Range Dependent Turbulence Characterization by Co-operating Coherent Doppler Lidar with Direct Detection Lidar

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Abstract: The backscattered signal power of a coherent Doppler Lidar (CDL) system that is used for wind sensing was validated against a direct detection Lidar system. In coherent detection, the received signal power depends on the overlap function of the backscattered and local oscillator fields. This overlap function is dependent on the loss of coherence of the backscattered field, which is influenced by refractive index variations of the atmosphere due to turbulence. A direct comparison of the backscattered signal power of the CDL with that of the direct detection Lidar requires that the effect of coherence loss and the overlap function as function of range is accounted for. In this study, we report on the CDL wind measurements and we present the analysis of the range dependent refractive index variations of the CDL by appropriately fitting the backscattered signal power with direct detection signal power measurements.

Keywords: Coherent Doppler Lidar, Wind Sensing, Direct Detection.

1. Introduction

Coherent Doppler Lidar (CDL) has been widely adopted in applications such as measuring atmospheric wind velocity, turbulence, aerosol concentration, cloud height and velocity, and detection of atmospheric constituents and pollutants. A CDL system for wind sensing was developed and operated at the Remote Sensing Laboratory at the City College of New York (CCNY). In our system, a 1.5µm polarized maintained (PM) fiber laser is used for its eye-safety, affordability, and availability where it is widely used in the telecommunication industry. The PM fiber optics ensures that the polarization state of the local oscillator remains aligned with that of the transmitted field. The system is capable of measuring vertical wind velocity for up to 3km. System's characteristics and main components were presented in previous papers [1-3].

In this paper, we examine the effect of range on signal to noise ratio (SNR) of backscattered signals of the CDL system. In section two, the system configuration is presented and system's main components are described. The effect of range on SNR of backscattered signals is presented in section three. In section four, wind measurement results are presented and SNR of CDL is compared with that of direct detection in vertical pointing.

2. System's Description

The system configuration is shown in Fig. 1 and consists of the following components: i) Laser source (ii) Accousto-optic modulator (AOM) (iii) Fiber amplifier (iv) Optical circulator (v) Optical antenna (vi) Balanced detector, and (vii) Signal processor. Optical components are connected with PM optical fibers. The laser source has two outputs: a low power seed laser that is used as a local oscillator (LO), and a high power output (0.5W) that is modulated, pulsed, and frequency shifted using an AOM. An RF source drives the AOM resulting in a 200 ns optical pulse with a 20 kHz pulse repetition rate (PRR) and a frequency shift of 84 MHz. These laser pulses are amplified by an erbium doped fiber amplifier (EDFA) then transmitted from port 1 to port 2 of the optical circulator.

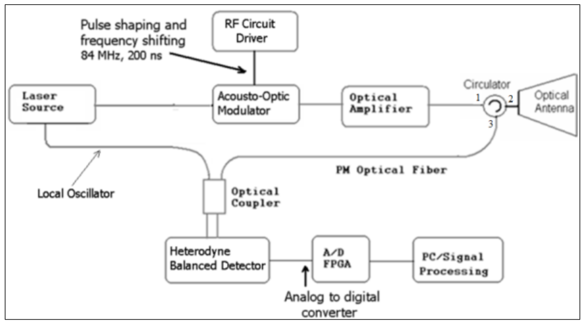

Fig. 1. Coherent Doppler lidar system configuration.

Laser pulses are transmitted into the atmosphere through a lens whereas backscattered signals are received back into the same lens and then transmitted from the optical circulator's port 2 to port 3. Backscattered and LO signals are optically combined using an optical coupler and heterodyne detected using a balanced photo detector. The RF electrical signals from the detector are acquired at a 400 MHz sampling rate using an analog to digital converter (ADC). Digital data is then streamed to a host PC for further processing.

