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Comparison of turbulence spectra derived from LiDAR and sonic measurements at the offshore platform FINO1

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Summary: Traditional meteorological masts, that are usually used for instance to perform a wind power curve measurement or wind resource evaluations, are very expensive to install in offshore locations. Therefore, we have to search for an alternative method to replace the standard wind measurements (from cup or sonic anemometers) used on a mast. The LiDAR technique is becoming in the last years a promising substitute with the advantage that higher vertical measurements over the whole rotor diameter can be performed (e.g. [1] [2] ,[3]). However, before taking LiDAR as an overall accepted wind measurement alternative we have to understand and validate how this technique derives both mean and turbulent wind speed parameters.
In the present work, wind measurements given by an up-ward pointing ground-based wind LIDAR (= VAD mode (velocity azimuth display mode) are analyzed and compared with in-situ mast measurements at the research offshore platform FINO1 in the North Sea. The comparison of the 10-min wind values shows a good reliability of the LiDAR in offshore conditions [4] . However, it is not verified sufficiently until now, how the LIDAR technique is performing on the higher frequencies. To this aim, results based on a spectrum study are presented.

Keywords: *LiDAR, spectrum analysis, sonic anemometer, offshore.*

1 THE FIELD MEASUREMENTS CAMPAIGN

A ground-based pulsed coherent lidar system, the WindCube, developed and manufactured by the French company Leosphere has been used in this study. The lidar system is located at the offshore platform FINO1 since July 2009. The FINO1 platform (lat. 54°0.86'N, long. 6°35.26'E), equipped with a 100 m lattice tower, is operating since September 2003 in the German Bight approx. 45 km to the northwest of the island of Borkum. For this comparison study in-situ measurements from the sonic anemometer at 80 m are used.

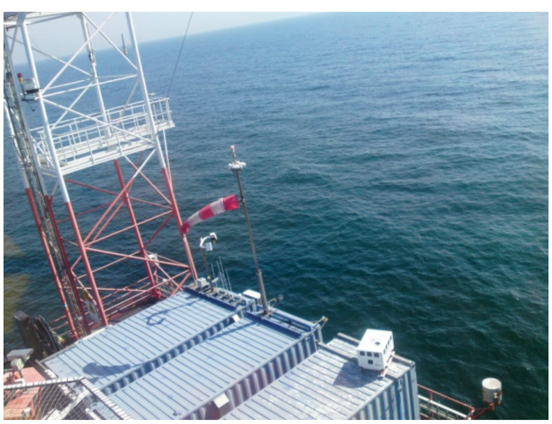


Figure 1 LiDAR position at the offshore research platform FINO1.

1.1 The windcube lidar system

Pulsed lidars, as their name implies, emit regularly spaced emissions of highly collimated light energy for a specified period of time (pulse length). The WindCube Doppler lidar system emits 200 ns pulses of 10 µJ energy at a wave length of 1.54 µm and employs a fiber optic technology which is eye-safe, providing a high level of performance. The range is settled as 40-200 m and the effective probe volume as 20 m.

1.1.1 Calculation of the resulting 3D wind vector

From LiDAR measurements, the estimation of the wind velocity vector (u, v, w) requires retrieval of the Line-Of-Sight (LOS) velocity (also called as radial velocity v_r). The Windcube, located at FINO1 platform, uses the velocity azimuth display (VAD) technique of lidar scanning (conical scan lidar beam at a fixed elevation angle) to derivate the 3D components of the wind.
This technique is based on the following radial velocity equation:

$$v_r = u \cdot \cos(\theta) \cdot \sin(\varphi) + v \cdot \sin(\theta) \cdot \sin(\varphi) + w \cdot \cos(\varphi) \quad [1]$$

where u, v and w are the wind vector components and θ and φ the azimuthal and zenithal angles of the wind vector.
The WindCube lidar performs four successively radial velocity measurements at azimuth-angle intervals of 90° around the circle formed by a conical scanning, i.e. at θ=0°, θ=90°, θ=180° and θ=270° and at a fixed elevation angle φ, as illustrated in Figure 2.

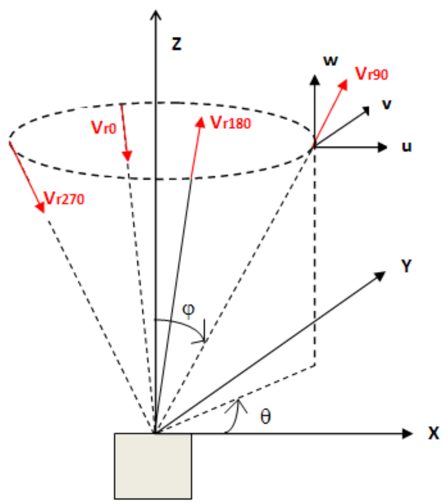


Figure 2 Sketch of the scan method performed by the WindCube LiDAR.

