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Calibration method for the reference parameter in Fernald and Klett inversion combining Raman and Elastic return

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ABSTRACT

A calibration method is proposed to invert the extinction coefficient for Fernald and Klett inversion by using the particle backscattering coefficient inversed with Raman and Elastic return signals. The calibration method is analyzed theoretically and experimentally, the inversion accuracy can be improved by removing the dependence on reference altitudes and intervals in conventional calibration methods, which resulted from the introduction of backscattering coefficient with relatively higher accuracy obtained by Raman–Mie inversion method. The standard deviation of this new calibration method can be reduced by about 20 × , compared to that of the conventional calibration methods of Fernald and Klett inversion. And, the more stable effective inversed range with this new calibration method can be obtained by removing the dimple phenomenon in clouds position.

1. Introduction

Atmospheric aerosol plays an important role in many atmospheric processes. Although only a minor constituent of the atmosphere, they have appreciable influence on the Earth's radiation budget, air quality and visibility, clouds, and precipitation in the troposphere and stratosphere by absorbing and scattering the solar radiation and the terrestrial long-wave radiation [1–3]. Therefore, much attention has been paid to the measurement of the tropospheric aerosol optical characteristics. Aerosol scattering coefficients, especially backscattering and extinction coefficients are important parameters for retrieval of an aerosol size distribution and the heat balance of the Earth [4].

There are some traditional inversion methods to obtain the aerosol characteristics, such as Klett inversion [5–7], Fernald inversion [8–10] and Raman–Mie inversion [2,6,11]. Until now the Fernald and Klett inversion methods for elastic backscattered lidar return processing have been considered basic methods for lidar determination of the atmospheric aerosol extinction profile [12–14]. However, the inversion accuracy of aerosol characteristics is dependent to the calibration of the reference parameter. For Fernald inversion method, its inversion accuracy relies on the backscattering ratios and reference altitude in its calibration equation [8,10,15]. For Klett inversion method, its inversion accuracy relies on the selection of different calibration equations and the intervals in these equations [6,7]. All these uncertain factors would enhance the inaccuracy of inversion results, which would not be helpful for obtaining the accurate aerosol extinction coefficient.

In Kim's research, Raman–Mie inversion [2], regardless of the geometric factor, can inverse the backscattering profiles with relatively higher accuracy than conventional inversion method on account of using the ratio of rotational Raman and Elastic return. Due to the use of real-time return signals, the backscattering coefficient obtained by this inversion method can be applied to the calibration in Fernald and Klett inversions. The inversion with this backscattering coefficient can be convenient because it

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ignores the selection of reference altitudes (for Fernald inversion) and calibration equations and intervals (for Klett inversion). However, there was seldom report about this improved calibration method in the current published research.

In this paper, this improved calibration method has been verified with experimental data obtained through the Beijing Institute of Technology (BIT) Raman–Mie lidar [16,17] and compared with the well-known calibration methods (Fernald and Klett). The detailed theoretical analysis and experimental discussion are carried out. The standard deviation of this improved calibration method decreased to about 0.00109 km^{-1} (for Fernald inversion) and about 0.0155 km^{-1} (for Klett inversion). And the more stable effective inversed range for Fernald inversion can also be obtained with this improved calibration method.

2. Theoretical analysis

According to lidar equation, Frederick G. Fernald put forward an inversion equation for aerosol backscattering coefficient. And the aerosol extinction coefficient (shorthand for EC-F) can be obtained with the extinction-backscattering ratio of aerosol. For the reference parameter of $\beta_{a,F}(r_m)$ in their research, it can be calibrated by the following equation [18,19]:

$$\beta_{a,F}(r_m) = [R(r_m) - 1]\beta_m(r_m) \tag{1}$$

where the subscripts a and m stand for aerosol and atmospheric molecule respectively, and the subscript F stands for Fernald inversion, β is the backscattering coefficient, r_m is a given constant reference altitude, $R(r_m)$, the aerosol backscattering ratio, can be assumed to be approximate 1.02–1.05 at the reference altitude according to the experiential value in many researches [4,8,19–22]. And the limit values of 1.02 and 1.05 are selected to calibrate $\beta_{a,F}(r_m)$ in our research, which are named as F102 calibration and F105 calibration respectively. In addition, the atmospheric molecule backscattering coefficient, calculated by the US Standard Atmosphere, is always the same for different observation data, which would lead to the same $\beta_{a,F}(r_m)$ under different observation data. Therefore, this crude parameter calibration method would inevitably lead to the inaccurate description of atmospheric characteristics.

