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Detection of Atmospheric Composition Based on Lidar

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Abstract. A summary overview about the types of lidar and their own applications on atmosphere detection is presented. Measurement of atmospheric aerosols by Mie lidar and Raman lidar is focused. The vertical profiles of aerosols in the atmosphere are retrieved. And at the same time, through analyzing aerosol vertical content distribution, the atmosphere boundary layer and the cloud are also observed. All the results show that the lidar has good performance on detecting the atmospheric composition.

1. Introduction
In recent years, natural disasters happened frequently. More and more awareness is attracted to the environment around us. The atmosphere is so important that we human being breath it. Various atmospheric constituents such as water vapor, aerosols and ozone, and their contents in the atmosphere directly affect our health. Therefore, atmosphere detection is one of the most concerns in the atmospheric science.

There are many detecting means such as satellite sensors, the various weather stations on the ground, aircraft, and balloons, and so on. There are blind spots by satellite sensor, because it is susceptible to clouds. Most of the equipments in the ground weather stations only detect the atmospheric parameters on the ground surface or about the whole atmosphere layer. Aircraft and balloon can not do continuous, long-term detection\textsuperscript{[1]}

Lidar, as an active detection tool, because of its high spatial and spectral resolution, excellent direction and coherence, large vertical span and high detection accuracy, it is widely used in atmospheric measurements.

2. Lidar Applications on Atmosphere Detection
At present, there are several main kinds of lidar for atmosphere composition detection, such as Mie Lidar, Rayleigh Lidar, Raman Lidar, Differential Absorption Lidar and Resonance Fluorescence Lidar. The Mie backscatter signals are strong and the technical requirements for Mie lidar are relatively simple. So, Mie lidar is widely used to detect large particles in the atmosphere. The atmospheric aerosols and clouds are usually retrieved. According to the vertical distribution of the back signals, aerosols’ content and distribution, the cloud height, cloud thickness and cloud shape can easily be judged. Because of its strong returns, the detection range is large. For example, the volcano eruption may produce an aerosol layer in the stratosphere, and the aerosol layer can be observed by Mie lidar\textsuperscript{[2]}.
Rayleigh lidar is based on the interaction of air molecules and laser. Rayleigh backscatters have the same wavelength with the out laser. Because there are a large number of aerosol particles and clouds in the lower atmosphere, Mie scattering and Rayleigh scattering are mixed together. But in the middle atmosphere, there are few aerosol particles and the main atmosphere composition is air molecules. So the lidar signal is only contributed by molecules and it is Rayleigh scattering. The temperature profiles of the middle atmosphere and the characteristics of gravity waves can be analyzed by Rayleigh lidar [3-4].

Raman lidar is different with the above two kinds. Raman scattering is inelastic and the scatter signals have a shifted wavelength. And also the backscatter cross section is much small. So, the echoes are weak. Raman lidar is mainly used to detect and identify molecular species that have high concentration in the atmosphere, such as nitrogen, water vapor, carbon monoxide, sulfur dioxide [5].

Absorption principle is used in Differential absorption lidar. There are two lasers out beams with similar wavelengths. The detected object will absorb one beam much and absorb another little. Then, through calculating the ratio of the two back signals and comparing the difference of the absorption cross-section on two wavelengths, the density distribution of the detected element will be retrieved. The Differential absorption lidar system needs more techniques and the structure is more complicated. The molecular ozone [6] and air pollutions such as sulfur dioxide, nitrogen dioxide, nitric oxide, can be detected.

Resonance fluorescence lidar is to receive the molecular and atomic resonance fluorescence. However, fluorescence easy to be interfered and often disappear in the collision. So, it is difficult to play in the low atmosphere. But at high altitude, the collision decreases significantly and the Resonance fluorescence lidar shows its advantages. It is mainly used to detect the atoms and ions in the middle and top atmosphere [7].

Currently, a number of lidar network have been established. They are Micro Pulse Lidar Network (MPLNET) [8], Regional East Atmospheric Lidar Mesonet (REALM) [9], Asian Dust Network (ADNet) [10] and European Aerosol Research Lidar Network (EARLINET) [11]. The EALRINT covers the largest area in Europe to do atmosphere observation. The observations include aerosol extinction coefficient, backscatter coefficient, lidar ratio, particle size, cloud, atmospheric boundary layer and other atmospheric parameters [12-14]. In particular, the transmission and movement of Sahara Desert dust have been observed over past several years [15-16]. The AD-Net is initiated by Japan and the lidar sites are located in Japan [17-18].

But in china, the lidar business is still relatively young. “Lidar Development Seminar for Atmospheric Research in China” sponsored by “Key Laboratory of Atmospheric Composition and Optical Radiation” was held on 5-8 November 2009 in Hefei. All the scientists studying on lidar, atmosphere and climate weather in china took part in it. The aim was to talk about establishing lidar network in china for atmosphere observation.

3. Observations of aerosol, cloud, nitrogen and boundary layer
A Lidar system has been developed and the lidar site is at the latitude $30^\circ32^\prime$N and longitude $114^\circ21^\prime$E in Wuhan [19]. Wuhan is the largest city in central China. The lidar consists of laser, telescope and signal recorder. The lidar out wavelengths are 532nm and 1064nm. The nitrogen and water Raman scattering signals, aerosol Mie backscatters and molecular Raleigh returns can be received. This information will be used to retrieve the vertical distribution of the atmospheric aerosols, clouds, atmospheric boundary layer, and atmospheric humidity.

