

Numerical prediction and validation of turbulence length scale development in complex terrain

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Introduction

Flow recirculation is known to occur frequently in extremely complex terrain (Finnigan, 1988), and the generated turbulent length scales can impose high loading and maintenance costs to exposed wind turbines. It is also known that most flow modelling tools in use in the industry fails to predict the presence or behavior of large-scale recirculating flow. Approximations such as the Reynolds Averaged Navier-Stokes approach used in most commercial CFD tools actually suppress these large scale turbulent fluctuations (Prospathopoulos et al, 2012).

Traditional measurement campaigns can provide point measurements to determine the atmospheric turbulence, but models are needed to determine the source and spatial distribution of the turbulence. As the turbulence generated by large scale recirculation is advected downwind, validations of the turbulence models requires measurements at several locations with a spatial and temporal resolution capable of describing the main length scales of the flow.

Recent development in lidar technology has made validation of turbulent flow in full scale viable. This study presents the methodology and results from a full scale experiment in a planned wind farm in highly complex terrain in Norway. The study is a cooperation between Meventus, Fraunhofer IWES and Statkraft, and it is funded by the Norwegian Research Council.

Approach

The extent and development of large-scale recirculation was measured and modelled in a full scale experiment in central Norway.

(1) Measurements were performed using a coherent Doppler lidar (1Hz, 18m range gate) operating in staring mode towards a ridge where the flow recirculation was expected to occur. The measurements were performed parallel to the mean flow, ensuring that the transport of the turbulent structures was measured directly.

(2) Simulations were performed using both a traditional k-Epsilon Reynolds Averaged Navier-Stokes (RANS) and Detached Eddy Simulation (DES) models to predict the measurements. Models were initiated using data from a 100 meter measurement mast.

(3) The results from the numerical simulations were compared to the lidar measurements to evaluate the different models ability to describe the turbulence generation, transportation and eventual dissipation.

As the lidar can only measure along its Line of Sight (LoS), it can only provide one-dimensional wind velocity. However, when validating the flow model using the measured wind data, a three dimensional description of the turbulent flow can be obtained.

Main body of abstract

Site description

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.

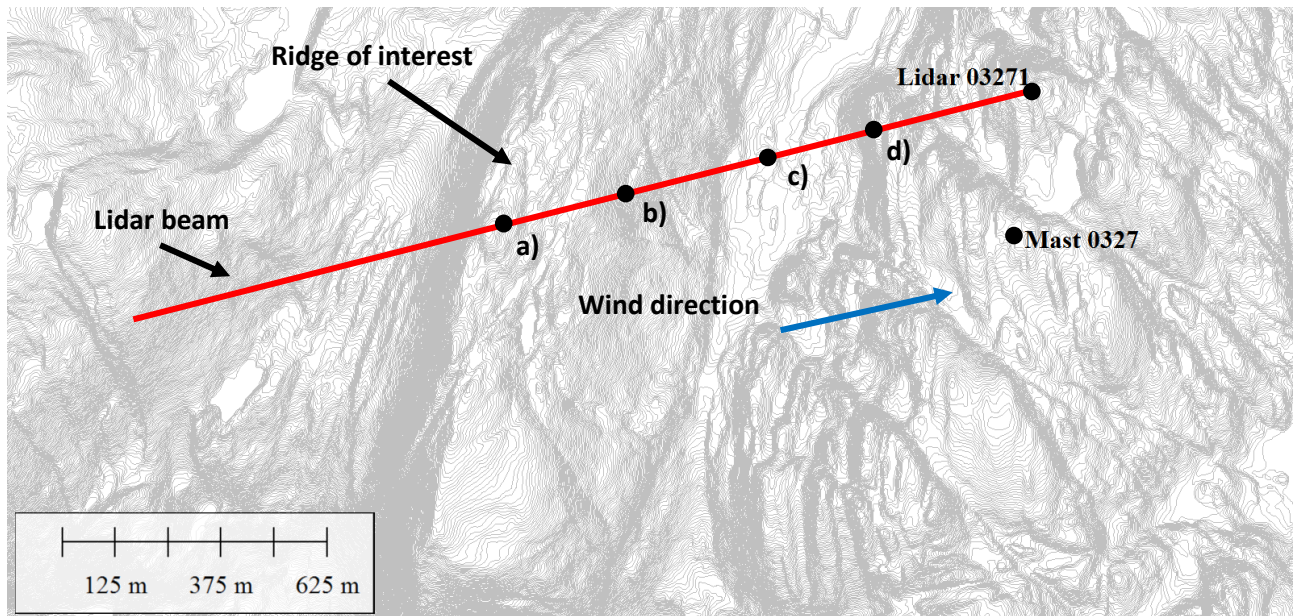


Figure 1- Map describing the location of the lidar and measurement mast, as well as the ridge of interest to the study. The point locations a) – d) are used for further evaluations

