Energy Measurement Studies for CO_2 Measurement with a Coherent Doppler Lidar System

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ABSTRACT

The accurate measurement of energy in the application of lidar system for CO_2 measurement is critical. Different techniques of energy estimation in the online and offline pulses are investigated for post processing of lidar returns. The cornerstone of the techniques is the accurate estimation of the spectrum of lidar signal and background noise. Since the background noise is not the ideal white Gaussian noise, simple average level estimation of noise level is not well fit in the energy estimation of lidar signal and noise. A brief review of the methods is presented in this paper.

Keywords: Coherent lidar, CO_2, Differential Absorption Lidar, energy estimation

1. INTRODUCTION

The application of a coherent 2-micron Doppler lidar system to CO_2 measurement is discussed in this paper. A differential absorption lidar or DIAL is a lidar system that utilizes the different CO_2 absorption level of different wavelength laser. The coherent Doppler lidar system is more advantageous than those using direct detection in that the former can resolve CO_2 level over different range levels, whereas the latter has challenge with.

In the estimation of CO_2 level, the energy level of the lidar backscatter returns is investigated. When the Differential Optical Thickness (DOT) and the Optical Slope (OS) are calculated, the accuracy in energy estimation will play a critical role in the accuracy of the final results. This paper will discuss one of the techniques of optimal energy level estimation from the signal analysis perspective, and the uniqueness of the optics system is not the main focus in this manuscript.

The paper is organized as follows: a brief discussion about the necessity of accurate energy estimation is reiterated in the next section, and the algorithm for an accurate estimation follows. A few screenshots of the software are shown to illustrate the features of the software using the real lidar data. The conclusion summarizes the discussion and presents a future research direction.

2. CO_2 MEASUREMENT WITH A COHERENT DOPPLER LIDAR

A coherent 2-micron pulsed Doppler lidar system called VALIDAR (Validation Lidar) was designed at NASA Langley Research Center and its application varies from wind profiling to CO_2 measurements, and its performance review can be found in many articles and journals[1 – 11]. The advantage of coherent Doppler lidar system over a direct detection system is its versatile application to projects of different nature. Unlike the direct detection system, the coherent Doppler lidar system does not require a hard target. Also, the coherent Doppler lidar system can resolve the CO_2 intensity along the line of sight (LOS), whereas the direct detection system is not capable of range resolution.

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The basic difference between wind profiling and CO_2 measurement lies in the scan pattern and the process of data acquisition. For wind parameter estimation, the lidar system scans a wind field as quickly as possible in order to maintain the stochastic stationarities in spectral and statistical analysis of the wind data. The nominal data acquisition parameters are 50,000 – 55,000 sample acquisition at 5 – 10 Hz trigger rate, while performing the spectral analysis of the range bin data to produce wind parameters. In order to achieve a reasonable signal-to-ratio (SNR) for wind parameter estimation, averaging is often implemented across the number of repeated lidar pulses (ensemble averaging). When predetermined number of look directions are scanned while accumulating a number of lidar pulses at each line of sight (LOS), the average of power spectra in each range bin is calculated, and based on the Doppler shift frequency, wind parameters are estimated.

The CO_2 measurements are performed in quite a different way. First, the number of lidar pulses accumulated is much larger than that in wind profiling. Often, in the order of hundreds of lidar pulses are collected to estimate the energy in the lidar backscatter signals. This is based on the assumption that the CO_2 concentration in the airfield does not vary too much during the long observation period. Wind profiling prefers a prompt sweep of airfield in order to maximize the correlation among the acquired data set, and the number of lidar pulses for averaging is often in the order of 10s. Second, wind parameter estimation involves the trigonometric decomposition of measurements since the direction as well as the magnitude of wind is of interest. Such calculation is very susceptible to noisy data and errors, often resulting in unreasonable wind parameter estimates in poor SNR environment. In case of CO_2 measurements, the critical phase of data analysis lies in the accurate energy estimation in each range bin.

