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SCATTERING EXPERIMENTS AT THE IPSWICH ELECTROMAGNETIC MEASUREMENTS FACILITY: BACKSCATTER FROM METAL CUBES

Robert V. McGahan

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441-5700

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APPROVED:

J. LEON POIRIER
Assistant Chief, EM Techniques Branch
Electromagnetic Sciences Division

APPROVED:

ALLAN C. SCHELL
Chief, Electromagnetic Sciences Division

FOR THE COMMANDER:

JOHN A. RITZ
Acting Chief, Plans Office

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Backscatter cross section measurements at broadside incidence were made on eighteen metal cubes at X-band. The measurements are compared with theoretical predictions made using Enhanced High Frequency Diffraction and Augmented Magnetic field Integral Equation solutions. A composite solution is formed and compared with the measurements, providing a validated backscatter solution for metal cubes from arbitrarily low to arbitrarily high frequencies.

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Electromagnetic Measurements Facility: Backscatter from Metal Cubes

Preface

I would like to acknowledge the assistance of Mr. David Gaunt in making the scattering measurements described in this report.

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Scattering Experiments at the Ipswich Electromagnetic Measurements Facility: Backscatter from Metal Cubes

1. INTRODUCTION

Scattering from metal cubes is an interesting problem from the theoretician's point of view. The cube is a symmetrical three-dimensional body but does not possess rotational symmetry. Solving for the scattering from a cube tests a theoretical method in various ways. It requires treating both co-polarized and cross-polarized edges and sides. It also requires consideration of circumferential (creeping) and multiple diffraction currents. Finally, since the cube is a finite body, the theoretical solution cannot use infinite or semi-infinite approximations. Thus, an accurate, efficient solution for scattering from a cube is a useful tool for evaluating other theoretical methods which have been developed to handle arbitrarily shaped bodies.

This effort began as a straightforward experimental validation of an interesting theoretical prediction but the initial results and the questions they raised drove us to expand the scope of the work. The result is a theoretical solution predicting the backscatter from metal cubes from extremely low frequencies to arbitrarily high frequencies. The theoretical prediction is validated by measurements on metal cubes with side lengths ranging from 0.15 to 4 wavelengths.

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Such a result, which has not heretofore been available, is useful as a benchmark to which various theoretical scattering solutions can be compared. It has proved useful in our work assisting the Cruise Missile Surveillance Program and validating the SRC predictive model operated by RADC/OC.

2. BACKGROUND AND IMPETUS FOR WORK

In 1980 and 1981 Yaghjian[1,2] presented augmented forms of Maue's electric- and magnetic-field integral equations, popularly referred to as EFIE and MFIE, respectively. Yaghjian's augmented electric field integral equation (AEFIE) and augmented magnetic field integral equation (AMFIE) eliminated the spurious resonances from the exterior solution of Maue's original equations. Numerical results obtained using a surface patch method of moments computer program confirm that the augmented integral equations in fact eliminate the spurious resonances for all perfectly conducting scatterers except the sphere.

No comprehensive measured data existed that could be used to confirm the augmented results, so backscatter measurements were made on sixteen metal cubes. These measurements, made at 10 GHz, indicated that the AMFIE was superior to the MFIE above resonance. However, the measured points were too few either to clearly define the resonance dip or to determine which solution was more accurate well below resonance. In addition the moment method solutions to both the MFIE and AMFIE were limited by available computer memory as to the number of surface patches that could be handled, thus causing errors at the higher frequencies. These two factors, coupled with the favorable results near resonance, encouraged us to expand both the experimental and the theoretical efforts.

A revised version of the computer program was written using symmetry considerations.[3] This allowed a solution using sixty-four patches per cube face, as opposed to sixteen in the original version. Still, this new solution began to show signs of inaccuracies for cubes of side length $4s/\lambda$ greater than about 1.5. An high frequency diffraction (HFD) solution, based on the geometrical theory of diffraction, was written to predict the backscatter in this size regime but it, too, had definite areas of disagreement with both the measured results and the AMFIE solution in

1. Yaghjian, A.D. (1980) Augmented electric- and magnetic-field integral equations which eliminate the spurious resonances. Paper presented at International URSI Symposium on EM Waves, Munich.