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 ($|\text{MOL}| > 450$) 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]
14.06.2016 13:00 – 22:30	8.3 (7, 10)	260 (250, 290)	(450)

Measurements

The measurements were performed using a StreamLine XR lidar operating in stare mode (constant azimuth and elevation) for periods of 10 minutes. The measurements were performed at 1 Hz using range gates of 18 meters, ensuring a temporal resolution of two times that of the spatial.



Figure 2 - Measurement setup with lidar system to the left and power supplies in the right of the picture.

The mast was instrumented with first class cup anemometry at five different heights (20.7, 40, 60, 80 and 100.5) while temperature sensors were located at 3 and 97 meters above ground level. A 3D sonic anemometer measuring at 1 Hz located at 98 meters above ground.

Simulation procedure

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 governing equation system is the Navier-Stokes based solver with RANS and LES turbulence models without heat transfer (neutral conditions).

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. However, in order to obtain the required eddy structures in the inlet profile for the DES simulation, a prolonged inlet with circulating flow was used. The velocity fluctuations were triggered by the surface shear induced by instability in the momentum equation.

A k-Epsilon based DES model was applied in the LES scope. 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).

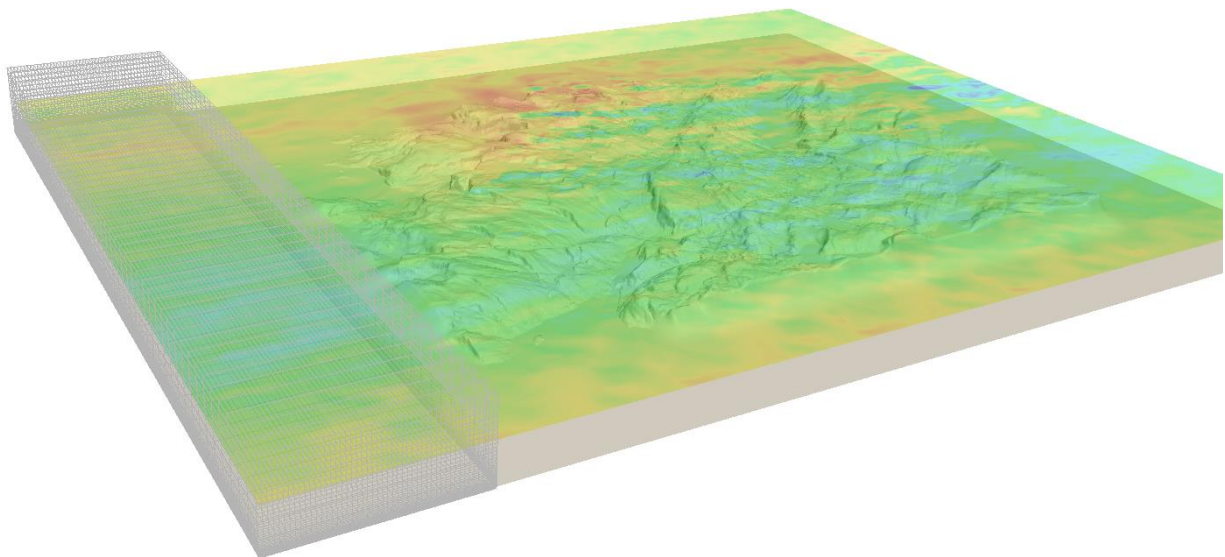


Figure 3 - Illustration showing the prolonged inlet used for cycling the flow for generation of suitable boundary conditions for the DES simulation. The ridge with the vertical cliff is seen in the center of the domain.

The DES simulation was executed over 25000 physical seconds, which corresponds to ~20 flow through time (FFT). The simulation results are averaged over 15 FFT, which can demonstrate a plausible statistical representation.

