Development of a High-Spectral-Resolution Lidar for Accurate Profiling of the Urban Aerosol Spatial Variations

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Abstract. A high-spectral-resolution lidar system at a wavelength of 355nm has been developed to accurately profiling of spatial variations of optical properties of aerosols, particularly for urban aerosols, Asian-dust and cirrus clouds, at Xi’an, China. Rayleigh- and Mie-scattering components by atmospheric molecule and aerosol respectively are separated by use of a high-resolution Fabry-Perot etalon. A vibration Raman line of water vapor at 407.5nm is filtered by a high-resolution grating for measurement of water vapor density. The solar background is blocked by using the grating and narrowband filter. As a result, the water vapor density and the main aerosol optical properties, such as the extinction coefficient, backscatter ratio/coefficient and optical depth, are obtained accurately without needs of assumption condition. Preliminary experiment shows that the system has the capability of making measurement up to a height of 15km for aerosol optical properties.

1. Introduction
Aerosol and water vapor are the important atmospheric parameters, which have direct relationship between the earth surface ecological environment and human activities, and affect the heat balance of the earth [1]. Recently, because of the speedup of the urbanization, aerosol particles produced by industry, traffic and architecture are released into troposphere directly. It causes the pollution of urban atmosphere intensely and affects human health. Urban aerosol has becomes a serious urban problems. Lidar, as a perfect observation tool, has played an important role in real-time observation of the aerosol of atmosphere spatial variations [2]. Current Mie lidar systems have been widely used to measure aerosol optical properties [3]. Because of its one channel system structure, aerosol measurements are limited by requirements for additional information on atmospheric transmission and lidar instrument calibration as well as on the vertical profile of molecular density [4]. Slant path techniques have been used to retrieve the aerosol extinction coefficient and the lidar ratio [5], but theses methods generally require a horizontally homogeneous atmosphere.

High-spectral-resolution lidar (HSRL) technique has a capability of overcoming those problems and achieves accurate measurement of aerosol optical properties [6]. The HSRL measures aerosol optical properties by distinguishing laser light which is backscattered by aerosols from that which is backscattered by air molecules [7]. This is possible because the molecular spectrum is Doppler broadened due to the thermal motion of the molecules, while aerosols result in minimal broadening of the returned spectrum. With the separation these two returned signals can be measured separately. So the aerosol extinction coefficient and the backscatter coefficient can be measured accurately without need of any assumption.
A HSRL system at 355 nm has been developed at Xi’an University of Technology for observing the urban aerosol over Xi’an, China. This HSRL system is used not only for accurate measurements of the extinction of aerosol and the lidar ratio, but also for water vapor profiles simultaneously. The configuration of lidar system and preliminary experiment result are described in this paper.

2. Configuration of the HSRL System

As be described above, the molecular spectrum is Doppler broadened due to the thermal motion of the molecules, while aerosols result in minimal broadening of the returned spectrum. Figure 1 shows a spectral diagram of the backscattered Rayleigh and Mie signals and the filter. The Fabry-Perot etalon (FPE) used as a Rayleigh-filter to permit the Rayleigh scattering passing through accurately and its center wavelength is therefore selected and located at high-frequency wing of the Rayleigh spectrum, which location also can avoid the interference of long-wavelength fluorescence. The schematic of the optical system of HSRL is shown in Figure 2.

