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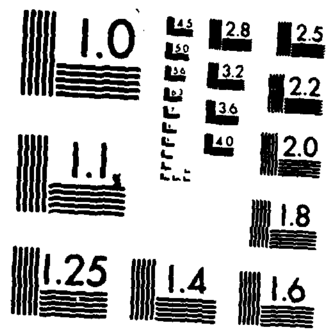

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RADC-TR-83-181
In-House Report
August 1983

SCATTERING EXPERIMENTS AT THE IPSWICH ELECTROMAGNETIC MEASUREMENTS FACILITY: CALIBRATION WITH PERFECTLY CONDUCTING SPHERES

Robert V. McGahan

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
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A new electromagnetic scattering facility located at Ipswich, Massachusetts is described. A 20 × 20 × 40 ft anechoic chamber was evaluated as to wall reflection coefficient at 10, 35, 98, and 140 GHz. The frequency stability of the measurement equipment was evaluated and was determined not to be a limiting factor in making radar cross section measurements. The backscatter radar cross sections of 24 metal spheres were measured at 10 GHz and compared with theory. The spheres ranged in size from 0.218 to 8.00 inches in diameter, corresponding to a ka range of 0.581 to 21.293. The measured

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radar cross sections differed from theory by less than 0.6 dB. Radar cross sections as low as -46 dBsm were measured. The calibrated facility will be used to measure canonical shapes for both metallic and non-metallic targets. The non-metallic results will be used for the Cruise Missile Surveillance Program.

Preface

The author would like to recognize the contributions of Mr. David Gaunt. Mr. Gaunt performed most of the measurements described herein and was instrumental in the construction of the monostatic radar cross section measurement system.

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Illustrations

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Scattering Experiments at the Ipswich Electromagnetic Measurements Facility: Calibration With Perfectly Conducting Spheres

1. INTRODUCTION

The Rome Air Development Center maintains a level of technical leadership that will provide superior C^3I capabilities for the U.S. Air Force. A number of internal centers of expertise were established, in selected areas, to strengthen RADC's technology base. One of these areas is that of scattering from terrain and targets.

A scattering effort had been maintained at the Ipswich, Massachusetts Electromagnetic Measurements Facility since about 1950, when scientists from the Cambridge Research Station, under Dr. Roy Spencer, began radar cross sections (RCS) measurements on metallic canonical shapes. This program progressed to measurements on birds for the DEW line radar and ultimately encompassed scale model measurements on the Mercury Space capsule and Atlas and Titan missiles. With the retirement and reassignment of key personnel the scattering effort was steadily de-emphasized until, in 1979, the outdoor ground plane was dismantled and the measurement system was disassembled.

At this time a new building was approved for the Ipswich site, under the Military Construction Program. A scattering chamber was specified and designed into the

(Received for publication 15 August 1983)

final building plans.[1] The building was started in 1979 an[illegible] in mid-1981. By October 1981 the absorber was installed in the chamber and construction of an X-band monostatic measurement system begun.

RADC/EEC is engaged in a bistatic RCS measurements program encompassing metallic and non-metallic targets. Initially, simple canonical shapes made of absorbing material will be measured. The results of the measurements on canonical shapes are expected to benefit the Cruise Missile Surveillance Program directly, since these targets can be closely simulated with a combination of canonical shapes.

The present work describes the new scattering chamber at Ipswich. The chamber was evaluated at 10, 35, 98 and 140 GHz and the frequency stability of the measuring equipment was evaluated as to its possible effect on measurement accuracy. A monostatic system for measuring radar cross sections at X-band, using the CW cancellation method, is described. Results of measurements on a series of metal spheres are compared to theoretical values computed using an exact solution of the Mie summation.[2]

The radar cross section σ is a measure of the scattering properties of a body and is defined as

$$\sigma = \lim_{R \to \infty} 4\pi R^2 \left| H_s / H_i \right|^2 \tag{1}$$

or

$$\sigma = \lim_{R \to \infty} 4\pi R^2 \left| E_s / E_i \right|^2 \tag{2}$$

where R is the distance from the observation point to the body, $|H_i|$ and $|H_s|$ are the magnitudes of the incident and scattered magnetic fields, and $|E_i|$ and $|E_s|$ are the magnitudes of the incident and scattered electric fields.[3] The cross section σ as defined in Eqs. (1) and (2) has units of length squared but is often normalized to either the projected area of the body or to wavelength squared. Radar cross sections are also commonly expressed in decibels relative to a square meter, $\sigma[\text{dBsm}] = 10 \log_{10}(\sigma_0)$, where σ_0 is in square meters.

In this report radar cross sections are normalized to the projected area ($A = \pi a^2$, where a = radius of sphere) unless otherwise noted. A convenient parameter

1. Mack, R. B. (1981) Basic Design Principles of Electromagnetic Scattering Measurement Facilities, RADC-TR-81-40, AD A103943.

2. Hancock, J. H., and Livingston, P. M. (1974) Program For Calculating Mie Scattering For Spheres, Using Kerker's Formulation, Over a Specified Particle Size Distribution, NRL Report 7808.

3. Methods of Radar Cross Section Analysis (1968) Crispin, J., and Siegel, K., Eds., Academic Press, New York, p 5.

against which to plot RCS is ka, where $k = 2\pi/\lambda$, the propagation constant for the frequency of operation. The quantity ka is a measure of the number of wavelengths in the circumference of a particular sphere.

2. DESCRIPTION OF FACILITIES

The Electromagnetic Measurements Facility is located on 60 acres at Great Neck in Ipswich, Massachusetts. The RCS measurements chamber is located in the main building, a 6270 square foot structure, completed in 1981. The main building and the measurements chamber are shown in Figures 1 and 2.

