

SCIENTIFIC REPORT



ACTION: ES1303 TOPROF

STSM: COST-STSM-ES1303-30536

TOPIC: Validation of real time turbulence estimation and measurement of wind gust using Doppler lidar.

VENUE: Technical University of Denmark (DTU), Risø Roskilde Denmark

PERIOD: 18 January – 05 february 2016

Host: Sven-Erik Gryning (DTU Wind Energy, Denmark)

Applicant: Lucie Rottner (Météo-France, CNRM, France)

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Contribution by: Lucie Rottner (Météo-France, CNRM, France), Irene Suomi (Finnish Meteorological Institute, Finland)



Introduction

A preliminary work on a new way to estimate atmospheric turbulence using high-frequency Doppler Lidar measurements has been recently achieved by Christophe Baehr (Météo-France, CNRM, Toulouse, France) and myself. The turbulence estimations are based on wind reconstruction using Lidar WindCube observations and a particle filter (Rottner L, Baehr C., 2014). The suggested reconstruction algorithm links the WindCube observations to numerical particles to obtain turbulence estimations every time new observations are available. The high frequency of the estimations is a new point which has to be validated (figure 1). Moreover, the presented algorithm enables to reconstruct the wind in three dimensions in the observed volume. We have thus locally access to the spatial variability of the turbulent atmosphere.

The suggested algorithm has already been applied to a reduced set of real observations. The obtained results are very encouraging : they show significant improvements on turbulent parameter estimations. The objective is now to validate the reconstruction algorithm using longer data sets (from one week to one month).

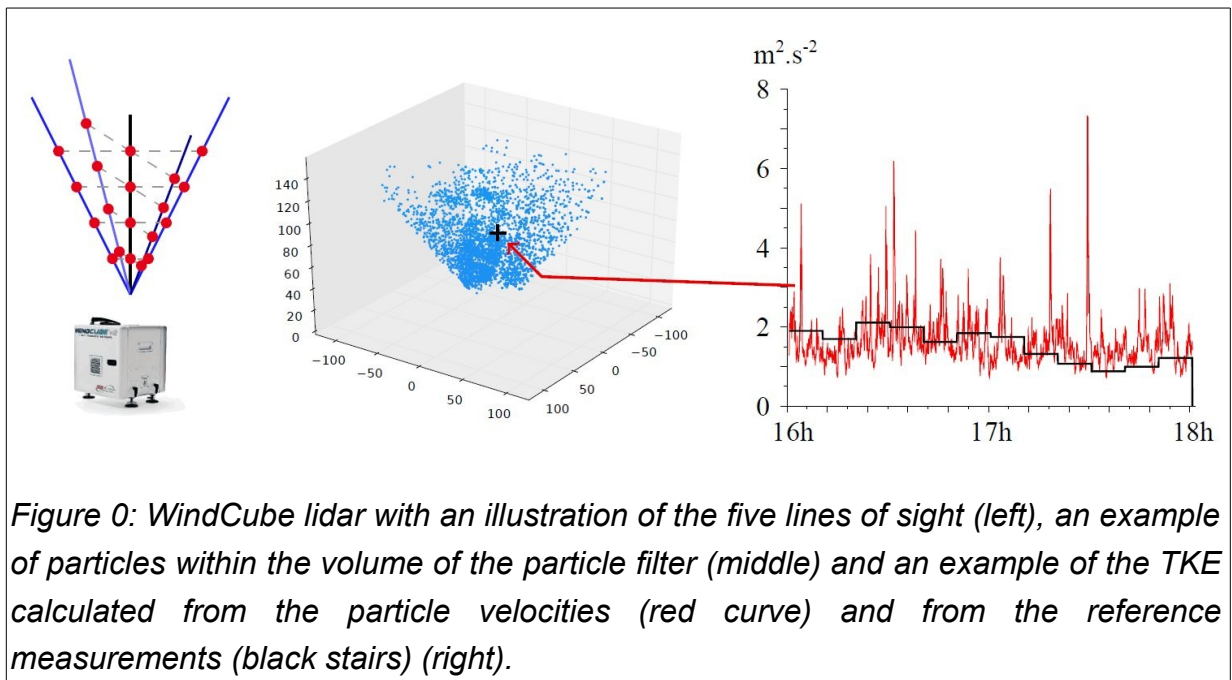


Figure 0: WindCube lidar with an illustration of the five lines of sight (left), an example of particles within the volume of the particle filter (middle) and an example of the TKE calculated from the particle velocities (red curve) and from the reference measurements (black stairs) (right).

