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Doppler Lidar Measurements of Tropospheric Wind Profiles using the Aerosol Double Edge Technique

Bruce M. Gentry[1], Steven X. Li[2], Savyasachee Mathur[2], C. Laurence Korb[1] and Huailin Chen[2]

[1]NASA Goddard Space Flight Center
Laboratory for Atmospheres, Code 912
Greenbelt, MD 20771 USA

[2]Science and Engineering Services, Inc.
4032 Blackburn Lane
Burtonsville, MD 20866

Abstract

The development of a ground based direct detection Doppler lidar based on the recently described aerosol double edge technique is reported. A pulsed, injection seeded Nd:YAG laser operating at 1064 nm is used to make range resolved measurements of atmospheric winds in the free troposphere. The wind measurements are determined by measuring the Doppler shift of the laser signal backscattered from atmospheric aerosols. The lidar instrument and double edge method are described and initial tropospheric wind profile measurements are presented. Wind profiles are reported for both day and night operation. The measurements extend to altitudes as high as 14 km and are compared to rawinsonde wind profile data from Dulles airport in Virginia. Vertical resolution of the lidar measurements is 330 m and the rms precision of the measurements is a low as 0.6 m/s.

1. Introduction

We have developed a ground based direct detection Doppler lidar capable of profiling winds in the free troposphere. The ground based lidar operates at 1064 nm, the fundamental wavelength of the Nd:YAG laser, and measures the Doppler shifted frequency of the laser signal backscattered by atmospheric aerosols. This experiment is a proof of principle demonstration of the recently reported double edge technique [1] for Doppler lidar wind measurement.

Research has established the importance of global tropospheric wind measurements for large scale improvements in numerical weather prediction[2]. In addition, global wind measurements provide data that are fundamental to the understanding and prediction of global climate change. These tasks are closely linked with the objectives of the NASA Earth Science Enterprise and Global Climate Change programs. NASA Goddard has been actively involved in the development of direct detection Doppler lidar methods and technologies to meet the wind observing needs of the atmospheric science community. A variety of direct detection Doppler wind lidar measurements have recently been reported indicating the growing interest in this area [3, 4, 5, 6].

Our program at Goddard has concentrated on the development of direct detection Doppler lidar systems based on the edge technique for atmospheric wind measurements [5]. Implementations of the edge technique using either the aerosol[1,4] or molecular[5,6,7] backscatter for the Doppler wind measurement have been described. The basic principles of the aerosol implementation have been verified in laboratory[8] and atmospheric lidar wind experiments[9]. The aerosol wind lidar measurements were obtained with a lidar operating at 1064 nm. These measurements demonstrated high spatial resolution (22 m) and high velocity sensitivity (rms variances of 0.1 m/s) in the planetary boundary layer (PBL). The aerosol backscatter is typically high in the PBL and the effects of the thermally broadened molecular backscatter can often be neglected. However, as was discussed in the original paper[5], the molecular contribution to the signal is significant above the boundary layer and a correction for the effects of molecular backscatter is required to make wind measurements. In addition, since the energy monitor channel used for normalization in the single edge technique measures the unfiltered sum of the aerosol and molecular signals the molecular signal can be a dominant source of shot noise in regions where the molecular to aerosol backscatter ratio is large.

To extend the operation of the aerosol edge technique into the free troposphere we have developed a variation of the edge technique called the double edge technique. The double edge technique has many of the same basic characteristics as the edge technique but with new capabilities particularly suited for measurement of winds in the free troposphere. In this paper a laboratory based aerosol double edge lidar is described and the first measurements of wind profiles in the free troposphere obtained with this lidar are presented.

2. Double Edge Technique

The details of the double edge aerosol method have been recently reported [1]. A brief summary is included here along with a description of the lidar instrument and data acquisition and analysis procedures.