2. Yaghjian, A.D. (1981) Augmented electric- and magnetic-field integral equations, Radio Science, **16**(No. 6):987-1001.

3. Yaghjian, A.D., and McGahan, R.V. (1985) Broadside radar cross section of the perfectly conducting cube, IEEE Trans. Antennas Propag., **33**(No. 3).

the latter's range of accuracy. Thus an enhanced HFD solution (EHFD) was devised[3] to extend the range of validity of the HFD solution to lower frequencies.

The enhanced solution was formed by considering the physical optics currents on the front face of the cube and all four front edges to generate the fields incident on the back edges of the cube. This differs from the usual but more simplistic approach of assuming that the front edges of the cube are right angle, doubly infinite wedges and using the known diffraction coefficients from such structures to determine the fields incident on the trailing edges of the cube and hence the diffraction from the trailing edges.

The EHFD solution agrees with the AMFIE solution in a common intermediate range of frequencies. This agreement with each other and with measurements allow us to place a high degree of confidence in each solution. The various solutions are shown compared to RCS measurements in Figures 6 to 11.

3. DESCRIPTION OF THE MEASUREMENTS

As noted in Section 2, the original sixteen measurements were found to be too few to draw meaningful conclusions, therefore, the measurement program was expanded. Two additional cubes were fabricated to fill in a size gap, and measurements were made at a number of frequencies rather than at 10 GHz only. The cube sizes and the frequencies at which RCS measurements were made are summarized in Table 1.

Table 1 also lists a parameter $4s/\lambda$ for each measurement. This parameter is analogous to the quantity ka used when discussing spheres. Each is the ratio of the circumference of the body to the wavelength of the illuminating energy. The measurements presented in this report are plotted as a function of $4s/\lambda$, in units of radar cross section (σ) divided by wavelength squared (λ^2).

Figure 1 shows the geometry used to analyze and measure the conducting cubes. The cube is oriented with faces horizontal and vertical. The incident energy is assumed to be a linearly polarized plane wave with the E and H vectors parallel to the vertical and horizontal edges, respectively. The backscatter cross section was measured for broadside incidence only. The cubes, ranging in size from $s = 5$ mm to $s = 100$ mm, are shown in Figure 2. The actual sizes are contained in Table 1.

Table 1. Side Length s, Measurement Frequencies, and 4s/λ for Metal Cubes

s(mm)	4s/λ at Measurement Frequency f[GH$_z$]								
	9.0	9.3	9.4	9.6	9.7	9.8	10.5	10.7	10.9
5	0.60						0.70		
7	0.84			0.90				1.00	
10	1.20		1.25			1.31	1.40		
12			1.51		1.55			1.71	1.75
15		1.86		1.92			2.10		2.18
20	2.40		2.51			2.62	2.80		2.91
26	3.12		3.[illegible]6	3.33		3.40	3.64	3.71	
32	3.84		4.01	4.10		4.18	4.48		4.65
40	4.80		5.02	5.12	5.18	5.23	5.60	5.71	5.82
50	6.00	6.20				6.54	7.00		
55	6.10								
60	7.20		7.53						
67	8.05			8.58					
75	9.01			9.61			10.51		
80	9.61								
88	10.57		11.04			11.51			
94	11.29			12.04		12.29			
100	12.01					13.08	14.01		14.54

