7.1 VERTICAL PROFILES OF VELOCITY VARIANCES AND TKE USING DOPPLER-LIDAR SCAN DATA

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Introduction

Vertical profiles of turbulence quantities have traditionally been very difficult to obtain above the region of the atmospheric boundary layer (ABL) sampled by towers. Development and application of Doppler lidar have added new possibilities into the remote sensing of wind.

Application of Doppler lidar scanning wind speed data for measurements of vertical profiles of turbulent quantities and momentum flux for the unstable boundary layer have been reported since the late 1990s by many researches, including Eberhard et at. (1989), Gal-Chen et al. (1992), Banta et al. (1997). Over the last decade, the High-Resolution Doppler Lidar (HRDL), designed and developed at the National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL), has been highly effective in the study of dynamic processes in the ABL because of its temporal and spatial resolution (2 Hertz and 30 m), narrow beam, and capability to measure the component of the wind velocity parallel to the lidar beam (radial velocity) with a precision of 10-20 cm/s (Grund et al.2001, Wulfmeyer et al. 2000).

Various methods have been proposed to determine the components of the wind field from radial velocity observations.

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A technique for using HRDL vertical-slice-scan wind speed data, in which mean streamwise velocity (U_h) and variance (σ_h) were calculated for vertically stacked, horizontally oriented bins, was employed during CASES-99 and described by Banta et al., (2002, 2006). In the following discussion, notation for the variables U_h, σ_h^2, and σ_h, will be used interchangeably with their functional form U_h (z), σ_h^2 (z), and σ_h (z).

In the present study, we apply this technique to calculate profiles of mean U_h and σ_h^2 from vertical-slice scans measured during two projects: the Cooperative Surface-Atmosphere Exchange study (CASES-99) and the Lamar Low-Level Jet Project (LLLJP). The CASES-99 experiment that took place in eastern Kansas in October 1999, was described by Blumen et al. ,(2001) and Poulos et al. (2002), Banta et al., (2002, 2003), and Newsom and Banta (2003). Detailed description of the LLLJP, carried out near the town of Lamar, Colorado in September 2003, instrumentation involved, data sets and preliminary results can be found in Kelly et al., (2004) and Pichugina et al., (2004, 2005).

Both projects had tall towers and other instrumentation, against which to verify the HRDL profiles. CASES-99 had a 60-m tower instrumented at 5-m intervals with sonic anemometers, and Lamar had a 120-m tower instrumented at 4 levels with sonic anemometers, and a Doppler sodar. Verification of the mean wind profile derived from HRDL data was straightforward, with highly correlated mean speeds between the lidar and other instruments for the most part, independent of sampling strategies and averaging procedures. Comparison of estimates of variance, on the other hand, proved highly sensitive to both the spatial and temporal averaging techniques and their intervals.

This paper will describe results from analysis techniques applied over a range of temporal and spatial scales which generate correlation coefficients of greater than 0.8 between tower and lidar derived quantities. It is organized as follows: Section 2 briefly describes the precision of the HRDL radial velocity measurements made during LLLJ project, Section 3 presents the results of the streamwise velocity calculations and comparison with sodar and sonic anemometer data, Section 4 discusses the sensitivity of streamwise velocity variance to both spatial and temporal averaging and presents results from comparisons with turbulent kinetic energy (TKE) calculated from sonic anemometer data, and Section 5 summarizes the results and draws conclusions.

