Wind Measurements with a 355 nm Molecular Doppler Lidar

Bruce M. Gentry[1] , Huailin Chen[2] and Steven X. Li[3]

[1]NASA Goddard Space Flight Center

Laboratory for Atmospheres, Code 912

Greenbelt, MD 20771 USA

[2]Science and Engineering Services, Inc.

[3] Orbital Sciences Corporation

Abstract

A Doppler lidar system based on the molecular double edge technique is described. The system is mounted in a modified van to allow deployment in field operations. The lidar operates with a tripled Nd:YAG laser at 355 nm, a 45cm aperture telescope and a matching azimuth-over-elevation scanner to allow full sky access. Validated atmospheric wind profiles have been measured from 1.8 km to 35 km with a 178m vertical resolution. The range dependent rms deviation of the horizontal wind speed is 0.4-6 m/s. The results of wind speed and direction are in good agreement with balloon sonde wind measurements made simultaneously at the same location.

Research has established the importance of global tropospheric wind measurements for large scale improvements in numerical weather prediction [1]. In addition, wind measurements from ground and airborne platforms provide data that are fundamental to the understanding of mesoscale dynamic processes, transport and exchange in the atmosphere .

A mobile lidar system utilizing direct detection Doppler lidar techniques for measuring wind profiles has recently been completed at Goddard. A variety of direct detection Doppler wind lidar measurements have recently been reported indicating the growing interest in this area [2, 3, 4, 5, 6]. The wind lidar program at Goddard has concentrated on the implementation of the direct detection Doppler lidar using the edge technique [7]. The basic principles of the edge technique have been verified in laboratory [8] and atmospheric lidar wind experiments [3].

The double edge technique, a variation of the edge technique, was developed to extend the wind measurement capability into the troposphere and lower stratosphere. The double edge method utilizes two high spectral resolution optical filters located symmetrically about the outgoing laser frequency. The details of the double edge method have been recently reported for lidar systems measuring the Doppler shift from either aerosol [9] or molecular [10] backscattered signals. Atmospheric measurements of winds using the aerosol implementation of the double edge technique have also been reported[11].

In this paper, we present a double edge molecular Doppler lidar system operating at 355nm and the results of the measurements of horizontal wind speed and direction made at NASA Goddard Space Flight Center in Greenbelt, Maryland (38:59:32N, 76:51:10W). The lidar measurements are compared with rawinsonde wind measurements taken simultaneously from the same location.

The molecular double edge technique uses two edge filters located in the wings of the thermally broadened molecular backscattered signal spectrum at 355 nm to determine the wind. This arrangement is shown in Figure 1. The two edge filter bandpasses, labeled 'Edge 1' and 'Edge 2', are shown along with the atmospheric backscattered spectrum. The atmospheric backscatter spectrum shows the characteristic narrow spike from aerosols along with the thermally broadened molecular spectrum. A Doppler shift in the incoming laser frequency is observed that is proportional to the average drift velocity of the molecular motion (the wind) along the line of sight of the laser beam. Due to the symmetric arrangement of the filters around the laser frequency the Doppler shift will cause the transmitted signal to increase in one edge filter and decrease in the other one. The ratio of the two edge channel signals is sensitive to the wind and provides a unique measure of the speed and direction. The wavelength of operation is chosen in the ultraviolet to take advantage of the λ^{-4} dependence of the molecular backscatter. The third etalon channel, labeled 'Locking' in Figure 1, is used to monitor the outgoing laser frequency to remove inaccuracy due to the frequency drift of the laser or the etalon.

The optical layout of the lidar system is shown in Figure 2. The transmitter is an injection seeded Nd:YAG laser that produces 15 ns pulses at a 10 Hz repetition rate. The energy per pulse at the tripled wavelength of 355 nm is 70 mJ. The spectral linewidth of the laser is about 80 MHz (FWHM), much smaller than the spectral widths of either the atmospheric signal (3.5 GHz) or the edge filters (1.7 GHz). The receiving optical system consists of a 45 cm aperture telescope and a 45 cm aperture scanner. The scanner has separately rotating azimuth and elevation mirrors to allow a variety of programmable scan patterns. The collected signal is focused into a 200 μm fiber optic cable to couple the signal from the telescope to the receiving box.