As an advanced research center on wind energy, the DTU gathers all the equipment and human expertise which are required to validate the reconstruction algorithm. For instance, several Doppler lidars are operated in Høvsøre at the foot of a high meteorological mast equipped with sonic anemometers. Besides, members of the DTU Wind Energy are world specialists of turbulence measurements.

The scientific mission has been the opportunity to get several data sets of lidar observations, and to set the basis of a collaborative work with Irene Suomi on wind gusts.

Objectives

The main objectives of the STSM were :

- Introduction to the DTU Wind Energy research fields
- Presentation of the turbulence estimation method, and presentation of results previously obtained
- Definition of the policy of use of the DTU data
- Downloading WindCube V2 data and anemometer data from the Høvsøre site
- Application of the reconstruction method to the DTU data
- Introduction to wind gusts measurements (Irene Suomi)
- Definition of the frame work with Irene Suomi : real time parameter required, number of cases to study, data format
- Performing the first test experiments to begin the work on the relationship between wind gusts and turbulent parameters
- Presentation of the first results

Results or Achievements

- **Observation data sets and validation of 3D wind reconstruction and turbulence estimation method**

The aim of the STSM was to get long data sets of WindCube V2 measurements. These data sets will then be used to validate the new method of turbulence estimation. The method gives access to turbulent parameters in real time : it is the innovative point which has to be validated.



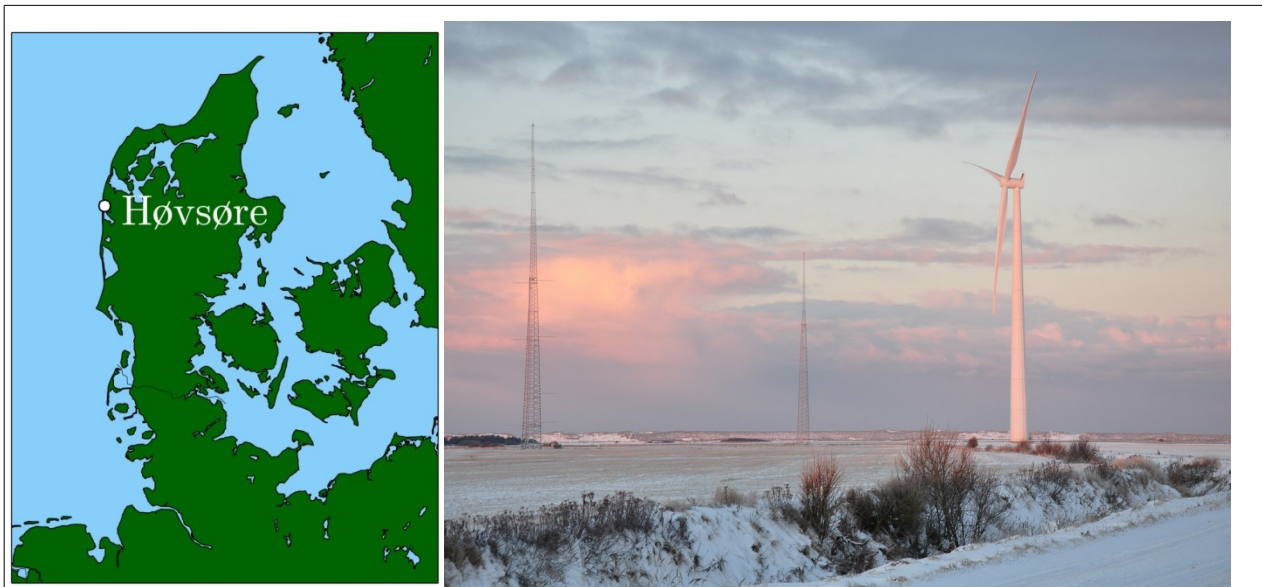


Figure 2: The Danish National Test Station for Large Wind Turbines is located at Høvsøre, at the western coast of Denmark (left). The 116.5 m tall meteorological mast is situated at left on the right hand side picture.

