SCIENTIFIC REPORT

ACTION: ES1303 TOPROF
STSM: COST-STSM-ES1303-TOPROF
TOPIC: Measurement of wind gusts using Doppler lidar
VENUE: Technical University of Denmark, Risø, Roskilde, Denmark
PERIOD: 7 – 11 December, 2015

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Introduction

Traditionally the wind gust measurements have been limited to about the lowest two hundred meters of the atmosphere which can be reached by weather masts. Doppler lidars could potentially provide information from higher levels and thereby fill this gap in our knowledge. To measure the 3D wind vector, we need information from at least three different lines of sight pointing towards different directions, (e.g. Lane et al., 2013). The instrument sensitivity depends on the amount of aerosol present and the velocity measurement uncertainty is directly related to the amount of signal (Pearson et al., 2009). It typically takes several seconds to measure each line of sight with sufficient sensitivity and therefore the temporal resolution of the wind measurement is of the order of tens of seconds, which is not sufficient for gusts (e.g. Suomi et al., 2015). However, the Doppler lidar can provide high resolution turbulent measurements, both in the vertical direction (O'Connor et al., 2010), and potentially in the horizontal direction (Vakkari et al., 2015). Recently Rottner and Baehr (2015) have developed a method to measure turbulence by reconstruction of the wind on the basis of Dopper lidar observations and a particle filter. We will go one step further and apply this method to study wind gusts using lidar by comparison with mast measurements. As discussed with the host Sven-Erik Gryning during this STSM, the main objectives of the work are to

- derive gusts from the available lidar parameters
- test the turbulence reconstruction method by Rottner and Baehr (2015) to estimate the gusts
- compare the results of the above methods and validate them against mast observations
- determine the minimum lidar requirements to estimate gusts and provide uncertainties for these estimates. This requires understanding of the relationship between wind gusts and turbulent intensity. By relating wind gusts to turbulence measurements, it would then be possible to extend the surface gust measurements with a vertical profile throughout the boundary layer.

The purpose of this STSM was to initiate the above described research work on the possibilities to measure the wind gusts using Doppler lidar. The focus of the STSM was in the planning of the work and on the first item of the list above.

Objectives

The main objectives of the STSM were

1) Get experience on working with the Doppler lidar data and traditional turbulence estimation methods from the data with the assistance of Ameya Sathe
2) Retrieve the data from the Doppler lidar measurement campaign on July 2012 - February 2013 collected at Høvsøre.
3) Discuss the plans of the present study with the supervisor of the STSM applicant's PhD work Sven-Erik Gryning and the other experts in the institute

Observations

High resolution lidar and weather mast data have been collected at the Danish National Test Station for Large Wind Turbines. It is located at Høvsøre on the western coast of Denmark, at about 1.7 km distance from the shoreline (Figures 1 and 2). A detailed description of the site is provided by Peña et al. (2015). There were lidar data available next to the weather mast from two different WindCube lidar versions, v1 and v2. v1 has four beams in a conical scan, each having a 28º zenith angle. v2 is similar to v1 but it has a fifth, vertical beam in addition to the four conical beams. The data availability is presented in Table 1. The 20 m level data will be used to calculate the surface layer fluxes and stability, other levels can potentially be used to compare lidar and sonic measurements.

Table 1: Data availability. Sign "x" refers to available data and sign "-" to missing data.

	LIDAR	SONIC						LIDAR				
z [m]	**VERSION**	**20**	**40**	**60**	**80**	**100**	**160**	**40**	**60**	**80**	**100**	**160**
10.6.2011-8.12.2011	V1	x	x	x	x	x	-	x	x	x	x	x
10.6.-8.12.2011	V2	x	-	-	x	x	x	x	x	x	x	x
12.7.2012-27.9.2013	V2	x	-	-	x	x	-	x	x	x	x	x
11.9.-7.11.2015	V2	x	x	-	x	x	x	x	x	x	x	x

As an example of the data, Figure 3 shows the comparison of the wind gust speed from the lidar (v2) and the sonic anemometer at 100 m level in 10.6.-8.12.2011. The wind speed maximum is underestimated by the lidar on average by about 0.15 m/s, which corresponds to about 5% difference between the wind gust speeds.

