WIND MEASUREMENTS WITH INCOHERENT DOPPLER LIDAR BASED ON IODINE FILTERS AT NIGHT AND DAY

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ABSTRACT

An incoherent Doppler wind lidar system at 532nm based on iodine filters is presented for wind measurements. Wind profile extends from 100m to 15km altitude at night and to 12km during daytime with a 136m vertical resolution. Two iodine filters are used to lock the transmitter laser frequency and to discriminate the Doppler frequency shift. A fiber, an interference filter for rejecting daylight and a photon counter are used for improving detection range. A unique feature of the system lies in its capability for aerosol backscattering mixing ratio measurement and the wind profile retrieval from a varied aerosol backscattering mixing ratio. The comparison experiments between the lidar and sonde were performed both at night and day. The relative error of wind direction and speed were 5.7% and 9.4% at night, and 5.8% and 18% in the daytime, respectively.

1. INTRODUCTION

At present, several research groups have been doing research on wind lidar systems. Goddard Lidar Observatory for Wind (GLOW) system designed by NASA/GSFC is a mobile Doppler lidar system based on double edge direct detection technology using two Fabry-Perot interferometers. Its detection range extends from 1.8km to 35km with a 178m vertical resolution. It operates at two wavelength: 355nm for molecular measurement and 1064nm for aerosol measurement [1]. Michigan Aerospace Corporation has designed two different GroundWinds systems, both of which have the maximum detection range of 20km [2, 3]. One system works at 532nm and uses three different Fabry-Perot interferometers to accomplish filtering and detecting Mie and Rayleigh backscattering. The other system works at 355nm and measures wind using Fabry-Perot interferometers. Liu et al. proposed the use of iodine filters for frequency analysis of backscattered light from both aerosol and molecule for tropospheric wind measurements and completed a laboratory demonstration in 1997 [4, 5]. At the same year, this wind measurement technique was independently demonstrated by Friedman et al. in tropical stratosphere, where aerosol influence is negligible [6].

In this study, we adopt some new methods for operation in daytime. Fiber is used for reducing near-field signal, narrow-band interference filter can reject broad-band daylight and photon counter can reduce the gain instability of analog mode PMT. Therefore the system has a capability for wind profile retrieval and aerosol backscattering mixing ratio measurement from a height of 100m to 15km at night and to 12km during daytime. The wind profile can be retrieved from a varied aerosol backscattering mixing ratio.

2. INSTRUMENTS DESCRIPTION

Table.1, Major parameters of the lidar system

Transmitter	
Wavelength	532 nm
Repetition	10 Hz
Pulse Energy	80 mJ
Pulse duration	10 ns
Pulse laser line width	100 MHz
Far-Field Full-Angle Divergence	100 μRads
Receiver	
Telescope aperture	28 cm
Field of view (at night)	250 μRads
Field of view (during daytime)	170 μRads
Interference filter bandwidth	0.11 nm
Interference filter peak transmission	76%

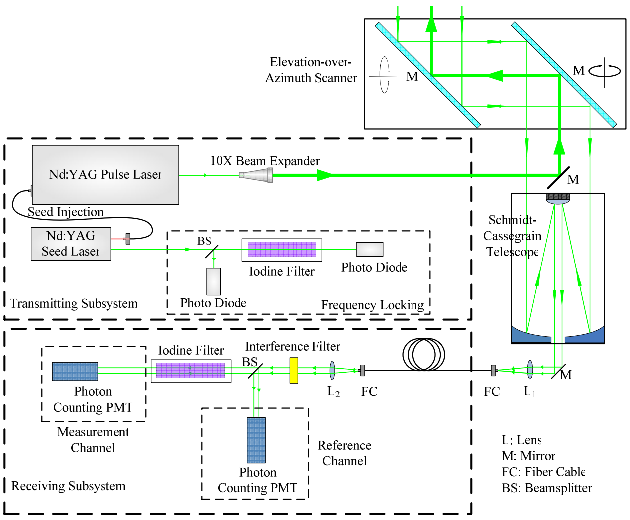

Fig.1, Schematic diagram for the optical system.