During the STSM, I have downloaded three kinds of wind observations from the DTU database. The observations come from the Høvsøre test center for large wind turbines (figure 2). The site has been described in details by Peña et al. (2015). First, WindCube V2 measurements have been downloaded. These observations are available at a frequency of 0.25Hz. Secondly, sonic anemometer measurements have been downloaded. The observations are available at different heights from 10m to 116m, at a frequency of 20Hz. The sonic data will be useful to validate the real time turbulence estimations given by the reconstruction algorithm. Then I have downloaded cup anemometer data and wind vane data averaged over 10 minutes. These data will be used to assess the estimation of wind direction and of turbulent intensity.

The downloaded data are resumed in the following table :

Date	Instruments
01-31/05/2013	Windcube V2 unit 139, sonic anemometer, 10min data
01-05/06/2013	Windcube V2 unit 139, sonic anemometer, 10min data
08-31/07/2013	Windcube V2 unit 139, sonic anemometer, 10min data
01-31/08/2013	Windcube V2 unit 139, sonic anemometer, 10min data
01-31/08/2013	Windcube V2 unit 139, sonic anemometer, 10min data
01-31/12/2013	Sonic anemometer, 10min data
01-05/12/2013	Windcube V2 unit 62
06-13/12/2013	Windcube V2 unit 62
01-31/01/2014	Windcube V2 unit 62, sonic anemometer, 10min data
01-28/02/2014	Windcube V2 unit 62, sonic anemometer, 10min data
01-31/10/2015	Windcube V2 unit 139, sonic anemometer, 10min data

The data from the DTU database have been formatted to be easily used by the reconstruction method. Then the first step of the validation work has begun. The reconstruction method has been applied to 2 hours of WindCube observations. The preliminary results I have obtained show the capability of the reconstruction method to estimate 3D wind and turbulence. The results are presented in the following paragraphs.

To validate the reconstruction method, the first point is to validate the 3D wind reconstruction. On figure 3, 30 minutes time series of the reconstructed wind and of the WindCube V2 wind are shown. We can notice that the time series are in very good agreement when the WindCube observations are fine. For the meridian wind (V) and for the vertical wind (W) there is a spike in the WindCube time series. It is linked to a transient measurement error. We can notice that the reconstruction method is able to remove the spike and to reconstruct coherent time series.

On figure 4 the power spectrum densities of the reconstructed wind and of the WindCube V2 wind are represented. The power spectrum densities are compared to the theoretical energy cascade. This cascade describes the energy transfer from large scales to small scales in the atmosphere. The figure 4 shows that the WindCube observations follow the energy cascade for the zonal wind (U) only. The power spectrum densities of the two other components are almost flat. It reflects that the



WindCube retrieves noisy wind observations. On the contrary, the slopes of the power spectrum densities of the reconstructed wind follow the energy cascade.