Figure 4 shows an example of a 10 min time-height cross-section of sonic and lidar horizontal wind speeds. The highest maximum at each measurement level is presented by a star. There is one gust event in lidar data, where the maxima occur closely to each other down to 80 m level and the colored pattern continues even down to the 40 m level. However, the same pattern of closely (in time) located highest maxima cannot be seen in the sonic anemometer data. This may be because of the different observation levels available from the compared to those from the lidar, but also because of the lidar measurement frequency: measurements along one line of sight (all levels) of a lidar observation are almost instantaneous, but one horizontal wind velocity observation requires radial velocities from four consequent lines of sight which take altogether nearly four seconds to measure. Despite of these fundamental differences between the measurement systems, the Figure 4 indicates that a lidar is capable of measuring similar features in the wind field as those seen in the sonic anemometer data.

Figure 1: The Danish National Test Station for Large Wind Turbines at Høvsøre, Denmark. The 116 m tall meteorological mast is on the left.

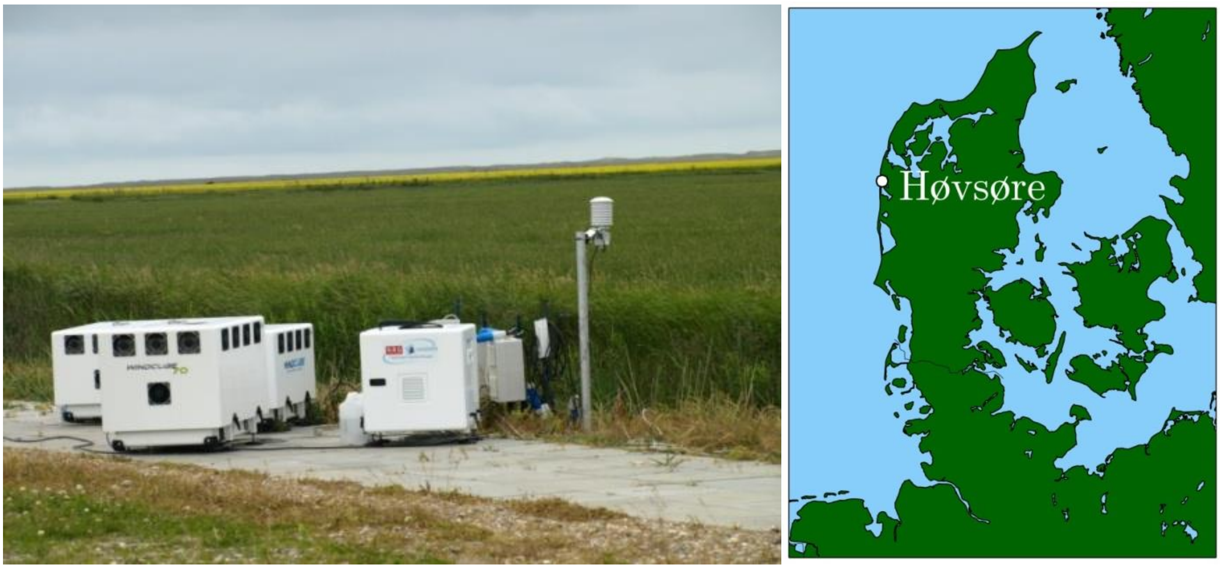

Figure 2: WindCube lidars (on the left) at Høvsøre, which is located in the western coast of Denmark (on the right).

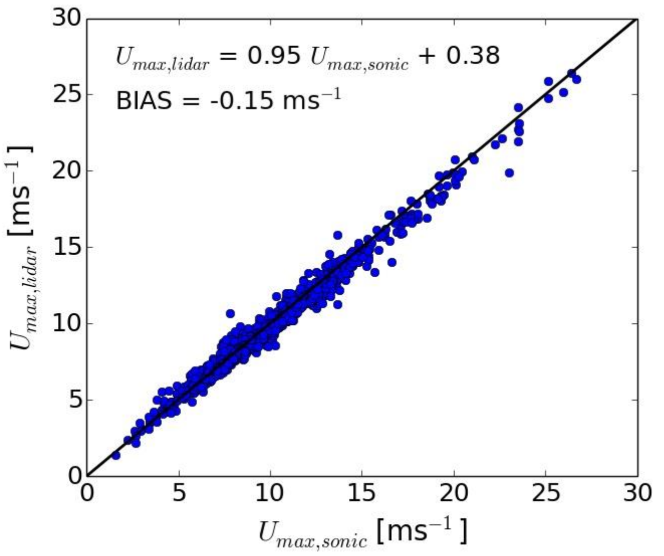

Figure 3: Comparison of wind gust speed from the lidar and the sonic anemometer at 100m level during 10.6.-8.12.2011.

