A Study of the Microwave Reflective Properties of Aerosols

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A STUDY OF THE MICROWAVE REFLECTIVE PROPERTIES OF AEROSOLS

BY

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B.S.E., FLORIDA TECHNOLOGICAL UNIVERSITY, 1972

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies program of Florida Technological University, 1973

Orlando, Florida
A STUDY OF THE MICROWAVE REFLECTIVE PROPERTIES OF AEROSOLS

Mr. Paul Speh

ABSTRACT

This thesis deals with the reflective properties of selected aerosols subjected to microwave radiation. The backscatter cross section of a sphere is developed analytically as a basis for experimental verification. The most pertinent material parameters necessary for maximum reflectivity are discussed and used to justify the aerosols selected for the experiment.

The experimental procedures and the equipment calibration techniques are prefaced by a discussion of the design and the construction of the aerosol chamber and the microwave source apparatus.

The experimental results and the calculated backscatter cross section of the aerosols listed are examined. Conclusions are discussed and applications of the results are offered for consideration.

Approved by: Ernst E. Erickson
Director of Thesis
ACKNOWLEDGEMENTS

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# LIST OF SYMBOLS

1. **cm.** centimeter  
2. **db.** decibel  
3. **\( \varepsilon_0 \)** permittivity of free space  
4. **\( j_n \)** spherical Bessel functions \(^{\text{reference 8}}\)  
5. **\( k_0 \)** wave number or propagation constant  
6. **mg.** milligram  
7. **\( \mu_0 \)** permeability of free space  
8. **\( \omega \)** angular frequency \((2\pi \text{ times frequency in Hertz})\)
CHAPTER I

INTRODUCTION

A. Background of Problem

The scattering of electromagnetic radiation by the atmosphere was first studied on a scientific basis by the sixteenth century scientist, Leonardo Da Vinci, who postulated that the brightness and color of the sky were due to the reflection of sunlight by the particles in the air. (1)

Later, scientists such as Brucke (1853), Govi (1860) and Tyndall (1869) studied artificial atmosphere in order to better understand the scattering of light by small particles. (1) Their experiments, in particular those of Tyndall, showed conclusively that scattering of light by tiny particles did account for the polarization and color of skylight.

The growing interest in light scattering was taken up by Lord Rayleigh in 1871. Rayleigh used the results of Tyndall's work combined with his own research and concluded that the incident electromagnetic wave in effect created an oscillating dipole of the particle which oscillated in sync with the incident field. (1)

The particle nature responsible for the scattering was considered by numerous researchers during the 1800's who assumed the particle composition to be ice or water, while Rayleigh even suggested common salt. (1) There were other scientists who considered the scatterers to be mineral particles and this speculation led eventually to
experiments on a smaller scale in the laboratory to study the nature of this scattering.

The problem of scattering by a sphere was studied in more detail by Clebsch (1863) who obtained the general solution for the elastic wave equation in terms of the vector wave function. Maxwell-Garnett (1904) studied particles smaller than the wavelength and used the relation established by Lorentz (1879) between polarizability and dielectric constant to explain his concept of spherical scattering.

Debye (1908) considered spherical scattering and used a potential function (Debye potential) rather than using the field vector components. Mie (1908) published a paper concerned with the colors produced by colloidally dispersed metal particles. He was careful not to restrict the particle size to less than the incident wavelength. (1)

Thompson (1893) published formulas for scattering by a perfectly conducting sphere with no size restriction derived from electromagnetic theory. He utilized the vector wave equation solution given by Lamb in 1881. The case of the dielectric sphere was taken up by Love (1899) in his paper, "The Scattering of Electromagnetic Waves by a Dielectric Sphere."

On through the twentieth century investigators probed into the mechanisms of scattering generally from a theoretical viewpoint. The real significance of the idea of backscatter or reflection from objects was to be realized in 1930 when the United States and Great Britain began to study the use of radio waves for object detection and ranging, RADAR. (2)

Radar became a necessity during World War II where the targets (scattering obstacles) were large and of very irregular shape.
Meteorology benefitted from the development of radar by utilizing the reflections of the transmitted signal from cloud formations and from rain drops. After the war scientists became interested in the validity of the theory concerning the backscatter cross-section of small spheres. One such investigator was Aden (1950) who published works concerned with the reflectivity of metal spheres and spherical rain drops of sizes comparable to the incident electromagnetic wavelength. His work centered around the theory of backscattering by Mie. Aden utilized logarithmic derivative functions in order to simplify the determination of scattering amplitude coefficients. (3)

In 1959 King and Wu (4) published a book which extensively discussed several problems involved in the experimental phase of obstacle scattering phenomena. These problems were the measurement techniques and the quality of data obtained from the techniques.

