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Session 2: LIDAR

Invited Presentation ...

Chemical Species Measurements in the Atmosphere Using Lidar Techniques
Philbrick, C.R. *(Slides & Paper)*

White Light Lidar (WLL) Simulation and Measurements of Atmospheric Constituents
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Supercontinuum LIDAR Measurements of Atmospheric Constituents
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Multistatic Lidar Measurements of Aerosol Multiple Scattering
Park, J.H., C.R. Philbrick and G. Roy
(Slides & Paper)

Multistatic LIDAR Measurements of Aerosol Multiple Scattering

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***Abstract*-Multiple scattering is an important factor in treating the penetration of radiation through an optically thick medium, such as clouds and fog. Experiments were conducted at DRDC and PSU aerosol chambers with different sizes of fog oil. The radial distribution of radiation scattered from the multistatic lidar beam can be analyzed from a CCD image to provide a measure of the spatial characteristics of multiple scattering. The changes in scattering characteristics are related to the number and size of scatterers in terms of optical depth within the scattering volume. The polarization ratio of the scattering phase function at different scattering angles is also a way to extract multiple scattering effects from multistatic lidar. Multiple scattering increases the depolarization of the scattered radiation as the scattering angle increases from 0° and 180° respectively.**

I. INTRODUCTION

Multiple scattering is the important factor in treating the penetration of radiation through an optically thick medium, such as clouds or fog. A multistatic lidar system, which was developed at Penn State University, has an ability to evaluate multiple scattering effects in a dense medium by measuring polarization ratio of the scattering phase function at different scattering angles. Measurements of aerosol properties as a function of scattering angle are particularly important for extracting information on the characteristics of the optical scatterers, such as particle sizes and number densities. A combination of multistatic imaging lidar techniques and polarization measurements can minimize effects of the device non-linearity as well as instrument uncertainties, improve spatial resolution near the transmitter, and reduce the dynamic range needed in the detector and electronics.

A knowledge of radial distributions of multiply scattered intensity over a range of small scattering angles is known to be important for describing the propagation of light beams in optically dense media. Therefore, measurements of radial distribution of multiple scattering can also be used to extract aerosol information.

II. EXPERIMENTAL

Experiments were conducted in a cooperative research project between researchers from Penn State University and from Defence Research and Development Canada Valcartier (DRDC). The DRDC Aerosol Research Chamber provided an opportunity to investigate multiple scattering characteristics. The multistatic lidar measurements were made in a 22-m long aerosol chamber located at the DRDC facility. The chamber has a 2.4 m × 2.4 m cross-section. It has doors at the ends of the chamber that can be opened quickly, see Fig. 1. The inside of the chamber is coated with optical-black paint to avoid reflecting light from the walls.

A small chamber has also been assembled at PSU to conduct scattering experiments in a better controlled laboratory environment using aerosols from a generator that have been characterized using a size spectrometer and CPC 3010, particle counter. The chamber is much smaller than that at the DRDC facility. However, it is much easier to control particle characteristics in the chamber. The PSU chamber is 360 cm long and has a 60 cm × 60 cm cross-section. Both chambers are shown in Fig. 1. The inside of the PSU chamber is also coated with black paint.

The optical setup of the multistatic receivers used for the measurements is shown in Fig. 2. The detailed setup of the multistatic lidar was also explained in a previous paper [1]. A CW Nd-VYO4 laser with a wavelength of 532 nm is used. The cameras used are commercial CCD cameras from Meade Instrument Corporation and are fitted with wide field lenses (fov approximately 48°). The choice of wide angle optics eliminates the need for spatial scanning to cover the desired range of scattering angles. The cameras interface with laptop PCs to record the images. The laser and two cameras were separated from the laser beam path and each camera was in line with the direction of the beam propagation inside the chamber. A polarization cube and a 90° polarization rotator were used to separate laser beam into two different polarized components. The polarization rotator was controlled remotely by a mechanical device. During the experiments, measurements were made simultaneously in backward and forward scattering direction.

The aerosol substitute in the DRDC chamber experiment was fog oil disseminated by a MDG Super Max 5000 fog-oil generator (refractive index of $n = 1.51 + 0i$) and glass spheres. The size distribution of fog oil was measured using a TSI 3934 SMPS, particle size spectrometer, and the results are shown in Fig. 3. In the PSU chamber, a TDA-5A Aerosol Generator made fog oil, which was well characterized by log-normal size distribution and the real part of refractive index of the fog oil used is 1.47. The measured size distribution is also shown in Fig. 3. Each parameter of the best fit log-normal size distribution of fog oil is tabulated in Table I.

