Wind velocity estimate and signal to noise ratio analysis of an all fiber coherent Doppler Lidar system

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1. Intorduction

In CDL, a laser pulse is transmitted into the atmosphere and the Doppler shifted signal that scatters off of atmospheric aerosol particles is detected by beating this signal with a local oscillator (LO) [1][2][3]. The resulting RF signal has a Doppler shift proportional to the speed of aerosol particles along the line of sight of the laser beam. In this paper, we present preliminary results from our all fiber 1.5µ.m CDL. The range dependence of the theoretical wideband SNR of an atmospheric backscattered signal is compared to experimental results using a 6” diameter refractive telescope. The system performance is dependent on optimizing the LO power [4] and our previous research presented a detailed analysis of an optimum LO power and its effect on detector’s efficiency [5][6].

2. System overview

Our system consists of following components (Figure 1): i) laser source, (ii) modulator, (iii) fiber amplifier, (iv) optical antenna, (v) detector, and (vi) signal processor. Our laser source has two outputs: a low power seed laser, which is used as a LO, and a high power output (0.5 W), which is modulated, pulsed, and frequency shifted using an acousto-optic modulator (AOM). Laser pulse widths are 200 ns wide and the repetition rate is 20 KHz. A high power Erbium-Doped Fiber Amplifier (EDFA) amplifies the pulses which then pass through a circulator and an optical antenna before being coupled in to the atmosphere. The counter-propagating backscattered signal from the atmosphere is received by the optical antenna and directed by the optical circulator to a 50/50 optical coupler, which optically mixes the backscattered signal with the LO signal. The mixed signal is detected by a heterodyne balanced PIN photo detector which generates an RF signal. Acquisition of the RF signal is made at a sample rate of 400MHz using an analog to digital converter card (ADC) and the data is streamed to the host and processed. The data acquisition card is also equipped with an on-board field programmable gate array (FPGA) where some initial investigations of pre processing algorithms have been performed.

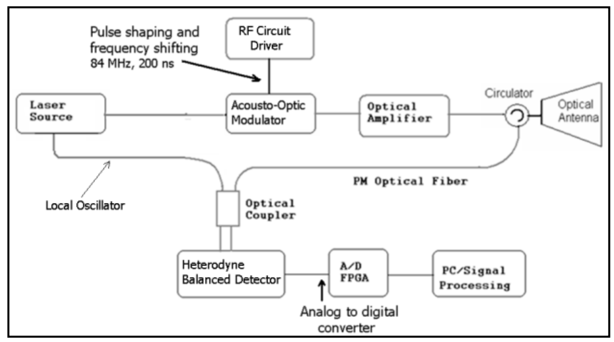

Fig. 1 Coherent Doppler lidar system configuration.

3. System operation

Our experimental setup is shown in Figure 2 which presents a few more details of the system. A laser source is connected to two serially connected AOMs through a single mode polarized maintained fiber. Each AOM shifts the frequency of the laser signal by 42 MHz resulting in a total shift of 84 MHz. The two AOMs are controlled by electronic circuits to generate a 200 ns pulse. The output of the AOMs feeds the EDFA, which is operated in an automatic current control mode. Amplified laser pulses are transmitted through an optical circulator from port 1 to 2. Insertion loss from port 1 to 2 is less than 1 dB. Back reflection from port 2 to 1 is down approximately 65 dB. To minimize the back reflection from port 2 back to port 1, the fiber tip at port 2 is angled and polished. The fiber tip is placed on a translation stage which allows for x, y, z, pitch, and yaw movement. This movement allows us to focus the laser beam at any desired distance in the atmosphere by changing the fiber holder’s position (z position) along the optical axis of the lens Signal processing involves dividing the time domain data into different time gates (Figure 3). Each time gate represents backscattered signal from a certain distance range. According to the required spatial resolution (Δr), the number of data points (M) in the time gates is determined as follows:

$$\Delta r = Mc\,T_s/2 \qquad (1)$$

where M is the number of points in a time gate, T_s is the sampling time, and c is the speed of light. Fast Fourier transform (FFT) is calculated and averaged over a large number of pulses for each range gate (Figure 5). Frequency shift (Doppler shift) in the power spectrum of the received signal can be estimated at each range gate to represent the wind velocity v (Figure 4) which is calculated using the following equation:

$$v = \lambda f/2 \qquad (2)$$

where λ is the wave length and f is the frequency shift (Doppler shift). Pulse energies are being limited to about 7 micro Jules for the results presented here but will be increased by about 3 dB in the near future after shortening the length of the fiber pigtails after the final amplifiers.

