A Comparison of Anemometer- and Lidar-Sensed Wind Velocity Data

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ABSTRACT

Comparisons between measurements of a wind component by a Doppler lidar and by a conventional anemometer are presented. The two measurement techniques provided thirteen 15 min data sets which agreed within 0.04 m s^{-1} on the average. The maximum difference was 0.12 m s^{-1}, which constitutes less than 3% discrepancy, referred to the period average. The results conclusively demonstrate the ability of Doppler lidar to measure winds with a high degree of velocity resolution and accuracy.

1. Introduction

This report presents the results of an experiment to compare wind measurements obtained from a continuous-wave CO_2 Doppler lidar and from a conventional anemometer. The ability of various types of remote probes to measure winds, particularly within the atmospheric boundary layer, has been frequently demonstrated in recent years. A comprehensive summary, with extensive references, has been given by Little (1972). Two very attractive features of remote probes are their abilities to measure atmospheric parameters without disturbing the flow as *in situ* sensors do and to scan through large volumes of the atmosphere as *in situ* sensors cannot. It is essential, however, that the accuracy and the velocity resolution of a remote probe be assured by comprehensive testing; it is intended that the results presented here provide an example of such a test by comparison. Another test between a CO_2 Doppler lidar and an anemometer, from a different point of view and at shorter range, has been presented by Lawrence *et al.* (1972).

2. Sensor description

The continuous-wave CO_2 Doppler lidar has a transmitted power level of 3 W, a beam diameter when focused at 150 m of 3 cm, and a wavelength of 10.59 μm. The coaxial lidar receiver mixes backscattered energy from atmospheric aerosols within the probing volume with a small fraction of the transmitted energy. The Doppler frequency shift of the backscattered energy is related to the wind component along the laser beam axis by the relationship

$$\Delta f = 2V/\lambda, \quad (1)$$

where Δf is the Doppler-frequency shift, λ the wavelength and V the wind component along the beam. In actual practice, the backscattered energy is from a volume of the atmosphere within which a random set of velocity values exist. As a result, the returned energy is not found at a single Doppler frequency shift, but is spread over a finite frequency band. It is necessary, therefore, to process the signal return in some manner to obtain a meaningful estimate of Δf for the sample volume selected. In our case the frequency spectra of Δf are obtained every 0.6 s with an electronic spectrum analyzer. The output of the analyzer is then fed to an eductor with a 5 s time constant. The analog output of the eductor, updated every 0.6 s, is then recorded on magnetic tape for off-line processing. The "estimate" of Δf required for Eq. (1) is obtained from the first moment of Doppler spectrum, and these first moments are then averaged over the time interval desired for an averaged value of V. Although not utilized in this study, the total backscattered intensity (zeroth moment) and frequency spread (second moment) are available as well.

The anemometers used were a prop-vane (R. M. Young Model 8002) and a three-axis propeller anemometer (R. M. Young Model 27002). The prop-vane was used to measure the horizontal wind components; the propeller anemometer, the vertical wind component. The prop-vane was mounted on a tower at a height of 31 m; the propeller anemometer at 38 m. Calibration of the anemometers was provided by the manufacturer.

3. Experimental procedures

The laser was located west of the tower with a beam elevation angle of 10.9° and oriented along an azimuth of 101°. The sampling volume was at a slant range of 147 m. This positioned the sampling volume 1 m below the prop-vane. The sampling volume was roughly a cylinder, 20 m long and 3 cm in diameter, centered beneath the prop-vane.

TABLE 1. Statistical results of lidar-anemometer comparisons.

Run no.	Correlation coefficient (1 min)	Averaging period (MDT)	Tower component (m s^{-1})	Doppler component (m s^{-1})
14	—*	1023–1038	3.13	3.19
15	0.972	1340–1353	4.32	4.34
		1353–1407	4.52	4.64
16	0.960	1432–1454	5.00	5.01
18	0.987	0702–0721	1.12	1.14
19	0.994	0745–0801	0.92	0.98
		0801–0816	0.75	0.77
		0816–0830	0.29	0.33
20	0.978	0844–0859	0.45	0.50
		0859–0914	0.62	0.63
		0914–0934	1.18	1.24
22	—*	1335–1350	0.35	0.38
		1350–1405	0.55	0.56

* Only 15 min averages of anemometer data were available.

