Remote Measurements of Boundary-Layer Wind Profiles Using a CW Doppler Lidar

F. KÖPP, R. L. SCHWIESOW[1] AND CH. WERNER

Institute for Optoelectronics, DFVLR Oberpfaffenhofen, D-8031 Wessling/Obb., Federal Republic of Germany

(Manuscript received 26 April 1983, in final form 14 September 1983)

ABSTRACT

We have demonstrated practical measurement of profiles of horizontal wind magnitude and direction to altitudes of 750 m by making radial velocity measurements with a Doppler lidar using conical scanning. Comparison with surface anemometers and with profiles measured by balloon sondes allows one to evaluate the consistency between lidar measurements and more conventional sensors. Overall we find a correlation coefficient of 0.83 and an rms difference of 1.3 m s^{-1} for magnitude and a correlation coefficient of 0.91 and an rms difference of 12° for direction when the lidar and sonde profiles are compared. The differences are not a result of lidar errors because comparisons of 20 s averages between the lidar and a sonic anemometer show a correlation coefficient of 0.98, an rms difference of 0.19 m s^{-1}, and a long-term average difference of 0.05 m s^{-1} for a single component. Profile differences are attributable to horizontal inhomogeneity in the wind field and uncertainty inherent in balloon sondes. Impaired visibility reduces the effective range of the lidar, and the vertical extent of the lidar sample region increases with height.

1. Background and application

Before any new sensor technique, particularly a remote sensing technique, can be used with confidence, it must be tested against more standard sensors. Continuous wave (CW) Doppler lidars operating at 10.6 μm have been compared with tower-mounted cup anemometers in previous studies (Hughes *et al.*, 1972; Lawrence *et al.*, 1972; Post *et al.*, 1978) and with a 3-axis propeller anemometer (Kennedy and Bilbro, 1979), but these studies measured only a single component of the wind rather than magnitude and direction, they did not measure profiles, and they present no data above 31 m altitude. Teoste and Capes (1978) provide a single profile from a pulsed Doppler lidar together with two radiosonde magnitude profiles to 8 km, but these authors make no quantitative comparisons between the profiles.

Our experiment was designed to test the ability of a CW Doppler lidar to measure the horizontal wind (both components) and the wind profile under a variety of conditions by comparing the lidar results with conventional balloon-sonde profiles to 750 m altitudes. Thus our study goes beyond previous work in considering two components and profiles and in making quantitative comparisons. In addition, we compare the radial component measured by a fixed lidar with the same component measured by a closely-located sonic anemometer to provide an additional check of the fundamental accuracy of the lidar.

Such an experiment on Doppler-lidar profiles is important because many applications in boundary-layer research, pollution monitoring, transportation, ballistics, and other fields require wind profile information. As a special case, the profile of the wind component transverse to a chosen direction can be derived from wind magnitude and direction. Other approaches to remote measurement of boundary-layer wind profiles using pulsed lidar and radar have been tested. After a discussion of the results of our experiment we compare the CW Doppler lidar profile method with other techniques.

2. Experiment

a. Site and conditions

We made measurements between mid-September and mid-November 1982 in a region of flat terrain in northern Germany near Meppen. In the immediate neighborhood of the lidar the site is mostly meadow with grass ~ 20 cm high, but the meadow is surrounded by trees 12 to 15 m high at a distance of 500 m, and a hedgerow of the same height extends NE from the lidar starting 30 m away. The two-story balloon-launch building is located approximately 200 m SW of the lidar site. Although the trees introduce turbulence, the site is basically simple terrain.

The lidar was able to measure profiles in conditions characterized by visual ranges from 40 km to approximately 100 m. Obstructions to vision included fog at short ranges, and rain and haze at intermediate visual ranges.

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[1] On leave from NOAA/ERL/WPL, Boulder, CO 80303.

b. *Instrumentation*

The lidar that we used is similar to other CW lidars operating at 10.6 μm wavelength that have been described by other authors (Hughes *et al.*, 1972; Lawrence *et al.*, 1972; Brown *et al.*, 1978; Vaughan, 1979; Schwiesow *et al.*, 1981; Schwiesow and Lawrence, 1982). Our system uses a 30 cm transceiver aperture diameter and a two-mirror scanning system. Table 1 gives further details on the system and Köpp (1982) describes the instrument.