The major system parameters and the schematic diagram for lidar are shown in Table.1 and Fig.1, respectively. The transmitting subsystem mainly consists of a seed laser and a pulse laser. The 532nm output of the seed laser is locked at the edge of iodine absorption line to stabilize the frequency within 200kHz. The laser is transmitted into atmosphere through a scanner and the backscattering light been collected by the telescope goes through a fiber with about 100μm aperture and passes through an interference filter. Then the light is split into two channels: measuring channel as frequency discriminator and reference channel as energy monitor.

3. WORKING AT NIGHT AND DAY

A key problem for lidar operating in the daytime is to reject daylight background in order to improve the Signal-to-Noise Ratio (SNR) and detecting range.

We use fiber coupled telescope to reduce receiving Field Of View (FOV) and restrain near-field signal. Actually, we can choose the parameters such as fiber's diameter and numerical aperture to determine the receiving FOV. In our system, the receiving FOV is 250 μRads at night or 170μRads in daytime which matches well with the 100μRads divergence of transmitted laser. So the background light can be reduced. In addition, atmosphere backscattering light from different distance is focused at different positions along the optical axis after the telescope. Thus, we can adjust the fiber input position so that the far-field signal is focused, and the near-field signal still out of focus. In this way, the strong signal from near-field is reduced to avoid PMT saturation while the weak signal from far-field mostly passes. Fig.2 shows the relationship between the reduction rate of backscattering signals and distance.

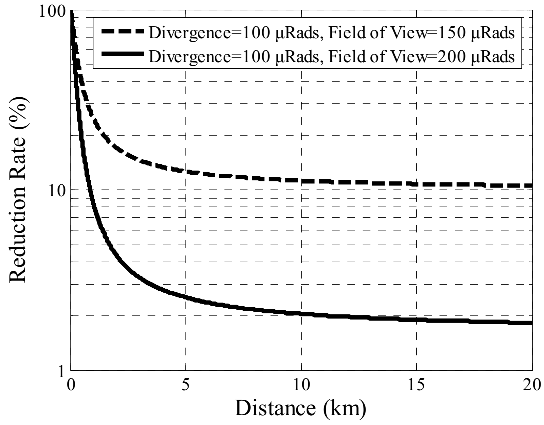

Fig.2, Backscattering signal reduction rate by fiber versus detection distance.

Interference filter with narrower line width, higher peak transmission rate can provide higher SNR. So we substitute the interference filter that has bandwidth of 0.11nm and peak transmission of 76% for that with 0.15nm bandwidth and 35% peak transmission in the previous system [7]. In this way, signal transmission is increased and background light is reduced. Fig.3 shows the comparison result of the two interference filters.

We also use a photon counter with a maximum count rate of 120MHz to reduce the gain instability of analog mode PMT. So SNR and detection range can be greatly improved especially in higher height. Fig.4 shows the backscattering signal measured in the daytime.

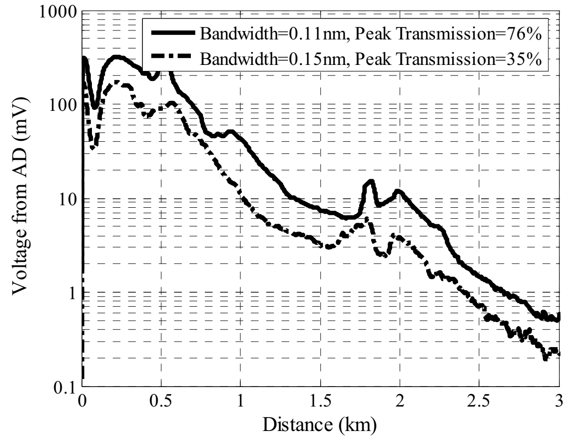

Fig.3, Comparison result of interference filters. Measuring interval is 90 minutes.

