Offshore winds using remote sensing techniques

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Abstract. Ground-based remote sensing instruments can observe winds at different levels in the atmosphere where the wind characteristics change with height: the range of heights where modern turbine rotors are operating. A six-month wind assessment campaign has been made with a LiDAR (Light Detection And Ranging) and a SoDAR (Sound Detection and Ranging) on the transformer/platform of the world’s largest offshore wind farm located at the West coast of Denmark to evaluate their ability to observe offshore winds. The high homogeneity and low turbulence levels registered allow the comparison of LiDAR and SoDAR with measurements from cups on masts surrounding the wind farm showing good agreement for both the mean wind speed and the longitudinal component of turbulence. An extension of mean wind speed profiles from cup measurements on masts with LiDAR observations results in a good match for the free sectors at different wind speeds. The log-linear profile is fitted to the extended profiles (averaged over all stabilities and roughness lengths) and the deviations are small. Extended profiles of turbulence intensity are also shown for different wind speeds up to 161 m. Friction velocities and roughness lengths calculated from the fitted log-linear profile are compared with the Charnock model which seems to overestimate the sea roughness for the free sectors.

1. Introduction

The growing of the wind energy industry needs to be supported on the assessment (as accurately as possible) of the wind resource due to the high sensitivity of the generated power and blade loads, among others, to the characteristics of the wind speed. In this growing process, the wind turbine’s size (hub height and diameter) has been incremented and, nowadays, the blade tip of the biggest turbines are reaching levels up to 200 m at their highest rotor position. Nevertheless, the actual knowledge of the vertical behavior of the wind at these heights is still immature. The studies have been focused in the surface layer, i.e. ~10% of the atmospheric boundary layer, where the Monin-Obukhov similarity theory predicts a log-linear profile for the mean wind speed. For horizontally homogeneous and stationary flow, this is given by:

\[
\bar{\mathbf{n}} = \frac{u_*}{\kappa} \left[ \ln \left( \frac{z}{z_o} \right) - \psi_M \right]
\]  

(1)

where \(\bar{\mathbf{n}}\) is the mean wind speed, \(z\) the height above ground, \(u_*\) the friction velocity, \(\kappa\) the von Karman constant (~0.4), \(z_o\) the aerodynamic roughness length and \(\psi_M\) the universal stability function. The analysis made by [1] of data from the Kansas experiment (up to 32 m) validated...
Eq. (1) and found the variation of $\psi_M$ with height and stability. A similar analysis made by [2] at Høvsøre (Denmark) validates Eq. (1) up to 80 m, but the study reports non-logarithmic deviations above this level. Offshore measurements analyzed in [3] also show correspondent deviations: both studies introduce the height of the boundary layer to correct the profiles, a length scale which at certain atmospheric conditions is comparable to the size of the actual wind turbines.

Wind assessment campaigns are therefore required to verify and validate the behavior of the wind at higher levels in the atmosphere. This can be done by making use of well-known standard instruments like cup and sonic anemometers, but they have to be placed at the corresponding measuring height, which is difficult for levels above 100 m due to costs and structural problems involved in the erection of high masts. One possible solution to these difficulties is the use of the so-called ground-based remote sensing techniques. They have been deployed in different environments with good results in both the performance and the accuracy of the instruments. An on-land comparison of mean wind speeds is presented by [4] from observations taken by a LiDAR against measurements from cups mounted at different heights on a 120 m high mast at Høvsøre. The slopes of the linear regressions were $\sim 0.98$ with correlation coefficients near the unity. A similar study has been done by [5] on both land and offshore sites with similar results when the LiDAR is compared with measurements from cups on masts. Previously, [6] performed the evaluation of two SoDARs and a LiDAR on a marine environment on the platform of the Nysted wind farm in the Danish Baltic Sea. In the latter, no direct comparison with data from masts was done due to the configuration of the wind farm, but both laser and sound systems show high agreement (slopes $\sim 1$). In the same study, wind speed profiles from the instruments were found at heights up to 200 m showing a systematic behavior with atmospheric stability. This is a big advantage (in comparison with the standard instruments) because they are able to measure profiles of wind speed characteristics along the range of heights which covers the whole wind turbine’s rotor. Single-point measurements on the turbine’s nacelle are the base for turbine characterization but for large turbines this observation may not be representative for the entire rotor plane.

2. The campaign at Horns Rev

The Horns Rev park is an offshore wind farm located in the North Sea at the West coast of Jutland (Denmark) at $\approx 12$ km from the coast line of Esbjerg (see Figure 1).

