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Error Analysis of Aerosol Extinction Cross Section Measurement due to Forward Scattering and Diffraction

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ABSTRACT

Aerosol is a useful mean in electro-optical defence. The optical transmissivity is usually used to evaluate the performance of the aerosol. However in transmissivity measurement, forward-scattered or diffracted light might reach the detector and would be incorrectly recorded as unscattered and transmitted one, which results in the final optical density rise and experimental extinction cross-section becoming erroneously low. Based on forward scattering and diffraction analysis, the beam efficiency and effective extinction efficiency are introduced to examine the error. The results indicate that large particles and detector increase the error. To minimise the error, the distance between the aerosol and the detector must be large enough, and the detector of small area and small view angle is favourable.

Keywords: Effective extinction efficiency, forward scattering, diffraction, optical transmissivity, aerosol, diffraction analysis, error analysis

1. INTRODUCTION

In modern defence technology, to protect targets from electro-optically guided weapons, aerosol is usually adapted to attenuate the energy of infrared radiation of targets and laser scattered. Scattering is an indispensable portion of attenuation. Usually, it is expected to increase scattering to enhance attenuation. Similarly, the analysis of scattering has yielded most of our present knowledge of elementary particle physics[1-4]. Hu, *et al*., for example, accomplished the discrimination between spherical and nonspherical scatterers even when multiple scattering occurs by transmitting a circularly polarised beam from the lidar and resolving the rotational sense of the polarisation in the receiver [1].

However, according to the scattering theory of aerosol [5,6], the forward scattering and diffraction occur for both spherical and nonspherical particles, which may influence the result of optical transmissivity measurement [7-9]. In this paper, based on the Mie's theory for homogeneous spheres, the effects of the forward scattering and diffraction on the transmissivity and extinction cross-section measurement have been analysed, the method to reduce the error of extinction cross-section has been put forward. The results are also applicable for aerosol of nonspherical particles.

2. EXPERIMENTAL SET-UP

If the particle number density is sufficiently low, which is usually satisfied in particle extinction cross-section measurement, the light will most likely be scattered only once when passing through the aerosol layer. Under these single scattering conditions, the reduced irradiance I(L) after passing through a sample of width L is related to the initial beam irradiance I_0 by $I(L) = I_0 e^{-\rho\sigma L}$, where □ is the numerical density of aerosol particle, and □ is the extinction cross section of each particle. The instrument actually records the transmitted optical density, *D*, through the aerosol. The optical density is a logarithmic measure of the beam attenuation defined by $D=\log[I_0/I(L)]$, so the experimental extinction cross section is given by

$$\sigma = (\ln 10)\, D/\sigma L \tag{1}$$

Some forward scattered or diffracted light might reach the detector and will be incorrectly recorded as unscattered and transmitted one. This may result in rise in the final optical density and experimental measurement of extinction cross section gets erroneously low.

3. FORWARD SCATTERING AND DIFFRACTION ANALYSIS

There exists an exact theory for scattering by a homogeneous, dielectric and/or magnetic sphere of any size. The scattered far field in spherical coordinates for a unit-amplitude incident field (where the time variation exp(-iùt) has been omitted) is given by

$$E_{s\theta} = \frac{e^{ikr}}{-ikr}\cos\phi \bullet S_2(\cos\theta) \quad E_{s\phi} = \frac{e^{ikr}}{ikr}\sin\phi \bullet S_1(\cos\theta) \tag{2}$$

In Eqn (2), $E_{s\phi}$ is the scattered far-field component in the scattering plane, defined by the incident and scattered

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directions, and $E_{s\phi}$ is the orthogonal component. The angle ϕ is the angle between the incident electric field and the scattering plane. S_1 and S_2 are the scattering amplitudes which can be expressed as functions of the Mie coefficients, a_n and b_n, and functions π_n and τ_n.

Parts of the scattering functions S_1 and S_2 are due to diffraction of the electromagnetic wave at the projected area of the sphere. Considering the scalar diffraction signal S_d, the scattered fields without diffraction become

$$E_{s\phi 0} = \frac{e^{ikr}}{ikr}\sin\phi g\left(S_1 - S_d\right),\quad E_{s\theta 0} = \frac{e^{ikr}}{-ikr}\cos\phi g\left(S_2 - S_d\right) \quad (3)$$

Thus the S_i (i=1, 2) are to be replaced by the differences $S_{i0} = S_i - S_d$ leading to the scattered power, S_0, of the scattering patterns without diffraction. The subtraction is performed at the field level.

Figure 1 shows the angular scattering diagram in logarithmic (dB) scale without (left) and with (right) diffraction peak for a copper sphere with $m = 0.603+6.37i$, and sphere size parameter $x = 17.7826$, S_1 upper, S_2 lower semicircle. Values normalised at the origin (0dB) to minimum. One can find that the diffraction contribution is strongly peaked forward around a scattering angle of $\theta_{max} = 180^\circ / x$. Simultaneously, both the diffraction and forward scattering will increase the optical density received by the detector.