HRDL observational data

During LLLJP, HRDL was located at l37.6657° N and 102.6668° W and 1357 m above sea level. The lidar operated with a pulse repetition frequency (PRF) of 200 Hz, typically averaging results from 100 pulses to form range-resolved, line-of-site (LOS) velocity estimates twice per second with a range resolution of 30m. Data were collected during the nighttime, from local sunset (0:00 UTC) until sunrise (10:00-12:00 UTC) in a scanning mode. Scans included both azimuth and elevation scans at various fixed angles. Similar detailed information about the CASES-99 experiment can be found in these references (Poulos et al., 2002, Banta et al., 2002). Despite the wide range of scans taken during the both experiments, the present paper will focus on analysis of data derived from vertical-slice scans only. These scans are performed by sweeping the elevation angle at fixed azimuth angle (or Range-Height Indicator, RHI scans in radar terminology). The fixed azimuth angle of these RHI scan was aligned parallel to the mean wind directions for periods of 10-20 minutes. The mean wind direction was found by using the lidar to perform an azimuthal scan from which the wind profile could be determined using the velocity-azimuth display (VAD) technique (Browning and Wexler 1968; Banta et al. 2002). The wind direction was verified by performing these VAD scans every ~20-30 min and the fixed azimuth angle of the RHI scans would be adjusted accordingly. The RHI scans outnumbered other scans taken during both experiments, accounting for 70-75% of time and they also proved to be very effective in the analysis of the surface layer structure (Drobinski et al. 2004), velocity field and atmospheric turbulence (Smalikho et al., 2005), gravity waves (Newsom and Banta, 2002) and low-level jet evolution (Banta et al., 2002, 2003).

The precision of the LOS velocity estimates, derived from time series analysis of staring data taken during the CASES-99 experiment, is described in detail by Newsom and Banta (2004). They showed that the measurement error varies smoothly and is generally less than 0.5 m/s for ranges less than 1800 m. A similar analysis of the Lamar data show the measurement error was about 0.3 m/s for ranges less than 1500 m and increased rapidly beyond this range. The precision of the LOS velocity is strongly dependent on signal strength (Rye and Hardesty, 1993). Clean atmospheric conditions during the LLLJ field experiment provided less scattering targets and hence lower signal strength and is probably responsible for the reduced range of HRDL. In our analysis, data were excluded for ranges greater than 1500 m and for ranges within the HRDL "dead" zone of 189 m.

LOS velocity data with low signal strength and data with very high signal strength (hard target hits) were rejected using a quality control technique developed to process CASES-99 data that is described by Banta et al. (2002), and Newsom and Banta (2004). The data in **Figure 1** illustrate this technique on a single RHI scan (a) obtained at 8:39:38 UTC on the night of September 5, 2003 with azimuth angle of 12 degree and a 0-20 degree range of elevation angles. The vertical axis is height in kilometers and the horizontal axis is distance from the lidar in kilometers The same scan is shown in (b) after removing

LOS velocity measurements corresponding to hard returns and low signal strength (the rejected data appear as white pixels in the plot, .Green pixels indicate missing data in both panels). This quality control technique was applied to all the data used in this study to ensure that they were unbiased.

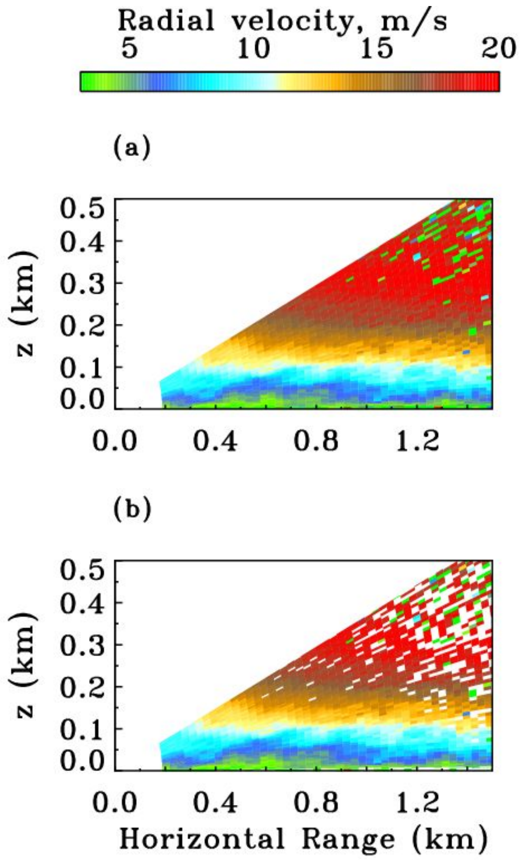

Figure 1. (a) Vertical-slice scan for 8:39:38 UTC on 5 September 2003 during the Lamar project before (a) and after (b) application of quality control procedure to remove radial velocity measurements corresponding to hard returns and low SNR. Vertical axis is height (km), horizontal axis is horizontal distance from HRDL position, and the color bar indicates wind speed (m s^{-1}). Green pixels indicate missing data in both panels.

