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Laser scanning of a recirculation zone on the Bolund escarpment

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Abstract

Rapid variations in the height of the recirculation zone are measured with a scanning wind lidar over a small escarpment on the Bolund Peninsula. The lidar is essentially a continuous-wave laser Doppler anemometer with the capability of rapidly changing the focus distance and the beam direction. The instrument measures the line-of-sight velocity 390 times per second and scans ten wind profiles from the ground up to seven meters per second. The results will be used to test computational fluid dynamics models for flow over terrain, and has relevance for wind energy. The development of multiple lidar scanning systems is done primarily for that purpose.

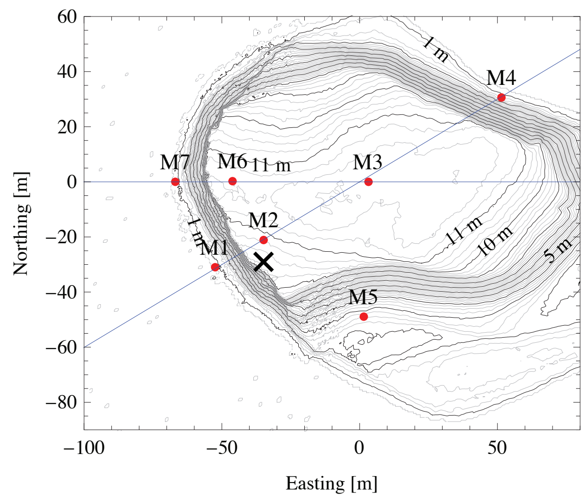

Figure 1: The position of seven of the ten meteorological masts in the Bolund Experiment. One mast is to the west in the fjord and the two last are to the east. The lidar is positioned between masts M6 and M3 twenty meters from the cliff pointing along the blue line (also called Line B in [1]) towards the cliff due west. The black cross is the position of a conically scanning standard ZephIR lidar.

1 Introduction

Flow over complex terrain is a challenge for wind energy, because it is often difficult to predict the turbulent flow implying uncertain estimates of power production and mechanical loading of the turbine. Scanning the wind flow with remote sensing devices offers great opportunities for wind energy and many lidar companies are starting to provide instruments to do that.

2 Experiment

Atmospheric flow over a small bluff with a 12-m tall vertical cliff have been studied experimentally at the Bolund peninsula in Roskilde Fjord, Denmark. The Bolund experiment was designed to provide a dataset for validation of numerical modeling of flow over complex terrain. The experiment undertaken during the winter 2007-2008 described in Berg et al. [1] engaged ten meteorological masts (see figure 1) and provided data for a blind comparison of fifty-seven models [2].

The models displayed the largest errors in the calculated mean wind speed and turbulent kinetic energy close to the surface in regions where flow separation occurred. Every model, ranging from Reynolds-Averaged Navier-Stokes (RANS) over large eddy simulation (LES) to physical model scale tests in flumes or wind tunnels, underestimated the turbulent kinetic energy in the highly disturbed region right downstream of the vertical cliff. The purpose of the present experiment, undertaken in the fall of 2011 long after the meteorological masts were removed, was to study in detail this unsteady recirculation zone with a scanning laser anemometer.

3 Instrument

The laser anemometer, which is a part of the "windscanner.dk" project at DTU Wind Energy, steers the focused beam with two independently moving prisms in a patented configuration [3]. Simultaneously, the focus is changed so the point of measurement can be moved rapidly in space.

The two hundred thousand Doppler spectra acquired every second are averaged down to 390 spectra per second from which the line-of-sight velocities are derived through calculation of the median of the power spectral density after a suitably chosen background has been subtracted. The instrument under the prism scanner is an improved version of the ZephIR lidar described in [4, 5], with a larger effective aperture, more sensitive detector, and an incorporation of an acousto-optical modulator in order to distinguish the sign of the line-of-sight velocity. The lidar measuring on Bolund is shown in figure 2. Two of these instruments have been used simultaneously to study the unsteady downwash from a hovering helicopter, see Sjöholm et al. [6].

Figure 2: The scanning lidar measuring upwind towards the cliff of Bolund. See figure 1.

