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New Lidar technology for aerosol measurements and extinction coefficient inversion

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ABSTRACT

This paper presents new Lidar technology with which to remove the noise effect in aerosol extinction coefficient inversion, thereby yielding coefficients with high accuracy. Based on the Lidar principle, the new inversion method is calculated theoretically. As a case study, aerosols were measured regularly using Mie Lidar in the northern suburbs of Nanjing City, China, using the new method to calculate the aerosol extinction coefficient. The laser source energy was varied to obtain Lidar return signals with different intensities, which were then used to remove the noise effect, yielding inverse aerosol extinction coefficients with high accuracy. A numerical simulation was performed to examine the aerosol extinction coefficients calculated using Lidar return signals with different laser powers. The simulation results reveal that the different laser energies yield identical profiles of inversed aerosol extinction coefficients, consistent with the experimental results. The experimental and simulation results demonstrate the validity of the theoretical calculations.

1. Introduction

Aerosol is an important factor in climate change and the atmospheric environment, yet there is a global lack of aerosol observational data [1–6]. Lidar is an effective tool for aerosol measurements, as it has a higher range resolution than other remote sensing methods, although limitations exist. The Lidar range resolution can be 7.5 m, but the sound range resolution usually is about 1 km (web site). For example, many assumptions are made in data inversion, and the resulting data are strongly affected by the boundary conditions [7]. In addition, aerosol measurements are affected by background noise and the thermal noise of the detector. Many methods have been proposed for the data processing of background noise, which is a concern for many researchers. One approach is to directly measure the noise (run the data acquisition system, blocking the laser beam), and another is to consider the electrical pulses during data collection or to take the value of the highest position of the echo signal as the background [8]. Even if background noise can be measured with reasonable accuracy, the thermal noise and electrical noise of the detector still have a large influence on the results.

This study, based on the principle of Lidar, aims to determine the influence of noise on aerosol detection accuracy and measurement error, combining various Lidar equations and inversion methods for the atmospheric aerosol extinction coefficient to explain theoretically how the noise effect influences Lidar aerosol measurements. In the present approach, the energy of the laser source is varied to obtain different signals and thereby eliminate the noise effect from the aerosol inversion.

2. Theory

2.1. Treatment of randomness thermal and electric noise signal

The background noise includes background light noise from the atmosphere and thermal and electric noise from detector and Lidar system. The background light noise from atmosphere depends on the used wavelengths, can be taken as constant [9,10]. Usually, according to empirical experiment, the thermal and electric noise is random, and empirical average of randomness noise is negligible. Fig. 1 is the background noise taken from our Lidar system.

In Fig. 1A, the random noise is taken from the running Lidar system with a cover over the telescope. therefore, the backscatter noise from the atmosphere is blocked by the cover over the telescope. In this case, the detected is thermal and electric noise from

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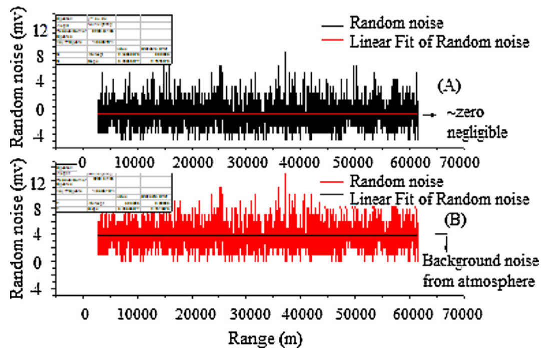

Fig. 1. (A) Random noise taken from the running Lidar system with a cover over the telescope. (B) Background noise taken from the running Lidar system with open the telescope.

the detector and operation Lidar system. We do linear fit calculation for the random noise, the fitted linear is negligibly small, almost zero. Fig. 1B is the background noise taken from the running Lidar system with open telescope, in this case the background noise includes background noise from the atmosphere and also thermal and electric noise. The linear fit calculation for the detected noise shows that the background noise from atmosphere (related to the filter central wavelength and the bandwidth) is almost constant, independent with range. Therefore, the background noise can be mainly considered as the noise from atmosphere, almost constant.

2.2. *Extinction coefficient calculation without background noise effect*

Let E_{01} and E_{02} be transmitted laser power, and $E_1(r)$ and $E_2(r)$ the respective return signals. It is assumed that the time interval of two measurements with different laser energies is small and that atmospheric conditions are constant, to ensure that all detected noises are equal. The noise (including background noise, and thermal noise and electrical noise of the detector) is written as $\delta(r)$. The mean value of noise can be considered as $\bar{\sigma}(r) = \frac{\sum_{1}^{i}\sigma(r_i)}{i}$. The mean value of noise at different laser power E_{01}, E_{02} should be written as $\bar{\sigma}_1(r)$ and $\bar{\sigma}_2(r)$. As discussed in Section 2.1, $\bar{\delta}(r) = \bar{\delta}_1(r) = \bar{\delta}_2(r) \approx$ constant.