HRDL's high spatial and temporal resolution allowed averaging procedures to be used to reduce the effect of random errors, as noted by Eberhard et al. (1989), and concluded by Newsom and Banta (2004) while still maintaining spatial and temporal resolution in the results on the same scale as those derived from the tower.

Techniques to determine precision of LOS velocity measurements have been studied previously and described by many authors, (Rye and Hardesty, 1993, Frehlich, 2001, 2004, Smalikho, 2001), We refer the reader to these references for further discussion of measurement precision.

The intention of our paper is to show the sensitivity of the streamwise velocity variance to both spatial and temporal averaging procedures and to determine the best value for the vertical bins and time intervals by comparing results with those taken with other instruments.

HRDL streamwise velocity

To calculate the horizontal wind component (or streamwise velocity, U_h), the LOS velocity measurements were divided by the cosine of the elevation angle. Estimates of the mean U_h and variance were obtained by first sorting the horizontal wind component results from either a single or multiple scans into height bins and then forming an average and variance from the results found within each bin. This technique will hereafter be referred to as temporal and spatial averaging.

To investigate the sensitivity of this procedure to spatial and temporal scales, we computed U_h and σ_h^2 by accumulating multiple scans over a different time intervals (1-,5-,10-, and 15-min) and vertical bin sizes (1-,5-,10-, and 15-m) before calculating the statistics. The reliability of the streamwise velocity estimates was determined by comparing results to those from different instruments using correlation and qualitative visual inspection of time-height cross sections as shown in **Figure 2.** This figure illustrates significant differences in the magnitude of streamwise velocity (left) and variance (right) between two nights, September 15th and 16th. On September 15th the wind speed was greater than 15 m/s most of the time (top) and on September 16th the wind speed was between 5 and 10 m/s (bottom panel). These examples were identified as "high-wind" and "low-moderate" nights according to classification of Banta et al. (2002). The analysis of all IOP nights from Lamar experiment shows that large variances (well above the instrumental uncertainty) were observed during strong-wind nights. So, for the purpose of illustration we selected two nights, September 5th and 15th from the Lamar experiment, when winds were about 15-25 m s^{-1}.

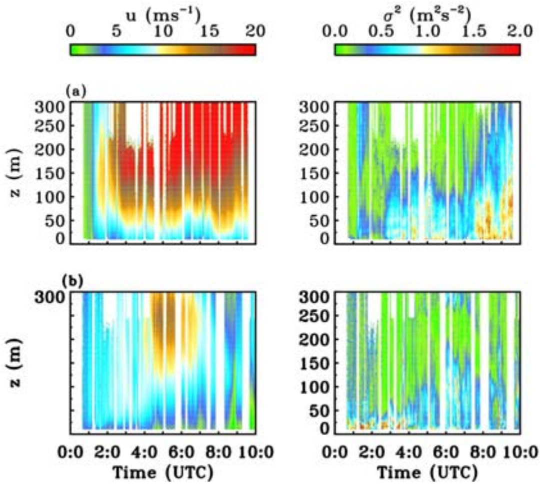

Figure 2. Sample time-height cross sections of streamwise velocity (left) and variance (right) for the "high" wind night of September 15 (a), and for the "low-moderate" wind night of September 16 (b). Nights from Lamar experiment were identified by wind speed magnitude according to Banta et al. (2002).

A Doppler sodar operated on Lamar site had a vertical measurement range from 20 to 1000 m in 10-m increments. The profiles of the horizontal wind speed and direction were available in 10-min time intervals, and we used these to compare with the lidar measurements. Sample profiles of the streamwise velocity calculated from HRDL RHI scans by averaging within 10 m bins (solid line) and wind speeds measured by sodar (+) are shown in **Figure 3**. These randomly chosen profiles show good agreement up to 200 m and minor difference in the shape of profiles above the height.

