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A method of determining multi-wavelength lidar ratios combining aerodynamic particle sizer spectrometer and sun-photometer

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ABSTRACT

The lidar equation solution for atmosphere requires knowledge of the lidar ratio along the lidar line of sight. The lidar ratio is depended on the wavelength of lidar, so it is difficult to determine the lidar ratios in multi-wavelength lidar. A method that determines the multi-wavelength lidar ratios combining sun-photometer and aerodynamic particle sizer spectrometer (APS) is proposed. The optimal lidar ratios at three wavelengths (355 nm, 532 nm and 1064 nm) are deduced from comparing the aerosol optical depth (AOD) derived from sun-photometer and the multi-wavelength lidar. The feasibility and practicability of this method is tested by the actual experiment. The uncertainty of determining lidar ratios in multi-wavelength lidar is reduced. The aerosol extinction coefficient retrieved using this method is improved with accuracy of 12.8%, 26.3% and 8.2% at 355 nm, 532 nm and 1064 nm respectively.

1. Introduction

Atmospheric aerosols have a significant impact on earth's climate [1,2]. It also influences on atmospheric environment and human health. Elastic backscatter lidar has been proven to be a very useful remote sensing tool to obtain the optical properties of atmospheric aerosols with its simple setup and easy to operate [3–5]. However, the elastic lidar equation includes two unknown variables, backscatter and extinction coefficient [6–8]. In order to derive aerosol optical parameter quantitatively from elastic lidar, the aerosol extinction-to-backscatter ratio or lidar ratio must be known in advance.

The multi-wavelength backscatter lidar is used more and more extensive for more optical parameters can be obtained. But the multi-wavelengths lidar ratios are difficult to determine than the single wavelength lidar because the lidar ratio is depended on lidar wavelength. Techniques to obtain the lidar ratio have been proposed for multi-wavelength backscatter lidar. A single average value of the lidar ratio for an aerosol layer can be estimated, with an assumption that the backscatter profiles at different wavelengths are similar shapes [9–11]. In practice, however, this assumption may be unrealistic and errors may be resulted in. A high-spectral-resolution lidar (HSRL) [12,13] or a combined elastic-Raman lidar [14,15] makes it possible to estimate lidar ratios at different wavelengths. A combined elastic-Raman lidar system can provide the information on both the backscattering and extinction coefficients alone the searched path. The basic problem with this method is the large difference between the Raman and elastic scattering cross sections, accordingly, the large difference in the intensity of the measured signals. Raman signals are about three orders of magnitude weaker than the signals due to elastic scattering. This may result in quite different measurement ranges or averaging times for the elastic and inelastic signals. For low-tropospheric measurements, the combined processing the data of elastic and Raman lidars may be an issue, because generally these measurements cannot cover the same range interval (r_0, $r_{\max}$), especially, in non-stationary atmospheres and daytime conditions [16]. A method of combining ground-based and spaceborne lidar to determine the lidar ratio has been developed [17]. Usually, it is difficult to acquire spaceborne and ground-based lidar data at the same time and in the same area of atmosphere.

In order to find an easy and practical method to determine the multi-wavelength lidar ratios, in this paper, a method of combining sun-photometer and aerodynamic particle sizer spectrometer measurements to determine the multi-wavelength lidar ratios is proposed. The aerodynamic particle sizer spectrometer is used to obtain the initial multi-wavelength lidar ratios and to correct the near-ground extinction coefficients. The sun-photometer is used to deduce the optimal multi-wavelength lidar ratios from comparing the AOD data between sun-photometer and multi-wavelength lidar. Relatively accurate multi-wavelength aerosol optical profiles can be acquired using the optimal lidar ratios.

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2. Methodology

Most of the aerosols exist in the near-ground atmosphere. There is insufficient overlapping area between the transmitting laser beam and the field of view of receiving telescope in monostatic lidar in the near-ground. So the near-ground signal of multi-wavelength lidar is needed to be corrected in advance.

2.1. Method of correcting the near-ground extinction profiles

The signal amplitude of aerosol backscatter is related to lidar wavelength. Therefore, in multi-wavelength lidar, the near-ground signal of each wavelength needs to be corrected respectively. In order to correct the near-ground optical data, firstly, the initial value of multi-wavelength lidar ratios must be known.

The backscatter β_λ and extinction α_λ coefficients are related to the aerosol size distribution $n(r)$ by Fredholm integral equations of the first kind [18]:

$$\alpha_\lambda = \int_{r_{\min}}^{r_{\max}} \pi r^2 Q_{ext}(r, \lambda; m) n(r) dr \tag{1}$$

$$\beta_\lambda = \int_{r_{\min}}^{r_{\max}} \pi r^2 Q_{bac}(r, \lambda; m) n(r) dr \tag{2}$$

Here r denotes the particle radius, λ is the wavelength, m is the refractive index, and the upper and lower limits of the particle sizes are r_{min} and r_{max}. Q_{ext} and Q_{bac} denote the extinction and backscatter efficiencies for individual particles weighted by their geometric cross-section πr^2 which can be calculated by Mie theory.