We used a surface-acoustic-wave, dispersive-delay-line spectrum analyzer (Alldritt *et al.*, 1978) to process the Doppler-shifted data. Velocity estimates from the homodyne spectrum are made by a peak finder, which produces a voltage output proportional to the velocity at the peak of the velocity spectrum. For the data reported here, the response time of the velocity readout was slightly slower than 50 ms. This form of analysis has three characteristics that are important to remember when interpreting the data. First, a homodyne system cannot determine the sign (plus or minus) of the radial velocity. Second, the velocity estimates have a threshold (approximately 1 m s^{-1} for our system) that comes from preventing the peak finder from locking onto the strong 0-frequency spectral spike. Finally, the velocity at the peak of the spectrum may not be a good estimate of the mean velocity (first moment of the spectrum) whenever the spectrum is not symmetric about the peak or is multipeaked. With a CW transmitter and the spectrum analyzer we used, there is no Nyquist limit on the velocity, but the analyzer bandpass limits the radial velocity measurement to ±32 m s^{-1}.

Staff from the Meppen Proving Ground of the Deutsche Bundeswehr provided balloon-sonde data in standard format. Balloons were tracked by radar. For the sonic-anemometer comparisons we used a Kaijo Denki model DAT-310 sensor aligned with the x-axis of the sonic within 4° of the line of sight of the lidar (radial component).

c. *Scanning and analysis*

We used a conical scan pattern, also called the velocity azimuth display (VAD) method, to retrieve mean horizontal wind magnitude and direction from radial velocity data around horizontal circles centered along the vertical of the lidar scanner (Lhermitte and Atlas, 1961; Waldteufel and Corbin, 1979). The range setting to the sample volume and the lidar elevation angle were varied to position the center of the lidar sample volume at the desired altitude. Geometric parameters for the scan are shown in Table 2. The ranges at low altitudes were chosen to place part of the lidar scan over surface-mounted cup anemometers. Elevation angles for higher altitudes were chosen for ease in changing altitudes. We prefer to use as low an elevation angle as practical for any given altitude in order to maximize the radial velocity component and minimize uncertainty caused by turbulence, but the practical limit of 1 km on range required a large elevation angle at the highest measurement altitude. We did not study the effect of changing elevation angle at a given altitude, but Teoste and Capes (1978) give some data on varying elevation angles. The vertical extent of the altitude region sensed is dependent upon the length of the lidar sampling volume (determined by the telescope optics) and the elevation angle. It is defined as the −3 dB points on the curve of lidar sensitivity versus range. Altitudes at 100, 350 and 750 m correspond to the center of height intervals for which sonde data were regularly taken.

TABLE 1. Doppler lidar system parameters.

CO_2 laser output power	3.5 W
Transceiver telescope	
aperture	30 cm
focal length	90 cm
Detector (lead tin telluride) area	0.25 mm^2
detectivity	5.7×10^{10} cm(Hz)$^{1/2}$ W^{-1}
Spectrum analyzer	
frequency resolution	30 kHz
velocity resolution	0.2 m s^{-1}
Range resolution at 100 m range	~10 m

Figure 1 shows an example of radial-velocity versus azimuth data for a four-revolution VAD scan. The six traces correspond to the six altitudes in Table 2. The effects of the threshold, direction ambiguity, fluctuations resulting from turbulence, and peak asymmetry can be seen in Fig. 1, especially on the data from lower altitudes.

To produce such data we used a fixed azimuth-scan rate of 30° s^{-1} for each elevation angle. The voltage of the peak finder as a function of time (azimuth) is transferred to a transient digitizer (Biomation 802), which stores the variation of the radial velocity for further processing and recording by a microcomputer system. A hybrid BASIC and assembly-language program processes the velocity versus azimuth data to find the maximum value and azimuth of the peak of the smoothed data. The velocity variation with azimuth is approximately a rectified sine function. The average of the maximum values of the radial component is multiplied by the reciprocal of the cosine of the elevation angle to estimate horizontal wind speed. For details of the method see Lhermitte and Atlas (1961), Browning and Wexler (1968) or Waldteufel and Corbin (1979). The 180° directional ambiguity is removed by choosing the direction closer to the direction of the next lower level, and the surface wind measured by a cup anemometer and fed directly to the microcomputer system is used to resolve ambiguity at the lowest VAD level. An offset local oscillator (Schwiesow and Cupp, 1981) will be used later to eliminate the ambiguity.