3. The CDL Backscattered Signals Range Dependence

In this section, we present the range dependence on SNR of the CDL heterodyne detection using a monostatic configuration, and we compare analytical and experimental results. Monostatic configuration was believed to have an improved performance due to the correlation of the transmitted and back scattered fields. This correlation is the result of wave-front tilts self correction in a monostatic configuration [4-6]. The SNR range dependence of a CLR monostatic system is evaluated by using the concept of back projected local oscillator (BPLO), which is the imaginary local oscillator field distribution projected at the target side of the receiver aperture, receiver lens, originating from the detector [4,7,8]. Frehlich *et al*. [4] derived an equation that describes SNR as a function of range assuming a Gaussian Lidar system i.e., transmitter and LO fields are deterministic, detector response function is uniform, and the detector collects all LO and backscattered power incident on the receiver aperture. The SNR was then found by calculating the overlap integral between the BPLO and the backscattered fields on the receiver plane assuming a distributed aerosol target. To take into account the effects of refractive turbulence on CDL performance, different techniques of wave propagation in random medium were used [9]. Analysis shows that the SNR is proportional to the product of direct detection power and heterodyne efficiency. The calculation of received power and SNR requires mutual coherence function of the backscattered field incident on the receiver. As for natural aerosol targets, backscattered field at each aerosol particle has a random phase, and the mutual coherence function of the total backscattered field is the integration of all mutual coherence functions from each aerosol particle. The SNR range dependence [5] is expressed as:

$$SNR(L) = \frac{\eta_D(L)\lambda E\beta K^{2L/1000}\pi D^2}{8hBL^2} \tag{1}$$

where η_D is the system efficiency given by:

$$\eta_D(L) = \frac{\eta_{total}}{\left\{1+\left(1-\frac{L}{L_F}\right)^2\left[\frac{\pi(A_C D)^2}{4\lambda L}\right]^2+\left(\frac{A_C D}{2S_O(L)}\right)^2\right\}} \tag{2}$$

The system efficiency factor describes the loss of the SNR due to a mismatch between the LO and backscattered fields as a result of loss of coherence of the backscattered field. The loss of coherence is caused by: a) incoherent aerosol targets, which causes its field phase-front curvature and LO to mismatch (second term in the denominator), and b) propagation through the atmospheric refractive turbulence, which also causes an expansion of the transmitted beam resulting a larger incoherent image at the target (third term in the denominator). Figure 2 shows the simulated wideband SNR range dependence. The parameters used are listed in Table 1.

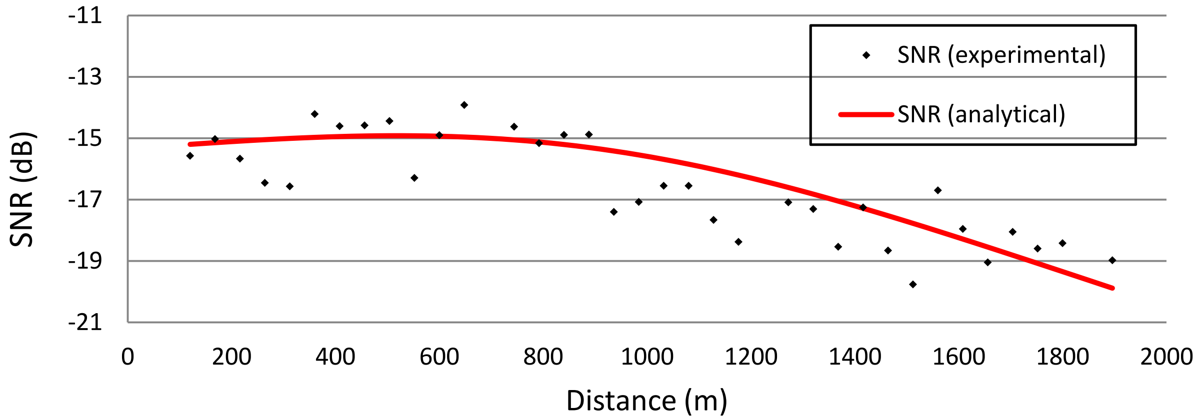

Fig. 2. Range dependence of wideband SNR of Doppler lidar's backscattered signals.

