S4-2 A double-edge Fabry-Perot filter based Rayleigh Lidar for simultaneous temperature and line-of-sight wind measurements

David A. Krueger and C. Y. She*
Physics Department, Colorado State University, Fort Collins, CO 80523

Abstract

It is well known that the difference between the two aerosol (Mie) and/or molecular (Rayleigh) scattering signals derived from a double-edge filter is sensitive to the Doppler shift of the scatterers, thus can be used for the measurement of line-of-sight wind. Rayleigh scattering is most effective in a region of the atmosphere where there is little or no aerosol. In this paper, we point out that in this case, the sum of the very same two signals is sensitive to the change in and can be used for the measurement of atmospheric temperatures. By processing both the normalized sum and difference of the two signals derived from a double-edge filter using a set of calibration curves derived from Rayleigh scattering theory, we proposed a double-edge Fabry-Perot filter based Rayleigh Lidar at 355 nm for simultaneous profiling of temperature and line-of-sight wind.

Introduction

It is well known that the frequency of backward scattered light from a moving scatterer is Doppler shifted from that of the incident laser beam by

$$\nu_D = 2\, V_R/\lambda \qquad (1)$$

where λ and V_R are respectively the laser wavelength and the scatterer's forward radial velocity. The first Doppler lidar proposed for global wind monitoring was based on heterodyne detection of scattered light. The coherent Doppler lidar has since been extensively studied both theoretically and experimentally[1]. A large mobile ground-based system has been built and considerable field data were collected demonstrating the feasibility as well as practical usefulness of lidar wind measurements[2]. Up to this point, most coherent Doppler lidars depend upon Mie scattering of aerosol for signal; its narrow bandwidth permits suppression of background noise by local oscillator leading to shot-noise limited detection.

Since the shot-noise-limited signal-to-noise for incoherent (direct) detection with same signal strength is in principle, a factor of $\sqrt{2}$ smaller than that of coherent detection, incoherent Doppler lidar was proposed[3] for wind sensing from an orbiting platform as well. In this case, Doppler signal may be enhanced by stronger scattering at shorter wavelength and by the use of a larger aperture free from atmospheric turbulence degradation. More recently, incoherent Doppler lidar via aerosol scattering for wind sensing has been successfully demonstrated[4], using an argon-ion laser and more recently a doubled Yag laser. These incoherent lidars, operating either in the Mie or in Rayleigh regimes, used a Fabry-Perot interferometer for frequency analysis with velocity resolution limited by the finesse of the interferometer. An alternate incoherent detection scheme recently proposed[5] and demonstrated[6] for wind measurements at 1.06 μm by setting the transmitting frequency at the edge of a Fabry-Perot interferometer (filter) to convert Doppler frequency shifts, ν_D, to changes in measured intensities. At high altitudes, in the stratosphere and mesosphere, signal bandwidth is broader due to higher wind speed making coherent detection less effective. Furthermore, since Doppler signal at these altitudes depends on Rayleigh scattering of air molecules, both shorter wavelength taking the advantage of λ^{-4} dependence and large receiver aperture are required to enhance the received signal. At long range, atmospheric turbulence, especially at shorter wavelengths, prevents coherent detection from being practical. Indeed, only incoherent Doppler lidars at 532 nm have been reported for wind measurements in the middle atmosphere[7,8]. extended the edge filter technique to what they termed the double-edge techniques, used earlier by Chanin's group at

---

*C. Y. She is currently on sabbatical leave at Radio Atmospheric Science Center, Kyoto University, Uji, Kyoto, 611, Japan; +81-774-38-3818, +81-774-31-8463(F), joeshe@kurasc.kyoto-u.ac.jp

532 nm[7,10], to Doppler-wind measurements at 355 nm. The use of 355 nm in a space- borne platform obviously gains signal advantages. This system for measuring line-of-sight winds has generated considerable interest for space applications, resulting in a number of simulations[11,12].

Signal from a set of double-edge Fabry-Perot interferometers

The returned backscattered Rayleigh (molecular) signal is Doppler-broadened. Its spectral width depends on atmospheric temperature, τ, and pressure, P, and its spectral center at ν_o is Doppler-shifted from the transmitting laser frequency ν_L by $2u/\lambda$, where λ is the wavelength of light and u is the line-of-sight wind velocity along the laser propagation direction, i.e., $\nu_o = \nu_L - 2u/\lambda$. The passband frequencies of the two interferometers, A and B, are centered respectively at ν_A and ν_B ($<\nu_A$) with the laser frequency, ν_L midway between them. The passband offset from the laser frequency in the unit of FWHM etalon resolution, $\Delta\nu$, is defined as $x = (\nu_L - \nu_B) / \Delta\nu = (\nu_A - \nu_L) / \Delta\nu$.