![Figure 1. Horns Rev wind park. (a) Location in the danish North Sea. (b) Wind farm layout.](image-url)

The layout is an oblique rectangle of $5 \times 3.8$ km where 80 Vestas V80 wind turbines are installed in 8 horizontal and 10 vertical rows. The turbine’s rotor diameter is 80 m with hub heights at 70 m Above Mean Sea Level (AMSL). In the vicinity of the wind farm, three meteorological masts were deployed to observe the open sea wind and the wake from the park: Mast 2 at the
North-west which registers a wide range of “free stream” (open sea) wind directions, and Mast 6 and 7 at the East of the park which are observing the farm wake due to the dominant wind direction coming from westerly sectors. Fetch distances to the nearest land interruptions are large on these directions where wind registers low turbulence levels. The masts are instrumented with cup anemometers and wind vanes as it is described in Table 1.

Table 1. Instrumentation of the masts at Horns Rev. The masts are operated by DONG energy.

| Mast           | Height AMSL [m] | Instrument          |
|----------------|----------------|---------------------|
| Mast 2         | 62             | Cup anemometer [ms$^{-1}$] |
|                | 45             | Cup anemometer [ms$^{-1}$] |
|                | 30             | Cup anemometer [ms$^{-1}$] |
|                | 15             | Cup anemometer [ms$^{-1}$] |
|                | 60             | Wind vane [Deg.]    |
|                | 43             | Wind vane [Deg.]    |
|                | 28             | Wind vane [Deg.]    |
| Mast 6 and 7   | 70             | Cup anemometer [ms$^{-1}$] |
|                | 60             | Cup anemometer [ms$^{-1}$] |
|                | 50             | Cup anemometer [ms$^{-1}$] |
|                | 40             | Cup anemometer [ms$^{-1}$] |
|                | 30             | Cup anemometer [ms$^{-1}$] |
|                | 20             | Cup anemometer [ms$^{-1}$] |
|                | 68             | Wind vane [Deg.]    |
|                | 28             | Wind vane [Deg.]    |

The LiDAR and SoDAR units were installed on the transformer/platform of the wind farm at 20 m height AMSL. The analysis is particularly focused on the LiDAR measurements due to continuous background noise observed in the SoDAR spectral data. This noise mainly comes from a sound alarm system for scaring birds that is used at the platform to avoid accidents with helicopters.

2.1. The wind direction and inflow sectors
The inflow wind at the masts and platform positions comes from three different main directions: “Free stream” wind from the North-westerly sectors (open sea), “Fetch” wind influenced by the land (Jutland) from the easterly sectors and “Wake” wind coming from the farm. In Figure 2, these main directions are shown as well as the wind roses at two different points around the wind farm (a detailed description is found in Table 2).

As Figures 2(b) and (c) show, the free stream wind was the dominant inflow sector during the campaign and, on the platform (where the instruments are installed) most of the profiles are measured on this sector characterized by high winds and low turbulence levels.

3. Remote sensing instruments
The instruments installed on the platform were the AQ500 wind profiler SoDAR from AQ systems which has an antenna transmitting sound pulses in three directions 120° apart (sent with an azimuth angle of $\sim$ 18°) and three parabolic dishes receiving the reflected signal, and the QinetiQ’s ZephIR Wind LiDAR which consists in a focused continuous-wave laser beam scanning conically at an azimuth angle of $\sim$ 30°. Both instruments measure the Doppler-shift of the sound or light backscatter signal. The returned signal in the LiDAR system comes from aerosols
Table 2. Wind direction for the different inflow sectors at each mast/transform position.

| Location | Free [°]     | Fetch [°]    | Wake [°]    |
|----------|--------------|-------------|-------------|
| Mast 2   | 174 - 13     | 13 - 105    | 105 - 174   |
| Platform | 270 - 10     | 10 - 135    | 135 - 270   |
| Mast 6   | 313 - 8 / 167 - 218 | 8 - 167    | 218 - 313   |
| Mast 7   | 285 - 6 / 170 - 250 | 6 - 170    | 250 - 285   |

and particles in the atmosphere while temperature fluctuations in the atmosphere layers reflect the pulses sent by the SoDAR. The Doppler-shifted frequency is transformed to a line-of-sight velocity, $V_{LOS}$, a velocity measured along the beam direction (see Figure 3). Horizontal and vertical components of the wind speed, and wind direction are calculated from $V_{LOS}$ using a fitting routine explained in [7]. The LiDAR spectra is produced $\sim 0.02 \text{ s}^{-1}$ for each bearing angle, $\theta$, completing the circumference in 1 s. The unit takes three rounds to scan each height producing 150 different spectra. The time to return to the original height is $\sim 18 \text{ s}$ allowing the measure of turbulence. The SoDAR spectra could not be accessed but standard deviations of 10 min mean wind speed components were extracted using the unit’s software.

