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Improved method for retrieving the aerosol optical properties without the numerical derivative for Raman–Mie lidar

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ABSTRACT

Raman–Mie light detection and ranging (lidar) is a very useful tool for research on atmospheric aerosol optical properties with high spatial–temporal resolution. However, many uncertainties still exist in data retrieval because traditional retrieval methods need to calculate the numerical derivative for aerosol extinction coefficient (AEC), which may cause large errors, particularly with low signal-to-noise ratios. Thus, we present an improved method for retrieving aerosol optical properties. We re-formulate the N_2-Raman lidar equation to obtain an unknown term which contains the AEC at the Mie wavelength. We replace the unknown term of the equation in traditional method for retrieving aerosol backscatter coefficient (ABC). Then, AEC can be retrieved by the accurate ABC and Mie lidar signal without calculating the numerical derivative. Tests on the simulated and measured signals show that results of our method and those of the traditional method have similar tendencies. However, our method is more accurate and robust, and the significant errors of AEC caused by the numerical derivative can be reduced.

1. Introduction

Aerosols have an important role in atmospheric processes, such as precipitation, radiation, and optical properties, and directly affect human health and the living environment. Accurate aerosol detection with high temporal–spatial resolution is critical. Compared with passive remote sensing techniques, such as sun photometry and microwave radiometry, light detection and ranging (lidar) is an effective active remote sensing tool for aerosol detection [1,2]. With the rapid development of laser technology, sophisticated spectroscopic techniques, photoelectric detection technology, and computer control technology, lidar has acquired unique advantages, including high sensitivity, high temporal–spatial resolution, and continuous monitoring [2,3]. Various useful algorithms for retrieving atmospheric properties have been proposed to improve the practicability of lidar [4–6]. Thus, lidar has been widely utilized in atmospheric aerosol detection since the 1960s [6–8]. A few lidar networks that perform routine measures, such as the Asian Dust Network [9], the European Aerosol Research lidar Network [10], and the lidar of the Atmospheric Radiation Measurement Program, have exhibited success and provide original data to significantly promote atmospheric aerosol research [11,12]. However, problems remain in the retrieval of aerosol optical properties [including the aerosol extinction coefficient (AEC) and aerosol backscatter coefficient (ABC)] via traditional methods of either Mie or Raman lidar. The signal-to-noise ratio (SNR) of the Mie lidar signal is a thousand times higher than that of the Raman signal under similar conditions. However, we need to assume the boundary value and lidar ratio (i.e., the ratio of the extinction coefficient and the backscatter coefficient) when retrieving the data of Mie lidar through the traditional Fernald method [4,13,14]. This method requires two assumptions that may cause many uncertainties [5,15]. Raman lidar can avoid these two assumptions, and the lidar ratio can be retrieved. Thus, Raman lidar has been widely utilized since its invention.

For Raman lidar, the SNR of the N_2 signal is very low because the N_2 scattering cross section is very small. The traditional retrieval method is very sensitive to SNR because of the numerical derivative in the solution [5]. To improve the accuracy of the retrieval, a de-noise method (e.g., sliding average method) is often used, but this method involves the loss of detail information [16].

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Several researchers investigated more stable and complicated methods to accurately calculate the numerical derivative, but these methods remain very sensitive to noise [17–19]. A few researchers have proposed methods by combining N_2-Raman and Mie signal, but these methods still do not completely avoid calculating the numerical derivative [20,21]. The improved method proposed by Molero and Pujadas can obtain ABC without calculating the numerical derivative for AEC, but it is affected by overlap near the ground [22]. An improved method for AEC proposed by Su with Fernald method [21], but it need to assume the lidar ratio is constant at first. Thus, the search for new or improved methods for aerosol optical properties is still important.

In this paper, we present an improved method for retrieving aerosol optical properties. Firstly, we re-formulate the N_2-Raman lidar equation to obtain an unknown term which contains the AEC at the Mie wavelength. Secondly, we replace the unknown term of the equation in traditional method for retrieving ABC. Thirdly, the retrieved ABC and Mie lidar equation are utilized to obtain more accuracy lidar ratio. Finally, the AEC can be obtained by the corresponding retrieved ABC and lidar ratio. The comparison of the aerosol optical properties retrieved by the traditional method and our improved method with simulated and measured lidar signal is discussed. The results verify that our method can obtain more accurate retrieval results than traditional methods without assumption or excessive de-noising means.

2. Principle and method

This section describes the retrieval of aerosol optical properties via the traditional method and our method.

2.1. Traditional method

The equations for Mie and N_2-Raman lidar with emission wavelength λ_L and λ_N can be expressed as follows:

$$P(\lambda_L, r) = \frac{C(\lambda_L)}{r^2} G(r)\beta(\lambda_L, r)\exp\left\{-2\int_0^r \alpha_a(\lambda_L, r`) + \alpha_m(\lambda_L, r`)dr`\right\} \tag{1}$$

$$P(\lambda_N, r) = \frac{C(\lambda_N)}{r^2} G(r)\beta(\lambda_N, r)\exp \times\left\{-\int_o^r [\alpha_a(\lambda_L, r`) + \alpha_m(\lambda_L, r`) + \alpha_a(\lambda_N, r`) + \alpha_m(\lambda_N, r`)]dr`\right\} \tag{2}$$

where $P(\lambda_x, r)$ is the received power from altitude r; subscripts L and N refer to the Mie and Raman backscatter of N_2, respectively; $C(\lambda_x)$ is the lidar constant that contains all altitude-independent terms; $G(r)$ is the geometric correction factor at r caused by the distance between the laser beam and telescope; $\beta(\lambda_x, r)$ is the backscatter coefficient; and $\beta(\lambda_N, r) = \sigma_N \cdot N(r)$, where σ_N and $N(r)$ are the backscatter cross section and molecular number density of N_2, respectively; $\alpha(\lambda_L, r)$ and $\alpha(\lambda_N, r)$ represent the extinction coefficient of Mie and N_2-Raman; and subscripts a and m in $\alpha(\lambda_x, r)$ refer to the contribution from aerosols and molecules, respectively.

