6.6 # MEASUREMENTS OF TURBULENCE PARAMETERS AND DISSIPATION IN COMPLEX TERRAIN

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1. Introduction:

The dissipation rate of turbulent kinetic energy is one of the key intrinsic parameters used to parameterize turbulence in environmental and in engineering flows. It represents the rate of energy transfer to smaller eddies in the inertial sub-range and the rate of conversion of kinetic energy of turbulence into heat in the viscous sub-range. This quantity characterizes the energy cascade in 3D atmospheric turbulence and is an important parameter characterizing the dynamical and dispersive state of the atmosphere. The dissipation rate is difficult to measure directly because of the required high spatial resolution, and thus may be inferred using measurements of quantities at scales larger than the dissipation scales. The direct measurements are made using sub-millimeter scale hot-film and hot-wire anemometers (e.g. Poulos et al. 2006) with application of the Taylor hypothesis, and indirect evaluations can be made using either the inertial sub-range of spectra measured by sonic anemometers (by fitting Kolmogorov spectra) or via empirical formulae combined with lidar data.

In this paper, the efficacy of the current generation of coherent Doppler lidar as a tool for turbulence parameter retrieval is evaluated through an intercomparison of lidar and sonic-based approaches.

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2. Experimental setup:

During March and April of 2006, a field study, the Terrain-induced Rotors EXperiment (TREX), was conducted in Owens Valley, California (*www.eol.ucar.edu/projects/trex/*), the purpose of the field experiment was to better understand the dynamics of mountain lee waves and rotors while simultaneously investigating the nocturnal boundary layer and thermally driven valley flows during quiescent periods. TREX datasets allow comparisons between traditional atmospheric measurement systems such as sonic and hot-film anemometers and remote sensors.

A large number of *in situ* and remote sensing instruments were positioned in the valley to investigate the turbulent rotational motions and downslope wind storms over the valley. Arizona State University (ASU) deployed a sodar/RASS, a flux tower, and a coherent Doppler lidar. The ASU coherent Doppler lidar emits 500 infrared laser pulses per second into the atmosphere. Aerosol particles present in the atmosphere scatter laser light back to the lidar, and the Doppler shift is measured, yielding radial velocities. Doppler lidar systems have been used in previous experiments to analyze flows in complex terrains. Banta (1999*)* deployed Doppler lidar near the Grand Canyon to observe various flow patterns.

Data from 'stare' scans carried out on April 30th and May 1st during TREX have been used in this paper for estimating the spatial averaging effects of the lidar and assessing the performance of the lidar in measuring the turbulence parameters. The stare scans were performed with 72m range gates using elevation angles of -1.39 and -0.53 degrees and azimuthal angles of 71.40 degrees and 72.19 degrees, respectively, on April 30th and May 1st. For these scans, the lidar was focused on two different meteorological towers where sonic anemometers were placed

The sonic towers were placed at a distance of 1.5km from the lidar. The lidar performed a number of different scans, in addition to the 'stare' scans on the towers where the sonic anemometers were placed.

3. Theoretical Considerations

Classical turbulence theories of Kolmogorov and others provide a theoretical foundation for dissipation estimates through a well-known relationship between the structure function and dissipation. The structure function can be expressed for in-situ measurements as in Frehlich, Hannon and Henderson, (1998):

$$D_v(s,r) = \left\langle \left[\; v'(r-s/2) - v'(r+s/2)\; \right]^2 \right\rangle. \qquad (1)$$

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

$$D_v(s,r) = 2\sigma_{v'}^2 \Lambda\left[s/L_o(r)\right]. \qquad (2)$$

where, $L_o(r)$ is the measure of the outer scale of turbulence, which is proportional to outer length scales such as the integral length scale L_i, $\sigma_{v'}^2$ is the variance of turbulent velocity fluctuations. For the von Karman's model (Hinze 1959),

$$\Lambda(x) = 1.0 - 0.5925485 x^{1/3} K_{1/3}(x)\,. \qquad (3)$$

where $K_{1/3}(x)$ is the modified Bessel function of order 1/3. L_i (or $\frac{1}{k_i}$) is the integral length scale and the relationship between L_i and L_o is given by

$$L_i = 0.7468343 L_o(r)\,. \qquad (4)$$

If the outer scale is very large $L_o << s$ then the Kolmogorov model is valid, viz.

