Retrieving aerosol backscattering coefficient for short range lidar using parameter selection at reference point

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A new method is proposed based on the analysis of lidar equation which selects aerosol backscatter ratio at a reference point for short range lidar in data processing. Simulation computation and experimental comparison results show that this method is reasonable and feasible. The method is applied to short range lidars, such as atmospheric monitoring lidar-2 (AML-2) and micro-pulse lidar (MPL).

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Atmospheric aerosols play an important role in the radiation rate of the earth through scattering and absorption. They can influence the lifetime and microphysical properties of clouds, precipitation rates and tropospheric photochemistry, and hence very important in climate change[1]. Lidar is a highly useful remote sensing tool in measuring the optical properties of atmospheric aerosols[2]. Thus far, a number of lidars have been applied to detect atmospheric aerosols[3−7].

Using lidar equation, aerosol extinction and backscatter coefficients can be retrieved through the traditional Fernald inversion method[8]. In this method, two parameters are supposed, the aerosol backscatter ratio R, which is defined as the ratio of total backscatter to molecular backscatter, and the aerosol extinction-to-backscatter ratio S_1. For the first assumption, the aerosol backscatter ratio R is easy to determine for long range lidar, which can reach tropopause, because there are few aerosols present in the free troposphere[9,10]. However, for short range lidar reaching only about 3−6 km, the proper aerosol backscatter ratio R at reference point is difficult to select, because the ratio changes with the weather conditions. To solve the above problem, a new technique is introduced in this letter. Simulation computation and experimental comparisons are made using different lidars.

The elastic lidar equation can be written as[11]

$$X(z) = P(z)z^2 = C[\beta_1(z) + \beta_2(z)]$$
$$\times \exp\left\{-2\int_0^z [\alpha_1(z') + \alpha_2(z')]dz'\right\}, \quad (1)$$

where $P(z)$ is the backscatter signal from a scatter volume at range z; C is the lidar system constant; $\beta_1(z)$ and $\beta_2(z)$ are the volume backscatter coefficients at range z for aerosols and molecules, respectively; $\alpha_1(z)$ and $\alpha_2(z)$ are the volume extinction coefficients at range z for aerosols and molecules, respectively. Dividing by $\beta_2(z)$, Eq. (1) is changed to

$$X(z)/\beta_2(z) = C[1 + \beta_1(z)/\beta_2(z)]$$
$$\times \exp\left\{-2\int_0^z [\alpha_1(z') + \alpha_2(z')]dz'\right\}. \quad (2)$$

If there are few aerosol regions, that is $\beta_1(z) \ll \beta_2(z)$, or if there are homogeneous aerosols regions where $\beta_1(z)/\beta_2(z)$ is constant, the lidar equation can be rewritten approximately as

$$X(z)/\beta_2(z) = C' \cdot \exp\left\{-2\int_0^z [\alpha_1(z') + \alpha_2(z')]dz'\right\}, \quad (3)$$

where C' is a new constant. From Eq. (3), the sum of aerosol and molecule extinction coefficients is obtained using the slope method presented as

$$\alpha_1(z) + \alpha_2(z) = -\frac{1}{2}\frac{d[\ln(X(z)/\beta_2(z))]}{dz}. \quad (4)$$

That is to say, in homogeneous aerosols regions, or $\beta_1(z)/\beta_2(z)$ being the constant region, Eq. (4) is reasonable; in other cases, however, Eq. (4) is not correct.

Based on the above analysis combined with the signal-to-noise ratio (SNR), we developed a new method for determining the aerosol backscatter ratio R at reference point for short range lidar inversion. The details of the method are presented below.

Firstly, supposing that the condition of Eq. (4) was fitted, the sum of the aerosol and molecule extinctions were obtained using Eq. (4). Secondly, at altitudes of over 2−5 km, we searched for approximative homogeneous aerosols and molecules regions according to the results of step one, and considered the center of the homogeneous aerosol and molecule regions as the reference point for data inversion. Thirdly, taking the reference point as center, the average value of aerosol and molecule extinctions was computed in the 300-m region. Through proportion coefficient, this average value was converted into the aerosol backscatter ratio R. The proportion coefficient was then determined by comparing the aerosol backscatter coefficient from this R with simultaneous measurements from the long-range lidar. Finally, applying the aerosol backscatter ratio R from the third step, we retrieved the aerosol backscatter coefficient using the Fernald method.