A scatter plot of 10-min, 10-m lidar U_h and sodar wind speed, obtained for the night of September 5 during the Lamar project, is shown in **Figure 4**. The best fit to the data is shown as a solid line with slope of 0.86 and correlation coefficient of 0.95. The low value of the slope in this case was due to smaller values of lidar wind speed below ~ 8 m s^{-1},

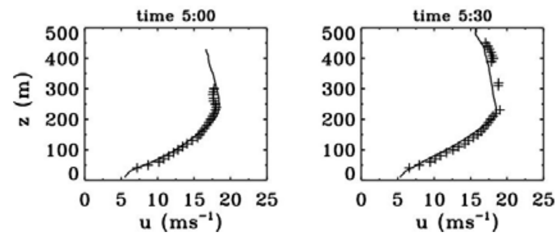

Figure 3. Sample of 10-min streamwise velocity profiles calculated from HRDL vertical-slice scans by averaging within 10-m bins (solid line) and wind speed measured by sodar (+).

which was probably caused from local topography as pointed out by Newsom and Banta (2003), and the 150 m separation between instruments.

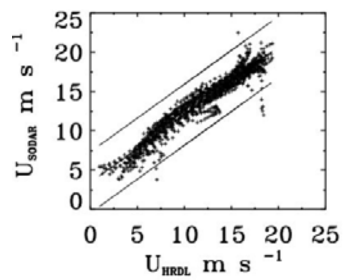

Figure 4. Scatter plot of 10-min, 10-m lidar streamwise velocity and sodar wind speed obtained for 11 hours during the night of September 5.

The accuracy of the mean streamwise velocity was also examined by comparing it against wind speed measured by sonic anemometers mounted on a meteorological tower 167 m away from the lidar. The lidar results were averaged to the same time resolution as the sonic data (1 minute) and streamwise velocity was derived at the four levels of sonic anemometer measurements: 54-, 67-, 85-, and 116-m, as indicated by dotted lines in **Figure 5**. In the time-height cross sections of HRDL streamwise velocity shown for the night of September 5th (top panel) each vertical line represents a vertical profile of the wind horizontally averaged within 1-m bins. The bottom panel of Figure 5 shows a time-series of sonic (solid line) and lidar (+) data retrieved at the heights of sonic measurements. In this plot both the sonic and lidar velocities at each level had been slightly displaced in ±5 m s^{-1} in order to show the evolution of the mean and oscillating motions for the individual heights. The scatter plots

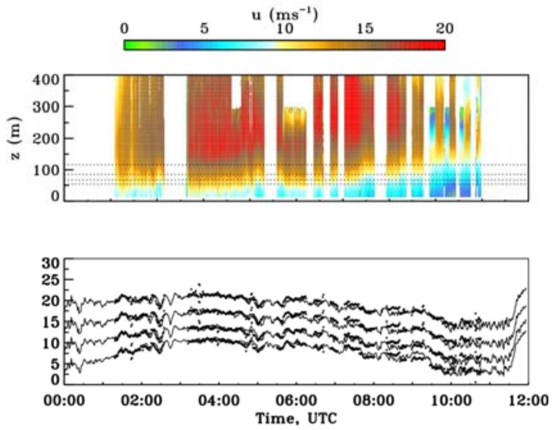

Figure 5. Time-height cross sections of HRDL streamwise velocity for the night of September 5 (top panel) where each vertical line represents a vertical profile of the wind horizontally averaged within 1-m bin. Dotted lines indicate tower levels of 54-, 67-,85-, and 116-m. The bottom panel shows time-series of sonic (solid line) and lidar (+) data retrieved at the heights of sonic measurements.

show good agreement between both instruments in (**Figure 6**) and have correlation coefficients of 0.95 for all four heights.

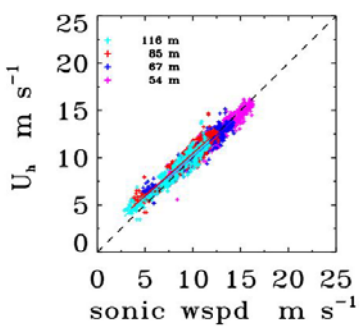

Figure 6. Scatter plot of sonic anemometer results (1-min average) and HRDL streamwise velocity (1-m bins) retrieved at heights of sonic measurements for the night of September 5.