Light from the fiber is collimated and split by beamsplitters into five beams. Two of the beams are energy monitors one having a photon counting photomultiplier (PMT) and the other an analog mode PMT. The remaining three collimated beams are directed along parallel paths through a Fabry-Perot etalon that is used to measure the frequency shift. The etalon has three sub-apertures corresponding to the filter bandpass functions labeled Edge1, Edge2 and Locking Channel in Figure 1. Each channel has nearly identical optical properties (peak transmission, finesse, free spectral range) with a slightly different bandpass center frequency. The offset in the bandpass frequency is created by depositing small 'step' coatings on one of the plates prior to applying the reflective coating. This method is similar to that employed by Chanin et al [2]. The separation of the two edge filters is chosen to be 5.1 GHz so that the sensitivity of the broader molecular signal is equal to that of the narrower aerosol signal[10]. The locking etalon is located 1.7 GHz from 'Edge1' filter (peak to peak) so that the crossover point of the two edge filter spectra is aligned to the half height point of the locking filter spectrum. Actively locking the laser and etalon at this point on the locking filter ensures the symmetry of the edge filter channels for the wind measurement. The locking is accomplished by sending a small portion of the transmitted laser signal into the telescope to make a reference measurement of the outgoing frequency. The reference signal transmitted through the locking channel etalon is detected by a PMT operating in analog mode and sampled by a boxcar integrator. The boxcar reference measurement is stored to provide correction for short term frequency jitter and is also used to lock the etalon (all three channels together) to the laser frequency. The atmospheric backscattered light transmitted through the edge filter etalon channels are detected by PMTs operating in photon counting mode. The experimental parameters of the 355 nm molecular lidar system are given in Table 1.

An intercomparison experiment was held on the evenings of November 16 and 17,1999. The lidar was operated in several modes during the experiment and correlative measurements of wind speed and direction were obtained from a portable rawinsonde system that was brought to Goddard and operated by personnel from Wallops Flight Facility.

Due to the dynamic range limit of the photon counting detectors two sets of measurements were obtained to cover the altitude range from 1.8 km to 35 km. The first set of wind measurements were made from 19:09 to 20:47 EST, November 17, 1999 at a reduced energy of 0.4 mJ/pulse to determine the lower altitude wind from 1.8 to 7 km. The second set of measurements was made from 21:05 EST, November 17 to 1:24 EST, November 18, 1999 at full power (~70 mJ/pulse) to measure the wind from 7 to 35 km. Vector wind data were obtained by rotating the scanner to measure line-of-sight wind profiles at four azimuth angles with a fixed elevation angle of 45 degrees. The photocounts in each of the three photon counting detector channels is binned with 250 m range resolution and integrated for 300 shots at each line of sight. Rawinsonde balloons were launched during the course of the evening to provide simultaneous wind profiles for comparison with the lidar.

The horizontal wind is determined by taking the ratio of the edge filter signals determined for each of the four lines of sight. The ratios taken at azimuth angles 180 degrees apart from one another are paired in the analysis to give two orthogonal components of the horizontal wind field.

Let $r_+(v_{LOS})=I_{1+}(v_{LOS})/I_{2+}(v_{LOS})$, $r_-(-v_{LOS})=I_{1-}(-v_{LOS})/I_{2-}(-v_{LOS})$, where, $I_{1,2}$ refer to the signals received through filters Edge1and Edge2, '+', '-' represent the two lines-of-sight measured for each component and v_{LOS} is the line of sight wind velocity for a given component. The atmosphere is assumed to be spatially uniform during the integration time.

