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To cite this article: J Mann *et al* 2014 *J. Phys.: Conf. Ser.* **555** 012066

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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. We observe a sharp interface between slow and fast moving fluid after the escarpment, and the interface is moving rapidly up and down. This implies that the position of the maximum velocity standard deviation is elevated a few meters above the surface. Close to the ground the mean wind is reversed relative to the general flow. The results are used to test computational fluid dynamics models for flow over terrain, and has relevance for wind energy. The preliminary comparison shows that the models are incapable of reproducing the reversed flow close to the surface, but more works needs to be done.

## 1. Introduction

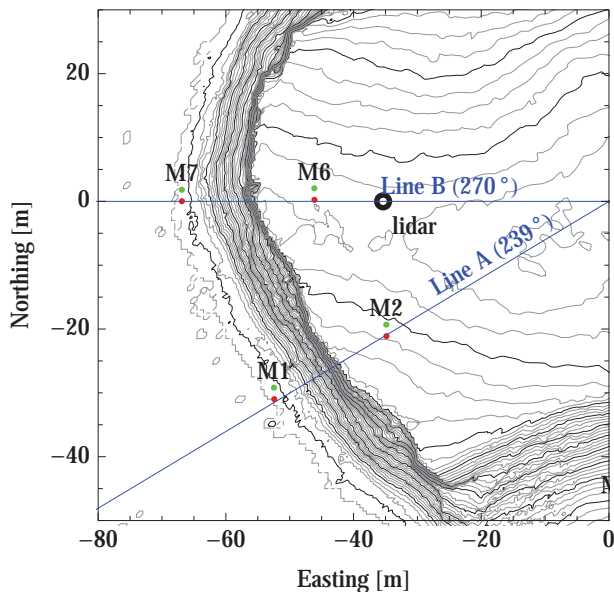
Flow over complex terrain is a challenge for wind energy, because it is often difficult to predict the turbulent flow implying uncertain estimates of power production and mechanical loading of the turbine. This gives rise to disputes among developers and owners of wind farms, and the uncertainties also increases the cost of providing means to finance the wind farm. Scanning the wind flow with remote sensing devices offers great opportunities for wind energy, for example, by pinpointing areas of enhanced turbulence or reduced mean wind speeds.

## 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. [4] engaged ten meteorological masts (see figure 1) and provided data for a blind comparison of fifty-seven models [3].

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





**Figure 1.** The position of four of the ten meteorological masts in the Bolund Experiment. One mast is to the west in the fjord and four more to the east. The lidar is positioned east of mast M6 twenty meters from the cliff indicated by a circle pointing along the blue line (also called Line B in [4]) towards the cliff due west. Green dots are the masts, while the red dots are the position of the sonic anemometers in the 2007-2008 experiment.

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 [6]. 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 exact way this is done is discussed in Angelou et al. [1].

The instrument under the prism scanner is an improved version of the ZephIR lidar described in [12, 2], 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. [11], and soon three instruments will measure simultaneously in a coordinated way.

Measuring turbulence with lidars is notoriously difficult because the measurement volume can be relatively large [5, 9, 7, 8]. However, in the present experiment the focus distance is small ranging from eight to 32 meters, implying that the measurement volume is relatively small [12]. For the present analysis we therefore ignore the effect of averaging.