The double edge technique uses two high spectral resolution optical filters in the measurement of the Doppler shift. The basic principle is illustrated in Figure 1. The filter bandpasses have similar spectral characteristics and are separated in frequency space so that their spectral edges overlap at their respective half width half maximum (HWHM) points. The filter edges have opposite slopes and are positioned symmetrically about the transmitted laser frequency. The transmitted laser frequency is located at approximately the HWHM of each filter. A frequency shift will produce a positive change in transmitted signal for one edge filter, with respect to its initial position. For the second filter with the same properties the corresponding signal change is opposite in sign and approximately equal in magnitude.

The backscattered aerosol spectrum retains the narrow width and shape of the transmitted laser pulse, approximately 40 MHz full width half maximum, that is narrow relative to the spectral width of the edge etalon filters. As noted above, when the narrow aerosol signal is located on the edge of the etalon transmission function, large changes in filter transmission are observed for small frequency shifts. In contrast, the molecular backscattered signal is broadened by the random thermal motion of the molecules. At a wavelength of 1064 nm, the width (FWHM) of the molecular backscatter spectrum is approximately 1200 MHz (T=260K) that is about 10 times the FWHM of the edge filter etalons. As a result, the broad molecular signal measured through the etalons appears as a slowly varying background and is relatively insensitive to small frequency shifts. In addition, since the edge filter etalons are narrow relative to the molecular spectrum, only a fraction (≈10%) of the molecular background signals reaches the detectors. Bandpassing the molecular signal significantly reduces the effects on the wind measurement both as a bias and as a source of shot noise.

The double edge algorithm includes a method to separate the fraction of the total signal due to the residual molecular background. Once that fraction is determined it can be subtracted from the measured signal leaving only the narrowband aerosol component. An energy monitor channel is used to provide the additional information required to determine the magnitude of the molecular correction. The energy monitor signal is proportional to the sum of the incident aerosol and molecular signal. This information can be used in combination with the edge channel measurements to separate the molecular and aerosol components of the atmospheric backscatter signal.

In Reference 1 we presented a detailed development of a procedure to utilize the two edge channel detector signals, I_1 and I_2, in conjunction with the energy monitor detector signal, I_{EM}, to determine the wind. An iterative procedure was presented that uses the measured signals to

1) determine the magnitude of the molecular contribution to the signal,
2) correct the measured signal for this molecular background leaving only the aerosol related component of the signal and
3) use the ratio of the corrected aerosol signals to determine the wind.

The iterative application of the above three steps is shown to accurately provide a unique solution for the Doppler shift using the aerosol backscatter even in regions of the atmosphere where the molecular backscatter is 10 times the aerosol backscatter.

In addition to the three measured signals, the procedure requires a knowledge of the etalon filter transmission functions and experimentally determined calibration terms that incorporate spectrally independent optical and electronic instrument information.

3. Experimental Description

The experimental details of the double edge lidar system are similar to the system used for the single edge measurements [8]. The lidar optical system is shown schematically in Figure 2. The experimental operating parameters are summarized in Table 1. The transmitter is a flashlamp pumped injection seeded Nd:YAG laser that produces 120 mJ pulses at 10 Hz at 1064 nm. The laser pulse length is 15 ns and the spectral width is 40 MHz. A small fraction of the outgoing laser energy is picked off and input into the receiver optical train to be used as a reference to provide the zero Doppler frequency in the wind measurement. The reference measurement is made for each shot and is also used to servo lock the etalon to the laser frequency in order to minimize the effects of frequency drifts of either the laser or the etalon. The remaining laser energy is transmitted coaxially with the telescope to a scan mirror that can be rotated in azimuth and elevation to direct the beam to different parts of the sky. The telescope and scan mirror have clear apertures of 40 cm. The atmospheric backscattered laser energy collected by the telescope is focused into multimode fiber optic and transferred to the receiver optics.

The receiver optics are a breadboard version of the double edge receiver utilizing various optical elements (collimating optics, beamsplitters, lenses, etc) available in our laboratory. Our primary interest in developing this breadboard version was to test two new technologies that are incorporated in the double edge system, namely the dual aperture Fabry Perot etalon edge filter and the photon counting Geiger mode avalanche photodiode detectors (APDs). The breadboard optical system is not optimized for optical throughput nor are the signal levels balanced and optimized for peak signal-to-noise. However, the principle features of the double edge receiver are incorporated and the performance, while not optimum, is representative of the measurement capability. An optimized receiver design has been developed that will correct for these deficiencies.

