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MEASURED MICROWAVE  
SCATTERING CROSS SECTIONS  
OF THREE METEORITE SPECIMENS

*by Wayne E. Hughes*

*Goddard Space Flight Center*

*Greenbelt, Md. 20771*

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16. Abstract  Three meteorite specimens were used in a microwave scattering experiment to determine the scattering cross sections of stony meteorites and iron meteorites in the frequency range from 10 to 14 GHz. The results indicate that the stony meteorites have a microwave scattering cross section that is 30 to 50 percent of their projected optical cross section. Measurements of the iron meteorite scattering were inconclusive because of specimen surface irregularities.			
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# MEASURED MICROWAVE SCATTERING CROSS SECTIONS OF THREE METEORITE SPECIMENS

Wayne E. Hughes  
*Goddard Space Flight Center*

## INTRODUCTION

One of the parameters still missing from our understanding of the solar system is an accurate count of the meteoroid and asteroid particle density in the size range between 1-mm and 20-km diameter. If the particles can be expected to reflect, or reradiate microwave energy, a simple radar ranging system can be one of the most reasonable techniques for performing an experiment to count such particles.

Although there have been numerous measurements of meteorite electrical and magnetic properties (refs. 1 to 3), none of these give reliable scattering cross sections of stony meteorites at frequencies in the X-band region of the spectrum.

In anticipation of a need to know the microwave scattering properties of some typical interplanetary materials, an X-band scattering cross-section experiment was conducted on two stony meteorites and one iron meteorite. The results of the experiment indicate that the stony meteorites have a microwave scattering cross section of 30 to 50 percent of their projected optical cross section. Although no definite cross section could be established for the third specimen, measurements indicated that the surface properties of iron meteorites may enhance the microwave return.

## DESCRIPTION OF METEORITES

The meteorites used in this experiment were loaned to NASA by the Smithsonian Institution. Two of them were of the carbonaceous chondrite type from observed falls, and the third was an iron meteorite from Canyon Diablo, New Mexico. The carbonaceous chondrites were labeled Allende 3655 and Colby 618. The iron meteorite was labeled Diablo 401. Each of the specimens is described in more detail.

### Allende 3655

A full description of the Allende meteorite shower is given in reference 4, and all of the background material and analysis information has been obtained from that source and from discussions with Roy S. Clarke, Jr., of the Smithsonian Institution.

Allende 3655 is from an observed meteorite shower that occurred early in the morning of February 8, 1969, near the city of Hidalgo del Parral in the south central part of the state of Chihuahua, Mexico.

The meteorite exploded during entry and scattered fragments over a 300-km<sup>2</sup> area. A total of approximately 1800 kg (2 tons) of specimens ranging in size from 1 g to 110 kg has been recovered, making Allende one of the largest collections of recovered stony meteorites. A photograph of Allende 3655 is shown in figure 1. The 893-g specimen had a projected area for the face shown, which is the side that faced the transmit and receive horns, of approximately 105 cm<sup>2</sup>. Clearly, the surface irregularities will affect the scattering properties; however, the large frequency range (10 to 14 GHz) over which the experiment was performed had a tendency to diffuse the surface variance. As the photograph shows, the specimen is composed of three distinct components approximately as follows: fine-grained black matrix, 60 percent; chondrules, 30 percent; and white aggregates, 10 percent. A complete chemical analysis for the bulk meteorite, a dark inclusion, the matrix, a chondrule concentrate, two individual chondrules, and a single aggregate is given in reference 4 and is reproduced in table 1. The table includes results reported by Gast (ref. 5).

