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COHERENCE OF VERTICAL VELOCITY FROM A ZENITH-POINTING DOPPLER LIDAR

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1. INTRODUCTION

Two-point turbulence statistics in the planetary boundary layer (PBL) above tower-measurement heights have important practical applications. Examples include estimating the effects of turbulence on structures, and spatial sampling requirements for wind measurements. However, measurements of these statistics are difficult to obtain with traditional in situ measurement techniques. One approach is to use two aircraft with similar instrumentation and flight characteristics (Lenschow and Kristensen 1988; Kristensen et al. 1989) flown in formation at constant separation.

With the development of Doppler radars and lidars, it is now possible to measure the radial velocity component as a function of distance and thus map out two-dimensional fields of radial velocity from a ground-based observation site. Here we use a zenith-pointing Doppler lidar to measure vertical cross-sections of the vertical velocity *w* and calculate the vertical coherence and phase angle at various separation distances for two daytime convective PBL cases. We chose two reference heights—one near the middle of the PBL (810 m) and the other at the minimum range of the lidar (390 m). These are compared with the predicted coherence for inertial subrange turbulence to demonstrate the utility of the lidar data for measuring two-point velocity statistics.

2. LIFT EXPERIMENT

During August 1996, the National Center for Atmospheric Research's Atmospheric Technology Division (NCAR/ATD) and NOAA's Environmental Technology Laboratory (ETL) deployed three lidars at a University of Illinois field site near Champaign, IL, to observe the high resolution structure of aerosol, winds, and ozone in the lowest few kilometers of the atmosphere as the PBL evolved from early morning to late evening. The site for Lidars in Flat Terrain (LIFT) was chosen because of the flat terrain, good aerosol scattering, and nearby radar wind profilers operated by the NOAA Aeronomy Laboratory. In addition to the lidars and permanent wind profilers, surface meteorological instrumentation and additional wind profilers were deployed, and radiosondes were launched on a regular basis (Cohn et al. 1998). Angevine et al. (1998) have summarized the concurrent Flatland Boundary Layer experiment, which shared instruments and had complementary objectives.

3. HIGH RESOLUTION DOPPLER LIDAR

One of the three lidars, the High Resolution Doppler Lidar (HRDL), was used for this study. It was developed and deployed by ETL and is described by Grund et al. (2001). It utilizes a solid-state thulium lutetium yttrium aluminium garnet (Tm:Yu, YAG) laser to generate coherent light pulses at 2.0218 μm wavelength which are transmitted and received by a 0.2 m telescope at a pulse repetition frequency of 200 s^{-1}. A beam-steering mechanism installed on the roof of the shipping container housing the lidar enables us to point and scan anywhere above the horizon. During LIFT, the laser generated 0.8 mJ pulses with a radial velocity precision of 0.25–0.35 m s^{-1} for 1 s averages, a range resolution of 30 m, and a minimum range (dead-zone) of about 390 m. Typically, the lidar was able to "see" several kilometers horizontally and, at zenith, was always able to see through the top of the PBL. Changes in aerosol scattering led us to vary the number of pulses averaged together, and thus the temporal resolution, on a daily basis.

Although HRDL was used in various scanning modes during LIFT, a majority of the observations (110 out of over 160 hrs) were with the laser beam pointing to the zenith, since a major focus of LIFT was to examine the vertical structure of *w* in a convective PBL. This takes advantage of the lidar's capability to measure range-resolved radial measurements, from which a two-dimensional field of *w* can be obtained by use of Taylor's

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hypothesis; i.e. that the field of turbulence is “frozen” as it advects past the lidar beam.

4. VERTICAL COHERENCE

Following Kristensen and Jensen (1979)(hereafter KJ), we define the coherence of a velocity component u_i separated by a vector distance $\mathbf{D}$ from a velocity component u_j by

$$Coh_{ij}(\mathbf{D},k) \equiv \frac{Co_{ij}(\mathbf{D},k)^2 + Q_{ij}(\mathbf{D},k)^2}{F_{ii}(k)F_{jj}(k)}, \qquad (1)$$

where k is wavenumber, $Co_{ij}(\mathbf{D},k)$ and $Q_{ij}(\mathbf{D},k)$ are the co- and quadrature spectra, and $F_{ii}(k)$ and $F_{jj}(k)$ are the spectra of the individual velocity component time series.