Figure 1 shows raw lidar returns for ON and OFF cases. The first 1,024 samples are used to monitor the quality of the lidar returns, and the total number of time series data acquired is 50,000. The left column corresponds to the case of ON, and the right column, OFF. The data were acquired in Park Falls, Wisconsin, USA on June 14, 2007. The ground lidar system VALIDAR was housed in a trailer, which was transported to a rural area in Park Falls for CO_2 concentration observation.

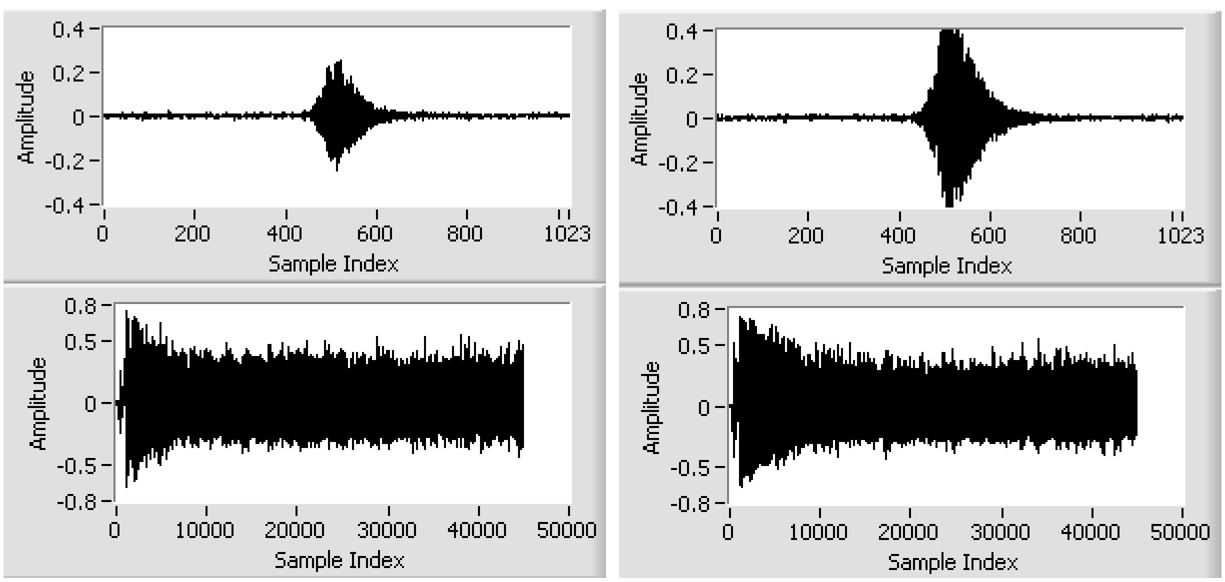

Fig. 1. The monitor pulses and the lidar returns for ON and OFF channels.

3. NOISE FLOOR ESTIMATION FOR ENERGY ESTIMATION

Once the raw lidar data returns are collected, the ones to be used for further analysis are selected by inspecting the monitor pulse located at the beginning of each lidar return. Once a lidar return passes such screening, the rest of the lidar pulse is divided into range bins with a pre-determined overlap ratio such as 50%. Subsequently, the periodogram in each range bin is calculated followed by the energy level estimation. The data from Park Falls, WI, USA had the following parameters: 50,000 samples with 1,024 monitor samples with 512 samples in each range bin with 50% overlap. The FFT size was 512, and the periodogram in each lidar return is ensemble averaged in each range bin. The energy level estimation is performed on the ensemble average of periodograms to determine ON/OFF status and the Differential Optical Thickness (DOT) and the Optical Slope (OS) are calculated using the resulting energy levels.