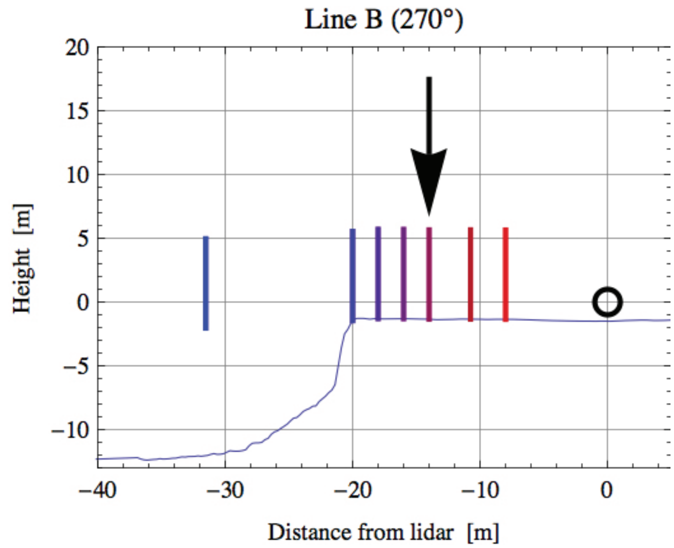

Figure 3: The position of the vertical scans relative to the Bolund escarpment. The position of the laser anemometer is indicated by a circle, and the position of the scan shown in figure 5 is indicated with an arrow.

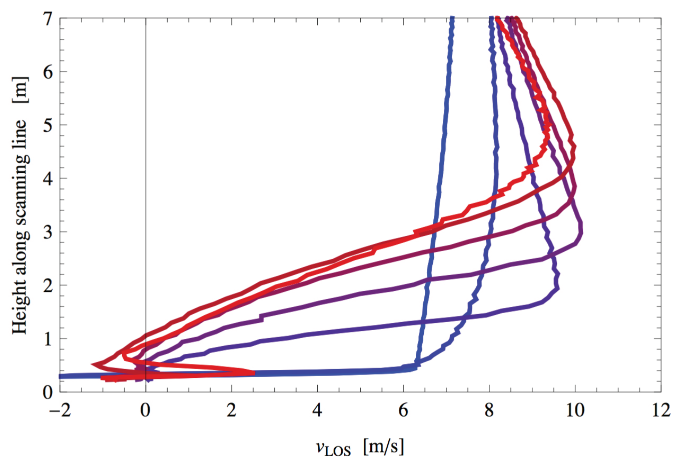

Figure 4: One hour average velocity profiles. The colors indicate the various positions as indicated in 3. Notice the reversed mean flow for some profiles in the lowest meter above the ground.

4 Results

The flow was scanned in seven vertical profiles at different distances from the escarpment extending from the surface and seven meters up, see figure 3. At every vertical position the wind profile was measured ten times per second allowing detailed unsteady characteristics to be derived. Between every seven vertical profiles the line-of-sight velocities were measured on a horizontal arc extending $\pm 30°$ from the blue horizontal line in figure 1. The focus distance during that operation was 120 m, and it allow for a determination of the undisturbed upwind speed and wind direction. The vertical mean profiles shown in figure 4 were taken when the wind was due west, and they show speed-up over the escarpment at the higher heights while a turbulent inner layer is growing rapidly from the edge. The lowest part of the turbulent layer show reversed mean winds. Close to the edge the height of the inner layer seems constant, while it is oscillating violently further downstream from the edge as seen in figure 5.

It is also possible to calculate the standard deviation of the velocity at every profile. The results are shown in figure 6. No compensation was done to account for consequences of the measurement volume on the turbulence, because the focus distance is quite short and consequently the measurement volume is limited. This issue is considered in [7]. With these reservations figure 6 shows that the strongest velocity fluctuations are elevated from the ground. We interpret that to be caused by the undulating sharp interface between slow and fast fluid, as also shown in figure 5.