Since the beginning of the space program, problems presented by the ion sheath covering the re-entry vehicles used by the United States have created a great deal of interest in research with plasmas. Plasma is a particular medium for the propagation of electromagnetic waves created through medium interaction of electrons with themselves. The protons and neutrons are in a rest state compared to the interacting electrons. (5) Microwave transmission and reflection experiments have found extensive use in the study and diagnosis of plasmas.

Most recent attention has been directed toward the use of radar and tropospheric scatter reflection from natural aerosol environments in the upper atmosphere with most of the research being accomplished under actual field conditions. (6) To study the reflective properties
of aerosol environments in a large space, several projects sponsored by the United States government have been conducted using rockets as delivery and disseminating devices for various conducting aerosols. One such project conducted by Marmo in 1956 used radar to study a nitric oxide gas cloud which was observed on radar more than 10 minutes. Cesium had been utilized to create a detectable cloud at 82 Kilometers. (2) The program "Firefly" conducted from 1959-1963 used sulfur hexafluoride carried aloft by an Aerobee vehicle for investigation of the F-layer of the ionosphere. (2) Project "Red Lamp" also released cesium at 120 Kilometers for scattering experiments.

Foppl, also interested in radar reflection from air borne material, reported on the use of barium and strontium in the Sahara Desert and in Sardinia in 1964. The conclusions drawn from these attempts at the generation of artifically ionized reflective clouds demonstrate that the use of aerosol environments for the reflection of radio and radar signals is feasible on a larger scale.

B. Purpose of the Study

In light of past and present research in the area of aerosol particle scattering, it is the purpose of this study to physically examine the reflective properties of certain aerosol materials and to determine which of these materials possess the required properties of an acceptable electromagnetic wave reflector.
CHAPTER II

A. Mie Theory for the Backscatter From a Sphere

The backscatter cross section, \( \sigma \), is a lumped measure of the ability of a scattering obstacle to reradiate energy in the direction of the source (3). The cross section discussed is termed quasi-monostatic since the transmitting antenna and the receiving antenna are separate but very close together as opposed to the bistatic case where the two antennae are separated by some distance. It is assumed that the target considered in this paper is approximated by a collection of \( N \) discrete scatterers and that the distance \( r' \) from the source to the scatterer is large compared to the radius \( a \) of just a single scatterer.

A single sphere is irradiated by a beam of polarized microwave radiation with the electric vector polarized as shown in Figure 1. Since the particle size is small compared to the incident wavelength, the instantaneous field experienced by the sphere is considered uniform over its extent. The problem studied is that of an isotropic homogeneous dielectric sphere in a uniform electromagnetic field.

The theory is that of Mie for scattering from a sphere (2). The solution utilizes vector wave functions and a spherical coordinate system. The use of boundary value methods for determination of the series terms for the scattered field provides generality regardless of sphere composition.

The coordinate system and geometry used for analysis are given in Figure 1.
Conventions used in Figure 1 are:

(a) The plane wave is incident moving in the -z direction.

(b) Harmonic time dependence assumed.

(c) $\exp(-\omega t)$ will be suppressed.

(d) The electric field vector of the incident field is polarized in the x direction.
The point, P, coordinates \((r', \theta', \phi')\) is outside the sphere \((r'>>a)\). The incident field is then

\[
\vec{E}^i = E_0 \hat{\mathbf{r}} e^{-ik_o z}
\]

(2.1)

\[
\vec{H}^i = \sqrt{\frac{\varepsilon_0}{\mu_0}} E_0 \hat{\mathbf{z}} e^{-ik_o z}
\]

(2.2)

The Mie solution for the scattered field at point P, at angular \(\omega\), is given by (7)

\[
\vec{E}^s(P, \omega) = E_o \sum_{n=1}^{\infty} \left( A_n \vec{M}_{n,1n} + B_n \vec{N}_{n,1n} \right)
\]

(2.3)

\[
\vec{H}^s(P, \omega) = -i \sqrt{\frac{\varepsilon_0}{\mu_0}} E_o \sum_{n=1}^{\infty} \left( B_n \vec{M}_{n,1n} + A_n \vec{N}_{n,1n} \right)
\]

(2.4)

where \(A_n\) and \(B_n\) are constants determined only by the sphere properties and independent of the scattering direction.