The limitations of this approach include the assumption of horizontal homogeneity of the wind field over the sensed height. Its temporal resolution for acquiring a full 3-D wind vector, obtained from four orthogonal measurement points, is about 1/4.6 Hz (0.22 Hz), i.e. each revolution takes about 4.6 seconds. However, the last three radial velocity values plus a new measured value are used to derive wind speed and direction profiles. Moreover, being a pulsed system, all mean wind speed, direction and turbulence data can be acquired simultaneously from several heights or range gates simultaneously. The measurement quality is assessed according to CNR (Carrier to Noise Ratio) defined threshold.

2 SPECTRAL ANALYSIS

The 10-min comparison addressed in [4] provide a measure of the mean characteristics of turbulent flow where higher frequencies of the wind are filtered out, although there is considerable information in the higher frequency data with relevance in wind energy application including wind load studies, wind turbine design among others.

Here the Power Spectrum Density (PSD) of wind velocity fluctuations is evaluated. We are trying to understand from the turbulence point of view how both measurements correlate to each other and to explain why turbulence measured with this LiDAR shows higher values respect to sonic measurements [4] .

2.1.1 Computation of the Wind Spectrum

To perform the spectral analysis, the Welch algorithm has been used. Here data blocks of one hour with availability higher than 90% were considered. The mean was removed and each data segment was tapered with a Hanning window prior to computing the periodograms for each individual segment. For the intercomparison purpose, the spectra were smoothed by averaging all spectra obtained at a specific wind direction, wind speed or atmospheric stability as will be shown later. Data segments of one hour were chosen so that larger-scale turbulent structures are captured. This algorithm used to compute the wind speed spectra is not affected by small gaps in the data series. LiDAR data are filtered to remove all data signal with Signal-to-noise ratios (CNR) below -22 dB.
Here high resolution data are used for this analysis. The LiDAR wind speed data are sampled at about 0.67 Hz and sonic measurements at 10Hz.

As a pre-analysis, the power spectrum from the lidar is compared to the power spectrum from the sonic anemometer at 80 m, and the results are illustrated in Figure **3**. To enhance the readability of the spectra, a log-log scale is used.

Note that the spectra represent an average over all observed wind speeds for the period selected. Atmospheric stability for this period was mostly near-neutral. Winds were coming from the Northwest sector.

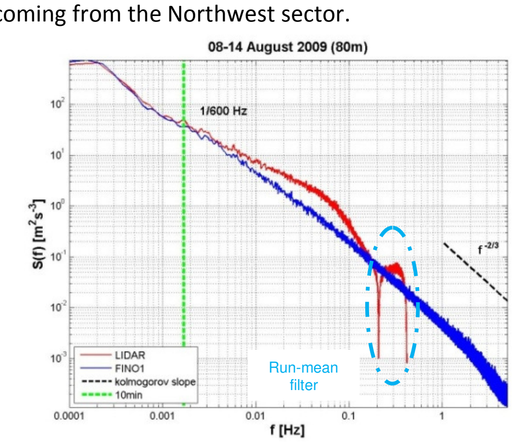


Figure 3 Averaged signal spectrum of sonic (blue line) and lidar (red lidar) of horizontal wind velocity spectra at 80 m height.

In Figure **3**, the cut-off frequencies differ because of different time resolutions of sonic and LiDAR measurements. The black dashed line represents the theoretical slope of a Kolmogorov inertial sub-range ($f^{-2/3}$). The green dashed vertical line corresponds to a frequency of 1/600 (10min). The loop at the end of the LiDAR- spectrum (about f>

0.21Hz) is a consequence of the temporal averaging algorithm which acts as a run-mean filter with a time window of about 4.6 sec. (time which laser beam takes to scan a full circle). Note that this LiDAR system cannot predict frequencies higher than about 0.21 Hz and, therefore, above that value it is better not to derive any conclusions from the spectrum.

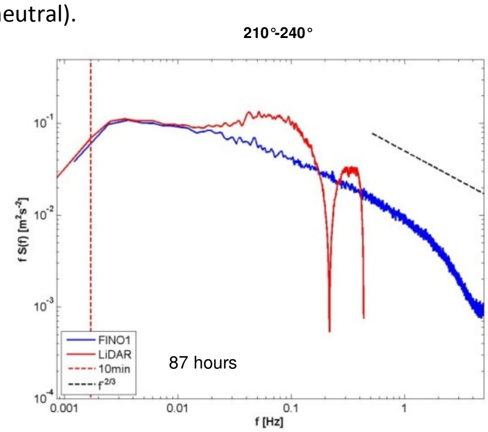
As can be clearly seen in Figure **3**, the lidar spectrum presents a signal increase at frequencies between 0.005 and 0.1 Hz. The cause of these apparently energy increase is unknown at present, but could be related to instrument noise, differences in sampling methods, or algorithm methods to construct the velocity vector. However, it is shown in the left hand of this figure that there is a good agreement between both wind spectra at low frequencies.