TABLE 2. Scan parameters.

Altitude (m)	Extent (m)	Range (m)	Elevation (°)
20	18–22	200	5.75
50	45–55	200	14.5
100	91–111	200	30.0
200	165–245	400	30.0
350	240–495	700	30.0
750	418–1180	1000	49.5

3. Results

a. Comparison with sonde

Figure 2 compares two lidar wind profiles with a radiosonde profile. As expected from the vertical extent of the lidar sample volume, the lidar-derived profiles do not show sharp vertical gradients. Overall, the agreement in wind magnitude and direction between the two different measuring techniques is satisfactory in a qualitative way.

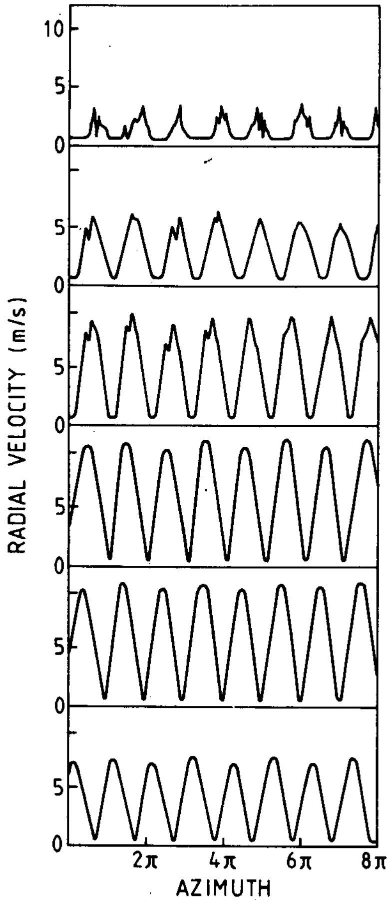

FIG. 1. Absolute value of the radial velocity versus azimuth for a four-revolution VAD scan, taken at altitudes centered at (from top to bottom) 20, 50, 100, 200, 350 and 700 m.

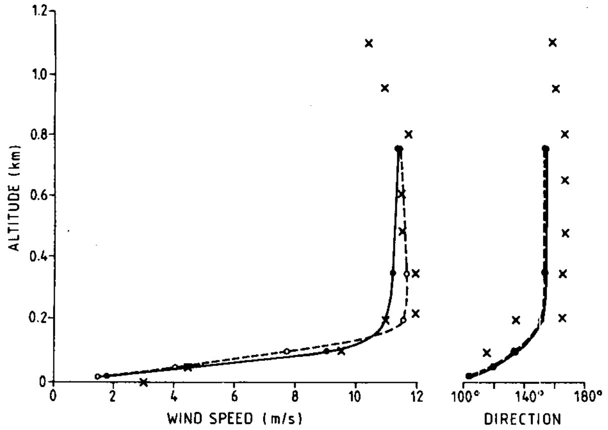

FIG. 2. One example of a comparison between Doppler-lidar- and balloon-sonde-derived wind profiles. The open circles connected by lines show VAD wind values over the time 2108 to 2129 MEZ (solid) and 2137 to 2156 MEZ (dashed), where the Xs are from the 2100 MEZ radiosonde.

Table 2 emphasizes that the lidar wind values are height-averaged measurements assigned to the height at the midpoint of the altitude range. Radiosonde winds are generally layer averages except when a significant shear exists and extra values are reported, as in Fig. 2. In quantitative comparisons, we have averaged radiosonde winds over height ranges similar to the lidar averaging interval. Exact correspondence in height averaging intervals is not possible because of the discrete radiosonde data set.

More quantitative comparisons are given in Fig. 3, where the diagonal lines indicate perfect identity between results from the two methods rather than a best fit to the data. The uncertainty or error in each data point can be considered to be the distance from the comparison point to the line. Since the ideal value of the point-to-line distance is 0, we can compute a squared difference (the distance squared), and from that an estimate of the rms difference of the distribution about the line. Similarly, a correlation coefficient between the two sets of data can be obtained by considering the sample differences about the mean. These properties of the lidar-sonde comparison are summarized in Table 3. The altitudes for the comparison are chosen to correspond approximately to the standard reporting heights for the radiosonde data. As expected, the rms differences decrease slightly with a larger number of points, and correlations also decrease because average values for smaller subsets of the data can fit a given subset better than the overall average fits it. There are only a few points at the lowest height because it was difficult to obtain radiosonde data soon after launch.