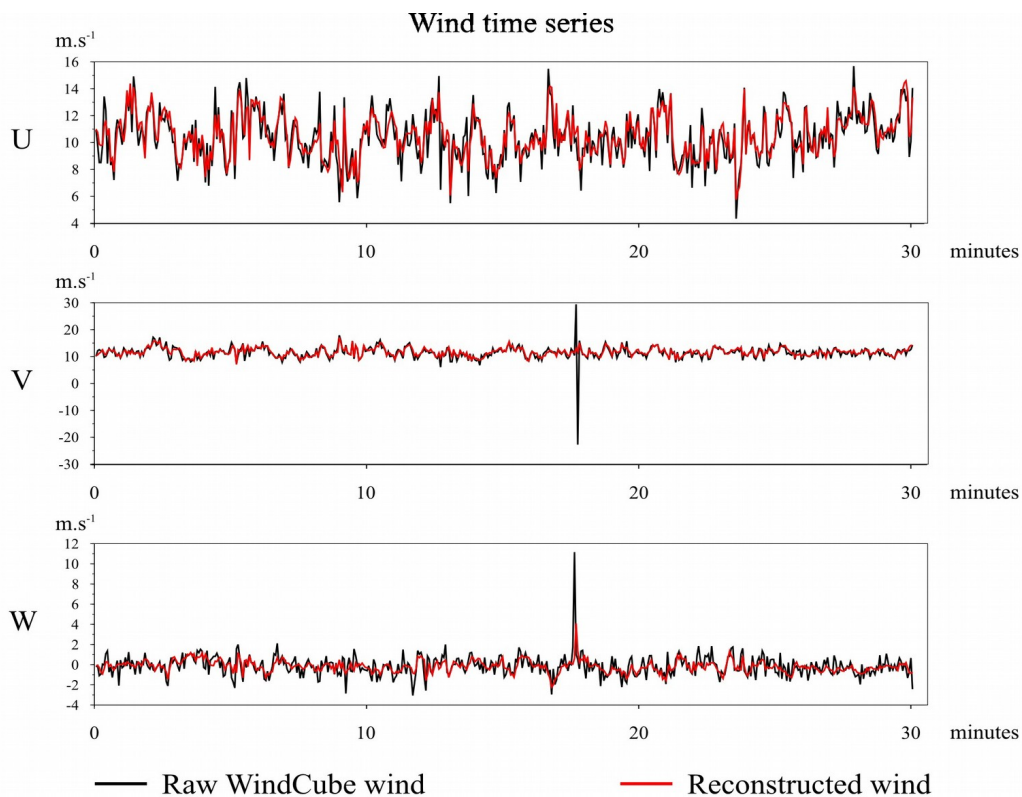


Figure 3 : Time series of the three components of the wind over 30 minutes from 4 pm, 10/06/2015. The raw WindCube wind is plotted in black, and the reconstructed wind is plotted in red.

The horizontal WindCube wind and the horizontal reconstructed wind have also been compared to sonic anemometer measurements. Figure 5 represents the horizontal winds averaged over 10 minutes, for a 210 minutes period. The figure shows a good agreement between the averaged winds.

The study of the reconstructed wind has shown that the reconstruction method is able to filter spikes in the time series. In addition, starting from noisy observations, the method retrieves 3D wind in good agreement both with sonic data and with the turbulence laws in the atmosphere.

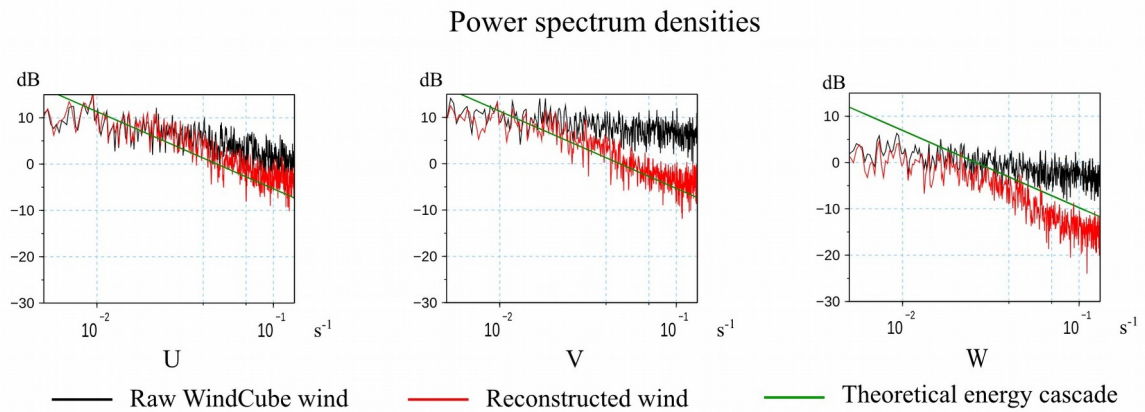


Figure 4 : Power spectrum densities of the reconstructed wind (red) and of the raw WindCube wind (black). The energy cascade is given by the green line.

