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Elastic back-scattering patterns via particle surface roughness and orientation from single trapped airborne aerosol particles

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ABSTRACT

We demonstrate a method for simultaneously measuring the back-scattering patterns and images of single laser-trapped airborne aerosol particles. This arrangement allows us to observe how the back-scattering patterns change with particle size, shape, surface roughness, orientation, etc. The recoded scattering patterns cover the angular ranges of $\theta = 167.7–180°$ (including at 180° exactly) and $\phi = 0–360°$ in spherical coordinates. The patterns show that the width of the average speckle intensity islands or rings is inversely proportional to particle size and how the shape of these intensity rings or islands also depends on the surface roughness. For an irregularly shaped particle with substantial roughness, the back-scattering patterns are formed with speckle intensity islands, the size and orientations of these islands depend more on the overall particle size and orientation, but have less relevance to the fine alteration of the surface structure and shapes. The back-scattering intensity at 180° is very sensitive to the particle parameters. It can change from a maximum to a minimum with a change of 0.1% in particle size or refractive index. The method has potential use in characterizing airborne aerosol particles, and may be used to provide back-scattering information for LIDAR applications.

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1. Introduction

Elastic light scattering is sensitive to aerosol particle size, shape, complex refractive index, surface roughness, and the molecular density distribution within the particle. Because of its sensitivity, it is considered to be a potential real-time, *in situ* aerosol classifier or identifier, especially in monitoring life-threatening bioaerosols from normal atmospheric background constituents e.g. [1–10]. Although there are various instruments based on elastic scattering that can determine the size, concentration, and asymmetry of particles, the rich information obtained from elastic scattering has not been fully utilized. To retrieve the parameters of a particle from its scattering pattern remains a challenge to the community. The advancement of computational capabilities and improved theoretical models have greatly improved numerical simulations, making it possible to calculate the light scattering from highly irregular, heterogeneous systems e.g. [11–18]. There remains a demand for experimental data from single particles that can be used for verification of theoretical calculations and help develop more accurate algorithms. One of the approaches is to trap single particles for detailed measurements such as obtaining the angular distribution of light-scattering intensity from a single trapped biological cell in liquid or from a trapped airborne droplet e.g. [19–23]. A stable trap can

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provide time-resolved dynamic measurements of particle properties in time as conditions change, supply more accurate scattering angle assignment and control the particle orientation that is very hard for flowing through systems e.g. [3–10]. There are currently limited publications of scattering patterns from single trapped solid airborne particles, especially in the exact and near back-scattering directions [24]. It is not trivial to obtain the scattering signals from a single micron-size particle at the exact back-scattering polar angle $\theta=180^\circ$ since stray scattered light from optical components can be significant [24,25]. Whereas, the forward-scattering region is determined largely by diffraction and is sensitive to particle morphology, the back-scattering region is sensitive especially to particle heterogeneities and surface structure, including surface roughness [26]. Many real applications operate in a LIDAR configuration, in which the exact back-scattering signal is analyzed for information.

Scattering patterns from a single complex particle with rough surface always appear with speckle-like islands, it is very difficult to retrieve particle parameters even just the size by comparing these patterns with theory. However, particle size can be approximately retrieved from the dependence of scattering intensity on the polar scattering angle θ. Such an intensity variation depends more strongly on the particle size than on the refractive index [27]. The frequency of the scattering intensity oscillation can be obtained through Fourier transformation, autocorrelation analysis or other pattern analysis algorithms and subsequently related to particle size [8,9,27]. Information about particle shape and orientation is more concentrated in the intensity variation along the Azimuthal scattering angle (ϕ) [8,9,27]. It is found that the median surface area of intensity peaks (the size speckle islands) is inversely proportional to particle size, especially in the near forward scattering region. This trend holds well for most particle types with substantial roughness or complexity [27–29].

In this paper, we investigated the sensitivity of the particle size, shape, surface roughness, or orientation on the back-scattering patterns. We designed and assembled an apparatus that can measure the back-scattering patterns and images of a single laser-trapped particle simultaneously. We trap both transparent and absorbing particles with arbitrary morphology using a recently developed trapping technology via a single shaped laser beam [30]. The recorded scattering patterns cover the range of $\theta=167.7\text{–}180^\circ$ (including at 180° exactly) and $\phi=0\text{–}360^\circ$ in spherical coordinates. Here θ is the polar angle relative to the z axis that is defined by the direction of the incident laser beam, and ϕ is the Azimuthal angle relative to some arbitrarily determined x axis, in this case, perpendicular to the laboratory floor.

2. Experimental arrangement

A schematic of the experimental arrangement with the corresponding coordinates is shown in Fig. 1. A power-adjustable 532 nm laser (up to 3 W) is used to trap airborne particles. The laser beam is spatially filtered (L6, PH2, L7) and then formed into a collimated hollow beam after passing two axicons (AL1, AL2). The hollow beam is reflected vertically

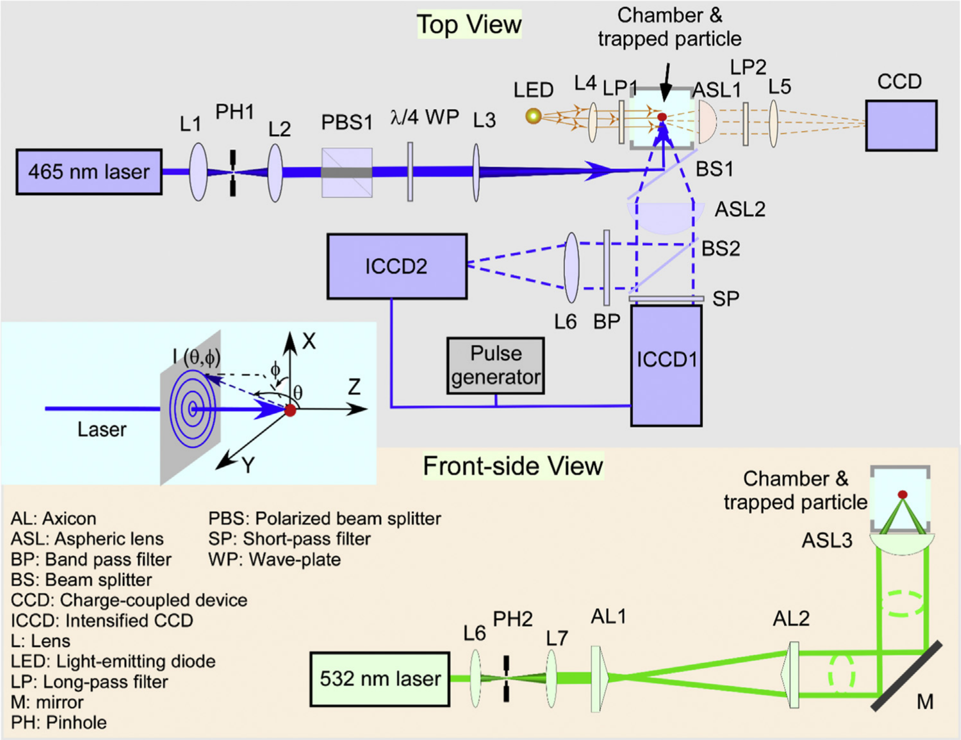

Fig. 1. Experimental setup for measuring elastic back-scattering patterns and images simultaneously from single, laser-trapped airborne aerosol particles. The inset shows the coordinate system, and the legend of acronyms is in the lower left.