# Low tropospheric wind profile from a 1.06 μm Doppler lidar

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**Abstract:** A 1 064 nm Mie Doppler wind lidar system based on the double edge technique is described. The Fabry-Perot(FP) etalon is used as the frequency discriminator, which analyzes the Doppler frequency shift from the atmospheric aerosol movement by wind. The system frequency measurement is calibrated by the known line-of-sight (LOS) Doppler shift produced by a rotating disk, and the calibration accuracy in velocity is less than 1% in the range of ±40 m/s. The continuous field wind profiles in eight days are carried out from Apr. 23, 2006.

**Key words:** Lidar; Wind; Fabry-Perot etalon; Aerosol; Direct detection

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# 1.06 μm 多普勒激光雷达的低对流层风场测量

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**摘 要：** 介绍了一套基于双边缘检测技术的 1 064 nm Mie 多普勒测风激光雷达系统。采用 Farbry-Perot 标准具作为频率检测器，分析了风场中大气气溶胶运动造成的多普勒频移。利用转盘硬目标的速度校准系统对接收机校准，在±40 m/s 的径向速度范围内，校准精度小于 1%。给出了从 2006 年 4 月 23 日起连续八天的风场测量结果。

**关键词：** 激光雷达； 风； Fabry-Perot 标准具； 气溶胶； 直接探测

## 0 Introduction

The three-dimensional wind data in global region will directly improve numerical weather prediction. Climate studies should also benefit from the use of the data in global circulation models in various ways. Therefore ESA has started the Atmospheric Dynamics Mission to provide the wind-profile measurements for advancing the atmospheric modeling and analysis[1], which will be launched in 2008. In 1999, NASA/Goddard built a mobile Doppler lidar system, the Goddard laboratory for observing winds(GLOW), which used direct detection Doppler lidar technique to measure wind profiles from the surface into the lower stratosphere [2]. The Groundwind is also a direct detection Doppler lidar system which utilizes backscatter signal from both Rayleigh and Mie scattering to measure Doppler shifts in the atmosphere from ground[3]. The Fabry-Perot etalon is so far used as the frequency determination in the most direct detection Doppler lidar systems, and the double edge technique with Fabry-Perot etalon could measure the Doppler shifts whichever from the aerosol and molecular backscatter. Compared with the other wind remote sensors, the lidar remote sensing is so far the

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only tool that is able to directly measure Doppler wind in the global region.

A 1 064 nm aerosol Doppler wind lidar with a dual Fabry-Perot etalon has been built up at Anhui Institute of Optics & Fine Mechanics, CAS, Hefei, China [4], which is designed to measure wind profiles based on the aerosol backscatter in the low troposphere. The lidar system on the roof of the main building of the institute (117.16E, 31.90N) has routinely operated and observed the wind profile. In the lidar system ,the frequency drifts of laser and the etalon has been controlled by a servo loop acting on the etalon tuning control in order to lock the wavelength of the transmitted laser at the most sensitive zone of the slope of the etalon. The lidar system is corrected in measuring a Doppler frequency (or line of sight speed) by probing the scatter from a rotating disk which produces a LOS speed in the range of ±40 m/s,and this scatter signal could be considered as the same spectrum as the aerosol[5]. Wind profiles of the lidar observation are continuously made in a few days, and the results are compared with the wind data from the local weather radar in some available layers.

## 1 Principle of Doppler measurement

The Doppler shift frequency produced by the aerosol movement projected in the line of sight (LOS) of the lidar transceiver is analyzed by a dual Fabry-Perot etalon. The etalon system consists of two sub-cavities, and they have a little difference in cavity length that forms the transmission curves as shown in Fig.1. The outgoing laser frequency is locked at the middle point of the curve slope. The received signal with Doppler shift produces a frequency shift, which will have a trans-mittance change or relative intensity difference. From measuring the intensity difference and the preprobed transmission curve, one can retrieve the Doppler shift[5].