Table 1. Parameters corresponding to analytical estimation of wideband SNR range dependence

Parameter	Description	Value	Parameter	Description	Value
L	Range (m)		L_F	Focal Range of	
B	Bandwidth	100 MHz		Optical Antenna	5 km
λ	Wave length	1545.2 µm	A_c	Correction Factor	0.76
E	Pulse Energy	7 µJ		*This value was calculated*	
D	Effective aperture Diameter	0.1 m		*based on truncation ratio* given in Ref. [10]	
τ	Pulse width	200 ns	Cn^2	Refractive Index	
β	atmospheric backscatter			Structure Constant	$2x10^{-14}m^{-2/3}$
	coefficient	$8.3x10^{-7}$ /m/sr	η_{total}	Total system efficiency	-6 dB
K	one way atmospheric		$S_o(L)$	Transverse coherent	
	transmittance	0.95 /km		length	$\sim (1.1\ kw^2 L\ Cn^2)^{-2/3}$
			kw	Wave number	2π/ λ

4. Wind Measurement Results

To obtain wind measurements, the instrument was installed and operated in a research vehicle that is located on the campus of the City College of New York, located in upper Manhattan, New York (latitude: 40°49'N, longitude: 73°56'W). Laser pulses are transmitted into the atmosphere through an opening in the vehicle's roof, which also allowed for the collection of the backscattered signals. Received signals are pre-processed in real time which is accomplished by programming the FPGA to calculate and accumulate the autocorrelation of backscattered signals from 10,000 laser pulses. Backscattered signals power is estimated by calculating the FFT of the accumulated autocorrelation. These calculations are carried out by a host computer after streaming the autocorrelation data from the FPGA. Wind velocities are calculated by estimating the Doppler frequency shift of the backscattered signals. Figure 3 (a) and (b) show vertical profiles of wind velocity and the SNR of backscattered signal, respectively, measured over a period of four hours (14:00-18:00 U.S. eastern daylight time (EDT)) on July 12th, 2012. To be able to compare backscattered signals of the CDL with that of the direct detection, CDL's backscattered signals' power are range corrected according to the inverse range dependence shown in (2). Figure 4(a) and (b) show the range corrected CDL backscattered signals power and the 1µm direct detection lidar, respectively, which was also operated at the remote sensing laboratory of the City College of New York during the same time period. Both graphs show a good agreement of signal intensity profiles and cloud patterns at approximately 14:15, 15:00 and 15:20. It is also noticed that signal power increased significantly at a height of approximately 2000 m at 14:15 and 15:20 due to clouds at that height. Both lidars also show a gradual increase of aerosol signal as a function of time.