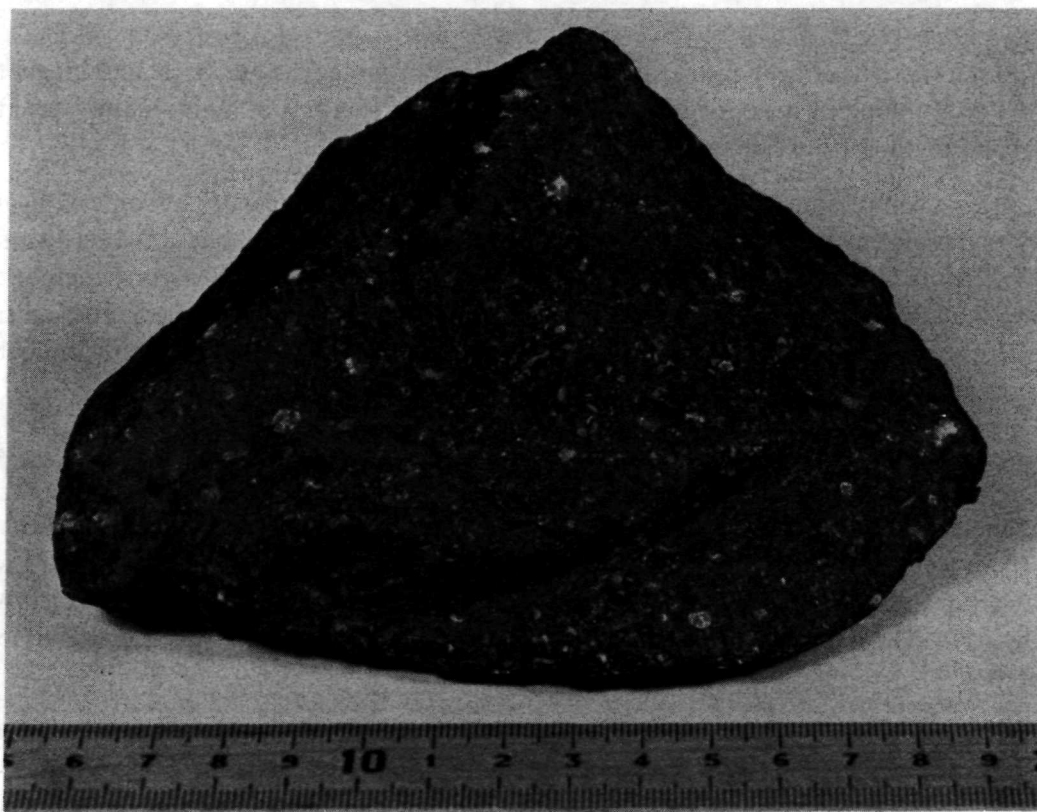


Figure 1.—Allende 3655 chondritic meteorite.

Table 1.—Analytical Data on the Allende Meteorite (E. Jarosewich, Analyst)