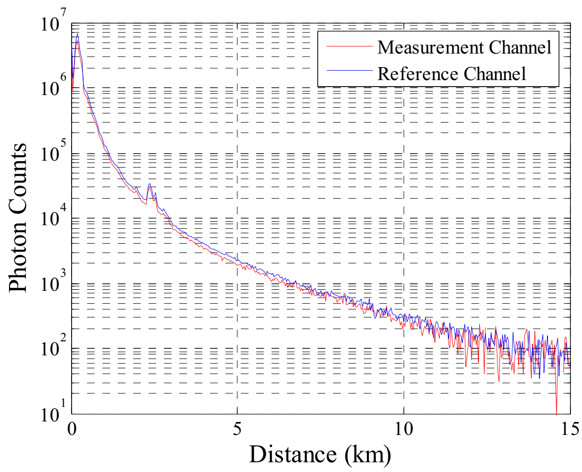

Fig.4, Backscattering signal measured in the daytime.

4. METHOD

4.1 Wind Profile Measurement

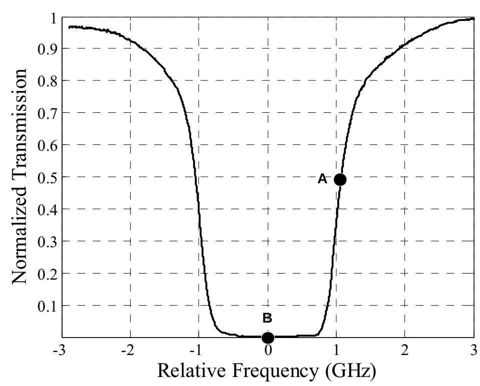

Fig.5, Normalized transmission for 1109 absorption line of iodine vapor filter. The temperature of cell tip and cell body are 65℃ and 70℃, respectively.

When wind profile is retrieved, wind field is assumed to be uniform and invariable during the measurement. The seed laser frequency of 532nm output is tuned to the half height (Point A in Fig. 5) at the high frequency edge of iodine 1109 absorption line.

When the elevation is θ and the azimuth is east, south, west and north respectively, the ratio of the measuring channel to the reference channel is given by

$$R_i = r_0 + \Delta r_v + \Delta r_{hi}, \quad i = E, S, W, N, \quad (1)$$

where r_0 is the ratio when line-of-sight wind velocity v_{LOS} is zero, Δr_v is the contribution owing to the vertical wind's projection on the line-of-sight, Δr_{hi} is ratio owing to the horizontal wind's projection on the line-of-sight. Taking the opposite direction east-to-west for example, two r_0 are equal and two Δr_v are equal too. Otherwise, Δr_{hi} have the same absolute value but opposite sign. So

$$(R_E - R_W)/2 = (\Delta r_{hE} - \Delta r_{hW})/2 = \Delta r_{EW}, \quad (2)$$

$$(R_E + R_W)/2 = r_0 + \Delta r_v. \quad (3)$$

Vertical wind ratio Δr_v is two orders of magnitude smaller than horizontal wind ratio Δr_{hi}, and Δr_{hi} is two orders of magnitude smaller than zero wind ratio r_0, so comparing with r_0, Δr_v can be ignored. Thus

$$(R_E + R_W)/2 \approx r_0. \quad (4)$$

Normalized wind ratio R_{Nor} is defined as $R_{Nor}=r/r_0$, it stands for the ratio of the measuring channel to the reference channel normalized by r_0, so that $R_{Nor}=1$ when line-of-sight velocity $v_{LOS}=0$. Then $\Delta R_{Nor}=\Delta r/r_0$ means the changes of normalized ratio owning to the line-of-sight velocity v_{LOS}. On east-to-west direction,

$$\Delta R_{NorEW} = \Delta r_{EW}/r_0 = (R_E - R_W)/(R_E + R_W). \quad (5)$$

Sensitivity S is defined as the slope of the changes of normalized wind ratio $\Delta R_{Nor}=\Delta r/r_0$ with respect to the line-of-sight wind velocity v_{LOS},

$$S = (1/r_0)\, dr/dv_{LOS} = (k/r_0)\, dr/df, \quad (6)$$

where f is laser frequency, and coefficient k is the Doppler shift of backscattering light caused by 1m/s wind velocity,. When the laser wavelength is 532nm, $k=3.76MHz/(m/s)$. Once we obtain dr/dv_{LOS} or dr/df in theory [7] or by experimental measurement, we know S. Then line-of-sight wind velocity can be written as