Results and discussions

The results are evaluated along the lidar Line of Sight (LoS), making a direct validation of the velocity possible. The turbulence kinetic energy (TKE) cannot be compared directly, calling for some approximation. In order to make a comparison with the RANS model possible, the measured TKE is estimated assuming isotropic turbulence.

The results indicate that there is a slight misalignment between the lidar beam and the simulation results, as the simulation results approaches the ground level as the lidar beam passes the ridge in question (located at approximately 1300 meters from the lidar). This is assumed to contribute to the large wind deficit just

downwind the ridge, as the simulation results are obtained in the wall-function region. Closer to the lidar, the DES model provides good estimates for the wind speed variations along LoS.

The DES model is found to overestimate the turbulence. However, the variations along LoS are captured. The overestimate seems to be connected to the wind speed deficit.

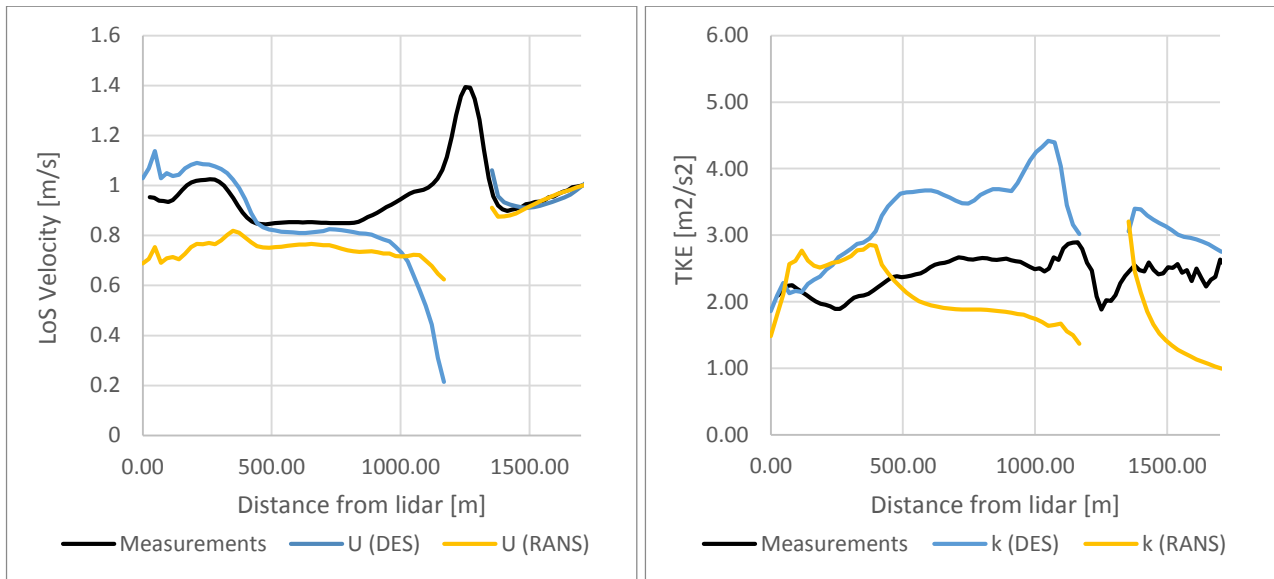


Figure 1 - Evaluation of line of sight velocity and turbulent kinetic energy along the lidar line of sight.

In Figure 4 it is clearly seen that the flow model manages to describe the larger temporal and spatial scales of the turbulent structures generated behind the ridge.