Compound	NMNH catalog no.								
	3509	3511	Average of the bulk analyses	3509	3510	3510	3529	3509	3510
	Bulk analyses			Dark inclusion	Matrix	Chondrules	Chondrule (type a) <sup>a</sup>	Chondrule (type c) <sup>b</sup>	Single aggregate <sup>c</sup>
SiO <sub>2</sub>	34.20	34.26	34.23	33.42	33.11	41.87	29.79	40.2	33.7
TiO <sub>2</sub>	.16	.14	.15	.13	.13	.26	.99	.12	1.3
Al <sub>2</sub> O <sub>3</sub>	3.36	3.18	3.27	2.56	3.07	5.57	31.61	17.8	26.6
Cr <sub>2</sub> O <sub>3</sub>	.51	.53	.52	.56	.55	.47	.06	.2	.1
FeO	27.22	27.09	27.15	31.48	29.68	9.44	.37	8.8	2.3
MnO	.18	.18	.18	.26	.22	.14	.02	.1	.0
MgO	24.50	24.75	24.62	23.91	21.42	34.34	10.82	15.2	13.1
CaO	2.65	2.57	2.61	3.00	2.67	4.06	26.76	5.3	21.6
Na <sub>2</sub> O	.44	.45	.45	.34	.44	.82	.11	10.6	1.1
K <sub>2</sub> O	.03	.03	.03	<.01	.03	.06	.00	.6	.05
P <sub>2</sub> O <sub>5</sub>	.23	.23	.23	.31	.25	.11	.00	n.d.	.0
H <sub>2</sub> O(+)	<.1	<.1	<.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H <sub>2</sub> O(-)	.00	.00	.00	.00	.00	.00	.00	n.d.	n.d.
C	.29	.29	.29	.37	.36	.00	.06	.02	n.d.
Cl	<sup>d</sup> n.d.	n.d.	—	n.d.	n.d.	n.d.	n.d.	<sup>d</sup> 2.0	n.d.
FeS <sup>e</sup>	3.98	4.08	4.03	1.95	5.49	1.78	.00	n.d.	n.d.
NiS <sup>e</sup>	1.64	1.56	1.60	2.26	1.05	.87	.00	n.d.	n.d.
CoS <sup>e</sup>	.08	.08	.08	.06	.09	.03	n.d.	n.d.	n.d.
Fe	.15	.19	.17	n.d.	.40	n.d.	n.d.	n.d.	n.d.
Ni <sup>e</sup>	.32	.40	.36	n.d.	.85	n.d.	.03	.05	.06
Co <sup>e</sup>	.01	.01	.01	n.d.	.02	n.d.	n.d.	n.d.	n.d.
Total	99.95	100.02	99.98	100.61	99.83	99.82	100.62	<sup>f</sup> 100.6	99.9
D, g/cm <sup>3</sup>			3.65	n.d.	n.d.	n.d.	3.25	2.80	3.18
Total Fe	23.85	23.84	23.85	25.71	26.56	8.47	.29	6.82	1.76
$\frac{100 \text{ FeO}}{\text{FeO} + \text{MgO}}$			38	42	44	13	2	25	9

Values are in weight percent unless otherwise indicated.

n.d. = not determined.

<sup>a</sup>1.5-g sample weight.

<sup>b</sup>0.31-g sample weight.

<sup>c</sup>Gast et al. (1970) reported the following results (ref. 5) on a similar inclusion (all in ppm): K, 96.4; Rb, 3.5; Sr, 180; Ba, 47.3; La, 4.63; Ce, 11.5; Nd, 8.40; Sm, 2.82; Eu, 1.30; Gd, 3.87; Dy, 4.90; Er, 3.44; and Yb, 3.96.

<sup>d</sup>M. Quijano-Rico (private communication), of the Max-Planck-Institut, Mainz, determined Cl by neutron activation, obtaining 224 ppm in bulk sample and 1.5 percent in chondrule type c. The difference between the 1.5- and 2.0-percent value is undoubtedly due to our use of a gravimetric method with a very small sample (33 mg).

<sup>e</sup>Calculated on the basis of microprobe data for metallic phase (percent): Ni, 68; Fe, 31; and Co, 1.6. Metallic Fe was determined chemically and metallic Ni and Co assigned on the basis of this analysis. The remaining Ni and Co were calculated as sulfides. The remaining S was calculated as FeS.

<sup>f</sup>Total of 100.99 corrected by 0.45, the Cl = 0.

## Colby 618

The Colby meteorite fell on July 4, 1917, within the corporate limits of Colby in central Wisconsin (ref. 6).

Macroscopically, the specimen is light gray in color with small white chondrules and darker gray chondrules intermixed throughout. One of the surfaces of the specimen has been sawed and polished,



Figure 2.—Colby 618 chondritic meteorite.