The transmission functions of the interferometers, A and B, are given as:

$$T_{A,B}(\nu) = (1 - \frac{L}{1-R})^2 \bullet [1 + (2F/\pi)^2 \sin^2(\pi \frac{\nu - \nu_{A,B}}{\Delta\nu_{FSR}})]^{-1} \tag{2}$$

where $\nu_{B,A} = \nu_L \pm \Delta m_o\, \Delta\nu_{FSR} = \nu_L \pm x\, \Delta\nu$ with plus sign for interferometer A. Our Eq.(1) here gives the dependence of Fabry-Perot transmission on per plate loss, plate reflectivity and effective finesse explicitly. The frequency spectrum of the received signal may be expressed as the correlation of transmission function, Eq. (1) and the returned signal spectrum of any symmetric functional shape[13] without restricting it to a Gaussian function as in earlier references[11,12]. This generalization is necessary because, strictly speaking, the backscatter Rayleigh spectrum is not a Gaussian function unless atmospheric pressure broadening is ignored or negligible.

The received signal count through each interferometer is given as:

$$N_{A,B}(\tau, P; u) = \rho N_0 \bullet \int R(\nu - \nu_0; \tau, P) T_{A,B}(\nu - \nu_{A,B}) d\nu \tag{3}$$

where, the integral may be regarded as the transmittance of the filter For Rayleigh signal, N_o and ρ are respectively the total signal counts delivered to the interferometers and the fraction delivered to each channel, $\rho \sim 0.5$. $R(\nu - \nu_0; \tau, P)$ is the normalized Rayleigh-Brillouin spectrum with $\nu_0 = \nu_L - 2u / \lambda$ and depends on atmospheric temperature and pressure. The normalized signal is the signal $N_{A,B}(\tau, P; u)$ divided by ρN_o, although we shall use the same notations, $N_{A,B}(\tau,P; u)$ for simplicity.

Simultaneous Determinations of temperature and line-of-sight wind

As pointed out that the difference and sum between the two normalized received signals, N_B and N_A, are, respectively, sensitive to line-of-sight wind, u, and temperature, τ. We thus form these two chosen combinations with $x = (\nu_L - \nu_B) / \Delta\nu$, and $\nu_0 = \nu_L - 2u / \lambda$:

$D(\nu_0, x) = (N_B - N_A)$ and $S(\nu_0, x) = (N_B + N_A)$ (4)

To project the anticipated value of measurement uncertainty, we need to know the measurement sensitivities, Σ_W and Σ_τ respectively for wind and temperature. Since we depend on two signals to determine the difference and sum signal, the measurement sensitivity, defined as the fractional signal change per unit velocity or temperature is thus twice that due to one signal. Respectively, they are:

$$\Sigma_W = 2[(\partial N_B / \partial u)/N_B] = \frac{4\int \frac{\partial R(\nu - \nu_0; \tau, P)}{\partial \nu_0} T(\nu - \nu_B) d\nu}{\lambda \int R(\nu - \nu_0; \tau, P) T(\nu - \nu_B) d\nu} \tag{5a}$$

$$\Sigma_\tau = 2[(\partial N_B / \partial \tau)/N_B] = \frac{4\int \frac{\partial R(\nu - \nu_0; \tau, P)}{\partial \tau} T(\nu - \nu_B) d\nu}{\lambda \int R(\nu - \nu_0; \tau, P) T(\nu - \nu_B) d\nu} \tag{5b}$$

Thus, the purpose of this paper is to evaluate the calibration curves for converting the combined normalized signals $D(\nu_0, x)$ and $S(\nu_0, x)$ to atmospheric quantities, τ and u, and to evaluate the associated measurement sensitivities, Σ_W and Σ_τ. Because the Rayleigh-Brillouin scattering function depends on pressure in addition to temperature and wind, we can only evaluate these quantities at a constant pressure. Since the fractional change in atmospheric pressure at a given altitude is much smaller than that of temperature and wind variations, we can use standard pressure for a given altitude to compute the calibration curves and associated measurement sensitivities. If pressure uncertainties can not be tolerated, we can always perform iteration to improve the pressure values along the profile.