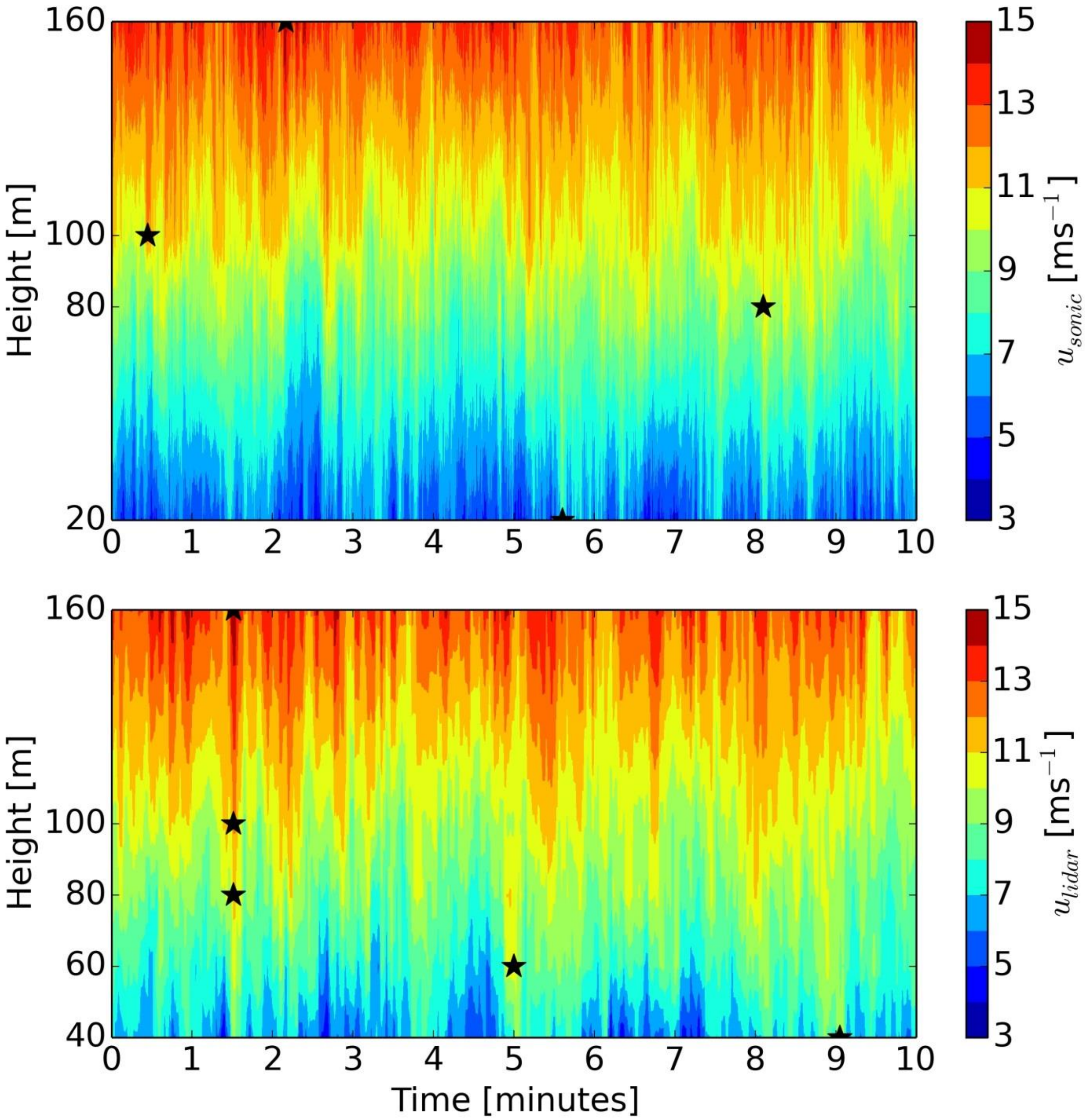

Figure 4: Example of a 10 min time-height cross-section of a sonic (top) and lidar (bottom) wind speed. The ticks on the vertical axis show the observation heights. The maximum at each observation level is presented as a black star in the plots.