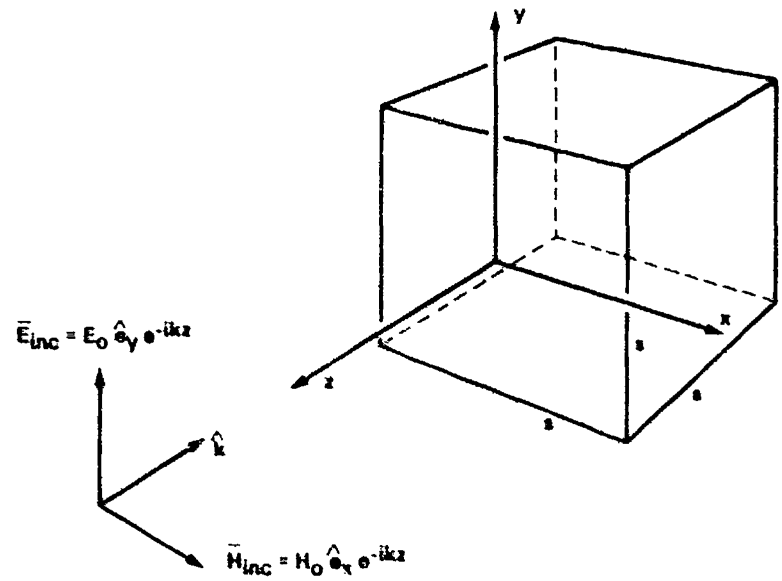

Figure 1. Perfectly Conducting Cube of Side s With Broadside Plane-Wave Incidence

Figure 2. Eighteen Metal Cubes, Side Lengths 5 mm to 100 mm

The anechoic chamber, target mounting arrangement, and measurement system[4] are shown in Figures 3 to 5. The measurement system is a single-horn, true monostatic, X-band setup using the CW cancellation method. The signal source is a Scientific-Atlanta model 2150, frequency synthesized to a stability of one part in 10^7 per twenty-four hours. This corresponds to a frequency drift of less than 1000 Hz per day at 10 GHz, which is more than adequate for this measurement technique.[4] The receiver is a Scientific Atlanta model 1771, a coherent, three channel, phase-locked unit with an 80 dB dynamic range. This receiver tracks the signal source in phase and amplitude, which allows measurements to be made independent of system phase shift and source fluctuations.

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4. McGahan, R.V. (1983) Scattering experiments at the Ipswich electromagnetic measurements facility: calibration with perfectly conducting spheres, RADC-TR-83-181, AD A138028.

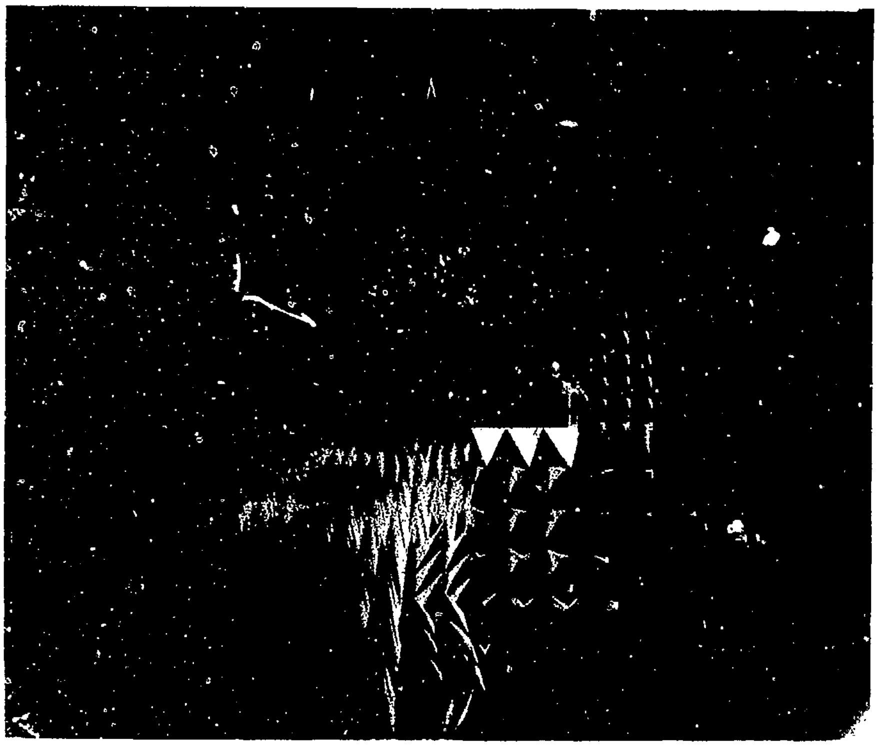

Figure 3. Anechoic Chamber and Calibration Sphere Used for the Cube RCS Measurements

