



# Atmospheric temperature dependence of the aerosol backscattering coefficient



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## ABSTRACT

In extracting vertical profiles of aerosol backscattering coefficient from lidar signals, the effects of atmospheric temperature are usually ignored. In this study, these effects are analyzed using a rotational Raman–Mie lidar system, which is capable of simultaneously measuring atmospheric temperature and vertical profiles of aerosols. A method is presented to correct the aerosol backscattering coefficient using atmospheric temperature profiles, obtained from Raman scattering signals. The differences in the extracted aerosol backscattering coefficient with and without considering temperature effects are further discussed. The backscattering coefficients for scattering off clouds are shown to be more sensitive to temperature than that of aerosols and atmosphere molecules; the aerosol backscattering coefficient is more sensitive to temperature in summer due to higher atmospheric temperatures.

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## Introduction

Aerosols play an important role in global climate change and have a leading role in the formation of regional atmospheric haze pollution. The coefficients dictating scattering are important in determining aerosol optical properties and thus an accurate measurement of the scattering coefficients of aerosols is crucial in gaining awareness and understanding of aerosols. Various methods have been developed to measure the scattering coefficient for atmospheric aerosols, including the use of radiosondes, optical particle counters, sun photometers, and satellite remote sensing detectors. Regarding satellite remote sensing detection, it has included the use of high-resolution imaging spectrometers such as MODIS (Engel-Cox, Holloman, Coutant, & Hoff, 2004), multi-angle imaging spectrometers such as MISR (Diner et al., 2001), and spaceborne lidar systems, such as the CALIPSO satellite monitor (Jean & Philippe, 2006). These methods have their own advantages and disadvantages; for instance, the accuracy obtained with satellite remote sensing detection is not sufficiently high, and continuous detection is difficult to achieve using a radiosonde. In contrast to these methods, lidar technology for extracting atmospheric aerosol scattering data has advanced in recent years and has high temporal-spatial resolution and detection sensitivity because

the laser is of short wavelength and oriented. Because elastic scattering from aerosol particles is strong, Mie scattering lidar is mainly used to detect atmospheric aerosol scattering data. Klett (1981, 1985) and Fernald (1984) both assumed a relationship between aerosol backscattering and extinction, and presented their methods for calculating both the backscattering and extinction coefficients of atmospheric aerosols using elastic backscattering signals. Kim and Cha (2005) obtained the backscattering coefficient of aerosols using rotational Raman backscattering and elastic backscattering signals without making any assumption. Using a chi-square test in simulations, Russo, Whiteman, Demoz, and Hoff (2006) found the minimum numerical uncertainty for the extinction coefficient of aerosols extracted using the Raman method.

In these methods to determine on the backscattering coefficient of aerosols, correction from variational effects of atmospheric temperature with height has been ignored. We present a method to analyze the effect of atmospheric temperature on the backscattering coefficient of aerosols and to correct for atmospheric temperature variations. The method involves using a rotational Raman–Mie lidar system.

## Raman–Mie lidar

The Raman–Mie lidar system designed by the Lidar Laboratory of Beijing Institute of Technology is located at the Beijing Institute of Technology in Beijing, China. This system enables vertical profiles of aerosols and temperature in the troposphere to be

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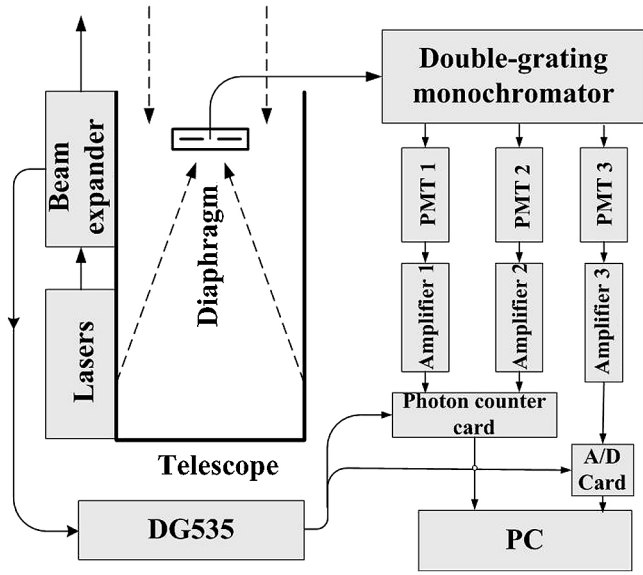


Fig. 1. Schematic of the rotational Raman-Mie scattering lidar system.

obtained by measuring Mie elastic scattering return signals and rotational Raman return signals, respectively. The lidar system is non-coaxial and consists of a laser, receiving optics, spectrometer, signal detection, and data acquisition units. Laser pulses are emitted from the Nd:YAG laser with a pulse energy of 60 mJ at 20 Hz. The wavelength is 532 nm after frequency doubling from the original 1064 nm. The laser beam divergence is 0.2 mrad following  $4 \times$  beam expansion. The receiving optics unit contains a 400-mm Newtonian telescope with field of view of 0.9 mrad, that is adjustable from 0.1 to 1.5 mrad using a diaphragm. The spectrometer comprises a multichannel double-grating monochromator, which selectively separates the rotational Raman returns of  $N_2$  and  $O_2$  molecules (529.05, 530.40, 533.77, and 535.13 nm) and the Mie scattering return (532 nm). The spectral resolution of the spectrometer unit is 0.23 nm. The rotational Raman and the Mie scattering return signals are detected by a photomultiplier tube (PMT) and collected separately using a photon counter card and an analog-to-digital card. The vertical resolutions of the Raman and Mie scattering paths in the lidar system are 30 and 2.5 m, respectively. Fig. 1 shows the system configuration.

