第21卷 第6期
2001年6月

光 学 学 报
ACTA OPTICA SINICA

Vol.21,No.6
June, 2001

**文章编号**:0253-2239(2001)06-0724-05

# Development of Lidar and Experimental Research for Measuring Atmospheric Aerosol *

Liu Zhishen1) Wu Dong1) Song Xiaoquan1) Liu Jintao1) John W Hair2)

1) Ocean Remote Sensing Laboratory of Ministry of Education, Peoples Republic of China,
Ocean University of Qingdao, Qingdao 266003
2) Department of Physics, Colorado State University, Fort Collins, CO, 80532, USA

**Abstract**: A new technique for measuring atmospheric aerosol characteristics using YAG lidar with iodine cell filter has been developed in the world. The theoretical analysis of the YAG lidar system was given and experimental YAG lidar system was built with 300 mm aperture receiving telescope and 150 mJ YAG laser pulse energy, assessment of the lidar system performance was given through numerical simulations and primary experiments. Backscattering signals from atmosphere were measured. The data measured show that theoretical analysis and experiment results are coincident.

**Key words**: atmospheric aerosol; YAG lidar; iodine filter

**中图分类号**:TB96 **文献标识码**:A

## 1 Introduction

Researches on atmospheric aerosols have attracted extensive attention due to its role in human activities, climate change and biochemical circulation. Aerosol originated from atmospheric pollution is one of the most important factors in atmospheric pollution monitoring. Atmospheric aerosol is also critical to the performance of visible remote sensing sensors and military electro-optical systems. Little data are available about the aerosol characteristics over the Eastern China Seas, where a large amount of dusts originated from the loess plateau exists in the atmosphere, making its distribution very complicated.

Atmospheric aerosols vary frequently with time, location and altitude. The components of aerosols are also very complicated, which make their refractive index and extinction properties difficult to measure.

The progress in modern lidar technology provides an effective means for measuring aerosols. The first attempt for lidar detection of aerosols was initiated by Fiocco *et al*.[1], and many other measurements have been carried out since then. The methods used include Mie scattering lidar, Rayleigh-Mie lidar, differential absorption lidar (DIAL) and multiple-wavelength lidar. Sasano[2] used DIAL technique to determine aerosol and molecular distribution, She *et al*.[3,4] of Colorado State University proposed to measure the vertical profiles of aerosol and atmospheric properties using multiple-channel high spectral resolution Rayleigh-Mie lidar. Two barium atomic filters were used in their system to measure atmospheric temperature, density and aerosol scattering parameters. Fischer[5] from University of Michigan used two Fabry-Parot interferometers to detect the vertical distribution of winds and aerosols. A new technique for measuring aerosols was described in the reference[6,7]. This technique directly measures the Rayleigh scattering component of atmospheric molecules. Iodine filter was used to block totally the aerosol scattering component in order to extract the contribution of Rayleigh component. Scattering ratio measured by lidar was then used to compute aerosol contribution. This high spectral resolution method has potential application in detection of aerosol in both troposphere and stratosphere, where aerosols are rare. We built a YAG lidar and did primary experiments without iodine filter near Qingdao seashore (36°04′N/ 120°19′E). The lidar analysis and results using iodine filter will be introduced in subsequent papers.

---

* This work was supported by China Natural Science Foundation (No. 49805001 1999~2001)

Received 21 September 1999; revised 21 April 2000

## 2　Methodology and experimental set-up

It is well known that Rayleigh scattering of air molecules，mainly due to Doppler broadening，yields a spectrum in the visible wavelength spread over about 2.7 GHz wide at temperatures near 300 K. The displacement of aerosol spectrum is confined to a region below 0.1 GHz. The back scattered signals measured with lidar are composed of the contributions from both aerosol and molecules. At the marine boundary layer，the aerosol scattering signal is usually several orders of magnitude higher than molecular scattering. A typical sketch of atmospheric scattering spectrum was given by H Shimizu *et al*.[8]. The typical variation of aerosol and molecular scattering with altitude was shown by McCormic.