The output of the fiber is collimated and a fraction of the collimated light is split off with a 20% reflecting beamsplitter and sent to the energy monitor detector. The beamsplitter is oriented at 10 degrees incidence angle to minimize sensitivity to polarization state. The transmitted signal is split again between the two edge channels with a second beamsplitter that is also oriented at 10 degress incidence. The resulting two beams propagate in parallel through the dual aperture Fabry Perot etalon edge filter. The etalon is a plane parallel Fabry Perot with an air gap of 5 cm giving a free spectral range of 3 GHz. The etalon is capacitively stabilized [10] and piezo-electrically tunable to allow precise control of the etalon gap and plate parallelism. A small silica 'step' has been deposited over one half of the surface of one of the etalon plates prior to deposition of the reflective coating. This step introduces an offset in the etalon bandpass frequency equal to one fringe FWHM for that half of the etalon aperture. This produces the double edge configuration described above with the two edge filter bandpasses built into a single optical-mechanical structure. This design is conceptually similar to that employed by Chanin et al [3]. The filter bandwidth (FWHM) for each etalon is approximately 125 MHz including the effects of aperture broadening and laser linewidth. By design this is also the nominal separation between the center frequencies of the two filter bandpasses produced by the step. The frequency response functions for the two channels thus cross at their half maximum transmission points. The outgoing laser frequency is maintained at the crossover point using the outgoing laser frequency reference measurement as an input to an active stabilization loop. If the laser or etalon frequency drifts with time, the servo adjusts the etalon gap using the piezoelectric tuning elements to offset the drift. This servo loop compensates for long term frequency drift in the laser or etalon. This approach is relatively simple and has been successfully implemented in our previous systems [7,8]. The reference data can also used to remove pulse-to-pulse frequency jitter in the Doppler shift measurement.

The light transmitted by the etalon in each of the two channels is incident on a beamsplitter that splits the signal in each channel between a silicon APD operating in analog mode and a silicon APD operating in Geiger or photon counting mode[11]. The use of Geiger mode APDs are a second major modification to the previous receiver design. The single photon detection sensitivity allows the measurement to be extended to the free troposphere where the return signals are small. The analog detectors are used for the reference sample of the outgoing laser pulse signal for each shot. The analog signal could also used for wind measurements in the boundary layer where the aerosol signal returns are large as has been previously demonstrated [8]. The analog signals are sampled with high speed digitizers and the data are stored for each shot. The photon counting signals are sorted into range bins in a multichannel scalar and integrated for a selectable number of shots prior to storage. Typical integration times are 10 seconds (100 shots) to 100 seconds (1000 shots).

The backscattered signal from the photon counting APDs in the each of the three channels is shown as a function of altitude for a typical profile in Figure 3. These data were obtained with the lidar pointing vertically for a 1000 shot integration. The detectors are gated off for the first 12 μsec (equivalent to 1.8 km) following the laser firing to avoid saturation of the detectors. The detected photocounts are collected in temporal bins of 3 μsec length (equivalent to 450 m range resolution). The background has been subtracted in each of the channels and a deadtime correction has been applied using calibration data supplied by the manufacturer.

4. Calibration

Accurate instrument calibration information is required to perform the Doppler shift measurement. The calibration procedure used to determine this information is similar to that described previously in the single edge experiments[7,8]. The two etalon filter bandpasses are scanned simultaneously by stepping the etalon piezoelectric elements through approximately one half of the 3 GHz free spectral range. The detector signals for the two edge channels and the energy monitor channel are recorded at each etalon position along with the etalon position information. The responsivity of the analog and photon counting detectors varies by several orders of magnitude. This leads to a large disparity in the optimum signal level to be used for the different detector types. For best results the calibration procedure is performed separately for the analog and photon counting detectors.