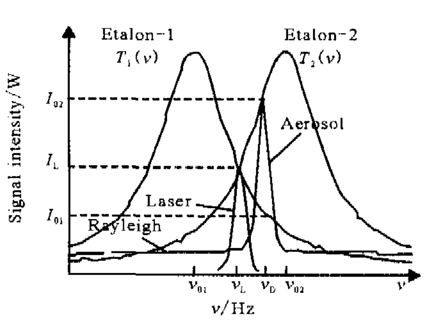


Fig.1 Spectral diagram of the dual etalon, laser and backscatter signal

The lidar system is used to analyze the Doppler shift from the Mie backscatter of the atmospheric aerosols, but the Rayleigh backscatter of the atmospheric molecule is also detected in the system. The relative intensity change from the Doppler shift of Rayleigh backscatter is different from that of the Mie backscatter, and the Rayleigh portion in the received signal must be eliminated in process. The etalon transmission is given by

$$h(\nu)=\frac{T_p}{1+\frac{4F^2}{\pi^2}\sin^2\left(\frac{\pi\nu\cos\theta}{\nu_{FSR}}\right)} \tag{1}$$

where $T_p$ is the peak transmission of the etalon, $F$ is the finesse of the etalon, $\nu$ is the frequency, $\theta$ is the incidence angle which is zero in the system,and $\nu_{FSR}$ is the free spectral range (FSR) of the etalon. The aerosol and molecule backscatter spectra, $f_{Mie}(\nu)$ and $f_{Rayleigh}(\nu)$, which have Gaussian profile, are given by

$$f_{Mie}(\nu)=\sqrt{\frac{4\ln2}{\pi\Delta\nu_L^2}}\,e^{\frac{4\ln2}{\Delta\nu_L^2}\nu^2} \tag{2}$$

$$f_{Rayleigh}(\nu)=\sqrt{\frac{4\ln2}{\pi\Delta\nu_r^2}}\,e^{\frac{4\ln2}{\Delta\nu_r^2}\nu^2} \tag{3}$$

where $\Delta\nu_L$ is the full width at half maximum (FWHM) of the aerosol backscatter spectrum which is the same as the transmitted laser ,is about 90 MHz for the Nd:YAG laser in the lidar system. The $\Delta\nu_r$ is the FWHM of the atmospheric molecular spectrum, which is given by

$$\Delta\nu_r=\sqrt{\frac{32kT\ln2}{\lambda^2M}} \tag{4}$$

where $k$ is the Boltzmann's constant, $T$ is the atmospheric temperature, $M$ is the mass of the atmospheric molecules, and $\lambda$ is the laser wavelength that is 1 064 nm in the system. The intensity of the received signal from each etalon includes the Mie and Rayleigh backscatters, which are respectively written by

$$I_{Mie}(\nu)_i=\int h(\nu-\nu_i)f_{Mie}(\nu-\nu_i)\mathrm{d}\nu \tag{5}$$

$$I_{Rayleigh}(\nu)_i=\int h(\nu-\nu_i)f_{Rayleigh}(\nu-\nu_i)\mathrm{d}\nu \tag{6}$$

where the subscript $i$ denotes the $i$-th ($i$=1,2) etalon channel. We define the ratio of the Mie intensities from two etalon channels as the response, given by

$$R(\nu)=\frac{I_{\mathrm{Mie}}(\nu)_1}{I_{\mathrm{Mie}}(\nu)_2} \tag{7}$$

In the lidar system the center difference $\nu_{21}=\nu_{20}-\nu_{10}$ of the etalon spectrum is designed as 200 MHz which corresponds to the speed dynamic range of about ±50 m/s. The etalon FWHM is about 170 MHz. The etalon transmissions and the response $R(\nu)$ are shown in Fig.2. If the incident light is equally assigned to the two etalons or in the factor of $a$ to etalon 1, the Eq.(7) will be given by

$$R(\nu)=a\frac{I_{\mathrm{Mie}}(\nu)_1}{I_{\mathrm{Mie}}(\nu)_2} \tag{8}$$

where $a$ is a constant that could be measured in advance.