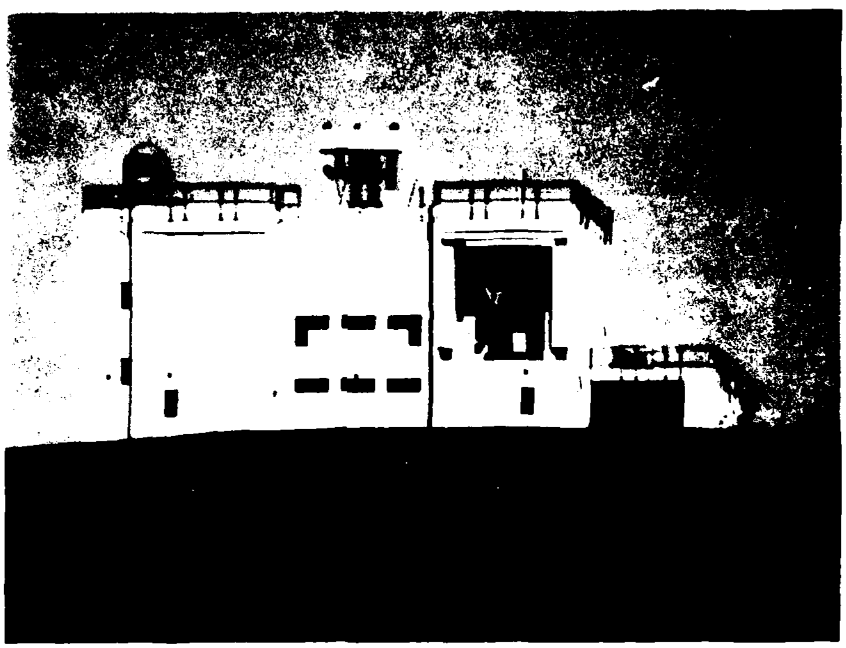

Figure 1. The Ipswich Electromagnetic Measurement Facility

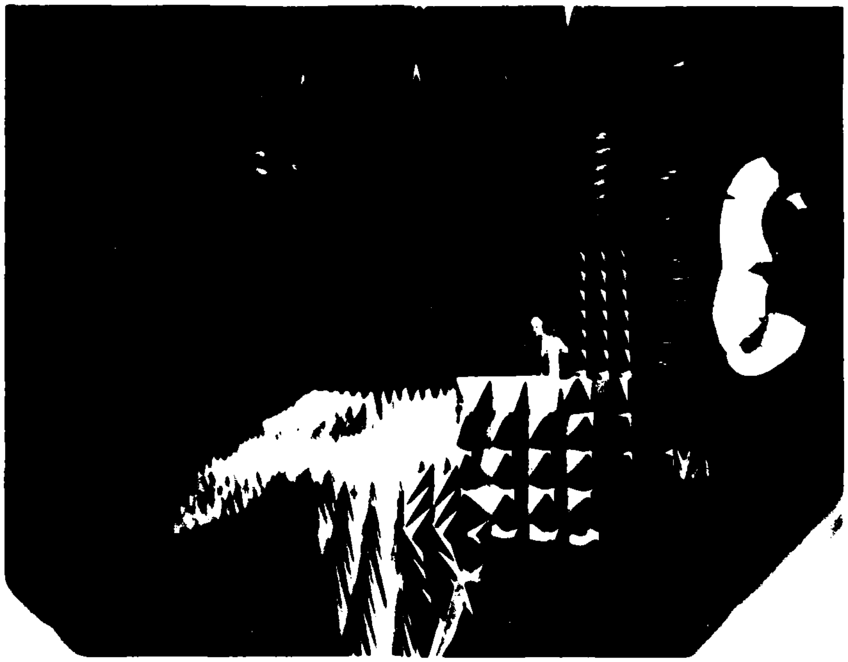

Figure 2. The Radar Cross Section Measurement Chamber at the Ipswich Electromagnetic Measurement Facility

The chamber is 38 ft long, 18 ft wide, and 20 ft high. Pyramidal absorber on the walls, floor, and ceiling reduces the usable dimensions to 34 ft × 14 ft × 16 ft, respectively. One end of the chamber is a wooden partition constructed of 2-in. × 6 in. studs and 3/4 in. plywood. This partition contains nine ports, with removable plugs, that allow various antenna/target configurations to be installed. Access to the chamber is through one of two sets of double doors located along the side wall of the chamber. These doors are also covered with absorber.

The absorber used in the chamber is AAP-24, a 24-in. thick pyramidal absorber, except for a section on the wall opposite the antenna ports. This section is 100 ft square and is covered with AAP-36, a 36-in. absorber. The magnitude of the reflection coefficient for these absorbers is specified by the manufacturer to be -40 dB at normal incidence.[4]

A series of measurements were made on the chamber walls at 35, 98, and 140 GHz. These measurements were made using a scatterometer constructed by

4. Product Information Guide (1979) Advanced Absorber Products, Amesbury, MA.

RADC/EEP for use in a project involving measurements of millimeter wave propagation over snow.[5] A Gunn oscillator at 35.1 GHz, and klystron oscillators at 96.1 and 140.1 GHz provide RF power. A single superheterodyne receiver, which uses a Gunn diode as the local oscillator, is used for all three frequencies. The transmitted signal is modulated by a 1 kHz squarewave. The modulation is detected in the receiver and fed to the Y axis of an XY recorder. The entire scatterometer can be rotated, by means of an electric motor, about a vertical axis. The rotation is sensed by a potentiometer and the resulting voltage is applied to the X axis of the recorder.

