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Spectral analysis of wind turbulence measured by a Doppler Lidar for velocity fine structure and coherence studies

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Abstract

Turbulence in the Kolmogorov inertial subrange has been measured remotely by a line-averaging range-gated pulsed coherent Doppler Lidar, i.e., a commercially available wind Lidar (Leosphere WindCube WLS7) modified in order to stare horizontally into the approaching turbulent flow at a platform situated at 125 meters height in the meteorology tower at Risø DTU, Denmark. Time series of wind turbulence was recorded by the Lidar as well as by a sonic anemometer mounted on the tower during December 2009 with wind approaching the probing Lidar laser beam from a variety of wind directions providing data for analysis of the influence of Lidar spatial filtering as well as for coherence analysis and studies of the Taylor's "Frozen Turbulence hypothesis".

1 Introduction

Remote sensing of the mean wind and turbulence by coherent Doppler Lidar (LIght Detection And Ranging) systems have during the last decade increasingly been deployed in wind energy research and industry mainly as ground based instruments for wind resource and profile measurements [1] and recently also for ground based 3D mapping of the wind and turbulence field as proposed in [2].

There is, however, an emerging interest in horizontal measurements in front of wind turbines at hub height for the prospects of providing information in advance of the wind field approaching the wind turbine to the control system of the turbine. This strategy has the potential to increase the power production and decrease the damaging loads. In an early study a cw wind Lidar was placed on the top of a wind turbine nacelle [3] for detection of the approaching gusts whose damaging consequences potentially could be avoided by controlling the pitch of the wind turbine blades as was theoretically analyzed in [4]. Recently a scanning cw Lidar was even operating inside the rotating spinner of a wind turbine [5].

A fundamental question regarding measurements of the approaching wind is if the turbulence structure measured in front of the turbine at a later time actually will reach the turbine as is expressed by the famous Taylor's "Frozen Turbulence hypothesis", which assumes that the turbulent eddies are translated by the mean wind speed. In this study we have a unique opportunity to study the evolution of the turbulence structure by using ten sensors in the form of the range gates of a remote sensing pulsed Doppler Lidar (WindCube) separated by 20 m on a horizontal line at about 125 meters height.

An additional crucial aspect of remote sensing Doppler Lidars is that they are not providing point measurements but rather an average of the wind component along the measuring laser beam with a characteristic sampling profile with a width of some tens of meters which acts as a low-pass filter on the wind spectra measured. This spatial filter effect was recently studied for a pulsed Lidar system called WindCube from the French company Leosphere and a continuous-wave (cw) Lidar called ZephIR from the English company Natural Power from the ground at the Risø DTU operated test station for large wind turbines at Høvsøre in Western Denmark [6, 7].

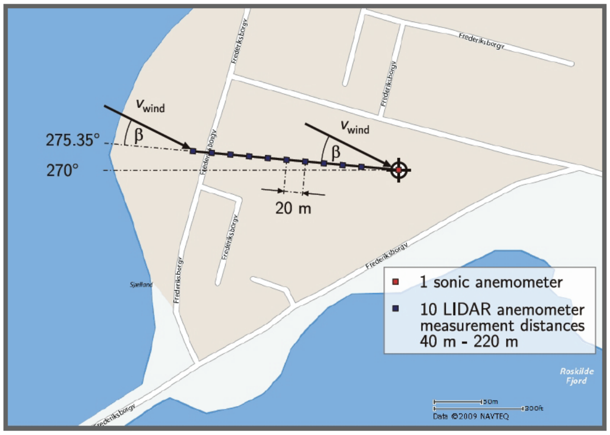

Figure 1: The measurement geometry around the meteorology tower at Risø on the east border of Roskilde fjord in Denmark.

2 The experimental setup

A commercially available remote sensing line-averaging range-gated pulsed coherent Doppler wind profiler Lidar (Leosphere WindCube WLS7) was modified in order to stare horizontally into the approaching turbulent flow at a platform situated at 125 meters height in the meteorology tower at Risø on the east border of Roskilde fjord in Denmark. Ten range gates centered at distances separated by 20 meters from 40 m to 220 m provided ten simultaneous measurements of the wind on a horizontal line in a westerly direction as can be seen in Figure 1 where the measurement geometry is illustrated.

Time series of wind turbulence was recorded during more than one month in the end of 2009 with wind approaching the probing Lidar laser beam from a variety of wind directions, different speed intervals and stability regimes. For comparison a sonic anemometer was mounted on the tower at the same height as the Lidar. The sampling rate of the sonic was 20 Hz whereas the Lidar was limited to a sample rate of only 0.43 Hz.