In order to check the reasonability of the above method, some simulation computation and comparisons with long range lidar were carried out.

Using standard atmospheric molecule model data, a pure molecular lidar backscatter signal was created in the vertical direction. For this simulation lidar signal, we retrieved the atmospheric extinctions using Eq. (4). The retrieval atmospheric extinction profile is shown in Fig. 1 as a dotted line. The solid line in Fig. 1 is the standard atmospheric molecule model extinction profile. To compare the two profiles, we used the conventional slope method equation to retrieve the atmospheric extinction profile again, which can be expressed as

$$\alpha_1(z) + \alpha_2(z) = -\frac{1}{2}\frac{\mathrm{d}\ln X(z)}{\mathrm{d}z}, \qquad (5)$$

the result is indicated as a dashed line in Fig. 1. It is shown that the retrieval atmospheric extinction profile is in agreement with the original standard atmospheric molecule model generated using Eq. (4). However, if the atmospheric extinction profile is retrieved using the conventional slope method stated in Eq. (5), the result greatly differs with the original standard atmospheric molecule model. This indicates that Eq. (4) is better than Eq. (5) in retrieving atmospheric extinctions in the cases where there are few aerosols in the vertical direction.

Our institute has both the atmospheric monitoring lidar-2 (AML-2) mobile and dual-wavelenth lidar (DWL) systems. The AML-2 mobile is a short range lidar[12], and can only reach about 5 km in 532 nm to detect atmospheric aerosols. Meanwhile, DWL is a long range lidar[13], and can reach about 18 km in 532 nm in detecting tropospheric aerosols. For the DWL, we can select a "clean" aerosol-free region in the free troposphere as a reference point, and assume that the aerosol backscatter ratio R is a constant at 1.01 and the lidar ratio as 50 sr for 532 nm. For AML-2, we use the proposed method to select the reference point within 2−5 -km altitudes, and decide on the aerosol backscatter ratio R. We assume the lidar ratio as 50 sr, which is the same value used in the DWL. Obviously, the aerosol backscatter ratio R changes with the atmospheric condition in AML-2. We retrieve the aerosols backscatter coefficients using the Fernald method for the two lidar backscatter signals.

The locations of AML-2 mobile and DWL are about 40 m away from each other. We selected almost simultaneous measurements between the two lidars for comparison. The atmospheric scenes were then classified into two types: few aerosols and some aerosols loaded over 2−4-km altitudes. Figure 2 shows the comparisons for the two cases.
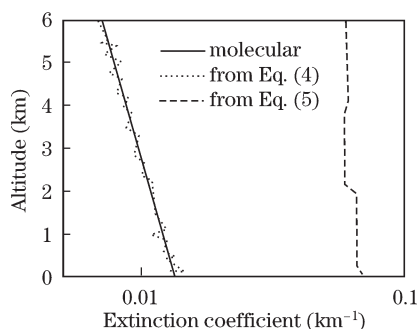

Fig. 1. Simulation computation of pure molecular backscatter signals.
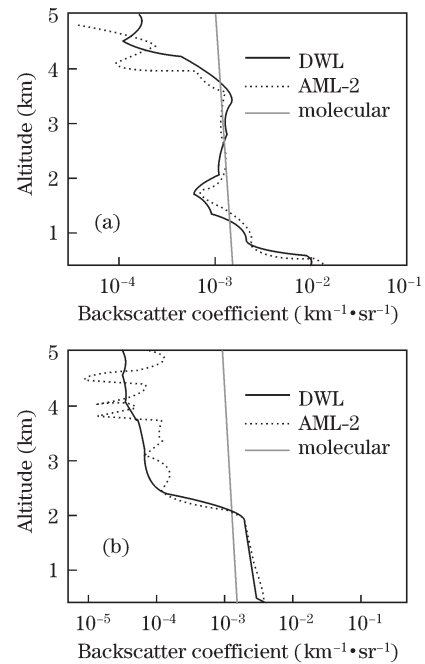

Fig. 2. Backscatter coefficient profiles retrieved using different methods from AML-2 and DWL with almost simultaneous measurements. (a) The profiles were acquired on Nov. 13, 2008 at 21:00 for DWL and 21:12 for AML-2 local time, respectively; (b) the profiles were acquired on Nov. 19, 2008 at 17:30 for DWL and 17:28 for AML-2 local time, respectively.