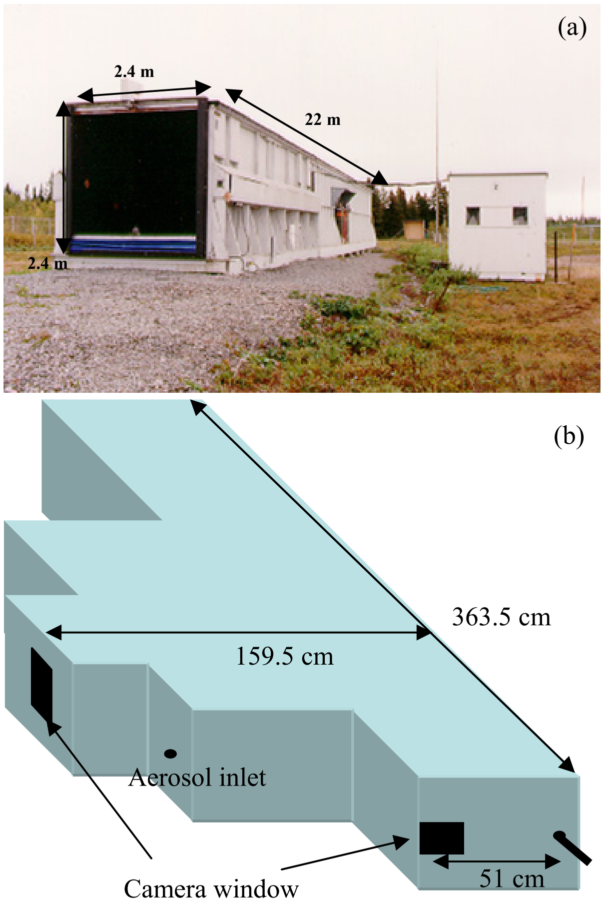

Figure 1. Aerosol chamber at (a) DRDC (b) PSU

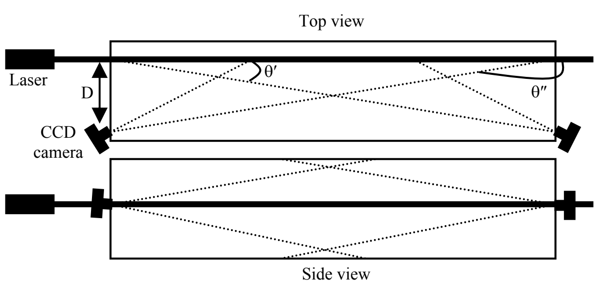

Figure 2. Optical setup of the multistatic receivers

In order to extract the optical characteristics of aerosols, it is very useful to measure the scattered intensities at back and forward scattering direction simultaneously. It was known that light scattering close to the forward scattering direction is sensitive to size but rather insensitive to refractive index and particle shape [2-3] and measurement of the polarization ratio in the backscattering region (at angles <175^{o}) provides a good experimental approach to observe the microphysical properties of aerosol particles [4-6].

TABLE I

Parameters of the best fit log-normal size distribution of each fog oil

Parameter	Fog oil (a)	Fog oil (b)
Median diameter[nm]	117.6	317
Geo. St. Dev	1.71	1.66
Total Conc.[#/cm^3]	6.03×10^4	1.09×10^6