To evaluate the contribution of the diffraction and forward scattering, the beam efficiency η_b is introduced, which is a quantity known from antenna theory to describe the fraction of the radiation contained in the main lobe. In analogy, here η_b can be defined as the fraction of radiation scattered in a given angular range, such as the forward peak. This quantity depends on the scatter-receiving angle θ_{lim} at the upper limit of integration

$$\eta_b\left(\theta_{\lim}\right) = \frac{1}{Q_{sca}}\int_0^{\theta_{\lim}} S(\theta)\sin\theta g d\theta$$
$$\eta_{b0}\left(\theta_{\lim}\right) = \frac{1}{Q_{sca}}\int_0^{\theta_{\lim}} S_0(\theta)\sin\theta g d\theta \quad (4)$$

The normalisation of S requires η_b=1 for θ_{lim}=π, which was used to test the numerical integration. The difference $\eta_{bd} = \eta_b - \eta_{b0}$ shown as dotted line in Fig 2 corresponds to the beam efficiency of the diffraction signal.

The solid and dotted curves reach constant values already for small angles. With increasing x, these reach for a smaller angle. Simultaneously, $\eta_{bd}(\theta_{lim})$ approaches a step function, thus indicating a clear distinction between diffraction at small θ_{lim} and more or less diffuse scattering above. This means for large particles, the forward scatter and diffraction are dominant.

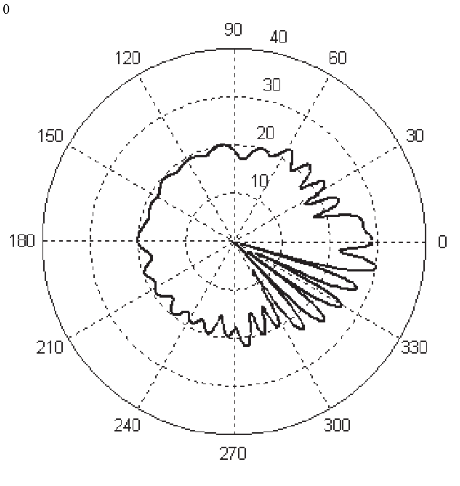
4. MEASUREMENT ERROR ANALYSIS

In aerosol transmissivity measurement, aerosol particles are far away from the detector. If the distance is L and the dimension of the detector is d, the radiation scattered by a particle only in a solid angle can be received by the detector. The solid angle corresponds an scatter-receiving angle, $\theta_{\lim}$=d/L, in radian, as shown in Fig. 3. Usually the aerosol particle is treated as a point without dimensions. For a certain detector the scatter-receiving angle varies with the distance. When the angle is known, one can get the beam efficiencies from Fig. 2 for a particle with certain size parameter x. Some typical values of the beam efficiency η_b are given in Table 1 for different values of x and L.

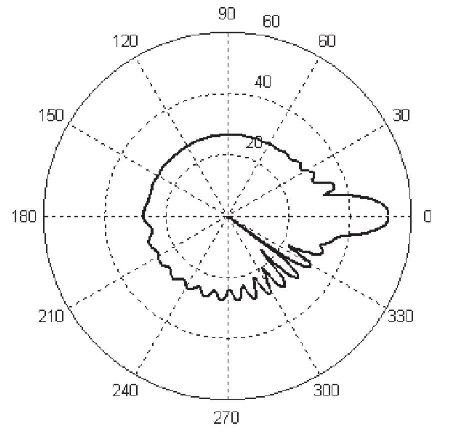
Furthermore, the beam efficiency can be used to estimate the effective scattering σ_s^* and extinction σ_e^* cross section (the absorption cross section σ_a being unaffected) from the experimental values σ_s and $\sigma_e = \sigma_a + \sigma_s$ obtained from the measurement, in which only the effect of scattering without forward scattering and diffraction is considered:

$$\sigma_s^* = \sigma_s + \sigma_s\eta_b \qquad \sigma_e^* = \sigma_e + \sigma_s\eta_b \quad (5)$$

It means the actual extinction σ_e is greater than the experimental values. The larger the scattering cross section and the beam efficiency, the greater the difference between



(a)



(b)

Figure 1. Angular scattering diagram in logarithmic (dB) scale (a) without and (b) with diffraction peak for a copper sphere, S_1 upper semicircle, S_2 lower semicircle.