Methods

During the STSM, the methodology on how to approach the derivation of the wind gusts using available turbulence information from a pulsed Doppler lidar was discussed with Sven-Erik Gryning and Ameya Sathe.

A wind gust (U_{max}) is defined as a short duration maximum of a turbulent wind speed time series. It is typically calculated as a maximum of the moving averages of the wind speed. Hence, the gust duration (t_g) is determined by the width of the averaging window. A gust can also be determined without any averaging, the gust is then simply the maximum of the turbulence time series, and then it represents an instantaneous measured value.

The measured wind gust can be expressed in terms of a mean wind speed and the maximum fluctuation from it:

$$U_{max} = U + u'_{max} \tag{1}$$

Furthermore, the fluctuation can be expressed as a function of the standard deviation of the wind speed: $u'_{max} = g_x \sigma_u$ where the constant of proportionality, g_x, is the peak factor, which is by definition:

$$g_x = \frac{U_{max} - U}{\sigma_u} \tag{2}$$

Now, the Equation for the wind gust can be written separately for a sonic anemometer (subscript S) and for a lidar (subscript L):

$$U_{max,S} = U_S + g_{x,S}\sigma_{u,S} \tag{3}$$

$$U_{max,L} = U_L + g_{x,L}\sigma_{u,L} \tag{4}$$

If no filtering (e.g. moving average) is applied to the raw, measured turbulent wind speed signal, it is clear that the above Equations 1 and 2 are not equal. Sathe et al (2011) compared extreme winds measured by wind lidars to those from cup anemometers at a weather mast and found that lidars are capable of measuring the maximum wind speeds, but there is an underestimation up to 10% ($U_{max,S} > U_{max,L}$). To remove this bias from the lidar measurements, we should be able to derive $U_{max,S}$ from the parameters available from lidars, i.e. express the true wind gust in terms of lidar parameters

$$U_{max,S} = f\left(U_L, U_{max,L}, g_{x,L}, \sigma_{u,L}, \sigma_{v,L}, \sigma_{w,L}, \ldots\right) \tag{5}$$

The derivation of the function f will be the first goal of this work. Lidars measure fairly accurately the mean wind speed ($U_S \approx U_L$), and hence there is no need to parameterize that. Instead, the difference between $\sigma_{u,L}$ from a lidar and $\sigma_{u,S}$ from a sonic anemometer must be evaluated. Sathe et al. (2015) have compared the wind velocity variances from a WindCube lidar and a sonic anemometer, i.e. the ratio

$$r_\sigma = u'^2_{lidar} \,/\, u'^2_{sonic} \tag{6}$$

where $u'^2 = \sigma_u^2$. This ratio can be expressed in terms of turbulence spectra:

$$r_\sigma = \frac{\int_0^\infty |\varphi_{lidar}(n)|^2 S(n)\,dn}{\int_0^\infty |\varphi_{sonic}(n)|^2 S(n)\,dn} \tag{7}$$

where $S(n)$ is the power spectrum as a function of frequency *n*. Function $|\varphi(n)|^2$ is a filter function, which represents how the true turbulence power spectrum ($S(n)$) is affected by the instrument characteristic and sampling frequency. In case of lidar measurements, we refer by the instrument characteristics to the factors related to the design of the pulsed lidar, such as the length of the range gate, the zenith angle of the conical beam, the measurement height, the volume averaging related to the combination of four beams to yield one horizontal wind velocity estimate, etc. According to Ameya Sathe, a complete understanding of the form of the function $|\varphi_{lidar}(n)|^2$ is not yet achieved, but it is more complicated than typically for example for sonic anemometers, for which it can be expressed as

$$|\varphi_{sonic}(n)|^2 = \left(\frac{sin(\pi n \Delta t)}{\pi n \Delta t}\right)^2 \frac{1}{1+(2\pi n l/U)^2} \qquad (8)$$

where *Δt* is the time interval between the consecutive data points, *U* is the mean wind speed and *l* is the sonic anemometer path length. Practically for sonic anemometers $|\varphi(n)|^2$ is very close to unity, therefore, we can consider the sonic anemometer measurements to represent the true turbulence.