Figure 2(a) shows a comparison between some aerosols loaded at 2−4 km altitudes on Nov. 13, 2008 at 21:00 for DWL and 21:12 for AML-2 local time. Within 2−4-km altitudes, aerosol backscatter coefficients are almost equal to the molecule backscatter coefficients. The two profiles are in good agreement over the 0.5−3.5-km altitudes. Above 3.5 km, there are some deviations between the two profiles due to weaker backscatter signals of the AML-2.

Figure 2(b) shows the comparison between the few aerosols loaded in 2−5 km-altitudes on Nov. 19, 2008 at 17:30 for DWL and 17:28 for AML-2 local time. Within 2−5 km-altitudes, aerosol backscatter coefficients are less than the molecule backscatter coefficients above 10 times. The weaker backscatter signals of AML-2 caused the retrieval aerosols backscatter coefficient in altitudes 3−5 km to have some fluctuations. Below 2 km, the two profiles are in good agreement.

For the DWL experimental data, we used two methods to retrieve the backscatter coefficient. One was the traditional method which selected a reference point in the free troposphere, and the other was our method which selected a reference point within 2−5 km in altitudes. The DWL data used were the same data in Fig. 2. The comparison results are shown in Fig. 3.

Figure 3(a) shows that the two backscattering coefficient profiles are in good agreement; Fig. 3(b) shows the same result. These results further indicate that our method is feasible.

A micro-pulsed lidar (MPL) is classified as a short range lidar, especially in day measurements, because of the laser energy microjoule degree. We compared the
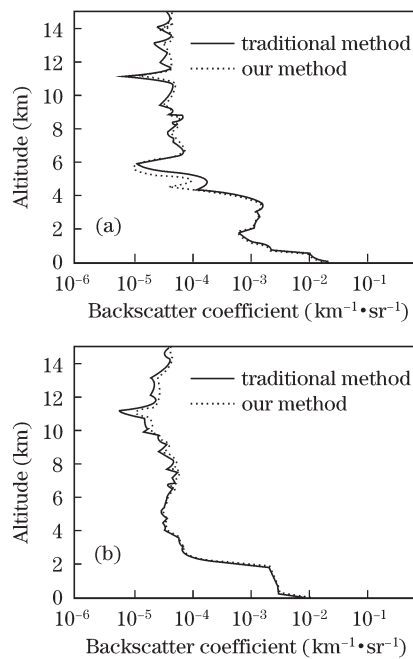
Fig. 3. Backscatter coefficient profiles retrieved using different methods from DWL measurements. DWL local time (a) 21:00 on Nov. 13, 2008 and (b) 17:30 on Nov. 19, 2008.

MPL with DWL in simultaneous measurements, and obtained results similar to that of the comparisons between AML-2 and DWL.

For the short range lidar, we searched for a relative "clean" point as a reference point at altitudes over $2-5$ km, and considered the aerosol backscatter ratio R changing from 1.1 to 1.5 at the reference point in the previous data processing. The value of R is generally selected according to atmospheric condition and experience. Thus, for the same lidar measurement, different persons have different inversion results. This causes uncertainty, and is also a practical problem for short range lidar. For the long range lidar, the above problem does not exist because the reference point is selected in the free troposphere in which there is a "clean" aerosol-free region in which the aerosol backscatter ratio R can be considered as a constant[11].

In conclusion, the presented method solves the above problem. Our method obtains sensitive information from backscatter lidar data including atmospheric conditions. Based on the information, we determine the aerosol backscatter ratio R. This method eliminates the influence of experience. Our method is applied to both AML-2 and MPL data processing. Simulation computation and comparisons indicate that the inversion results retrieved by this method are good. Therefore, our method is reasonable and feasible.

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