The correlation coefficients for all 11 nights from the Lamar experiment are shown in **Table 1.** Better correlation was observed for the "high-wind" nights (5, 6, 9, 10, and 15 of September). The low correlation observed for the rest of the nights was due partially to atmospheric conditions, when wind speed remained below 7-8 m s^{-1} (2^{nd} and 12^{th} of September) and partially to small sample sizes such as the night of September 3rd, when HRDL measurements were obtained only for 3 hours from 4:30 till 7:40 UTC.

Similar analysis for all IOP days from both experiments shows highly correlated mean speeds among the lidar and other instruments, independent of sampling strategies and averaging procedures.

HRDL velocity variance

Unlike the mean speeds, the variance estimates proved very sensitive to both temporal averaging and height of vertical bins, with lidar variances differing from tower-measured variances by a factor of two or more.

Sample profiles of 5-min mean U_h (left) and σ_h (right) calculated by averaging within 1- , 5- , and 10-m vertical bins are shown in **Figure 7.** As mentioned above, the size of the averaging bins in the vertical has no effect on the mean velocity, yet does produce significant differences in variance. In general, the differences are larger for heights of 20-70 m above ground level and smaller above the jet speed maximum.

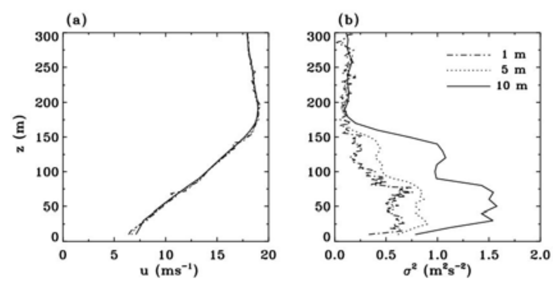

Figure 7. Sample profile of 5 min streamwise velocity (a) and variance (b) calculated by averaging HRDL vertical-slice data within 1- , 5-, and 10- m vertical bins to illustrate the sensitivity of variance to the size of the vertical averaging bin.

Similar conclusions could be made through visual inspection of time-height cross sections for the duration of the night as displayed in **Figure 8**, where σ_h^2 averaged within 1 m (a) and 10 m (b) vertical bins for the night of September 5^{th}. The figure illustrates the increase of variances of almost a factor of two for the larger bin size. The differences are most significant in the atmospheric layer of 10-150 m.

Profiles of the mean wind U_h and σ_h^2, for all strong wind nights from both experiments, are composited in **Figure 9** (a) and (b)

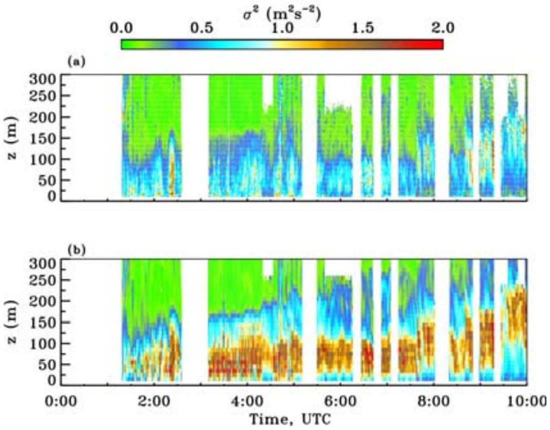

Figure 8. Time-height cross sections of HRDL streamwise velocity variance shown for the night of September 5. Each vertical line represents a variance profile of the streamwise velocity horizontally averaged within 1m bin (a) and 10 m bin (b). Color bar indicates magnitude of variance ($m^2\ s^{-2}$).

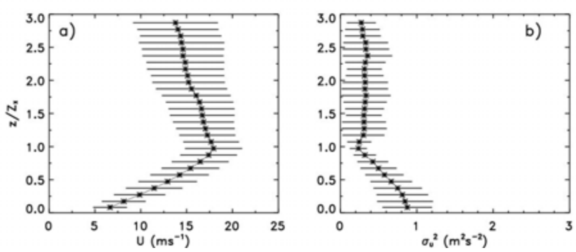

Figure 9. Composite profiles for all "high-wind" nights from CASES-99 and Lamar showing streamwise velocity (a) and variance (b). All heights are normalized by Z_X, the height of the Low –Level jet. Mean value for each vertical level (for vertical intervals of 0.1 Z_X) is indicated by * and horizontal error bar indicates ±1 standard deviation for the 10min vertical profiles comprising the dataset.

