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Turbulence length scales in complex terrain

Numerical prediction and validation

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Abstract

Flow recirculation occur frequently in complex terrain, and the generated turbulent length scales can impose high maintenance costs to exposed wind turbines. Most flow modelling tools in the industry fails to predict large-scale recirculating flow, and RANS models (used in several commercial tools) actually suppress these features. However, models resolving the temporal fluctuations can describe turbulence more accurately.

In this study, a StreamLine XR lidar was used to provide a dataset for flow model validation in highly complex terrain. A comparison of a DES and RANS model was performed, and the DES prediction of the turbulence length scale development was investigated in detail. The results show the superiority of the DES model over the RANS model in cases where large scale recirculation is present. It is also found that despite the spatial filter effect in the DES model, the main characteristics of the turbulence length scale development are well described in the model.

Experimental setup

The site is located in central Norway, approximately 3 kilometers from the coastline. The lidar was located approximately 345 meters north of a 100 meter measurement mast. The large-scale turbulence structures of interest in this study are expected to be generated downwind of ridge located approximately 1300 meters southwest of the lidar (see figure 1). The ridge has a steep vertical cliff with an elevation of 150 meters facing westward.

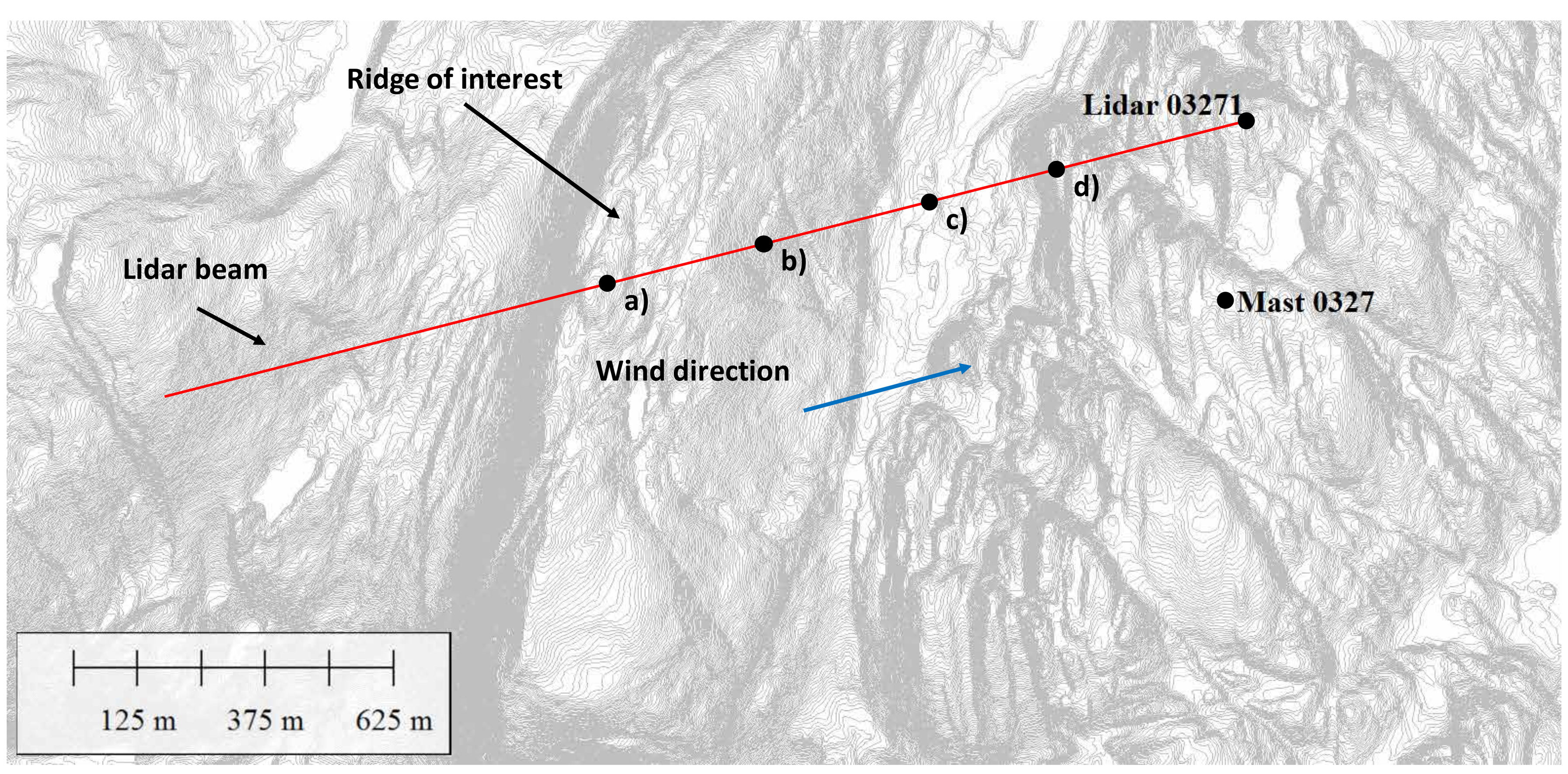

Figure 1 – Map describing the location of the lidar and measurement mast, as well as the ridge of interest to the study. The point locations a) – d) are used for further evaluations