For an incident laser intensity I_0 into the receiver the signal measured in the first edge channel is

$$I_1(\nu) = c_1 I_0 \tau_1(\nu) \tag{1}$$

where $\tau_1(\nu)$ is the unity peak normalized transmission function of etalon edge filter 1 and c_1 is a constant that is a function of the beamsplitter ratios, optical efficiency and detector responsivity of channel 1. Similarly the detected signal in edge filter channel 2 is

$$I_2(\nu) = c_2 I_0 \tau_2(\nu) \tag{2}$$

where $\tau_2(\nu)$ is the unity peak normalized transmission function of etalon edge filter 2 and c_2 is a constant that is a function of the beamsplitter ratios, optical efficiency and detector responsivity of channel 2. Finally the detected signal in the energy monitor channel is given by

$$I_{EM} = c_3 I_0 \tag{3}$$

where c_3 is a constant that is a function of the beamsplitter ratios, optical efficiency and detector responsivity of the energy monitor channel.

The normalized transmission, I_{Nx}, of the two etalon channels is obtained by taking the ratio of the each of the two edge detector signals with the energy monitor detector signal giving

$$I_{N1}(\nu) = \frac{I_1(\nu)}{I_{EM}} = \frac{c_1}{c_3}\tau_1(\nu) \tag{4}$$

and

$$I_{N2}(\nu) = \frac{I_2(\nu)}{I_{EM}} = \frac{c_2}{c_3}\tau_2(\nu) \tag{5}$$

Redefining the constant terms $\mathbf{C}_1=c_1/c_3$ and $\mathbf{C}_2=c_2/c_3$ and solving equations (4) and (5) for the peak normalized transmission τ yields,

$$\tau_1(\nu) = \frac{I_{N1}(\nu)}{\mathbf{C}_1} \tag{6}$$

and

$$\tau_2(\nu) = \frac{I_{N2}(\nu)}{\mathbf{C}_2} \tag{7}$$

We note that due to differences in beamsplitters, detector responsivities and optical efficiencies there may be different values of $\mathbf{C}_1$ and $\mathbf{C}_2$ for the analog and photon counting detection in each of the channels. However, the resulting etalon transmission curves should be independent of these terms that allows reference information from the analog channels to be used in the analysis of the photon counting data.

A calibration scan of the etalon transmission in each of the two channels is shown for the photon counting detectors in Figure 4. A nonlinear least squares fit of the data is also shown. A calibration scan such as this provides knowledge of the etalon transmission and spectral slope of the filter spectral bandpasses as well as the channel dependent calibration constants $\mathbf{C}_1$ and $\mathbf{C}_2$.

A final step in the calibration is to use the measured data to generate a function based on the ratio $\tau_1(\nu)/\tau_2(\nu)$ that can be used in the Doppler shift measurement. The natural log of the ratio of the measured etalon transmission curves shown in Figure 4 is plotted in Figure 5. It can be seen that in the region between the etalon peaks the curve is single valued i.e. each value of transmission ratio has a unique corresponding frequency. This curve is parameterized with a cubic spline and used in the data analysis procedure to evaluate the Doppler shift as will be described in the following section.

5. Data Analysis

The data collected in the three photon counting channels are averaged and stored as a function of range for a pre-selected number of shots. The stored data are analyzed to produce line-of-sight wind profiles following the procedure outlined previously in Section 2. Finally, multiple line-of-sight profiles taken at different scan angles can be combined to produce true horizontal wind speed and direction information.

The first step in the analysis is to take the measured photocounts in each of the channels and apply a deadtime correction that is determined from data supplied by the manufacturer. A baseline for the background counts, determined from data collected just prior to the firing of the laser Q-switch, is then subtracted from the three channels.