To detect aerosol，it is necessary to separate the aerosol scattering from molecular scattering. Previously，measurements of atmospheric parameters（such as atmospheric density for different altitudes）and Rayleigh scattering theory were used for computing directly the contribution from molecular scattering. These theoretically calculated values have significant error due to the influence of many parameters.

At present，high spectral resolution Fabry-Perot interferometers are extensively used in incoherent lidar systems. But F-P etalon is very expensive，and it has some disadvantages such as narrow field of view and low receiving efficiency，etc. At the beginning of 1990s，a novel type of atomic or molecular absorption filter with high resolution was developed，which possesses advantages as ultra-high $Q$ value（$10^5 \sim 10^6$），narrow bandwidth（0.001 nm），wide field of view（180°）. It has been successfully used in applications such as laser frequency stabilization，communication and lidar receiving system. Iodine molecular filter，which can work at low temperature and has several absorption lines near the output wavelength of double-frequency Nd∶YAG laser（532 nm），can serve as a high resolution filter in place of Fabry-Perot interferometer. Iodine filters are used in our experimental system as shown in Fig.1.

In our system，a continuous wave YAG laser pumped with a semiconductor laser is used as the seeder laser（Lightwave Inc.）. The master laser is pulsed Nd∶YAG（Continuum Corp.）. The iodine filter is used for removing the aerosol component from the total back scattered signals（block 3）. Another iodine filter is used for frequency-lock（block 4），an F-P etalon is used for frequency calibration（block 5）. Aerosol scattering can be extracted from the signals received by the detectors in these two channels.

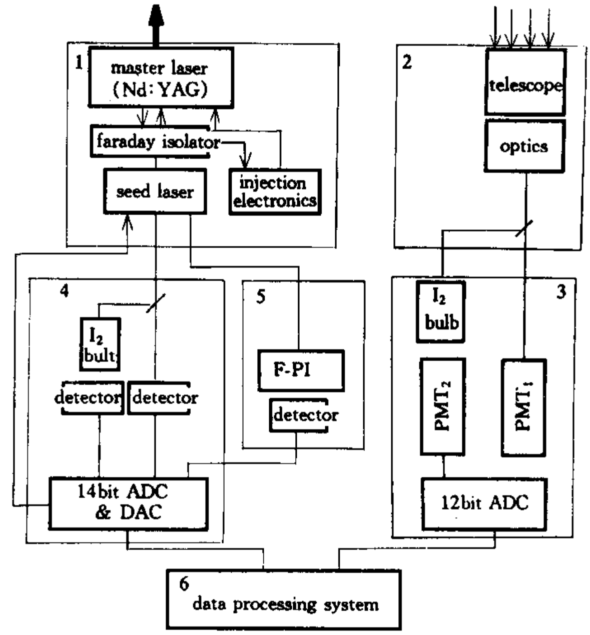

Fig.1　Block diagram of the lidar system for detection of aerosol

Our lidar system has been successfully used to measure atmospheric winds[6,7]. The lidar system used to measure aerosols primarily was changed from that lidar system（Fig.2）.

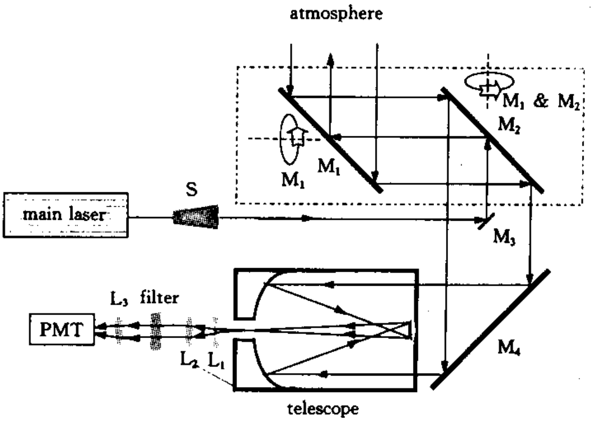

Fig.2　Experimental setup of the lidar system for detection of aerosol

## 3　Theretical analysis and computer simulations

Based on Rayleigh scattering theory and aerosol models as used in LOWTRAN (Low Resolution Transmittance Code), FASCODE (Fast Atmospheric Signature Code), computer simulations were carried out for assessment of the system performance.

