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For the depolarization of linearly polarized light by smoke particles

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ABSTRACT

The CALIPSO satellite mission consistently measures volume (including molecule and particulate) light depolarization ratio of ~2% for smoke, compared to ~1% for marine aerosols and ~15% for dust. The observed ~2% smoke depolarization ratio comes primarily from the nonspherical habits of particles in the smoke at certain particle sizes. In this study, the depolarization of linearly polarized light by small sphere aggregates and irregular Gaussian-shaped particles is studied, to reveal the physics between the depolarization of linearly polarized light and smoke aerosol shape and size. It is found that the depolarization ratio curves of Gaussian-deformed spheres are very similar to sphere aggregates in terms of scattering-angle dependence and particle size parameters when particle size parameter is smaller than 1.0π. This demonstrates that small randomly oriented nonspherical particles have some common depolarization properties as functions of scattering angle and size parameter. This may be very useful information for characterization and active remote sensing of smoke particles using polarized light. We also show that the depolarization ratio from the CALIPSO measurements could be used to derive smoke aerosol particle size. From the calculation results for light depolarization ratio by Gaussian-shaped smoke particles and the CALIPSO-measured light depolarization ratio of ~2% for smoke, the mean particle size of South-African smoke is estimated to be about half of the 532 nm wavelength of the CALIPSO lidar.

1. Introduction

When natural light propagates through a space with scattering particles or voids or interacts with a surface, the scattered or reflected light can be polarized; when a polarized light passes through a medium with scatterers or impinges on a material interface, the scattered or reflected light may be depolarized. For e.g., NASA's space-borne lidar on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite [1] measures the Earth–atmosphere system with linearly polarized laser pulses. As shown in Figs. 1 and 2, the CALIPSO lidar data consistently show a volume (including molecule and particulate) light depolarization ratio of ~2% for South-African smoke, compared to ~1% for marine aerosols and ~15% for dust. Why does smoke have a volume depolarization ratio of ~2%? Moreover, measurements from many optical remote sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) have some dependence on the polarization of

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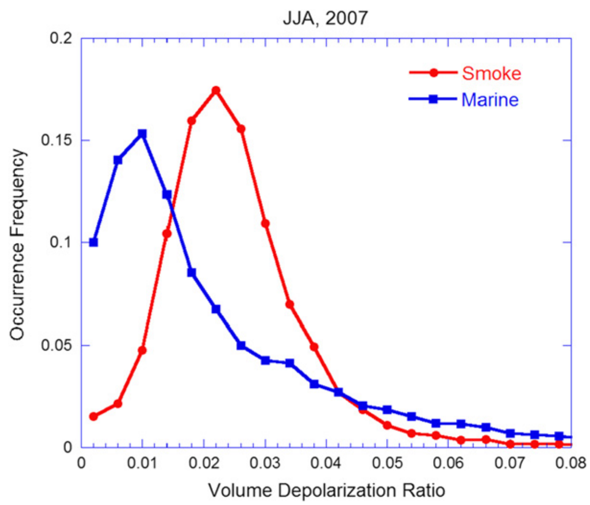

Fig. 1. Nighttime occurrence frequencies of volume depolarization ratios of South-African smoke and marine aerosols measured by the CALIPSO in June, July, and August, 2007.

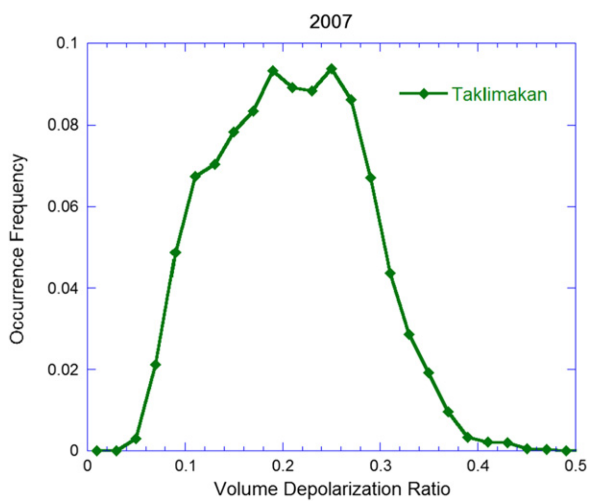

Fig. 2. Nighttime occurrence frequencies of volume depolarization ratios of Taklimakan dust aerosols measured by the CALIPSO in 2007.