The signal incident on the edge channel detectors includes contributions from the aerosol backscattered laser signal, the molecular backscattered laser signal and background contributions from internal detector noise and solar background. Following the notation of Reference 1, the signal measured on the nth (n=1 or 2) edge detector channel can be written as

$$I_n = c_n[I_A \tau_n(\nu_n + \Delta\nu) + R_T f_n(\nu_n + \Delta\nu) + B_{opt}] + B_{elec} \tag{8}$$

where c_n is the optical calibration constant associated with the nth detector channel; I_A is the total aerosol backscattered signal; $\nu_n+\Delta\nu$ is the Doppler shifted frequency relative the center frequency of the nth filter; τ_n is the transmission of the nth edge filter for the aerosol signal, i.e. the unity peak normalized convolution of the laser spectrum and the filter function of the nth edge filter; R_T is the total molecular backscattered signal; f_n is the transmission of the nth edge filter for the molecular signal i.e. the convolution of the molecular backscattered spectrum, the laser spectrum and the filter function of the nth edge filter; B_{opt} is the optical (e.g. solar) background transmitted by the nth edge filter and B_{elec} represents the electrical background current associated with the nth channel detector and accompanying electronics. The background terms c_nB_{opt} and B_{elec} are assumed to be slowly varying and spectrally flat in the measurement region. Thus they are seen as nearly constant offset terms on each of the detectors. These values can be measured when the laser signal is not present and an appropriate background correction determined for each detector.

The two background corrected edge channel signals can be written in the form

$$I_1 = \mathbf{C}_1[c_3 I_A \tau_1(\nu_1 + \Delta\nu) + c_3 R_T f_1(\nu_1 + \Delta\nu)] \tag{9}$$

and

$$I_2 = \mathbf{C}_2[c_3 I_A \tau_2(-\nu_2 + \Delta\nu) + c_3 R_T f_2(-\nu_2 + \Delta\nu)] \tag{10}$$

where we note that the definitions of the measured calibration constants $\mathbf{C}_1=c_1/c_3$ and $\mathbf{C}_2=c_2/c_3$ are used.

The background corrected energy monitor signal can be written as

$$I_{EM} = c_3(I_A + R_T) \tag{11}$$

Solving Eq. 11 for the total molecular backscattered signal gives

$$c_3 R_T = I_{EM} - c_3 I_A \tag{12}$$

Equations (9), (10) and (11) may be used to determine the aerosol contribution c_3I_A, in terms of the measured signals, measured calibration constants and etalon transmission functions (see derivation of Eq. 12 in Ref 1).

$$c_3 I_A = \frac{\dfrac{I_1}{\mathbf{C}_1} + \dfrac{I_2}{\mathbf{C}_2} - c^* I_{EM}}{\tau_1(\nu_1 + \Delta\nu) + \tau_2(-\nu_2 + \Delta\nu) - c^*} \tag{13}$$

where $\tau_1(\nu_1+\Delta\nu)$ and $\tau_2(\nu_2-\Delta\nu)$ are the etalon transmission values for the two respective edge channels evaluated at the Doppler shifted laser frequency and

$$c^* = f_1(\nu_1 + \Delta\nu) + f_2(-\nu_2 + \Delta\nu)$$

Equations 12 and 13 represent the molecular and aerosol components of the incoming signal that are used in the first two steps of the iterative process: determination of the molecular contribution and subsequent application of the correction for the molecular background to Eqs. 9 and 10. Following the subtraction of the molecular terms, $c_3R_Tf_n(\nu+\Delta\nu)$, and taking the ratio of the corrected signals I_{1c} and I_{2c} gives

$$\frac{C_2 I_{1c}}{C_1 I_{2c}} = \frac{\tau_1(\nu_1 + \Delta\nu)}{\tau_2(-\nu_2 + \Delta\nu)} \tag{14}$$

Taking the natural log of this ratio and inputing it into the cubic spline function determined in the calibration procedure gives the value of the Doppler shifted frequency.

We note that τ_1 , τ_2 and c* are all functions of the Doppler shift. Initial values for these quantities are calculated assuming $\Delta\nu=0$. These zero Doppler values are used to determine an initial molecular correction. A Doppler shift is then determined from Eq. 14 using the molecular corrected aerosol signals and new values for τ_1 , τ_2 and c* are calculated. The process is repeated to convergence. Typically one or two iterations of the three step procedure are required for convergence.