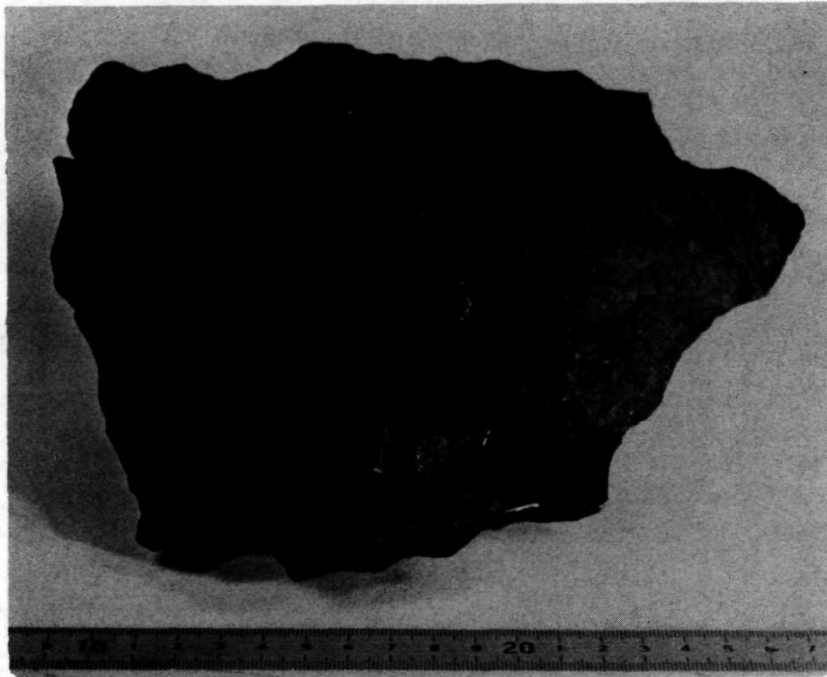


Figure 3.—Diabolo 401 nickel-iron meteorite.

and on this surface bright shiny granules of metal are clearly visible. An analysis of the stone is found in reference 6, which indicates about a 45-percent silica content, 16 percent ferrous oxide, and 32 percent magnesium oxide, with approximately 1 percent iron-nickel alloy. The Colby specimen of 2.06 kg has one side which clearly had been exposed during atmospheric entry and shows a fusion crust that is smooth and dark gray in color. The remaining sides, except the polished side, are relatively flat and had been exposed by fracture. The side that had been exposed during entry provided a relatively good reflecting surface for microwave energy, but since this feature would not exist on interplanetary materials, this side was not used for the scattering experiment. A photograph of the Colby 618 specimen is shown in figure 2.

### Diablo 401

The Diablo 401 specimen was found near the famous Canyon Diablo, or Meteor Crater, near Flagstaff, Ariz. The 16.8-kg specimen is composed principally of nickel-iron alloy (ref. 7). The external surface of the specimen (shown in fig. 3) is quite rough with several large spherical holes 2 to 3 cm in diameter and 1.5 to 3 cm deep. These holes were of the proper dimensions to present resonant effects at the frequencies of the experiment, and at some angles they tended to focus the microwave energy so that the sample appeared to be of very large scattering cross section. When the specimen was moved slightly, the reflected energy scattered away from the receiver and the specimen appeared to be of small cross section. Because of these variations, the data obtained from the Diablo specimen cannot be used to establish any meaningful scattering cross section.

### DESCRIPTION OF THE TEST FACILITY

The scattering experiment was performed using the GSFC Anechoic Chamber Facility, modified slightly so that separate transmit and receive horns could be employed. The physical layout is depicted in figure 4.