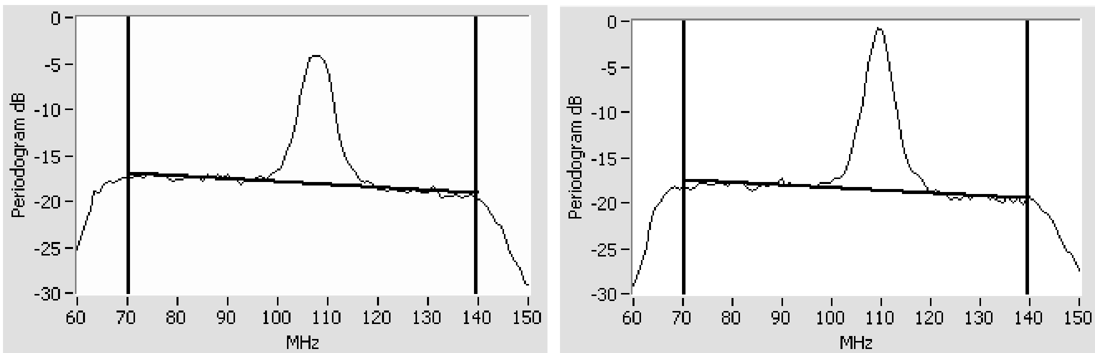

Fig. 2. Noise floor fitting for energy estimation.

Figure 2 depicts the process of energy estimation. Note that the background noise is not white due to the characteristics of laser analog electronics, and commonly known noise whitening algorithm using the tail of lidar returns will not work effectively in our case. In order to estimate the energy of the lidar return, which is equivalent to the area under the power spectra of it¸ an accurate level of noise as well as the begin and the end of the signal component is crucial. Also, note that visual identification of such boundaries seems heuristic and straightforward to human eye, but such process can be highly nonlinear, which makes its implementation challenging in code programming.

One of the many different versions of signal boundary estimation and energy calculation is to start with pre-determined frequency bandwidths where only noise is assumed to be present. In Figure 2, the frequency ranges 75 MHz – 95 MHz and 125 MHz – 135 MHz are used for the noise bandwidths. The approach shown in Figure 2 is to fit the noise frequency response with a first-order polynomial while minimizing the mean square error (MSE). Different versions such as estimating two noise floors separately in the left and the right of the signal peak had been implemented and tested, but are not discussed in this paper. Where the linear regression line intersects the periodogram for the first time as you span out from the center of the signal peak to both ends is used as the begin and the end of the signal component. The energy of a signal is equivalent to the area under its power spectra by the Parseval's theorem. (The scaling factors are assumed to be taken care of in our implementation.) Once the signal boundaries are identified, a numerical method of integral is applied to estimate the area underneath the power spectra.

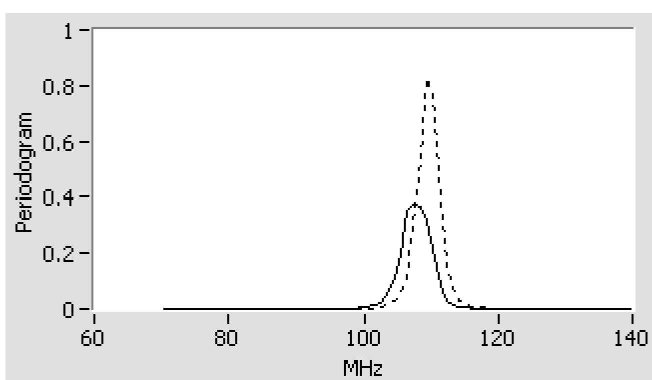

Fig. 3. ON and OFF pulses without noise in linear scale.