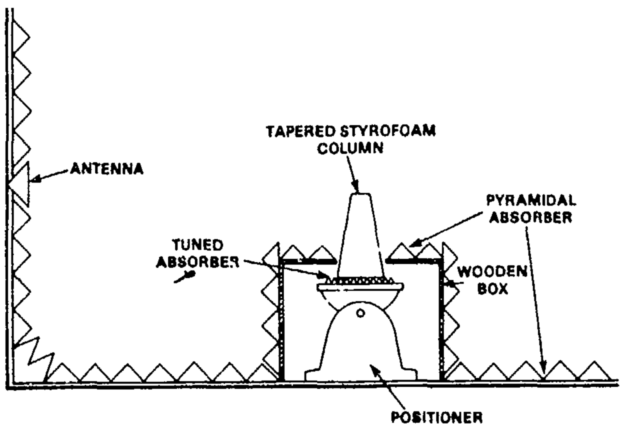

Figure 4. Target Mounting Arrangement for Cube RCS Measurements

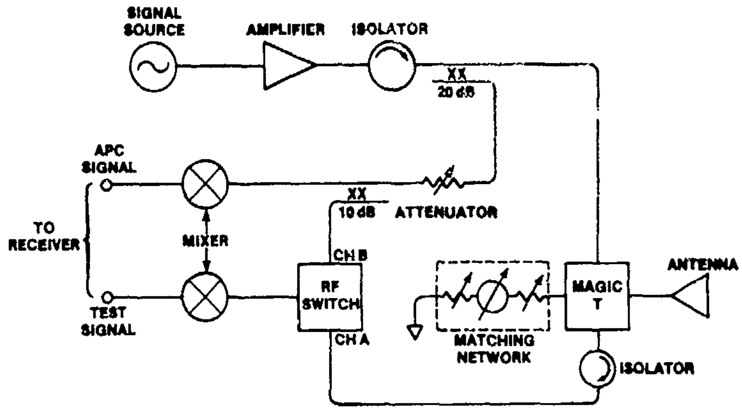

Figure 5. Measurement System for Cube RCS Measurements

4. DISCUSSION

Figure 6 shows the cube measurements compared with the Physical Optics solution. For $4s/\lambda$ above about 5.5 the PO solution shows the general trend of the RCS behavior and may be adequate for some purposes but below this value it is clearly inadequate.

Figures 7 and 8 show the HFD and EHFD solutions, respectively. The two are similar above $4s/\lambda = 3.5$ and both agree well with the measurements in this region. In particular the slignt changes in slope about $4s/\lambda = 5$ and 9 are predicted. However, the EHFD solution predicts a pronounced plateau at $4s/\lambda = 2.5$ which is missed completely by the HFD solution, but confirmed by the measurements. The resonance dip about $4s/\lambda = 1.5$ is clearly picked out by the EHFD solution while the height of the local maximum about $4s/\lambda = 1.0$ is in error by about 4 dB. The HFD solution cannot predict these phenomena.

The MFIE solution is shown in Figure 9. This solution was computed using 64 patches per cube face, or 384 patches per cube, taking two hours on a CDC 6600 computer. There are still spurious resonances and these cannot be eliminated even by taking more patches. The local maximum at $4s/\lambda = 2.5$ are predicted accurately and the trend of the curve out to $4s/\lambda = 15$ is generally correct, but less accurate than either the HFD or EHFD solution.