James D. Klett proposed another inversion equation for atmospheric extinction coefficient (shorthand for EC-K) and gave a good estimate for the reference parameter $\alpha(r_m)$ over a specified interval $\Delta r = r_m - r_0$ as follows [7]:

$$\alpha(r_m) = \frac{1}{2}\frac{H(r_0) - H(r_m)}{r_m - r_0} \tag{2}$$

$$\alpha(r_m) = \frac{\exp\{[H(r_0) - H(r_m)]/k\} - 1}{\frac{2}{k}\int_{r_0}^{r_m} \exp\{[H(r) - H(r_m)]/k\} dr'} \tag{3}$$

where $H(r) = \ln[r^2 p(r)]$ is defined as the logarithmic range-adjusted power parameter corrected with geometric factor at altitude r, r_o is a selected altitude around the reference altitude r_m with small distance, k depends on the lidar wavelength and various properties of the obscuring aerosol and has a typical value of 1.0 [5]. So the calibration for $\alpha(r_m)$ is defined as K-Diff calibration (Eq. (2)) and K-Inte calibration (Eq. (3)) respectively. It is obvious that $\alpha(r_m)$ seriously depends on the interval Δr. Assuming the selectable intervals are 0.1 km, 0.2 km and 0.3 km respectively, there would be six possible inversed results. Therefore, the Klett inversion would inverse different results at the same reference altitude, and it would extend the inversion time owing to the choice of the calibration equations (Eqs. (2) and (3)) and intervals, which is not helpful for obtaining accurate atmospheric information.

According to Raman–Mie method, using the ratio of rotational Raman and Elastic lidar return, the aerosol backscattering coefficient at reference altitude can be expressed as follows [2,11]:

$$\beta_{a,R}(r_m) = \left[\frac{1}{C}\frac{P_E(r_m)}{P_R(r_m)} - 1\right]\beta_m(r_m) \tag{4}$$

where the subscript R stands for Raman–Mie inversion, $P_E(r_m)$ and $P_R(r_m)$ are return signals of Elastic scattering and rotational Raman scattering respectively at reference altitude r_m, C is a constant associated with the system structure, which can be calculated according to the signal intensity ratio and the assumptive backscattering ratio. It can be seen that $\beta_{a,R}(r_m)$ (in Eq. (4)) depends not only on the atmospheric molecule backscattering coefficient calculated by the US Standard Atmosphere, but also on the return signals of the day. Because the observation data of different dates are different from each other, the parameter $\beta_{a,R}(r_m)$ is variety at the same reference altitude for different observation data. Therefore, this reference aerosol backscattering coefficient inversed by Eq. (4) can be applied to the calibration of reference parameter in Fernald and Klett inversions with different forms as shown below:

$$\begin{cases} \beta_{a,F}(r_m) = \beta_{a,R}(r_m) & \text{for Fernald} \\ \alpha(r_m) = S_a\beta_{a,R}(r_m) + S_m\beta_m(r_m) & \text{for Klett} \end{cases} \tag{5}$$

where lidar ratio remains constant over the range being investigated, S_a applies only to the particulate scatters, the equivalent ratio for the molecular scatters, S_m is just $8\pi/3$. Muller et al. showed that the parameter of S_a has mean values about 38 ± 7 sr within the planetary boundary layer in Beijing [23]. And the mean lidar ratio of 45.8 sr (slightly larger than the upper error limit) obtained by Hao et al. is used in our research [24]. Furthermore, this two kinds of calibration formula in Eq. (5) can be named as FR calibration (for Fernald) and KR calibration (for Klett), respectively.

3. Experimental detail

The BIT Raman–Mie lidar is located at the LIDAR Lab. (39°57′N, 116°19′E) of Beijing Institute of Technology in Beijing, China. The lidar system can measure aerosol and temperature profiles in the troposphere with pure rotational Raman return and elastic return. The system has a bistatic configuration and consists of laser emission, receiving optics, spectrometer, signal detection, and data acquisition units. The laser wavelength is 532 nm at 20 Hz after the frequency is