A detailed assessment of wind data from the measurement mast was used to identify a time period with constant wind speeds and wind direction. The estimated Monin-Obhukov length scale was found to be near-neutral (|MOL|>450) for the entire period (see table 1 for details).

Table 1 – Wind conditions observed during experiment

Time period	Wind speed @ 100 m mean (min, max) [m/s]	Wind direction @ 100 m mean (min, max) [°]	Monin-Obhukov length scale (min) [m]
14.06.2015 13:00 – 22:30	8.3 (7, 10)	260 (250, 290)	(450)

Numerical setup

The numerical domain was constructed by Fraunhofer IWES' terrainMesher, and the simulations were performed in OpenFOAM. A region covering a 9.5km x 7.3km area orthogonal to the wind direction was meshed by ~56 million degrees of freedom. The inlet setup was first estimated by a RANS simulation using the k-Epsilon model. This simulation also served as the starting point for the DES simulation.

A k-Epsilon based DES model was applied in the LES scope, and a 2nd order Gauss linear differencing scheme was used. This method adjusts the modeled length scale to the grid size, and adopts to fully RANS scale in the near surface region. The DES method compensates the disadvantage of algebraic LES models, for which the mesh cut off does not have to be in the local equilibrium state and the RANS wall functions can be automatically utilized. The turbulence equation system is according to Bechmann and Sorensen (2010).

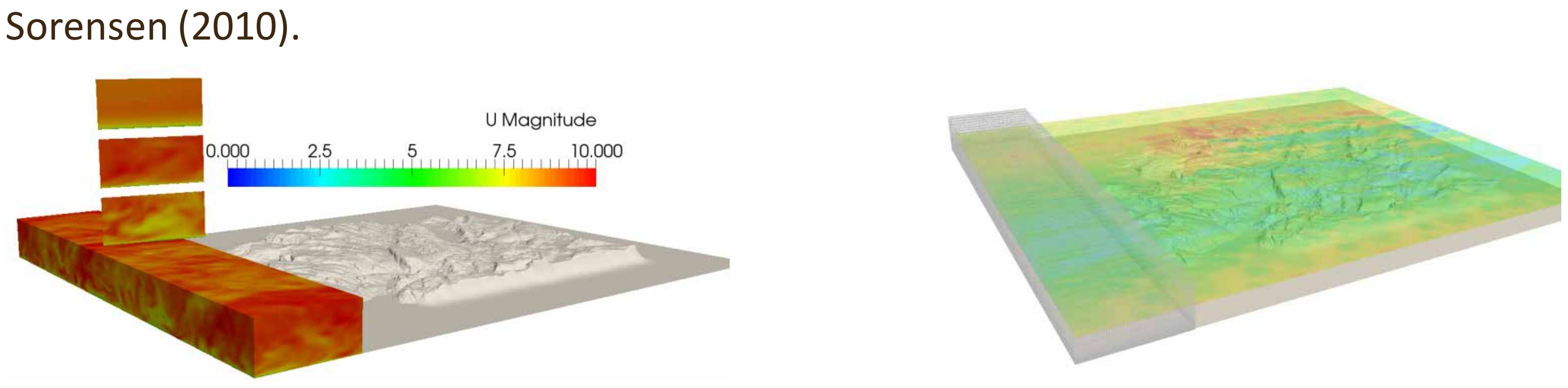

Figure 2 – Illustration showing the prolonged inlet used for cycling the flow for generation of suitable boundary conditions for the DES simulation (left). Resulting instantaneous flow field (right).

