How good are remote sensors at measuring extreme winds?

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Abstract

This article describes some preliminary efforts within the SafeWind project, aimed to identify the possible added value of using wind lidars to detect extreme wind events. Exceptionally good performance is now regularly reported in the measurement of the mean wind speed with some wind lidars in flat terrain. For turbulence measurements, recent theoretical work has revealed that the components of the Reynolds stress tensor are subjected to significant spatial attenuation and contamination by the cross-components of the horizontal and vertical wind speed. Thus, with the conical scanning of the lidar and velocity azimuth display technique of processing data, precision turbulence measurements are not possible. But how faithfully do wind lidars measure extreme wind events? Our study uses mast and wind lidar data from a flat terrain site. The continuous wave ZephIR lidar and the pulsed WindCube (WLS-7) lidar are investigated. The data analysis consists of cup-lidar comparisons of the mean wind speed, the maximum wind speed, probability distributions of the time difference of the maximum wind speed, and variation of the gust factors with mean wind speed and atmospheric stability. We examine to what degree each of the different instruments are able to detect extreme events, and attempt to identify the differences in the measurements of the extreme events between cups and lidars. The data analysis showed that both lidars are capable of measuring the maximum wind speed within a 10-min period up to an underestimation of about 10\% with respect to the cup anemometer. The Windcube is capable of measuring the gust factor that is comparable to that of the cup anemometer, whereas the ZephIR always underestimates it. The conclusion is still speculative and more theoretical work is required to deduce firm conclusions.

1 Introduction

Wind energy has expanded rapidly for several decades and every year thousands of multi-megawatt wind turbines are being installed all over the world. Wind turbines are designed for fatigue and extreme loads. Turbulence is one of the main driving factors for the fatigue loads, whereas extreme winds result in extreme loading. The IEC design requirement standard \cite{IEC} quantifies extreme winds in different ways, e.g. a 50 year extreme wind, wind gusts, extreme turbulence etc. In an ideal world, we would like to have long term measurements of these extremes so that wind turbines could be designed with a fair degree of confidence to sustain extreme loads. However, we live in a real world, and hence, long term measurements of extreme winds are scarce, particularly at the site of interest where the wind turbines operate. Nevertheless, rapid expansion of wind energy in the last decade has led to some dedicated measurement campaigns for wind energy, both onshore and offshore, e.g. \cite{NREL, DNV}. These sites have tall meteorological masts (> 100 m height) and are equipped with cup and sonic anemometers to measure wind speeds. Tall meteorological masts are very expensive, and offshore, the costs increase significantly. The advent of remote sensing devices like lidars gives a further boost to the development of wind energy. In recent years with the introductions of the ZephIR as a continuous-wave (CW) lidar developed by Natural Power, and the WindCube as a pulsed lidar developed by Leosphere, there has been a surge in the verification campaigns of comparing the lidar mean wind speed with that of a cup anemometer for wind energy applications \cite{SZ, WLS, ZW}. \cite{Kawecki} discuss the advantages and disadvantages of CW and pulsed lidars. Studies have also been carried out to measure turbulence by lidars but they are subjected to volume averaging effects \cite{Greenshields, Drijkoningen, Mamiit}. \cite{Kawecki} concluded that wind lidars cannot be used to measure turbulence precisely using the conical scanning and velocity azimuth display of data processing.

In this paper we attempt to find out if lidars can measure extreme winds. We focus our analysis on the measurements of the maximum wind speed in a 10-min period and the gust factor. We perform data analysis
on the measurements carried out by the ZephIR and Windcube, and compare it with the results from the cup anemometer. Generally, any research study is carried out such that at first theoretical models are developed or explained, calculations from the theoretical models are performed, and finally the theoretical results are compared with the measurements. In this study we digress from the usual approach in that we first perform data analysis, and then provide motivation for future theoretical work. We do this because at first it was important to know if wind lidars can measure any extreme winds. This approach was also motivated from the results of [11], where large systematic errors were observed in turbulence measurements. Section 2 describes the measurement campaign, section 3 explains the outline of the data analysis. Section 4 describes the results in detail, section 5 briefly outlines the foundation for the theoretical work, and section 6 concludes the analysis.

