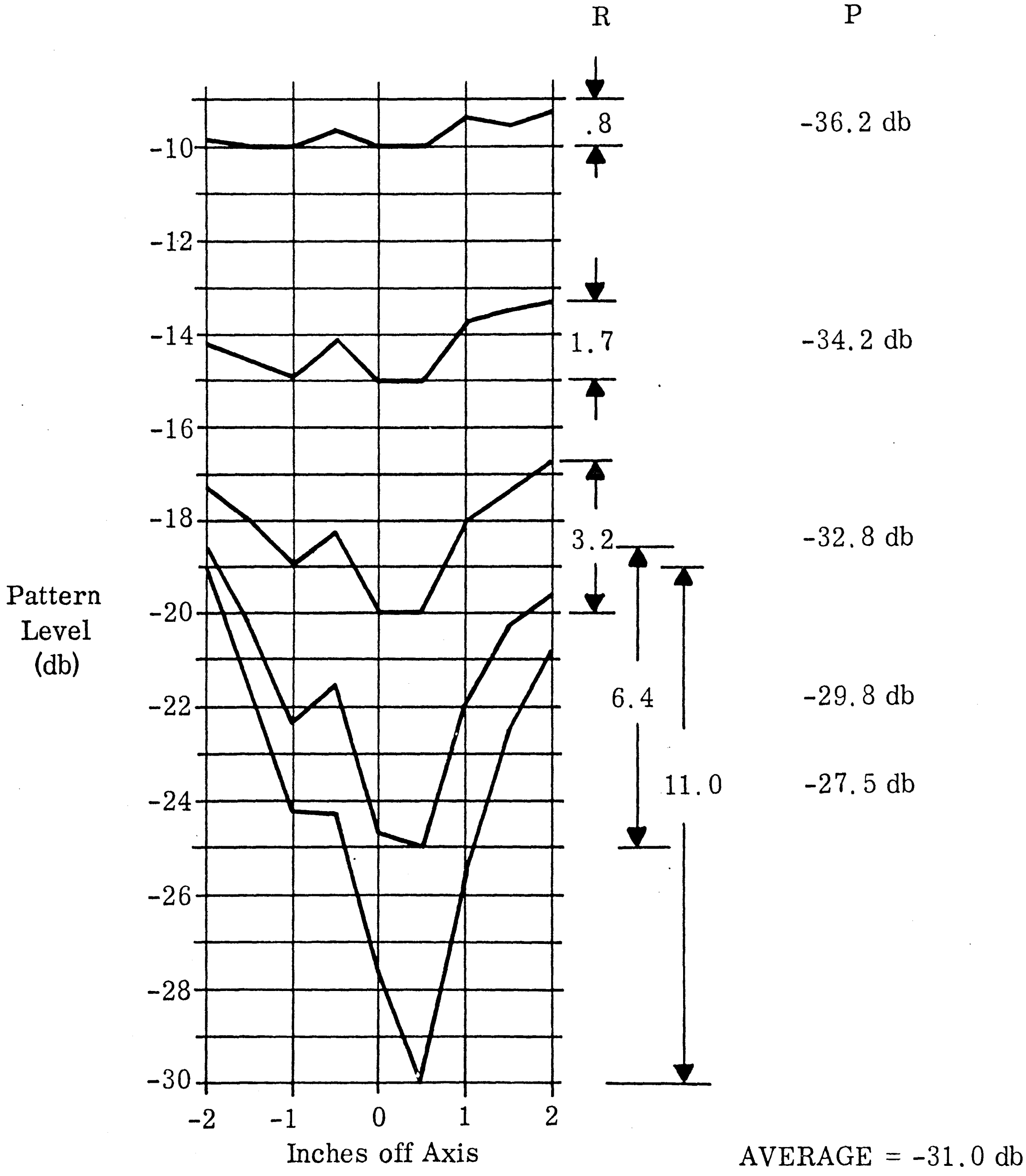


FIG. 12: SCALE MODEL TEST WITH VHP-2 AND AN-72 COMBINATION, 8 in. RANGE

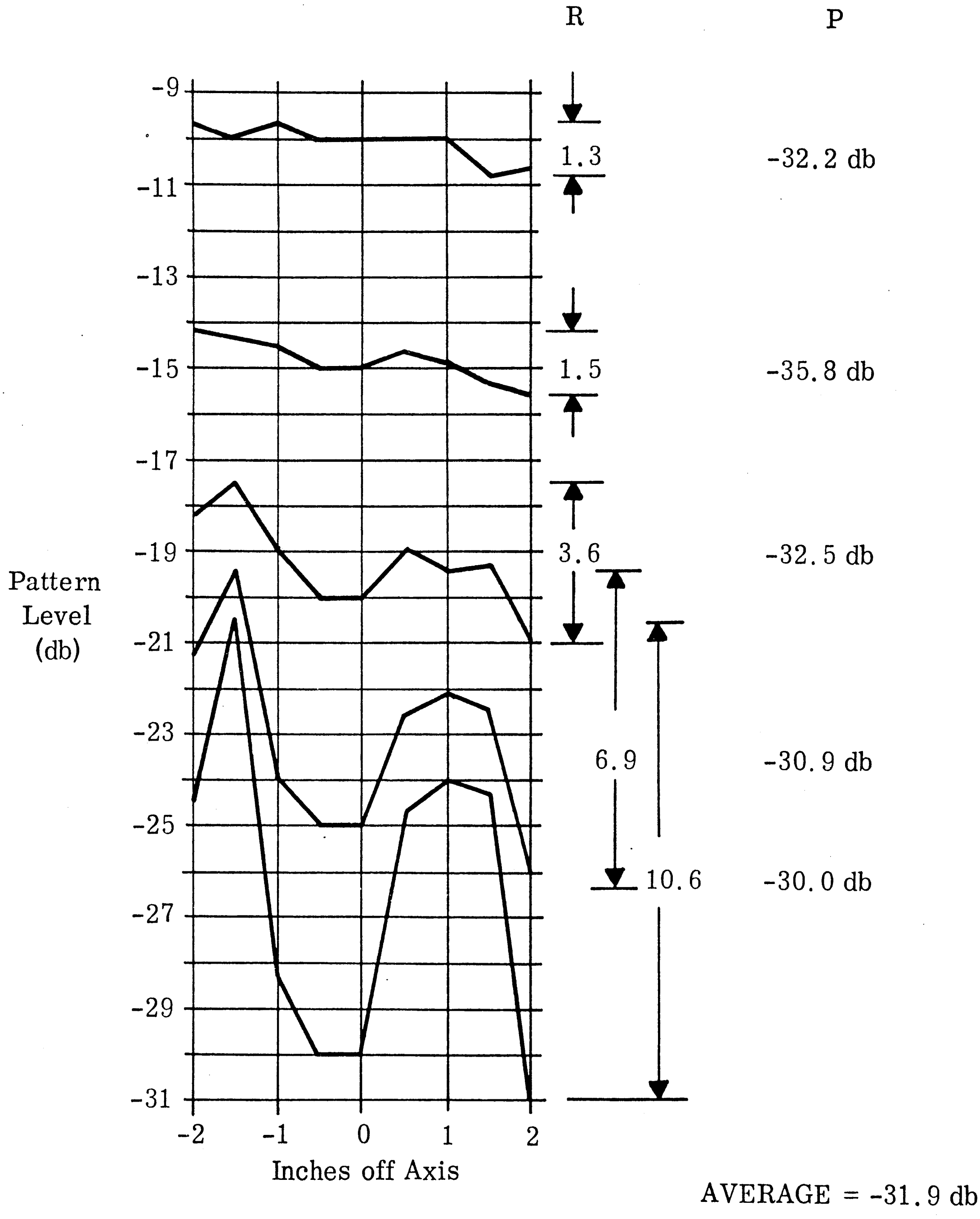
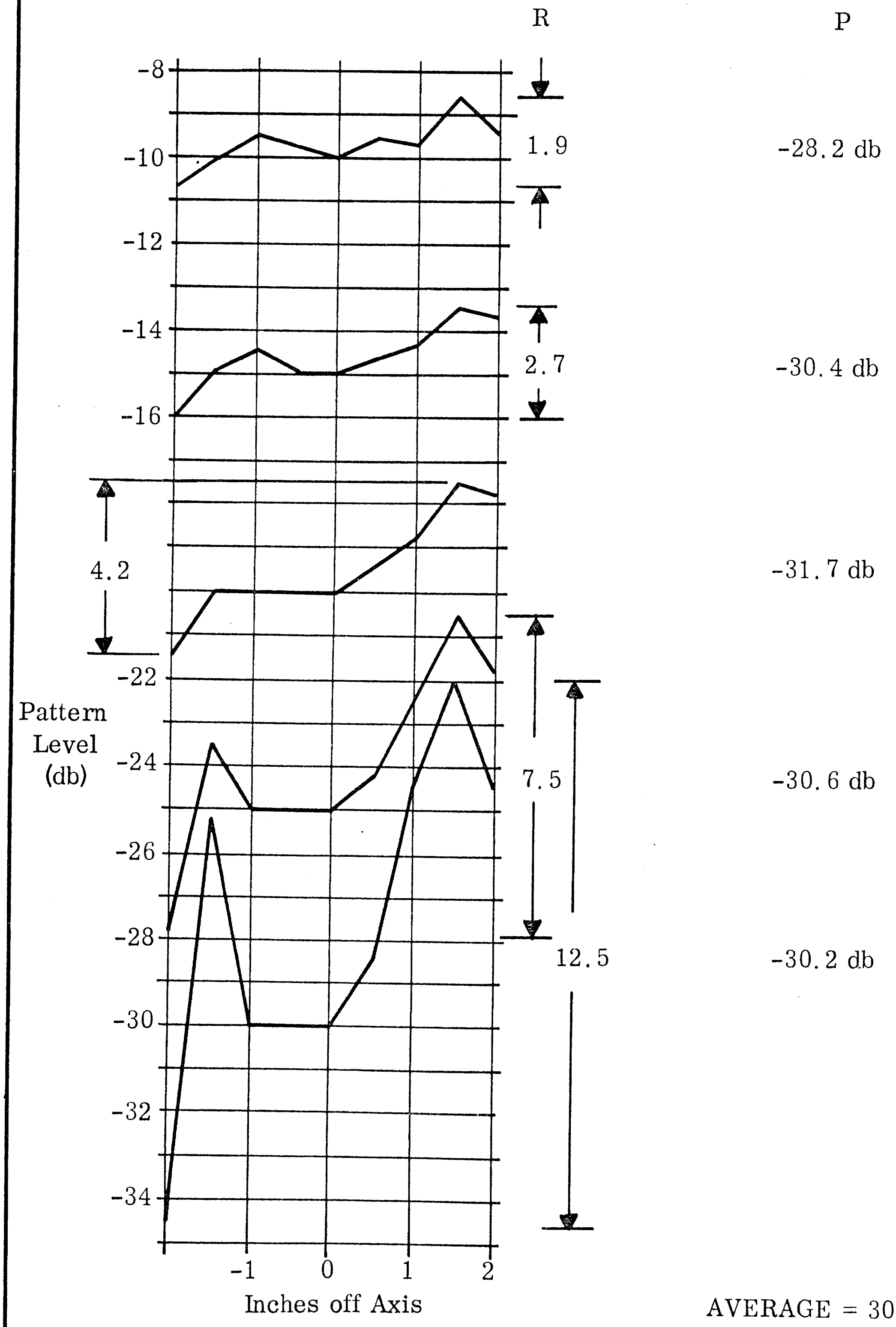
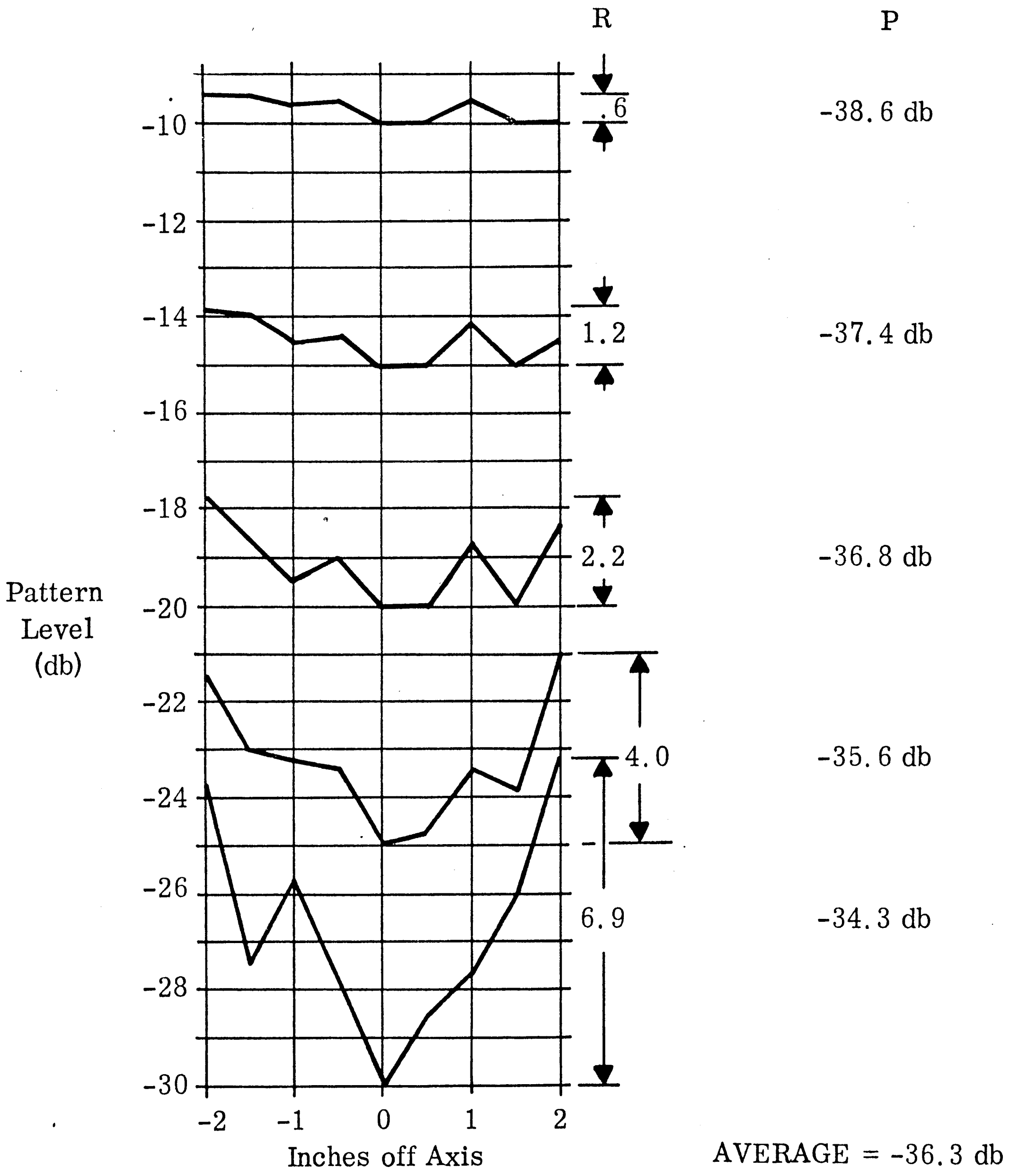