Atmospheric aerosols can generally be divided into continental, urban and maritime, according to their origination. Their size distributions vary with time, location and altitude. Most of the aerosols are confined below 5 km in the troposphere, but with a Junge layer at about 20km altitude in the stratosphere. The scattering properties of aerosols are also variable with wavelength, size distribution and refractive index.

The aerosol back scattering coefficient, $\beta^{\pi}_{a}(\lambda)$, is empirically expressed as

$$\beta^{\pi}_{a}(\lambda) = c_1 \lambda^{-c_2}, \qquad (1)$$

where a and $\pi$ mean the back scattering from the aerosol and in the opposite direction ($\pi$ direction) to the light source emission direction respectively, $c_1$ and $c_2$ are constants which vary with altitudes. Single scattering is assumed due to the small laser divergence angle and limited receiver field of view.

For atmospheric molecular under 100 km altitude, the Rayleigh back scattering coefficient, $\beta^{\pi}_{m}(\lambda)$, is:

$$\beta^{\pi}_{m}(\lambda) \equiv N\sigma_{\pi}(\lambda) = 1.39\left(\frac{550}{\lambda}\right)^4 \times 10^{-8}\ \mathrm{cm^{-1}sr^{-1}}, \qquad (2)$$

where m and $\pi$ mean the back scattering from the atmospheric molecules and in the opposite direction to the light source emission direction respectively, $N$ is the atmospheric molecular number in unit volume, $\sigma_{\pi}(\lambda)$ is the atmospheric molecular back scattering cross section. We can see that, Rayleigh back scattering is inversely proportional to the incident wavelength with power of 4. In this meaning, short wavelength lidar as double frequency Nd:YAG laser (532 nm) can get intenser back-scattering signal than $CO_2$ laser (10.6 μm)[9] by 5 orders of magnitude.

Assume laser output photons to be $N_0$, $T(z)$ is atmosphere transmittance at range $z$. These photons are incident through a layer of atmosphere with thickness $\Delta z$. After scattering by molecules and aerosol, the photons were received by the telescope with a field of view $A/z^2$ after another path through atmosphere with $T(z)$. The photons arriving at the detector are:

$$N(z) = N_0(\beta^{\pi}_{m,a})\Delta z \frac{A}{z^2}\eta_o T^2(z), \qquad (3)$$

where $\beta_{m,a}$ are the volume back scattering coefficients of molecules (m) and aerosol (a) respectively.

$$T(z) = \exp\left[-\int \alpha(\nu, z)\mathrm{d}z\right], \qquad (4)$$

where $\alpha(\nu, z)$ is the attenuation coefficient of the atmosphere, here it is assumed to be 0.15 /km. $\eta_o$ is the optical collection efficiency.

The lidar system parameters used in our simulations are listed in Table 1.

Table 1. Lidar system parameters used in simulations

| | |
|---|---|
| laser output photon number | $N_0 = E_0\lambda/hc = 4.02\times10^{17}$<br>($E_0 = 150$ mJ, $\lambda = 532$ nm) |
| receiver area | $A = 0.07\ \mathrm{m}^2$<br>(telescope diameter $D = 0.3$ m) |
| range resolution | $\Delta z = 500$ m |
| system receiving efficiency | $\eta_o = 0.5$ |

Using these parameters and the relations between wavelength and back scattering coefficient from Eq. (1) and Eq. (2), the received photons of 532 nm YAG lidar system as scattered by aerosol and molecules for different altitudes are simulated and the result is shown in Fig. 3 for single laser pulse.

