AN EVALUATION OF ESTIMATIONS OF ATMOSPHERIC TURBULENCE FROM COHERENT DOPPLER LIDAR DATA

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1. INTRODUCTION:

The evolution and structure of atmospheric boundary layer is complicated in urban and suburban areas due to the superposition of small scale effects (caused by the irregular boundaries in the urban area) on the larger mesoscale structures in the atmosphere (e.g., structures due to diurnal effects etc.) and the resulting atmospheric flows are therefore highly site specific (Frehlich and Cornman 2002; Frehlich, Hannon and Henderson 1998). Due to high population densities in the urban areas and trends in the urbanization, it is important to understand the dispersion in cities. The range and scanning capabilities of coherent Doppler lidar, which enable the exploration of atmosphere over very large areas and throughout the depth of the boundary layer (Davies et al. 2004), make the lidar, an interesting and promising instrument for observations of atmosphere. The velocity estimate obtained from the lidar is the spatial average of the instantaneous velocity over the sensing volume, which depends not only on the instantaneous velocity of the wind along the lidar beam axis but on the lidar parameters as well. In order to get quality measurements of turbulence, the spatial averaging effects of the lidar have to be estimated. The data from the stare scans that were performed by the Karlsruhe lidar on two days (4th and 5th of October) in Germany and that from the ASU lidar for three days (6th, 7th and 14th of July) in Oklahoma JU2003 experiment are analyzed for estimating the spatial averaging effects of the lidar and assessing the performance of the lidar in measuring the turbulence parameters.

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2. THEORY:

2.1 Structure function:

One important characterization of the turbulent velocity is the second order structure function defined by (Frehlich, Hannon and Henderson 1998)

$$D_v(s,r) = \left\langle [v'(r - s/2) - v'(r + s/2)]^2 \right\rangle.$$

For locally stationary turbulence and using the relation between the autocorrelation, structure function and von Karman energy spectrum for energy containing eddies, the structure function can be written as

$$D_v(s,r) = 2\sigma_{v'}^2(r)\Lambda[s / L_0(r)]$$

where $L_0(r)$ is a measure of outer scale of turbulence. The above functions are for point measurements (e.g., sonic anemometers) and need considerable correction for lidar estimated quantities.

2.2 Estimation of dissipation:

For energy containing eddies (Hinze 1975), dissipation in highest wave number range equals work done by the energy containing eddies. Therefore,

given $\frac{1}{(u')^2}\frac{d(u')^2}{dt} \propto -u' k_e$ for energy containing eddies

and $\varepsilon(t) = \frac{-3}{2}\frac{d(u')^2}{dt}$ for the equilibrium range,

one obtains $\varepsilon = A\frac{(u')^3}{l_e}$ - Equation (1) where l_e or $\frac{1}{k_e}$ is the integral length scale and l_e and $L_0(r)$ are related as l_e=0.75 $L_0(r)$

3. EXPERIMENTAL SETUP:

3.1 Karlsruhe Experiment:

During July and October 2004, the Instituet fuer Meteorologie und Klimaforschung, Tropospheric Section (IMK-TRO), Forschungszentrum Karlsruhe / Universitaet Karlsruhe, Germany, and the lidar group of Arizona State University (ASU) collaborated to obtain a dataset for the comparison of IMK's new coherent Doppler lidar with data from traditional atmospheric measurement systems like sonic anemometers, tethersondes, radiosondes, a radar profiler and a sodar. The experiment took place near Karlsruhe, Germany, and was centered at the Forschungszentrum just north of the city of Karlsruhe.

Additionally during 07/09 and 10/04-06 'stare' scans of range gate length of 105.33m were performed at an elevation angle of 4.1^0, azimuthal angle of 221.3^0 and reliable measurements were available up to a frequency of 10Hz. For these scans, the lidar focused on 100m level of the 200m meteorological tower, making the comparison between lidar measurements and in-situ measurements possible. The main purpose of the experiment was to better understand the performance of lidar for measuring turbulence parameters and to study better the convective storms that are frequent during the experiment period in Karlsruhe, Germany. Our approach is to compare the lidar measurements with the in-situ instrument measurements.