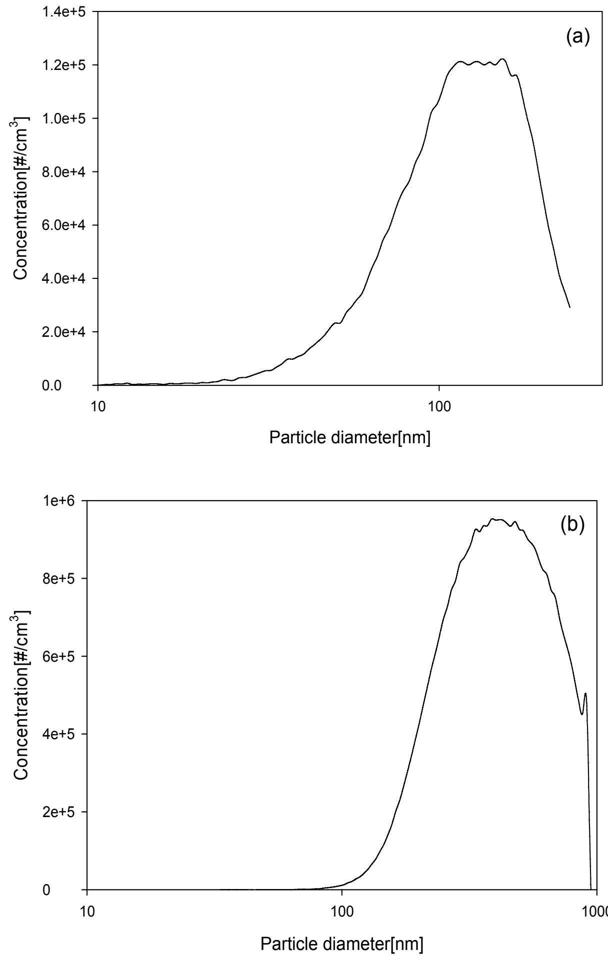

Figure 3. Size distribution of fog oil of (a) a MDG Super Max 5000 fog oil generator at DRDC chamber (b) a TDA-5A aerosol generator at PSU chamber

III. THEORY

The geometry of the bistatic lidar is shown in Figure 4. The laser beam is transmitted in the horizontal direction and the camera, which is separated from the laser by a distance D, can be located at both forward and back scattering directions. The received power from a scattered volume within unit angle $d\alpha$, which is the field of view of one pixel, can be described as [7]

$$P_r = P_t \frac{KAT_t T_r \beta(z,\theta)}{D} d\alpha \qquad (1)$$

where P_r is the received power, P_t is the transmitted power, K is the optical efficiency of the receiver, A is the collecting area of the receiver, and T_t and T_r are the atmospheric transmittance from the laser to scatterers and from scatterers to the receiver, respectively, and $\beta(z,\theta)$ is the scattering coefficient, which is a function of range z and scattering angle θ. The scattering angle, θ, can be denoted as either θ' in the forward direction or θ'' in the backward direction in Fig. 2.

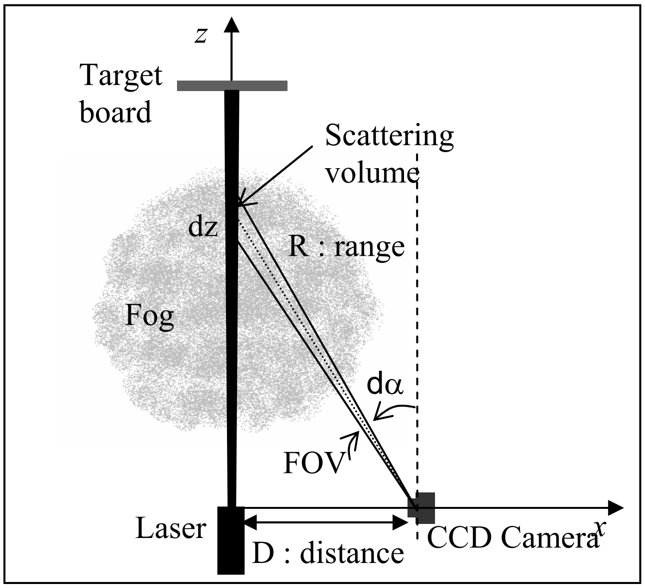

Figure 4. The geometry of a bistatic Lidar

The benefit of multistatic arrangement is that the received signal intensity does not depend upon the square of the range, $1/R^2$ as in the case of a typical monostatic lidar, due to the relationship, $dz = \frac{R^2}{D} d\alpha$, which means that the detector is not required to have a large dynamic range for signal detection. However, measurements of scattered intensity ratio remove most of the concerns about device non-linearity and setup uncertainties because of the multistatic lidar technique [4, 6].

In this experiment, the effects of a multiple scattering propagation of narrow light beams in aerosols can be investigated using two features; the radial distribution of scattered light and the change of polarization ratio compared to single particle scattering. The radial distribution of multiply scattered light as a function of optical depth was examined by Bissonnette [8]. It was found that the central part of the transmitted beam, which has its Gaussian shape, is not affected by multiple scattering. The on-axis beam extinction along the direction of beam propagation is governed by Beer-Lambert's law. The narrow central part of the beam is surrounded by a wide aureole, which is due to multiple scattering, increases with optical depth. Bissonnette's earlier results are shown in Fig. 5 for comparison with our results.