The scatterometer was placed in the center of the chamber, after removal of part of the floor absorber, with the antennas aimed horizontally at one of the long (side) walls. A flat metal plate was placed at the wall, at the same height as the transmitting and receiving antennas. Figure 3 shows this arrangement. The return signal level from the plate was defined to be 0 dB and the pen of the XY recorder positioned at the top of the chart paper. The paper was calibrated by switching in increasing values of attenuation with a coaxial step attenuator. The step sizes are not uniform due to a non-linear AGC amplifier in the receiver.

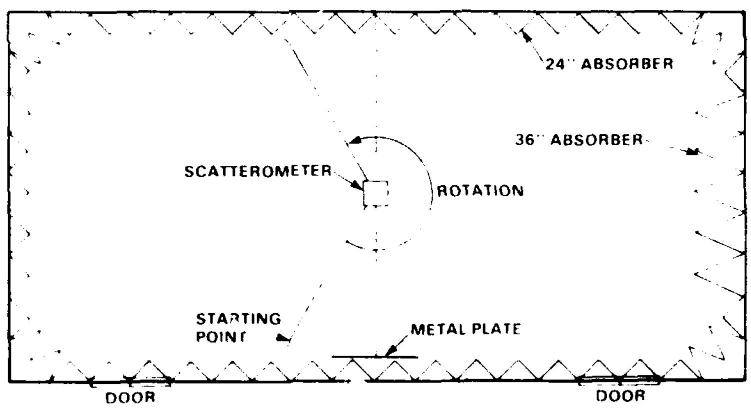

Figure 3. Experimental Arrangement for the RCS Measurements Chamber Absorber Evaluation

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5. Lammers, U.H.W., and Hayes, D.T. (1980) Multipath Propagation Over Snow at Millimeter Wavelengths, RADC-TR-89-54, AD A087747.

To measure absorber reflectivity at a given frequency, the scatterometer was set up as described above and the recorder paper calibrated. The scatterometer was rotated clockwise until the antennas pointed off the calibration plate and at the absorber-covered wall. The scatterometer was then rotated counterclockwise approximately 270°, moving the antenna beams in turn across the calibration plate, along the long wall (past one set of double doors), across the back wall (traversing the 36-in. absorber), and along the other long wall, passing through the point directly opposite the calibration plate.

Since the calibration plate was placed at the wall, and the scatterometer was in the center of the chamber, this procedure allowed direct comparison of the calibration plate to absorber-covered wall at the same distance, without having to move the plate. Measurements were taken with the doors open and closed. The above described procedure provided a measurement of the 36-in. absorber at normal incidence, although at a different range than the 24-in. absorber. Additional attenuation was inserted while the scatterometer was pointed in the vicinity of the metal plate, to allow the peak of the return signal to be plotted, and was removed as the antenna beams moved away from the plate. Figures 4 through 6 show the results of these measurements at the three frequencies. It can be seen from these plots that the backscatter from the absorber is at least 40 dB below the incident energy level at these three frequencies, as claimed by the manufacturer. This was true for normal incidence as well as grazing angles up to 68° from normal. The slightly higher return at 98 GHz is believed due to a resonance effect caused by the paint used to coat the absorber. The energy levels returned from the absorber are low enough in any case that they will not prohibit RCS measurements at these frequencies.

A monostatic scattering measurement system was designed and built, and is shown in block diagram form in Figure 7. The system uses the CW cancellation method, and consists of a signal source whose output is fed through a bandpass filter and an isolator, a nulling network, an antenna and a receiver. The transmitter is a Scientific-Atlanta 2150B signal source. This unit has a digitally operated control box which commands a frequency synthesizer. The manufacturer's literature specifies a frequency accuracy of one part in 10^6, and a frequency stability of one part in 10^7 per 24 hours. The synthesized RF output power is +9 dBm at X-band. When a higher signal level is required an HP495A TWT amplifier is used. A Scientific-Atlanta 1770 receiver is used, along with an 1833A dual ratiometer and an 1823 phase display, both also from Scientific-Atlanta. This receiver has two channels, an automatic phase control (APC) channel and a signal channel.

The APC channel is used to phase lock the receiver local oscillator to the transmitter. The signal channel is actually two channels, designated A and B. Each can be monitored by the ratiometer, which displays signal levels in dB. Manual switches allow one to monitor channels A and B simultaneously, or channel B and the ratio A/B. When the latter mode is used the signals A and B are fed to an external switch which is operated synchronously with an identical switch in the receiver. This multiplexing arrangement allows two signals to be applied to the signal channel of the receiver.