respectively. The height in all profiles has been nondimensionalized by the height of the lowest low-level jet wind maximum Z_X, which represents the top of the surface-based shear layer or the "momentum BL" as defined by Mahrt et al. (1979). The mean value for each vertical interval of 0.1 is indicated by * and horizontal error bar indicates ± 1 standard deviation for the 10-min vertical profiles comprising the dataset (Banta et al., 2006). Some individual 10-min profiles were excluded from the sample, if the profile was not deep enough to accurately determine Z_X, if the U_h and $\sigma_h{}^2$ profile appeared too noisy, or if the profile was transient, non-adjusted, or layered as noted in Banta et all. (2006). As shown in Figure 9, the uncertainty in the mean U_h, averaged over all profiles in dataset, did not vary much with height below the composite jet maximum. The composite velocities above this point were wide spread due to different shapes of the individual profiles. The composite variance was almost at 27 % larger at the surface than below the height of the composite jet nose, with a maximum value of 0.84 $m^2\ s^{-2}$ at the surface, and minimum of 0.23 $m^2\ s^{-2}$.

A histogram analysis of the entire Lamar-03 data set is presented in **Figure 10.** The distribution of variances calculated by averaging within 1-m bins is shown on the top panel and within10-m bins on the bottom panel. The total number of occurrences is shown along the left vertical axis, and percentages of occurrences are indicated along the right vertical axis. The dotted line in both plots shows a mean value of 0.38, and 0.64 respectively. Corresponding results were obtained for the entire CASES-99 data set (not shown), with a slightly lower means (0.36 and 0.53 for 1- and 10-m respectively), and very similar shape for the distribution. Profiles of streamwise velocity variances derived from HRDL data show good agreement with tower-measured TKE - having very similar shape profiles in the stable boundary layer. This result was also shown by Banta et al. (2006) in their in figure 4 on selected number of profiles.

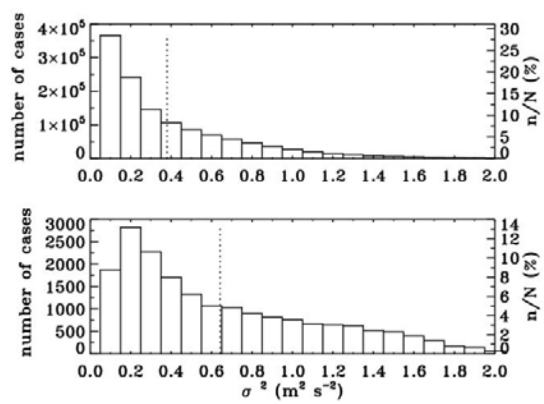

Figure 10. Histogram of streamwise velocity standard deviation for all IOP days during Lamar-03 (top panel) and Cases-99 (bottom panel), calculated by averaging data over 10 min and within 10 m vertical bins. Total number of occurrences are shown along left vertical axis, and percentages of occurrences is indicated along the right vertical axis. Dotted line indicates a mean standard deviation for the data set of 20680 points (top) and 41055 points (bottom)

An example of the time-height cross sections of σ_h^2 (a) and time-series of tower-measured TKE (b) in Figure 11, shows good agreement in the evolution of both variables through the night of September 15th. Dotted lines in (a) indicate tower levels of sonic anemometer measurements at 54-, 67-, 85-, and 116-m.

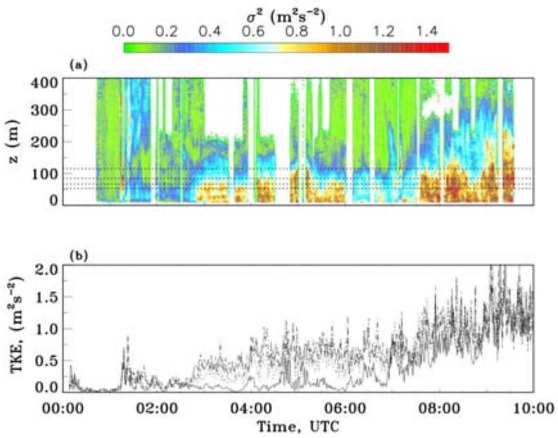

Figure 11. Time-height cross sections of HRDL streamwise velocity variance (top) for the night of September 5 show a good agreement in pattern with time series of wind speed measured by sonic anemometers at 4 heights (b).