incoming light [2]. Understanding the polarization and depolarization of light in the Earth–atmosphere system is a critical issue for highly accurate inter-calibration of Earth–atmosphere radiation data obtained by these optical remote sensors with those from NASA's Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission [3], which is recommended implementation by the National Research Council as a means of initiating a benchmark climate record of unprecedented accuracy. Understanding the depolarization of linearly polarized light by air molecules and aerosols is also very important for NASA Langley Research Center's Ground-to-Space Laser Calibration (GSLC) project, which is proposed to use polarized laser shot from the Earth surface to calibrate space-borne sensors' polarization properties during clear-sky period. Both current data analyses and future measurement inter-calibrations need knowledge on light polarization and depolarization by Earth–atmosphere components including aerosols.

In this study, we will employ the three-dimensional (3D) finite-difference time domain (FDTD) technique [4–6] to study the depolarization of linearly polarized light by small sphere aggregates and nonspherical Gaussian-shaped particles, to reveal the physics between the depolarization of linearly polarized light and the nonspherical smoke particle shape and size. Historically, there have been significant number of studies on light scattering by fractal-like soot agglomerates [7–13]; and there are also significant work [7,14,15] for the depolarization of the backscattered light (at the scattering angle of 180°) by nonspherical particles. However, our objective for this report is not to conduct a comprehensible research on the light scattering by aerosols or clouds, but to study the depolarization properties of scattered light at all scattering angles for small irregular smoke particles under a linearly polarized incidence, to find a better way to characterize small aerosols using polarized laser and to estimate background aerosols' depolarization effect on the transfer of linearly polarized laser in the atmosphere, with special care about the depolarization ratio of forward-scattered light as required by the GSLC project.

2. Method

The depolarization of a linearly polarized incident light by a particle is calculated through the single-scattering phase matrix elements. For any light interacting with a particle, we have

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \frac{\sigma_s}{4\pi R^2} \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix} \begin{bmatrix} I_0 \\ Q_0 \\ U_0 \\ V_0 \end{bmatrix}, \quad (1)$$

where I_0, Q_0, U_0, and V_0 denote the Stokes parameters of incident light and I, Q, U, and V denote the Stokes parameters of scattered light. σ_s is the scattering cross-section of the particle and R denotes the distance from the observation point to the center of the particle. P_{11}, P_{12}, ..., P_{44} are the phase matrix elements. Note that for linearly polarized incident light interacting with randomly oriented particles, Eq. (1) becomes

$$\begin{bmatrix} I \\ Q \\ 0 \\ 0 \end{bmatrix} = \frac{\sigma_s}{4\pi R^2} \begin{bmatrix} P_{11} & P_{12} & 0 & 0 \\ P_{12} & P_{22} & 0 & 0 \\ 0 & 0 & P_{33} & -P_{43} \\ 0 & 0 & P_{43} & P_{44} \end{bmatrix} \begin{bmatrix} I_0 \\ Q_0 \\ 0 \\ 0 \end{bmatrix}. \quad (2)$$

Thus, it reduces to 2 dimensional problems, as

$$I = \frac{\sigma_s}{4\pi R^2}(P_{11} I_0 + P_{12} Q_0), \text{ and} \quad (3a)$$

$$Q = \frac{\sigma_s}{4\pi R^2}(P_{12} I_0 + P_{22} Q_0), \quad (3b)$$

with $I = I_1 + I_2$ and $Q = I_1 - I_2$, where I_1 and I_2 denote the intensity of scattered light components parallel and perpendicular to the scattering plane, respectively; $I_0 = I_{01} + I_{02}$ and $Q_0 = I_{01} - I_{02}$, where I_{01} and I_{02} denote the intensity of incident light components parallel and perpendicular to the incidence plane, respectively. For a linearly polarized incidence such as that from the CALIPSO lidar, we can use a coordinate system in which we have $I_{02}=0$, and thus $I_0=I_{01}$ and $Q_0=I_{01}$. Therefore, from Eqs. (3a) and (3b), we have