\(\vec{M}_{o,1n}\) and \(\vec{N}_{o,1n}\) are spherical vector wave functions dependent only on P and are given by

\[
\vec{M}_{o,1n} = \frac{1}{\sin \theta} \hat{\mathbf{r}} h_n^{(1)}(k_o r') P_n'(\cos \theta') [\sin \phi'][\hat{\mathbf{\phi}}]
\]

(2.5)

\[
\vec{N}_{o,1n} = \frac{n(n+1)}{k_o r'} h_n^{(1)}(k_o r') P_n'(\cos \theta') [\sin \phi'][\hat{\mathbf{\phi}}] \hat{\mathbf{r}}
\]

(2.6)

The upper subscripts, upper signs, and upper trigonometric functions in the brackets are used when appropriate in equations (2.5) and (2.6).

The spherical Hankel function, \(h_n^{(1)}(k_o r')\), is given by the relation

\[
h_n^{(1)}(k_o r') = \sum_{\nu=0}^{\infty} \frac{i^{n-\nu} e^{ik_o r'} \Gamma(n+1+\nu)}{\Gamma(n+1-\nu)} (2ik_o r')^{-\nu}
\]

(2.7)
The associated Legendre functions are defined as

\[ P_n'(\cos \theta') \cdot \sin \theta' \pi_n(\cos \theta') \]  

(2.8)

and

\[ \frac{d}{d\theta'}[P_n'(\cos \theta')] = \tau_n \cos \theta' \]  

(2.9)

where

\[ \pi_n(\cos \theta') = \cos \theta'[\frac{2n-1}{n-1}]\pi_{n-1}(\cos \theta') - [\frac{n}{n-1}]\pi_{n-2}(\cos \theta') \]  

(2.10)

The series of equations (2.3) and (2.4) are exact for scattering in any direction and for any distance from the sphere. For the far field case where \( r' \gg a \), the scattered field at point \( P \) becomes

\[ \bar{E}^a(P, \omega) = E_o \frac{e^{ikr'}}{k r'} [\cos \phi S_1(\theta') \hat{\theta} - \sin \phi S_2(\theta') \hat{\phi}] \]  

(2.11)

where

\[ S_1(\theta') = \sum_{n=1}^{\infty} (-1)^{n+1} [A_n \frac{P_n'(\cos \theta')}{\sin \theta'} + iB_n \frac{d}{d\theta'} P_n'(\cos \theta')] \]  

(2.12)

and

\[ S_2(\theta') = \sum_{n=1}^{\infty} (-1)^{n+1} [A_n \frac{d}{d\theta'} P_n'(\cos \theta') + iB_n \frac{P_n'(\cos \theta')}{\sin \theta'}] \]  

(2.13)

\( S_1(\theta') \) and \( S_2(\theta') \) are the complex far field amplitudes of the scattered radiation in the \( \theta \) and \( \phi \) polarization directions.

For far field regions, the local scattered wave is planer and therefore only the electric field \( E \) is given. The \( H \) field is related to the \( E \) field and is given by

\[ |H| = \sqrt{\frac{\varepsilon}{\mu_0}} |E| \]  

(2.14)
Let the scattering function be defined as

\[ F(\Theta, \phi') \hat{\tau} = \cos \phi' S_1(\Theta') \hat{\Theta} - \sin \phi' S_z(\Theta') \hat{\phi} \]  

(2.15)

where \( \hat{\tau} \) is a unit vector in the polarization direction of the scattered field at \( P \). The scattering cross section in any polarization direction, \( \hat{n} \), for an incident polarized wave in the x direction is given by

\[ \sigma_n(\Theta, \phi') = \frac{4\pi}{k_o^2} |F(\Theta, \phi')|^2 |\hat{\tau} \cdot \hat{n}|^2 \]  

(2.16)

