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SIGNAL TO NOISE RATIO CHARACTERIZATION OF COHERENT DOPPLER LIDAR BACKSCATTERED SIGNALS

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ABSTRACT

An eye-safe coherent Doppler Lidar (CDL) system for wind measurement was developed and tested at the Remote Sensing Laboratory of the City College of New York (CCNY). The system employs a 1542 nm fiber laser to leverage components' availability and affordability of the telecommunication industry. A balanced detector with a bandwidth extending from dc to 125 MHz is used to eliminate the common mode relative intensity noise (RIN). The system is shot noise limited i.e., the dominant component of received signals' noise is the shot noise. Wind velocity can be measured under nominal aerosol loading and atmospheric turbulence conditions for ranges up to 3 km while pointing vertically with 0.08 m/s precision.

1. INTRODUCTION

Coherent Doppler Lidar (CDL) is widely used for remote sensing of the atmosphere. The first CDL wind-sensing system was reported by Huffaker *et al.* [1] in 1970, where a 10.6 µm cw CO_2 laser was used. Since the late 1980s, researchers started to deploy CDL systems with newly developed solid-state lasers which lead to advantages of size, weight, reliability, and lifetime. Operation at shorter wavelengths allows for higher spectral resolution, which means higher velocity resolution. Much effort has been put into 2 µm pulsed systems mainly intended for wind measurements [2] [3]. Hawley *et al.* [4] developed a 1.06 µm pulsed CDL system for wind sensing. Karlsson *et al.* [5] reported a 1.5 µm cw all-fiber wind sensing CDL system. An all-fiber coherent Doppler lidar for wind sensing was developed and tested at the Remote Sensing Laboratory of the City College of New York (CCNY) that utilizes 1.5 µm fiber laser pulsed at 20 KHz [6] [7] [8].

2. SYSTEM'S CONFIGURATION

The system's configuration is shown in Fig. 1 and consists of a 1542 nm fiber laser with two outputs; one output is used as a local oscillator (LO) whereas the other output is pulse shaped and then amplified before being transmitted into the atmosphere. For pulse shaping, the system uses two acousto-optic modulators (AOM) with 42 MHz frequency shift each, resulting in an 84 MHz total frequency shift of the input laser frequency. An optical amplifier is then deployed to increase the pulse energy to 14 µj at a repetition rate of 20 kHz before transmitting the pulse into the atmosphere. The laser pulse is coupled to the telescope (100 mm Diameter) with an optical circulator. The telescope also collects the backscattered atmospheric signals and via the same circulator directs the signals to an optical coupler. The Local oscillator and atmospheric backscattered signals are optically combined using a 2x2 variable coupler. The two outputs of the coupler are fed to a balanced detector to eliminate the common mode relative intensity noise (RIN) of the laser source that mixed the local oscillator with the atmospheric signal. Received signals are sampled at 400 MHz using an analog to digital converter card (ADC) equipped with an FPGA for signal pre-processing. The balanced detector has a bandwidth extending from dc to 125 MHz and provides transimpedance amplification and a second stage voltage amplification. Anti-aliasing filters precede the ADC of the receiver.

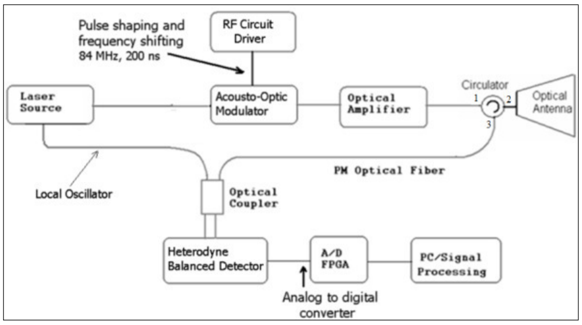

Fig. 1 Coherent Doppler lidar system's configuration.

3. THE SYSTEM’S SNR ANALYSIS

The system’s receiver has a non-flat frequency response. Figure 2 shows the response of the receiver due only to shot noise from the local oscillator. The power spectra of received signals need to be corrected for the detector’s non-flat gain shape. This is done by dividing the power spectrum of received signals by power spectrum of reference (shot noise) signal.

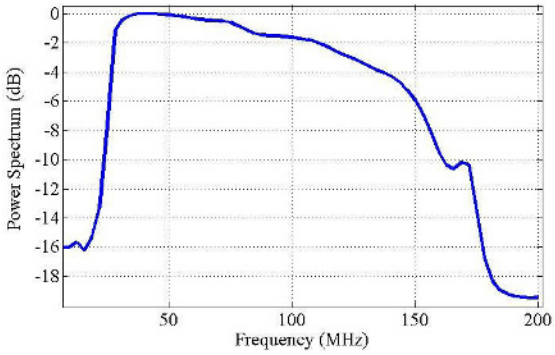

Fig. 2 Non-flat response of the receiver. This response was obtained by applying only the (LO) to the balanced detector while turning off and removing the input to the final amplifier. The vertical axis is in dB and normalized to the peak.