$$I_1+I_2=\frac{\sigma_s}{4\pi R^2}(P_{11}I_{01}+P_{12}I_{01}), \tag{4a}$$

and

$$I_1-I_2=\frac{\sigma_s}{4\pi R^2}(P_{12}I_{01}+P_{22}I_{01}). \tag{4b}$$

From Eqs. (4a) and (4b), we can derive out

$$I_1=\frac{\sigma_s}{8\pi R^2}(P_{11}+2P_{12}+P_{22})I_{01}, \tag{5a}$$

and

$$I_2=\frac{\sigma_s}{8\pi R^2}(P_{11}-P_{22})I_{01}. \tag{5b}$$

So we have the depolarization ratio of the scattered light as

$$\frac{I_2}{I_1}=\frac{P_{11}-P_{22}}{P_{11}+2P_{12}+P_{22}}. \tag{6}$$

Eq. (6) shows that for any particles whose $P_{11}=P_{22}$ (such as spherical particles), the depolarization ratio is zero. However, irregularly shaped particles such as smoke, dust, and ice cloud particles do not have $P_{11}=P_{22}$, thus they can depolarize the incident light and result in a nonzero perpendicular intensity of scattered light.

3. Results

Fresh smoke particles often form as chains of nanometer-sized particles. With aging, these chains tend to collapse into irregular aggregates of small particles. As examples, the depolarization ratios of double-sphere aggregates, quadruple-sphere aggregates, and Gaussian particles [16–19] are calculated with the 3D FDTD method [4–6] with a uniaxial perfectly matched layer (UPML) [20] absorbing boundary condition (ABC). The accuracy of the 3D UPML FDTD light scattering model was reported in Sun et al. [6]. Fig. 3 shows the depolarization ratios of scattered light from randomly oriented double-sphere smoke particles under a linearly polarized incidence at a wavelength of 532 nm. Based on the data derived from Raman lidar observations of aged fire smoke in [21], the refractive index of smoke particles at the wavelength of 532 nm is given as 1.53+0.001i in this study. This refractive index may not be exact for smoke particles from different sources, but it will not seriously affect our conclusion for this study. We can see that the depolarization ratios of scattered light from randomly oriented double-sphere smoke aggregates have different behaviors at different scattering angles and size parameters. In the forward-scattering direction, the depolarization ratios are very small, for the double-sphere smoke particle with a single-sphere size parameter sphere ($x=2\pi a/\lambda$, where a is the radius of the sphere and λ is the incidence wavelength) of 0.25π the depolarization ratio is ~0.20%, whereas for the double-sphere smoke particle with a single-sphere size parameter of 0.5π the depolarization ratio is ~0.10%. Larger particles result in smaller depolarization ratios in the forward-scattering direction. On the contrary, at the backscattering direction, the depolarization ratios are relatively large, for the double-sphere smoke particle with a single-sphere size parameter of 0.25π the depolarization ratio is ~0.80%, whereas for the double-sphere smoke particle with a single-sphere size parameter of 0.5π the depolarization ratio is ~10.0%, which is similar to the depolarization ratio for randomly oriented spheroids at similar aspect ratio and size parameter reported in [14]. Larger particles result in larger depolarization ratios in the back-scattering direction. At scattering angles of ~90° to ~120°, the depolarization ratios show maxima. For small particles, the maximum depolarization ratios occur at ~90° and can reach ~100%, which means parallel and perpendicular components of the scattered fields are nearly equal. Fig. 4 shows the depolarization ratios of scattered light from randomly oriented quadruple-sphere smoke particles under a linearly polarized incidence at a wavelength of 532 nm. We can see that depolarization ratio curves of quadruple-sphere smoke