In interpreting the data it is important to note that the rms differences do not necessarily represent a measurement technique error, which is discussed more

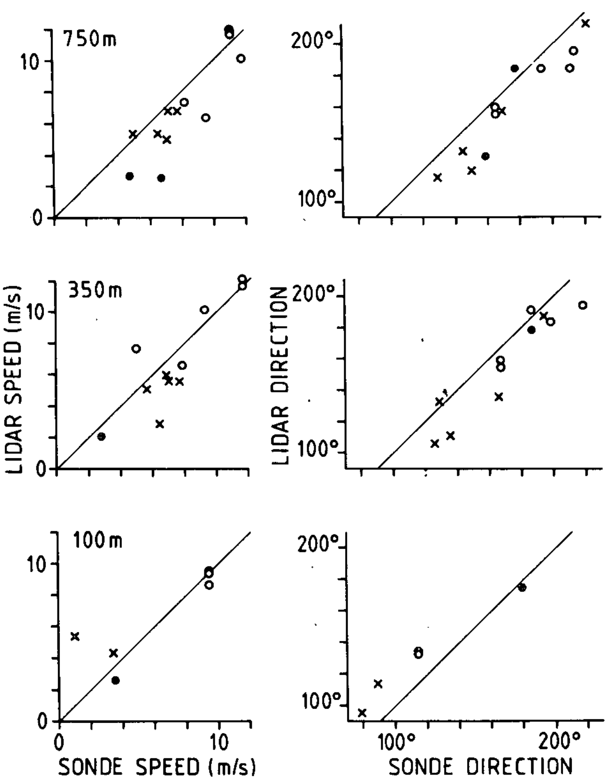

FIG. 3. Overall results of lidar-sonde comparisons under clear conditions (visibility > 10 km, open circles), moderately clear conditions (visibility between 1 and 10 km, crosses), and fog (visibility approximately 100 m, filled circles). The comparisons were made at altitudes of 100, 350 and 750 m above the surface.

fully in Section 3c. The correlation coefficient depends on the probability distribution of the data about the mean. In the case of an improper distribution, the correlation coefficient can underestimate the dependence between the two measurement methods.

The rms differences between winds measured by sonde and by lidar are not unreasonably large in light of the wide differences between the techniques and the fact that the sonde data were not smoothed in altitude dependence. For example, the lidar uses tracers of 2 to 4 μm diameter for the wind field, but the sonde tracer is approximately 2 m in diameter. Lidar velocities are determined from a Doppler shift whereas sonde velocities are determined from changes in the balloon range. The lidar sensing volume is centered over the scanner on the average, but the balloon drifts with the wind so that the two techniques measure different regions of the atmosphere that may have different wind values. In addition, it was not possible to take both lidar and sonde profiles completely simultaneously because of the time (approximately 20 min) required to scan the profile with the data transfer system used for most of the experiment. For the last part of the experiment, an improved transfer system allowed a profile to be measured in approximately 5 min.

b. *Effect of atmospheric conditions*

Data in Fig. 3 are coded into three classes of visual range. There is no significant, systematic difference between lidar and sonde data except at higher altitudes under low-visibility conditions. Here the lidar makes a consistent underestimate of the velocity. The reason for the underestimate is that under low-visibility conditions (e.g., 100 m visual range determined by a visible-wavelength transmissometer) the velocity data at a 1000 m range setting are dominated by returns from scatterers at ranges less than the range setting. In general, these lower-elevation scatterers move with velocities less than those of tracers in a higher part of the focal volume because the magnitude of the wind usually increases with height.