For the case of backscatter where \( \theta = 0 \), \( F(\theta', \phi') \) is defined as

\[ F(\theta, \phi') = F(0, \phi') = F(0) \]  

(2.17)

and

\[ S_z(0) = S_z(\theta) = F(0) \]  

(2.18)

The scattering function then takes the form

\[ F(0) \hat{\tau} - F(0) \hat{\phi} = -\hat{\chi} \sum_{n=1}^{\infty} (-i)^{n+1} \frac{n(n+1)}{2} (A_n + i B_n) \]  

(2.19)

and the backscattered field is polarized in the same direction as the incident field when the incident polarization is linear. For a sphere, the backscatter cross section is then

\[ \sigma(\theta) = \frac{4\pi}{k_o^2} |F(0)|^2 \]  

(2.20)
B. Backscatter from a Dielectric Sphere.

In the case of the dielectric sphere, the wave number $k_1$, is

$$k_1 = \omega \sqrt{\varepsilon \mu} = k_0 m_1$$  \hspace{1cm} (2.21)

where $m_1$ is the refractive index of the medium and is given as

$$m_1 = m_r + im_i$$  \hspace{1cm} (2.22)

Equation (2.22) defines the case of the lossy sphere and $m_1 = m_r$ covers the lossless case. For the situation considered here, $\mu_0 = \mu_1$.

The coefficients of the Mie solution for the dielectric sphere are given as (2)

\[
A_n = (-i)^n \left( \frac{2}{\pi} \right)^{n-1} \left[ j_n(k_0a)[k_{a,n}(k_0a)]' - j_n(k_1a)[k_{a,n}(k_1a)]' \right] 
\]

\[
B_n = (-i)^n \left( \frac{2}{\pi} \right)^{n+1} \left[ h_n(k_0a)[k_{a,n}(k_0a)]' - j_n(k_0a)[k_{a,n}(k_0a)]' \right] 
\]

The bracketed terms [ ] with the prime denote differentiation with respect to either $k_0a$ or $k_1a$, depending on which appears in the brackets.

For an arbitrary index of refraction $m_1$, the region of $k_1a < 0.8$ is considered and the coefficients $A_n$ and $B_n$ are expanded into a power series in $k_0a$. From Stratten(8), page 571, it is found that only $A_1, A_2$ and $B_1, B_2$ are necessary for preservation of terms up to and including $(k_0a)^5$. For $\mu_1 = \mu_0$, the coefficients are [with necessary corrections (2)]
A_1 = \frac{1}{30} \left( m_i^2 - 1 \right) (k_o a)^5 \quad (2.25)

A_2 = 0 \quad (2.26)

B_1 = i \left[ \frac{m_i^2 - 1}{m_i^2 + 2} (k_o a)^3 + \frac{3}{30} \frac{(m_i^2 - 1)(m_i^2 - 2)}{(m_i^2 + 2)^2} (k_o a)^5 \right] \quad (2.27)

B_2 = \frac{1}{18} \frac{m_i^2 - 1}{m_i^2 + 3} (k_o a)^5 \quad (2.28)

With these coefficient values determined, the far field backscatter function becomes

\[ F(\theta) = \frac{m_i^2 - 1}{m_i^2 + 2} (k_o a)^3 + \left[ \frac{3}{30} \frac{(m_i^2 - 1)(m_i^2 - 2)}{(m_i^2 + 2)^2} - \frac{1}{6} \frac{(m_i^2 - 1)}{2(m_i^2 + 3)} \right] (k_o a)^5 \quad (2.29) \]

For small values of $k_o a$, as in the case of an aerosol particle, and in the frequency range of interest, only the first term is significant and the result is the backscatter cross section for small dielectric spheres are given by

\[ \sigma(\theta) = 4 \pi a^2 \left| \frac{m_i^2 - 1}{m_i^2 + 2} \right|^2 (k_o a)^4 \quad (2.30) \]

While an explanation of the backscatter cross section was given in the beginning of this chapter, the terms were not fully defined. The actual backscatter cross section of an obstacle is defined to be the ratio of the total power $P_{\text{isotropic}}$ reradiated by a fictitious isotropic scatterer (that maintains the same field $E^s$ in the direction toward the source) to the real magnitude $S^i$ on the Poynting vector of the incident plane wave at the obstacle (4). This then gives

\[ \sigma_B = \frac{P_{\text{isotropic}}^s}{S^i} = \lim_{r \to \infty} 4\pi r^2 \frac{|E^s|^2}{|E|^2} \quad (2.31) \]
A. Material Selection Criteria

In order to provide a varied range of materials for investigation, it was necessary to determine the parameters most pertinent to microwave reflection in the frequency range chosen for study. In addition, the size of the aerosol particles and the method of dissemination had to be determined. Secondary properties of the materials such as toxicity, corrosiveness, and chemical stability also had to be considered in the selection.