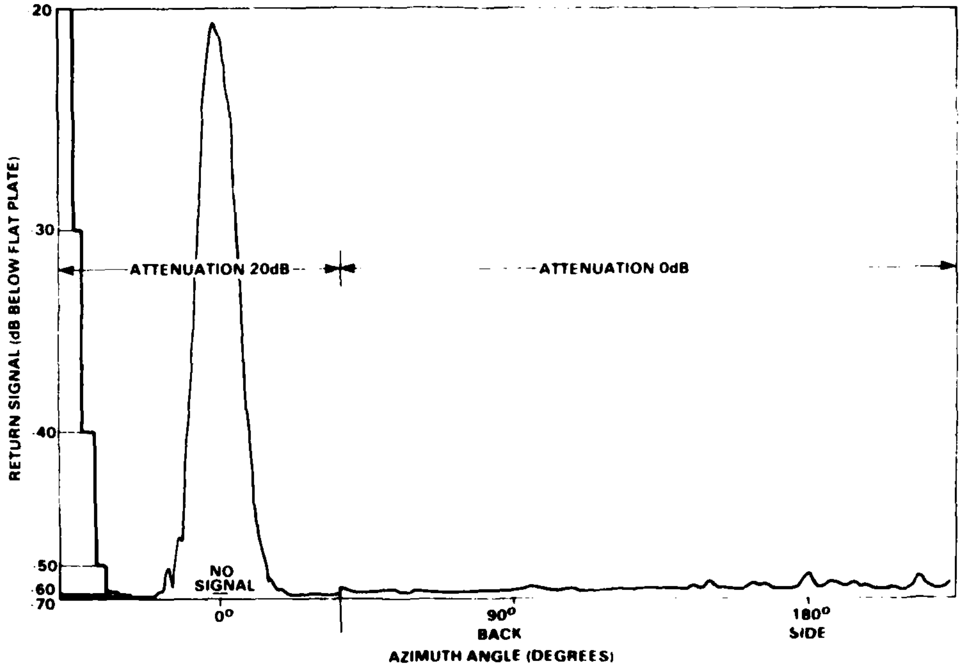

Figure 4. Plot of Return From Chamber Walls vs Azimuth Angle Compared to a Flat Metal Plate, Frequency = 35 GHz

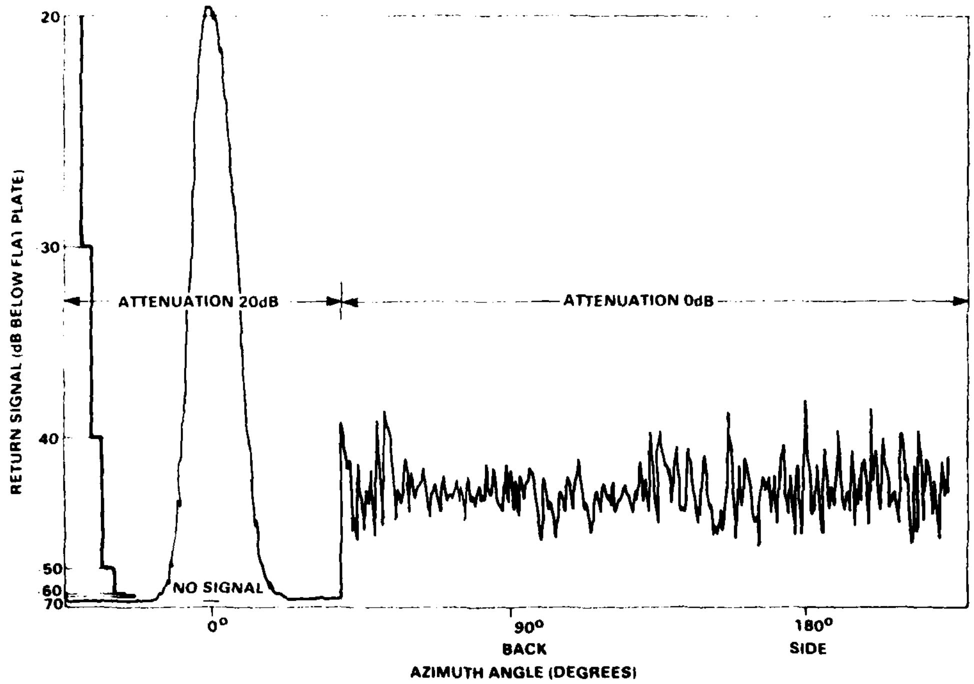

Figure 5. Plot of Return From Chamber Walls vs Azimuth Angle Compared to a Flat Metal Plate, Frequency = 98 GHz

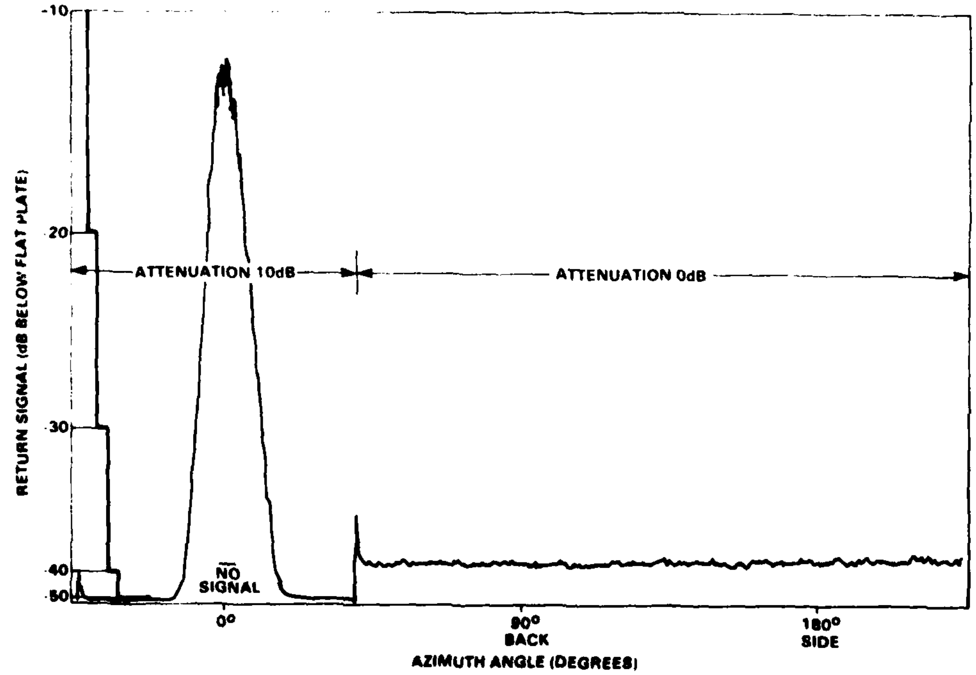

Figure 6. Plot of Return From Chamber Walls vs Azimuth Angle Compared to a Flat Metal Plate, Frequency = 140 GHz