2 Description of the measurements

The measurements were performed at the Danish National Test Center for Large Wind Turbines at Høvsøre, Denmark. Figure 1 shows the layout of the test center and the location of the used reference meteorological (met.) mast, a 116.5 m tall extensively equipped mast located at the coordinates 56°26’26” N, 08°09’03” E, (indicated by a dark diamond in Fig. 1b). The site is about 2 km from the west coast of Denmark. The eastern sector is characterized by flat homogeneous terrain, and to the south is a lagoon.

Our reference measurements for this study are the cup anemometer measurements taken at 40, 60, 80 and 100 m. The high frequency measurements are carried out at 10 Hz and then the respective 10-min statistics (mean values and standard deviations or variances) are estimated. All cup anemometers are placed on the South booms of the met. mast (Fig. 2a), resulting in unusable data when the wind is from the North due to the wake of the mast, and also the wake of the wind turbines. In combination with the cup measurements, wind speeds from a ZephIR (coordinates 56°26’26.9556” N, 08°09’2.448” E) and a WindCube (coordinates 56°26’26.0556” N, 08°09’3.226” E) are used. The ZephIR is located about 35m North of the met. mast and the WindCube is located about 5m North-West of the met. mast. Reference and lidar data were collected over two different time periods, for the WindCube between January and April 2009, and for the ZephIR between May and November 2009. In our analysis we also use the sonic anemometer measurements at 20 m to quantify atmospheric stability. Since sonic anemometers are placed on the North boom of the met. mast (Fig. 2a), they would be influenced by the mast wake when the wind blows from the south. Hence, only data periods with easterly (50°–150°) and westerly (230°–300°) winds are analyzed. The wind rose Fig. 2b shows that although the dominant wind direction is West-North-West, there is also sufficient data in the eastern sector.
The precision of the cup anemometer measurements is estimated to be about ±1%. From comparisons with cup anemometers, the mean error of the WindCube in typical flat coastal conditions is within ±0.05 m/s with a standard deviation in mixed shear conditions of about 0.15 m/s. The corresponding uncertainty for the measurements made with a ZephIR is slightly higher (A detailed list of different error sources is given in [12]).

3 Outline of the data analysis

We perform the data analysis in the following four steps:

1. Comparison of the mean wind speed - Even though previous studies have proved that wind lidars measure the mean wind speed fairly accurately [4, 5, 6], at first it is necessary to compare the mean wind speed and obtain a reduced data set where the correlation of the mean wind speeds is quite good. Only then we can have confidence in the comparisons of the extremes measured by wind lidars with the cups anemometer. We apply the following filters on the corresponding lidars such that only those data sets that comply with the filters are chosen:
   - ZephIR - Air temperature > 3°C, Turbulence parameter < 0.1, Number of points in the fit > 110, cloud height > 800 m, and rain = 0 mm; We have arbitrarily chosen the number of points to be greater than 110 because the ZephIR makes three scans before re-focusing on a different height, and every scan consists of 50 points. We filtered the cloud height using the ceilometer observations, since [7] concluded that the ZephIR observations are corrupted at low cloud heights. The filter of air temperature was applied since we compare the measurements with the cup anemometer, and the measurements are not reliable at air temperatures below 3°C due to the possibility of sensor icing.
   - WindCube - Air temperature > 3°C and lidar availability = 100%.

The total data availability after applying these filters in the chosen directional sector was about 44% for the ZephIR and 60% for the Windcube.

2. Comparison of the maximum wind speed - The maximum value of the wind speed within a 10-min period is chosen for each instrument.