The specific substances chosen are listed in Table 1. The relative dielectric constant of each material is given in column 1 of the Table. Comments on material properties given in the Table were considered secondary to the material dielectric constant. Substances such as nitrobenzene and ferrocyanic chloride were tested in the chamber but were found to be highly toxic and corrosive, respectively. The data that could be obtained from these substances were not considered pertinent to this report since the purpose of the paper is to provide information concerning the practical application of aerosols as microwave reflectors. Materials were selected that could be put into a stable liquid or powder form.
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<tr>
<th>Material</th>
<th>Dielectric Constant @ 25°C</th>
<th>Comments on Material Properties</th>
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<tr>
<td>1. Ethylene Glycol</td>
<td>37.10</td>
<td>Slightly toxic</td>
</tr>
<tr>
<td>2. Water (H₂O)</td>
<td>78.54</td>
<td></td>
</tr>
<tr>
<td>3. Barium Titanate (BaTiO₃)</td>
<td>1020 (approx.)</td>
<td>Supplied only in approx. particle size of 5 microns</td>
</tr>
<tr>
<td>4. Ozone + Water Vapor</td>
<td>2.27</td>
<td>Ozone generation rate - 50 mg./hr.</td>
</tr>
<tr>
<td>5. Benzene (C₆H₆)</td>
<td>2.27</td>
<td></td>
</tr>
<tr>
<td>6. Toluene (C₇H₈)</td>
<td>2.79</td>
<td>99.5% pure</td>
</tr>
<tr>
<td>7. Methanol</td>
<td>32.63</td>
<td>Poisonous</td>
</tr>
<tr>
<td>8. Cryolite (Na₃AlF₆)</td>
<td>174.5</td>
<td>Greenland Felspar used as laser mirror coating</td>
</tr>
</tbody>
</table>

**TABLE 1.**

SELECTED AEROSOLS AND THEIR DIELECTRIC CONSTANTS
(Reference 10)
Materials were chosen for a variety of dielectric constants values. The dielectric constant of a material is the permittivity of the material measured with respect to the permittivity of free space from the relationship

\[ \varepsilon_R = \frac{\varepsilon}{\varepsilon_0} \]  

(3.1)

where \( \varepsilon \) is the material permittivity and \( \varepsilon_0 \) is the permittivity of free space. The relationship relating the dielectric constant of the material to its wave propagation properties is given by

\[ k = \omega \sqrt{\varepsilon \mu} \]  

(3.2)

where \( k \) is defined as the propagation constant or wave number of the material and \( \varepsilon \) is the permittivity of the material as given by equation (3.1). The parameter \( \mu \) is the magnetic permeability of the substance given by

\[ \mu = \mu_R \mu_0 \]  

(3.3)

where \( \mu_0 \) is the permeability of free space and \( \mu_R \) is the relative permeability of the material. For the substances studied,

\[ \mu_R = 1 \]  

(3.4)

For free space, the wave number is given by

\[ k_0 = \omega \sqrt{\varepsilon_0 \mu_0} \]  

(3.5)

From equations (3.2) and (3.5), the refractive index \( m \), is determined as

\[ m = \frac{k}{k_0} \]  

(3.6)
where the parameter $m$ may be complex as

$$m = m_{\text{real}} + i m_{\text{imaginary}}$$  \hspace{1cm} (3.7)

For the lossless dielectric sphere, equation (3.7) has only a real part and equation (3.6) gives

$$m = \sqrt{\varepsilon_R}$$  \hspace{1cm} (3.8)

Applying this result to equation (2.30), the backscatter cross section becomes

$$\sigma(\theta) = 4\pi a^2 \left| \frac{\varepsilon_R - 1}{\varepsilon_R + 2} \right|^2 (k_0 a)^4$$  \hspace{1cm} (3.9)