Polarization ratio is a useful parameter because spatial and temporal aerosol number density variations in measurements made at different scattering angles are canceled out [9]. Pal and Carswell [10] were among the first to experimentally study the variation of the polarization ratio, δ_p, associated with scattering from homogeneous spheres [11]. In mathematical form, the polarization ratio is given by

$$\delta_p = \frac{I_{//}(\theta)}{I_{\perp}(\theta)} \qquad (2)$$

where $I_{//}(\theta)$ is scattered intensity from incident parallel polarization, $I_{\perp}(\theta)$ is scattered intensity from incident perpendicular polarization, and θ is scattering angle. Depolarization can be caused by anisotropy of the atmospheric molecules, nonsphericity of particle, or by multiple scattering. However, depolarization components from the first two factors are generally smaller and are ignored in this experiment because it can be assumed that the polarization ratio from the molecular anisotropy is very small [12], and the fog oil aerosols generated in this experiment are almost spherical. Therefore, a reasonable assumption is that the primary source of depolarization is multiple scattering.

IV. RESULTS

Good agreement is shown with Bissonnette's result and the result obtained from a multistatic lidar. The data in Fig. 5 (b) were obtained from three images with different number densities in the chamber. However, the data in Fig. 5 (c) were analyzed along the beam path from one image. As can be seen in Fig. 5 (b) and (c), there is little difference between τ = 2.5 and τ = 1.4 and as the optical depth increases, the multiply scattered intensity also increases. From the results of Fig. 5, one can define the limitations under which calculations of aerosol multiple scattering are valid.

Polarization ratios at both backward and forward directions are shown in Fig. 6. In order to compare single scattering with multiple scattering, polarization ratio of single scattering is also included in the graphs, which represent the results calculated from the best fit log-normal size distribution of fog oil (see Fig. 3(a)) using the Mie theory for particle scattering.

During the measurements at DRDC, the optical depth inside the chamber was almost 2, which means there are multiple scattering effects in the scattered radiation. In the data shown in Fig. 6, some background and CCD readout noise were introduced in each pixel, which is summed in the beam-containing regions. In each scattering region, multiple scattering causes the scattered radiation to be more depolarized as the scattering angle increases from 0° and 180° respectively.