We consider here the coherence of the vertical velocity along the vertical axis z obtained from the HRDL data at two different heights (i.e. two different Doppler velocity range gates) in the PBL. KJ obtained analytical expressions for the coherences in (1) assuming the turbulence is homogeneous and isotropic, and that the spectra follow the Kolmogorov relation

$$E(k) = \alpha \varepsilon^{2/3} k^{-5/3} \qquad (2)$$

where α is the Kolmogorov constant and ε the viscous dissipation. Using the notation of KJ, the mean wind direction is defined by a vector $\mathbf{i}_1$ and the displacement direction by a vector $\mathbf{i}_2$. Thus, the coherence of w with displacement along the z axis is their $Coh_{22}(Dk)$. They obtained theoretical expressions for the cross-spectra of Kolmogorov turbulence and substituted these into (2) to obtain

$$Coh_{22}(Dk) = \left(\frac{Dk}{2}\right)^{5/3} \left[\frac{2K_{5/6}(Dk) + \frac{3}{4}DkK_{1/6}(Dk)}{\Gamma(5/6)}\right]^2 \qquad (3)$$

where $K_{5/6}$ and $K_{1/6}$ are modified Bessel functions of the second kind and Γ is the gamma function. We expect that this relation holds for $D \ll \ell_w$, where ℓ_w is the integral scale of w. In addition, for isotropic turbulence, the phase angle, defined by

$$\phi_{ij}(Dk) \equiv \arctan\left[\frac{Q_{ij}(Dk)}{Co_{ij}(Dk)}\right] = 0. \qquad (4)$$

5. CASE DESCRIPTIONS

There are a total of 13 cases with useful vertical HRDL data during LIFT. Here we show results from two cases with relatively large and constant PBL depth, and stationary velocity structure.

The first case is 2 August 1996 from 1700 to 2000 UTC (1100 to 1400 LST) with vertical profiles every 2 s.

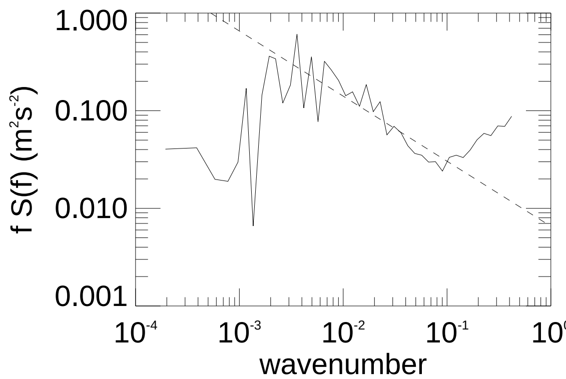

Figure 1: Vertical velocity spectrum at 810 m height ($z/z_i \approx 0.6$) on 2 August 1996.

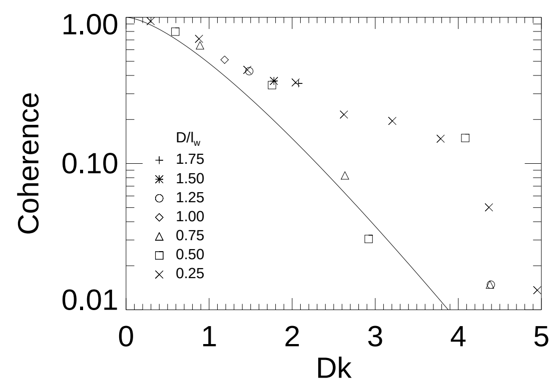

Figure 2: Coherence of vertical velocity on 2 August 1996 for altitudes below a reference level of 810 m. The curve in this and subsequent coherence plots is the predicted coherence for Kolmogorov turbulence.

Radiosonde and lidar backscatter data indicated that the PBL height ranged between 1200 and 1500 m, and the radiosonde and profiler data indicated a mean wind speed of 3 m s^{-1}. Scattered fair-weather Cu existed throughout the period.

The second case is 12 August 1996 from 1700 to 1930 UTC with profiles every 5 s. Radiosonde and lidar backscatter data indicated that the PBL height ranged between 1400 and 1500 m, and the radiosonde and profiler data indicated a mean wind speed of 6 m s^{-1}. There were scattered Cu with considerable vertical development.

6. RESULTS

The coherences in the figures are based on averages of 50 spectral estimates obtained over the entire time periods of 3 hrs on 2 August 1996 and 2.5 hrs on 12 August 1996. From Kristensen and Kirkegaard (1986), the bias

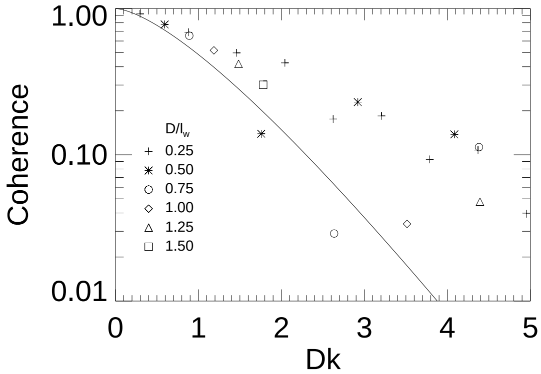

Figure 3: Coherence of vertical velocity on 2 August 1996 for altitudes above a reference level of 810 m.