Horizontal wind over 10 minutes at 100m

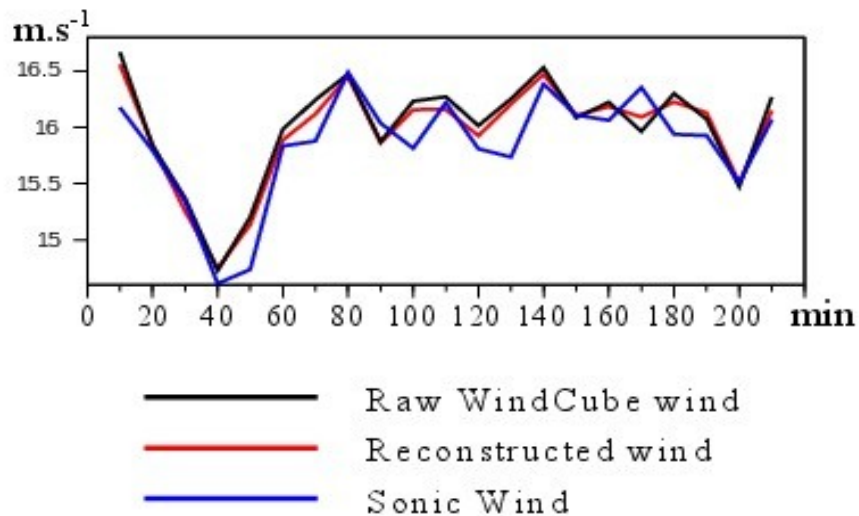


Figure 5 : Averaged horizontal wind over 10 minutes, for a 210 minutes period. The sonic anemometer wind is plotted in blue, the WindCube wind is plotted in black, and the reconstructed wind is plotted in red.