ABC can be retrieved by the traditional method as follows [22,23]:

$$\beta_a(\lambda_L, r) = \frac{P(\lambda_L, r)\cdot P(\lambda_N, r_f)\cdot N(r)}{P(\lambda_L, r_f)\cdot P(\lambda_N, r)\cdot N(r_f)}\beta_m(\lambda_L, r_f) \frac{\exp\left\{-\int_{rf}^r \alpha_a(\lambda_N, r`) + \alpha_m(\lambda_N, r`)dr`\right\}}{\exp\left\{-\int_{rf}^r \alpha_a(\lambda_L, r`) + \alpha_m(\lambda_L, r`)dr`\right\}} - \beta_m(\lambda_L, r); \tag{3}$$

where subscripts a and m represent aerosol and molecular scattering, respectively, and r_f is the reference altitude, which is set to 10 km in this study. At the reference altitude, ABC is much less than the atmosphere molecules backscatter coefficient. Thus, $\beta_m(\lambda_L, r_f) + \beta_a(\lambda_L, r_f) \approx \beta_m(\lambda_L, r_f)$. However, we also need to determine $\alpha_a(\lambda_L, r)$ if we want to obtain $\beta_a(\lambda_L, r)$. Traditionally, $\alpha_a(\lambda_L, r)$ is obtained by the following equation [5,23].

$$\alpha_a(\lambda_L, r) = \frac{d/dr\left[ln\left(N(r)/P(\lambda_N, r)r^2\right)\right] - [\alpha_m(\lambda_L, r) + \alpha_m(\lambda_N, r)]}{1 + \lambda_L/\lambda_N}, \tag{4}$$

where $N(r)$ is the N_2 molecular number density and λ_x is the wavelength of Mie at 532 nm and wavelength of N_2-Raman backscatter at 607 nm. In Eq. (4), the numerical derivative causes a large error because of the noise of the lidar signal. Least-squares fitting is usually applied to reduce the error caused by the derivatives calculation. Thus, we propose our improved method to retrieve AEC without the numerical derivative.

2.2. Improved method

2.2.1. Aerosol backscatter coefficient

The improved method can obtain $\beta_a(\lambda_L, r)$ without calculating $\alpha_a(\lambda_L, r)$. Generally, the wavelength dependence of AEC is stated as $\alpha_a(\lambda_L)/\alpha_a(\lambda_N) = \lambda_N/\lambda_L$ [6]. Eq. (2) can be rewritten as

$$\exp\left\{\int_0^r [\alpha_a(\lambda_L, r`)]dr`\right\} = \left[\frac{P(\lambda_N, r)r^2}{C(\lambda_N)G(r)\sigma_N N(r)T_m(r)}\right]^{\gamma}, \tag{5}$$

where

$$\gamma = -\frac{\lambda_N}{\lambda_N + \lambda_L},$$

$$T_m(r) = \exp\left\{-\int_0^r [\alpha_m(\lambda_L, r`) + \alpha_m(\lambda_N, r`)]dr`\right\}.$$

However, a few unknown items exist in Eq. (5) and need to be eliminated. We consider r_f is the reference altitude same as Eq. (3), where $G(r_f) = 1$. Eq. (5) can be rewritten as

$$\exp\left\{\int_{rf}^r [\alpha_a(\lambda_L, r`)]dr`\right\} = \left[\frac{P(\lambda_N, r)r^2\cdot N(r_f)\cdot T_m(r_f)}{P(\lambda_N, r_f)r^2\cdot N(r)\cdot T_m(r)}\cdot\frac{1}{G(r)}\right]^{\gamma}, \tag{6}$$

When substituted into Eq. (3), we can obtain an accurate ABC at wavelength λ_L by

$$\beta_a(\lambda_L, r) = \frac{P(\lambda_L, r)\cdot P(\lambda_N, r_f)\cdot N(r)}{P(\lambda_L, r_f)\cdot P(\lambda_N, r)\cdot N(r_f)}\beta_m(\lambda_L, r_f)\frac{\exp\left\{-\int_{rf}^r \alpha_m(\lambda_N, r`)dr`\right\}}{\exp\left\{-\int_{rf}^r \alpha_m(\lambda_L, r`)dr`\right\}}\cdot \left[\frac{P(\lambda_N, r)r^2\cdot N(r_f)\cdot T_m(r_f)}{P(\lambda_N, r_f)r^2\cdot N(r)\cdot T_m(r)}\cdot\frac{1}{G(r)}\right]^{\gamma`} - \beta_m(\lambda_L, r) \tag{7}$$

where, $\gamma' = \lambda_L - \lambda_N/\lambda_L + \lambda_N$. $[1/G(r)]^{\gamma'}$ can be regarded as 1 where $G(r)$ is greater than 0.8 when λ_L is equal 532 nm and λ_N is equal 607 nm. In general, altitude higher than 500 m satisfy the conditions.

ABC can be retrieved by the method without the calculation of the extinction coefficient, which may cause a large error. As it will be shown latter, this improved method is more accurate than that retrieved by the traditional method described in Eq. (3). The ABC result of this method is employed in our improved method to retrieve a more accurate AEC than that of the traditional method.