The reference signal is obtained using the balanced detector while LO is turned on and no atmospheric received signals are present (final amplifier is turned off), i.e. this power spectrum only represents shot noise. The SNR can be presented as follows:

$$SNR = \frac{P_{sig}^{(N)}}{P_{nois}} \qquad (1)$$

where, P_{nois}, and $P_{sig}^{(N)}$ are the noise and signal power spectra accumulated over N pulses, respectively. For a shot noise limited receiver system, the noise power is due to shot noise: $P_{shot}^{(N)}$ which can be written as:

$$P_{shot}^{(N)} =< P_{shot} > \pm\, \sigma_{shot}^{(N)} \qquad (2)$$

where; $< P_{shot} >$ is the average shot noise power, which is a fixed level characterized by the laser source, and $\sigma_{shot}^{(N)}$ is the shot noise variation around its fixed level when averaged N times (standard deviation of the shot noise for N accumulation). The mean shot noise fixed power level is given by:

$$P_{shot} = 2eiB \qquad (3)$$

where; e is the electronic charge, i is the photo-current, and B is the detector’s bandwidth. Since shot noise follows Poisson’s distribution then the averaged shot noise variation $\sigma_{shot}^{(N)}$ can be expressed as:

$$\sigma_{shot}^{(N)} = \frac{P_{shot}}{\sqrt{N}} \qquad (4)$$

Therefore, SNR, equation (1), can be re-written as:

$$SNR = \sqrt{N}\left(\frac{P_{sig}^{(N)}}{P_{shot}}\right) \qquad (5)$$

Correcting for the non-flat detector’s gain involves dividing accumulated measured signals’ power spectrum by a reference signal’s power spectrum, which can be expressed as:

$$\frac{P_{measured}}{P_{ref}} \qquad (6)$$

where; $P_{measured}$ is the measured signals’ power, which includes both signals and noise powers, and can be expressed as:

$$P_{measured} = P_{sig}^{(N)} + P_{Noise} \qquad (7)$$

$$= P_{sig}^{(N)} + P_{shot}^{(N)} \qquad (8)$$

P_{ref} is the power spectrum of LO when no received signals are input to the detector, i.e. only represents shot noise. As a result, the ratio between measured power and ref. power (equation 6) can be written as:

$$\frac{P_{measured}}{P_{ref}} = \frac{P_{sig}^{(N)}}{P'^{(N)}_{shot}} + \frac{P_{shot}^{(N)}}{P'^{(N)}_{shot}} \qquad (9)$$

$$= \frac{P_{sig}}{P_{shot}} + 1 \qquad (10)$$

This quantity has an average value $< \frac{P_{measured}}{P_{ref}} >$ and a (fluctuation) standard deviation value σ that can be expressed as follows:

$$\sigma = \sqrt{\frac{2}{N}} \qquad (11)$$

In our analysis, we calculate the following parameter: $\frac{P_{measured}}{P_{ref}} - 1$ by dividing signals power spectrum by a reference signals power spectrum and then subtracting one, which results to:

$$\frac{P_{measured}}{P_{ref}} - 1 = \frac{(SNR)}{\sqrt{N}} + \sqrt{\frac{2}{N}} \qquad (12)$$

Therefore, when accumulating 10,000 pulses and in order to extract signal out of noise, the signal power should be at least equal to noise power, i.e. SNR =1. As a result, the value we calculate is equal to: $\frac{1}{\sqrt{10{,}000}} + \frac{\sqrt{2}}{\sqrt{10{,}000}} = 0.024$, which is the value we set as a threshold below which received signals are ignored. It is worth noting that the signal power we report is not really the signal power, but it's the signal power normalized to the shot noise, in other words, it is the SNR for a single shot. To verify that the standard deviation (fluctuation) of the result of equation 10 (measured signals divided by reference signals) follows: $\sqrt{\frac{2}{N}}$ relationship, the ratio of measured noise to a reference shot noise was characterized by calculating the standard deviation of approximately 250k points. Each point is a measured noise power accumulated 10k times divided by a reference shot noise power also accumulated 10k times. The standard deviation is found to be 0.0155, approximately 10% more than what we estimated in equation 13. This difference can be a result of an effect of other noise sources such as thermal noise, i.e. the system is not 100% shot noise limited. In other words, the total noise in the receiver is not solely due to shot noise, but other noises have a small contribution as well. The histogram of the power ratio of the 250k analyzed points is shown in figure 3.