Vertical profiles of Turbulent intensity

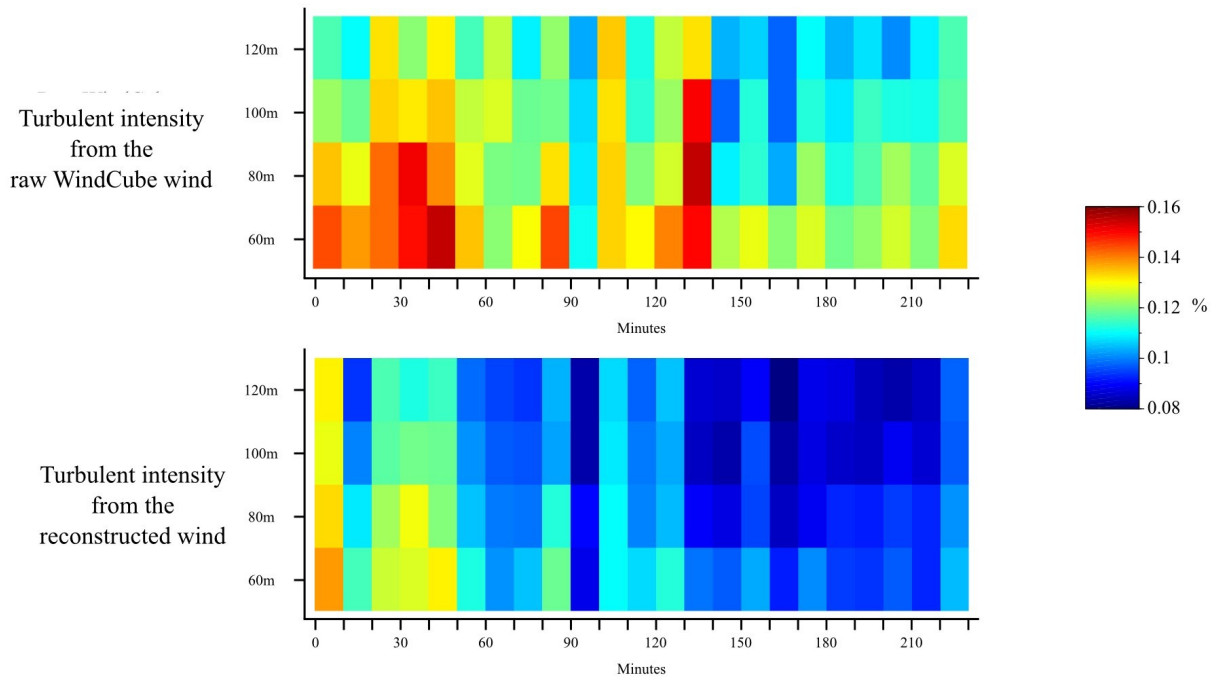


Figure 6 : Vertical profiles of turbulent intensity from the raw WindCube data (upper part) and from the reconstructed wind (lower part).

Having validated the reconstructed wind, I have worked on the turbulent intensity. The turbulent intensity is an important parameter to design wind turbines. Indeed, the turbines are calibrated for a specific range of turbulent intensity. To measure the turbulent intensity, cup anemometers are the reference instruments. By comparison with cup anemometers, the lidar WindCube V2 is known to overestimate the turbulent intensity. Previous results have shown that the reconstruction method retrieves good estimation of the turbulent intensity. The data downloaded from the DTU database will be used to assess this point.

On figure 6 the vertical profiles of turbulent intensity obtained from the WindCube V2 data and from the reconstructed method are represented. We can notice that the reconstructed turbulent intensity is lower than the WindCube turbulent intensity. However, the two profiles show the same temporal evolution. The objective will be to compare the turbulent intensity calculated over several days from the WindCube data,

from the reconstructed wind, from the sonic anemometer data and from the cup anemometer data.

- **Measurement of wind gusts using Doppler lidar (with Irene Suomi)**

This work is done in collaboration with Irene Suomi. The aim is to study the dependence of wind gusts on turbulence measurements using the reconstruction method. The objective is to study the link between the turbulent intensity, or the turbulent kinetic energy -calculated in real time using the reconstruction method- and the wind gusts. Besides, among the outlines, there is the issue of the extension of the surface gust measurements throughout the boundary layer. During the STSM, a new question has also been raised : can we use the statistical characteristics of the particle system used in the reconstruction method to retrieve the extreme wind values measured by sonic anemometers ?

This work has begun by a presentation about wind gusts (Suomi et al., 2015). Then Irene Suomi and I have first defined the ideal cases which would be selected. According to the geography of the Høvsøre test site, only easterly strong winds should be chosen for gust study. To be in the optimal working range of the reconstruction method, we have to choose periods when the turbulence is the more developed. Thus data from 10 am to 6 pm should be selected. In October 2015, winds were mainly easterly at Høvsøre. In addition, the 10/06/2015 horizontal winds higher than 16m/s have been observed during the afternoon. We have thus decide to begin our study with this case. A first work on wind gust has already been done.

In this preliminary study, we investigate how information about the particle velocities could be used in the derivation of a gust estimate. Figure 7 shows the first results of such analysis. At first, the data was divided into 10 min bins. The mean horizontal wind speeds calculated from the reference sonic anemometer, directly from the original lidar measurements and from the reconstructed wind speed agree well (the dashed lines on figure 7). The wind speed maxima, i.e. the gusts, were calculated from sonic anemometers by applying a 3.8 s moving average to the measured 20Hz wind speed signal and the gust was determined as the maximum of each 10 min period of the signal. The length of the moving average window, 3.8 s, was chosen to be the same as the time taken for a lidar to measure a full set of five beams, i.e. it is the resolution of the lidar measurements (as well as of the reconstructed velocity).

On figure 7, the wind gust speed of the reconstructed wind agrees well with the sonic anemometer gusts of 3.8 s duration, but the original lidar wind speed maxima are slightly higher than the sonic ones. Figure 7 also shows that the unrealistically

high maximum in the lidar wind gust speed centered at 85 min is efficiently removed by the reconstruction method.