$$v_{LOS,EW} = \Delta r_{EW} \cdot dv_{LOS}/dr = \Delta R_{NorEW}/S. \quad (7)$$

So the horizontal wind velocity projection on east-to-west direction $v_{h,EW}$ is

$$v_{h,EW} = v_{LOS,EW}/\cos\theta. \quad (8)$$

On south-to-north direction, v_{SN} can be obtained by the same way,

$$v_{h,SN} = v_{LOS,SN}/\cos\theta. \quad (9)$$

Therefore, the horizontal wind velocity and direction can be calculated based on the relationships in trigonometry

$$v_h = \sqrt{v_{h,EW}^2 + v_{h,SN}^2}. \quad (10)$$

4.2 Aerosol Backscattering Ratio Measurement

The laser frequency is tuned to the valley of iodine 1109 absorption line (Point B in Fig.5) for aerosol backscattering mixing ratio R_b measurement. Iodine has a great absorption efficiency (measured to be 70dB) so that the aerosol backscattering will be mostly absorbed. Thus, the molecular backscattering can be measured independently. We can get R_b [7]

$$R_b = \beta_a/\beta_m \quad (11)$$

where β_a and β_m are aerosol and molecular volume backscatter (extinction) coefficients respectively.

5. EXPERIMENTAL RESULTS

In the experiment, the Doppler lidar operates at an elevation of 65° and four azimuths of east, south, west and north, respectively, for wind measurement, then at zenith for R_b and sensitivity measurement. Integration time of each direction is 300 seconds. The lidar signals been collected by the photon counter with a 4MHz sampling frequency has a vertical resolution of 34m. Making a 4 points average, then we obtain the wind profile and R_b with 136m vertical resolution. The standard deviation of these 4 points was shown by error bar in Fig.6 to Fig.8. Comparison experiments were performed between the sonde launched at Qingdao meteorological station and our lidar located at Ocean University of China. The horizontal distance is 900m.

5.1 Working at Night

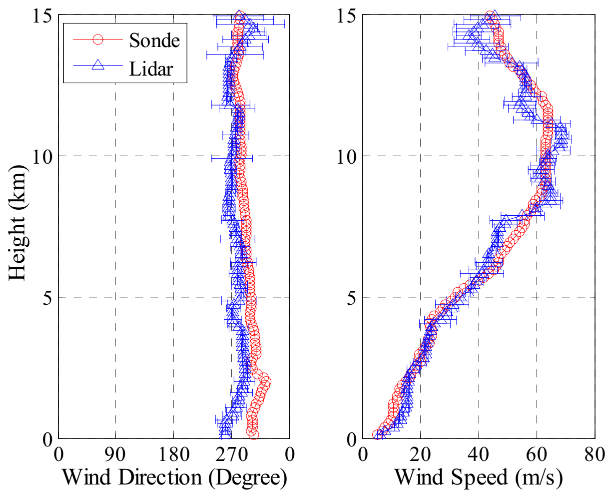

Fig.6, Comparison experimental results of wind profile between sonde and lidar on April 21, 2005. The weather condition was sunny. Lidar measurements were from 20:20 to 20:50, and sonde worked from 19:15 to 19:55.

Comparison measuring results at night on April 21, 2005 is shown in Fig.6. The detection range extends from 100m to 15km. The standard deviation of wind direction is 19° and that of wind speed is 4.2m/s. The relative error of wind direction and wind speed is 5.7% and 9.4%, respectively. As expected, wind direction comparison results above 2km were better than that below 2km owing to spatial difference between sonde and lidar.

5.2 Working in the Daytime

The wind profile comparison results and R_b measuring result in the daytime on October 21, 2005 are shown in Fig.7 and Fig.8, respectively.