B. Aerosol Particle Size

In order to properly study the reflective properties of the aerosols, it was decided that the size range of approximately 1-100 microns would be tested in the chamber. Due to the polydispersity of the aerosols generated, the ranges chosen were 1-25 microns, 25-75 microns, and 75-100 microns. Preliminary experiments indicated that particle size in the range 1-50 microns provided questionable meter readings.
CHAPTER IV

A. Microwave Source and Receiving Apparatus

The microwave equipment necessary for proper measurement of the backscatter cross section of the materials studied is shown in Figure 3. The equipment shown in Figure 2(a) generated the source signal. The microwave equipment utilized in the experiment was operated in the X-band region which covers 8.0 to 12.4 Gigahertz. The frequency chosen for the measurements was 8.98 Gigahertz or a wavelength of 3.34 cm. This signal was generated by the klystron tube type Varian 6315. The klystron oscillator was modulated with a 1000 Hertz signal for detection in the receiver. The isolator shown in Figure 2(a) served to reduce the loading effects on the klystron oscillator. The operating frequency was measured by the tuned cavity frequency meter. In order to monitor the level of the transmitted wave, the 10 decibel directional coupler was used as shown to sample a small quantity of the signal for measurement with the power meter. Separate X-band horns were used for the transmitting and receiving horns.

The diagram of Figure 2(b) shows the receiving apparatus used to monitor the backscattered signal from the scattering medium. The slide tuner served to provide a small tuning range over which the receiving system could be peaked to the received signal. The detector shown was a detecting diode in a guide mount. The 1000 Hertz modulation signal was fed from this unit and monitored on the SWR meter.
(a) Transmitting Apparatus

(b) Receiving Apparatus

FIGURE 2.
MICROWAVE TRANSMITTING
AND
RECEIVING APPARATUS
B. Aerosol Chamber and Equipment Configuration

The need for a chamber for the containment of the aerosol being tested was determined during preliminary equipment setup. With no chamber it was found that residual background reflections were too high to allow data to be recorded properly. A chamber was then designed with microwave absorbing material used on the four walls and the rear of the chamber to attenuate the background reflections as much as possible.

The chamber was constructed of 1/4" plexiglas and measured 2 ft. by 2 ft. by 3 ft. The walls and the rear of the chamber were lined with 20 decibel rubber coated absorbing material. A small square hole was cut in the side of the chamber to provide easier access with the aerosol generator. The front of the chamber was provided with an opening for the transmitting and receiving horns. The pedestal shown in Figure 3 was only utilized during the calibration phase of the experiment. The complete physical layout of the chamber and the measuring equipment are shown in the same figure.

Other noise in the system was traced to the diode in the detector mount and after many changes, a reasonably quiet diode was selected. By selecting the proper level of transmitted signal, the diode noise could just be overcome and the sensitivity of the system still maintained.

C. Aerosol Generator

The physical study of an aerosol microwave reflector dictated the use of a suitable aerosol generator and laboratory test procedures. The method of generation chosen was that of atomization of a liquid
FIGURE 3

PHYSICAL LAYOUT OF AEROSOL CHAMBER AND MEASURING EQUIPMENT
by the gas propellant Freon. The mechanics of the generator are shown in Figure 4. The aerosol produced by the generator in this Figure is a polydisperse medium as opposed to a monodisperse medium where all the particles generated are the same size. For this reason a mean particle size was used for determination of the backscatter cross section of one particle.

The material to be atomized was placed in the small container and the Freon gas from the gas container drew the liquid carrier up the tube to form a thin liquid thread. This thread was then torn apart to form small liquid spheres. The droplets formed in the resulting aerosol varied in size. The approximate size of the particles was determined by the orifice hole diameters used in the generator. The smaller the hole, the finer the particle size generated. The small brass inserts shown in Figure 4 were drilled to the necessary diameter and were changed each time a new series of materials of a different particle size range were put through the chamber.