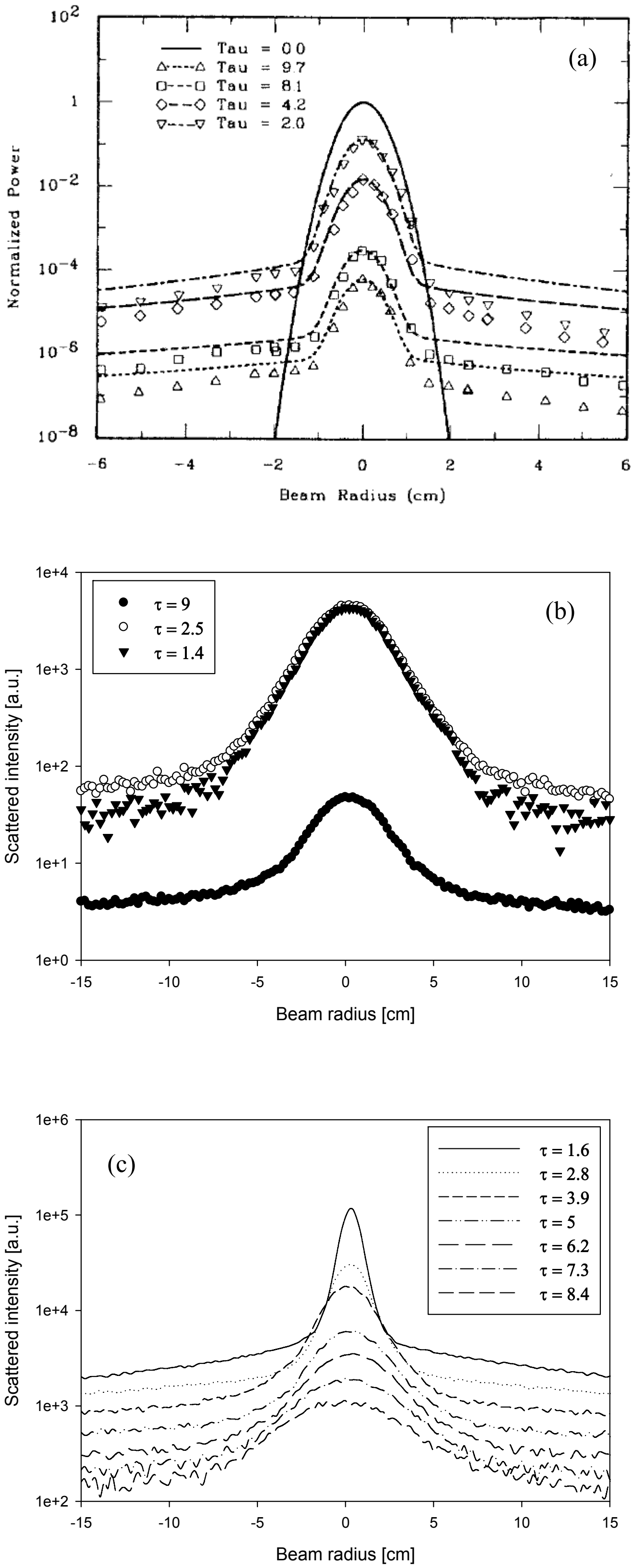

Figure 5. Radial distribution of multiply scattered beam (a) The symbols represent the measurements and the curves represent Bissonnette's model [8] (b) PSU small chamber data with different concentrations (c) different optical depths in one image at forward direction.

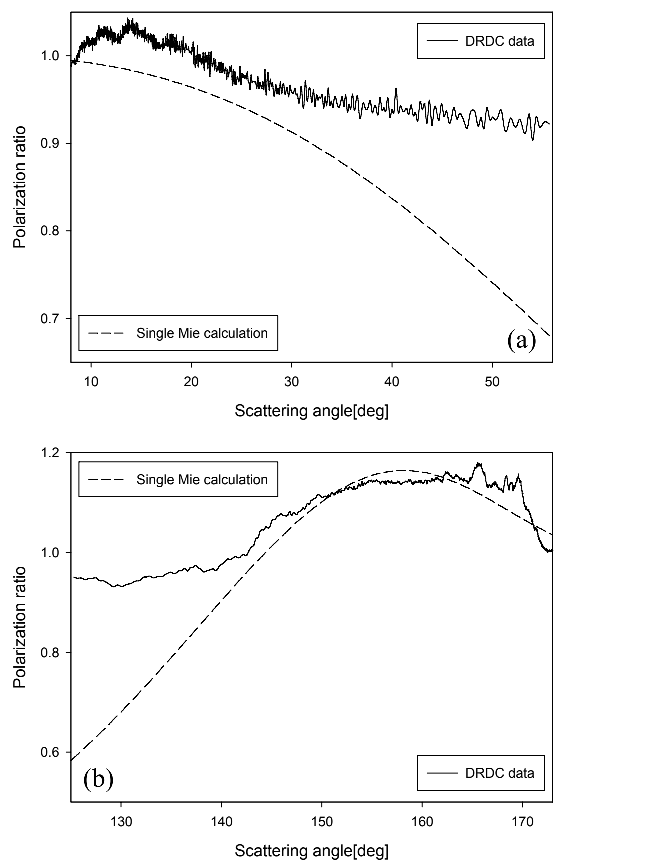

Figure 6. Polarization ratio at (a) forward scattering region (b) backscattering region.

V. CONCLUSIONS

Using the multistatic lidar and the measurements of radial distribution of scattered radiation and polarization ratio, multiple scattering can be distinguished from single scattering over different angular ranges. Experiments were conducted at two different aerosol chambers at DRDC, and PSU Lidar Laboratory to obtain a better controlled experimental environment. Radial distribution of scattered radiation from the multistatic lidar can be easily analyzed from a CCD image and shows the spatial characteristics of multiple scattering. The changes in the scattering characteristics are related to the extinction coefficient, or the size/number density, given in terms of optical depth within the scattering volume.

Polarization ratio of the scattering phase function at different scattering angles provides another way to extract multiple scattering effects from multistatic lidar. Multiple scattering increases the depolarization of the scattered radiation as the scattering angle increases from 0° and 180°.

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