The new remote sensing based wind profile measure-

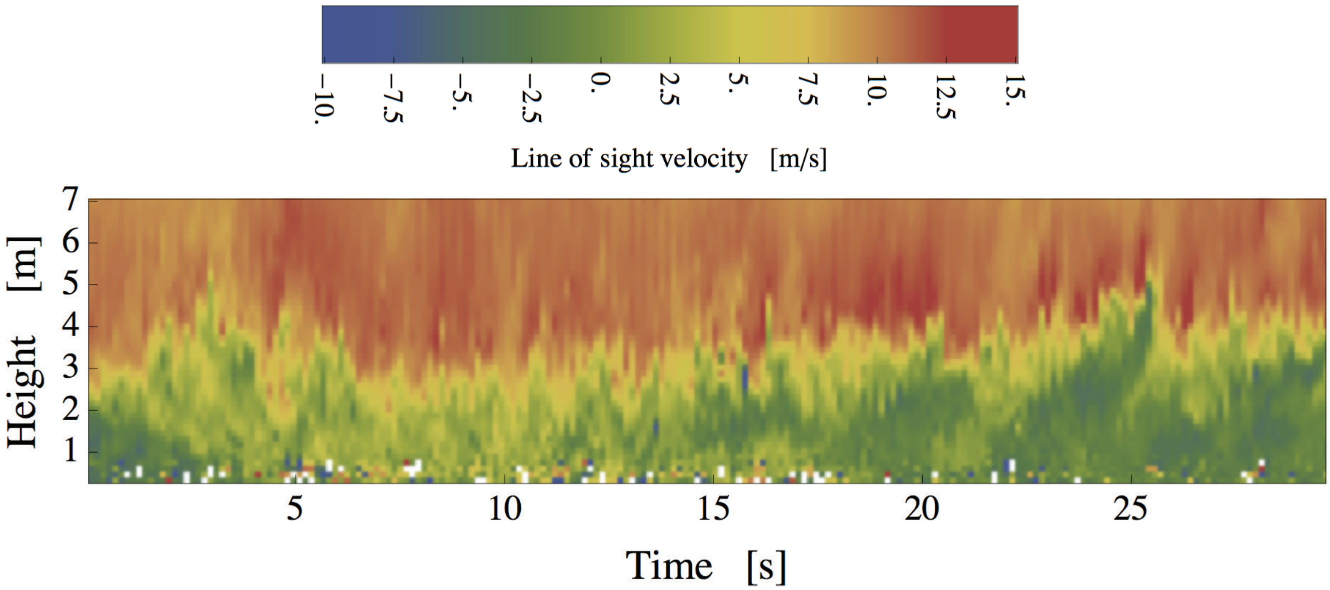

Figure 5: Example of a scan of the line-of-sight velocity lasting 30 seconds. The velocities of 300 consecutive profiles are plotted. Near the ground the instrument fails occasionally. A sharp and rapidly varying interface between fast and slowly moving air is observed. The distance from the cliff is approximately 6 m, while the height of the turbulent layer varies from 2 to 5 m.

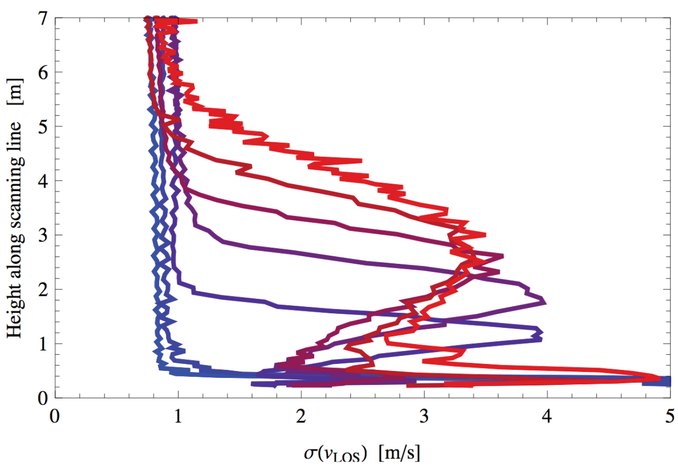

Figure 6: One hour profile of the standard deviation of the line-of-sight velocity. The colors are the same as in figure 4.

ments provide a unique dataset for validation of unsteady flow modeling over complex terrain for wind energy.

5 Future work

The analysis presented here is based on the first hour of data of the experiment, and the last twenty-five hours remains to be analyzed. Spectral analysis of the measured time series and detailed comparison with previous measurements on masts M6 and M7 is also outstanding.

Preliminary modeling of the flow with RANS and LES has limited success, probably due to inappropriate meshes. At DTU Wind Energy we are currently pursuing ways to improve the simulations, and we encourage others to compare their models with these new laser Doppler scans.

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