FIG. 13: SCALE MODEL TEST WITH AN-72, 8 in. RANGE



AVERAGE = 30.1 db

FIG. 14: SCALE MODEL TEST WITH AN-73, 8 in. RANGE



AVERAGE = -36.3 db

FIG. 15: SCALE MODEL TEST WITH AN-73, 16 in. RANGE

because the patterns were lined up at their peaks, the interference level (when the dipole is broadside to the transmitter) is arbitrarily set at zero.

The data which was obtained with these room conditions is disappointing in that there is so little correlation between the apparent performance of the room and the rating of the absorbing material. A similar lack of correlation between antenna pattern deterioration and room material was previously found in scale model tests at the Naval Research Laboratory (Wright and Wright, 1962). It is therefore obvious that further study is needed to provide a more reliable and sensitive method for determining the performance of small anechoic rooms.

IV

SUMMARY AND RECOMMENDATIONS

Under the terms of the present study most attention has been given to methods of testing absorbers at frequencies as low as 200 Mc and to ways of evaluating the performance of anechoic chambers. These topics have been discussed in detail in the preceding sections and our recommendations concerning them will be considered shortly. In addition, however, the Radiation Laboratory has acted in a consultative capacity on matters relating to the general layout and specification of the anechoic rooms proposed by NASA-Langley. Our suggestions and recommendations concerning the low frequency room have been communicated to the NASA personnel at conferences held during the course of the work, and are summarized in the following section.

4.1 The NASA Langley Low Frequency Room

(i) The room should be as large as possible.

Although the room dimensions have been fixed at approximately 30, 35 and 100 ft for the height, width and length respectively, the relatively small size is a matter for some concern. At 200 Mc these dimensions correspond to 6, 7 and 20 wavelengths approximately, and each will be further reduced by about 2 wavelengths due to the probable thickness of the absorber to be mounted on the walls. Nevertheless, we are encouraged by our own measurements on the 1: 40 scale model (see Section 3.3) and by the work of Wright and Wright (1962) to believe that good pattern data on low gain VHF antennas could be obtained in a room of this size.

(ii) The end walls should be cylindrical or wedge shaped, but it does not appear advantageous to build permanent baffles for the other walls.

The maximum room dimensions are already fixed, but it is still possible to modify the interior shape of the room. Baffles are frequently added to the side walls, ceiling and floor to improve the quiet zone performance by causing all reflected energy to suffer at least two reflections before entry into this region. The design of such baffles is based on geometrical optics and ray tracing techniques, and though their advantages have been questioned (see, for example, Wolfe et al, 1961; Clark et al, 1961), it is believed that they may be effective in situations where the room is very large in terms of wavelengths and where the reflections from the absorbing material are specular. In the present case, however, the baffles would extend several feet into the interior of the room, further reducing the limited space available, and it is therefore recommended that the side walls, floor and ceiling be designed without permanent baffles.

On the other hand, it definitely appears desirable to have the end walls in the form of a vertical wedge or cylinder. The rear wall is believed to be the main contributor to the room cross section in radar scattering measurements, and in pattern studies both the transmitting and receiving antennas often have their beams normal to the rear wall, thereby introducing the likelihood of errors in the measured level of the back lobe. A wedge-shaped end could decrease the wall return by 10 db or more due to the lower cross section of absorber panels for non-normal incidence (see Figs. 6 and 7), and it seems probable that to curve the wall would produce a further reduction. Our recommendation is that each of the end walls be formed by a section of a circular cylinder with axis vertical and radius 15 ft or so, positioned such that its chord plus the combined thickness of the absorber on its surface and the side walls equals the 35 ft width of the room. An alternative arrangement is one in which the two halves of an end wall form a vertical wedge making an angle of about 15^{o} with the longitudinal axis of the room, and this may be equally effective.

(iii) The antenna and model supports should be adjustable in height in addition to having the usual azimuth and tilt capability. The test antenna support pedestal should be on a track running most of the length of the room (along the room's center line), with access via one or more side tracks. 'Switch tracks' should be provided so that alternative pedestals can be wheeled into the test position (making it possible to place a standard gain antenna in the same position as the antenna being tested, and also permitting work on two vehicles in parallel; minor adjustmants to one antenna would not then occupy the room unnecessarily). Since the design of the end walls is quite complex, the track entry to the room should be from the side.