Figure

4

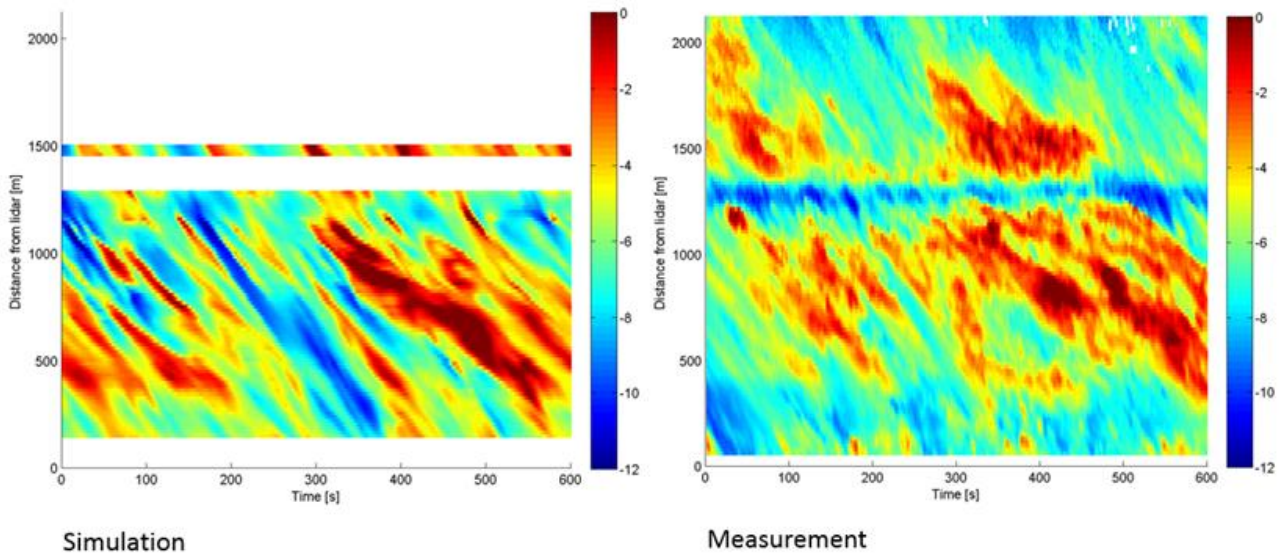


Figure 4 - Line-of-sight velocity [m/s] modelled (left) and measured (right) along a line in direction az=262 and el=0 deg from the lidar towards the ridge. Time period of 600 seconds

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 longitudinal wind speed based on the measured wind speed at 100 meter at the measurement mast (Kaimal et al, 1972):

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

The results show how the model manages to predict the increased turbulence level at the lower frequencies ($f < 0.01$ Hz), but there is a significant cut-off in the higher frequencies.

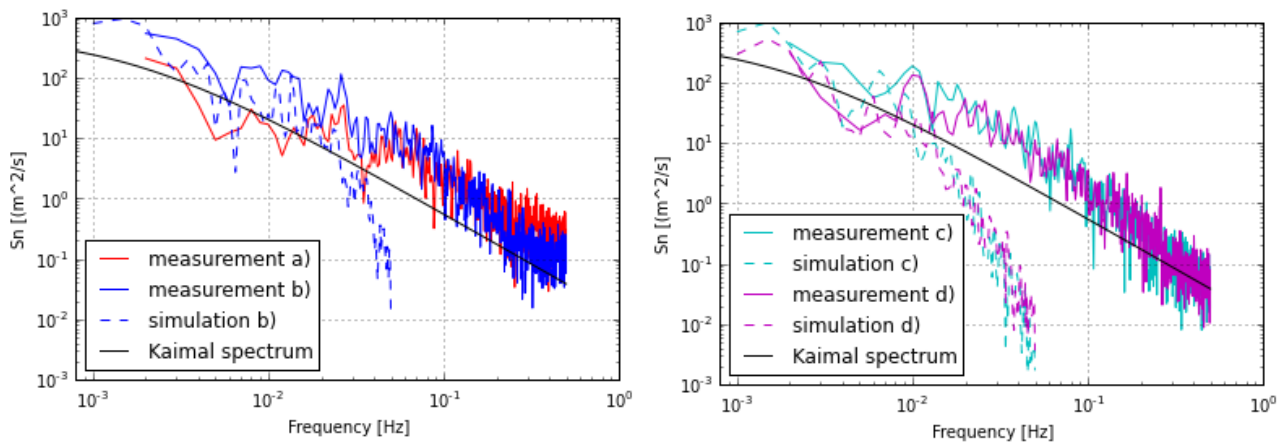


Figure 5 - Power spectral density of measured and modelled wind speed at location a) to d) compared to the estimated Kaimal spectrum at 100 meter height at the measurement mast.

Conclusion

High-resolution doppler lidars are found to be a powerful tool for validating numerical predictions of turbulence in complex terrain. 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. The further work will focus on the applicability of the DES model in different flow regimes and situations.

Learning objectives

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. This study shows how recent development in lidar technology provides a valuable tool for validating numerical predictions of turbulent flow. 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.

References

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