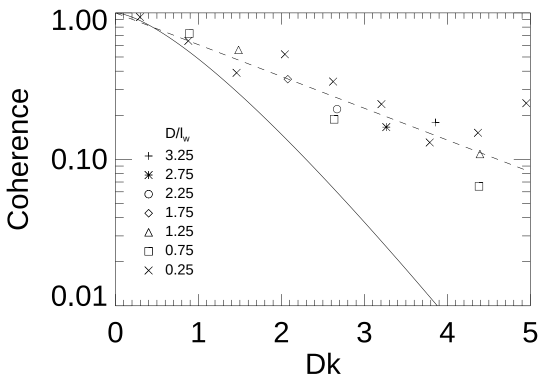

Figure 4: Coherence of vertical velocity on 2 August 1996 for altitudes above a reference level of 390 m. The dashed line is $e^{-0.5Dk}$.

in the coherence is about 0.02 when the true coherence is zero. Figs. 1 and 5 show the w spectra at 810 m height on both days, which were used to estimate $\ell_w \simeq 240$ m on 2 August and 600 m on 12 August. On the first day, the w spectrum is noise-limited for $k > 0.08$ m^{-1}. On both days, the spectra show some indication of a slope steeper than $-5/3$ at high wavenumbers (before noise is significant). According to the analysis of Dobrinski et al. (2000), the averaging effects of the pulse length start to attenuate the spectra in that region. The coherences in Figs. 2 and 6 are calculated from 810 m height downwards to 390 m in decrements of 60 m, and in Figs. 3 and 7 from 810 m upwards to 1170 in increments of 60 m. In Figs. 4 and 8, the coherences are calculated from 390 m upwards in increments of 120 m, except for the first increment of 60 m.

Generally, on both days the measured coherences exceed the model coherences, with the second day in better agreement, as we expected because of the smaller values of D/ℓ_w on that day. However, there is no noticeable

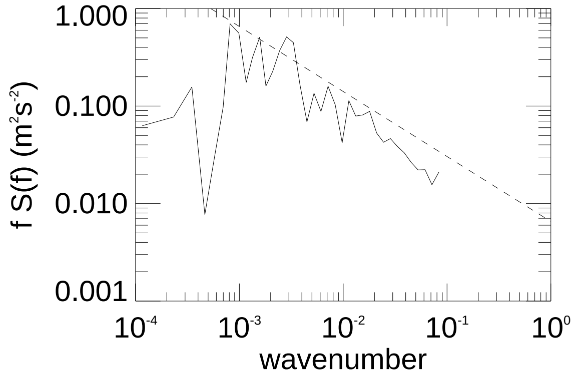

Figure 5: Vertical velocity spectrum at 810 m height ($z/z_i \approx 0.56$) on 12 August 1996.

D/ℓ_w dependency of the departure of the measurements from the model; that is, the points for different values of D/ℓ_w generally collapse onto the same curve, especially for small Dk. Surprisingly, the departure from the model curve becomes greater for large Dk, especially for small values of D/ℓ_w. There is no noticeable difference between the coherences calculated from 810 m upwards and from 810 m downwards. However, the coherences calculated from 390 to 1170 m on the first day are all well above the model curve, and can be better approximated by e^{-aDk}, with $a \simeq 0.5$. These results also differ from the predictions of the Kristensen et al. (1989) model which takes into account the dependency of the coherences on D/ℓ, but generally predicts a reduction in coherence with increasing D/ℓ, especially at low wavenumbers, where the predicted coherence does not go to one for $Dk \to 0$. As pointed out by KJ, exponential fits have a long history for estimating coherences in the PBL; however, data that they present for $Coh_{22}(Dk)$ for $D \ll \ell$ show good agreement with the Kolmogorov model. Davis (1992) estimated $Coh_{22}(Dk)$ from two aircraft flying in stacked formation and obtained an exponential fit with $a \approx 0.25$.

Fig. 9 shows that on 12 August, the phase angle is insignificantly different from zero, indicating that there is negligible tilt in w with z over the height range of 390 to 1170 m. The same is true for 2 August.

The results here indicate that HRDL is capable of measuring two-point turbulence statistics of the radial wind component in the PBL. We have used this capability to estimate the vertical coherence from the top of the lidar dead-zone to the upper part of the PBL, and compared the results with a model coherence based on Kolmogorov turbulence.

Acknowledgements

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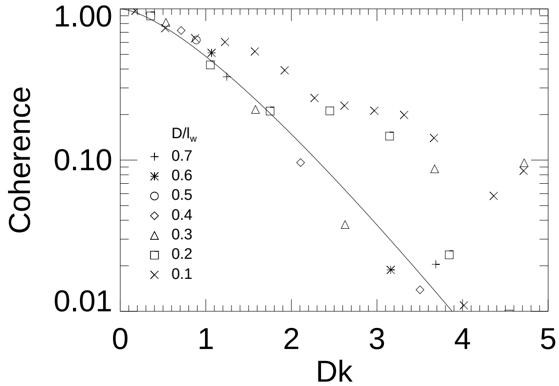

Figure 6: Coherence of vertical velocity on 12 August 1996 for altitudes below a reference level of 810 m.