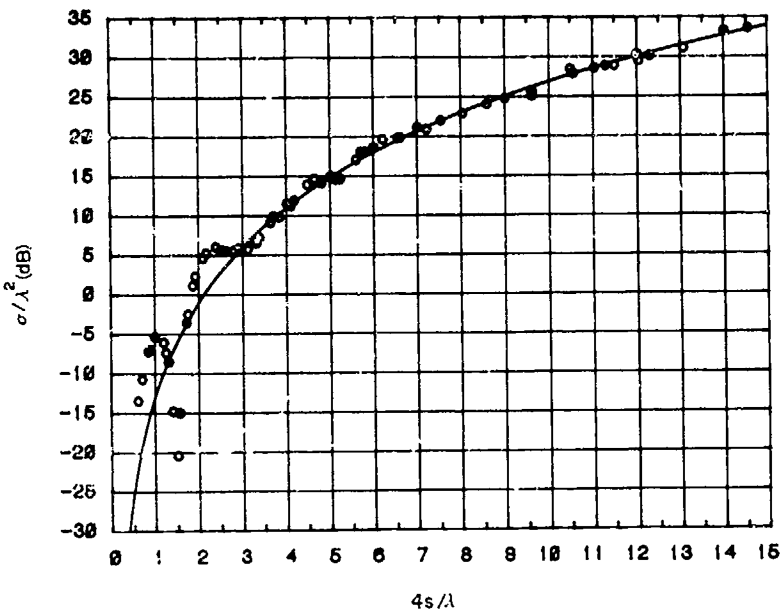

Figure 6. Cube RCS Measurements Compared With Physical Optics Solution. Theory ———, Measured oo

Figure 10 shows the AMFIE solution. Note that the spurious resonances have been eliminated but the curve shows a behavior similar to an underdamped oscillation in the region above $4s/\lambda = 6$. This true even though 384 patches were used for this solution also. And again, adding more patches will improve the prediction in this region only at the expense of computer time and storage. The AMFIE solution does not predict the behavior about $4s/\lambda = 1$ and 1.2 as well as the MFIE solution but excels in the range $1.6 \leq 4s/\lambda \leq 3.5$, which, coupled with the measured results, allows us to place a high degree of confidence in these solutions. The MFIE solution has always been recognized as correct below resonance. The composite solution was formed using the MFIE from $4s/\lambda = 0$ to 1.5. From $4s/\lambda = 1.6$ to 5.1 the AMFIE was used, and the EHFD from $4s/\lambda = 5.2$ to 15. The theoretical solution was terminated at $4s/\lambda = 15$ for convenience, but can be carried as far as desired, limited only by computer time. The composite solution is shown in Figure 11, where it is compared with the measured results.

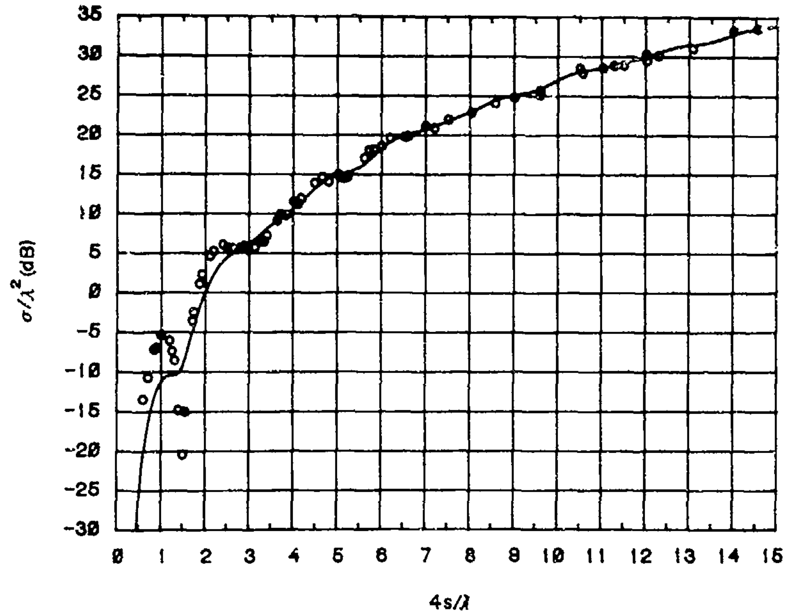

Figure 7. Cube RCS Measurements Compared With High Frequency Diffraction Solution. Theory ———, Measured oo