3.2 JU2003 Experiment:

A large field experiment, dubbed Joint Urban 2003, focusing on urban and suburban flows and dispersion phenomena took place in Oklahoma City during summer 2003. A variety of atmospheric measurement systems were deployed during the experiment – providing unprecedented opportunities to investigate questions related to urban flows and dispersion. Two Doppler lidars were deployed with the main purpose of giving deeper insight into the coupling between the free-stream wind and urban centers. One lidar belongs to the Arizona State University (ASU) and the other to the Army Research Laboratory (ARL). ASU lidar's location allowed scanning of flows upstream of the CBD (the predominant winds were southeasterly). The 'stare' scans are performed at an elevation angle of 7.8^0 and 10.75^0 and at an azimuthal angle of 297.01^0 and 228.9^0 by ASU and ARL Doppler lidars, respectively.

4. POST-PROCESSING OF THE LIDAR DATA:

Though lidar offers great advantages, its performance decreases with 1) increase in distance due to low SNR values at greater distances, 2) changes in lidar parameters, and 3) due to errors caused by the velocity estimation algorithm. Typically lidar data requires filtering before some type of analysis.

4.1 De-noising Lidar data:

In our implementation, the data is first filtered to remove the noisiest data. A two step process is used. The first step is to define a threshold value for SNR and to neglect all measurements with SNR values less than the threshold value. The second step is based on the velocity jump between two adjacent measurements with respect to time for the same range gate. Very high velocity jumps are then neglected. Then, the estimation error due to the effect of lidar parameters and velocity estimation algorithm is filtered from the data using the technique of velocity spectrum method described in Frehlich et al. (2001). The structure function derived from lidar velocity estimates is fitted to the model structure function (with consideration of the effect of spatial averaging done by the lidar, Frehlich et al. (1997)) by minimizing the weighted error between them. Through this fit, the values for variance of velocity fluctuations and outer scale of turbulence are derived.

5. RESULTS AND SUMMARY:

It is important to develop reasonable expectations for the level of accuracy associated with estimations of dissipation using the data from the current generation of coherent Doppler lidar (i.e., with typical range-gate size from 50-100 m). Performance of the two step filter proved to be satisfactory for closer range gates, but extensive filtering is required for more distant range gates. Due to the high noise in the data at greater distances as seen in Figure 1, only first 20 range gates are filtered and considered for analyses. Various parameters obtained. from the Karlsruhe lidar are compared with the 100m sonic anemometer measurements (Figures 2, 3, 6).

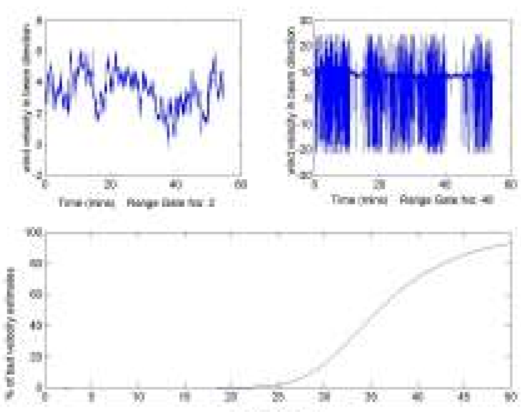

Figure 1. lidar velocity estimates on Oct 5th at 1200Hrs from Karlsruhe.

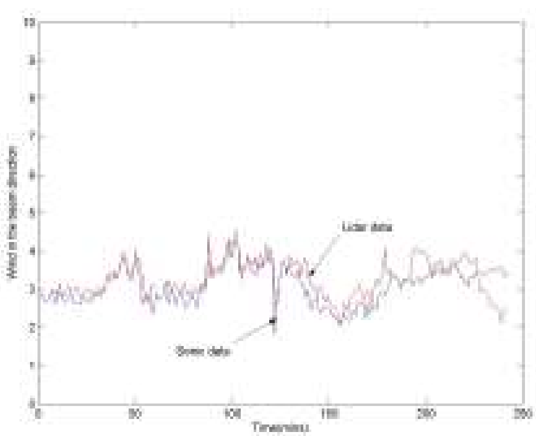

Figure 2: Comparison of measurements from the karlsruhe lidar and the 200m tower (at 100m level) on oct 5th from 1700 hrs local time.