As the response of the etalon system is a single function of Doppler shifted frequency, the relationship between the response and the Doppler shift will be written by

$$R(\nu_0+\Delta\nu_d)=R(\nu_0)+\Delta\nu_d\frac{\partial R(\nu)}{\partial\nu} \tag{9}$$

where $\Delta\nu_d$ is Doppler shifted frequency and $\nu_0$ is the emitted laser frequency. Therefore the LOS speed could be given by

$$\nu_{\mathrm{LOS}}=\frac{\lambda}{2}[R(\nu_0+\Delta\nu_d)-R(\nu_0)]\left(\frac{\partial R(\nu)}{\partial\nu}\right)^{-1} \tag{10}$$

The response is not linear in the range of Doppler shift variation, in fact the solution of Eq.(10) will utilize the iteration 2 times to reach a good accuracy.

The wind vertical profile is retrieved from LOS wind speeds in three fixed directions. We set the zenith angle of laser beam to 45° and azimuth angle is set as an interval angle of 120° in horizon and the east is one of beam directions. The horizontal wind velocity could be given by

$$V_H=\frac{2\sqrt{2}}{3}\sqrt{V_1^2+V_2^2+V_3^2-V_1V_2-V_2V_3-V_1V_3} \tag{11}$$

$$\theta=-\arctan\left(\frac{\sqrt{3}(V_3-V_2)}{2V_1-V_2-V_3}\right)-\frac{\pi}{2}\mathrm{sign}\left(\frac{\sqrt{2}}{3}(2V_1-V_2-V_3)\right) \tag{12}$$

where $V_H$ is horizontal wind speed, $\theta$ is the angle of the wind direction from the north in clockwise. $V_1$, $V_2$ and $V_3$ are the LOS wind speeds in the emitted laser beams.

## 2 Prototype lidar system

The 1 064 nm aerosol Doppler wind lidar was entirely built up in March 2004. The lidar system consists of four parts, i.e. the laser transmitter, the scanner and telescope, the FP etalon receiver, and the controlling sub-systems, as shown in Fig.2.

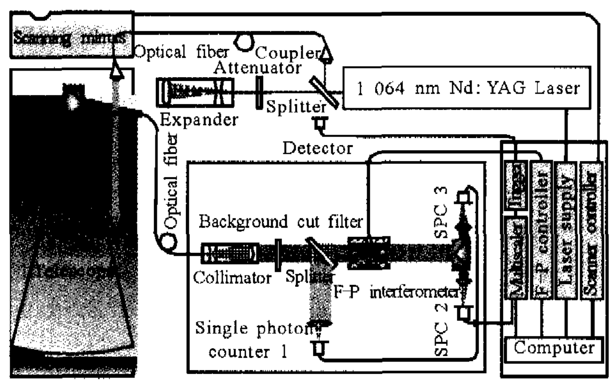


Fig.2 Diagram of the aerosol Doppler lidar system

The laser of a seeded Nd:YAG continuum laser Model 8050 is expanded by an 8X expander to compress the beam divergence to less than 0.1 mrad, and gets through a reflective mirror mounted in a Cassegrain telescope and points to the atmosphere by a two-dimensional scanner. The received backscatter light is coupled to a 105 mm multimode fiber connected to the receiver. The collimated light passes through the interference filter (IF) with the bandwidth of 0.52 nm@ 1 064 nm. The light is split to two beams by the 80/20 (T/R) beam splitter (BS), and the 80% light is incident into the dual FP etalons with balanced intensity for each, respectively, and then detected by two photon counting mode Si:APD detectors, respectively. The rest 20% light is detected by the monitor detector, a photon counting mode Si:APD. Little part of transmitted laser light is coupled directly into the receiver through an optical fiber, and used as the reference frequency. The operating commands of laser shooting, *XY* scanner and FP etalon are sent out by the computer through RS232 interface. Tab.1 lists the parameters of the lidar system.