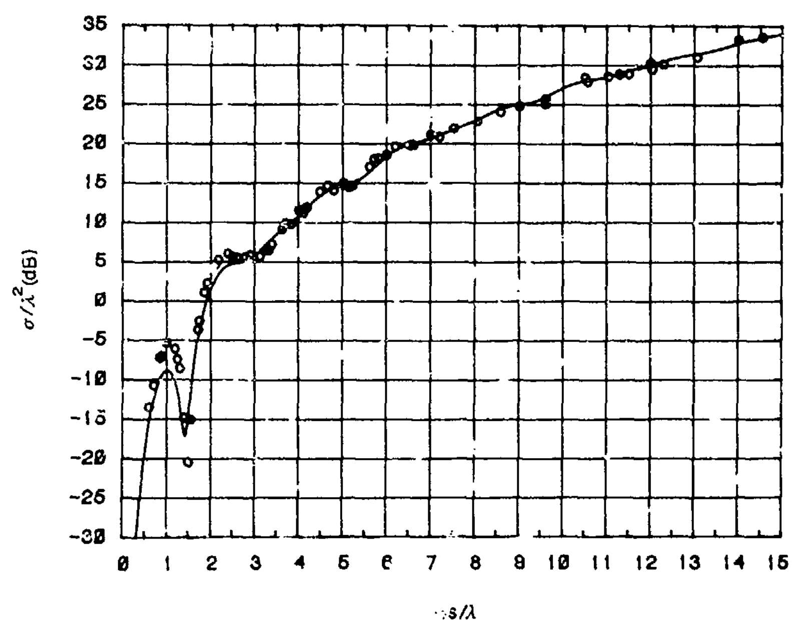

Figure 8. Cube RCS Measurements Compared With Enhanced High Frequency Diffraction Solution. Theory ———, Measured oo

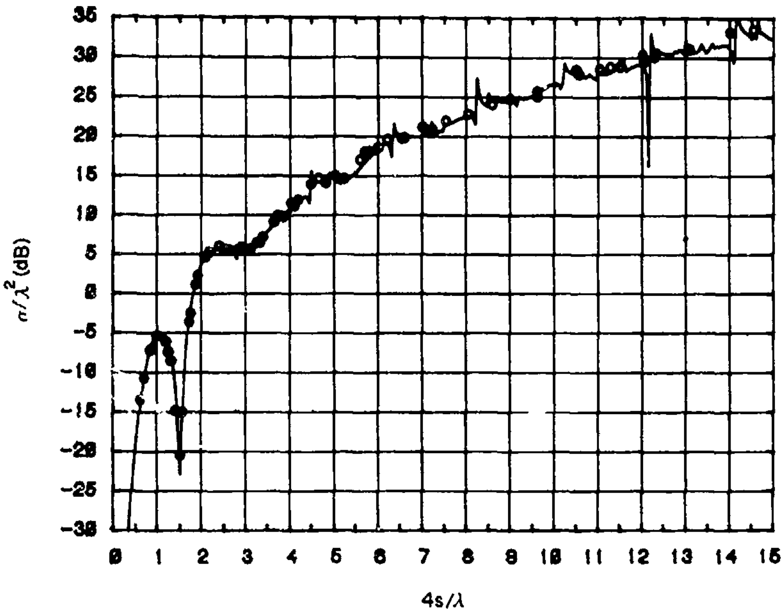

Figure 9. Cube RCS Measurements Compared With MFIE Solution. Theory ———, Measured oo