Knowing a real number size distribution $n(r)$ of the aerosol particles, the extinction and backscatter coefficients can be obtained by these two formulas. Accordingly, the lidar ratio S_λ at different wavelength near-ground can be obtained by [19]:

$$S_\lambda = \frac{\int_{r_{\min}}^{r_{\max}} \pi r^2 Q_{ext}(r, \lambda; m) n(r) dr}{\int_{r_{\min}}^{r_{\max}} \pi r^2 Q_{bac}(r, \lambda; m) n(r) dr} \tag{3}$$

In order to correct the near-ground extinction coefficient and obtain the whole range optical depth from the extinction profiles at three wavelengths the initial lidar ratios need to be acquired. The lidar ratios calculated from (3) are the near-ground lidar ratios, which are not fitted to all altitude along the lidar line of sight. Therefore, the lidar ratios must be corrected using the sun-photometer AOD data.

Fernald-Klett algorithm [20] is adopted to invert the multi-wavelength lidar data. The lidar ratios of three wavelengths obtained above are used in this algorithm. The method of correction of near-range multi-wavelength lidar optical parameter based on the particle size distribution [21] is adopted in this paper. Signals from range 0 to 10 km are analyzed because the aerosols above 10 km can be negligible. The near-ground is a rich region of aerosols, so the correction of aerosol optical data in this area is benefit for us to understand the aerosol effect on climate change in this region.

2.2. Method of determining multi-wavelength lidar ratios

One of the most important parameters in aerosol measurement is AOD. It is an optical parameter that represents the magnitude of depletion of solar insolation due to scattering and absorbing processes caused by aerosols. It can be derived directly from solar radiation measurements using the sun-photometer. It can also be derived from aerosol extinction coefficient measured by lidar. In contrast, retrieval with ground-based sun-photometer has good accuracy. It provides high spectral and temporal resolution, as well as cost saving compared to the other methods.

A comparison between the AOD from the multi-wavelength lidar and the sun-photometer makes it possible to correct the multi-wavelength lidar ratios at the corresponding wavelength.

The AOD from lidar can be defined as:

$$\tau_{\lambda\_lidar} = \int_z \alpha_\lambda dz \tag{4}$$

Here τ_{λ_lidar} denotes the AOD at wavelength λ from lidar, α_λ is the extinction coefficient profile at wavelength λ derived from lidar. z is the atmospheric depth which is 0–10km. The contribution of aerosols over 10 km can be negligible. The AOD from the multi-wavelength lidar at 355 nm, 532 nm and 1064 nm can be obtained from the corrected aerosol extinction coefficient profiles using (4).

Because the wavelengths used by sun-photometer (340 nm, 500 nm and 1020 nm) slightly differs from the wavelengths used by multi-wavelength lidar (355 nm, 532 nm and 1064 nm). The AOD from sun-photometer is needed to be corrected at the corresponding wavelength. Angstrom [22] indicated that the wavelength dependence of the AOD can be given as:

$$\tau(\lambda) = b\lambda^{-a} \tag{5}$$

Here $\tau(\lambda)$ denotes the AOD at wavelength λ, b is atmospheric turbidity coefficient which equals $\tau(\lambda)$ at λ=1μm and a is the particle size or called Angstrom index. The angstrom exponent a can be calculated by AOD values in two wavelengths derived from sun-photometer measurements according to Eq. (5). The relationship of AOD between two wavelengths can be obtained by:

$$\frac{\tau(\lambda_1)}{\tau(\lambda_2)} = \left(\frac{\lambda_1}{\lambda_2}\right)^{-a} \tag{6}$$

It can be found that the AOD is inversely proportional to the wavelength λ. The AOD from sun-photometer can be corrected to the same wavelength as the multi-wavelength lidar by multiplying the coefficients according to (Eq. 6) at three wavelengths respectively.

In general, the aerosol extinction coefficient and AOD increases with the lidar ratio. The AOD derived from the lidar can be defined as a function of the lidar ratio. It can be given as:

$$\tau_{\lambda\_lidar} = f(s_\lambda) \tag{7}$$

Here τ_{λ_lidar} denotes the AOD derived from the lidar at wavelength λ. S_λ is the lidar ratio at wavelength λ. Accordingly, the relationship of AOD between lidar and sun-photometer can be defined as:

$$\tau_{\lambda\_sun} = \tau_{\lambda\_lidar} + e \tag{8}$$

Here τ_{λ_sun} denotes the AOD derived from the sun-photometer at wavelength λ. e is the AOD difference between lidar and sun-photometer. It is caused by improper lidar ratio S_λ. The AOD derived from the sun-photometer is considered to be accurate. After substituting τ_{λ_lidar} in (Eq. 8) with the expression (Eq. 7), the τ_{λ_sun} can be written as:

$$\tau_{\lambda\_sun} = f(s_\lambda) + e \tag{9}$$

It can be seen that the τ_{λ_sun} is the function of lidar ratio S_λ also. Therefore, the difference e changes with the different S_λ. The normal range of lidar ratio is 1∼100sr. Searching the S_λ in the range of [1, 100], there is always a value S_λ that minimizes the difference e, which is the optimal lidar ratio we expected.

The schematic used for determining the optimal lidar ratio S_λ is given in Fig. 1. It is an iteration loop process, when new lidar ratios (355 nm, 532 nm and 1064 nm) are derived, the extinction coefficient profiles need to be inversed and the near-range signals need to be corrected again, the optical depth from lidar need to be refreshed until the difference e is the minimum in the searching range.