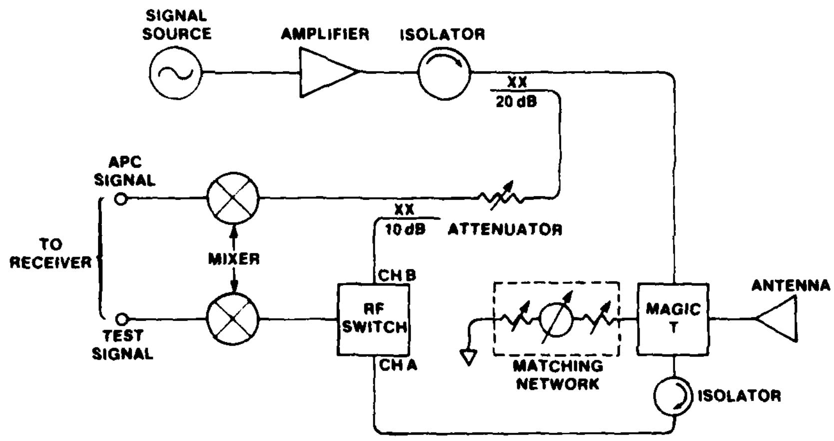

Figure 7. Block Diagram of the X Band Monostatic RCS Measurement System

The RCS measurement system operates as follows. The transmit signal is passed through a directional coupler, after the above mentioned filter and isolator. The major portion of the signal is fed into a hybrid (Magic Tee) where part is directed to the nulling network and part to the antenna, where it is radiated. The coupled portion of the transmit signal (-20 dB) is passed through a variable attenuator, mixed, and fed to the APC channel of the receiver. A portion of this APC signal is coupled off (-10 dB) at the RF level, making it -30 dB with respect to the transmitted signal. This signal is then passed through a variable attenuator and fed to the reference port (channel B) of the external synchronous switch. The received signal passes through the antenna to the hybrid, where a portion of it is directed to the matching network and a portion is fed through an isolator to the signal port (channel A) of the synchronous switch. The ratio A/B is proportional to the radar cross section of the target and can be displayed on the ratiometer by means of the synchronous switching arrangement. By properly calibrating the system, radar cross sections can be read directly off the ratiometer in dBsm.

Before making measurements, the system must be nulled to reduce, insofar as possible, reflections from objects other than the desired target. The nulling process consists of adjusting the matching network, which comprises a phase shifter and two attenuators, while transmitting into an empty* chamber. This adjustment, an iterative process, introduces a signal into the hybrid that has the proper phase and amplitude to cancel both the stray reflections due to imperfections in the hybrid

*An empty chamber is considered to be the room plus target mount and necessary absorber, but not the target.

and any signal reflected from the empty chamber. The signal level in channel A is then a minimum. When a target is placed in the chamber the received signal can be presumed to be due to the target and not the chamber. This presumption is valid only if the presence of the target does not introduce reflections, from parts of the chamber or mount, strong enough to unbalance the system. This point should be considered whenever a target is to be measured. In actual practice the nulling signal and the transmitter signal drift with time in phase and amplitude. A very small change in either signal is sufficient to cause the system to become unbalanced. These changes can be caused by thermal gradients across the equipment or the chamber, movement of the chamber walls due to wind, or interaction between stray leakage signals from the equipment and people present in the equipment rooms. These effects can be minimized by careful shielding, insulating, and shock mounting, but cannot be completely eliminated.

Measuring a calibration target of known radar cross section, such as a sphere, in close time proximity to the measurement of each unknown target, however, allows the errors due to the effects of signal drift to be minimized. The radar cross section σ of a test target is found by means of the relationship

$$\sigma = M + (C - T) , \tag{3}$$

where M is the measured radar cross section of the target in question, C is the measured RCS of the calibration target, and T is the theoretical RCS of the calibration target. The terms in this equation are in units of decibels relative to a square meter (dBsm). Since the ratiometer can display the RCS of a target in dB, the calibration process shown in parenthesis in Eq. (3) can be done by nulling the system, placing the calibration target in the chamber, and adjusting the gain of the ratiometer until the A/B is equal to the theoretical RCS. As long as the system remains nulled the reading on this ratiometer is the RCS of the target being measured, in dBsm.

The calibration target need not be measured after every test target, but must be measured often enough to ensure that the system null has not drifted. For the present set of measurements the calibration target was measured and the empty chamber null was checked after every test target. The system was renulled whenever necessary.

The chamber was evaluated at 10 GHz using a method reported by Buckley.[6] This method involves comparing the return from the empty chamber to that from a known target. A signal is transmitted into the empty chamber and the system is nulled. The output from the hybrid is then very close to zero. The nulling signal

6. Buckley, E. F. (1968) Outline of evaluation procedures for microwave Anechoic Chamber, Microwave Journal.

consists of two components. One component cancels the error due to system imperfections and the other component cancels the reflections from the chamber. This latter component is the one we desire to measure. By moving the antenna a small amount we can change the phase of the chamber reflection by 180°, while leaving the nulling signal unaltered. The signal at the output of the hybrid is now equal to twice the magnitude of the return from the empty chamber.

When a target of known RCS is placed on the chamber, a signal of known amplitude is added to the existing signal in the hybrid. Rotating this target (usually a sphere) slightly off-center on the positioner rotates the phase of this second signal through 180°, thus causing the output of the hybrid to cycle from a minimum value of S-2C, to a maximum value of S+2C, where S is the theoretical RCS of the sphere and C is the (unknown) RCS of the chamber.

The recorded signal excursion at the receiver output can then be equated to the ratio of the above values,

$$V = (S-2C)/(S+2C), \tag{4}$$

and a value for the RCS of the chamber can be calculated. An alternative value can be calculated, based on the possibility that the sphere return might be smaller than twice the chamber return. In this case

$$V = (2C-S)/(2C+S) . \tag{5}$$

Repeating the measurement for a different size sphere will yield two additional values for the chamber RCS. Two of these values will be nearly equal and two will be widely divergent. The two nearly equal values will be close to the RCS of the chamber. The two can be averaged with additional values to obtain a value for the RCS of the chamber.