From the data in Fig. 3 we see that for visual ranges greater than 1 km a Doppler lidar of the type used in this experiment can measure wind profiles to altitudes of 750 m. At 100 m visual range in fog the profile capability extends to only a few hundred meters altitude, but more sophisticated processing of the velocity spectra should extend this limit.

c. *Verification by sonic anemometer*

In order to determine if the rms differences in Table 3 were caused by instrumental inaccuracy or by inhomogeneities in the wind field, we compared the output of the laser Doppler anemometer peak finder with the lidar at a fixed azimuth and elevation to the same radial wind component measured by a standard sonic anemometer at a range of 200 m from the lidar scanner. For that comparison, the lidar was pointing in a fixed direction. The sonic anemometer was located within 0.5 m horizontally of the center of the lidar sample volume with the sonic's x-axis aligned within 4° of the lidar axis. Both the sonic anemometer and the lidar sample volume were 4 m above the surface. The fluctuating wind values from each instrument were averaged for 20 s periods to produce three velocity values per minute.

Figure 4 shows a comparison of the wind values for 48 min of data taken on two different days. The statistical features of the comparison are given in Table 4, which also shows the results of a comparison of 1

TABLE 3. Lidar-sonde comparison.

	Magnitude		Direction	
Altitude (m)	rms difference ($\mathrm{m\ s^{-1}}$)	Correlation	rms difference (deg)	Correlation
100	1.5	0.87	14	0.98
350	1.2	0.87	13	0.93
750	1.4	0.88	13	0.94
all	1.3	0.83	12	0.91

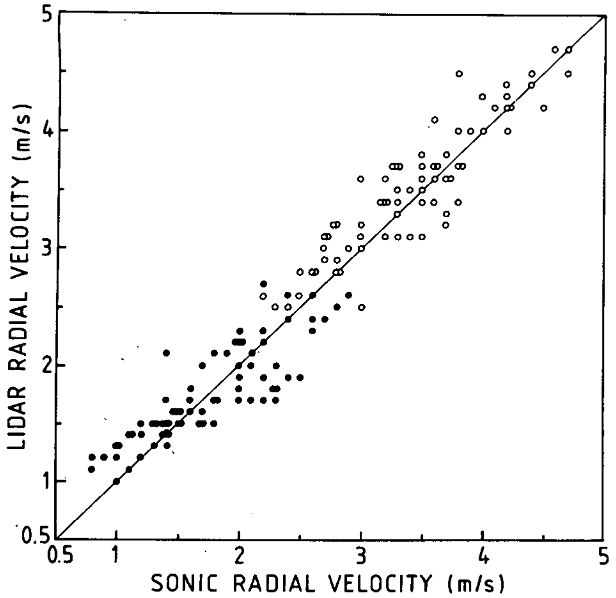

FIG. 4. A comparison of the radial velocity component measured by a sonic anemometer and the laser-Doppler anemometer. The data points from 1 November 1982 (open circles) and 2 November 1982 (filled circles) represent 20 s^{-1} averages. The data show an rms difference of 0.19 m s^{-1} from a perfect fit (identity) line and a correlation coefficient of 0.97.

min averages. The results show that the two independent methods of wind measurement agree closely despite the inherent differences between a remote, volume-averaged measurement and a point measurement. The radial extent of the laser-Doppler sample volume was approximately 40 m, compared to 20 cm for the sonic, so that some turbulent eddies that are sensed by the lidar may not appear in the sonic sensing volume, and smaller eddies that are measured at the sonic anemometer may not be large enough to influence the entire lidar sensing volume enough to affect the volume-averaged velocity value. An additional difference is that the lidar sensing volume was offset 0.5 m in the crosswind direction from the sonic to avoid optical interference from the sonic supporting structure.

We used a sonic anemometer rather than a cup because Doppler-lidar and cup-anemometer comparisons had already been done satisfactorily and because we were interested in measuring the rms differences between 20 and 60 s mean values rather than just long-term average differences.

The correlation coefficients and difference of average velocities are similar to comparisons between a CW Doppler lidar and a cup anemometer by Post *et al.* (1978). The difference of 0.05 m s^{-1} between the 48 min data averages provides an upper limit on the systematic error in the Doppler-lidar velocity estimates, and the rms difference of 0.19 m s^{-1} is an estimate of the typical difference between a point and a volume-averaged wind measurement of 20 s averages in daytime boundary-layer wind fields.