3. Comparison of the time difference of the maximum wind speed - We compare the probability density function (PDF) and the cumulative distribution function (CDF) of the time difference of the maximum wind speed between different instruments. I.e. say for one 10-min period, from the high frequency data,
we note the time of the occurrence of the maximum wind speed for the ZephIR and the same for the cup. We take the difference between the recorded time of the cup and the ZephIR, and from many such 10-min periods we construct the PDF and CDF for different instruments accordingly.

4. Comparison of the gust factor - Two definitions of the gust factor are available,

\[
\langle \eta \rangle = \left\langle \frac{u_{\text{max}}(\tau) - \bar{u}}{\sigma} \right\rangle
\]

(1)

where \( \eta \) is the gust factor, \( \langle \rangle \) denotes ensemble average, \( u_{\text{max}}(\tau) \) is the maximum wind speed averaged over time \( \tau \), \( \bar{u} \) is the mean wind speed and \( \sigma \) is the standard deviation. We use \( u_{\text{max}}(\tau), \bar{u} \) and \( \sigma \) from each 10-min period to estimate the ensemble average gust factor.

\[
\langle \eta \rangle = \left\langle \frac{u_{\text{max}}(\tau)}{\bar{u}} \right\rangle
\]

(2)

We choose the definition from Eq. (1), since it makes the gust factor independent of the turbulence at a particular site.

4 Results

The ZephIR transmits the laser beam through a constantly rotating prism, giving the required half-opening angle of nominally 30°. Each of up to five heights are scanned for one or three seconds, corresponding to one or three complete rotations of the prism. The beam is then re-focused to the next height in the sequence and the scanning procedure is repeated. Up to five different heights can be selected, the sequence (with five heights and three second scans) taking up to 20 seconds to complete. Thus the ZephIR spends less than 20% of the time required to make a wind profile on any one of the five heights. The Windcube measures at four azimuth angles, and at each azimuth angle all heights are scanned simultaneously. It takes about 8 s for the Windcube to scan all four azimuth angles. Details of the working principles of the CW and pulsed lidars, and in particular the ZephIR and the Windcube are given in [13]. Hence, we just explain the results obtained from these instruments.

4.1 Mean wind speed

![Figure 3: Comparison of the mean wind speed measured by the ZephIR and Windcube with that of the cup anemometer at 80 m. The subscripts QQ and WC are for the ZephIR and Windcube respectively.](image)

(a) ZephIR

(b) Windcube

\( \pi_{QQ} = 0.98834 \pi_{\text{cup}} \)

\( R^2 = 0.99050 \)

Data = 6627

\( \pi_{WC} = 0.98979 \pi_{\text{cup}} \)

\( R^2 = 0.99909 \)

Data = 4529
Fig. (3) shows that there is a good correlation (slope ≈ 0.99) of the mean wind speed measured by both lidars as compared to the cup anemometer. The scatter in the observations is also very low ($R^2 > 0.99$) for both lidars. Thus, the dataset obtained by applying the filters to the respective lidars is acceptable for the analysis of extreme winds. For the sake of brevity, we only show the results at 80 m height. The correlations at other heights are equally good.

### 4.2 Maximum wind speed

![Graphs showing comparison of maximum wind speed measured by ZephIR and cup anemometer at different heights.](image)

Figure 4: Comparison of the maximum wind speed measured by the ZephIR and the cup anemometer at different heights.