D. Calibration of the Chamber

In order to provide meaningful data on the tested materials, it was necessary to have a reference scattering obstacle of known cross section. The object chosen was a conducting aluminum disk (assumed perfectly conducting) of radius 1.46 cm. and thickness 0.8 mm. This obstacle was chosen since values of its cross section are found in numerous references (2) and (4). From reference (2), the backscatter cross section of the disk for a signal wavelength of 3.34 cm. and the angle from normal incidence equal to 5 degrees was found to be
FIGURE 4
AEROSOL GENERATOR MECHANICS
The standard disk was mounted on a small styrofoam pedestal which was transparent to the microwave signal and placed in the chamber as shown in Figure 5.

During the calibration the pedestal was placed at a distance of 15 inches from the transmitting horn and the standard disk was adjusted so that a maximum reflected signal was observed on the receiver monitor. In the experiment, the aerosol was injected into the chamber at this distance after the standard and the pedestal were removed.
FIGURE 5.
REFERENCE STANDARD MOUNTED
ON TEST PEDESTAL
CHAPTER V

A. Experiment Basis

The basis for the experimental portion of the project was the selection of a reference target with a known backscatter cross section and then comparing the measured reflected signal from the aerosols tested with this reference. For the given cross section of the standard and under the initial equipment conditions covered in the previous chapter, the reference signal level was measured and recorded at the beginning of each test. The aerosol was then injected into the chamber through the side access hole for a fixed period of time. The received signal level in decibels was noted and recorded. This reading was compared to the reference signal level and the value of the reflected signal below the value of the reference signal was recorded. The meter reading was then observed for a period sufficiently long to allow the aerosol to settle and the meter to return to its initial value.

B. Experimental Procedure

The experiments discussed in this chapter required careful preparation of the materials, the measuring equipment, and the chamber. Quasimonostatic measuring techniques made proper equipment location a necessity. Once the apparatus was set up for the experiment, only the calibration pedestal, the calibration standard and the chamber access door were moved. The access door was provided
to allow cleaning of the chamber walls and the microwave absorbing material after the testing of each aerosol. Any accumulation of aerosol material residue on the chamber absorbing walls gave erroneous readings since the smaller particles generated tended to adhere to the microwave absorber and form larger drop reflectors.

The transmitting and receiving apparatus were set according to Figure 3 and the angle between the horns was set at 10 degrees. This equipment was given a one hour warm-up period prior to the tests in order to insure a maximum stability of the klystron oscillator. The frequency and the output signal level of the oscillator were checked before each test cycle so that consistent readings could be obtained from one cycle to the next.

At the beginning of each material test, the standard was placed on the styrofoam test pedestal and the receiver meter reset to the reference signal level. The standard and the pedestal were then removed and the access door sealed in place for the aerosol test. The aerosol generator was set just outside the chamber access hole on the side and the generator valve activated for a period of 5 seconds. The level of the received signal was recorded. The chamber was then cleaned, dried and set up again for another test run. The backscatter cross section of the aerosol was determined by comparing the reflected signal from the aerosol with that of the standard target.

C. Experiment Results

The materials tested were put through the chamber in the order listed in Table 2. For the particle range 1-25 microns, benzene,
toluene, methanol, and ethylene glycol gave no detectable reflected signal. The ozone used in the test was generated in a small 50 mg./hr. electrostatic generator. This substance was utilized as the propellant and water was used as the liquid in the aerosol generator. This produced an ionized aerosol in the desired size range. The results were the same as with the other materials; no detectable reflected signal. It was not determined whether this condition was the result of the small particle size or the small ozone concentration.

Water was used next for the test and showed no reflection. The material was then changed from water with a dielectric constant of 78.54 to Cryolite, with a dielectric constant of 174.5. This was the first of two materials tested in a powder form. The particle size of the Cryolite was found to be approximately 3 microns in diameter. The substance was placed in the generator container and covered with water. The resulting aerosol was water droplets acting as a carrier of the Cryolite particles. From this, the reflected signal was still undetectable. As a final try for a detectable reflected signal, barium titanate with a very large dielectric constant of approximately 1020 was injected into the chamber by the same method given for the previous material. Only slight meter fluctuations were noted.

For the size range 25-75 microns, no detectable change in the meter readings was observed for any of the materials except Cryolite and barium titanate. Cryolite gave a change of approximately 1/2 db. and barium titanate showed a change of about 1 db.