Following this procedure, using a 2.625- and an 8.000-in. diameter sphere a chamber RCS of -32.9 dBsm was determined. Dividing this value by ten and taking the inverse logarithm gives the RCS in square meters. Performing this operation yields 0.0005 m^2 for the radar cross section of the chamber.

An experiment was performed to determine whether the signal source stability would be a limiting factor in the accuracy of the RCS measurements. The system was nulled and the output of the signal channel of the receiver was applied to the pen input of an antenna pattern recorder. The signal source was then allowed to sweep a known amount above and below the center (nulled) frequency, f_o. At the same time the chart recorder was allowed to run on its internal time base so that the paper advanced as the frequency was swept out of and back into the null. Allowing the source to sweep through two successive nulls enabled calibration of the chart paper in Hertz division since the extremes of the frequency excursion were known. The portion of the curve depicting the bottom of the null was then redrawn on an expanded scale, as a function of null depth in dB vs frequency deviation about f_o. The manufacturer's specification for signal source stability was then superimposed on this curve. This is shown in Figure 8. The published specification for frequency stability of one part in 10^7 translates to a maximum frequency deviation of 1 kHz at a center frequency of 10 GHz. From this, and inspection of Figure 8, it can be concluded that the stability of the signal source will have no effect on the accuracy of the measurement.

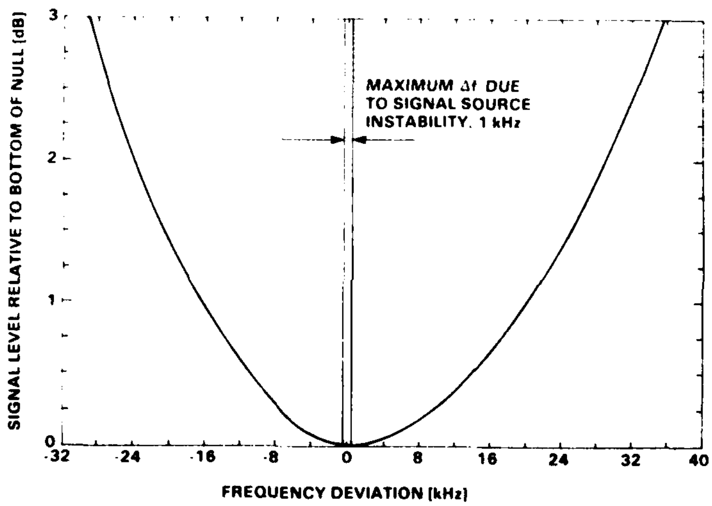

Figure 8. Plot Showing the Signal Source Frequency Stability Specification Superimposed on the System Null. Frequency = 10 GHz

Five small metal spheres, covering a ka range from 0.282 to 0.581, were measured to determine the lower limit of system sensitivity. Four RCS measurements were made on each sphere and the results are shown in Table 1. The averages of the four sets of measurements are also tabulated, along with the theoretical RCS for each sphere. The average RCS values for each sphere are plotted in Figure 9 along with a curve showing theoretical RCS for the ka range in question.

Table 1. Results of Four Sets of RCS Measurements on Five Small Metal Spheres, and the Average of the Four Measurements for Each Sphere

Diameter (inches)	ka	Measured RCS (dBsm)				
		Trial 1	Trial 2	Trial 3	Trial 4	Average
0.106	0.282	-57.4	-56.7	-57.9	-58.0	-57.5
0.124	0.330	-58.6	-56.6	-56.4	-56.4	-57.0
0.151	0.402	-53.6	-51.7	-51.9	-51.5	-52.2
0.212	0.565	-49.4	-49.9	-48.9	-49.1	-49.3
0.218	0.581	-46.5	-46.5	-45.4	-45.4	-46.0

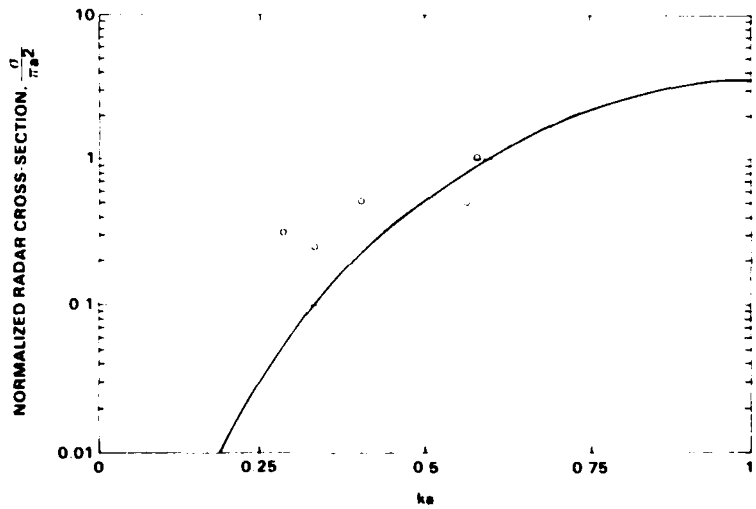

Figure 9. Average Values of RCS Measurements on Small Spheres, for System Sensitivity Tests. Theory ______, Measured o

The measurements were made at a distance of 12 ft, and a power level of +24 dBm at the input to the antenna. The antenna was a rectangular horn, with a 4-in. by 6-in. aperture. This antenna has a calculated gain of 19.6 dB, with an effective aperture of 6.5×10^{-3} m^2. Using the radar range equation, and a figure of 81 percent for the efficiency of the horn antenna,[8] we can calculate the power densities at

8. Silver, S., op cit, pp. 182-187.

the target position and, for a given target σ, the power present at the receiver input. The receiver has a specified sensitivity of -80 dBm. Based on this sensitivity, and the above mentioned antenna parameter, the system should be capable of detecting targets having radar cross sections as low as -52.4 dBsm at a distance of 12 feet.