Figs. (4) and (5) show the comparisons of the maximum wind speed of the ZephIR and Windcube respectively with that of the cup anemometer at different heights. For the ZephIR (Figs. 4a–4d) it is observed that the maximum wind speed is underestimated by about 10%. There is not much variation of the slope ($\approx 1\%$) at different heights. The scatter ($R^2$) in the observations at all heights is about 0.98. For the Windcube (Figs. 5a–5d) it is observed that the maximum wind speed is underestimated by about 3–6%. There is slightly larger variation of the slope with height as compared to that for the ZephIR, where the underestimation in the maximum wind speed decreases with height. The scatter in the observations at all heights is also much lower than that observed...
for the ZephIR, consequently giving a higher $R^2$ value for the Windcube as compared to the ZephIR. Thus, the lidars seem to measure the maximum wind speed reasonably well. The observations in Figs. (4) and (5) contain information about the mean wind speed, and this could be the reason for good correlations of the maximum wind speed for both lidars. It would be interesting to compare the maximums by subtracting the corresponding mean wind speeds.

### 4.3 PDF of the time difference between the maximum wind speed

Since the comparison of the maximum wind speed yielded good correlations between the lidars and cups, it is interesting to check if all the instruments measure the same maximum. Figs. (6a) and (6b) show the time difference of the maximums between cup anemometer and the ZephIR and Windcube respectively. Ideally, if the lidars and cups measured the same maximum then the PDF would be a delta function at $x = 0$ s, where $x = t_{\text{cup}} - t_{\text{lidar}}$, and $t_{\text{cup}}$, $t_{\text{lidar}}$ are the times of the maximum wind speed (recorded from the high frequency data) for the cup and lidar respectively. Alternatively, if both instruments measured totally random maximums, then the PDF would be a a triangle distribution with the peak located at $x = 0$ and the tails located at $x = \pm 600$ s.}

Figure 5: Comparison of the maximum wind speed measured by the Windcube and the cup anemometer at different heights.
s. However, Figs. (6a) and (6b) show that both lidars alternatively measure the same and random maximums as compared to the cup anemometer. The broad shape of the PDF for the ZephIR indicates that it measures more random events as compared to the Windcube. A primary reason for this behaviour is that ZephIR updates the velocity vector about every 20 s (due to very low duty cycle), whereas the Windcube updates every 2 s. If we draw a straight line from the tail of the distributions following the curve with the same slope until it intersects at \( x = 0 \) s, then all observations under the triangular area signify random events, whereas those above that are within the area of the narrow peak signify same events. We observe that for more than 70% of the time the ZephIR does not measure the same maximum as that of the cup, whereas the Windcube measures the same maximum about 50% of the time. An offset in the PDF for the ZephIR indicates that the time of the measurement for the ZephIR and the cup may not be synchronized correctly. It is also observed that there is not much variation of the PDF with height for both lidars.

Figs. (7a) and (7b) show the PDF and CDF of the time difference of the maximum wind speed for all instruments (including sonic anemometer) at a height of 100 m. It is observed that the sonic and cup anemometer measure the same maximum number of times than both lidars, as indicated by the blue narrow peak in Fig. (7a). The effect is clearly seen in Fig. (7b), which shows the CDF of the time difference of the maximums.

### 4.4 Gust factors

Figs. (8a) and (8b) shows the variation of the gust factor with respect to the mean wind speed and atmospheric stability for different instruments at 80 m. The choice of \( \tau \) depends on the structure for which the gust factor is being estimated. Wind turbines respond on a scale of 1 to 3 s, and hence we estimate the gust factor for two values of \( \tau \) for the cup anemometer. For the ZephIR and Windcube, we directly use the observations recorded at the measurement frequency of the respective lidars. For the \( \sigma \), we use the observations from the sonic anemometer, since it gives the best estimate of the standard deviation as compared to cups and lidars. Also, from [11] it is clear that \( \sigma \) is subjected to large systematic errors for the lidars, and hence we cannot use those measured by lidars. Since \( \pi \) is measured quite accurately by both lidars as compared to the cups (see Fig. 3), we use the corresponding observations for the respective instruments.

It is observed that the gust factor for the ZephIR is much lower compared to that of the Windcube and cup anemometer. We are yet to provide a satisfactory explanation of this but relate this behaviour primarily to the low duty cycle of the ZephIR. It would be interesting to observe the gust factor by focusing at only one height for the ZephIR. In that case however, the primary purpose of the lidars for wind profiling will not be achieved.