(iv) All of the front half of the room and the rear wall should be covered with VHF absorbing material. A UHF absorber may be used for the remainder.

In the interests of economy, the more expensive VHF material should not be used except where absolutely necessary. Since most of the VHF antennas will be quite small, probably under 2 λ in maximum dimension, the far field requirement can be satisfied by a range of 40 ft or less. With the test pedestal on a movable dolly, it will be possible to make all of these measurements in the front half of the room, and this section can be completely lined with the VHF absorber. At the higher frequencies, where high gain antennas may sometimes be involved, greater ranges will be required, and tests on these antennas could be carried out in the rear half of the room. It is therefore both appropriate and economical to line this area with UHF absorbers.

(v) The performance of the absorbers used should equal or exceed the following values:

Absorber	Frequency (Mc)	Reflection Coefficient
VHF	200 - 300	-30 db - 35 db
VHF	300 - 500	-35 db or better
UHF	500 - 1250	-30 db - 40 db
UHF	1250 - 25000	-40 db or better

(vi) The manufacturer should test all the absorbing material supplied using a test procedure approved by NASA. The test frequencies should be 200 and 500 Mc (approx.), and one in each of the L- and X-bands. If the tests show the absorber to be quite uniform in its performance, sample to sample, 100 percent testing may be relaxed.

(vii) After installation the manufacturer should evaluate the room using one of the pattern comparison techniques described in Section 3.1.1. The tests should be made with both horizontal and vertical polarization using transmitting and receiving antennas with apertures on the order of 2 λ and 1 λ respectively at 200 Mc (standard gain horns may be used at higher frequencies), and the recommended room performance should equal or exceed the following values:

Required Performance over 10 ft. Circle (db)	Frequency (Mc)	Range (ft)
-30	200	40
-40	1250	65
-50	9300	65

4.2 VHF Absorber Test Procedures

The known methods for testing absorbing materials have been examined to determine their suitability for use in evaluating high performance absorbers at 200 Mc. Since each method has one or more major drawbacks at frequencies as low as this , it is necessary to select the one which could most nearly provide the needed information, and our recommendation is that the tests be performed using a a flared waveguide system with the guide width of order 3 wavelengths. Although the reflection coefficient measured in a waveguide is in general different from the free space value, and can be either greater or less, the discrepancy can be expected to decrease with increasing size of guide. A discussion of this effect was given in Section 2.2.3, and in Appendix B the relationship between the reflection coefficients was determined for two simple types of absorbers. For these cases at least it has been shown that a measurement of the VSWR in a waveguide specifies the free space reflection coefficient to within limits whose values are functions of the waveguide dimension, and whilst practical absorbers will differ considerably from the idealized forms treated here it would at least seem prudent to require that the measurements be carried out in a guide of dimensions such that even these extreme errors will not affect the acceptability or otherwise of the material. From Fig. B-3 in Appendix B it is seen that a material which registers at -35 db in a waveguide will have a free space reflection coefficient of -32 db or better if the guide is flared to at least 3 λ. Note that the analysis of Appendix B ignores the presence of any higher order modes, and these will always tend to make the material in the waveguide look better than it really is.

In measuring high performance absorbers in a waveguide, errors can be caused by discontinuities between the slotted line and the sample. The effect of these should be determined and, if significant, accounted for in the subsequent tests using the technique described in Section 2.2.3.

For the evaluation of absorbers at 500 Mc, the flared waveguide system again is recommended. At L- and X-bands, however, more flexibility is possible, and providing that the precautions outlined in Section 2.2 are followed, measurements at these frequencies can be made in waveguides or free space or by the arch method.

4.3 Evaluation of the NASA Anechoic Rooms

Several methods for evaluating the performance of anechoic rooms were discussed in Section 3, and most of these were found valuable in testing rooms intended for some particular application. Since the low frequency room is to be employed primarily for pattern measurements, it is recommended that the evaluation be carried out using an antenna pattern comparison technique of the type employed by either Emerson and Cuming, Inc., or the B.F.Goodrich Company. The procedures are outlined in Section 3.1.1, and they are suggested partly because the provide more complete data than most of the other methods, but also because they lead to performance figures or curves that permit the contrasting of one room with another. It should be emphasized, however, that none of the room performance figures are meaningful unless complete information about the test conditions (range, frequency, polarization, type of antennas, etc) is also included.

Our experience with the antenna pattern comparison test in the course of the present study suggests that it is less sensitive to room design than would be desirable at VHF. Other workers have shown it to be satisfactory at higher frequencies, and since it is based on the evaluation and comparison of antenna patterns, it is obviously called for with a room whose main purpose is pattern measurements.

In the case of the NASA Langley research room, we would again recommend the above test procedures, but would also advocate the measurement of the equivalent room cross section as described in Sections 3.1.2 and 3.2. The method involves two-way transmission, and for a room which is to be used for radar cross section measurements, this is clearly an appropriate type of evaluation.

V

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VI

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APPENDIX A

THE INFLUENCE OF EDGES ON THE FREE-SPACE MEASUREMENT OF ABSORBING MATERIALS

In seeking to reduce the radar cross section of aircraft, missiles, etc., by placing a layer of absorbing materials on selected portions of the surface, care is necessary to avoid the creation of a line singularity at the termination of the material. In some cases the singularity appears almost as intensive as the edge of a metal sheet, and it is therefore customary to fair in the material by tapering its thickness or, if this is impractical, to break up the singularity by cutting notches of dimension comparable to the wavelength under consideration.

Although these facts are well known, their relevance to the free space measurement of absorbing materials has only recently been appreciated. The procedure in this type of measurement is to take a piece of the material several wavelengths in dimension and mount it on a metal surface of the same size. In practice, however, it is desirable to have the metal fractionally smaller than the dielectric so as to ensure that none of the metal is visible around the edges when the specimen is viewed from the absorbing side. A comparison of the reflected power when the specimen is viewed from the front and from the back is then taken as a measure of the absorbing properties of the material.

This is a valid procedure only if the contribution from the edges is small compared with that from the bulk of the plate, and if this condition is not satisifed the method will in general underestimate (but could overestimate) the absorbing capabilities of the material. The extent to which it does so depends on the size of the plate, the intrinsic reflection coefficient of the absorber and the nature of its construction. In general, the better the material, the larger the plate which is necessary to provide an accurate measure of its absorption. A qualitative discussion of this effect has been given by Clark et al (1961), but it appears desirable to have some criterion to show how large a plate must be used.

Consider first a square metal plate of linear dimension a illuminated at normal incidence by a distant transmitter. The back scattered field can be estimated by the physical optics method and providing only that a is comparable to, or greater than, the wavelength λ the far field amplitude S is

$$S = -\frac{i(ka)^2}{2\pi} , \tag{A-1}$$

where the time convention is $e^{-i\omega t}$. S is independent of the polarization and in terms of S,

$$\sigma = \frac{\lambda^2}{\pi} |S|^2 . \tag{A-2}$$

In addition to the contribution (A-1), we can imagine returns coming from the edges. Each of these will show an extreme polarization sensitivity, but since the plate is square, the total return from all four edges will be independent of polarization. We can therefore choose the incident electric vector to be parallel to two of the edges and confine our attention to this case.

The usual method for 'modelling' edges is to replace them by thin wires (radius << λ). Using the formula for the scattered field arising from a cylinder of length a and radius b at normal incidence, the far field amplitude attributable to one of the edges is

$$S = \frac{ika}{\pi} \sum_{n=-\infty}^{\infty} (-1)^n \frac{J_n(kb)}{H_n^{(1)}(kb)}$$

(Mentzer, 1955) and if kb << 1,

$$S \simeq \frac{\frac{ka}{2}}{\left\{\log_e \frac{kb\gamma}{2} - i\frac{\pi}{2}\right\}} , \tag{A-3}$$

where $\gamma = 1.781072\ldots$ is the exponential of the Euler-Mascheroni constant. When substituted into (A-2), equation (A-3) leads to Chu's formula (see Van Vleck et al, 1947) for the cross section of a thin wire.

In practice, (A-3) is only valid if $a >> \lambda$, but for smaller values of a it gives a reasonable estimate of the average return over a range of frequencies. We shall therefore use it even down to $a = \lambda$. It can also be claimed that the addition of edge returns to the physical optics result is superfluous, and that the effect of the edges is already included in (A-1). A definite answer to this question is impossible owing to the uncertainty about the approximations implied by (A-1). Moreover, for a metallic plate it does not much matter whether we include (A-3) or not, since it is small compared with the physical optics result for all plates under consideration (typically 10 percent for $a=\lambda$, decreasing rapidly with increasing ka). For an absorbing plate, however, the edges may be the dominant contributor.

Let us assume that the voltage reflection coefficient of the material is R, but is R_e for the edges where $R_e > R$. Whereas for the metal plate the total far field amplitude is

$$-i\frac{(ka)^2}{2\pi}\left\{1+\frac{i\frac{\lambda}{a}}{\log_e\left(\frac{a}{\lambda}\cdot\pi\gamma\frac{b}{a}\right)-i\frac{\pi}{2}}\right\}, \qquad \text{(A-4)}$$

for the absorbing plate the corresponding value is

$$-i\frac{(ka)^2}{2\pi}R\left\{1+\frac{R_e}{R}\;\frac{i\frac{\lambda}{a}}{\log_e\left(\frac{a}{\lambda}\cdot\pi\gamma\frac{b}{a}\right)-i\frac{\pi}{2}}\right\}, \qquad \text{(A-5)}$$

and hence the ratio of the measured power reflection coefficient $|R_m|^2$ to the actual (intrinsic) power reflection coefficient $|R|^2$ is

$$\left|\frac{R_m}{R}\right|^2 = \left|\frac{\log_e\left(\frac{a}{\lambda}\cdot\pi\gamma\frac{b}{a}\right) - i\frac{\pi}{2} + \frac{R_e}{R}\, i\frac{\lambda}{a}}{\log_e\left(\frac{a}{\lambda}\cdot\pi\gamma\frac{b}{a}\right) - i\frac{\pi}{2} + i\frac{\lambda}{a}}\right|^2 . \tag{A-6}$$

If $R_e = R$, the measured and intrinsic values are, of course, equal, but the larger R_e/R is, the larger the value of a/λ necessary to obtain a reasonable estimate of R by this type of measurement.