d. Measurement uncertainty

In the lidar, the basic uncertainty in measurement of the radial wind component is the uncertainty in the wavelength of the P-20 transition of CO_2 and in the speed of light. These uncertainties are negligibly small, so the Doppler lidar can be considered an inherently self-calibrated instrument. In practice, nonlinearities in the spectrum analyzer introduce an uncertainty of approximately 2%. When the velocity spectrum is not symmetric about its peak, then the peak finder will not provide a correct estimate of the mean velocity in the sample volume. This uncertainty is difficult to determine objectively because it varies, depending on atmospheric condition, and because we are not yet able to record the full velocity spectrum at the data rates provided by the surface-acoustic-wave spectrum analyzer (Alldritt *et al.*, 1978). From photographs of the spectrum we estimate this uncertainty at ±0.4 m s^{-1} for an instantaneous velocity value, but it rapidly averages to zero. In a 20 s average the peak-finder uncertainty is less than ±0.1 m s^{-1}, and it is still less in the estimate of wind magnitude from a VAD scan except in the case of a clear atmosphere with a cloud deck below 1 km, in which case the spectrum is multipeaked and asymmetric.

There are a number of uncertainties inherent in using a VAD method to extract mean wind speed and direction. Departures of the wind field from horizontal homogeneity, including deformation and nonlinear effects, cause possible errors that we cannot quantify from the data. Browning and Wexler (1968) and Rabin and Zrnić (1980) discuss these effects as applied on a larger scale to radar. Deformation should be relatively less important compared to horizontal inhomogeneity on the scale of a few hundred meters than it is on the radar scale of a few kilometers. The use of VAD analysis with lidar implies that the wind values are averaged over a horizontal distance at least equal to the diameter of the scan circle. The effects of horizontal inhomogeneity on the accuracy of Doppler-lidar wind estimates from VAD scans is an active area of research.

For a comparison study, we take the reference sondes and sonic anemometer as given standards and do not try to analyze their uncertainty. Numerous other studies have addressed these instruments. In particular, tracking balloons below 350 m is a difficult procedure, as reflected in the few data points at 100 m in Fig. 3. Overall, the lidar uncertainty is less than uncertainty

TABLE 4. Lidar–sonic comparison.

Average period (s)	rms difference (m s^{-1})	Correlation	Overall average (m s^{-1}) Lidar	Overall average (m s^{-1}) Sonic
20	0.19	0.97	2.64	2.59
60	0.12	0.98	2.64	2.59

caused by atmospheric inhomogeneity. We have not included lidar uncertainty in the values in Tables 3 and 4 because it is not the major source of differences in the comparisons.

e. Application example

Figure 5 presents six vertical profiles of the wind taken during and after the evening of 29 September 1983, when the development of a low level jet was forecast for the area. The six data points for each profile are similar to those in Fig. 2, but only the relatively smooth curves are shown in Fig. 5 to avoid cluttering the diagram.

Although the existence of such a jet is open to discussion, the profiles demonstrate one application of CW-Doppler-lidar wind profiles to boundary-layer research. After sundown the wind gradient near the surface increased, as one would expect with the probable increasing stability in the lapse rate. The wind continued to decrease below approximately 150 m and increase above until near 2130 mid-European time (MEZ) when a velocity maximum at approximately 200 m altitude occurred. After that time the kinetic energy in the flow decreased, but a relative maximum in the profile near 300 m persisted until the next morning. The 0600 MEZ radiosonde in Fig. 5 helps fill the time gap between VAD data at 2308 on 29 September and 0820 on 30 September 1982, and verifies the decrease of the wind above the 300 m relative maximum. Analysis of the boundary-layer physics of the profile changes is not pertinent to the point of this paper, but the data give an example of the use of the lidar for studies to at least 750 m altitudes.

4. Comparisons and conclusions

a. Results from other techniques

Winds have also been derived from the movement of inhomogeneities in the ambient aerosol backscatter coefficient that are tracked by visible-wavelength lidar. Sroga *et al.* (1980) used a horizontal spatial average of approximately 1 km to measure wind profiles to approximately 350 m altitude. The comparison with pilot-balloon profiles shows what the authors call rms errors of 1.1 m s^{-1} in magnitude and 7° in direction. The corresponding values from comparison with a tower-mounted anemometer are 1.0 m s^{-1} and 10°. These lidar-sonde differences are similar to the differences we found even though the principle of the lidar wind measurement used by Sroga *et al.* is completely different from the operating principle of our lidar. The lidar-sonde differences are attributed by Sroga *et al.* to the uncertainty of comparing a measurement made at a single point with a lidar measurement averaged over a considerable spatial extent.