On figure 7, the maxima of the sonic anemometer data ($U_{\max, \text{sonic}}$, the raw 20Hz measurements) are clearly higher than the ones derived from the original or reconstructed lidar measurements. One possibility to estimate the wind gust is to take the maximum of the particle velocities as the gust estimate. However, in this case it leads to unrealistically large wind speed maxima. However, potentially the information about the particle velocity distributions within the turbulence model could be used to fill the gap between the lidar maxima and the maxima of the raw sonic anemometer signals.

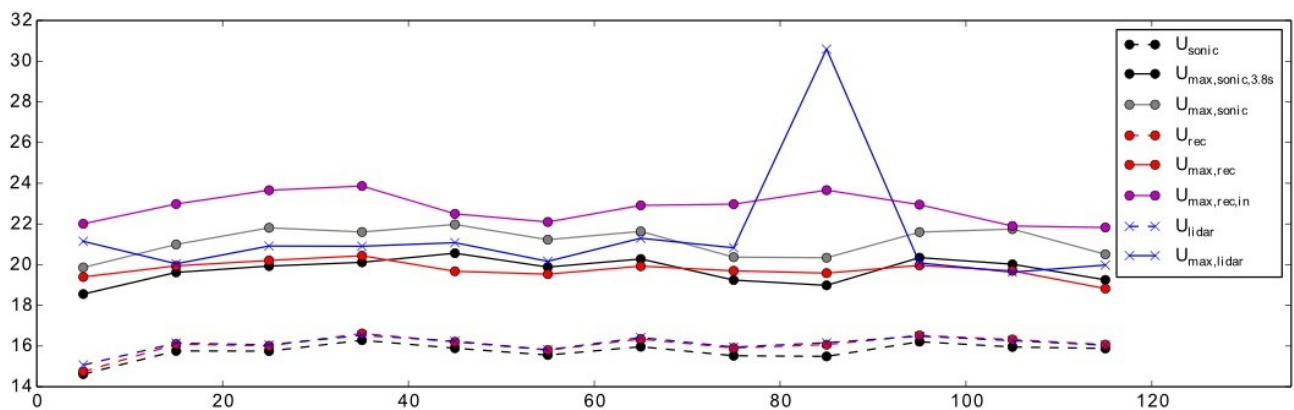


Figure 7 : Mean wind (U) and wind gust (U_{\max}) speed calculated from the original lidar, reconstructed lidar (red) and sonic anemometer measurements. For the latter, U_{\max} is calculated as the maximum of 3.8 s moving averages and as the maximum of the original raw (20 Hz) signal.

- **Designing new experiences to work on wind gust measurements**

During the STSM and to support it, DTU started another lidar measurement campaign at the National Test Centre for Large Wind Turbines at Østerild (57° 3' 0.27" N, 8° 52' 55.70" E) which is located north of Høvsøre. The advantage of this site is that there is a 250 m high, extensively instrumented meteorological mast, which will provide good quality reference measurements from sonic anemometers at heights 8, 40, 103, 175 and 241 m (figure 8). Since the 25/01/2016, a WindCube V2 has been calibrated to measure winds at 40m, 70m, 103m, 106m, 140m, 175m, 178m, 210m, 241m, 244m, 270m and 290m. The data from this site will be used to complete the gust study that will be done with the data from Høvsøre. For the comparison with anemometer data, we have to remind that the lidar has an offset from North of 52.5deg.