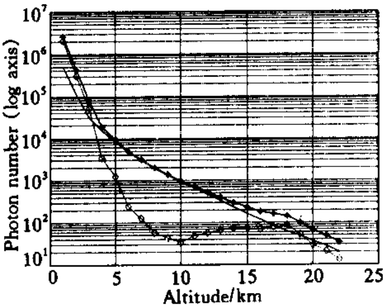

Fig. 3 Computer simulation result for lidar-received-photons as scattered by aerosol and molecules at different altitudes (single pulse) ( * : aerosol and molecules; ◇ :aerosol; solidline : molecules)

## 4 Experimental results

A set of lidar system was built to measure the atmosphere backscattering with the ability to receive signal averaged with adjustable pulse number. The main components and their parameters are as follows: Cassegrain telescope (aperture $\phi$ = 300 mm, focal length: 780 mm), interference filter (bandwidth: 2.6 nm, center wavelength: 532.2 nm), EMI Inc.

9214B type PMT and 40 MHz 12 bit A/D sampling card etc. In most practical experiments, multiple-pulse-average technique is used to improve signal-to-noise ratio of the system.

In order to receive the back scattering signal from atmosphere in the 2π solid angle upper semi-sphere, we used the scanning receiving system (Fig. 2). The laser beam emitted from the main laser was spread by a beam expander. After reflected by a reflector ($M_3$), laser beam entered the atmosphere by the rotation scanning system ($M_1$ and $M_2$). The back scattering signal from atmosphere was received and reflected by $M_4$ into the Cassegrain telescope. PMT was used to detect the back scattering light signal out of the telescope. Also the light signal was filtered by 532.2 nm interference filter and collimated by the lens set $L_1$, $L_2$ and $L_3$ before PMT detection.

The back scattering signal from atmosphere has been measured around Qingdao seashore (36°04′N/120°19′E) with our YAG laser lidar system [Fig. 4(a) and Fig. 4(b)]. Fig. 4(a) shows the signal of the atmosphere back scattering with single laser pulse and Fig. 4(b) shows the signal averaged with 100 laser pulses. The pulse average can improve the signal-to-noise ratio of system. Also it can remove the fluctuation of the atmosphere.

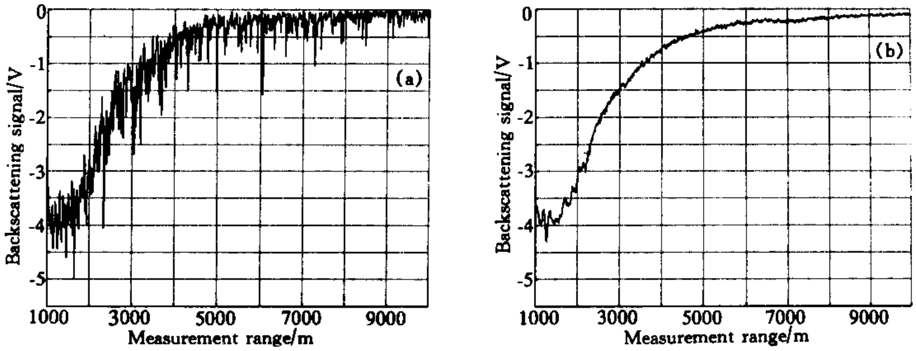

Fig. 4　The back scattering signal from atmosphere around Qingdao seashore. (a) The measurement result of atmosphere backscattering signal for one laser pulse; (b) The measurement result of atmosphere back scattering signal averaged with 100 laser pulses

With Eq. (3), the experimental results show that the PMT receiving system with 12 bit A/D sampling card can measure the return signal in the range of 0 ~ 8 km. The calculated corresponding receiving photons are shown in Fig. 5.