Results

The results are evaluated along the lidar Line of Sight (LoS), making a direct validation of the velocity possible. The measured TKE is estimated assuming isotropic turbulence. The DES model provides an excellent prediction of the wind velocity (normalized against upstream free flow velocity). The development of the turbulence is well predicted, however some overestimation is seen.

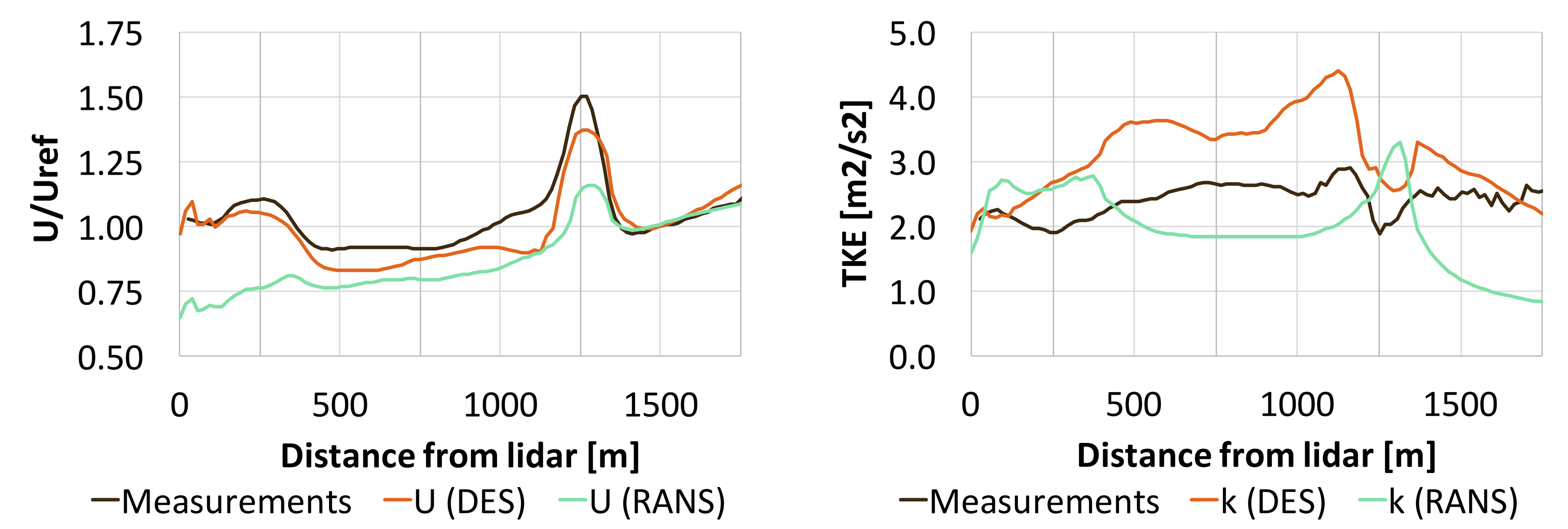

Figure 3 – Evaluation of line of sight velocity and turbulent kinetic energy along the lidar line of sight