Table 2 contains the pertinent results for these sphere measurements. The sphere diameters, projected areas, and ka values are tabulated, along with the measured and theoretical received powers for each. Examination of this table, in conjunction with Figure 9, allows us to draw a conclusion about the system sensitivity. We see that measurements on spheres as small as 0.218 in. in diameter (ka = 0.581) are possible with this system. The measurements on smaller ka value spheres are unreliable and inaccurate and, in addition, the received power is leveling off near -80 dBm, indicating that the measurement system sensitivity is limited by noise rather than by background reflections.

Table 2 shows that the RCS measurements become unreliable near -50 dBsm. This is close to the lowest RCS theoretically measurable (-52.4 dBsm) with the system. The discrepancy can be accounted for by small losses in the waveguide circuitry which were not measured or accounted for in the loss budget. Since the system is noise limited rather than background limited, radar cross sections even lower than -46.5 dBsm can be measured by increasing transmitter power.

3. CALCULATIONS AND MEASUREMENTS

A series of 24 metal spheres was measured at a frequency of 10 GHz. The spheres ranged from 0.218 to 8.000 in. in diameter, corresponding to a ka range of 0.58 to 21.28. The backscatter cross sections were measured, and compared with theoretical values obtained from a computer program which solves the Mie summation.

The computer program used was written by Hancock and Livingston of the Naval Research Laboratory[2] for computing scattering from aerosols. The program was designed to calculate bistatic scattering from spheres having a complex refractive index and had to be modified to handle metal spheres. Several programs were available for the theoretical part of this task, however, the number and extent of convergence checks in the NRL program made it the most suitable by far of those considered. In addition, planned work on dielectric spheres will require the use of the program in its original form so the task of modifying it and adapting it to the RADC computer was doubly justified. The program was also modified to handle an extended range of ka values.

Table 2. Theoretical and Measured Radar Cross Section for Five Small Spheres. The expected and actual received power levels are also shown

Diameter (inches)	ka	πa^2 (m^2)	Theoretical RCS		Measured RCS		Power Received (dBm)	
			dBsm	m^2	dBsm	m^2	Theory	Measured
0.218	0.581	2.41×10^{-5}	-46.5	2.24×10^{-5}	-46.0	2.51×10^{-5}	-74.1	-73.6
0.212	0.565	2.25×10^{-5}	-47.2	1.91×10^{-5}	-49.3	1.17×10^{-5}	-74.8	-76.9
Theoretical Limit of System Sensitivity							-80.0	- ---
0.151	0.402	1.16×10^{-5}	-55.8	2.63×10^{-6}	-52.2	6.03×10^{-6}	-83.4	-79.8
0.124	0.330	7.79×10^{-6}	-60.9	8.13×10^{-7}	-57.0	2.00×10^{-6}	-88.5	-84.6
0.106	0.282	5.69×10^{-6}	-64.9	3.24×10^{-7}	-57.5	1.78×10^{-6}	-92.5	-85.1

After the program was made to run on the RADC computer, representative test cases were run for metal spheres and checked against published results. Various ka values were selected and the bistatic radar cross sections were calculated, from 0° to 180°. Comparison of these RCS values with those in the literature showed excellent agreement in most cases. Where a discrepancy was found, further investigation and cross referencing to other sources invariably showed that the computer program was correct. The errors were found to be due to such things as mislabelled graphs, faulty registration in reproducing curves, and inadvertent use by one worker of a previous worker's incorrect results. A high degree of confidence is placed in the results from this program, which has been used to calculate scattering from spheres as small as ka = 0.01 and as large as ka = 170.00.

The measurements on the metal spheres were made with the system described in Section 2. The spheres were mounted on a styrofoam column which was placed on top of an antenna positioner. Although the reflections from the positioner and styrofoam could be tuned out in the empty chamber the addition of a target introduced stray reflections. The strength of these reflections increased as the size of the target increased. To eliminate these effects the positioner was shielded by a wooden enclosure covered with absorber. A piece of flat, tuned[4] absorber was placed between the styrofoam column and the metal surface of the positioner turntable, as this was found to be a strong source of reflections. The target mounting arrangement is shown in Figure 10. With this arrangement the receiver port of the hybrid could be isolated from the transmit port by 110 dB. This isolation (null) would last 10 min or more. Occasionally nulls of 120 dB were obtained but they were shortlived. Most measurements were made with 110 dB nulls.

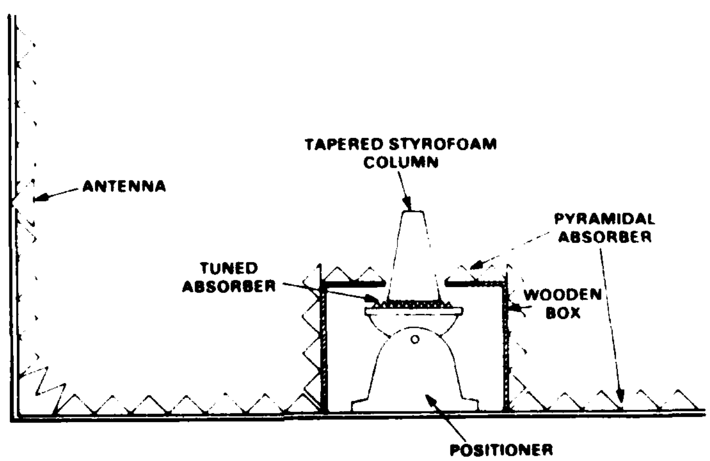

Figure 10. Target Mounting Arrangement for X Band RCS Measurements, Showing Positioner Shielding

The measured RCS values for the spheres are listed in Table 3. The values are graphed in two ways. One plots RCS, normalized to projected area, vs ka and the second plots RCS in square centimeters vs ka. These graphs are shown in Figures 11 and 12.