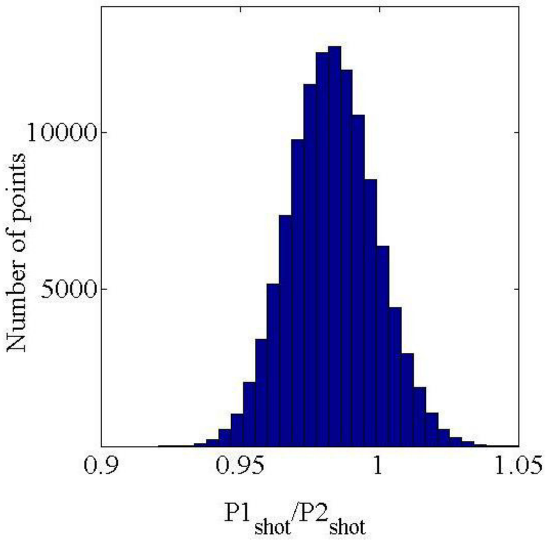

Fig. 3 The histogram of the ratio of measured noise power (10k accumulations) to a reference shot noise power (also 10k accumulations)

4. MEASUREMENTS

The SNR of backscattered signals and vertical wind velocity vs. time and height measured at the Remote Sensing Laboratory of the CCNY between 14:00-1800 (EDT) on July 12th, 2012 are presented in Fig. 4 (A) and (B) respectively. Over the course of four hours backscattered signals were measured up to approximately 2.5km vertically. Initially the SNR peaks between 0.5km and 1km. Cloud patterns appear at approximately 14:20 and 14:40 at 2km where the SNR is significantly greater than that of lower altitude. The SNR continues to peak at 1km throughout the measurement period. Fig. 4(B) shows the vertical wind velocity vs. time and height. Downdrafts are represented by red colors whereas updrafts are represented by blue colors. Vertical velocities are dominated by downdrafts during the first hour of measurements followed by updrafts dominance for the following hour. It is worth noting that the laser beam was focused at approximately 2km.

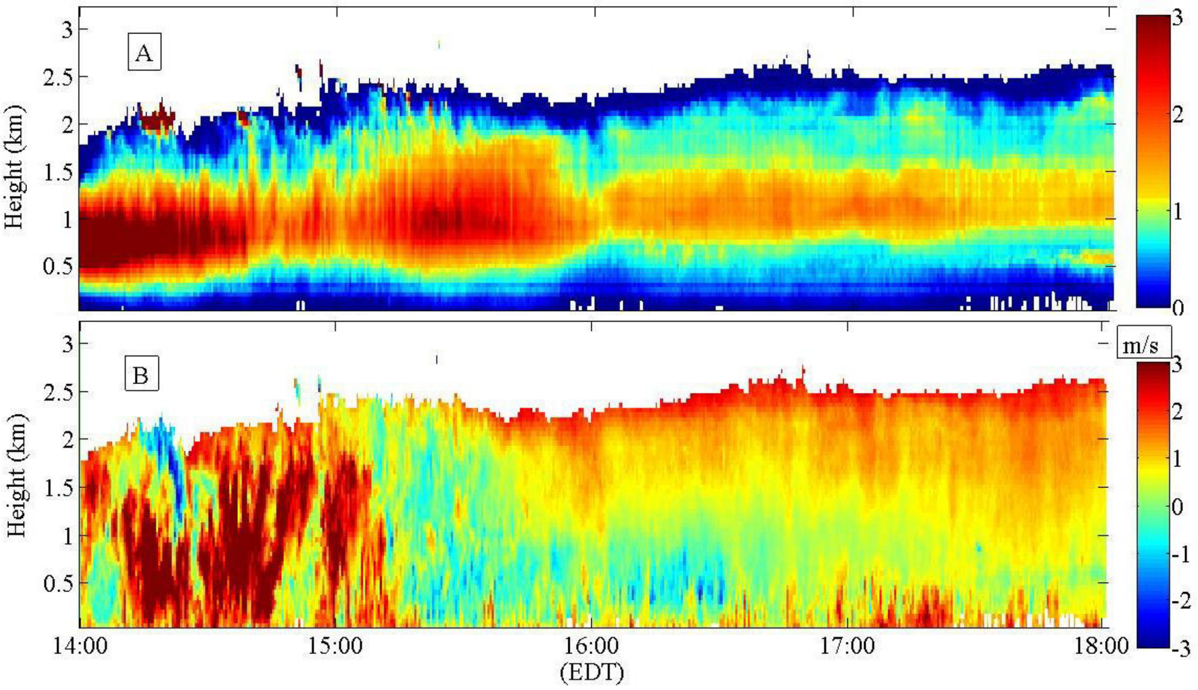

Fig. 4 SNR of backscattered signals(A), and Vertical wind velocity (m/s) (B) vs. time and height measured at CCNY Remote Sensing Laboratory between 14:00 – 18:00 EDT on July. 12th, 2012.

5. CONCLUSION

The SNR of backscattered signals of a shot noise limited CDL system for wind measurement was analyzed and presented. The measured signals power spectrum is divided by a reference signals power spectrum to remove the effect of a non-flat receiver's frequency response. In order to obtain a measurement realization, the ratio of received signals power to the reference signals power has to be greater than 1.025. The measured fluctuation of the signal power divided by a reference power is 0.015 whereas the calculated shot noise fluctuation is 0.014 for 10,000 accumulated pulses. A 10% difference between measured and calculated shot noise shows that the system is not 100% shot noise limited.

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