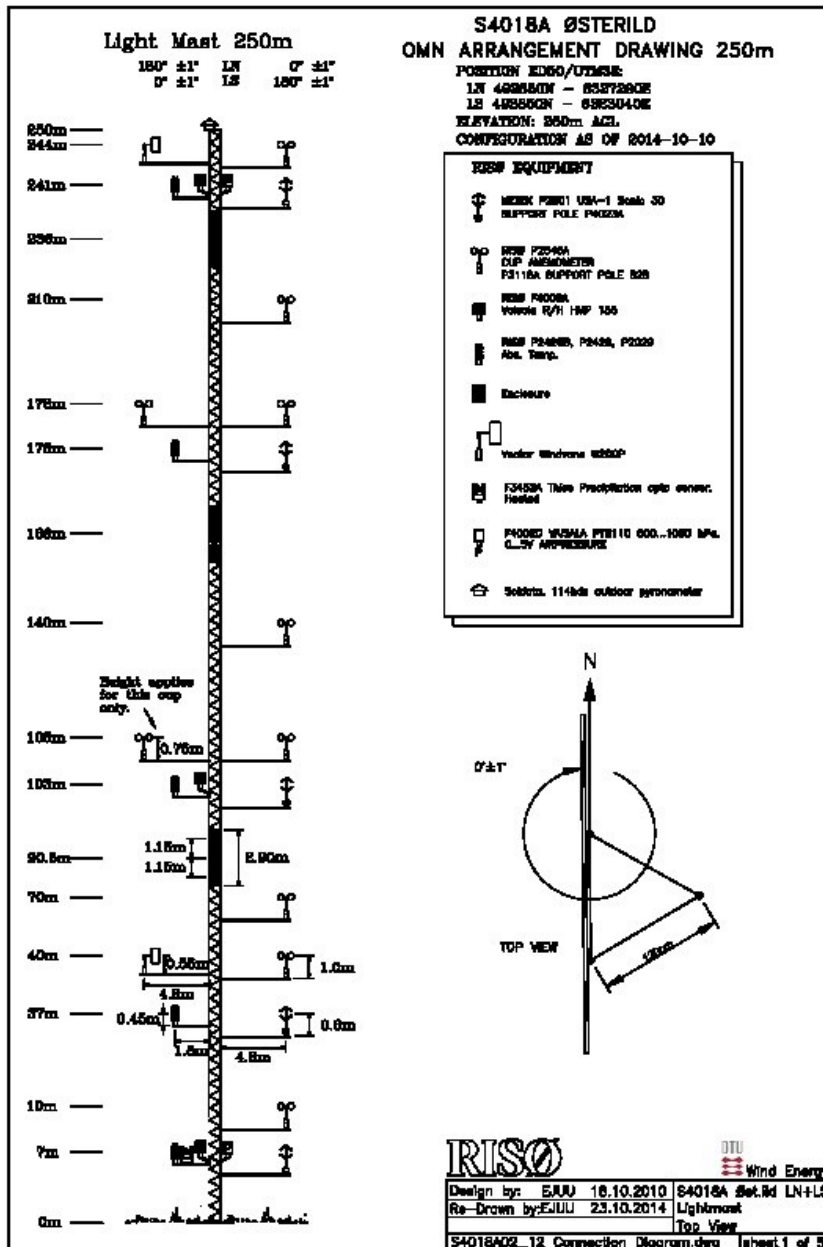


Figure 8 : Meteorological mast at Østerild. Cup anemometers, sonic anemometers and wind vanes are hanged at different heights. The WindCube V2 has been calibrated to measure wind at the same heights.

Conclusions

The scientific mission has given me the opportunity to get several data sets of lidar observations. I have also presented and discussed the reconstruction algorithm with experts on turbulence measurement using Doppler lidar. Moreover, Irene Suomi and I have begun a new work on wind gust. The basis of this collaborative work has been set, and we expect to obtain innovative results in the next few months. To conclude, as all the objectives have been met and exceeded, and as an interesting work on wind gust measurements in collaboration with Irene Suomi has begun, this STSM was a successful mission.

Deliverables

As an outcome of this STSM an abstract was submitted to the 22nd Symposium on Boundary Layers and Turbulence, which will be held in Salt Lake City, Utah, USA during 20–24 June 2016 (Suomi et al., 2016). Another abstract related to turbulence estimation will also be submitted before the end of February 2016 to the International Symposium for the Advancement of Boundary Layer Remote Sensing (Rottner et al., 2016).

References

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