$$D_v(s) = C_v \varepsilon^{2/3} s^{2/3} \qquad (5)$$

where ε is the energy dissipation rate, C_v =2 the Kolmogorov constant (Monin and Yaglom 1975, p. 485), and

$$\varepsilon = A\frac{\sigma_v^3}{L_o} \quad (6)$$

where A is a parameter with a value of approximately 1 (for Davies et al. 2004, *A* = .933668). These functions are based on point measurements and thus do not account for the spatially averaging inherent in the lidar measurements. In order to obtain turbulence parameter estimations using lidar data, several steps must be performed. Firstly, the errors related to the radial velocity are corrected, and, secondly, a deconvolution is carried out to account for the spatial averaging effects. The parameters of the wind field σ_v^2 and L_o are determined by minimizing the error between the lidar-based structure function and another relation which can be obtained using the integral relating point-measured velocities and lidar-measured velocities (spatially averaged), and the empirical relation in Eqns 2 and 3 (see Frehlich et al. (1997, 1998). Turbulent kinetic energy dissipation rate can then be estimated using (Eqn.6).

Estimation of the dissipation of turbulent kinetic energy with high-speed sonics was conducted via the inertial sub-range (e.g. see Lundquist 2004). The dissipation rate is estimated from the frequency spectrum in the inertial frequency sub-range, which is given by:

$$\varepsilon = \frac{2\pi}{U}\left[\frac{f^{5/3}S_u(f)}{\alpha}\right]^{3/2} \quad (7)$$

Where U is the mean streamwise speed, α the kolmogorov constant for the velocity component (here 0.55), $f^{5/3}S_u(f)$ the mean compensated spectral intensity in the inertial sub-range of the streamwise component and f the frequency.

4. Results:

Examples of a lidar-measured (spatially averaged velocities) structure function, a fit to this estimate using the empirical relations with σ_v^2 and L_o as fitting parameters, and the corresponding estimated point-wise structure function (using Eqn 2) are shown in Fig. 1.

Note that the pointwise structure function is more than a factor of two higher than the lidar-based structure function at small separations s. This illustrates the impact of the spatial filtering of the velocity over the pulse volume.

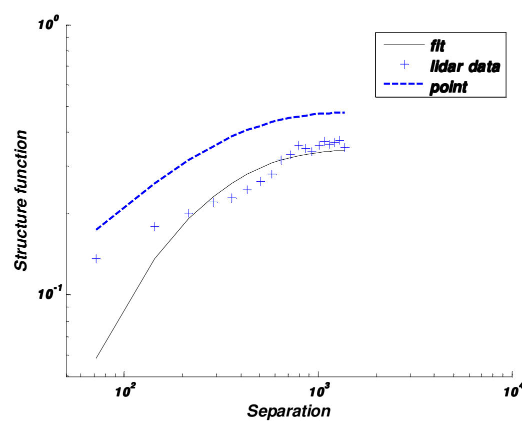

Fig.1. Structure functions ($m^2 s^{-2}$) vs. separation (m) on 30th April at 0940-1040 hrs. Doppler lidar estimates for the velocity structure function (+), the best fit model (__), based on the point measurements (--).

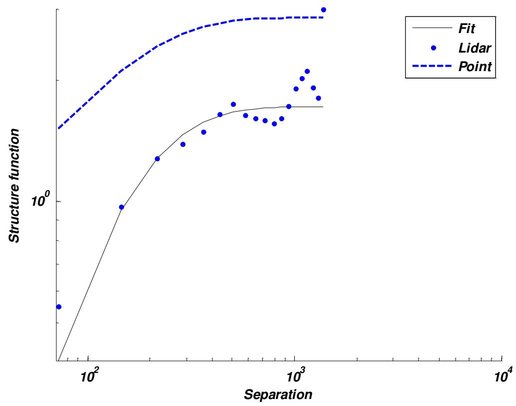

Fig.2. Structure functions (m^2s^{-2}) vs. separation (m) for 30th April at 1640-1740 hrs. Doppler lidar estimates (.), the best fit model (__), point measurements (--).