Figure 3 shows the ON and the OFF pulses after removing the noise component in linear scale. The periodogram was in dB scale for noise floor estimation, and the energy is estimated in linear scale based on the Parseval's theorem. Once the energy of ON and OFF pulses is estimated, the DOT and the OS are calculated. The DOT in each range bin is defined by:

$$ln\,(S_{OFF} / S_{ON}), \quad (1)$$

where S_{OFF} and S_{ON} are the energy of OFF and ON channel, and $ln\,(x)$ is the natural logarithm of variable x. The OS is defined in (2):

$$\text{Optical Slope}\,(R_1) = ln\,(\,S_{ON}\,(R_1)\; S_{OFF}\,(R_2) \,/\, [S_{ON}\,(R_2)\; S_{OFF}\,(R_1)]\,), \quad (2)$$

where $S_{ON}\,(R_1)$ is the energy of ON channel in Range 1 and $S_{OFF}\,(R_1)$ is the energy of OFF channel in Range 1.

Figure 4 shows the Energy distribution of ON and OFF channels versus range and the DOT versus range. The ON channel shows lower energy level due to CO_2 absorption. The resulting OS is shown in Figure 5.

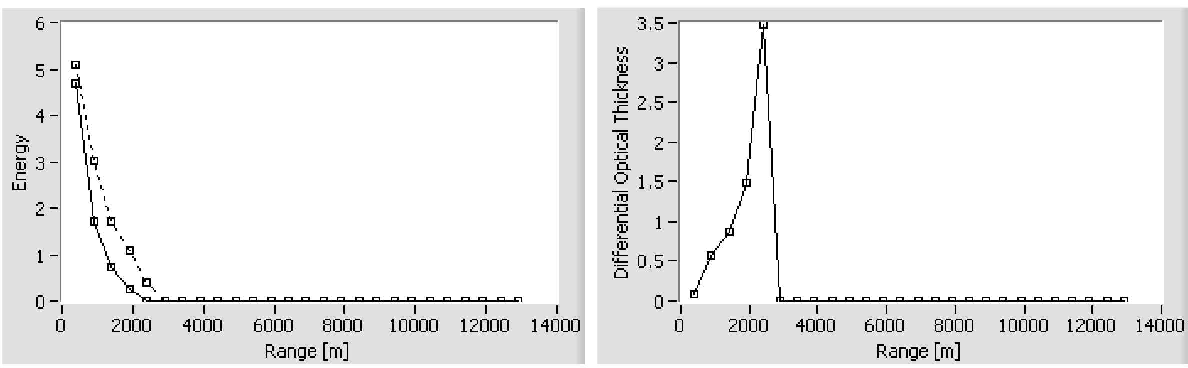

Fig. 4. Energy distribution and the DOT of ON (solid line) and OFF (dotted line) for different range bins.

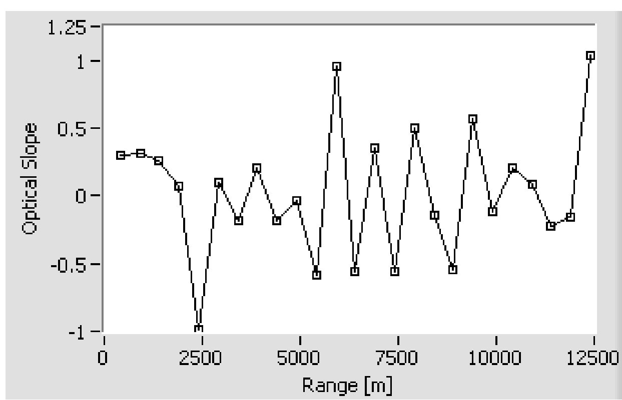

Fig. 5. The Optical Slope vs. Range.