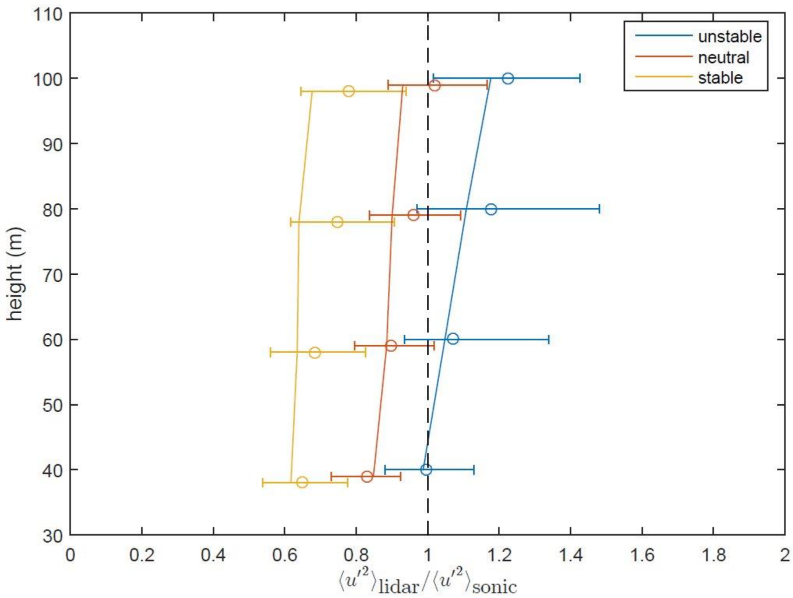

Figure 5: The ratio of the wind velocity variances from a pulsed lidar and sonic anemometer in the direction of the mean wind. Circles with error bars show the observations, vertical lines the model results (Sathe et al. 2015, their Figure 5.4b).

Figure 5 shows that the ratio r_σ depends on the measurement height and on the surface layer stability. In unstable conditions the ratio can become even larger than unity, due to the larger measurement volume of the lidar compared to that of the sonic anemometer.

After the determination of the ratio r_σ it is possible to derive the function f of Equation 5, because also the peak factor g_x can be expressed in terms of turbulence spectra using filter functions (e.g. Suomi et al., 2015).

Summary

This STSM had three goals, which all were successfully achieved. Firstly, the discussions with Ameya Sathe helped the grantee in understanding the turbulence measurements with a pulsed lidar using conical scanning. This information can be further used in derivation of the gusts from lidar measurements. Secondly, the host institute provided high resolution turbulence measurements from four different lidar campaigns in the direct vicinity of the meteorological mast located at Høvsøre, western Denmark. Simultaneous lidar and mast measurements enable a direct comparison of lidar gusts with the ones measured by the sonic anemometers at the mast. The first comparisons show that the maxima measured by a pulsed lidar are slightly smaller than the ones measured by a sonic anemometer. The underestimation was on average about 5%.

Third goal of this STSM was to plan the next steps of this lidar gust study together with the host Sven-Erik Gryning. The next step will be to analyse carefully the lidar data and compare the results with the sonic anemometer measurements to find the best method to estimate the “true” gust using only the parameters directly available from the lidar. Here the “true” refers to the sonic anemometer measurements which are considered as a reference. Then, the turbulence reconstruction method by Rottner and Baehr (2015) can be applied to the same lidar data to study its potential to the gust measurements. These results can then be validated against the earlier derived gust estimates from the lidar as well as against the sonic anemometer measurements.

Finally, after finding the best practices for gust determination, the methodology will be generalized by finding the minimum requirements / practices and their uncertainties in estimation of gusts using a pulsed Doppler lidar. The results of this work will be published in a peer-reviewed scientific journal, which will be an outcome of this STSM. In addition, the results can potentially be extended to a European Doppler lidar network, within this EU COST Action TOPROF (Towards Operational Profiling).

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