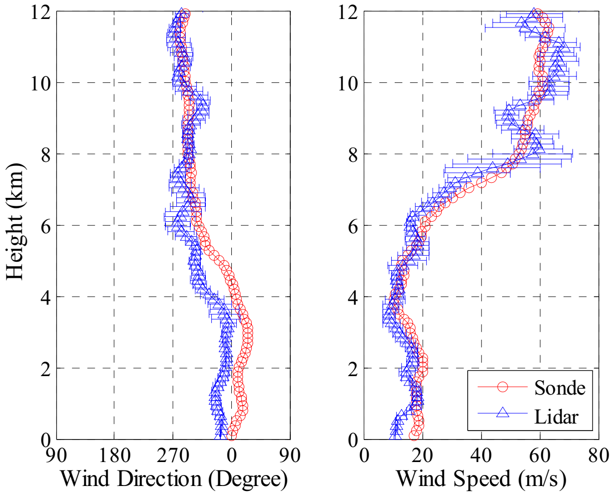

Fig.7, Comparison experimental results of wind profile between sonde and lidar on October 21, 2005. The weather condition was sunny. Lidar measurements were from 17:00 to 17:30, and sonde worked from 19:17 to 19:50.

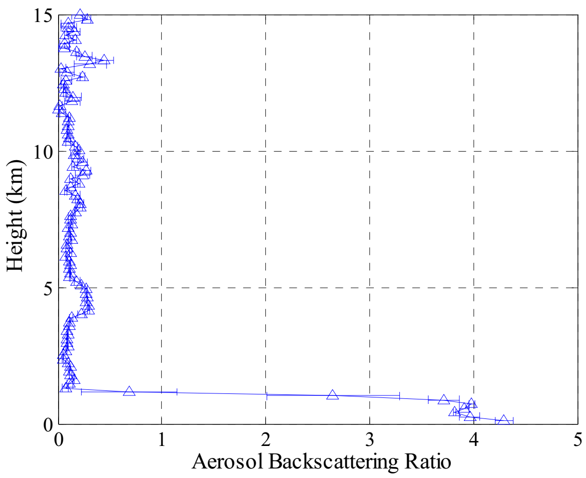

Fig.8, Measuring result of R_b by lidar from 16:25 to 16:35, on October 21, 2005. The weather condition was sunny.

In wind profile comparison, the time interval between lidar and sonde measurements was about 140 minutes and the detection range extends from 100m to 12km. The standard deviation of wind direction is 24° and that of wind speed is 5.5m/s. The relative error of wind direction and wind speed is 5.8% and 18%, respectively.

From the measuring result of R_b (Fig.8), the atmospheric boundary layer can be observed, obviously, at the height of 1km. And the air above the boundary layer was quite clear that the aerosol did almost not exist.

6. CONCLUSION

In conclusion, the detection range of our lidar can reach to 15km at night and 12km during daytime. The comparison experiments between lidar and sonde were performed and the relative error of wind direction and speed were 5.7% and 9.4% at night, and 5.8% and 18% in daytime. The result shows that the wind direction and speed measured by our lidar are in good agreement with the sonde wind measurements made simultaneously.

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7. REFERENCES

1. Bruce M. Gentry, et al., Wind Measurements with a 355 nm Molecular Doppler Lidar, *Optics Letters*, Vol.25, No.17, 1231-1233, 2000.

2. James G. Yoe, et al., GroundWinds 2000 field campaign: demonstration of new Doppler lidar technology and wind lidar data inter comparison, *Lidar remote sensing for industry and environment monitoring III*, SPIE proceedings series Vol.4893, 327-336, 2003.

3. Michael T. Dehring, et al., Space lidar simulations derived from the GroundWinds New Hampshire and Hawaii instruments, *Lidar remote sensing for environmental monitoring IV*, Proceedings of SPIE, Vol.5154, 84-92, 2003.

4. Z. S. Liu, et al., Proposed ground-based incoherent Doppler lidar with iodine filter discriminator for atmospheric wind profiling, *Application of Lidar to Current Atmospheric Topics*, SPIE 2833, 128-135, 1996.

5. Z. S. Liu, et al., An incoherent Doppler lidar for ground-based atmospheric wind profiling, *Appl. Phys.* B 64, 561-566, 1997.

6. J. S. Friedman, et al., Middle-atmospheric Doppler lidar using an iodine-vapor edge filter, *Optics Letters*, Vol.22, 1648–1650, 1997.

7. Z. S. Liu, et al., Low-altitude atmospheric wind measurement from the combined Mie and Rayleigh backscattering by Doppler lidar with an iodine filter, *Applied Optics*, Vol.41, 7079-7086, 2002.