Table 3. Measured Radar Cross Sections for Twenty-four Metal Spheres in dBsm and Square Meters

Sphere		RCS	
Diameter	ka	dBsm	m^2
0.218	0.581	-46.4	2.29×10^{-5}
0.500	1.330	-35.5	2.82×10^{-4}
0.656	1.745	-42.0	6.31×10^{-5}
0.813	2.161	-32.6	5.50×10^{-4}
0.875	2.327	-30.9	8.13×10^{-4}
0.938	2.494	-31.3	7.41×10^{-4}
1.000	2.662	-32.3	5.89×10^{-4}
1.125	2.995	-33.8	4.17×10^{-4}
1.250	3.328	-29.9	1.02×10^{-3}
1.375	3.659	-28.2	1.51×10^{-3}
1.500	3.992	-30.4	9.12×10^{-4}
1.688	4.491	-28.0	1.58×10^{-3}
1.750	4.659	-27.0	2.00×10^{-3}
1.875	4.990	-26.7	2.14×10^{-3}
1.938	5.758	-27.5	1.78×10^{-3}
2.000	5.324	-28.0	1.58×10^{-3}
2.125	5.656	-26.1	2.45×10^{-3}
2.375	6.321	-25.5	2.82×10^{-3}
2.500	6.654	-25.7	2.69×10^{-3}
3.000	7.985	-23.8	4.17×10^{-3}
4.000	10.647	-20.0	1.00×10^{-2}
5.000	13.308	-18.6	1.38×10^{-2}
6.000	15.970	-17.4	1.83×10^{-2}
8.000	21.293	-14.8	3.33×10^{-2}

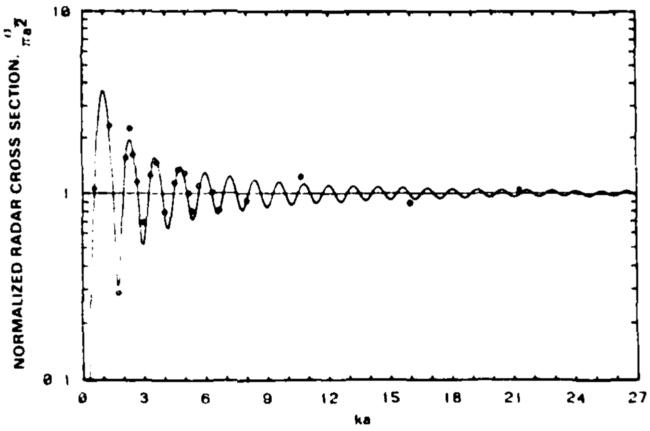

Figure 11. Measured RCS Values of Metal Spheres Compared to Theory, Normalized RCS vs ka. Theory _____, measured o

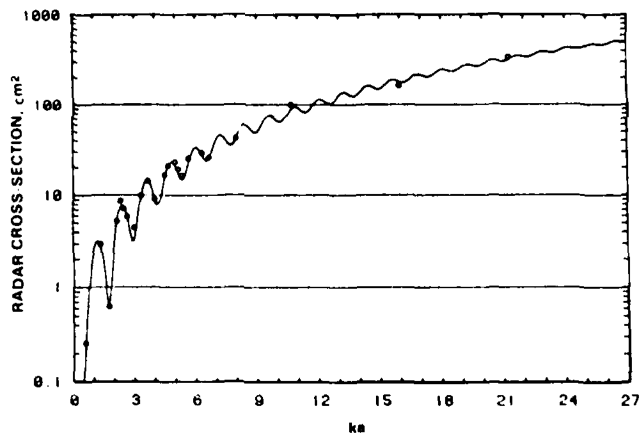

Figure 12. Measured RCS Values of Metal Spheres Compared to Theory, cm^2 vs ka. Theory _____, measured o

4. DISCUSSION

The accuracy of sphere measurements is easy to ascertain because an exact solution exists. In this case the theoretical RCS values were provided by a computer program written to calculate the scattering from dielectric spheres and modified to handle metal spheres. The largest discrepancy was for the sphere of diameter 0.218 in. (0.56 cm), corresponding to a ka of 0.58. The measured value differed from theory by 0.6 dB. Measurements on this sphere were always in error by about this same amount no matter how much care was taken to insure a deep null was present. This situation is due to the small RCS (-46.5 dBsm) of this sphere, which puts it near the lower limit of system sensitivity, as was shown in Section 2.

The remaining spheres could be measured with errors of less than 0.6 dB. A number of measurements were made on each sphere. The values included in this report are representative of the degree of accuracy obtained.

These monostatic results on metal spheres serve only as a benchmark for the X-band measurements program. The real effort in this program will be placed on investigating scattering from dielectric shapes. Monostatic measurements have been made on dielectric spheres and are the subject of a future report. In addition, a series of metal cubes has been measured in anticipation of future measurements of dielectric cubes. A bistatic system has been built and preliminary measurements using it are underway.

This report has described the RCS measurements facility at Ipswich, Massachusetts. An X-band monostatic system, which uses the CW cancellation method of measurement was designed and built. The system has a sensitivity of -46.5 dBsm. Monostatic measurements on a series of metal spheres were described. Measurement errors were shown to be less than 0.6 dB, over the range $0.58 < ka < 21.28$.

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