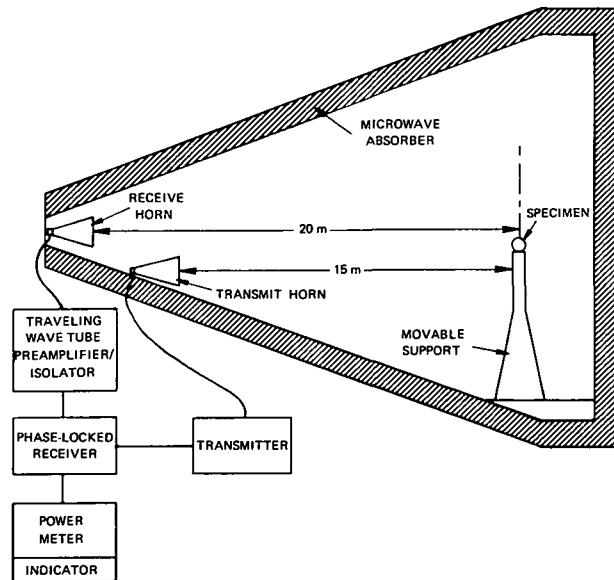


Figure 4.—Radar scattering test setup.



The transmitter was a wideband sweep generator operating in the cw mode at frequencies from 10 to 14 GHz. The frequency and power were continuously monitored, and a small amount of signal (-20 to -30 dBm) was coupled to the receiver as a reference to maintain phase lock between the receiver and the transmitter. The transmitter power  $P_t$  was maintained at 40 mW throughout the measurements.

Two metal calibrating spheres were used as standards. One was 12 cm in diameter and the other was 8 cm in diameter. Both were machined from solid blocks of aluminum to a tolerance of  $\pm 0.025$  cm.

The specimens or calibrating spheres were supported on a movable mounting platform whose position was varied over a 30-mm range in steps of  $2 \pm 0.1$  mm.

A low-noise traveling wave tube amplifier was used as a receiver preamplifier and isolator to prevent local oscillator power from entering the test chamber and causing interference.

## EXPERIMENTAL RESULTS

The Diablo 401 specimen produced a scattering cross section that was highly dependent upon orientation. At some orientations the cross section is much less than that of an 8-cm-diameter metal sphere; however, a slight rotation of the specimen can produce a scattering cross section much larger than that of a 12-cm-diameter metal sphere. Because of the variation in cross section, the possibility that the surface roughness and cavities may have been filled with other materials that had weathered away and the presence of rust, or iron oxide, on the surface, the specimen does not represent material which may be encountered in space. All of the scattering data are inconclusive and therefore are not presented in detail.

On the other hand, the data obtained with the Allende 3655 and Colby 618 specimens appear to present a reasonable result and can be used to estimate the probability of detecting such materials if they are present within the radar beam.

Representative data obtained in the experiment are illustrated in figure 5, which is a plot of the standing wave patterns for the two stony specimens along with the patterns of the two calibrating spheres at a frequency of 13 GHz. The results were representative of those at other frequencies.

The sphere of 8-cm diameter has a  $2\pi r/\lambda$  value of 5.78 (where  $r$  is the sphere radius and  $\lambda$  is the wavelength at the lowest frequency of 6.9 GHz) so that at the lowest frequency there may be an error as large as 20 percent attributable to long wavelength or Rayleigh scattering (refs. 8 and 9). At the highest frequency of 14 GHz,  $2\pi r/\lambda$  is 11.7 and the resonant scattering can be neglected. Likewise, the  $2\pi r/\lambda$  value at the lowest frequency for the 12-cm-diameter sphere is 8.79, so that it too is in the optical region and its scattering cross section can be taken to be approximately its projected optical area  $\pi r^2$ .