6. Lidar Observations

The ground based wind lidar was operated from our laboratory at Goddard Space Flight Center (38:59:32N, 76:51:10W) during the summer of 1997 beginning in June. Wind data were collected in a variety of conditions including operation in day and night. Vector wind data are obtained by rotating the scan mirror to measure line-of-sight wind profiles for at least two azimuth angles. In the examples presented here the scan mirror is programmed to cycle between a vertical profile and two profiles taken at orthogonal azimuth angles for an elevation angle of 45 degrees. Profiles of the line-of-sight component of the wind are calculated for each of the directions using the double edge analysis procedure. Horizontal wind speed and direction are then calculated from the two 45 degree elevation line-of-sight profiles.

Figure 6 shows a vector plot of horizontal wind speed and direction for 8 lidar profiles taken beginning at 19:02 EDT on June 27, 1997. In this example the lidar data from the photon counting detectors are integrated for 1000 laser shots and 450 m range bins giving a vertical resolution of 320 m. The total time between each independent lidar profile for this case, including transit time for the scan mirror mechanism, is approximately 6 minutes. For comparison, the NWS rawinsonde wind data taken at 19:00 EDT at Dulles airport (38:57:00N , 77:26:20W) in Virginia, approximately 40 km away, are also shown.

An estimate of the instrumental precision can be obtained by averaging independent lidar profiles to get the mean and standard deviation of the wind speed and direction vs. altitude. Figure 7 shows the mean and standard deviation of the horizontal wind speed and direction obtained by averaging the 8 independent lidar profiles shown in Figure 6. Once again the 19:00 EDT Dulles rawinsonde upper air sounding is shown for comparison. The 1 σ standard deviation of the lidar speed averaged over altitudes from 3 to 7.5 km is 1.5 m/s with a minimum value of 0.61 m/s. The standard deviation includes variance due to atmospheric variability during the 48 min observation time in addition to the variance due to instrumental effects. As shown, the lidar data are in good agreement with the rawinsonde data.

A similar plot is shown Figure 8 for lidar wind data taken in the afternoon of June 26, 1997 beginning at 12:56 EDT. The mean and standard deviation of seven profiles of wind speed and direction taken over a period of 42 minutes is shown. In this case the lidar was operated during daytime and atmospheric conditions allow measurements to an altitude of 11 km. The Dulles rawinsonde from 7:00 EDT is shown for comparison. Once again good agreement is observed between the lidar and rawinsonde data.

7. Summary

A ground based direct detection Doppler lidar system using the double edge aerosol technique has been developed. The experimental design is presented along with a summary of the calibration and data analysis procedure used. The lidar has been used to obtain profiles of wind speed and direction in the free troposphere to altitudes as high as 12 km under a variety of conditions including both day and night time operation. The measurements demonstrate the ability of this approach to measure wind in the free troposphere where the molecular contribution to the backscattered signal is significant.

This experiment serves as a proof of principle demonstration of the aerosol double edge method. In addition, several new technologies have been incorporated that allow the range of the system to be extended into the free troposphere. These include the dual aperture capacitively stabilized Fabry Perot etalon used for the two edge filters and the single photon counting silicon APD's that allow greatly improved detection sensitivity. Many of the components from the lidar system described here will be mounted in a mobile van based Doppler lidar system to be completed in the spring of 2000. The capability of this system to operate in the field under a wide variety of conditions will allow a more complete validation of the double edge measurement technique and related technologies.

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Transmitter

Wavelength (nm) :	1064
Repetition rate (Hz) :	10
Energy per pulse (J) :	0.12
Pulse duration (ns) :	15
Divergence full angle (rad) :	1.5×10^{-3}
Laser bandwidth (MHz) :	40

Receiver

Telescope diameter (m) :	0.406
Field of view (rad) :	2×10^{-4}
Interference filter bandwidth (nm) :	5
APD quantum efficiency :	0.40 (analog mode) 0.035 (Geiger mode)

Fabry-Perot interferometer

Spectral width FWHM (MHz) :	125
Free Spectral Range (GHz) :	3
Clear Aperture (mm) :	45 (x2)
Acceptance angle (rad) :	1.5×10^{-3}

Table 1 - Instrument parameters for double edge lidar experiment.