Another technique for measuring boundary-layer wind profiles is the FM–CW radar. Although Chadwick *et al.* (1976) give two profile comparisons between the radar and a tethered balloon, they do not evaluate the comparison numerically. The rms differences between radar and balloon and between upward and downward scans of the balloon appear to be approximately 1.5 m s^{-1}.

Other studies do not apply directly to our investigation of the lidar-sonde comparison in the first 1000 m of the atmosphere, but they do indicate the effects of atmospheric inhomogeneity. Jasperson (1982) found an rms difference of 1.0 m s^{-1} between two pilot balloons launched simultaneously 20 m apart and gathering data over altitudes of 0 to 5 km. Fukao *et al.* (1982) found a standard deviation of 4.9 m s^{-1} between UHF-radar and rawinsonde estimates of wind throughout the troposphere. All these other studies support the view that the differences in wind profiles measured by lidar and sonde are caused by atmospheric inhomogeneity rather than instrumental error.

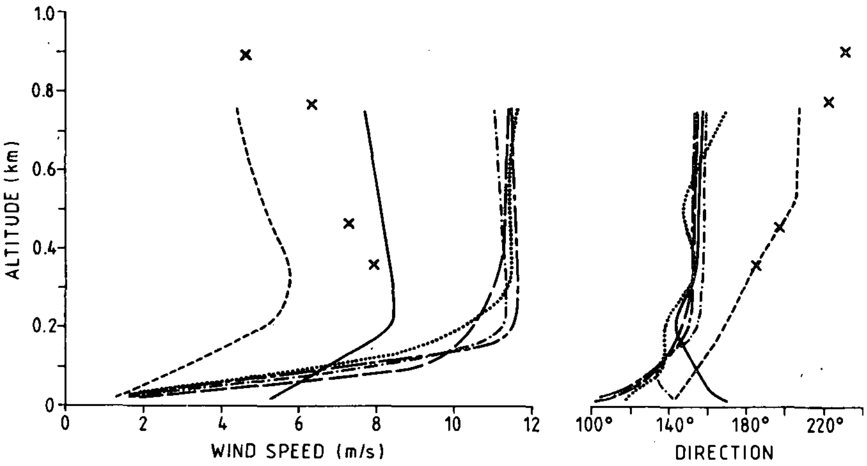

FIG. 5. Composite of vertical wind profiles 29–30 September 1982 (times in MEZ): (solid line) 1621; (long dash line) 2108; (short-long dash line) 2137; (dot-dash line) 2226; (dotted line) 2308; (short dash line) 0820. The crosses are radiosonde data at 0600.

b. Conclusions

A CW infrared Doppler lidar of the type used in this study can measure wind profiles to altitudes of at least 750 m whenever the visual range is a few hundred meters or greater. There is an rms difference of 1.3 m s^{-1} in magnitude and 12° in direction between profiles measured by lidar and those measured by balloon sonde in our series of tests, but this difference is caused by atmospheric inhomogeneity rather than instrument error. When the effect of inhomogeneity is reduced by comparing the lidar with a fixed sonic anemometer, the comparison for 60 s averages is an rms difference of 0.12 m s^{-1}. Because average velocity values differ by only 0.05 m s^{-1}, this difference is caused largely by the difference between a 20 cm and a 40 m sample volume length rather than by instrumental error. It is likely that the lidar wind profiles are more representative of the average wind profile in the first 750 m than are sonde-derived profiles because the lidar inherently provides a spatial average.

c. Further research

The wind field is not usually the same at all points of a full VAD scan because of atmospheric inhomogeneity, especially near the surface. It would be useful to compare velocity profiles extracted from various sectors of the scan for consistency. One application of the partial VAD scan is to measure profiles in a region of the atmosphere not centered over the lidar scanner.

Any comparison study can be extended to include other surface topography and weather conditions and to increase the number of profiles analyzed. We expect that the rms difference of a lidar-sonde comparison would increase in complex (hilly) terrain and under more unstable conditions, and it would be less than we found if measured over extremely homogeneous terrain (prairie or ocean) and with a more stable lapse rate. Additional variables can be derived from the lidar velocity spectra with further processing. For example, wind fluctuations on scales smaller than the lidar resolution volume can be estimated from the width (second moment) of the spectrum.