The differential equations corresponding to the Lidar equation are as follows:

$$P_1(r) = E_1(r) - \bar{\delta}_1(r) = E_{01}\frac{c\tau}{2}A\frac{\beta(r)}{r^2}\exp\left[-2\int_0^r \sigma(r)\mathrm{d}r\right] \tag{1}$$

$$P_2(r) = E_2(r) - \bar{\delta}_2(r) = E_{02}\frac{c\tau}{2}A\frac{\beta(r)}{r^2}\exp\left[-2\int_0^r \sigma(r)\mathrm{d}r\right] \tag{2}$$

$E_1(r)$ and $E_2(r)$ are measured Lidar return signal intensities including noise effect; consequently, there is an error in the results of atmospheric aerosol inversion by $E_1(r)$ and $E_2(r)$. The noise is generally removed during the inversion, but it is difficult to quantify the noise exactly under normal circumstances. $P_1(r)$, $P_2(r)$ is the noise free return signal (in other words $P_1(r)$ and $P_2(r)$ are the return signals after noise treatment), respectively, at different transmission powers E_{01}, E_{02}. c is the velocity of light, τ is the laser pulse duration. $\beta(r)$ is the backscatter coefficient. $\sigma(r)$ is the extinction coefficient. Background noise can be removed by subtracting Eq. (2) from Eq. (1), as follows:

$$P_1(r) - P_2(r) = E_1(r) - E_2(r)$$
$$= (E_{01} - E_{02})\frac{c\tau}{2}A\frac{\beta(r)}{r^2}\exp\left[-2\int_0^r \sigma(r)\mathrm{d}r\right] \tag{3}$$

Considering $\Delta P(r) = P_1(r) - P_2(r)$, $\Delta E(r) = E_1(r) - E_2(r)$, and $\Delta E_0 = E_{01} - E_{02}$, Eq. (3) becomes

$$\Delta P(r) = \Delta E(r) = \Delta E_0\frac{c\tau}{2}A\frac{\beta(r)}{r^2}\exp\left[-2\int_0^r \sigma(r)\mathrm{d}r\right] \tag{4}$$

Eq. (4) does not contain noise signals; consequently, the atmospheric aerosol extinction coefficient without error can be calculated from this equation.

According to Klett's analytical inversion algorithm [7], we have the following equations:

$$\sigma(r) = \frac{\exp(S - S_m)/k}{\sigma_m + \frac{2}{k}\int_r^{r_m}[\exp(S - S_m)/k]\mathrm{d}r} \tag{5}$$

$$S(r) = \ln[r^2 P(r)] \tag{6}$$

In Eq. (5), $\sigma(r)$ is aerosol extinction coefficient, k is wavelength dependence, it is 0.6 – 1, in this paper it is taken as 1. r_m is reference location, $\sigma_m = \sigma(r_m)$ is boundary value of aerosol extinction coefficient at r_m. $S_m = S(r_m)$. In general case, we set the position where the atmosphere is clear as reference location r_m, at the position r_m we can believe it is free aerosol loading, so that boundary value of extinction coefficient $\sigma_m = \sigma(r_m)$ can be assumed as molecular extinction coefficient which can be calculated from standard atmospheric conditions; if clear atmospheric condition is hard to satisfied, we can try to find the smooth range in Lidar range corrected signals ($P(r) \times r^2$), where the aerosol loading is homogeneous. In this case, we can use slope method to calculate the aerosol extinction coefficient in the smooth range, then using it as boundary value of aerosol extinction coefficient σ_m [11]. When the boundary value is determined, the aerosol extinction coefficient profile can be inversed by Eqs. (5) and (6), it is traditional inversion method.

According to Eq. (4), we also can use Klett method Eq. (5) to inverse aerosol extinction coefficient, in this case Eq. (6) should be changed to Eq. (7):

$$S(r) = \ln[r^2 \Delta P(r)] \tag{7}$$

It is apparent that E_0, which is the energy of the laser source, and $P(r)$, which is the energy of the return signal, have changed from Eqs. (1) and (2). It is assumed that if the laser energy is H times the original energy E_0, the Lidar echo power will be H times the original. In this case, there is no change in the atmospheric conditions, background noise, or aerosol parameters over a period of 1 – 2 min. The Eq. (6) then becomes

$$S_e(r) = \ln[r^2 HP(r)] = \ln H + \ln[r^2 P(r)] = \ln H + S(r) \tag{8}$$