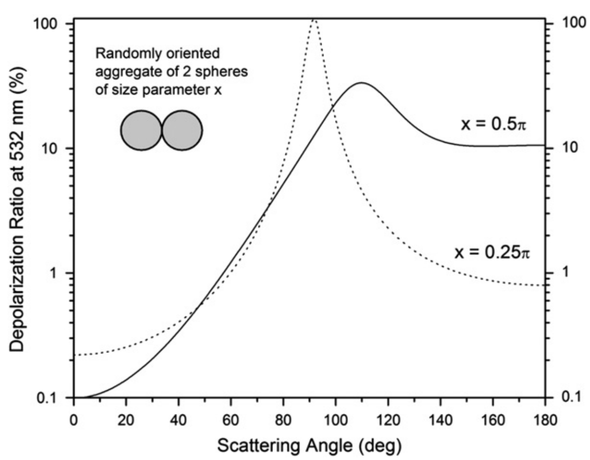

Fig. 3. Depolarization ratio of scattered light at 532 nm as a function of scattering angle for randomly oriented double-sphere aggregates of smoke particles.

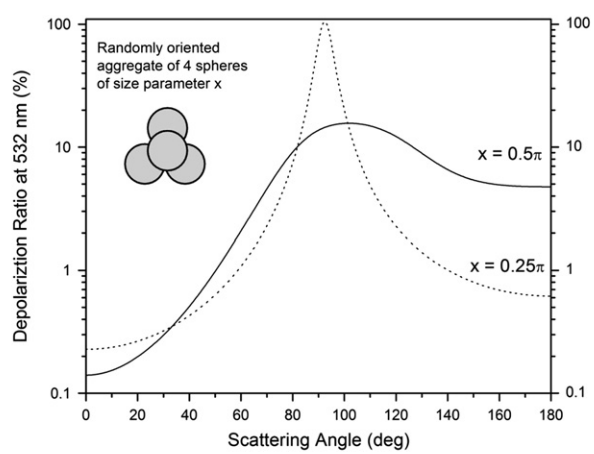

Fig. 4. Depolarization ratio of scattered light at 532 nm as a function of scattering angle for randomly oriented quadruple-sphere aggregates of smoke particles.

particles are very similar to those for double-sphere smoke particles, but in the forward-scattering direction the depolarization ratios are larger than those for double-sphere smoke particles and at back-scattering direction the depolarization ratios are smaller than those for double-sphere smoke particles, due to the more centrally symmetric quadruple-sphere particle shapes. For more practical particle shapes, we calculate the depolarization ratios of scattered light from Gaussian-deformed spheres. In this study, the correlation angle and the relative standard deviation [16–19] that define the shape of the Gaussian particles are set to be 30° and 0.4, respectively. The resultant particle shape and the depolarization ratios of scattered light from Gaussian smoke particles of various size parameters are shown in Fig. 5. The curves of different colors denote the depolarization ratios as functions of scattering angle for different particle size parameters from 0.1π to 1.0π (upper panel) and from 1.1π to 2.0π (lower panel). Compared with the data in Figs. 3 and 4, Fig. 5 shows that the depolarization ratio curves of Gaussian-deformed spheres are very similar to sphere aggregates in terms of scattering-angle dependence and particle size parameters when particle size parameter is smaller than $\sim 1.0\pi$. This demonstrates that small randomly oriented nonspherical particles have some common depolarization properties as functions of scattering angle and size parameter. When smoke particle size parameter is smaller than $\sim 1.0\pi$, the depolarization ratio of scattered light is sensitive to the nonsphericity of the particle, but not very sensitive to a specific shape. This can be very useful information for characterization and active remote sensing of smoke particles using polarized light. Based on this information, smoke particle size could be reliably retrieved with the measured depolarization ratio of the scattered linearly polarized incident light. Note that in this study, limited by our light scattering model's high requirement for computer CPU and memory, we only calculated the depolarization ratios of Gaussian-deformed spheres up to a size parameter of 2.0π. Since aged smoke particles generally have very small sizes [21], our limit in the calculated particle size should be good enough for showing the general behavior of depolarization properties of smoke particles. Moreover, since the CALIPSO lidar data typically show a light depolarization ratio of ~2% for South-African smoke, from the results in Fig. 5 the mean particle diameter of South-African smoke is estimated to be about half of the wavelength of the CALIPSO 532 nm lidar. Volume molecular scattering could contribute to the ~2% depolarization ratio of smoke, but considering the significantly smaller optical thickness of air molecules than that of smokes under a pulsed lidar incidence, we guess that this specific depolarization ratio is mostly due to the smoke particles themselves. Air molecules may increase the air parcel's depolarization ratio a little bit, but should not contribute much.