### 4. Results

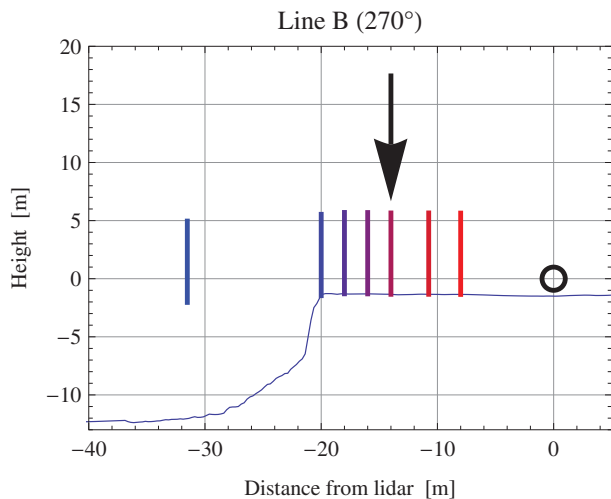
The flow was scanned in seven vertical profiles at different distances from the escarpment extending from the surface and seven meters up, see figure 4. At every vertical position the wind profile was measured ten times per second allowing detailed unsteady characteristics to be derived. Between every seven vertical profiles the line-of-sight velocities were measured on a horizontal arc extending  $\pm 30^\circ$  from the blue horizontal line in figure 1. The focus distance during that operation was 120 m, and it allows for a determination of the undisturbed upwind



**Figure 2.** The scanning lidar measuring upwind towards the cliff of Bolund.



**Figure 3.** Escarpment seen from south. See figure 1.

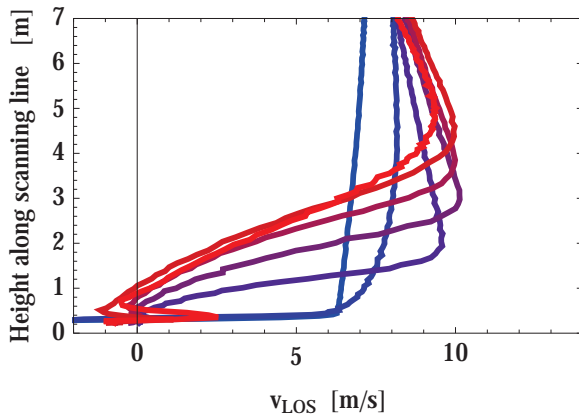


**Figure 4.** The position of the vertical scans relative to the Bolund escarpment. The position of the laser anemometer is indicated by a circle, and the position of the scan shown in figure 7 is indicated with an arrow.

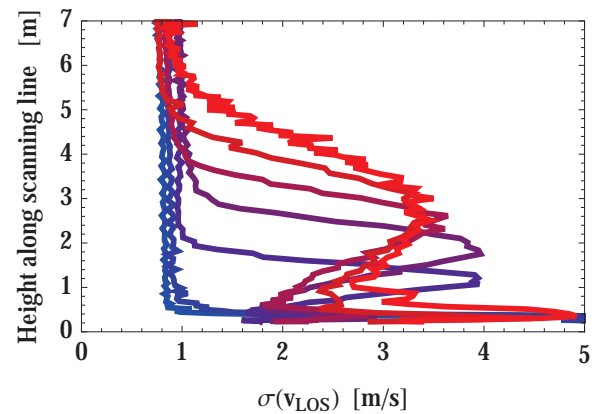
speed and wind direction. The vertical mean profiles shown in figure 5 were taken when the wind was due west, and they show speed-up over the escarpment at the higher heights while a turbulent inner layer is growing rapidly from the edge. The lowest part of the turbulent layer show reversed mean winds. 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 7.

It is also possible to calculate the standard deviation of the velocity at every profile, given the reservations mentioned towards the end of section 3. 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 [10]. 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 7.