We now define the sensitivity θ to be the fractional change in the measured ratio r for a given velocity :

$$\theta = \frac{\partial r}{r \partial v} = \frac{\partial I_1}{I_1 \partial v} - \frac{\partial I_2}{I_2 \partial v} \qquad (1)$$

The sensitivity is determined by the spectral characteristics of the two edge filters which can be measured in calibration scans (see Fig.1) and by the spectral properties of the atmospheric backscattered return. As noted previously the aerosol and molecular components of the backscattered signal have different spectral characterisitics. The offset between the two filters is chosen to have equal sensitivity to either molecular or aerosol signal. The approximate value of θ for our system for small Doppler shifts is 0.0065/(m/s). The velocity component is now given by

$$\mathbf{v}_{LOS} = \frac{r_{+}(\mathbf{v}) - r_{-}(-\mathbf{v})}{(r_{+}(\mathbf{v}) + r_{-}(-\mathbf{v}))} * \frac{1}{\theta} \tag{2}$$

The horizontal wind speed and direction are determined from the two orthogonal line of sight wind velocities.

Figure 3 shows a summary of the comparison results of wind speed and direction. Solid dots represent the lidar measured results along with error bars. The crosses are the sonde measurement results. Thirty scan cycles are averaged for low altitude measurement from 1.8 to 7 km with a vertical resolution of 178 m. Wind errors range from 0.6 m/s at 1.8 km to 4 m/s at 7 km.

The high altitude winds from 7 to 35 km are determined from the average of 80 scan cycles. Mean wind speed and resultant error bars are given for 178 m vertical resolution from 7 to 25 km. Wind errors in this region are 0.4 m/s at 7 km, 0.7 m/s at 10 km, 1.8 m/s at 15 km, 3.9 m/s at 20 km. For altitudes above 25 km the vertical resolution is 707 m and the observed errors are 6.5 m/s at 30 km.

The lidar measurements are in very good agreement with the balloon results. The wind profiles of both the lidar and rawinsonde show clear evidence of a mid-level jet at 12.5 km with a local maximum speed of 30 m/s. A second higher level jet is observed with a speed of nearly 50 m/s at 35 km. A local minimum in the wind speed of 12 m/s is observed at 21 km.

In conclusion, we have developed and successfully demonstrated operation of a 355nm Doppler wind lidar system based on the double edge technique. Lidar measured profiles of wind speed and direction have been obtained to altitudes of up to 35 km. The lidar measurements are validated by comparing with independent rawinsonde wind measurements with very good agreement.

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Wavelength	355 nm
Telescope/Scanner Aperture	0.45 m
Laser Linewidth (FWHH)	80 MHz
Laser Energy/Pulse	70 mJ
Etalon FSR	12 GHz
Etalon FWHH	1.7 GHz
Edge Channel Separation	5.1 GHz
Locking Channel Separation	1.7 GHz
Etalon Peak Transmission	>60 %
PMT Quantum Efficiency	25%

Table 1 - Molecular Doppler Lidar System Parameters

Figure 1 – Spectrum of the atmospheric backscattered Rayleigh and aerosol signals along with three etalon transmission functions.

Figure 2 – System diagram of the 355 nm molecular wind lidar system.

Figure 3 - Profiles of wind speed and direction measured by the molecular lidar system compared with data from a colocated balloon sonde on Nov. 17, 1999.