A spectral analysis was performed at four different distances from the lidar system [a) 1300m, b) 1000m, c) 600m and d) 400m], and the results were compared to the predicted Kaimal spectrum for the longitudal wind speed based on the measured wind speed at 100 meter at the measurement mast (Kaimal et al, 1972):

$$\frac{nS_u(n)}{u_*^2} = \frac{105f}{(1+33f)^{5/3}}$$

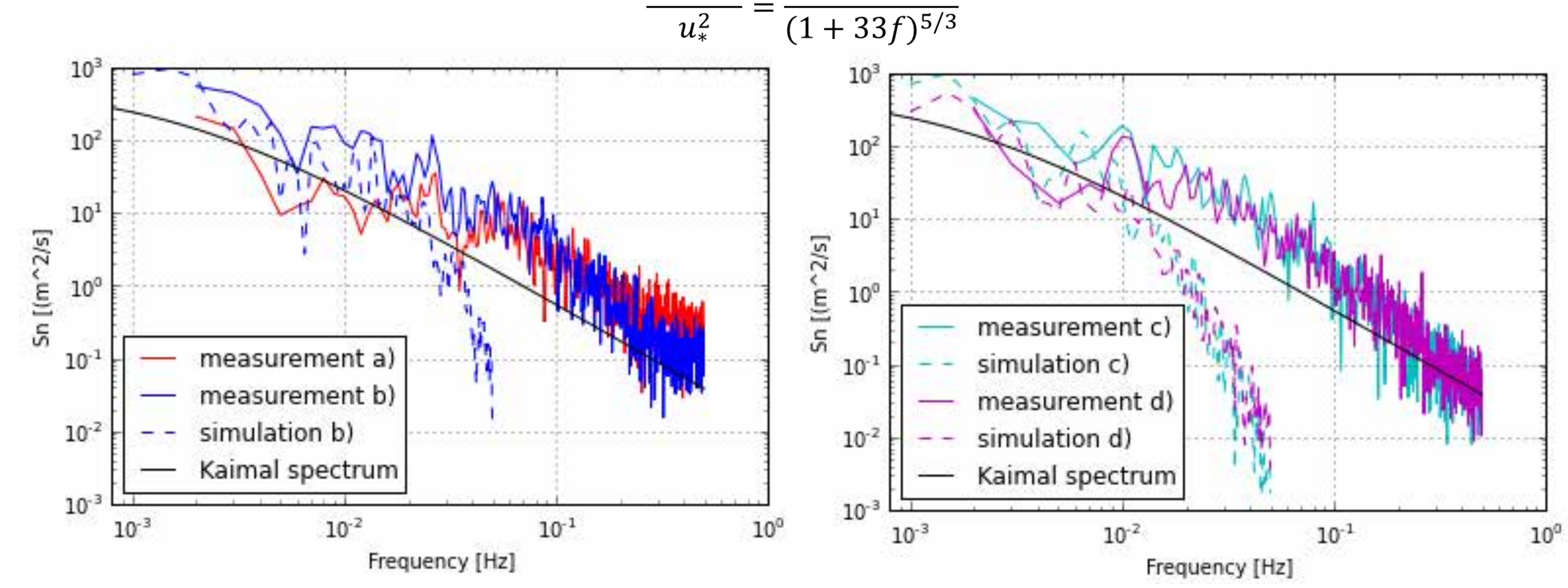

Figure 4 – Power spectral density of measured and modelled wind speed at location a) to d) compared to the estimated Kaimal spectrum at 100 meter height at the measurement mast. The simulation results at a) is omitted as it falls within the RANS-part of the boundary layer

The measurements show an increase in turbulence for f<0.1 Hz, roughly corresponding to the length scale of the ridge of ~100m (L=U/f). The DES model predicts the increased turbulence level at the lower frequencies (f<0.01 Hz), but there is a significant cut-off in the higher frequencies. This is due to the spatial filter imposed by the discrete grid resolution. However, it is clear that the main characteristics of the flow are described by the flow model.

Conclusions

The comparison of a RANS and DES model downwind a ridge in complex terrain show that the DES model applied better describes the generation and transport of large turbulent structures downwind a ridge in complex terrain.

Better predictions of turbulence in complex terrain are needed to reduce the risk of fatigue and high maintenance cost for wind turbines in complex terrain. Advanced DES models in combination with high resolution scanning lidars provide an efficient toolbox for predicting the presence of recirculation and other complex flow phenomena in extremely complex terrain.

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