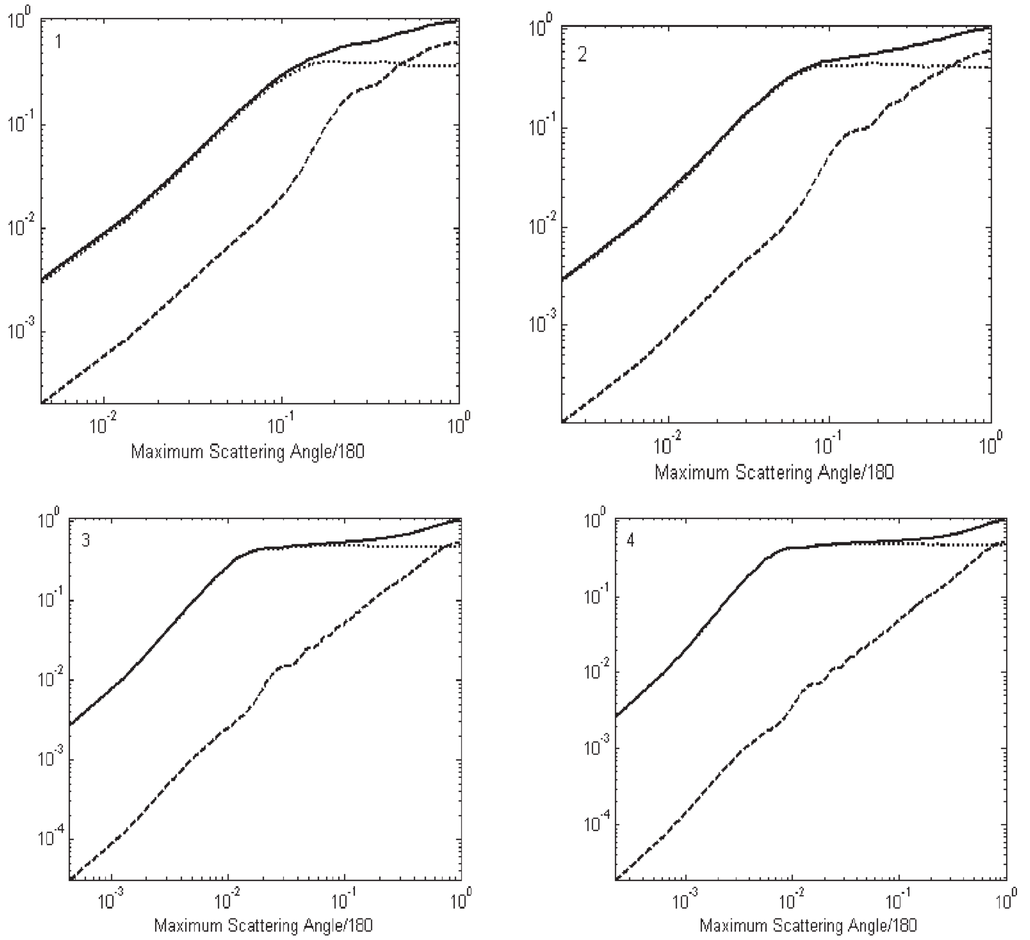


Figure 2. Beam efficiencies η_b (solid line) and η_{b0} (dashed line) and their difference (dotted line) of a dielectric sphere versus θ_{lim} for refractive index *m*=0.603+6.37i; size parameter: 1:*x*=5, 2:*x*=10, 1:*x*=50, 1:*x*=100.

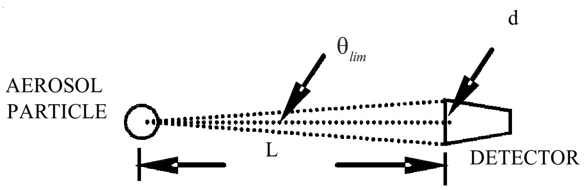


Figure 3. Schematic of light scattering from aerosol particle to detector.

the effective value and experimental one of the extinction cross section. The ratios of the two values are also shown in Table 1.

From Table 1 one can find for one size parameter, the smaller the distance between the particles and the detector, the greater the beam efficiency and the ratio. That is to say, the error of the extinction cross section is greater. So, to reduce the error resulting from forward scattering and diffraction, the distance between the particles and the detector should be large enough, especially for aerosols of large particles or short wavelength of radiation used in the measurement. However, for a purely absorptive aerosol, the distance has nothing to do with the error due to the zero scattering cross sections of particles.

Moreover, the detector of small area and small view angle is also favourable for decreasing the error resulting

Table 1. Typical values of the beam efficiency and the ratio of the effective extinction cross section to experimental one

L / x	10 m		50 m		150 m		500 m	
	η_b	σ_e^*/σ_e	η_b	σ_e^*/σ_e	η_b	σ_e^*/σ_e	η_b	σ_e^*/σ_e
5	0.356	1.342	0.026	1.025	0.006	1.006	0.001	1.001
10	0.494	1.474	0.093	1.089	0.015	1.014	0.003	1.003
50	0.543	1.521	0.431	1.414	0.183	1.176	0.038	1.037
100	0.549	1.527	0.473	1.454	0.397	1.381	0.085	1.082

from forward scattering and diffraction. To enhance view angle, focus panel array of detectors is a good chance. For example, focus panel array CCD is widely adopted in infrared camera. Each CCD has very small area and view angle, which reduces the error significantly.[10]

5. CONCLUSION

Based on the Mie's theory for homogeneous spheres, the effects of the forward scattering and diffraction were analysed on the transmissivity and extinction cross section measurement, and it has been concluded that the distance between the aerosol particles and the detector must be large enough. However, for aerosol consisting of inhomogeneous or nonspherical particles, the effects of forward scattering and diffraction also exit.

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