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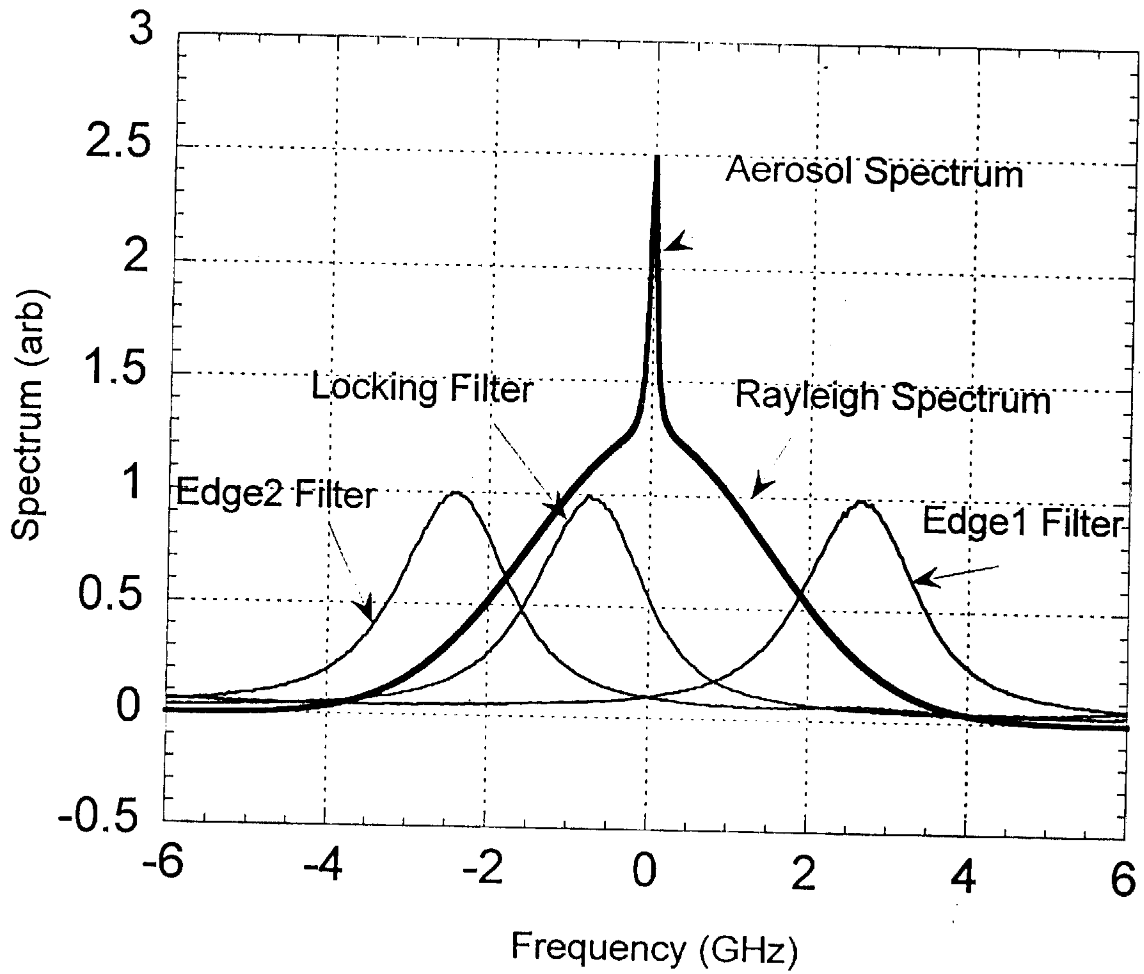


Aerosol Spectrum
Locking Filter
Rayleigh Spectrum
Edge2 Filter
Edge1 Filter
Spectrum (arb)
Frequency (GHz)
3
2.5
2
1.5
1
0.5
0
-0.5
-6
-4
-2
0
2
4
6