4. CONCLUSION

A new approach to energy estimation for CO_2 measurement is presented in this paper. The accuracy in energy estimation plays a critical role in CO_2 concentration measure indices such as the Differential Optical Thickness and the Optical Slope. The coherent Doppler lidar system for the DIAL application is designed and integrated at NASA Langley Research Center in Hampton, Virginia, USA. Due to the analog laser electronics, the background noise is not white, which complicates the energy estimation of signal power spectra. Energy estimation also requires the accurate identification of the boundaries of signal component, and it is achieved by first estimating the noise floor by curve fitting. The noise floor was modeled by a first order polynomial while minimizing the mean square error in approximation. Once the noise floor is modeled, the signal boundaries are found by searching for the first crossing of the noise floor fit and the power spectra curve moving from the center of the signal power spectra to both ends of the frequency range (DC and the half of sampling frequency). Once the signal boundaries are found, a numerical method of integral is applied to find the area under the signal-only power spectra in linear scale using the principle of Parseval's theorem. This paper shows one of the variants of different energy estimation methods. The noise floor fit can be raised incrementally while calculating the DOT and the OS to find the optimal noise floor as well. The quality of the CO_2 measurement indices is inspected to identify the optimal noise floor, and it will be used throughout the analysis of the data sets. The details and the results of this adaptive approach will be presented in a future paper.

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REFERENCES

[1] J. Y. Beyon and G. J. Koch, "Novel Nonlinear Adaptive Doppler Shift Estimation Technique (NADSET) for the Coherent Doppler Lidar System VALIDAR," in *Proc. of the Defense and Security Symposium 2006* (6236-1), Orlando, FL, April, 2006.

[2] J. Y. Beyon and G. J. Koch, "Resolution Study of Wind Parameter Estimates by a Coherent Doppler Lidar System," in *Proc. of the Defense and Security Symposium 2006* (6214-3), Orlando, FL, April, 2006.

[3] J. Y. Beyon and G. J. Koch, "Wind Profiling by a Coherent Doppler Lidar System VALIDAR with a Subspace Decomposition Approach," in *Proc. of the Defense and Security Symposium 2006* (6236-5), Orlando, FL, April, 2006.

[4] J. Y. Beyon, G. J. Koch, and Z. Li "Noise Normalization and Windowing Functions for VALIDAR in Wind Parameter Estimation," in *Proc. of the Defense and Security Symposium 2006* (6214-4), Orlando, FL, April, 2006.

[5] J. Y. Beyon and G. J. Koch, "Novel nonlinear adaptive Doppler-shift estimation technique for the coherent Doppler validation lidar," *Optical Engineering*, Vol. 46, No. 1, pp. 016002-1 – 016002-10, January 2007.

[6] J. Y. Beyon, G. J. Koch, and S. Ismail "Signal processing techniques for heterodyne differential absorption lidar," in *Proc. of the Defense and Security Symposium 2007* (6567-53), Orlando, FL, April, 2007.

[7] G.J. Koch, J.Y. Beyon, B.W. Barnes, M. Petros, J. Yu, F. Amzajerdian, M.J. Kavaya, and U.N. Singh, "High-Energy 2-μm Doppler Lidar for Wind Measurements," *Optical Engineering*, Vol. 46(11), pp. 116201-1 – 116201-14, November, 2007.

[8] J. Y. Beyon, G. J. Koch, M. J. Kavaya, and M. Sahota, "Comparison of theoretical and empirical statistics of wind measurements with validation lidar (VALIDAR)," in *Proc. of the Defense and Security Symposium 2008*(6968-59), Orlando, FL, March, 2008.

[9] B. Demoz, "The Howard University Beltsville Research Campus: Highlights from the Recent Wind Lidar and Water Experiemnts," Wind Lidar Working Group Meeting, June, 2009.

[10] G. J. Koch, "Ground-Based Testing of the DAWN 2-Micron Doppler Lidar and Comparison with Other Sensors," Wind Lidar Working Group Meeting, June, 2009.

[11] K. Vermeesch, G. Koch, B. Gentry, T. Bacha, H. Chen, and B. Demoz, "Comparisons of Ground-Based, Radiosonde, and Aircraft Wind Measurements at the Howard University Beltsville Research Site," Wind Lidar Working Group Meeting, June, 2009.