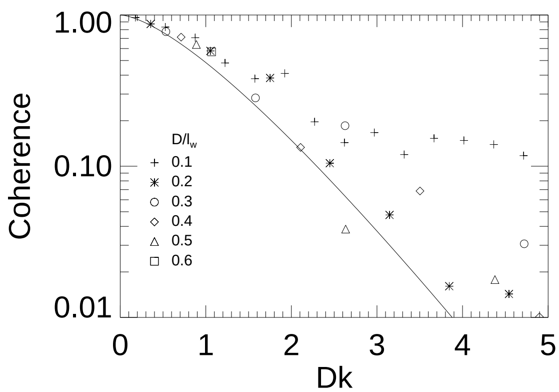

Figure 7: Coherence of vertical velocity on 12 August 1996 for altitudes above a reference level of 810 m.

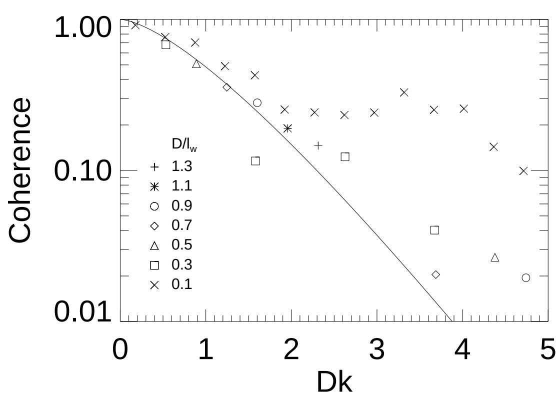

Figure 8: Coherence of vertical velocity on 12 August 1996 upwards from a reference level of 390 m.

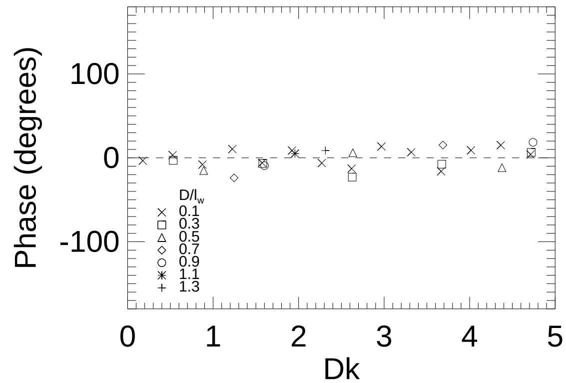

Figure 9: Phase angle on 12 August 1996 upwards from a reference level of 390 m.

REFERENCES

Angevine, W. M., A. W. Grimsdell, L. M. Hartten, and A. C. Delany, 1998: The flatland boundary layer experiments, *Bull. Amer. Meteor. Soc.*, **79**, 419–431.

Cohn, S. A., S. D. Mayor, C. J. Grund, T. M. Weckwerth, and C. Senff, 1998: The lidars in flat terrain (lift) experiment, *Bull. Amer. Meteor. Soc.*, **79**, 1329–1343.

Davis, K., 1992: *Surface fluxes of trace gases derived from convective-layer profiles*, Ph.D. thesis, University of Colorado, Boulder.

Dobrinski, P., A. M. Dabas, and P. H. Flamant, 2000: Remote measurement of turbulent wind spectra by heterodyne doppler lidar technique, *J. Appl. Meteor.*, **39**, 2434–2451.

Grund, C. J., R. M. Banta, J. L. George, J. N. Howell, M. J. Post, R. A. Richter, and A. M. Weickman, 2001: High-resolution doppler lidar for boundary layer and cloud research, *J. Atmos. Ocean. Technol.*, **18**, 376.

Kristensen, L. and N. O. Jensen, 1979: Lateral coherence in isotropic turbulence and in the natural wind, *Bound. Layer Meteor.*, **17**, 353–373.

Kristensen, L. and P. Kirkegaard, 1986: Sampling problems with spectral coherence, Technical Report R-526, Risø National Laboratory, DK-4000, Roskilde, Denmark.

Kristensen, L., D. H. Lenschow, P. Kirkegaard, and M. Courtney, 1989: The spectral velocity tensor for homogeneous boundary-layer turbulence, *Bound. Layer Meteor.*, **47**, 149–193.

Lenschow, D. H. and L. Kristensen, 1988: Applications of dual aircraft formation flights, *J. Atmos. Ocean. Technol.*, **5**, 715–726.