First, we receive aerosol Mie backscatter signals at 532nm. The vertical distribution of Mie backscatters reflects the vertical distribution of aerosol contents. Formula one is Mie lidar equation:

$$P(\lambda_c, r) = C_0 P_0(\lambda_c) \frac{\epsilon(r)}{s^2} \Delta r \beta(\lambda_c, r) \exp \left[ -2 \int_0^{\Delta r} \alpha(\lambda_c, r) dr \right]$$

The laser output wavelength is $\lambda_c$, $P(\lambda_c, r)$ is the Mie returns received at distance $r$, $P_0(\lambda_c, r)$ is the laser output power, $\epsilon(r)$ is the overlap function between the laser beam and the field of view of the receiver, $\beta(\lambda_c, r)$ is the backscatter coefficient of aerosol, $\alpha(\lambda_c, r)$ atmosphere extinction coefficients at wavelength $\lambda_c$, $C_0$ contains all other distance independent parameters.
Figure 1 shows a series of aerosol Mie backscatters at the night on September 12, 2009, from the local time 21:00 to 21:50. As we know that the strength of Mie back signals represents the content of aerosols in the lower atmosphere. So, we can get the vertical aerosol density distribution from the profiles of lidar data. For example, from the time 21:00 to 21:20, the maximum of the Mie signal is about in the range of 0 to 1.3 km, and during the time 21:20 to 21:50, the maximum falls below 1 km. And the maximum of the signal strength becomes larger. And at the same time, we can observe that there is a cloud appearing during the time at height 2.2 km. From the changes of these signal profiles, we see that the atmospheric aerosols fall down as the deep night coming. Because people’s activities deduce in the night and the temperature becomes low.

The aerosols can be observed by Mie scatters, and also can be retrieved by Raman scatters. Raman lidar equation can be written as:

\[
P(\lambda_X, \lambda_L, r) = CP(\lambda_X) \frac{\epsilon(r)}{r^2} \Delta r \beta_c(r) \exp \left\{ - \int_{0}^{r} \left[ \alpha_{mol}(\lambda_L, r) + \alpha_{mol}(\lambda_X, r) \right] + \left[ \alpha_{aer}(\lambda_L, r) + \alpha_{aer}(\lambda_X, r) \right] dr \right\}
\]  

\(P(r, \lambda_X, \lambda_L)\) is the power received from distance \(r\) at the Raman-shifted wavelength \(\lambda_X\) if the laser output wavelength is \(\lambda_L\). \(\alpha_{mol}(\lambda_L, r)\) and \(\alpha_{mol}(\lambda_X, r)\) are the molecular extinction coefficients at wavelength \(\lambda_L, \lambda_X\). \(\alpha_{aer}(\lambda_L, r)\) and \(\alpha_{aer}(\lambda_X, r)\) are the aerosol extinction coefficients. Because the nitrogen has the largest density in the atmosphere, the Raman scatter is strong. The X molecular is nitrogen. The laser \(\lambda_L\) is 532 nm and nitrogen Raman scatter wavelength \(\lambda_X\) is 607 nm. Then the aerosol extinction profile can be expressed by [20]

![Figure 1. A series of aerosol Mie backscatters at the night on September 12, 2009.](image-url)
Figure 2 shows the series of nitrogen Raman backscatters at the night on September 12, 2009, from the local time 21:00 to 21:50. As we know that the nitrogen is stable in the atmosphere and its percentage is 78%, so the backscatter profiles are stable too, not vary much.

\[
\alpha_{mol}(\lambda, r) = \frac{d}{dr} \left[ \ln \frac{n_s(r)}{r^2 P(r, \lambda_x, \lambda_y)} \right] - \alpha_{mol}(\lambda_x, r) - \alpha_{mol}(\lambda_x, r) \times \frac{1}{1 + \frac{\lambda_x}{\lambda_y}}
\]

Figure 3. Atmosphere aerosol extinction coefficient at 532nm observed at 19:30-22:30 local time in the night on October 12, 2009.
Figure 3 shows the vertical distribution and continuous change of atmospheric aerosols below 3 km. This atmospheric aerosol observation is during the local time 19:30 to 22:30 in the night on October 12th in 2009. It is clear that there is a very stable atmospheric aerosol layer below 1.3 km. Because in early October, there has been no rain and wind for several weeks and there is an inversion layer over Wuhan. The dust is accumulated and difficult to disperse. Atmosphere boundary layer is characterized by the high density of aerosol particles, so, the stable aerosol layer between 0 and 1.3 km can be seen as the atmosphere boundary layer.

Figure 4 is a photograph of Wuhan taken by a reporter on October 9th. The photo shows that the air quality and visibility are very poor.

4. Conclusion
A Mie and Raman lidar has been used to detect the vertical distributions and changes of atmospheric aerosols and nitrogen during the night over Wuhan. The cloud and the atmosphere boundary layer have also been observed. These meteorological data are very important for knowing and forecasting the weather change rules. The lidar system can do real time, continuous and long-term observation of their vertical distribution profiles.

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