Acknowledgments. H. C. Korff and his staff from the Meppen Proving Ground provided the sonde data for comparison. M. Klier and U. Hauenstein helped with the field experiment and data reduction.

REFERENCES

Alldritt, M., R. Jones, C. J. Oliver and J. M. Vaughan, 1978: The processing of digital signals by a surface acoustic wave spectrum analyzer. *J. Phys. E, Sci. Instrum.*, **11**, 1–4.

Brown, A., E. L. Thomas, R. Foord and J. M. Vaughan, 1978: Measurements on a distant smoke plume with a CO_2 laser velocimeter. *J. Phys. D, Appl. Phys.*, **11**, 137–145.

Browning, K. A., and R. Wexler, 1968: The determination of kinematic properties of a wind field using Doppler radar. *J. Appl. Meteor.*, **7**, 105–113.

Chadwick, R. B., K. P. Moran, R. G. Strauch, G. E. Morrison and W. C. Campbell, 1976: A new radar for measuring winds. *Bull. Amer. Meteor. Soc.*, **57**, 1120–1125.

Fukao, S., T. Sato, N. Yamasaki, R. M. Harper and S. Kato, 1982: Winds measured by a UHF Doppler radar and rawinsondes: comparisons made on 26 days (August–September 1977) at Arecibo, Puerto Rico. *J. Appl. Meteor.*, **21**, 1357–1363.

Hughes, A. J., J. O'Shaughnessy, E. R. Pike, A. McPherson, C. Spavins and T. H. Clifton, 1972: Long range anemometry using a CO_2 laser. *Opto electronics*, **4**, 379–384.

Jasperson, W. H., 1982: Mesoscale time and space wind variability. *J. Appl. Meteor.*, **21**, 831–839.

Kennedy, L. Z., and J. W. Bilbro, 1979: Remote measurement of the transverse wind velocity component using a laser Doppler velocimeter. *Appl. Opt.*, **18**, 3010–3013.

Köpp, F., 1982: A direct laser Doppler anemometer for remote sensing of atmospheric flows. *Int. Symp. on Applications of Laser-Doppler Anemometry to Fluid Mechanics*, Lisbon, 12.1.1–12.1.10.

Lawrence, T. R., D. J. Wilson, C. E. Craven, I. P. Jones, R. M. Huffaker and J. A. L. Thomson, 1972: A laser velocimeter for remote wind sensing. *Rev. Sci. Instrum.*, **43**, 512–518.

Lhermitte, R. M., and D. Atlas, 1961: Precipitation motion by pulse Doppler. *Preprints Ninth Weather Radar Conf.*, Kansas City, Amer. Meteor. Soc., 218–223.

Post, M. J., R. L. Schwiesow, R. E. Cupp, D. A. Haugen and J. T. Newman, 1978: A comparison of anemometer- and lidar-sensed wind velocity data. *J. Appl. Meteor.*, **17**, 1179–1181.

Rabin, R., and D. Zrnić, 1980: Subsynoptic-scale vertical wind revealed by dual Doppler-radar and VAD analysis. *J. Atmos. Sci.*, **37**, 644–654.

Schwiesow, R. L., and R. E. Cupp, 1981: Offset local oscillator for a CW laser Doppler anemometer. *Appl. Opt.*, **20**, 579–582.

——, and R. S. Lawrence, 1982: Effects of a change of terrain height and roughness on a wind profile. *Bound.-Layer Meteor.*, **22**, 109–122.

——, R. E. Cupp, P. C. Sinclair and R. F. Abbey, Jr., 1981: Waterspout velocity measurements by airborne Doppler lidar. *J. Appl. Meteor.*, **20**, 341–348.

Sroga, J. T., E. W. Eloranta and T. Barber, 1980: Lidar measurement of wind velocity profiles in the boundary layer. *J. Appl. Meteor.*, **19**, 598–605.

Teoste, R., and R. N. Capes, 1978: High-altitude infrared radar wind measurements. *J. Appl. Meteor.*, **17**, 1575–1578.

Vaughan, J. M., 1979: Remote wind measurement in the atmosphere using laser Doppler methods. *Laser 79 Opto-electronics*, W. Waidelich, Ed., IPC Sci. Tech. Press, 461–469.

Waldteufel, P., and H. Corbin, 1979: On the analysis of single-Doppler-radar-data. *J. Appl. Meteor.*, **18**, 532–542.