In the range 75-100 microns, benzene and toluene gave only small meter fluctuations. Methanol and ethylene glycol both resulted in changes in approximately 1 db. The ionized aerosol of ozone and
water gain only produced some questionable meter fluctuations. Water showed a meter reading change of about 1-1/2 db. The two materials which gave the largest reading changes were Cryolite and barium titanate. The substance Cryolite gave a reading change of 2 db. The barium titanate resulted in a change of approximately 3-1/2 db.

All meter readings noted were increases in signal level over that of the residual reflections of the chamber. The experimental results are summerized in Table 2. All reflected signal levels are given below that of the reference signal level in decibels. Equation (3.9) was used to calculate the backscatter cross section for the single aerosol particles of each material.
Klystron Power Output - 70 milliwatts

<table>
<thead>
<tr>
<th>Material</th>
<th>Reflected Signal Level Below Reference in Decibels</th>
<th>Aerosol Cloud Backscatter Cross Section</th>
<th>Theoretical Backscatter Cross Section of a Single Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Benzene</td>
<td>--------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Toluene</td>
<td>--------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Methanol</td>
<td>11 db. (75-100 microns)</td>
<td>5.85 cm.²</td>
<td>5.68 x 10⁻¹¹ cm.²</td>
</tr>
<tr>
<td>4. Ethylene Glycol</td>
<td>11 db. (75-100 microns)</td>
<td>5.85 cm.²</td>
<td>5.98 x 10⁻¹¹ cm.²</td>
</tr>
<tr>
<td>5. Ozone + Water</td>
<td>--------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Water</td>
<td>10-1/2 db. (75-100 microns)</td>
<td>6.55 cm.²</td>
<td>6.51 x 10⁻¹¹ cm.²</td>
</tr>
<tr>
<td>7. Cryolite</td>
<td>11-1/2 db. (25-75 microns)</td>
<td>5.20 cm.²</td>
<td>2.36 x 10⁻¹² cm.²</td>
</tr>
<tr>
<td></td>
<td>10 db. (75-100 microns)</td>
<td>7.35 cm.²</td>
<td>6.79 x 10⁻¹¹ cm.²</td>
</tr>
<tr>
<td>8. Barium Titanate</td>
<td>11 db. (25-75 microns)</td>
<td>5.85 cm.²</td>
<td>2.43 x 10⁻¹¹ cm.²</td>
</tr>
<tr>
<td></td>
<td>9 db. (75-100 microns)</td>
<td>9.25 cm.²</td>
<td>6.98 x 10⁻¹¹ cm.²</td>
</tr>
</tbody>
</table>

**TABLE 2.**

SUMMARY OF EXPERIMENTAL RESULTS
CHAPTER VI

A. Conclusions

The results of the experiment conducted for this thesis indicate that with the equipment utilized and under the experimental conditions given, two materials in the 25-75 micron range and five materials in the 75-100 micron range produced measurable reflections. Of these substances, the greatest reflections were recorded with the materials which had the largest dielectric constants. From all the materials tested, Cryolite and barium titanate best satisfied the requirements, for the conditions given, of a practical microwave reflector. While meter fluctuations were detected with other particles in the 25-75 micron range, it was not possible to say that they were the result of reflections from the aerosol being tested or just due to changes in spatial particle concentration.

From equation (2.30), the backscatter cross section of a sphere varies as the inverse of the fourth power of the wavelength and as the sixth power of the sphere radius. The cross section also varies considerably with small values of the index of refraction but as the index increases above that of water, the equation dependency on this factor diminishes. Since the wavelength is basically a fixed parameter for a working microwave system, the controlling parameter determining the effective backscatter cross section of particles in the size range studied was the radius of the particle.
An increase in the backscatter cross section of the aerosol cloud could be accomplished by increasing the density of the particles in the cloud whereas materials with dielectric constants much greater than 100 cause a negligible increase the fall rate of the aerosol to a prohibitive value. Further study of other properties of these materials could possibly provide more insight into the reflective properites.

B. Microwave Reflective Aerosol Applications

Reflective aerosols have a wide range of possible applications in the fields of both radio tropospheric scatter and radar. An easily disseminated aerosol could be utilized to provide a temporary artificial reflective layer in the upper atmosphere for long distance tropospheric scatter communications. In the area of radar, an aerosol could possibly give an aircraft protective cover in the event of enemy radar interrogation.
REFERENCES CITED