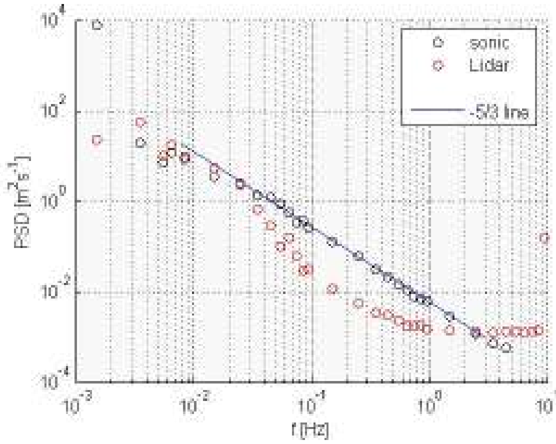

Figure 3: Power Spectral density versus frequency at 2200 Hrs on Oct 5th from Karlsruhe experiment.

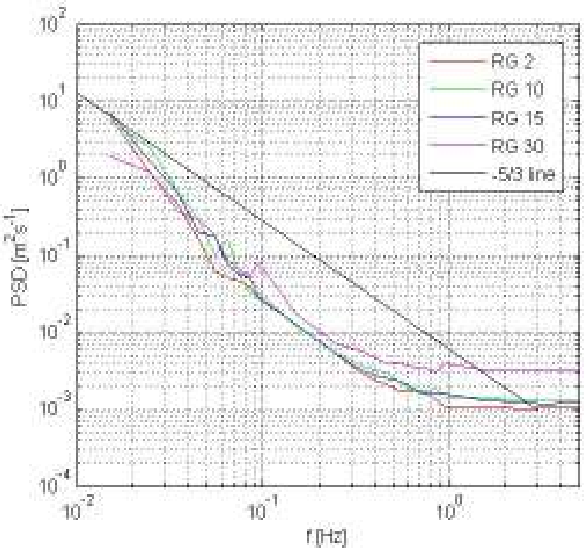

Figure 4: Power Spectral density versus frequency at 2200 Hrs local time on Oct 5th from Karlsruhe at different range gates.

The estimation error is calculated using the technique of velocity spectrum method, and the filtered estimate of radial velocity is used to calculate the spectra of velocity fluctuations (Figure 4). The structure function from lidar measured velocity estimates is then obtained (Figure 5). By correcting the lidar derived structure function values for the spatial averaging, point structure function values (i.e. values that are free from spatial averaging effect), variance of fluctuations, and outer scales of turbulence at different times are obtained. Using the Equation (a), local eddy dissipation rates are obtained for Karlsruhe experiment and JU2003 experiment. Comparison between the in-situ measurements and Karlsruhe lidar measurements show some agreement.

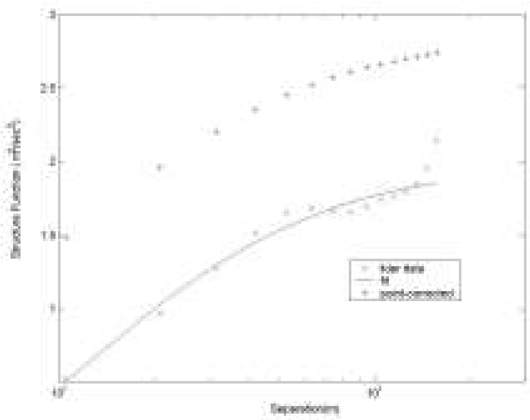

Figure 5: Typical second order Structure function plot.

