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Aerosol characteristics inversion based on the improved lidar ratio profile with the ground-based rotational Raman–Mie lidar

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ABSTRACT

An iterative method, based on a derived inverse relationship between atmospheric backscatter coefficient and aerosol lidar ratio, is proposed to invert the lidar ratio profile and aerosol extinction coefficient. The feasibility of this method is investigated theoretically and experimentally. Simulation results show the inversion accuracy of aerosol optical properties for iterative method can be improved in the near-surface aerosol layer and the optical thick layer. Experimentally, as a result of the reduced insufficiency error and incoherence error, the aerosol optical properties with higher accuracy can be obtained in the near-surface region and the region of numerical derivative distortion. In addition, the particle component can be distinguished roughly based on this improved lidar ratio profile.

1. Introduction

Atmospheric aerosols, only a minor constituent of the atmosphere, have attracted much attention due to their important role in climate change, such as absorbing and scattering the solar radiation and the terrestrial long-wave radiation and acting as condensation nuclei of clouds [1–3]. Lidar is considered to be a kind of powerful remote-sensing technique used for aerosol measurements [3–7]. Until now, some inversion methods have been proposed to obtain the aerosol characteristics, such as Klett inversion method [8,9], Fernald inversion method [10–12] and Raman–Mie inversion method [13,14].

Aerosol backscatter coefficient (ABC) and aerosol extinction coefficient (AEC) are two important parameters for researching the atmospheric aerosol characteristics. But the inversion accuracy of these two important parameters is affected by geometric factor, calibration factor and lidar ratio (LR) value [4,15]. Among them, the geometric factor and calibration factor are related with the lidar system, while LR value is determined by the aerosol properties. The LR value can be assumed or calculated, which may influence the inversion accuracy in the whole investigated range. For traditional Fernald method, a single LR value is usually assumed over the whole investigated range without considering the different optical properties of atmospheric aerosols and cloud particles [4,10,15,16]. And Takamura proposed a method to obtain an average LR value supplemented by sun photometer and optical particle counter [17]. However the assumed or averaged LR value cannot sufficiently reflect the properties of aerosols and would cause some insufficiency error for the inversion of ABC and AEC parameters.

To improve the inversion accuracy, some researchers obtained LR profile based on the ratio of extinction to backscatter coefficient with different lidar systems [18–21]. However, owing to the signal-to-noise ratio (SNR) of backscatter returns and the operation of numerical derivative to lidar equation, the LR profile would get some negative results, which would cause incoherence in AEC profile. Gong proposed a method to obtain LR profile avoiding the operation of numerical derivative. According to the defined performance function, the optimal LR at certain altitude is obtained with the assumption that LR value changed from 1 to 100 sr [22]. In fact, LR value may greater than 100 sr for some specific aerosols, such as soot and coarse mineral, so the obtained LR profile may not be accurate entirely in some regions. Therefore, a new method to improve LR profile and then enhance the inversion accuracy of aerosols is urgently needed.

In this paper, an iterative method is proposed to obtain LR profile and AEC profile according to the derived inverse relationship between atmospheric backscatter coefficient and LR. The feasibility of this iterative method has been analyzed by the simulation and verified by the actual case measured from ground-based rotational Raman–Mie lidar in Beijing, China (39°57′N, 116°19′E) [4,15]. Compared with Fernald method and defining method, the iterative method can obtain more accurate retrieval results as a result of ignoring the assumption of single LR value and the operation of numerical derivative especially in the near-surface region and the region of numerical derivative distortion. Furthermore, the particle component can also be distinguished roughly according to the improved LR profile.