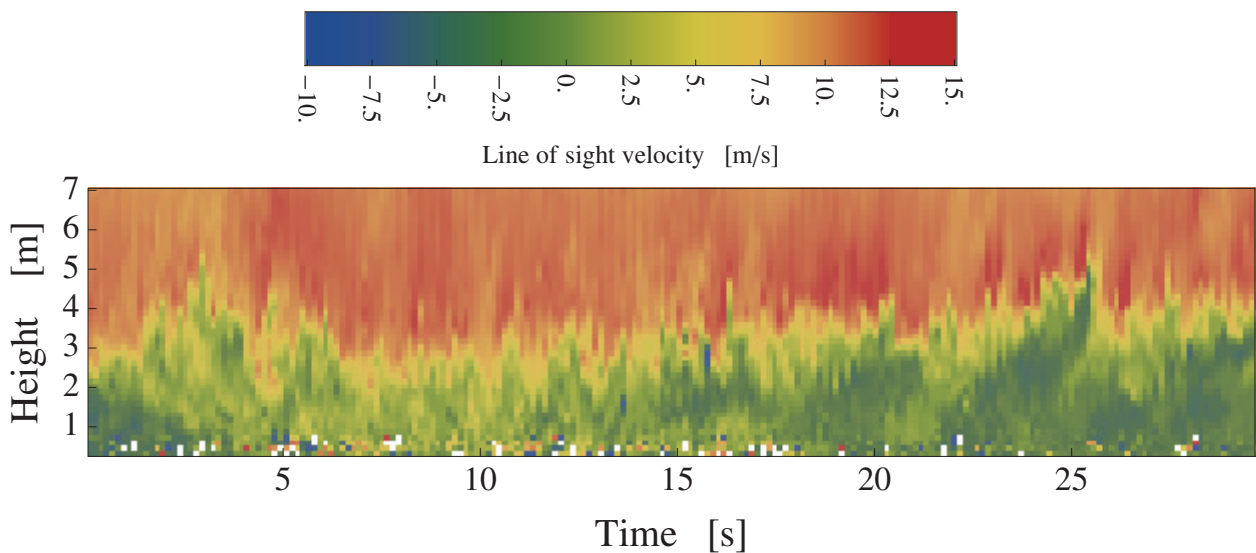
The new remote sensing based wind profile measurements provide a unique dataset for validation of unsteady flow modeling over complex terrain for wind energy.



**Figure 5.** One hour average velocity profiles. The colors indicate the various positions as indicated in 4. Notice the reversed mean flow for some profiles in the lowest meter above the ground.



**Figure 6.** One hour profile of the standard deviation of the line-of-sight velocity. The colors are the same as in figure 5.



**Figure 7.** 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.

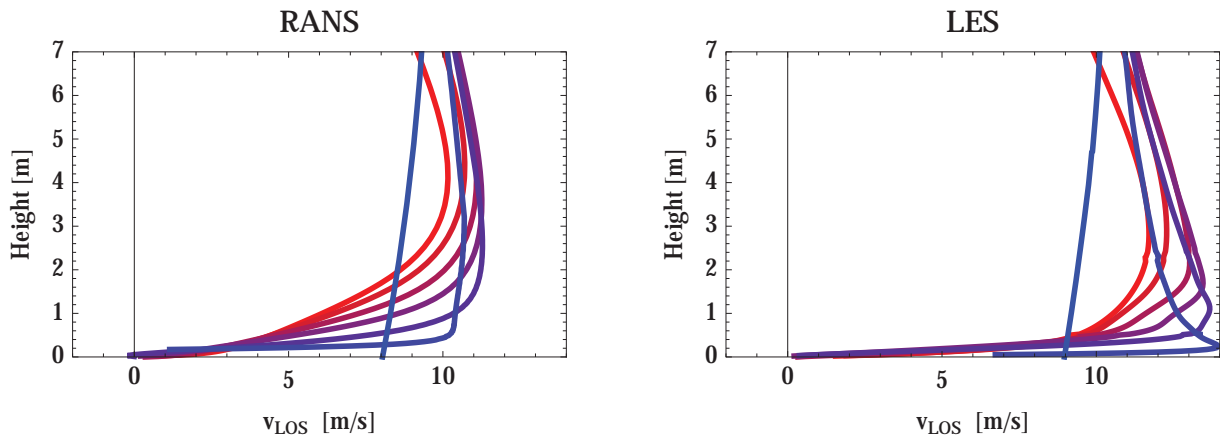
## 5. Preliminary modeling

Preliminary modeling of the flow with RANS and LES has limited success, probably due to inappropriate meshes. The model we use is a multi-block finite volume solver for incompressible Navier-Stokes equation in curvilinear coordinates called EllipSys3D [13]. Both large eddy simulation (LES), detached eddy simulation (DES) and Reynolds-Averaged Navier-Stokes (RANS) has been tested. The LES and DES have the domain size given in Table 1, while the RANS used five million grid cells distributed over a larger domain.