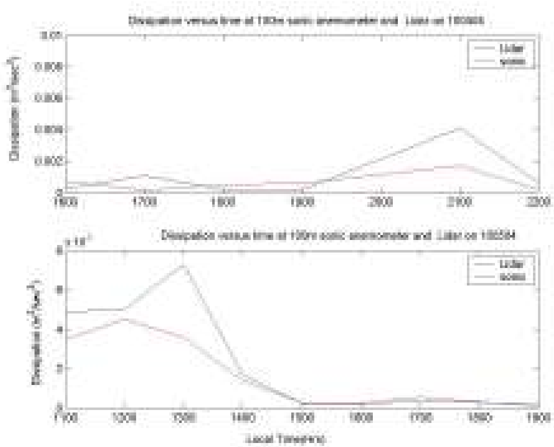

Figure 6: Comparison of Dissipation estimates between lidar and sonic anemometer from Karlsruhe.

A comparison between estimates of dissipation from sonic and lidar data as a function of time is given in Figure 4. At 16:00 to 18:00 local time on the 4th, the two estimates of dissipation differ by up to a factor of approximately 10. Note that these results are for 100m above a forest canopy with height of 20-30 meters. From 18:00 Hrs onwards for October 4th, both sonic and lidar estimates agree that the dissipation ranged from .001 to .002 m^2/s^3. On the 5th, the maximum difference of .005 to .03 exists, a factor of approximately 6, between the lidar and sonic estimates at 13:00 local time. From 15:00 onwards, both estimates indicate that the dissipation levels drop significantly to a level similar to those on the 4th. The estimated values for local dissipation rate from JU2003 experiment are shown in Figure 7.

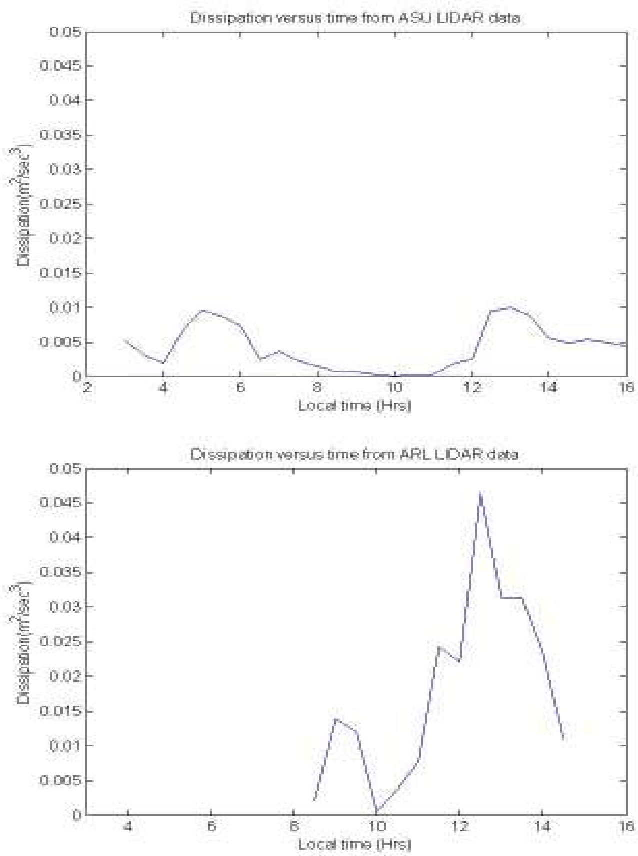

Figure 7: Estimated Dissipation values on 14th of July from JU2003 experiment.

For our case of flow over a forest canopy in Karlsruhe, we have found that dissipation trends over time can be approximately reproduced with lidar data. The lidar dissipation estimates generally appear to be within a factor of 2 to 10 of the sonic measurements, and often are significantly better. An examination of the theoretical underpinnings of the estimation method shows potential dangers of misapplication of the method stemming from violation of requirements associated with classical turbulence theory. The foundation of the method is a deconvolution employing an empirically-based curve resting on the expectation of a von Karman turbulence field. The type of lidar data used in these estimation methods does not have direct knowledge of velocity information below the size of the range gate, rather, this information is supplied through theoretical relations for von Karman turbulence behavior. As the radial resolution of coherent Doppler lidar improves, the estimation methods are likely to become more robust.

6. REFERENCES:

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