**Tab.1 Parameters of the aerosol Doppler lidar system**

| | Item | Parameters |
|---|---|---|
| System | Zenith angle | 45° |
| | Wavelength | 1 064 nm |
| | Laser energy | 100 mJ/pulse |
| | Laser beam divergence | 0.5 mrad |
| | Optical efficiency | 80% |
| Receiver | Telescope diameter | ϕ300 mm |
| | Interference filter | 0.52 nm |
| | Detector type | Si:APD |
| | Quantum efficiency | 18% |
| | Etalon FSR | 3.5 GHz |
| | Etalon FWHM | 190 MHz |
| | Etalon center interval | 200 MHz |
| | Etalon peak transmittance | >60% |

### 2.1 Etalon and laser locking process

Parameters of the dual etalon are optimally designed by considering the speed dynamic range, velocity sensitivity, and the signal-to-noise ratio. The dual etalon is air-spaced and designed as D shape with semicircle for each channel. Two semicircle cavity lengths are slightly different while obtaining the desired transmission propertie [2]. This difference is about 32.5 nm, which corresponds to the central interval of about 200 MHz.

The stability between the dual etalon and laser frequency seriously affects the accuracy of the frequency measurement. As the frequency of seeded laser is slowly changed by the environmental temperature, the transmitted laser frequency must be locked to the etalon curves. Usually the laser frequency is located at the crossing point of the two transmission curves. During the wind measurements, the frequency of the reference light from the transmitted laser is determined by the etalon transmissions, and the program will calculate the laser frequency offset if it deviates from the cross point. From the offset the control program will tune the etalon cavity and make the cross point back to the laser frequency, as shown in Fig.1. The direction and magnitude of the frequency change could be determined by comparing the transmittances of two etalons. In this way the effect of the long term frequency fluctuation could be minimized. The locked frequency result in the long term is shown in Fig.3.The standard deviation is 4.83 MHz float in 12 h.

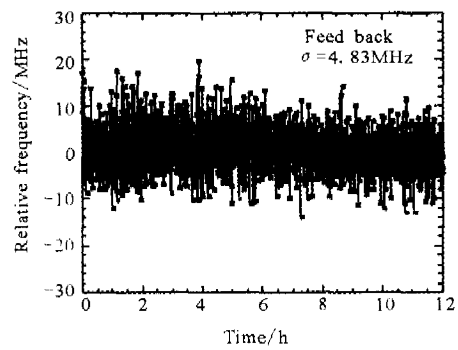


Fig.3 A 12 h experimental result of frequency lock point

### 2.2 Doppler shift corrector

The Doppler shifted frequency is determined by the dual etalon based receiver of the lidar system, and the laser frequency of the system is locked to the cross point of the dual etalon. In this way the receiver measures the Doppler shift between the emitted laser and received light. To verify the ability of measuring the Doppler shift, one can use the receiver and detect the surface displacement velocity of a hard target. The early experiment by B. Gentry is to measure a moving solid target in a line track[4]. Z. S. Liu has used a rotating target with 600 mm disk and 37.5 m far from the receiver [5]. We have designed a corrector of Doppler shifted frequency, which measures the backscattered signal from the Lambert surface of a rotating disk. The corrector can produce a Doppler shifted frequency in a speed range of ±50 m/s in the LOS direction, and the speed could be changed continuously. The volume of the corrector is 346 mm×285 mm×175 mm as shown in Fig.4,and the detail construction of the corrector could be found in reference [6].The velocity results measured by lidar and the speed corrector are shown in Fig.5. Each data point is an average result of 100 measurements.The standard deviations of the 10 points range from 0.1 to 0.9 m/s. The slope of linear fitting of the two results is 1.01.