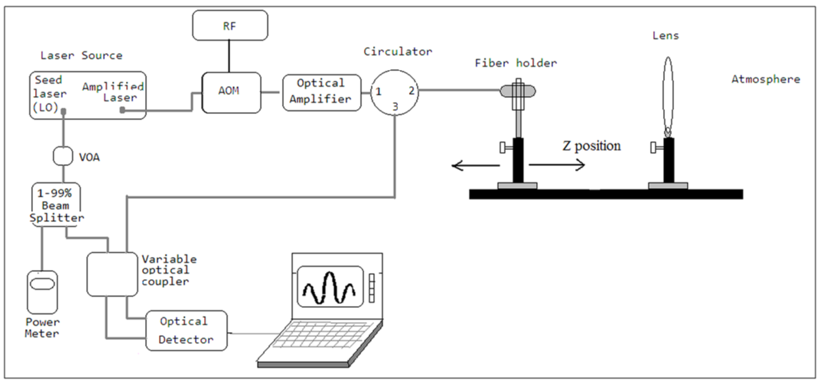

Fig. 2 Setup to observe scattered signal.

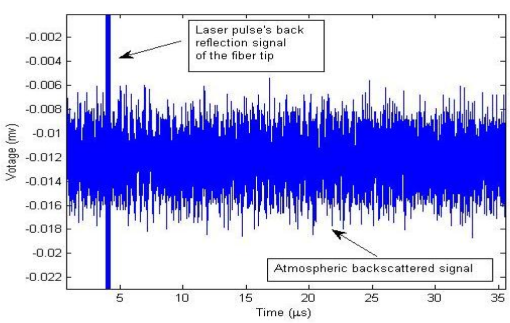

Fig. 3 Backscattered time domain data.

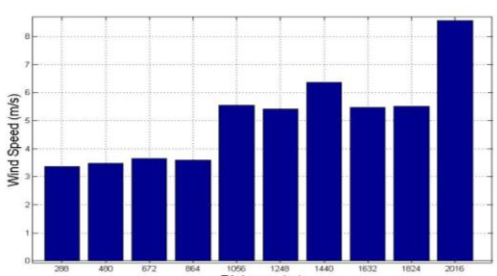

Fig. 4 Estimated line of sight (LOS) wind velocity vs. distance.

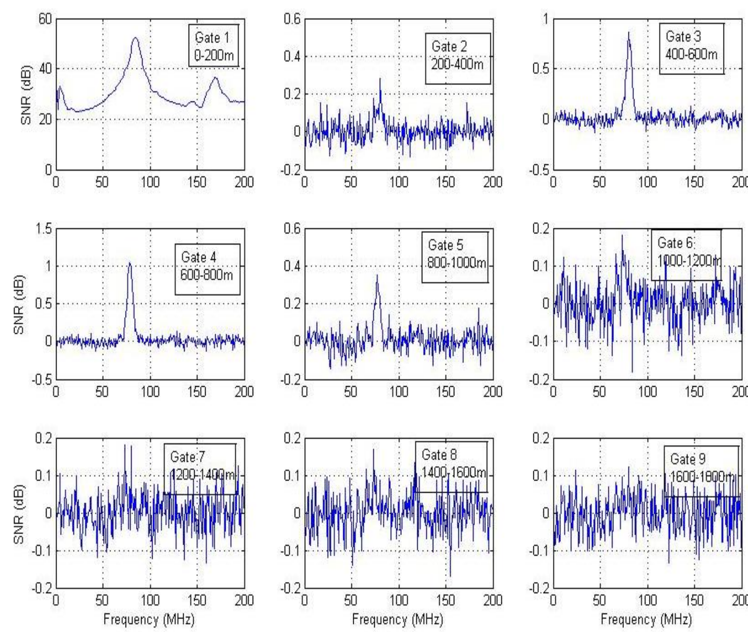

Fig. 5 Backscattered signal power spectrum at different range gate.