The variance-TKE comparisons were also sensitive to the temporal averaging procedure, unlike the mean wind profiles. Therefore, TKE was calculated for 1-min samples for the CASES and Lamar tower datasets, and 5-, and 10-min means were then calculated by averaging 5 or 10 consecutive 1-min values for the tower data, consistent with the procedure devised and recommended by Vickers and Mahrt (2003). Vertically binned data from HRDL were also averaged for 5-min and 10-min intervals. Comparisons between 5-min HRDL σ_h^2 and tower-measured TKE are shown in **Figure 12.** Regression analysis of the 5-min data, when lidar variances were averaged within 1-m bin, yielded correlation coefficients better than 0.84 for the all four levels. This agreement was not as good for the 10-min averaged or 10-m binned data with the correlation coefficient decreasing to 0.57 as shown in Table 2, but the results in any case were essentially the same, showing proportionality of both variables under stable conditions, with the proportionality constant close to 1 (Banta et al, 2006).

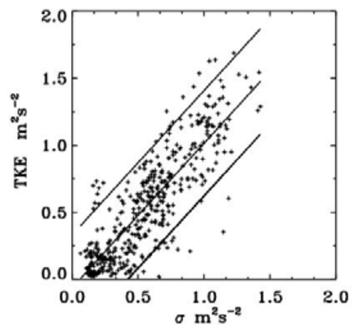

Figure 12. Scatter plot for the comparison of the 5 min horizontal velocity, calculated from HRDL vertical slice scans by averaging within 1m vertical bins and TKE calculated by sonic anemometers at four different heights.

Summary

The accuracy of the streamwise wind component and variance, computed from High Resolution Doppler Lidar (HRDL) vertical slice scans have been studied by comparison with direct in situ and sodar measurements

Analysis of the data, obtained during the Cooperative Surface-Atmosphere Exchange study in eastern Kansas in October 1999 (CASES-99) and a field campaign in September 2003 in southeast part of Colorado, near Lamar, show very high sensitivity of the turbulence profiles estimates to the spatial and temporal averaging procedures.

A procedure using 1-m vertical bins and 10-min averaging intervals was shown to produce good agreement between lidar and tower–measured variances. Because of the sensitivity of this technique to averaging parameters, it seem advisable at this time to recommend that it be applied under conditions when other measurements, such as those from in situ or sonic anemometry, are available to corroborate the values obtained from the lidar scan analyses.

Table 1. Coefficients of correlation between wind speed, measured by sonic anemometers at 4 tower levels during Lamar-03 experiment, and streamwize velocity, derived from HRDL vertical-slice scans.

day	54 m	67 m	85 m	116 m
02	0.76	0.72	0.72	0.78
03	0.65	0.56	0.64	0.53
05	0.96	0.95	0.95	0.95
06	0.90	0.90	0.88	0.87
09	0.80	0.79	0.78	0.76
10	0.93	0.94	0.94	0.94
11	0.76	0.76	0.72	0.85
12	0.70	0.69	0.75	0.72
13	0.81	0.82	0.84	0.85
15	0.94	0.93	0.93	0.92
16	0.82	0.77	0.78	0.86

Table 2. Coefficients of correlation between Turbulent Kinetic Energy (TKE), measured by sonic anemometers at 4 tower levels during the night of September 15, 2003, and streamwise velocity variance, derived from HRDL vertical-slice scans.

Bin size (m)	Height (m)	5 min	10 min
1	116	0.76	0.65
	85	0.84	0,78
	67	0.85	0.75
	54	0.85	0.73
5	116	0.71	0.65
	85	0.81	0.67
	67	0.77	0.70
	54	0.79	0.73
10	116	0.50	0.49
	85	0.59	0.56
	67	0.58	0.55
	54	0.58	0.58

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