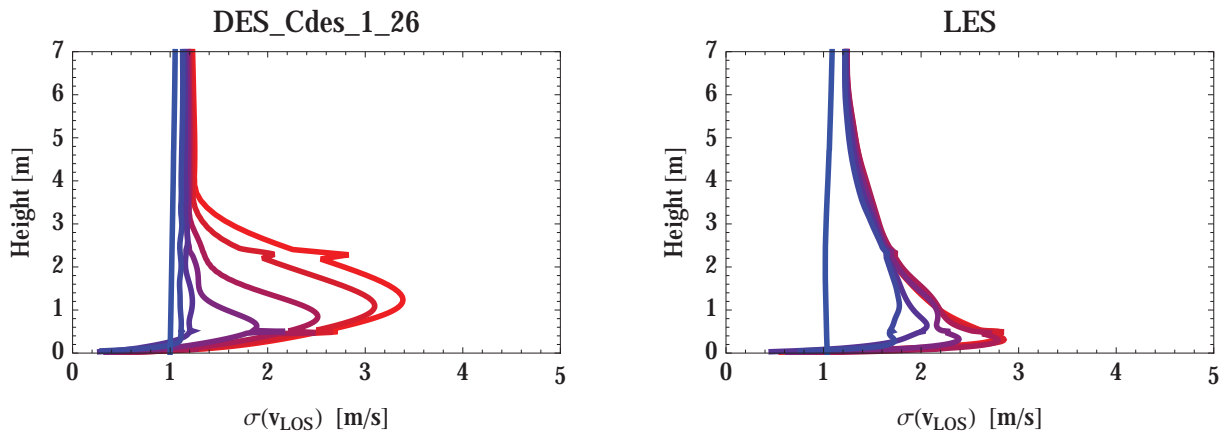


**Table 1.** Calculation domain of EllipSys3D for the Bolund peninsula LES and DES.

	range [m]	Cells
Streamwise	$-362 < x < 785$	320
Spanwise	$-368 < y < 385$	192
Wall normal	$0.75 < z < 520$	256



**Figure 8.** Mean wind profiles calculated by RANS (left) and LES (right). The figures should be comparable to Figure 5 except from a scaling factor on the velocities.



**Figure 9.** Profiles of the standard deviation of the velocities calculated by DES (left) and LES (right). The figures should be comparable to Figure 6 except from a scaling factor on the velocities.

For the mean none of the models succeed in producing a reversed flow zone close to the surface. Two of the models are shown in Figure 8 showing mediocre comparison with the measurements in Figure 5.

All models do not model the measured standard deviations very well. And example of two of the model may be seen in Figure 9. Generally, standard deviations are underestimated by the models.

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.

## 6. Future work and Conclusion

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. A more detailed account for the averaging of the velocities made by the lidar should also be done. Finally, analysis of any dependence of turbulent region above the cliff on the direction of the approaching wind is also outstanding.

The lidar measurements reveal reversed flow close to the surface of Bolund after the escarpment and a sharp, undulating interface between slow and fast moving fluid, which is an qualitative observation that would have been difficult to do with a mast with a few anemometers. Much modeling work remains to reproduce these observations.

## Acknowledgments

The authors gratefully acknowledge the financial support from the Danish Agency for Science, Technology and Innovation through grant no. 2136-08-0022, the [windscanner.dk](http://windscanner.dk) project. The work was partially supported by the [Center for Computational Wind Turbine Aerodynamics and Atmospheric Turbulence](#) under the Danish council for strategic research, Grant No. 09-067216. We would also like to thank three anonymous reviewers whose comments have improved the manuscript significantly.

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