3 Analysis of the spatial volume averaging effect

For detailed analysis, three periods with the mean wind at some different but small angles, β, to the Lidar measuring direction were selected and the time series of the wind during those periods are

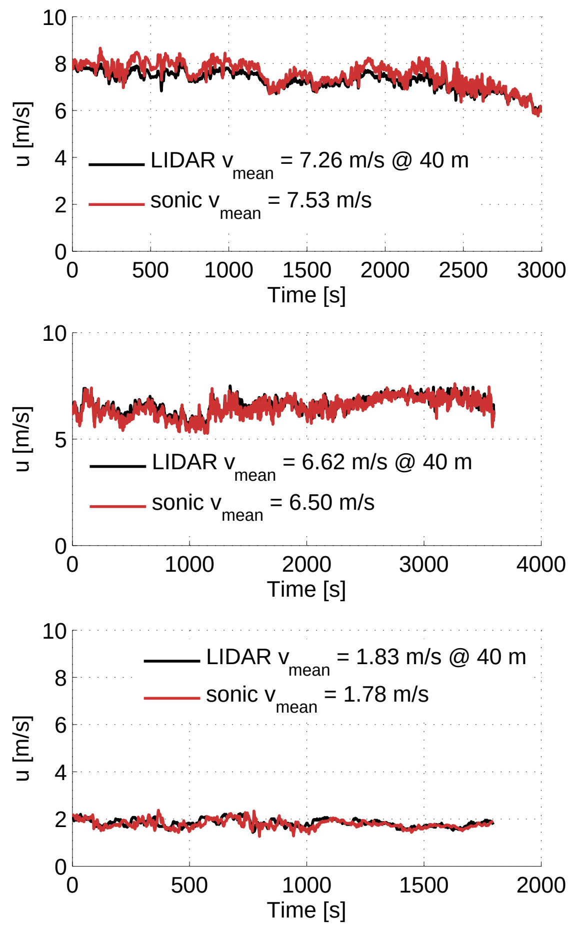

Figure 2: Time series of wind velocities for the three different periods with different angles between the mean wind direction and the Lidar measuring direction.

given in Figure 2, where it can be seen that the first two periods had a wind speed around 7 m/s and the third period had a lower wind speed of about 2 m/s and also less turbulence. The first two periods occurred at the night towards December 1 between 22:50 and 23:40 and between 00:20 and 01:20, respectively. The last period occurred in the morning of December 21 between 09:50 and 10:20. The angle between the mean wind direction and the Lidar measuring direction was 0.4, 20.9 and 10.4 degrees for period 1, 2 and 3, respectively.

Based on the time series recorded, the spectra of the wind velocity could be calculated as seen in Figure 3 where power spectra of the Lidar-measured wind velocity are compared with spectra of the corresponding wind component measured by the sonic anemometer mounted on the tower

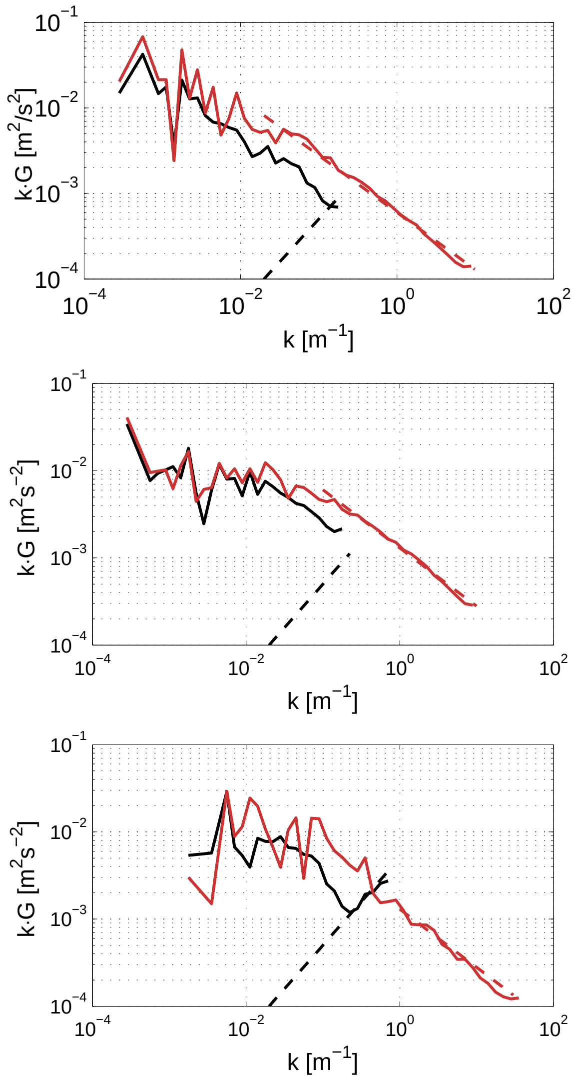

Figure 3: Power spectra of the wind velocities for the three different time periods.

for the three time periods described above. The black dashed line represents the noise level in the Lidar measurements and presence of noise is clearly seen in the spectrum from the third period featuring low turbulence. The red dashed line represents the slope of -2/3 present in a theoretical Kolmogorov inertial subrange spectrum, which the experimentally obtained spectra based on the sonic measurements perfectly follows. The effect of the spatial filtering of the Lidar can clearly be seen as a lowered amount of energy present at the higher frequencies in the Lidar-based spectra.