No information is available about R_e/R but it appears probable that its magnitude will be large for good absorbers, particularly if the material is of a 'flat' construction rather than pyramidal. Since the phase is certainly unknown, there is no point in taking into account the phase difference between the body and edge contributions, and we shall therefore replace (A-6) by

$$\left|\frac{R_m}{R}\right|^2 = \frac{\left\{\log_e\left(\frac{a}{\lambda}\cdot\pi\gamma\frac{b}{a}\right)\right\}^2 + \left(\frac{\pi}{2}\right)^2 + \left|\frac{R_e}{R}\right|^2\left(\frac{\lambda}{2}\right)^2}{\left\{\log_e\left(\frac{a}{\lambda}\cdot\pi\gamma\frac{b}{a}\right)\right\}^2 + \left(\frac{\pi}{2}\right)^2 + \left(\frac{\lambda}{a}\right)^2} . \tag{A-7}$$

This is equivalent to adding the cross sections attributable to the body of the plate and the two edges, and as such is an average result. Although (A-7) indicates that $|R_m|^2/|R|^2 < 1$, values greater than unity are possible for particular phase differences between the two contributors.

In the following Figure, values of $|R_m|^2/|R|^2$ are plotted as a function of a/λ for $a/b = 900$ (an entirely arbitrary choice) and

$$\left|\frac{R_e}{R}\right|^2 = 10,\ 10^2, 10^3, 10^4 .$$

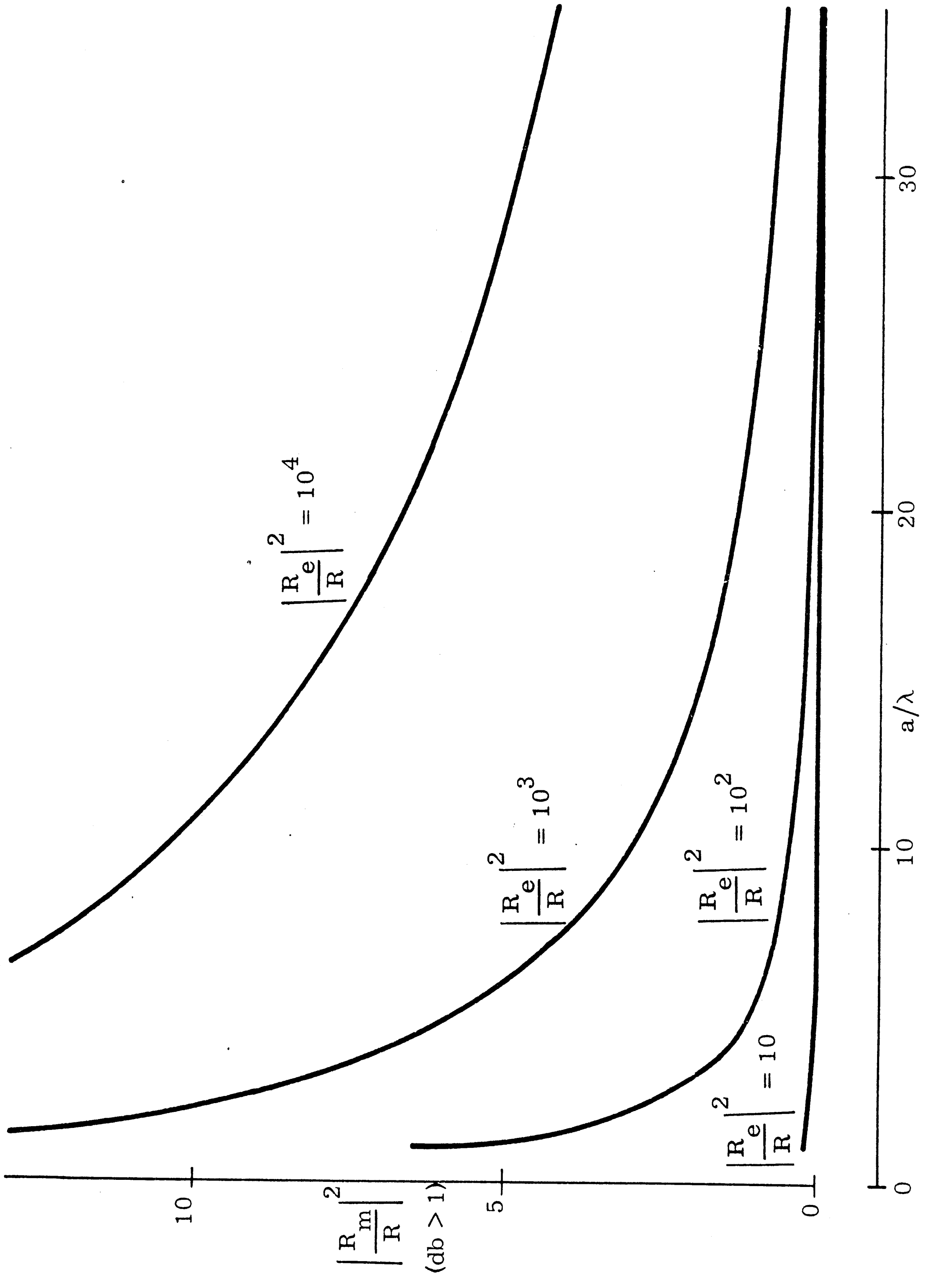

FIG. A-1: FREE SPACE MEASUREMENT ERRORS ATTRIBUTABLE TO EDGE EFFECTS

Thus, for example, the curve for the 10^2 case corresponds to any of the following situations: -20 db absorber with 0 db (i.e. metal) edges, -30 db absorber with -10 db edges, or -40 db absorber with -20 db edges. It is felt that such a value for $|R_e/R|^2$ may be typical of many absorbers, and even 10^3 possible for some. In this last case a plate 10 λ in dimension is necessary to determine the power reflection coefficient within 3 db, and bearing in mind that the curves in Fig. A-1 are average values (an in-phase addition of the two components would magnify the edge effect) it would seem desirable to substantially exceed this size of plate in any free-space measurements of a high performance absorber.

APPENDIX B

A DIFFICULTY INHERENT IN THE WAVEGUIDE MEASUREMENT OF ABSORBING MATERIALS

At VHF frequencies or lower the free space method for testing absorbing materials is inconvenient because of the large sample size which is necessary before edge effects can be ignored, and it is therefore customary to make such measurements in an enclosed system. The most widely used method of this type is the so-called waveguide method in which a sample of the material is placed in a rectangular guide and illuminated by the dominant mode. Unfortunately no waveguide mode propagates in quite the same manner as a plane wave in free space, nor does it have the same wave impedance, and consequently if the measurements are carried out in a waveguide of 'small' dimension (such that the first order modes are below cut-off) the reflection coefficient which is deduced may differ considerably from the intrinsic (or free space) reflection coefficient associated with the material.

In order to minimize this difference the measurements are usually performed in a flared-out guide. The flaring is carried out slowly so as to reduce the direct excitation of the higher order modes, and when interpreting the measured values of the VSWR it is assumed that the field incident on the material is still the dominant mode alone in spite of the increased dimensions of the guide in the region where the sample is placed. But even with a waveguide whose dimensions are several times the free space wavelength, the difference between the wave impedance and the impedance of free space may still be significant when testing very high performance materials, and the purpose of this Appendix is to get some hold on the minimum guide dimensions which are necessary for an adequate test procedure.

Consider a rectangular waveguide whose dimensions in the vicinity of the sample are a and b with $a > b$. For a TE_{mn} mode propagating in such a guide, the wave impedance is

$$Z_{mn} = Z_o \left\{ 1 - \left(\frac{k_{mn}}{k}\right)^2 \right\}^{-1/2} , \qquad \text{(B-1)}$$

where

$$k^2_{mn} = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 ,$$

$$k = \frac{2\pi}{\lambda} ,$$

λ = free space wavelength,

and

Z_o = intrinsic impedance of free space.

The complex reflection coefficient of the sample in the guide is

$$R_w = \frac{Z^{sw} - Z_{mn}}{Z^{sw} + Z_{mn}} , \qquad \text{(B-2)}$$

where Z^{sw} is the impedance of the sample when illuminated by a TE_{mn} mode. In free space, on the other hand, the reflection coefficient is ideally

$$R = \frac{Z^s - Z_o}{Z^s + Z_o} , \qquad \text{(B-3)}$$

and the question now arises as to the extent to which R_w is a valid estimate of $|R|$. Note that a measurement of the VSWR in the guide specifies the magnitude of R_w but gives no information about its phase.