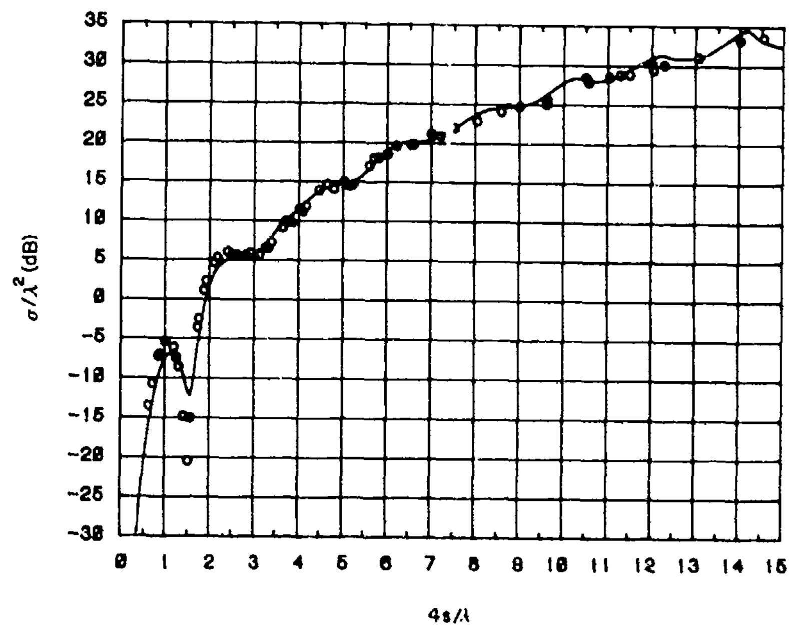

Figure 10. Cube RCS Measurements Compared With AMFIE Solution. Theory ———, Measured oo

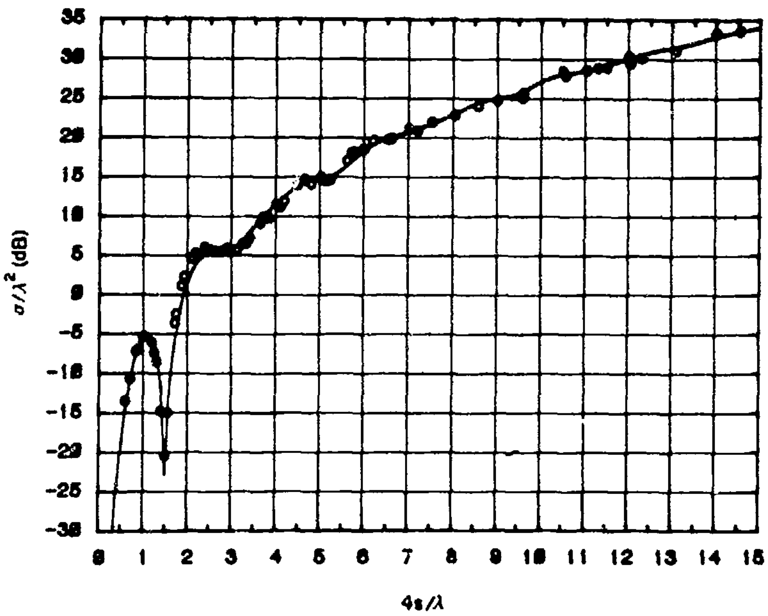

Figure 11. Cube RCS Measurements Compared With Composite Solution. Theory ———, Measured oo

5. CONCLUSION

Backscatter measurements have been presented for metal cubes ranging in size from 5 mm to 100 mm in side length. The measurements are compared with various theoretical predictions and a composite theoretical curve has been developed. The measurements agree with theory to within 1 dB. The estimated measurement error is ± 0.5 dB for this system, thus the measurements comprise a reliable validation of the composite theoretical solution.

These measurements, along with the composite theory, provide a baseline tool against which unproven theories may be tested. By this means the overall accuracy as well as specific regions of validity of such theories may be determined. This has particular application to the SRC predictive model at RADC/OC.

Future work in this area will include extension of the cube theory and measurements to other than broadside incidence, to bistatic RCS, and to penetrable (non-metallic) cubes.