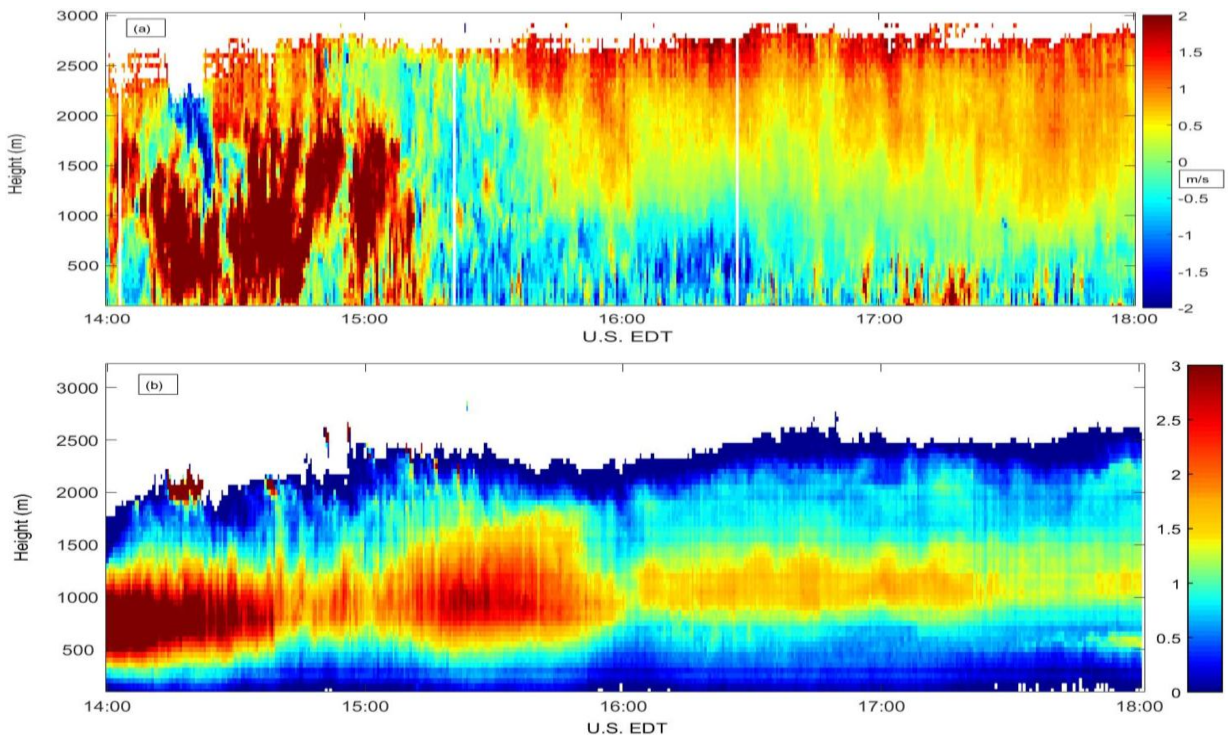

Fig. 3. Vertical wind velocity (a) and SNR(dB) of received signals (b) vs. height and time measured at the CCNY Remote Sensing Laboratory on July 12th, 2012 from 14:00-18:00 U.S. EDT.

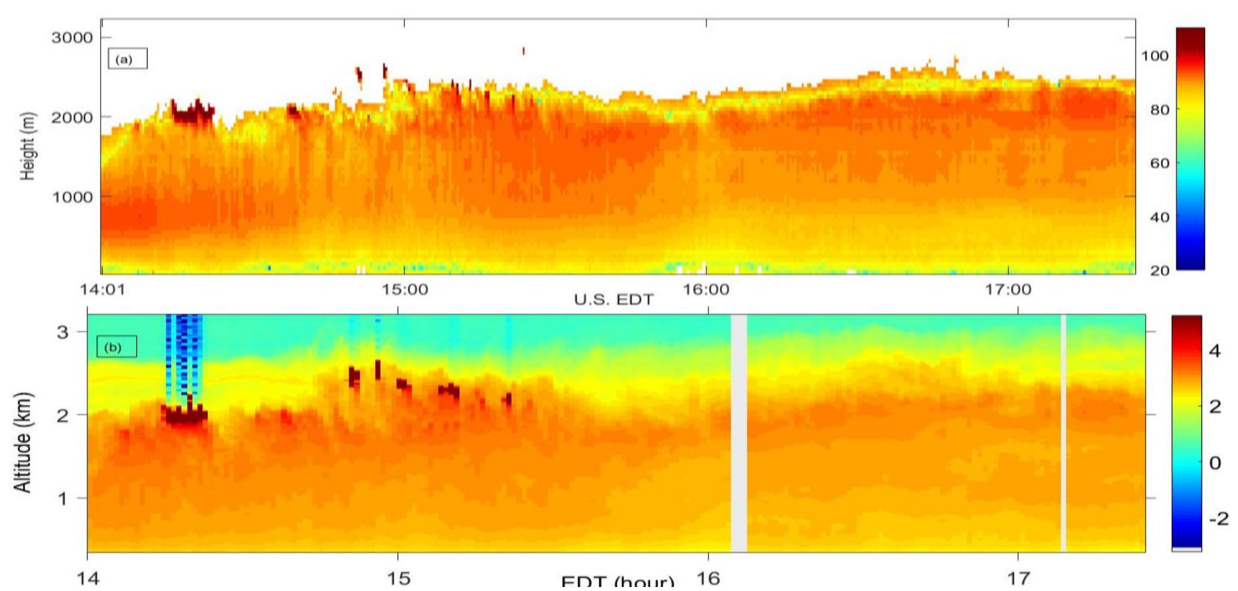

Fig. 5. Range corrected backscattered signal power (a) and the 1 µm direct detection lidar signal power (b) vs. height and time. Both profiles show a good agreement around 14:35, 15:60, and 16:15, where clouds' patterns are observed at the same heights. Aerosols concentration profiles also show a good agreement in the two measurements.

CONCLUSION

In conclusion, the turbulence and range effects on the CDL backscattered signals were corrected for which allowed to compare signals power with these of a direct detection lidar. Both lidars show a strong agreement of aerosol profiles and cloud pattern which validates measurements of the newly developed CDL instrument. More future work can be done to analytically compare backscattered signals power from both lidars.

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