Unfortunately a direct comparison of (B-2) and (B-3) is possible only under very restricted circumstances. One such case is that in which the absorber can be treated merely as a surface at which the impedance is specified. We then have

$$Z^{sw} = Z^s , \qquad \text{(B-4)}$$

and by eliminating this factor from (B-2) and (B-3)

$$R = \frac{1+R_w-(1-R_w)\quad 1-\left(\frac{k_{mn}}{k}\right)^2}{1+R_w+(1-R_w)\quad 1-\left(\frac{k_{mn}}{k}\right)^2} \quad . \qquad \text{(B-5)}$$

If $\left(\frac{k_{mn}}{k}\right)^2$ is so small that the difference between Z_{mn} and Z_o can be neglected, equation (B-5) gives

$$R = R_w$$

(as is otherwise obvious from B-2 and B-3). The two measurement procedures are therefore equivalent for a waveguide of sufficiently large dimensions. If Z_{mn} and Z_o are sensibly different, however,

$$\frac{R}{R_w} \simeq \frac{4Z_o Z_{mn}}{(Z_o+Z_{mn})^2} + \frac{Z_{mn}-Z_o}{Z_{mn}+Z_o}\,\frac{1}{R_w} \quad , \qquad \text{(B-6)}$$

and for given Z_{mn} and Z_o the maximum and minimum values of $\left|\frac{R}{R_w}\right|$ are obtained by replacing R_w by $\pm\,|R_w|$, respectively. Since the first term on the right hand side of (B-6) is not greater than unity (and can only equal unity if $Z_{mn}=Z_o$), the minimum value of $\left|\frac{R}{R_w}\right|$ is always less than unity, whereas the maximum value is less than or greater than unity as

$$R_w \gtrless \frac{Z_{mn}-Z_o}{Z_{mn}+Z_o} \quad . \qquad \text{(B-7)}$$

Hence, if $|R_w| > \frac{Z_{mn}-Z_o}{Z_{mn}+Z_o}$ the free space reflection coefficient must be less than the reflection coefficient measured in the guide. To interpret $|R_w|$ as $|R_o|$ will therefore underestimate the free space absorbing capabilities, and the waveguide method will then represent a valid testing procedure. But if

$$|R_w| < \frac{Z_{mn} - Z_o}{Z_{mn} + Z_o} ,$$

the reflection coefficient in free space may either be greater or less than the value measured in the guide depending on the (unknown) phase of R_w. The waveguide method now provides a valid test only if the departure of $|R_w|$ from $|R_o|$ lies within acceptable limits.

To obtain some actual values for the maximum differences between $|R_w|$ and $|R_o|$ as a function of the size of the guide it is convenient to return to the 'exact' equation (B-5). For a given $|R_w|$, the maximum and minimum $|R|$ can be found by replacing R_w by $|R_w|$ and $-|R_w|$ respectively. Let us also restrict our attention to the dominant (TE_{10}) mode, in which case $k_{mn} = k_{10}$ with

$$\frac{k_{10}}{k} = \frac{\lambda}{2a} .$$

In Figs. B-1 through B-4, these extreme values of R are plotted as functions of a/λ for 20, 30, 35 and 40 db absorbers as judged by the waveguide reflection coefficient. Because of the smallness of the chosen $|R_w|$, the free space reflection coefficient can be either greater or less than $|R_w|$ in all cases, but it should be emphasized again that these curves represent the maximum possible departure of $|R|$ from $|R_w|$. If the actual phase of R_w were known, the true $|R|$ would be found to lie somewhere between these extremes.

The above discussion has been based on a very idealized absorber which can be replaced by an impedance sheet at whose surface $Z_{sw} = Z_s$. With any real absorber Z_{sw} and Z_s will almost certainly differ, but a simple derivation of the relationship between them is possible only for a homogeneous isotropic material