The *in situ* anemometers were sampled once a second by a computer-controlled data acquisition system (Kaimal *et al.*, 1966) and 1 min averages of the three wind components were computed and listed in real time. The laser data were recorded every 0.6 s and processed later to obtain corresponding 1 min averages by computing the first moment of the 1 min averaged spectra. The anemometer data were used to compute 1 min averaged components along the lidar line of sight. Data for 168 min were obtained over a range of average wind speeds from roughly 0.3 to 5.0 m s^{-1}. Weather conditions ranged from clear skies to moderate snowfall, with mildly convective, nonshear situations predominant.

The 1 min averages were used to obtain correlation coefficients as one statistical measure of the agreement between the two data sets. Average values of the wind components over periods ranging from 12 to 20 min were also computed for direct comparison of absolute mean values.

4. Results

A summary of the results is given in Table 1. The correlation coefficients over runs of ~15 min range from 0.96 to 0.99. The average correlation coefficient is 0.979. The mean values for the 13 periods show differences between lidar and anemometer values ranging from 0.01 to 0.12 m s^{-1}. The overall mean difference between lidar and anemometer values is 0.04 m s^{-1}.

A time-sequence plot of the data for Runs 15 and 16 (Fig. 1) shows how well the two data sets track each other.

From Fig. 1 we note that, under changing wind conditions, the lidar data generally show higher and lower values than the anemometer values. This result was generally true for the entire data set. This is an expected feature of the comparison since the laser is not limited in its response to turbulent fluctuations in the wind whereas the anemometers are.

On the other hand, the comparison of the average values shown in Table 1 is mildly surprising in that the laser values are consistently higher than the anemometer values. In general, one expects the anemometers to overestimate the mean wind speeds in turbulent conditions (Izumi and Barad, 1970).

Nevertheless, the overall conclusion must be that the agreement is excellent and that one may therefore use the laser for atmospheric wind speed measurements with great confidence. There are only two significant practical limitations to the Doppler lidar as a remote sensor. One is that it depends on natural aerosols for the scattered return. In perfectly clear air, no return is obtained. It is estimated (Post and Schwiesow, 1976) that an aerosol concentration of roughly 5000 m^{-3} for particles of radius 2 μm or larger is sufficient to give adequate signal return for this apparatus to make Doppler laser wind measurements to a range of 150 to 200 m. This is an aerosol concentration typical of a clear day in rural areas with visibilities in excess of 50 km. This limitation may be reduced significantly with an improved spectrum analyzer.

The other limitation is a range limitation. Because the length of the volume resolved by the focused lidar beam increases as the square of the range, the practical resolved range of this lidar is limited to roughly 500 m. And, of course, heavy snowfall, rain or dense fog will limit the range of the device because of attenuation from scattering and absorption effects.

However, these limitations do not affect the potential of the device for a number of significant atmospheric studies. Tower-induced turbulence is an ever-present problem with *in situ*, tower-mounted probes

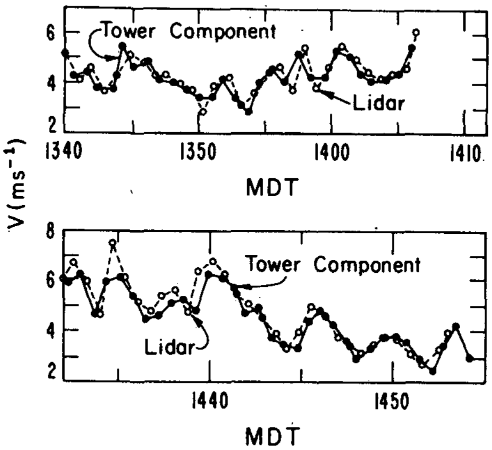

FIG. 1. Runs 15 and 16 of lidar-anemometer comparisons on 27 February 1976. Lidar and anemometer data points occur at different times because of time offsets between the separate data processing procedures.

(Angell and Bernstein, 1976). Absolute calibration of conventional anemometers for measurement of a turbulent wind field is an inexact science at best (MacCready, 1966). It is therefore desirable to exploit remote sensing techniques as much as possible.

The lidar used in this study is limited at the moment in that it measures only the line-of-sight wind component. However, this limitation may be eliminated by operating the laser in a VAD (Velocity-Azimuth-Display) mode or by adopting a coherent differential Doppler mode (Schwiesow *et al.*, 1977).

Work is underway to permit real-time processing of the laser wind data and to introduce various electronic modifications to improve the signal-to-noise ratio of the device. On the basis of the results reported here, we are planning to use the lidar to measure vertical wind speeds over a depth of 300 m at the Boulder Atmospheric Observatory, a new research facility of the Wave Propagation Laboratory (Hall, 1977). We believe that the laser is an excellent device to measure vertical wind speeds with an accuracy impossible to achieve with *in situ* instruments mounted on a tower.

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