The radar range equation may be used to define the scattering cross section

$$\sigma = \frac{P_r (4\pi)^3 R_1^2 R_2^2}{P_t G_1 G_2 \lambda^2}$$

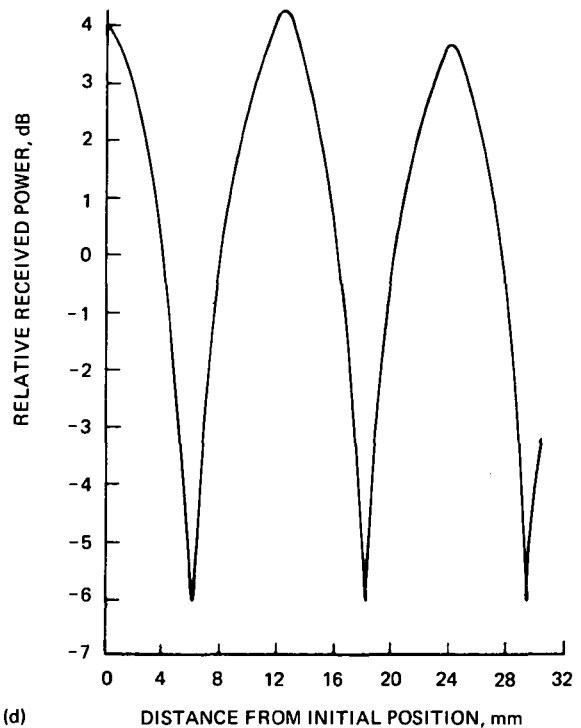
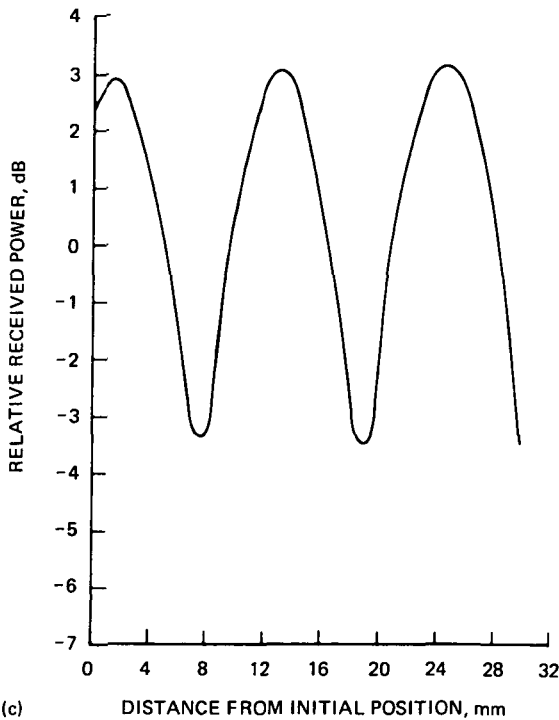
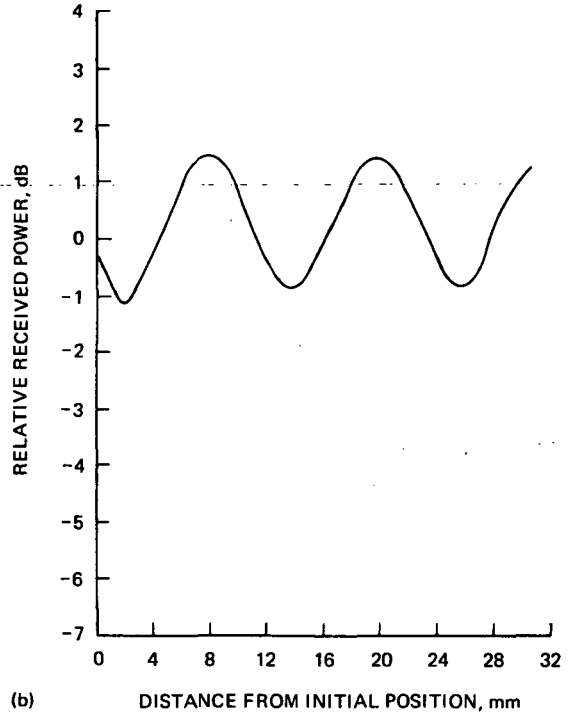
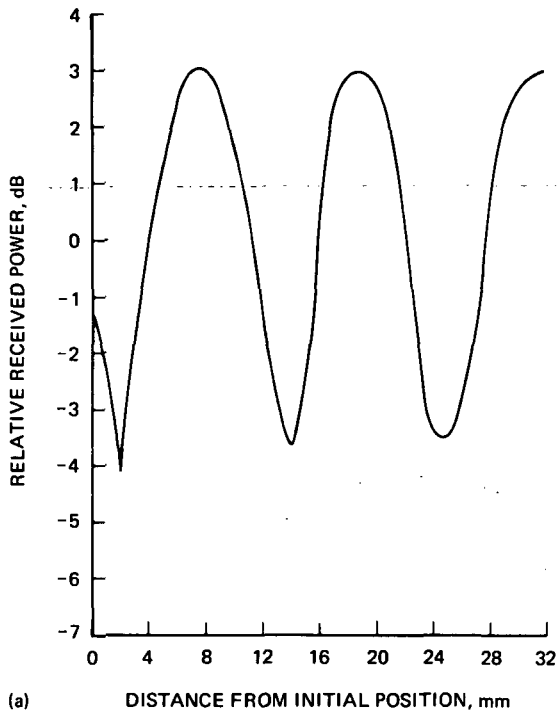