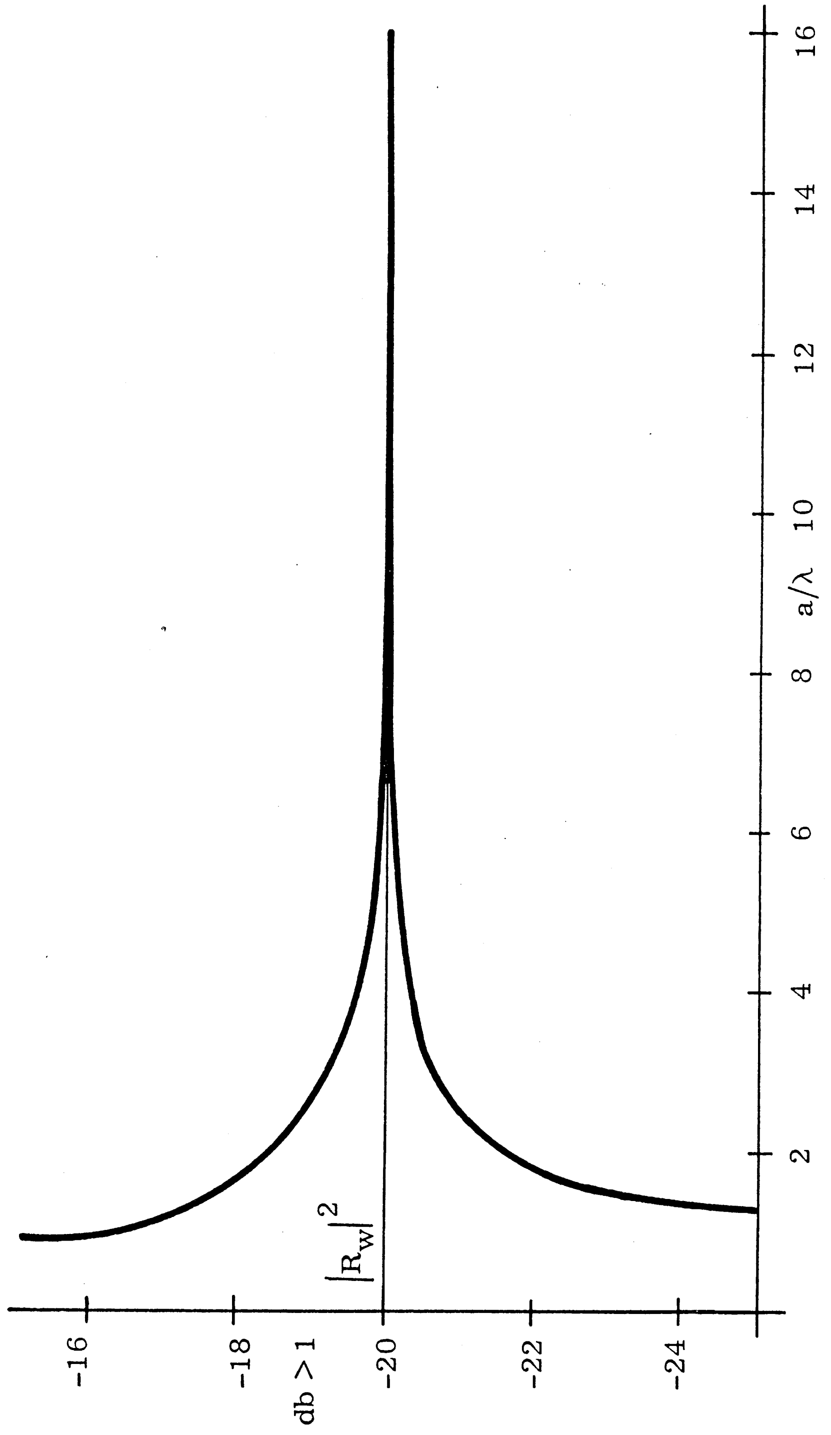

FIG. B-1: LIMITING VALUES OF $|R|^2$ FOR $|R_w|^2 = 10^{-2}$

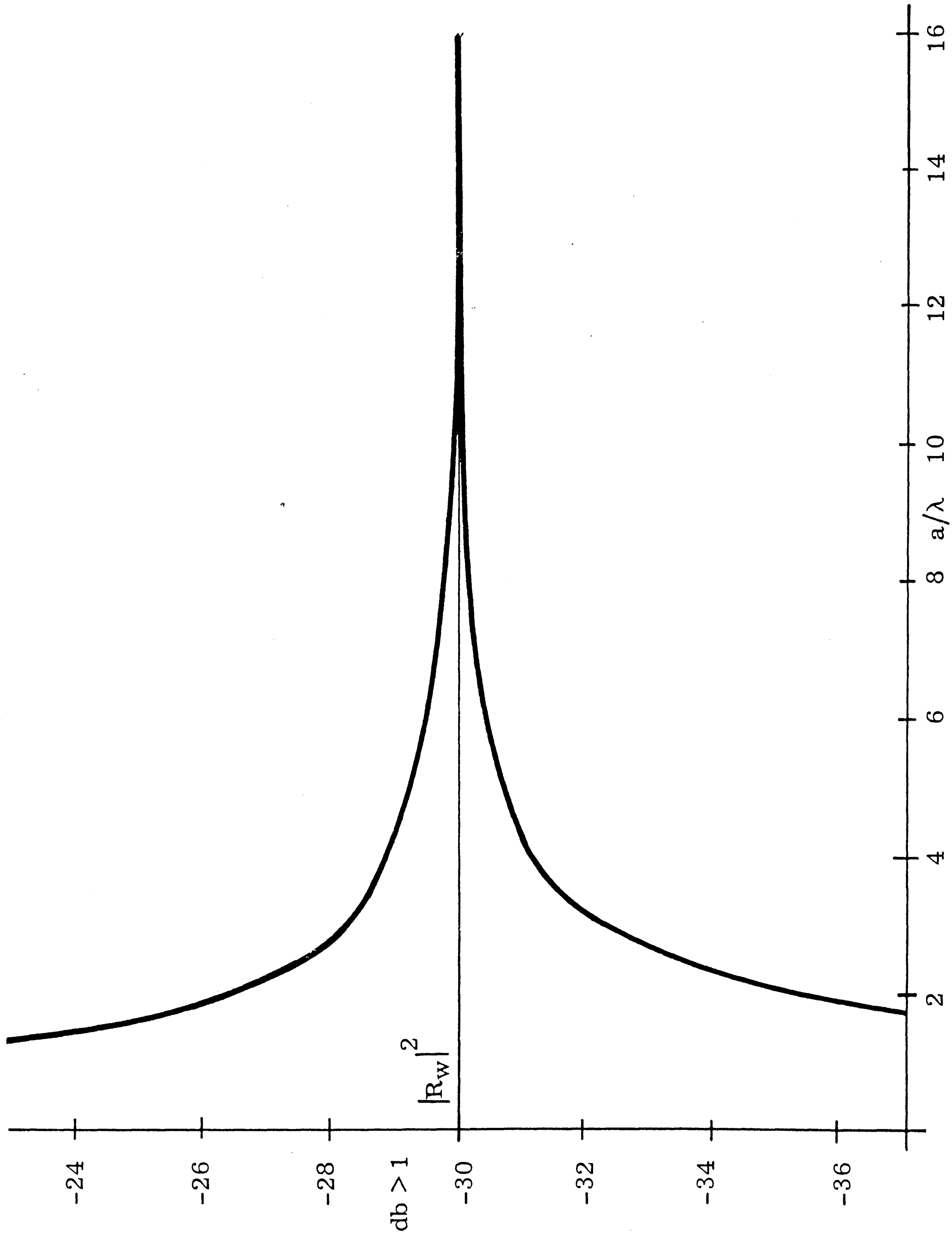

FIG. B-2: LIMITING VALUES OF $|R|^2$ FOR $|R_W|^2 = 10^{-3}$

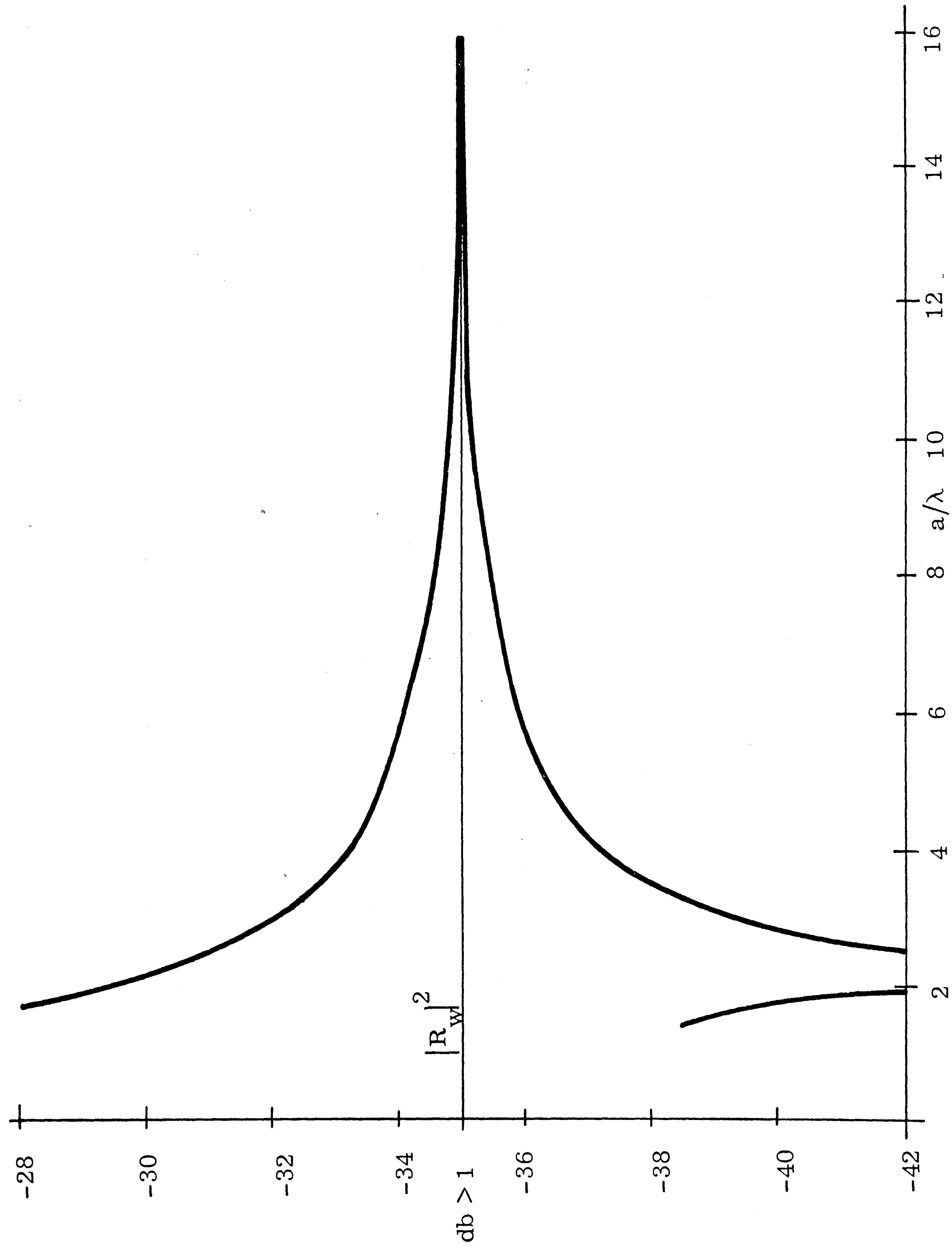

FIG. B-3: LIMITING VALUES OF $|R|^2$ FOR $|R_w|^2 = 10^{-3.5}$

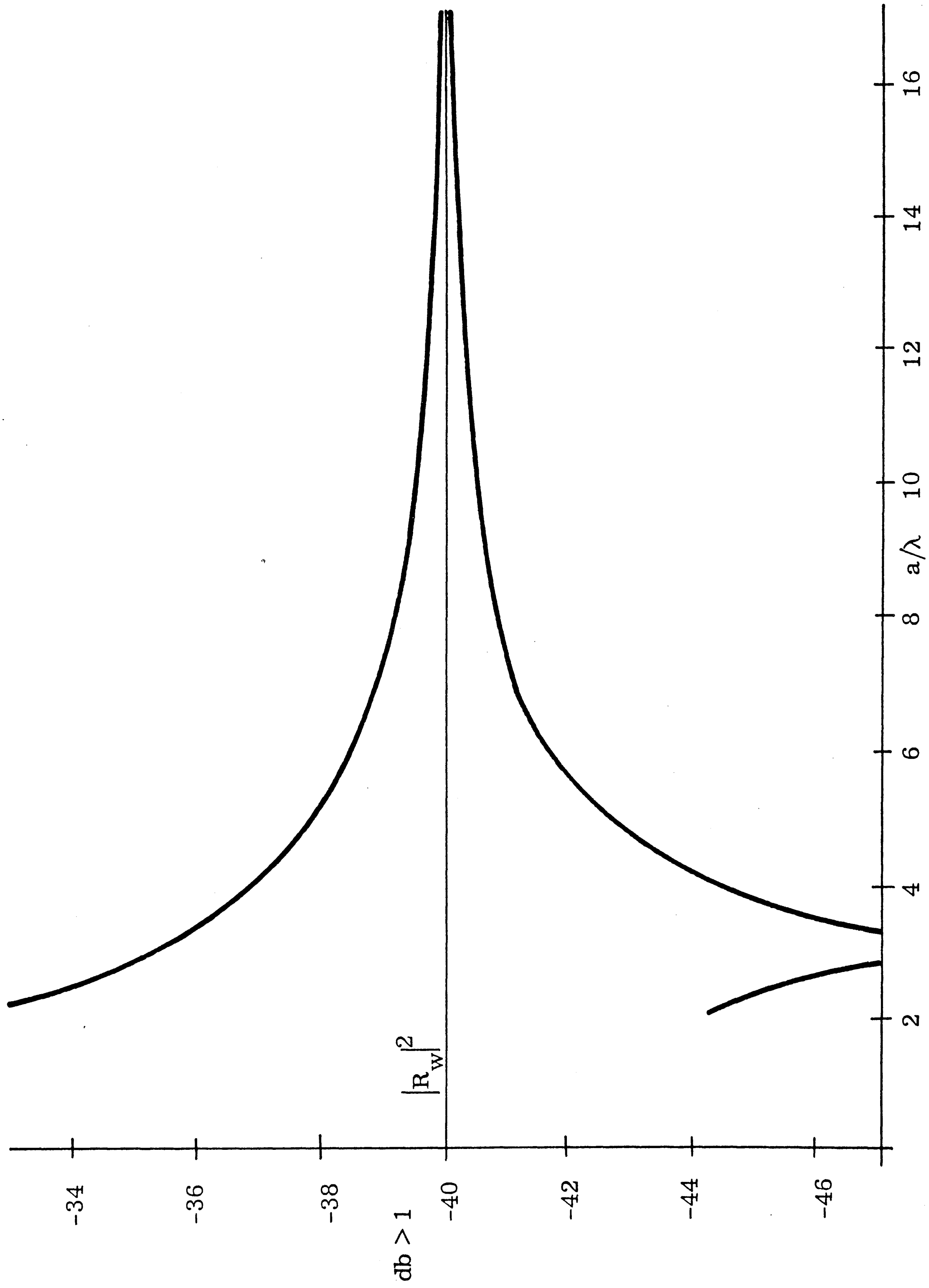

FIG. B-4: LIMITING VALUES OF $|R|^2$ FOR $|R_w|^2 = 10^{-4}$

whose thickness is large compared with the skin depth. In this case

$$Z_{sw} = Z_s \left\{ 1 - \left(\frac{k_{mn}}{k}\right)^2 \frac{\epsilon_o \mu_o}{\epsilon \mu} \right\}^{-1/2} \tag{B-8}$$

where ϵ and μ are the (complex) permittivity and permeability respectively of the material, and the suffix 'o' denotes the same quantities for free space. The equation analogous to (B-5) is then

$$R = \frac{(1+R_w)\sqrt{1-\left(\frac{k_{mn}}{k}\right)^2 \frac{\epsilon_o \mu_o}{\epsilon \mu}} - (1-R_w)\sqrt{1-\left(\frac{k_{mn}}{k}\right)^2}}{(1+R_w)\sqrt{1-\left(\frac{k_{mn}}{k}\right)^2 \frac{\epsilon_o \mu_o}{\epsilon \mu}} + (1-R_w)\sqrt{1-\left(\frac{k_{mn}}{k}\right)^2}} , \tag{B-9}$$

and under most circumstances of practical interest this can be approximated by an equation which differs from (B-6) merely by having Z_{mn} replaced by $Z_{mn} Z_s / Z_{sw}$. Unfortunately a complex R_w implies a complex Z_{sw} and it is not immediately obvious that the maximum and minimum values of $|R| / |R_w|$ can be obtained by giving R_w the values $\pm|R_w|$ respectively, but if this is indeed so, the criterion corresponding to (B-7) is

$$|R_w| \gtrless \left| \frac{Z_{mn} Z_s - Z_o Z_{sw}}{Z_{mn} Z_s + Z_o Z_{sw}} \right| . \tag{B-10}$$

Since $|Z_{sw}| > |Z_s|$, the upper sign is appropriate for a wider varity of materials than was the case with (B-7), and consequently $|R_w|$ will exceed $|R|$ in more circumstances than originally.