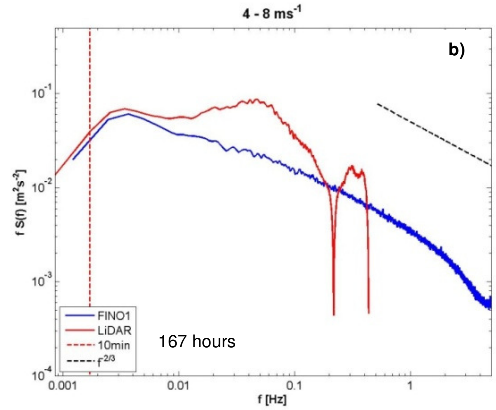
It is well known that the shape of the turbulence spectra depends among others on the thermal stratification, the height above the ground surface, and the wind velocity. In the next section the measurement data are divided in intervals according to wind speed, wind direction and atmospheric stability to check whether any of these parameters have a direct influence on the lidar spectra shape.

2.1.2 Averaged wind spectra varying with wind direction, wind speed and atmospheric stability

As explained before, hourly spectra calculated as before were grouped by sector of 30°. Here the product f·S(f) of frequency f in Hz and the power density spectrum S(f) is used so that the area between two frequencies represents the variance contributed by that frequency interval.

Figure 4 shows an example of the non-normalized general average spectra by wind direction (210-240=30° sector), by wind speed interval of 4-8 ms^{-1} and atmospheric stability (neutral).





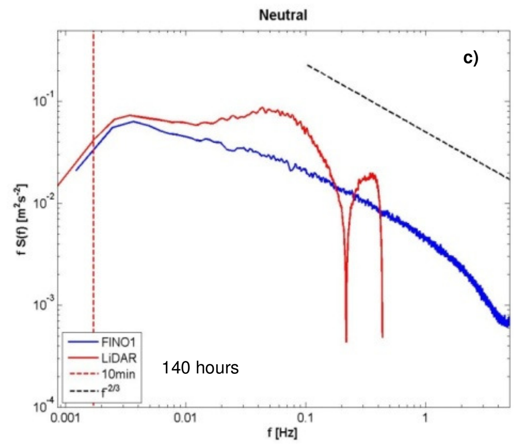


Figure 4 Averaged signal spectrum by wind direction (a)), wind speed (b)) and atmospheric stability (c)) of sonic (blue) and LiDAR (red) of horizontal wind velocity spectra at 80 m height. Number of hours used in the averaging is indicated on the graphs.

As can be seen by Fig. 4, the described deviaton between LIDAR and cup spectra persists for all applied filters. However the energy increase in the LIDAR spectrum is smallest fot the chosen 30° sector.

2.1.3 Turbulence wind power spectrum of the radial wind velocities

One of the averaging mechanisms applied during the WindCube LiDAR measurement is the probe length which leads to an averaging of the wind component along the laser beam within a sampling width of 20 m. Here, we focus on the radial velocity intercomparison in order to avoid the algorithm methods used to derivate the horizontal wind speed and thus to check whether the anomalous shape of the lidar spectra at certain frequencies can be a consequence of this velocity derivation algorithm or not.

In order to compare the radial velocity along the laser beam, the 10Hz sonic data are projected onto a vector aligned with the same azimuth and elevation angle as the lidar beam (line-of-sight). It is worth to mention that only wind from directions in between 270° to 300° have been considered so neither the sonic data nor the LiDAR beams are under flow distortion of the mast or wind farm.

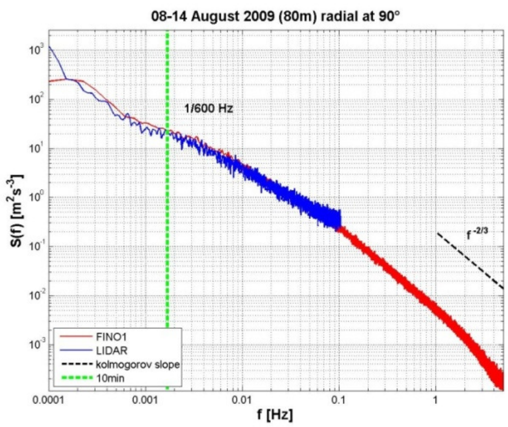


Figure 5 Comparison (sonic (red) versus lidar (blue)) of radial velocity spectra at 80m. In this example, the sonic data were projected onto a vector aligned into the 90° beam direction.

From Figure 5 it can be shown that there is a good agreement between both radial wind spectra which suggests that the probe-length averaging seems not to have an influence on the shape of the horizontal wind lidar spectrum.

3 CONCLUSIONS

In general there is a good agreement between both wind spectra (LiDAR and sonic) at low frequencies. However, the LiDAR spectra present an signal increase at frequencies between 0.005 and 0.1 Hz, which is independent on wind direction, wind speed or stability conditions. The cause of these apparently energy increase is unknown at present, but could be related to differences in sampling methods, or algorithm methods to construct the velocity vector. Moreover, the radial wind spectra comparison suggests that the probe-length averaging seems not to have an influence on the shape of the horizontal wind lidar spectrum. For the global turbulence this effects leads to a systematic overestimation.

4 ACKNOWLEDGEMENT

Within the joint research project RAVE (Research at AlphaVEntus), the RAVE-LIDAR project was set up to prepare the application of remote sensing measurements using lidar systems at the German Offshore test site [5] . Part of the work that is carried out by DEWI is presented in this report.

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