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2. Method

The range-corrected elastic backscatter lidar return can be expressed by the following equation:

$$X(z) = CO(z)\left[\beta_a(z) + \beta_m(z)\right] \exp\left\{-2\int_0^z \left[\alpha_a(z') + \alpha_m(z')\right] dz'\right\} \quad (1)$$

where $X(z)$ is the range-corrected backscatter return at altitude z; C is the lidar system constant; $O(z)$ represents the geometric factor profile of lidar system; β_a and β_m represent ABC and atmospheric molecular backscatter coefficient (MBC), respectively; $\alpha_a(z) = S_a(z)\beta_a(z)$ and $\alpha_m(z) = S_m\beta_m(z)$ are AEC and atmospheric molecular extinction coefficient (MEC), respectively; S_a is the aerosol LR which value depends strongly on the aerosol composition, size distribution and refractive index as well as on the lidar wavelength [23]. The equivalent ratio for the atmospheric molecules, S_m, is just $8\pi/3$.

For traditional Fernald method and its improvements, LR profile in the investigated range used an assumed single value or averaged value, then AEC can be obtained with the expression of $\alpha_a(z) = S_a\beta_a(z)$, such fixed LR value of treatment can be simply called as Fernald method.

By rearranging Eq. (1), LR profile can be obtained directly from the measured signal $X(z)$, according to

$$S_a(z) = -\frac{\frac{1}{2}d\left\{\ln\frac{X(z)}{O(z)[\beta_a(z)+\beta_m(z)]}\right\}/dz + \alpha_m(z)}{\beta_a(z)} \quad (2)$$

where $\beta_a(z)$ is the result inversed with Raman–Mie method [13], $\beta_m(z)$ and $\alpha_m(z)$ can be calculated accurately with a regional and seasonal atmospheric model corresponding to the lidar measurement condition or the data of a nearby radiosonde ascension. Then AEC can be obtained with the expression of $\alpha_a(z) = S_a(z)\beta_a(z)$. For convenience, this method is named as defining method owing to the acquisition principle of LR. Moreover, LR profile obtained from this method is theoretically accurate without assuming any parameters and atmospheric condition. But, owing to the SNR of backscatter returns and the operation of numerical derivative, the obtained LR profile and the consequent AEC would generate some incoherence error.

The iterative method makes use of the fact that the deviation between the Fernald solution ($\beta_{a,F}(z)$), which is calculated with single LR, and the Raman–Mie solution ($\beta_{a,R}(z)$) which contains the information of incomplete LR. The flow diagram of the iterative method is generalized simply and shown in Fig. 1. Müller et al. showed that LR has mean values of about 38 ± 7 sr within the planetary boundary layer in Beijing [23]. And a representative value of 50 sr [24], slightly larger than the upper error limit, is used for the initial iteration in our analysis. According to Eq. (1), the initial lidar-ratio-dependent ABC in the first step ($i = 1$) can be expressed as follow:

$$\beta_{a,F,i}(z) + \beta_m(z) = \frac{X(z)\exp\left[-2(S_{a,i} - S_m)\int_{z_0}^{z}\beta_m(z')dz'\right]}{K - 2S_{a,i}\int_{z_0}^{z} X(z')\exp\left[-2(S_{a,i} - S_m)\int_{z_0}^{z}\beta_m(z'')dz''\right]dz'} \quad (3)$$

where $K = \frac{X(z_0)}{\beta_{a,F}(z_0)+\beta_m(z_0)}$ is the calibration parameter; z_0 is a given constant reference altitude. After a series of algebraic transformations, the atmospheric backscatter coefficient (expression of $\beta_{a,F}(z) + \beta_m(z)$) is approximately inversely proportional to the aerosol LR (see Appendix for detailed mathematic operations).

Therefore, based on the derived inverse relationship, an increment factor for LR at some fixed altitude z_f in the first step can be written as follow:

$$\Delta S_i(z_f) = \frac{\frac{1}{\beta_{a,R}(z_f)+\beta_m(z_f)} - \frac{1}{\beta_{a,F,i}(z_f)+\beta_m(z_f)}}{\frac{1}{\beta_{a,R}(z_f)+\beta_m(z_f)}} \quad (4)$$

where $\beta_{a,F}(z_f)$ and $\beta_{a,R}(z_f)$ are ABCs obtained from Fernald method [10] and Raman–Mie method [13] at fixed altitude of z_f, respectively, $\beta_m(z_f)$ is MBC at fixed altitude of z_f.