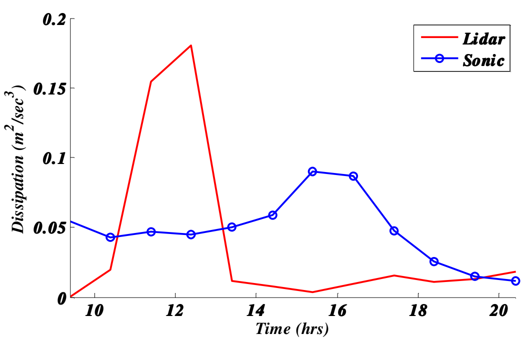

Fig. 3: Comparison of dissipation estimates from the lidar and sonic anemometer for 30th of April (TREX data).

The lidar dissipation estimates generally appear to be within a factor of 2 to 5 of the sonic measurements.

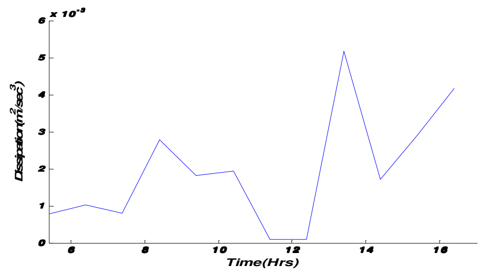

Fig. 4. Dissipation versus Time on 1st of May from TREX (Lidar)

The power spectral density (PSD) versus frequency plot for components of the wind velocity from the sonic anemometer measurements can be seen in Fig. 5. The data shown in Fig.5 is for 2140-2240 hours on 30th of April at TREX. The mean velocity during 2140-2240 hours was approximately 5 m/s. It can be seen in Fig.5 that the isotropy extends up to a frequency of 10^{-3} Hz. But during the night time, at frequency ~ 10^{-1} Hz, a clear difference can be seen between the u, v, and w components of the spectrum, indicating anisotropy. Note that for the smaller scales, the differences are reduced, and at larger scales, the differences increase.

The -5/3 line in the plots corresponds to the Kolmogorov's inertial subrange law, which is a typical result obtained by sonic anemometers and other point-sensor data.

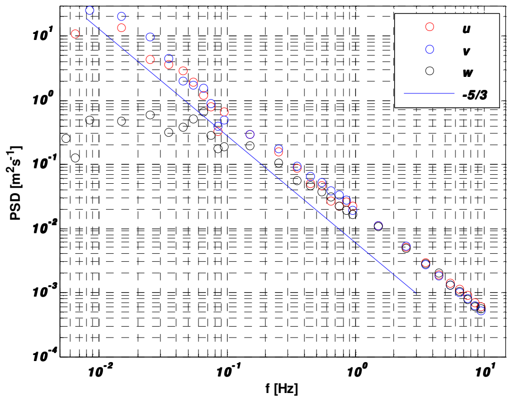

Fig.5 Power spectral density versus frequency at 2140-2240 Hours local time on April 30th.

5. Summary

The turbulence parameters σ_v^2, L_o and ε were determined for TREX data assuming a von Karman spatial spectrum of the random velocity field. The intercomparison of lidar and sonic anemometer dissipation retrievals provides an evaluation of utility of Doppler lidar systems for educing turbulence parameters. The lidar-based retrieval is generally within a factor of two to five of the sonic method. The structure function for small separations is significantly different between calculations based on (range-gate averaged) lidar data and those based on point-sensors. A further assessment of the nature of the accuracy of the lidar retrievals with specific focus on how violations of underlying assumptions required for the empirical relations is needed. The dissipation estimates should become more robust with decreasing range-gate size, and one might expect that future generations of coherent Doppler lidar allow more effective dissipation retrievals.

Acknowledgements

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