## Method

The rotational Raman return is associated only with atmospheric molecules at certain rotational quantum numbers. To obtain strong rotational Raman scattering spectral lines, we used the rotational Raman signals  $J=6$  and 12 of  $O_2$  molecules and  $J=9$  and 17 of  $N_2$  molecules. The Mie scattering return is associated with aerosols and atmospheric molecules. The return power ( $P$ ) for the rotational Raman and the Mie elastic lidar signals are given by

$$P_R(z) = \frac{C_1}{z^2} \beta_R(z) \exp \left\{ -2 \int_0^z [\alpha_m(r) + \alpha_a(r)] dr \right\}, \quad (1)$$

$$\left\{ P_M(z) = \frac{C_2}{z^2} [\beta_a(z) + \beta_m(z)] \exp \left\{ -2 \int_0^z [\alpha_m(r) + \alpha_a(r)] dr \right\} \right\} \quad (2)$$

here  $\alpha$ ,  $\beta$ , and  $C$  are the extinction coefficient, the scattering coefficient, and a constant that does not depend on altitude; subscripts

$R$ ,  $M$ ,  $a$ , and  $m$  denote rotational Raman, Mie scattering, aerosol, and atmospheric molecule, respectively. Because the rotational Raman frequency shift is small (only 1–3 nm at 532 nm), the rotational Raman scattering frequency can be assumed to be approximately the same as the laser frequency ( $10^{-9}$  error in magnitude). This also means that the rotational Raman and Mie scattering signals yield the same extinction coefficient. Taking the ratio of their expressions, we obtain

$$\frac{P_M(z)}{P_R(z)} = \frac{C_2}{C_1} \frac{\beta_a(z) + \beta_m(z)}{\beta_R(z)}. \quad (3)$$

Because molecular number density varies, both the rotational Raman and Rayleigh backscattering coefficient are sensitive to atmospheric temperature. The aerosol scattering coefficient  $\beta_a$  can be solved from Eq. (3) after the rotational Raman backscattering coefficient  $\beta_R$  and the molecular Rayleigh backscattering coefficient  $\beta_m$  are calculated. The procedure is given below.

Integrating the aerostatics equation and the ideal gas state equation, we can obtain an expression for the atmospheric molecular number density:

$$N_m(z) = \frac{N_0 T_0}{T(z)} \exp \left[ - \int_0^z \frac{Mg}{RT(z')} dz' \right], \quad (4)$$

where  $N_0$  ( $2.55 \times 10^{19}$  molecules/cm<sup>3</sup>) is the atmospheric molecular number density at mean sea level,  $T_0$  the real atmospheric temperature at ground where the lidar system located, and  $T$  the atmospheric vertical temperature retrieved with the rotational Raman signal (Behrendt & Reichardt, 2000; Cooney, 1972) using

$$T(z) = \frac{1}{A[\ln M(z)]^2 + B \ln M(z) + C}. \quad (5)$$

here  $M(z)$  is the ratio of the higher-order and lower-order channel return signals for rotational Raman scattering;  $A$ ,  $B$ , and  $C$  are constants, which can be calibrated by fitting the ratio  $M(z)$  with the measured temperature profiles (radiosonde) using the least squares method. Because the atmospheric molecular Rayleigh scattering occurs as an independent scattering (Sun, 1986), it can be written as

$$\beta_m(z) = 3.439 \times 10^{-7} \frac{\pi^2 N_m(z)}{\lambda^4 N_0^2}. \quad (6)$$

Combining Eqs. (4)–(6), the molecular Rayleigh backscattering coefficient  $\beta_m$  can be obtained.

The relationship between the rotational Raman spectrum strength of molecules and temperature obeys a Boltzmann distribution; the rotational Raman scattering coefficient for molecules is related to the rotational quantum number  $J$ , which is expressed as

$$\beta_R(z) = \beta_{\lambda J} = n(z) F_J \sigma_{J-J'}, \quad (7)$$

where  $n(z)$  is the number density of  $N_2$  or  $O_2$  molecules, which can be obtained using Eq. (4) with the volume ratio of  $N_2$  or  $O_2$  molecules in air;  $\sigma_{J-J'}$  is the differential scattering cross section; the physical meaning of  $F_J$  is the percentage of molecules in the initial rotational quantum state  $J$ , which is written as

$$F_J = \frac{2hcB_0}{(2I+1)^2 kT} g_I(2J+1) \exp \left[ - \frac{B_0 hc}{kT} J(J+1) \right]. \quad (8)$$

here  $h$ ,  $k$ ,  $g_I$ ,  $B_0$ , and  $I$  are the Planck constant, the Boltzmann constant, the statistical weight factor determined by the nuclear spin, the rotational constant, and the nuclear spin quantum number, respectively.

For diatomic molecules ( $N_2$  or  $O_2$ ), the rotational Raman transitions need to meet  $\Delta J = \pm 2$ , where the plus and minus signs

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