As with the thin sheet absorber previously discussed, a knowledge of the phase of R_w would permit a unique determination of $|R|$, and equally, of course, if we were to know the materials constant ϵ and μ for the absorber in advance, the ambiguity is again removed. But if only $|R_w|$ can be measured there is a range of possible $|R|$ consonant with this and if we are to rely on the waveguide method for a testing procedure it would appear desirable that the guide dimensions be chosen so that all of the $|R|$ which can correspond to the $|R_w|$ differ by no more than is acceptable.

One more word of caution is necessary however. The above treatment has been based on two very idealized types of absorbers. For a practical material which will almost certainly not be homogeneous, and will vary in both the transverse and longitudinal directions, there is no general method for determining the relationship between Z_s and Z_{sw}, and it is quite feasible that the maximum discrepancy between $|R|$ and $|R_w|$ will differ from the values obtained in the simple cases we have treated. The discrepancy may well be less (as equation B-10 would indicate), but also could be more. Nevertheless, if we are to specify an adequate testing procedure, it would appear essential to base the specification on those cases for which a theoretical treatment is possible. Referring, therefore, to Figs. B-1 through B-4 and regarding $|R_w|$ directly as an estimate of $|R|$, the estimate will never be more than 3 db too large for all materials of up to 40 db performance (Fig. B-4) if $a/\lambda > 4$. If the best absorber to be tested has only a 35 db performance, it is sufficient that $a/\lambda > 3$, but note that for all relatively good absorbers an unflared guide $(a/\lambda < 1)$ would be highly undesirable.

APPENDIX C

A METHOD OF DETERMINING SMALL RADAR CROSS SECTIONS IN THE PRESENCE OF ROOM REFLECTIONS

If, on the grounds of prohibitive cost, lack of time, or other reasons, satisfactory microwave anechoic chamber performance cannot be achieved, it becomes necessary to devise a scheme by which to separate small model cross sections from background effects. It is the purpose of this appendix to present such a scheme.

The method makes extensive use of model "rocking", which is the process of moving the model (and its support pedestal) longitudinally within the chamber a small distance, usually a wavelength or so. During the rocking motion, the received power attains maximum and minimum values due to phase changes of the target signal with respect to the stationary background. The ratio of these values is called "the rock" and is usually recorded in db. The background level can be thought to arise from two sources, the chamber walls and the pedestal. Although the background is balanced out in the conventional CW system, model shadowing alters the room illumination; hence the background which was balanced out in the absence of the model is not the same as that which prevails when the model is in the test position. The model cross section which one records under this condition is perturbed (or sometimes even masked) by background effects and may not be the true cross section one desires.

Separation of the model cross section from the pedestal return is accomplished by the adjustment of the relative phase between these two components. Phase adjustment is effected by merely mounting the model in different positions on the styrofoam pedestal. If the positions are separated by small enough intervals, at least one position will correspond to a phase angle of zero and one will correspond to a phase angle of π. Separation of the combined model-pedestal cross section from the background is possible if the model and pedestal are rocked together for each model position.

The balanced room and pedestal condition is depicted in Fig. C-1(a); σ'_r is the effective room cross section, σ_p is the effective pedestal cross section, and σ_{c_1}, σ_{c_2} are balancing signals which are adjusted by means of tuners and attenuators in the microwave system. Fig. C-1(b) shows what happens when the model is mounted on the pedestal: the model cross section σ_m is added and the shadowing effect changes the pahse and amplitude of $\sqrt{\sigma'_r}$. In Fig. C-1(c), the three signals $\sqrt{\sigma'_r}$, $\sqrt{\sigma_{c_1}}$ and $\sqrt{\sigma_{c_2}}$ have been combined and replaced with the resultant signal $\sqrt{\sigma_r}$. The cross section which is displayed on the recorder is the square of the magnitude of the sum of the signals of Fig. C-1(c) and is

$$\sigma = \left[\sqrt{\sigma_r} + \sqrt{\sigma_p}\cos\phi + \sqrt{\sigma_m}\cos(\phi+\theta)\right]^2 + \left[\sqrt{\sigma_p}\sin\phi + \sqrt{\sigma_m}\sin(\phi+\theta)\right]^2 .$$

This value is usually calibrated with a standard scatterer whose cross section is large enough that the effects of pedestal and background are negligible.

When the angle θ is zero,

$$\sigma = \sigma_r + (\sqrt{\sigma_p} + \sqrt{\sigma_m})^2 + 2\sqrt{\sigma_r}(\sqrt{\sigma_p} + \sqrt{\sigma_m})\cos\phi .$$

As the model and pedestal are rocked, ϕ changes, causing σ to reach maximum and minimum values σ_1 and σ_3, respectively:

$$\sigma_1 = (\sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m})^2 , \qquad \text{(C-1)}$$

$$\sigma_3 = (\sqrt{\sigma_r} - \sqrt{\sigma_p} - \sqrt{\sigma_m})^2 . \qquad \text{(C-2)}$$

When $\theta = \pi$, the recorded cross section is

$$\sigma = \sigma_r + (\sqrt{\sigma_p} - \sqrt{\sigma_m})^2 + 2\sqrt{\sigma_r}(\sqrt{\sigma_p} - \sqrt{\sigma_m})\cos\phi.$$

For this condition, the maximum and minimum values of σ are σ_2 and σ_4, respectively:

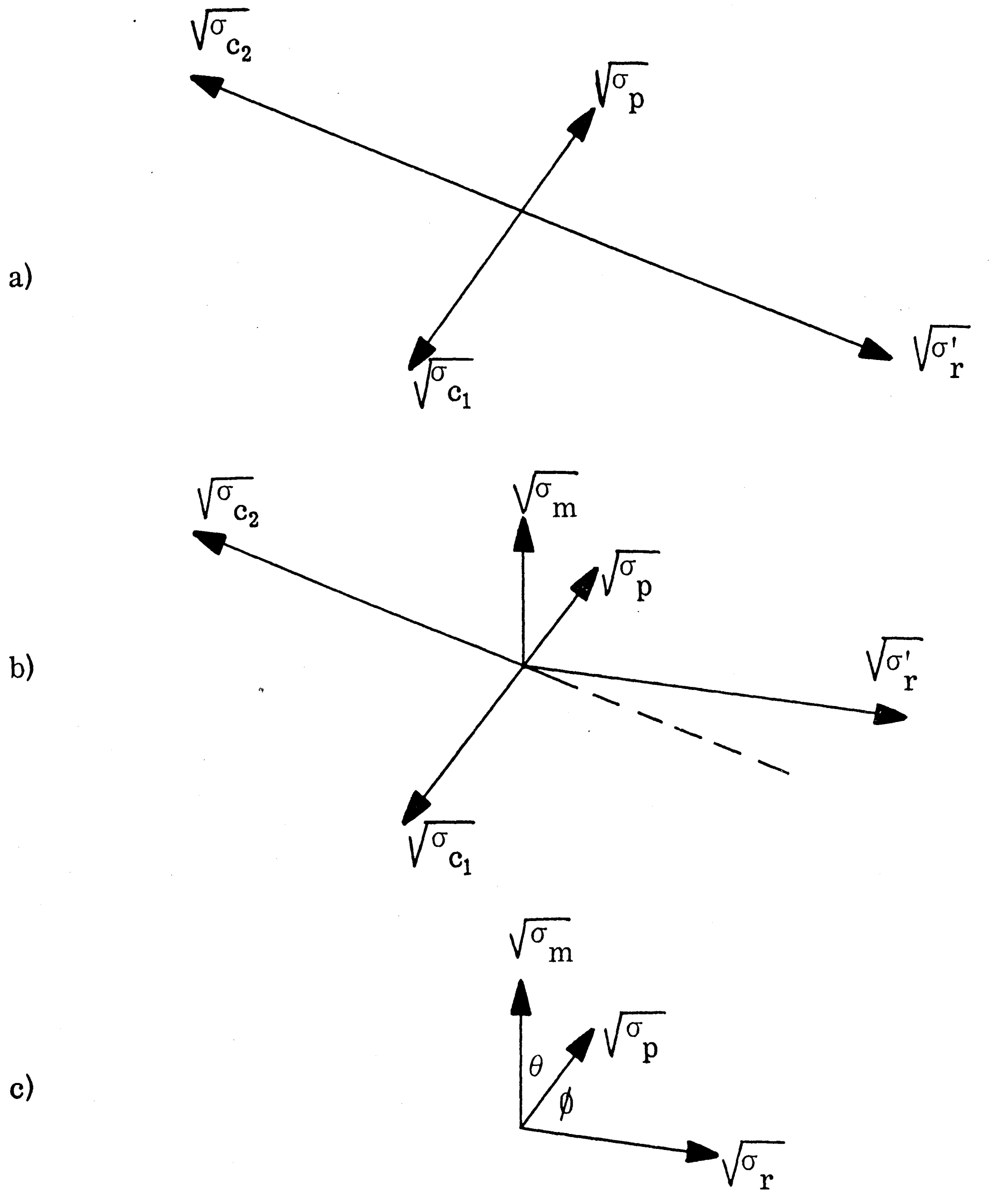

FIG. C-1: a) THE BALANCED ROOM AND PEDESTAL,
b) THE EFFECT OF SHADOWING BY THE MODEL
c) COMBINING $\sqrt{\sigma_{c_1}}$, $\sqrt{\sigma_{c_2}}$ AND $\sqrt{\sigma'_r}$ INTO ONE SIGNAL, $\sqrt{\sigma_r}$.