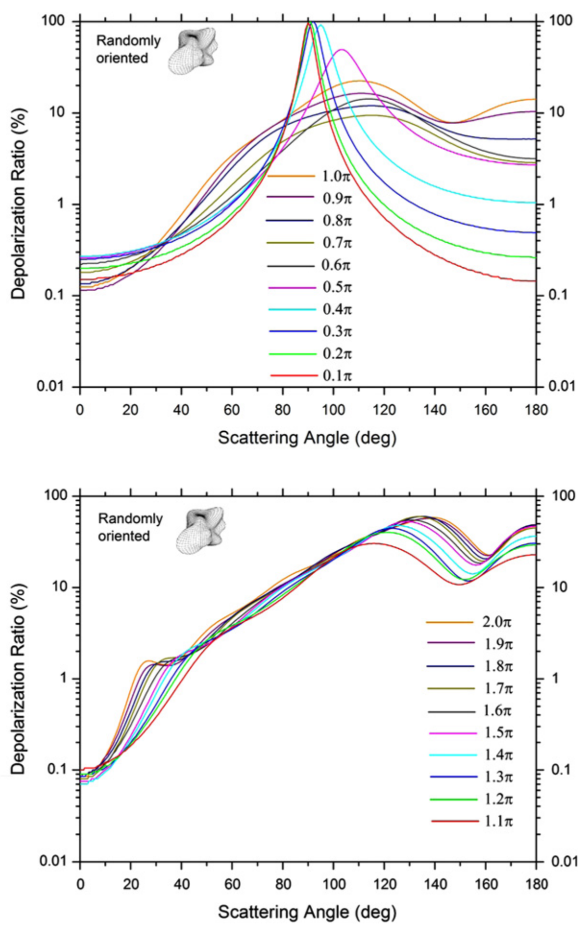

Fig. 5. Depolarization ratio of scattered light at 532 nm as a function of scattering angle for randomly oriented Gaussian-shaped smoke particles of size parameters from 0.1π to 1.0π (upper panel) and from 1.1π to 2.0π (lower panel).

4. Conclusion

In this study, the depolarization of linearly polarized light by small sphere-aggregated and irregular Gaussian-shaped smoke particles is studied, to reveal the physics between the depolarization of linearly polarized light and smoke aerosol shape and size. The 3D UPML FDTD light scattering model [6] is used to study the single-scattering depolarization ratio of smoke particles. It is found that the central symmetry of particle shape significantly reduces depolarization ratio for smoke particles. The depolarization ratio curves of Gaussian-deformed spheres are very similar to sphere aggregates in terms of scattering-angle dependence and particle size parameters when particle size parameter is smaller than 1.0π. This demonstrates that small randomly oriented nonspherical particles have some common depolarization properties as functions of scattering angle and size parameter. This result is in agreement with [22,23]. This may be very useful information for characterization and active remote sensing of smoke particles using polarized light. The results also show that in the forward-scattering direction, the depolarization ratios are very small, larger particles result in smaller depolarization ratios in the forward-scattering direction. This means that aerosols' single-scattering effect on the depolarization of polarized laser used by the GSLC project in the forward-scattering direction is very limited, though multiple scattering could be an issue. At the backscattering direction, the depolarization ratios are relatively large, larger particles result in larger depolarization ratios in the back-scattering direction. From the calculation results for light depolarization ratio by Gaussian-shaped smoke particles and the CALIPSO-measured light depolarization ratio of ~2% for smoke, the mean particle size of South-African smoke is estimated to be about half of the 532 nm wavelength of the CALIPSO lidar.

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