Figure 5.—Standing wave patterns at 13 GHz as support is moved. (a) Allende 3655 specimen. (b) Colby 618 specimen. (c) Calibrating sphere, 8-cm diameter. (d) Calibrating sphere, 12-cm diameter.

where

$P_r$  = power received

$P_t$  = power transmitted

$R_1$  = range from transmitter

$R_2$  = range from receiver

$G_1$  = gain of transmit antenna

$G_2$  = gain of receive antenna

$\lambda$  = free space wavelength

The variables are the scattering cross section and the power received. If the 12-cm sphere is used as a reference, the power received from the 8-cm sphere, the Allende 3655 specimen, or the Colby 618 specimen can be equated to the received power that would be reradiated or reflected by a spherical metal target of equivalent radius  $r_{eq}$  by the following equation:

$$r_{eq}^2 = r_{ref}^2 \frac{P_{eq}}{P_{ref}} = 36 \frac{P_{eq}}{P_{ref}} \quad \text{cm}^2$$

As an example, for the 8-cm sphere the power ratio should be 4/9, or 3.5 dB less than that received with the 12-cm sphere in place. Figure 6 displays the results of the experiment in terms of replacing

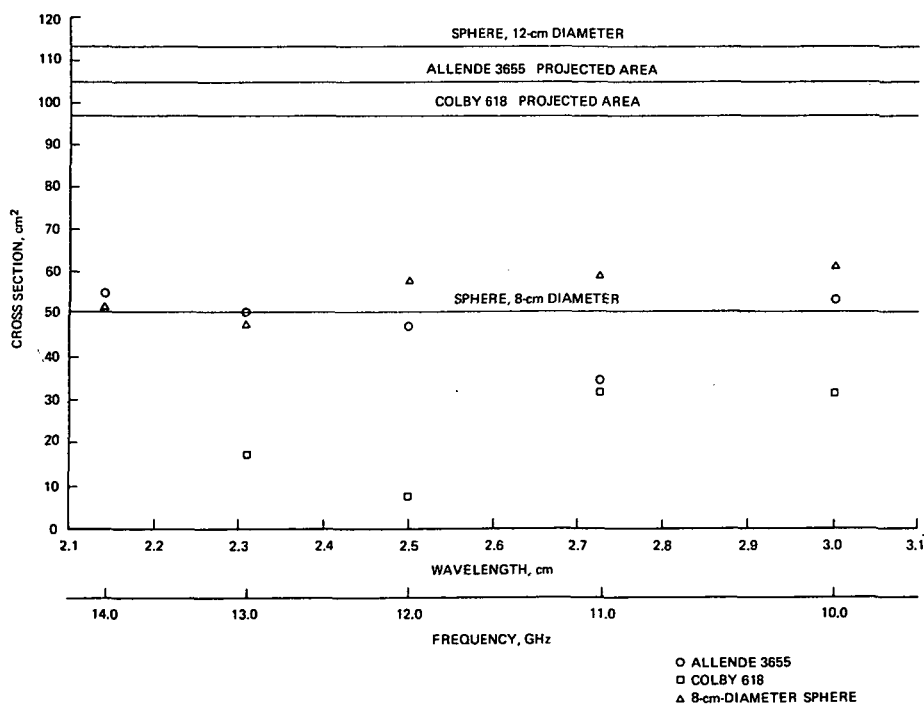


Figure 6.—Comparison of measured and calculated cross sections.