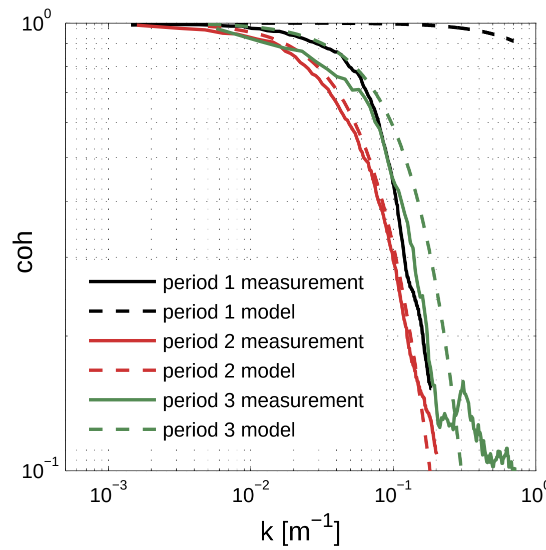

Figure 4: Comparison between measured and modeled coherence with a separation D=20 m for the three different periods.

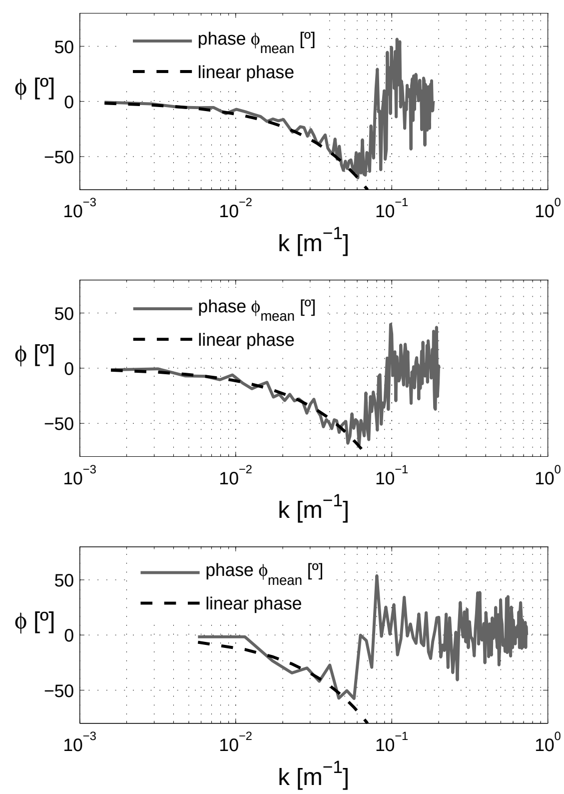

Figure 5: The phase of the lidar measurements in comparison with a linear phase.

4 Analysis of the coherence

The coherence between Lidar data from consecutive range gates separated by 20 meters was calculated using the number of partitions corresponding to the number of 10-minute periods in each interval. In Figure 4 the average of the coherence of all nine adjacent range gate pairs is given together with a theoretical prediction recently derived at Risø [8]. The partitioning estimation bias [9] has been removed from the coherence calculated and the result has been smoothed with a relative bandwidth filter with a bandwidth of 0.5.

Finally, in Figure 5 the phase of the measured Lidar data averaged as the coherence is compared with a phase that is varying linearly with the wave number as expected if the hypothesis of frozen turbulence is valid.

5 Discussion and Conclusions

The unique experimental investigation of inertial subrange turbulence measured by Lidar and sonic anemometer together with the extended theoretical work provides new insights into turbulence fine structure and coherence measured by remote sensing wind Lidars.

In particular, it can be concluded from inspection of Figure 4 that the coherence is almost unity for low wavenumbers meaning that the large eddies are translated without changing their structure over this distance and all fluctuations are traveling with the same speed for small wavenumbers up to about $k = 0.06\ m^{-1}$ as can be seen in Figure 5. A more detailed analysis will provide guidance in the evaluation of wind turbine control strategies based on remotely sensed wind and turbulence approaching wind turbines [10].

Acknowledgments

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