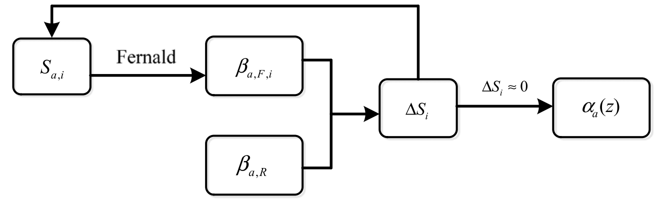

Fig. 1. Flow diagram of the iterative method.

With $\Delta S_{i=1}(z_f)$, the LR value at altitude of z_f is improved by the following expression:

$$S_{a,i+1}(z_f) = S_{a,i}(z_f)\left[1 + \Delta S_i(z_f)\right]. \quad (5)$$

By applying the improved $S_{a,2}(z_f)$ and the Fernald method (step $i = 2$), we obtained the improved $\beta_{a,F,i=2}(z_f)$ at altitude of z_f. After inserting $\beta_{a,F,i=2}(z_f)$ into Eq. (4) and $\Delta S_{i=2}(z_f)$ into Eq. (5), we further improve LR again. Based on the threshold of algorithm stop of $S_{a,i+1}(z_f)$-$S_{a,i}(z_f)$ < 0.5 sr [22], simulation indicates that about 15–20 iterations would be sufficient to remove the deviation basically between the Fernald solution $\beta_{a,F}(z_f)$ and the Raman–Mie solution $\beta_{a,R}(z_f)$ at altitude of z_f. Repeating the above operation over the whole investigated range, the LR profile ($S_a(z)$) can be retrieved completely. Then the accurate AEC can be calculated based on this improved LR profile according to the expression of $\alpha_a(z) = S_a(z)\beta_{a,R}(z)$.

3. Simulation

The elastic (Mie) and Pure Rotational Raman (PRR) signals with laser wavelength of 532 nm and Gaussian noise under standard atmosphere were simulated and shown in Fig. 2a. In our simulation, the near-surface aerosol layer and an optical thick layer were simulated at 0–2 km and 4–6 km. From Fig. 2b, the assumed true ABC and AEC changed around the corresponding MBC and MEC respectively. And the assumed true aerosol LR are from 80 sr to 50 sr linearly at 0–2 km, from 50 to 65 sr linearly at 4–4.5 km, from 65 to 50 sr linearly at 5.5–6 km, 65 sr at 4.5–5.5 km, and 50 sr at other altitude, respectively as shown in Fig. 2c.

Fig. 3a shows the true ABC and the average standard deviation (denoted as the error bars) of ABCs obtained from iterative method, Raman–Mie method and Fernald method in about 15 simulated experiments. The results of these three methods are all in good agreement with true ABC. The standard deviation for Fernald method is smaller than that for the other two methods owing to the used higher SNR Mie return signal. Moreover, the ABC obtained from iterative method is calculated based on that obtained from Raman–Mie method as shown in Method section, so the standard deviation of iterative method is almost similar to that of Raman–Mie method. Fig. 3b quantitatively shows the relative errors of iterative and Raman–Mie methods in the near-surface aerosol layer and optical thick layer are almost equal to zero, whose average relative error is about 90 times smaller than that of Fernald method as listed in Table 1. And from Table 1, an approximately consistent relative error can be found among these three inversion method between 2 and 4 km. Therefore, the ABC obtained from iterative method is as accurate as that obtained from Raman–Mie method.

Fig. 3c shows the true LR and that obtained from iterative method, defining method and Fernald method. It can be seen that in aerosol layer, the LR profiles obtained from defining method and iterative method are more consistent with true LR profile than that obtained from Fernald method. Compared with that obtained from iterative method, the LR profile obtained from defining method is easy to be negative and does not match the true value at the low SNR region, which can be attributed to the numerical derivative when solving lidar equation. Fig. 3d shows the relative error of Fernald method is obviously larger than that of the other two methods in the near-surface aerosol layer and optical thick