![Figure 1. Spectral diagram of the backscattered lidar signals and the filter.](image1)

![Figure 2. Schematic of the optical system of HSRL.](image2)

The HSRL system employs the injection seeded Nd:YAG pulsed laser as the light source. In order to enhance the capability of daytime measurement and to consider the requirement of eye-safety, a UV wavelength of 355nm of the third harmonics of laser is selected. Laser beam is collimated by the beam expander and transmitted vertically upward by a scanner. The atmospheric backscattering light is collected by a telescope which has a field of view of 0.1 mrad and then is coupled into a multimode fiber. The output of the fiber is collimated again and sent directly into a high-resolution grating (HRG).
The received lidar return signals are diffracted spectrally by HRG. The vibration Raman signal of the water vapor for derivation of water vapor distributions is firstly separated and then detected by a photomultiplier (PMT-3). The one order diffracted signal of HRG is divided into two parts; one of the signals is directly detected by PMT-2 as an energy monitor signal, which is used for calibration of the lidar signal, and another signal is transmitted to the FPE for filtering the Rayleigh scattering spectrally and detected by PMT-1. The interference of solar background is blocked with a high rejection rate by combining the HRG with FPE, which configuration ensures the system to be run effectively under daytime measurement. The parameters of the HSRL system are given in Table 1.

Table 1. Parameters of the HSRL.

| Parameter                                      | Value                      |
|-----------------------------------------------|----------------------------|
| Light source: Nd:YAG laser                    |                            |
| Wavelength                                    | 354.7 nm                   |
| Pulse energy                                  | 200 mJ                     |
| Pulse repetition rate                         | 20 Hz                      |
| Telescope:                                    |                            |
| Efficient aperture                            | 250 mm                     |
| Field of view                                 | 0.1 mrad                   |
| Focal length                                  | 1.0 m                      |
| Optics:                                       |                            |
| Fiber core diameter                           | 100 μm                     |
| Grating                                       | 2400 gr/mm                 |
| Fabry-Perot etalon:                           |                            |
| Frequency shift                               | 2.5 GHz                    |
| FWHM                                          | 500 MHz                    |
| Peak transmission                             | 60%                        |
| Detector: Photomultiplier tubes               | Hamamatsu R3896            |
| Quantum efficiency                            | 23% at 355 nm              |

3. Retrieval of Lidar Data

3.1. Optical properties of aerosol

As described above, with the separation there are two equations to describe the returned signal given by:

\[ P_a(z) = K \cdot \frac{E A \beta_a(z)}{z^2} \cdot \exp\left\{-2 \int_0^z [\alpha_a(z) + \alpha_m(z)] dz\right\} \quad (1) \]

\[ P_m(z) = K \cdot \frac{E A [\beta_m(z) + \beta_a(z)]}{z^2} \cdot \exp\left\{-2 \int_0^z [\alpha_a(z) + \alpha_m(z)] dz\right\} \quad (2) \]

Where \( P_a(z) \) and \( P_m(z) \) are the power received from altitude \( z \) in the aerosol and molecular channels, respectively; \( K \) is the lidar optical system efficiency; \( E \) is the transmitter pulse energy; \( A \) is the area of receiving telescope; \( \beta_a \) and \( \beta_m \) are the aerosol and the molecular backscatter coefficients respectively; \( \alpha_a \) and \( \alpha_m \) are the aerosol and the molecular extinction coefficients respectively. The backscatter ratio \( S(z) \) is obtained from (1) and (2):

\[ S(z) = \frac{P_a(z)}{P_m(z)} = \frac{\beta_m(z) + \beta_a(z)}{\beta_m(z)} \quad (3) \]

where \( \beta_m(z) \) is obtained from an independent estimate of the atmosphere gas density profile.
The aerosol backscattering coefficient is derived by (3):

$$\beta_a(z) = [S(z) - 1] \cdot \beta_m(z) \quad (4)$$

The aerosol extinction coefficient may be calculated from (1):

$$\alpha_a(z) = -\frac{1}{2} \left( \frac{d\ln(P_m(z))}{dz} \cdot \frac{z^2}{\beta_m(z)} - \frac{1}{\beta_m(z)} \cdot \frac{d\beta_m(z)}{dz} \right) \quad (5)$$