The SoDAR unit observed winds every 15 m starting at 50 up to 230 m AMSL. Nevertheless, its actual range depends on the signal to noise ratio which was very low during the period of campaign due to the sound alarm system. The SoDAR data is therefore very reduced and has low quality for most of the heights above 70 m. LiDAR observation heights were selected at 63, 91, 121 and 161 m where a fifth one was left for cloud correction. This is one of the biggest weaknesses of this LiDAR configuration because the Doppler-shifted spectra can be contaminated by strong backscatter from behind-lying, faster moving, clouds or fog. The data presented in this article has not been cloud-corrected but algorithms to avoid this effect are being currently tested at Risø. Another source of error in the LiDAR measurements is the probe volume ($\propto \Delta z_L$).
Figure 3. LiDAR scanning configuration. The SoDAR scanning mode is alike. (a) Wind decomposition. For the LiDAR: $z_2 > z_1$, $\Delta z_{L2} > \Delta z_{L1}$. (b) Measurements of $V_{LOS}$ for one height at each bearing position $\theta$ and the fitted curve.

which is increasing with height ($\propto z^2$) setting a limit in the vertical range $\sim 200$ m.

4. Comparison of LiDAR, SoDAR and mast data
Observations of the normalized horizontal mean wind speeds from the SoDAR and LiDAR are compared in Figure 4 for the platform free stream sectors. The wind speeds are normalized with the highest measurement value.

It is observed that the amount of data decreases with height (higher signal to noise ratio on the SoDAR) due to sound-alarm system and fixed echoes detected from the platform (there is a crane near the instruments). Differences in wind speed can be also observed due to the scanning configuration: $V_{LOS}$ points at an angle $\sim 30^\circ$ from the zenith in the LiDAR while the angle reduces to $\sim 18^\circ$ in the SoDAR and, despite of the flow high homogeneity, wind can be influenced by the platform structure. The availability of observations at different heights is much higher for the LiDAR unit and therefore, this study is now focused on this device.

A similar comparison is done in Figure 5 but for LiDAR measurements of normalized horizontal mean wind speed and measurements from cups at the different masts at their overlapping heights on their overlapping free stream sectors.

The correlations for all masts are high ($\sim 0.98$) and the slopes of the linear regressions approximate the unity. Mast 6 shows the highest correlation and has no offset probably due to its proximity with the platform and narrower free stream sector. The wind speed observations from the LiDAR are lower than the ones measured by the top cup anemometer of Mast 2 apparently due to an speed up effect on all the top cup anemometers at Horns Rev, but this effect is clearly detected on the wind speed profiles shown in Section 5.
4.1. Free stream turbulence
The LiDAR is able to perform observations of turbulence. A measure of the degree of turbulence is the turbulence intensity, $I = \sigma / u$, where $\sigma$ is the standard deviation of the mean wind speed $u$. From the cup observations on Mast 2, the longitudinal component of the turbulence $I_u$ can be compared at different heights and normalized horizontal mean wind speeds in Figure 6 (a) for the free stream sectors.

Turbulence intensity decreases with higher wind speeds until a wind speed level where the aerodynamic roughness of the water is increased generating, in contrast, more turbulence. The levels of turbulence are also reduced as expected with height. In Figure 6 (b), the same graph is shown but for the LiDAR measurements which reveal the same characteristics of turbulence intensity for increasing wind speeds and heights. Nevertheless, the LiDAR observes lower turbulence levels for the overlapping height (62 m). This is due to an attenuation of the standard deviation of the mean wind speed mainly caused by the LiDAR’s finite measuring volume. The degree of attenuation is dependant on wind speed and height (around 60 m AMSL, LiDAR’s $\sigma_u$ values are 20% less than the observed by a cup).

5. Extended profiles
5.1. Horizontal mean wind speed
Horizontal mean wind speed profiles measured by the cups on masts 2 and 6 are extended with LiDAR observations for their overlapping free stream sectors for five different wind speed bins in Figure 7.

The match between profiles is good for all the range of wind speeds (specially for the middle
Figure 5. Comparison of normalized horizontal mean wind speeds observed from the LiDAR and cup measurements on masts. (a) LiDAR at 63 and Mast 2 at 62 m. (b) LiDAR at 63 and Mast 6 at 60 m. (c) LiDAR at 63 and Mast 7 at 60 m.