the specimens with metal spheres of equivalent diameter, neglecting effects of the resonant region (Mie region) and the Rayleigh region (long wavelength region). The data indicate that meteorites of the Allende type may present a microwave scattering cross section of approximately 47 percent of their projected optical cross section and that meteorites of the Colby type may present a scattering cross section of approximately 31 percent of their optical cross section.

## **ACKNOWLEDGMENTS**

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National Aeronautics and Space Administration  
Greenbelt, Maryland, March 30, 1972  
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## Appendix

### PROBABILITY OF DETECTING A PARTICLE IN THE ASTEROID BELT

The microwave scattering cross section data for meteorites are useful in determining the parameters of a radar particle detector that could be used to count the density of material in some particular region of space. For example, one can determine the probability of radar detection of a particle approximately the size of Allende 3655 in the asteroid belt. The conventional model (ref. 10) of particle density versus particle mass given by

$$\log S_a = -0.84 \log m - 15.79$$

where

$$S_a = \text{spatial density, } m^{-3}$$

$$m = \text{particle mass, g}$$

can be used to determine the volume that will contain one particle whose mass is approximately the same as Allende 3655. The volume that should contain one such particle is

$$\frac{1}{\text{antilog}(-0.84 \log m - 15.79)} \approx 2 \times 10^{18} \quad m^3$$

The time required for a radar beam to sweep out this volume is given by

$$t = \frac{V}{vR^2} \tan \frac{\theta}{2}$$

where

$$t = \text{time, s}$$

$$V = \text{volume containing one particle, } m^3$$

$$v = \text{relative velocity between spacecraft and particle, } m \text{ s}^{-1}$$

$$R = \text{maximum detectable range, m}$$

$$\theta = \text{radar 3-dB beamwidth}$$

If values are assumed for some of the radar parameters, then  $R^2$  can be found from the radar

range equation:

$$R^2 = \left[ \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 kTB S/N} \right]^{1/2} = 8.38 \times 10^8 \quad \text{m}^2$$

$$\theta = 1.2 \frac{\lambda}{D} = 9 \times 10^{-3} \quad \text{rad}$$

$$\tan \frac{\theta}{2} = 4.5 \times 10^{-3}$$

$P_t$  = power transmitted =  $10^3$  W

$G$  = antenna gain = efficiency  $(\pi D/\lambda)^2 = 0.5(\pi D/\lambda)^2 = 8.77 \times 10^4$

$D$  = antenna diameter = 4 m

$\lambda$  = wavelength =  $3 \times 10^{-2}$  m

$\sigma$  = radar cross section of target =  $5 \times 10^{-3}$  m<sup>2</sup>

$kTB$  = receiver noise

$k$  = Boltzmann constant =  $1.38 \times 10^{-23}$  J K<sup>-1</sup>

$T$  = receiver effective noise temperature = 300 K

$B$  = receiver bandwidth = 1 MHz

S/N = signal-to-noise power ratio = 6

If the relative velocity between the radar and the particles is assumed to be  $1.5 \times 10^4$  m s<sup>-1</sup>, then detection of one particle of Allende 3655 size should occur in a period

$$t = \frac{V}{vR^2} \tan \frac{\theta}{2} = 3.61 \times 10^7 \text{ s} = 417.5 \text{ days}$$

Consequently, particles as large as Allende 3655 will be encountered infrequently in the asteroid belt if the accepted model of particle number density as a function of particle mass is correct.

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