$$\sigma_2 = \begin{cases} \left[\sqrt{\sigma_r} + (\sqrt{\sigma_p} - \sqrt{\sigma_m})\right]^2, & \sqrt{\sigma_p} > \sqrt{\sigma_m} \\ \left[\sqrt{\sigma_r} - (\sqrt{\sigma_p} - \sqrt{\sigma_m})\right]^2, & \sqrt{\sigma_p} < \sqrt{\sigma_m} \end{cases} \qquad \text{(C-3)}$$

$$\sigma_4 = \begin{cases} \left[\sqrt{\sigma_r} - (\sqrt{\sigma_p} - \sqrt{\sigma_m})\right]^2, & \sqrt{\sigma_p} > \sqrt{\sigma_m} \\ \left[\sqrt{\sigma_r} + (\sqrt{\sigma_p} - \sqrt{\sigma_m})\right]^2, & \sqrt{\sigma_p} < \sqrt{\sigma_m} \end{cases} \qquad \text{(C-4)}$$

The quantities σ_1, σ_2, σ_3 and σ_4 are all measurable; that is, they are read from the recorder output.

The analysis is more easily carried out if the roots of equations (C-1) through (C-4) are extracted; observe that this operation is accompanied by plus and minus sign options which must be considered. Upon the extraction of roots, one obtains four linear equations in terms of three unknowns $\sqrt{\sigma_r}$, $\sqrt{\sigma_p}$ and $\sqrt{\sigma_m}$, in which the coefficient of each term depends upon the relative magnitude of each unknown. The redundancy is needed to help identify the signs of the coefficients because it is not known at the outset which of the unknowns is largest or smallest. The possible relative values of $\sqrt{\sigma_r}$, $\sqrt{\sigma_p}$, and $\sqrt{\sigma_m}$ fall into six cases and equations (C-1) through (C-4) are slightly different for each case. The cases are.

case a: $\sqrt{\sigma_r} < \left|\sqrt{\sigma_m} - \sqrt{\sigma_p}\right|$, $\quad \sqrt{\sigma_p} > \sqrt{\sigma_m}$

case b: $\sqrt{\sigma_r} < \left|\sqrt{\sigma_m} - \sqrt{\sigma_p}\right|$, $\quad \sqrt{\sigma_p} < \sqrt{\sigma_m}$

case c: $\sqrt{\sigma_r} > \left(\sqrt{\sigma_m} + \sqrt{\sigma_p}\right)$, $\quad \sqrt{\sigma_p} > \sqrt{\sigma_m}$

case d: $\sqrt{\sigma_r} > \left(\sqrt{\sigma_m} + \sqrt{\sigma_p}\right)$, $\quad \sqrt{\sigma_p} < \sqrt{\sigma_m}$

$$\text{case e:}\quad \left|\sqrt{\sigma_m} - \sqrt{\sigma_p}\right| < \sqrt{\sigma_r} < \left(\sqrt{\sigma_m} + \sqrt{\sigma_p}\right), \qquad \sqrt{\sigma_p} > \sqrt{\sigma_m}$$

$$\text{case f:}\quad \left|\sqrt{\sigma_m} - \sqrt{\sigma_p}\right| < \sqrt{\sigma_r} < \left(\sqrt{\sigma_m} + \sqrt{\sigma_p}\right), \qquad \sqrt{\sigma_p} < \sqrt{\sigma_m}$$

The six sets of equations are

$$\left.\begin{aligned} \sqrt{\sigma_1} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_2} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} - \sqrt{\sigma_m} \\ \sqrt{\sigma_3} &= -\sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_4} &= -\sqrt{\sigma_r} + \sqrt{\sigma_p} - \sqrt{\sigma_m} \end{aligned}\right. \quad \text{case a} \qquad \left.\begin{aligned} \sqrt{\sigma_1} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_2} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_3} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} - \sqrt{\sigma_m} \\ \sqrt{\sigma_4} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} - \sqrt{\sigma_m} \end{aligned}\right. \quad \text{case d}$$

$$\left.\begin{aligned} \sqrt{\sigma_1} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_2} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_3} &= -\sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_4} &= -\sqrt{\sigma_r} - \sqrt{\sigma_p} + \sqrt{\sigma_m} \end{aligned}\right. \quad \text{case b} \qquad \left.\begin{aligned} \sqrt{\sigma_1} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_2} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} - \sqrt{\sigma_m} \\ \sqrt{\sigma_3} &= -\sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_4} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} + \sqrt{\sigma_m} \end{aligned}\right. \quad \text{case e}$$

$$\left.\begin{aligned} \sqrt{\sigma_1} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_2} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} - \sqrt{\sigma_m} \\ \sqrt{\sigma_3} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} - \sqrt{\sigma_m} \\ \sqrt{\sigma_4} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} + \sqrt{\sigma_m} \end{aligned}\right. \quad \text{case c} \qquad \left.\begin{aligned} \sqrt{\sigma_1} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_2} &= \sqrt{\sigma_r} - \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_3} &= -\sqrt{\sigma_r} + \sqrt{\sigma_p} + \sqrt{\sigma_m} \\ \sqrt{\sigma_4} &= \sqrt{\sigma_r} + \sqrt{\sigma_p} - \sqrt{\sigma_m} \end{aligned}\right. \quad \text{case f}$$

The solutions of the six sets of equations can be arranged as in Table C-1 Note that, because of the redundancy, each unknown may be expressed in terms of one pair of the measured quantities while a check of this value is given in terms of

TABLE C-1: SOLUTIONS FOR THE SIX CASES

case	σ_r	σ_p	σ_m
a	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_2})$
	$\frac{1}{2}(\sqrt{\sigma_2} - \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_1} + \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_3} - \sqrt{\sigma_4})$
b	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_2})$	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_3})$
	$\frac{1}{2}(\sqrt{\sigma_2} - \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_3} - \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_1} + \sqrt{\sigma_4})$
c	$\frac{1}{2}(\sqrt{\sigma_1} + \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_2} - \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_2})$
	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_4} - \sqrt{\sigma_3})$
d	$\frac{1}{2}(\sqrt{\sigma_1} + \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_2})$	$\frac{1}{2}(\sqrt{\sigma_2} - \sqrt{\sigma_3})$
	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_4} - \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_4})$
e	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_2})$
	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_3} + \sqrt{\sigma_4})$
f	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_3})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_2})$	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_3})$
	$\frac{1}{2}(\sqrt{\sigma_2} + \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_3} + \sqrt{\sigma_4})$	$\frac{1}{2}(\sqrt{\sigma_1} - \sqrt{\sigma_4})$

the other pair. When all the numbers in Table C-1 are computed, the correct case must be selected. The solutions for $\sqrt{\sigma_r}$ are inspected and it will be found that four cases may be eliminated immediately, since the alternate solutions within a given case will agree in only one pair of cases. In selecting which of the remaining pair is correct, several runs, each for a different frequency, are compared. For most models, one expects $\sqrt{\sigma_m}$ to change with frequency while $\sqrt{\sigma_p}$ should be frequency insensitive; the comparison of runs quickly indicates the proper case. Observe that the final case selected will yield two values for σ_m; the agreement between these values gives one a measure of the worth of the data.

Two checks are available to verify the selection of the proper case. Firstly, the empty pedestal may be rocked, yielding a value for $\sqrt{\sigma_p}$ which may be compared with that given by the two solutions of the selected case. Secondly, the experiment may be repeated for a different antenna-model range. This operation should change the room contribution $\sqrt{\sigma_r}$, but $\sqrt{\sigma_p}$ and $\sqrt{\sigma_m}$ should not change.

In conclusion, it should be pointed out that the method is applicable for only discrete azimuths of model orientation. Some shapes, such as the sphere and cylinder, are relatively easy to work with, while others, such as the cone, may require extensive effort to produce the necessary model-to-pedestal phase variation. Complex shapes may or may not present problems, depending upon their shapes and the orientation desired. The most attractive feature of the method is that small cross sections may be measured in the presence of interfering scattered signals which are of the same order of magnitude. Another advantage is that one has a measure of the room and pedestal contributions as well. In terms of square meters, model radar cross sections as low as 3.1×10^{-6} have been separated from a room contribution of 1.5×10^{-6} and a pedestal return of 1.7×10^{-6}. These values were obtained at X-band for a working range of 44 in. in the Radiation Laboratory anechoic room. It should be noted that the σ_r obtained by this method is not the equivalent room cross section obtained by Buckley's technique (see Section 3.1.2). The smaller σ_r obtained by the present method is that caused by room unbalance due to model shadowing.

A disadvantage of this method is that a relatively large amount of labor must be invested in recording the data and performing the calculations.

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