Fig 1

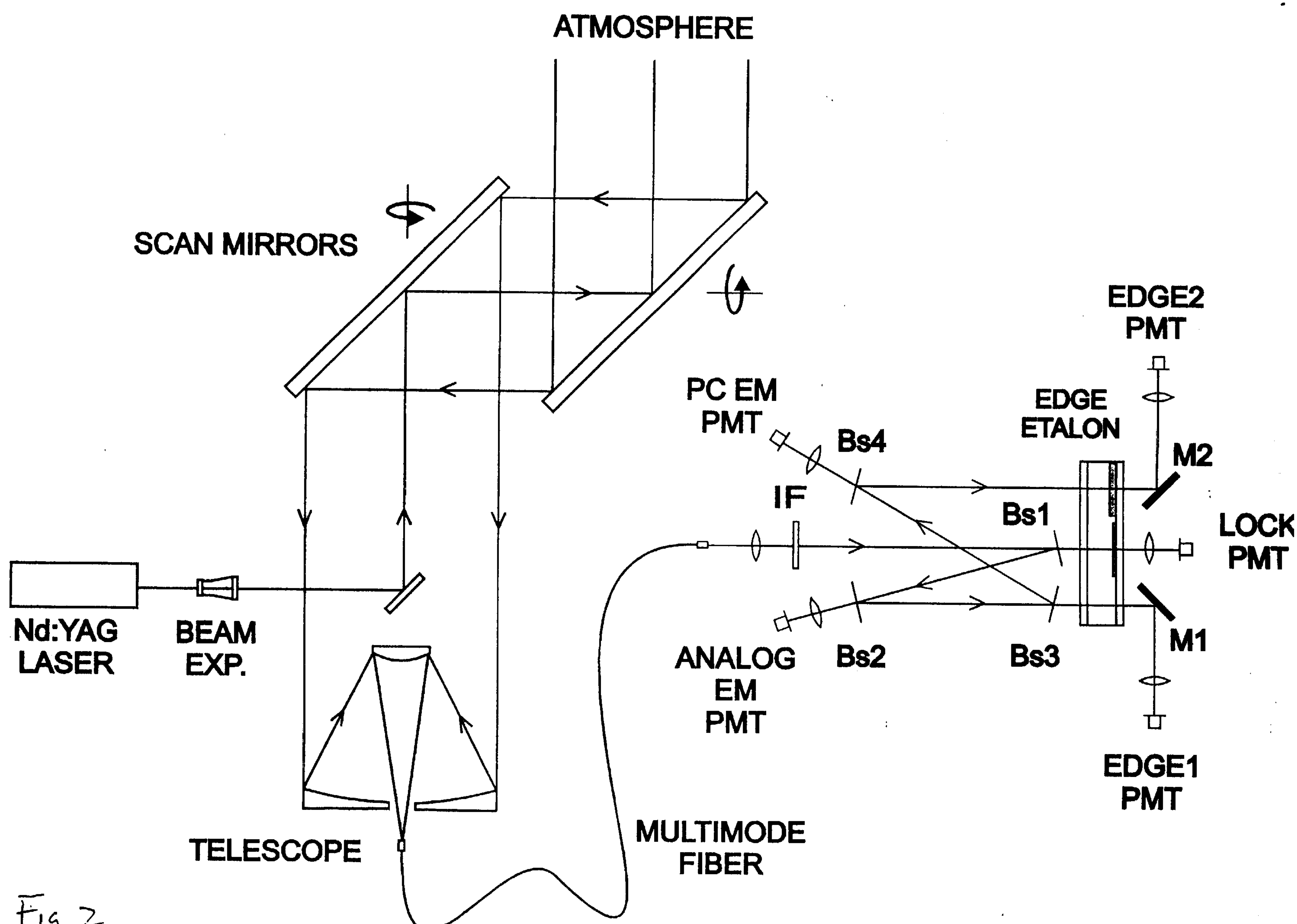
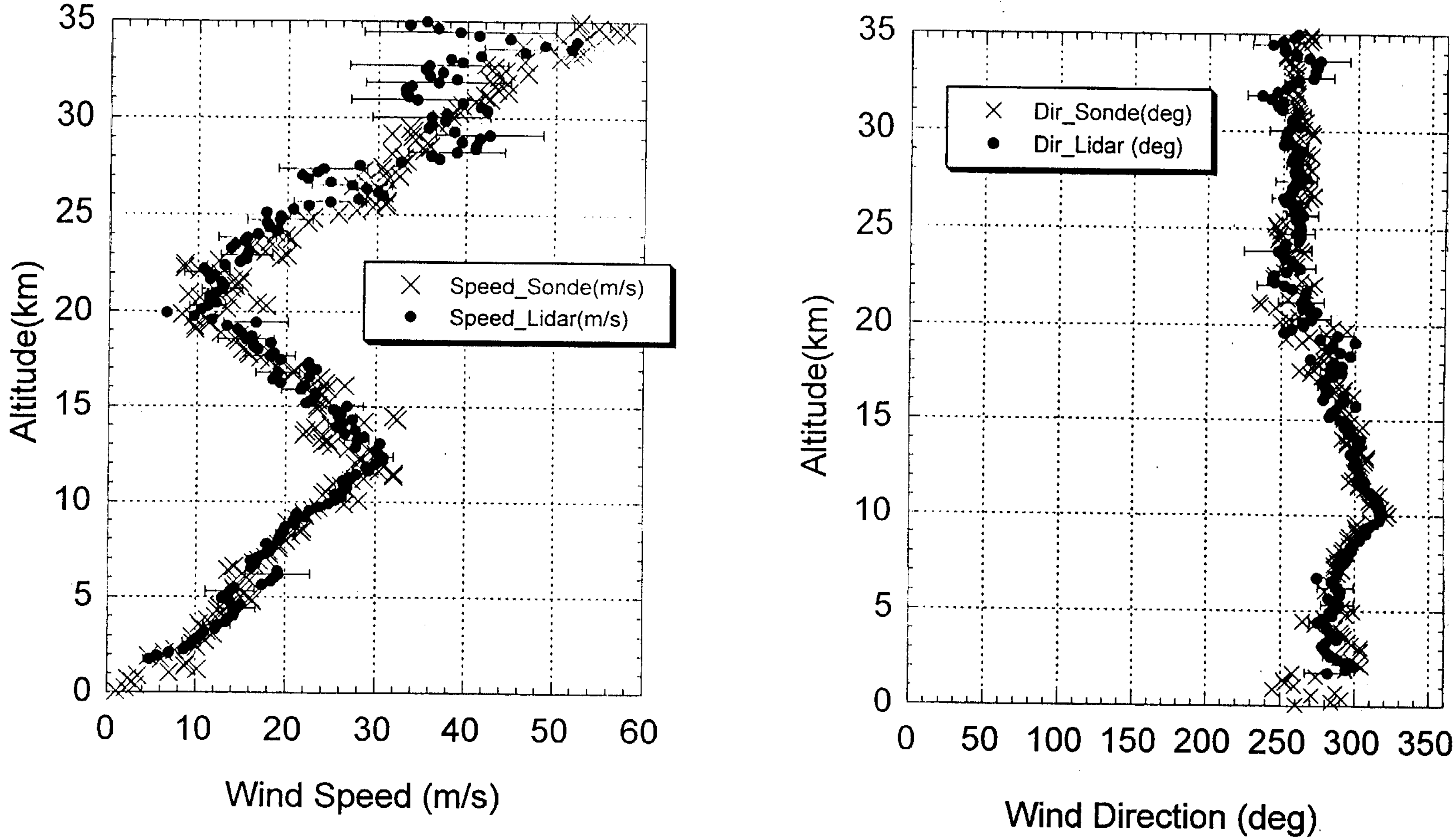

ATMOSPHERE
SCAN MIRRORS
EDGE2 PMT
PC EM PMT
EDGE ETALON
Bs4
M2
IF
Bs1
LOCK PMT
Nd:YAG LASER
BEAM EXP.
ANALOG EM PMT
Bs2
Bs3
M1
EDGE1 PMT
TELESCOPE
MULTIMODE FIBER

Fig 2



Altitude(km)
Wind Speed (m/s)
Speed_Sonde(m/s)
Speed_Lidar(m/s)
Altitude(km)
Wind Direction (deg)
Dir_Sonde(deg)
Dir_Lidar (deg)

Fig 3