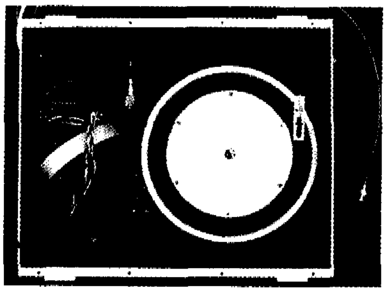
Dimensions 346 mm× 285 mm× 175 mm

Fig.4 Speed corrector for Doppler wind lidar

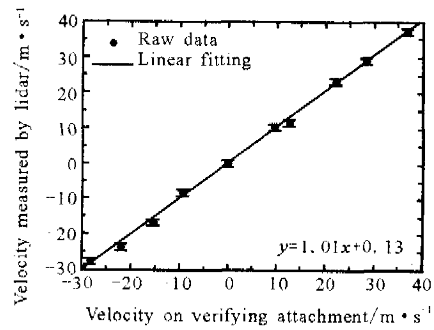


Fig.5 Velocity measurement results by lidar and the corrector

## 3 Wind profile observation

The aerosol Doppler lidar system is automatically controlled by a computer. The lidar takes the measurements of the LOS wind speed in three directions with the interval angle of 120° in horizon and at a fixed elevation angle of 45°. The LOS Doppler frequency or speed could be retrieved principally from the discussion of C.L. Korb [3]. One could then deduce wind vector (magnitude and direction) from the three direction LOS wind measurements. The wind profile will be taken in every 10 min and each measurement will spend about five min. The returned signal is with 30 m range resolution. The lidar was fully started operating by November 2005, and many day continuous operations have been carried out. Figure 6(a) is an example of wind profiles of speed and direction obtained from Apr. 23, 2006 to Apr. 30, 2006, where the color bar describes the wind speed magnitude. Figure 6 (b) shows the wind direction during that period.

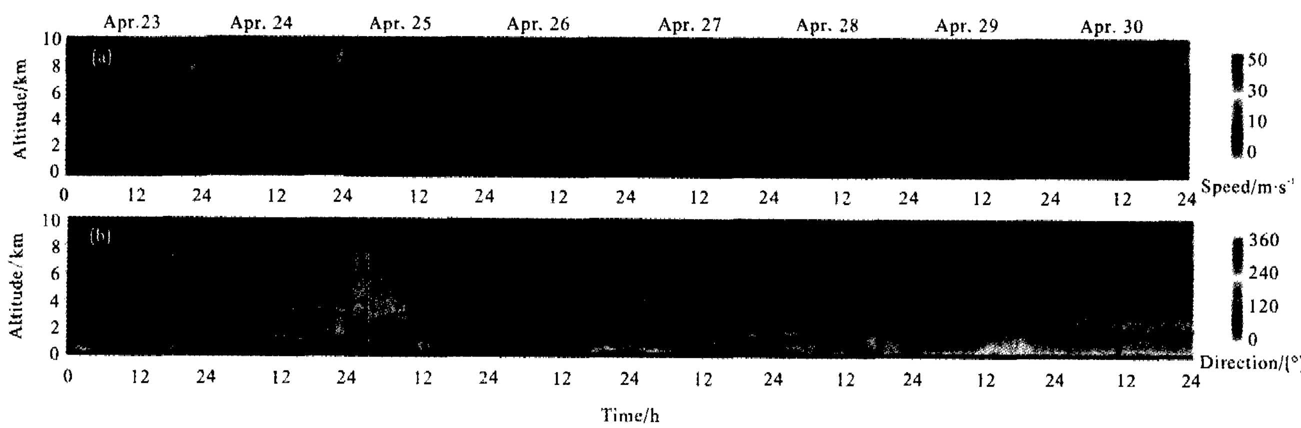


Fig.6 Comtinuous wind observation in eight days

## 4 Conclusion

The 1.06 μm aerosol Doppler lidar built at Hefei has probed the low troposphere wind profiles routinely. Comparison of wind vector between the lidar and the meteorological radar shows a good agreement, and the lidar will be used for the local meteorological research.

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