For specificity, we evaluate the performance of the proposed lidar using a Fabry-Perot system described by McGill and Spinhirne[12] suited for molecular based scattering that was proposed and considered as practical for Doppler wind measurements at 355 nm. The parameters of this system were listed in Table 3 of their paper. For the purpose of measurement sensitivity analyses, we only need these system parameters: loss per plate, L = 0.002, plate reflectivity, R = 0.8, free spectral range, $\Delta\nu_{FSR}$ = 12 GHz, effective finesse, F_{eff} = 9.24, and the full spectral width at half maximum (FWHM), $\Delta\nu = \Delta\nu_{FSR} / F_{eff} = 1.3$ GHz. The effective finesse here, includes the loss of resolution due to less than unity plate reflectivity, etalon defect, laser linewidth and finite etalon aperture[11,12]. The passband offset (in etalon FWHM), $x = (\nu_L - \nu_B) / \Delta\nu$, was chosen[12] to be 1.875; in terms of free spectral range, the passband offset would be $\Delta m_o = (\nu_L - \nu_B) / \Delta\nu_{FSR} = 0.203$. This x value is chosen so that the system has comparable wind measurement sensitivities for aerosol and molecular based scattering, as deemed practical. Using these parameters, the sample measurement calibration curves and sensitivities are shown in Fig. 1 and Fig. 2 respectively. The solid calibration curves in Fig. 1 use the Rayleigh/Brillouin scattering function appropriate for values of velocities of (-25, 0, and 25 m/sec) and values of pressures and temperatures of (0 km, 1000 mb, 288 K), (5 km, 540 mb, 255 K) and (10 km, 265 mb, 223 K) as given by the 1976 US Standard Atmosphere. The dashed calibration curves in Fig. 1 use a Gaussian scattering function appropriate for 288 K, 255 K and 223 K and essentially zero pressure. The nearly horizontal lines are for constant velocity and the nearly vertical lines are for constant temperature. Consider signals from 5 km altitude that give experimental values of (NB - NA) and (NB + NA) corresponding to point A in the figure. This will give values of (T,u) of (274 K, 25 m/sec) if one assumes that the Gaussian lineshape is adequate but values of (255 K, 22.5 m/sec) if one uses the Rayleigh/Brillouin lineshape. Thus using the correct lineshape can be very important. If one measures signals from much higher altitudes where the pressure is much lower, then the difference between the Rayleigh/Brillouin and Gaussian lineshapes can be neglected. The parameters used by Flesia and Korb[9] are similar: $\Delta\nu_{FSR}$ = 12 GHz, F_{eff} = 7.71, and x = 1.67, giving the etalon offset from laser frequency of 2.6 GHz instead of 2.4 GHz used by McGill and Spinhirne.

Conclusion and Discussion

Using the received photocount difference and sum of the lidar returns passing through the two interferometers with symmetrical passband offsets as signal, we proposed simultaneous temperature and line-of-sight wind measurements based on Rayleigh scattering. The measurement sensitivities for this system degined for wind measurements are nominally 0.75%/(m/s) for wind and 0.25%/K for temperature. Same photocounts for a 1 m/s wind measurements gives a 3 K temperature measurements using the proposed scheme. Therefore, since the wind measurement sensitivity is the same as the systems already considered[9,12], we suggest that the double-edge molecular technique proposed for space wind measurements can yield temperature information as well, if the aerosol scattering is negligible and the retrieval method with the calibration curves presented here is followed.

Acknowledgement: Discussions with Sam Lin of Naval Research Laboratory and partial support from the Integrated Program Office are acknowledged.

References

1. R. M. Huffaker (ed.), *Feasibility study of satellite-borne lidar global wind monitoring system*, NOAA Tech. Memo. REL WPL-37, Washington DC, 1978.

2. M. J. Post and R. E. Cupp, Optimizing a pulsed Doppler lidar, *Appl. Opt.* , 29, 4145 , 1990.

3. V.J. Abreu, Wind measurement from an orbit platform using a lidar system with incoherent detection: an analysis, *Appl. Opt.* 18, p. 2992, 1979.

4. V.J. Abreu, et.al, Observations of winds with an incoherent lidar detector, *Appl. Opt*, 31, 4509, 1992.

5. C. L. Korb, B. M. Gentry, and C. Y. Weng, Edge technique: theory and application to the lidar measurement of atmospherioc wind, *Appl. Opt.* 31, pp. 4202-4213, 1992.

6. Korb, C.L. , B.M. Gentry and Steven X. Li, "Edge Technique Wind Measurements with High Vertical Resolution", *Appl. Opt.*, 36,5976-5983, (1997).

7. M.L. Chanin, et.al., A Doppler lidar for measuring winds in the middle atmosphere, *Geophysical Research Letters,* 16, 1273-1276, 1989.

8. C.A. Tepley, et.al, The Doppler Rayleigh lidar system at Arecibo, *IEEE Trans. Geosci. Remote sens.*, 31, 36, 1993.

9. C. Flesia and C. L. Korb, "Theory of the double-edge molecular technique for Doppler lidar wind measurement", *Appl. Opt.*, **38**, 432-440 (1999).

10. A. Garnier, and M. L. Chanin, Description of a Doppler Rayleigh lidar for measuring winds in the middle atmosphere, *Appl. Phys. B*, **55**, 35-40, 1992.

11. J. A. McKay, Modeling of direct detection Doppler wind lidar, I. The edge technique, *Appl. Opt.*, **37**, 6480-6486, 1998.

12. M. J. McGill, and J. D. Spinhirne, Comparison of two direct-detection Doppler lidar techniques, *Opt. Eng.*, 37, 2675-2686 (1998).

13. D. A. Krueger, L.M. Caldwell, R. J. Alvarez III and C. Y. She, Self-consistent method for determining vertical profiles of aerosol and atmospheric properties using a high spectral resolution Rayleigh-Mie lidar, *J. Atm. Oceanic Tech.*, 534-545 (1993).

Fig. 1