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1 The Windcube requires about 8 s to scan at four azimuth angles, but it updates the velocity vector using the previous three measurements. Hence, the velocity vector is updated every 2 s.
Figure 7: Comparison of the pdf and cdf of the time difference of the maximum wind speed between different instruments at 100 m.

Figure 8: Comparison of the gust factor against mean wind speed and atmospheric stability between cups and lidars at 100 m.

Fig. (8a) shows a slight decrease in the gust factor for the cups with increasing mean wind speed. In principle, at higher wind speeds, the time scales are smaller, which should result in the increase of the maximum wind speed. However, the observations are not classified according to atmospheric stability, and it could play a role in the anomalous behaviour of the gust factor for the cup anemometer. For both lidars, there is not much variation in the gust factor with the mean wind speed.

Fig. (8b) shows the variation of the gust factor with respect to atmospheric stability. Obukhov length $L$ was used to classify atmospheric stability according to [14, 15]. 20 Hz sonic observations at 20 m of wind speed and temperature at 20 m were used to estimate $L$ using the eddy covariance technique as done in [11]. We observe that for the cups the gust factor increases slightly under stable conditions as compared to the unstable conditions. This is most likely because of the smaller length scales under stable conditions that result in higher probability of recording a higher maximum. Also, $\sigma$ is lower under stable conditions than the unstable conditions. For the
lidars, the smaller length scales are filtered out under stable conditions, and hence, we observe a decrease of the gust factor under stable conditions.

5 Foundation for the theoretical work

From the theory of [16] and [17],

\[ \langle \eta \rangle = f \left( \frac{m_2(k_1)}{m_0(k_1)} \right)^{\frac{1}{2}}, \]

(3)

where \( m_n(k) \) is the \( n\)th moment of the single dimensional spectrum defined as,

\[ m_n(k_1) = \int_{-\infty}^{\infty} k_1^n F(k_1) dk_1, \]

(4)

where \( F(k_1) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{11}(k) dk_2 dk_3 \) is the spectrum of \( u \) velocity, \( \Phi_{11}(k) \) is the component of the three dimensional spectral velocity tensor \( \Phi_{ij}(k) \), and \( k = (k_1, k_2, k_3) \) is the wave vector. From [11], we understand that the variances measured by lidars are subjected to large systematic errors. Thus, the lidar spectra will also be subjected to large systematic errors. From Eq. (3) we see that the gust factor is a function of the spectra measured by the respective instrument.

6 Conclusions

We draw the following conclusions:

1. Both lidars are capable of measuring the maximum wind speeds in a 10-min period to within an underestimation of 10% as compared to the cup anemometer. It is worth noting that the comparison is made for the instantaneous maximum value observed in a 10-min period. It would be interesting to compare \( u_{max} \) averaged over a certain period \( \tau \), with the contribution of \( \bar{u} \) subtracted from it.

2. The PDF of the time difference of the maximum wind speed between the cups and lidars indicate that random events dominate the distribution, especially for the ZephIR. However, the use of \( u_{max}^{\tau} \) will most likely reduce the number of maximum events.

3. Windcube measures gust factors that are comparable to that of the cup anemometers but the ZephIR always underestimates it. A primary reason is that the ZephIR updates the velocity vector at one height quite infrequently (about every 20 s), whereas the Windcube updates every 2 s. A good comparison between the Windcube and the cups could be due to the systematic errors arising from the contribution of the all components of the Reynolds stress tensor. This has to be further verified.

To answer the question posed in the title, it could be concluded that at this stage the answer is speculative and more theoretical work is required to deduce firm conclusions.

The future work includes modelling the spectra measured by lidars and theoretically estimating the systematic errors in the gust factors of lidars as compared to those of the cup/sonic anemometer.

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