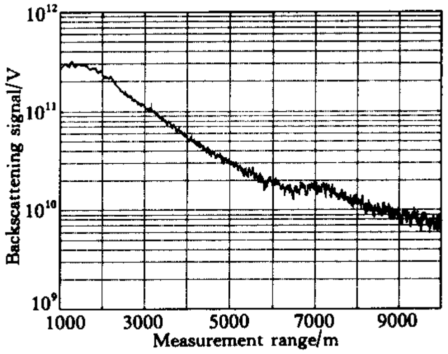

Fig. 5　The received photons by lidar retrieved from the back scattering signal

## 5　Discussion

This technique directly measures the Rayleigh scattering component of atmospheric molecules, meanwhile the aerosol scattering component can be removed by using an iodine cell filter. Combined with the scattering ratio, the aerosol contribution can be separated from molecule component. The theoretical analysis and primary experimental results show that the aerosol around Qingdao seashore can be measured by YAG lidar system with iodine cell filter. And the photons theoretically simulated and experimentally measured are coincident.

Experimenal results show that the PMT receiving system with 12 bit A/D sampling card can measure the return signal in the range of 0 ~ 8 km. If we need to measure the return signal in the range of 10 km ~ 30 km, the photon counting technique will be necessary.

The authors gratefully acknowledge the support of China Natural Science Foundation (No. 49805001), and Prof. Zhou Jun, Anhui Institute of Optics and Fine Mechanics, The Chinese Academy of Sciences, for his helpful discussion.

## Reference

[1] Fiocco G, DeWolf J B. Frequency spectrum of laser echoes from atmospheric constituents and determination of the aerosol content of air. *J. Atmos. Sci.*, 1968, **25**(3):488～496

[2] Sasano Y. Simultaneous determination of aerosol and gas distribution by DIAL measurement. *Appl. Opt.*, 1988, **27**(9):2640～2641

[3] She C Y. Remote measurement of atmospheric parameters: New applications of physics with lasers. *Contemp. Phys.*, 1990, **31**(1):247～260

[4] Krueger D A, Caldwell L M, Alvarez Ⅱ R J *et al*.. Self-consistent method for determining vertical profiles of aerosol and atmospheric properties using a high spectral resolution Rayleigh-Mie lidar. *J. Atmos. Ocean Tech.*, 1993, **10**(2):533～545

[5] Fischer K W, Abreu V J, Skinner W R *et al*.. Irgang, Visible wavelength Doppler lidar for measurement of wind and aerosol profiles during day and night. *Opt. Engng.*, 1995, **34**(2):499～511

[6] Liu Zhishen, Chen Weibiao, Hair J W *et al*.. Proposed ground-based incoherent Doppler lidar with iodine filter discriminator for atmospheric wind profiling. *Proc. SPIE*, 1996, **2833**:121～135

[7] Liu Zhishen, Chen weibiao, Zhang Tinglu *et al*.. An incoherent Doppler lidar for ground-based atmospheric wind profiling. *Appl. Phys.* (*B*), 1997, **64**(2):561～566

[8] Shimizu H, Lee S A, She C Y. High spectral resolution lidar system with atomic blocking filters for measuring atmospheric parameters. *Appl. Opt.*, 1983, **22**(9):1373～1381

[9] Schwiesow R L, Cupp R E, Derr V E *et al*.. Aerosol backscatter coefficient profiles measured at 10.6 μm. *J. Appl. Meteorol.*, 1981, **20**(1):184～194

---

# 激光雷达研制及其探测大气气溶胶的实验研究

**刘智深**1)　**吴　东**1)　**宋小全**1)　**刘金涛**1)　John W Hair2)

1)，青岛海洋大学海洋遥感研究所，青岛 266003
2)，科罗拉多州立大学物理系，美国科罗拉多州柯林斯堡，80532

（收稿日期：1999-09-21；收到修改稿日期：2000-04-21）

**摘要：** 作为一种激光探测大气气溶胶特征的新技术，采用分子滤波技术的高光谱分辨率激光雷达在国际上得到了发展。给出了对这种 YAG 激光雷达系统的理论分析并建立了实验装置，其接收望远镜孔径为 300 mm，YAG 激光脉冲能量为 150 mJ。通过数值模拟与初步测量估计了激光雷达性能，测量了大气回向散射信号，测量结果表明实验结果与理论分析一致。

**关键词：** 大气气溶胶；激光雷达；碘滤波器