4. Velocity estimates and velocity uncertainty

The Doppler frequency shift can be estimated by finding the centroid of the discrete power spectrum of the backscattered signal after removing the background noise [7] [8], and various velocity estimation techniques have been proposed [9]. We use the maximum likelihood estimator (MLE) technique to estimate the wind velocities as shown in Figure 4. To estimate the wind speed, the backscattered signals were time gated such that each gate was formed of 128 samples. An FFT was calculated for each range gate, and about 10,000 pulses were accumulated. The uncertainty in the velocity estimate throughout 2 km range is determined to be between 0.15 to 0.65 ms^{-1} depending on the SNR and the number of accumulations [10].

5. SNR Analysis

Wideband SNR of a pulsed CDL system can be analytically estimated under certain conditions [11][12][13]. In this section, wideband SNR range dependence was measured and compared with analytical results. In our analysis, we have used equations (3) and (4) of Ref. [4] to calculate the range dependence of the wideband SNR as follows:

$$SNR(L) = \frac{\eta_D(L)\lambda E\beta K^{2L/1000}\pi D^2}{8hBL^2} \qquad (3)$$

where η_D is the system efficiency given by:

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

The parameters used were: wavelength 1.5452 μm, pulse energy 7 μJ, bandwidth 100 MHz, atmospheric backscatter coefficient 8.3×10^{-7} $m^{-1}sr^{-1}$, atmospheric transmittance = 0.95 km^{-1} , pulse width 200 ns, refractive index structure constant 2×10^{-14} $m^{-2/3}$, system efficiency -8.1 dB. We have theoretically and experimentally evaluated the performance of a 6” diameter antenna, while focusing the laser beam at approximately 1.8km. Figure 6 shows theoretical and experimental wideband SNR range dependence. Curve is estimated results and plots are measured results. It is clear that there is a good agreement between measured and estimated wideband SNR.

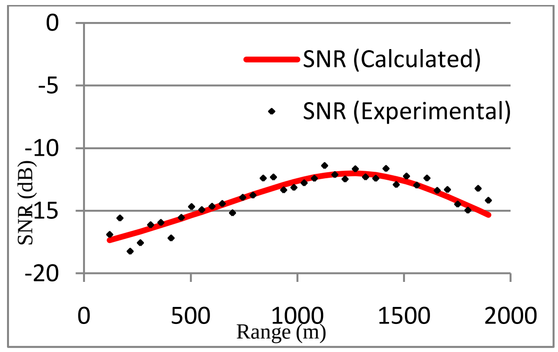

Fig. 6 Wideband SNR range dependence (points, experimental; solid curve, theoretical).

Parameter	Descriptions	Value
L	Range (m)	
B	Bandwidth	100 MHz
λ	Wave length	1545.2 μm
E	Pulse Energy	7 μJ
D	Effective aperture Diameter	0.15 m
τ	Pulse width	200 ns
β	atmospheric backscatter coefficient	8.3×10^{-7} /m/sr
K	one way atmospheric transmittance	0.95 /km
L_F	Focal Range of Optical Antenna	1.8 km
A_c	Correction Factor *(This value was calculated based on truncation ratio given in Ref.[9])*	0.76
Cn^2	Refractive Index Structure Constant	2×10^{-14} $m^{-2/3}$
η_{total}	Total system efficiency	-2.2 dB
$S_o(L)$	Transverse coherent length ~ $(1.1\, kw^2 L\, Cn^2)^{-2/3}$	
kw	Wave number = 2π/ λ	

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

6. Conclusion

An eye-safe, mobile, all-fiber coherent Doppler lidar instrument for wind sensing have been designed and implemented. Our instrument was confirmed to measure wind velocities up to approximately 2 km while operating at 59% of its full power. We also present an analytical and experimental wideband SNR range dependence, which helps us to optimize the performance of the optical antenna.

7. References:

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