The aerosol optical depth from the altitude $$z_1$$ to $$z_2$$ is obtained by,

$$\tau_a = \int_{z_1}^{z_2} \alpha_a(z)dz = \frac{1}{2} \int_{z_1}^{z_2} \left( \frac{d\ln(P_m(z))}{dz} \cdot \frac{z^2}{\beta_m(z)} - \frac{1}{\beta_m(z)} \cdot \frac{d\beta_m(z)}{dz} \right)dz \quad (6)$$

### 3.2. Water vapor density

In order to obtain the water vapor density, the Rayleigh signal which is detected by PMT-2 is used to eliminate the effect of the atmospheric transmission and the range dependence of lidar returns. The water vapor channel output power of PMT-3, $$P_H$$, is described in the form of lidar equation as

$$P_H(z) = K \cdot \frac{E_A r \beta_H(z)}{z^2} \cdot \exp\{-2 \int_{z_1}^{z} [\alpha_a(z) + \alpha_m(z) + \alpha_H(z)]dz\} \quad (7)$$

where $$\beta_H(z)$$ and $$\alpha_H(z)$$ are the backscatter coefficient and extinction coefficient of water vapor Raman scattering ($$\lambda_H = 407.5$$ nm) in the range $$z$$, respectively [8].

Assuming the atmospheric transmission at $$\lambda_0$$ and $$\lambda_H$$ are approximately the same, the ratio of water vapor Raman power to molecular Rayleigh power $$S_H(z)$$ can be written as

$$S_H(z) = \frac{\beta_m(z)}{\beta_H(z)} \quad (8)$$

and the water vapor backscatter coefficient is

$$\beta_H(z) = N_H(z) \cdot \frac{d\sigma_H(\pi)}{d\Omega} \quad (9)$$

where $$N_H(z)$$ is the water vapor density, and $$d\sigma_H(\pi)/d\Omega$$ is the differential cross section of water vapor Raman scattering. Therefore, the water vapor density $$N_H(z)$$ can be retrieved directly by (8) and (9), and is given as

$$N_H(z) = \frac{\beta_m(z)}{S_H(z)} \cdot \frac{d\sigma_H(\pi)}{d\Omega} \quad (10)$$

### 4. Preliminary experiment results

In order to verify the measurement capability of the lidar system in a practical application, a preliminary experiment in profiling of the aerosol and cirrus cloud was carried out with experimental parameters listed in Table 1, and the performance of the lidar system is shown in Figure 2. The FPE filter is stabilized with temperature controller and the laser frequency is also stabilized by controlling the frequency of seeder with an outside voltage and is drifted to the location with a relative frequency of 2.5GHz to the center frequency of FPE. The PMTs are operated in analog mode and have a time constant of 200ns, corresponding to a range resolution of 30m.

Figure 3 shows the experimental results; the curves in the left panel are the range-corrected energy monitor and Rayleigh signals, and the curve in the right panel is the derived backscatter ratio. The urban atmospheric boundary layer height was clearly observed to reach a height of 2.2km, and an optically cirrus cloud layers were observed during the experiment at 10 km to 14km with a maximum backscatter ratio of 5.8. The observation showed that the lidar system have an capability of measuring aerosol profile up to a height of 15km with 200 mJ of laser energy, 4 minute integration time and a 25-cm-diameter telescope.
5. Conclusion

The UV HSRL system has been developed to measure optical properties of urban aerosols, cirrus cloud and even to water vapor profiles. The HSRL measures the parameters by distinguishing between laser light which is backscattered from aerosols and molecules. The Rayleigh backscatter signal is obtained by the transmission through the Fabry-Perot etalon, and the signal which contains the Mie and Rayleigh backscattering is detected as the energy monitor for calibration of laser output and retrieval of lidar data. With the HSRL, the high-accuracy measurement of aerosol extinction coefficient and the lidar ratio are achieved without any assumption about relationship between the extinction and backscatter coefficients of aerosol, or the requiring horizontally homogeneous atmosphere. The preliminary experiment showed that the HSRL system has a capability of measuring the optical properties of aerosol and cirrus cloud up to a height of 15km.

References
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