Figure 6. Turbulence intensity variation with normalized horizontal mean wind speed at different heights. (a) Observations from cups on Mast 2. (b) LiDAR observations.

one $u = 0.48$). This confirms the high homogeneity of the flow on these free wind sectors. Nevertheless, it is detected an overestimation of the mean wind speed at the mast top cup anemometers (at 62 m on Mast 2 and 70 m on Mast 6). Mast shadow effects were previously studied at all cups to avoid the wake from booms which resulted in the elimination of the affected wind sectors, but the speed up is still present at the top ones. Apparently, it is the
A comparison of the extended profiles with theoretical log-linear profiles is shown in Figure 8. It is assumed that the averaged mean wind speed profiles over all stabilities for each wind speed can be represented by the neutral log-linear profile in the surface layer, i.e. the profile derived from Eq. (1) but neglecting stability ($\psi_M \approx 0$). In this way, Eq. (1) is simplified to $\bar{u} = \bar{u}^* \kappa \ln \left( \frac{z}{z_0} \right)$. The values of $\bar{u}^*$ and $z_0$ can be estimated then from at least two measurements of wind speed at different heights. This was done for the first two measurements on Mast 2 (15 and 30 m) and first three on Mast 6 (30, 40 and 50 m). In Figure 8, the measurements at the top anemometers were omitted.

The graphs are shown in a semi-logarithmic scale were the fitted profiles follow straight lines. Deviations are small between the measured and fitted profiles for both masts (especially for...
Mast 6 which is closer to the platform). The deviations are greater for the highest and lowest range of wind speeds than for medium values.

The good fitting between the measurements and the log-linear expression allow us to compare the estimated friction velocities and roughness lengths with a common sea surface model, e.g. the Charnock’s model, where the water waves are dependant on the friction velocity:

\[ z_o = C_h \frac{u_*^2}{g} \]  

(2)

Here \( C_h \) is the Charnock’s parameter (~ 0.016) and \( g \) is the gravitational acceleration. The comparison is shown in Figure 9.

![Figure 9](image)

**Figure 9.** Comparison of estimated \( u_* \) and \( z_o \) values with the Charnock’s model for both Mast 2 and Mast 6.

The Charnock’s model tends to overestimate the roughness length for the range of friction velocities in the analysis for both mast data. Nevertheless, the points just represent the results from the corresponding overlapping free stream sectors where neutral conditions were assumed. The Charnock’s model, despite of its large use, was derived from measurements on a large reservoir. The open sea characteristics (wave age, fetch, water depth, etc.) can strongly deviate from the conditions of his experiment.

5.2. Longitudinal component of the turbulence intensity

Vertical profiles of the longitudinal component of the turbulence intensity are shown in Figure 10 for different normalized horizontal mean wind speeds using the cups measurements at masts 2 and 6, and LiDAR observations for the overlapping free stream sectors.

Figure 10 shows how turbulence intensity decreases with height. The profiles derived from LiDAR and the cups on masts do not match because the LiDAR attenuates the standard deviation but the behavior observed by both instruments is very alike: at the highest mean wind speed \((u = 0.80)\), \( I_u \) shows the strongest variations with height while for the lowest wind speed \((u = 0.32)\) these variations produce a smoother curve. The lowest values for \( I_u \) are registered for intermediate mean wind speeds \( u = 0.48 \), also observed on Figure 6. The speed up effect is also detected from the profiles where the turbulence intensity is strongly reduced at the top anemometers due to higher values of horizontal mean wind speeds.

6. Conclusions

Offshore winds can be studied using ground-based remote sensing instruments. They observe winds accurately at the range of heights were wind turbines are planned to operate. Specifically, these techniques have the ability to perform wind profiling on sites where conventional techniques
Figure 10. LiDAR (dash lines) and cups measurements (solid lines) of the longitudinal component of the turbulence intensity at different heights. (a) Mast 2 and LiDAR observations. (b) Mast 6 and LiDAR observations.

become weak. The observation of winds at different levels is important because the turbine’s rotor size is increasing and faces the variations on wind characteristics along the atmosphere. In particular, the LiDAR observations and profiles matched well the measurements and profiles obtained from the cups on masts which allowed the extension of profiles for offshore mean wind speeds up to 161 m. Both techniques complement each other: speed up effects and mast shadow effects are avoided by the LiDAR and SoDAR but they face problems with clouds, fog and atmospheric conditions (amount of pollutants or temperature variability) which are avoided by cups.

The work needs to be continued by analyzing the differences found in the profiles under different atmospheric stability conditions. In this article, profiles of mean wind speed and turbulence intensity were averaged for certain wind speed bins, and on a free an “non-turbulent” sector but current analysis of the data has revealed high deviations from the neutral log-linear profile which has a stronger effect on the loads and performance of actual wind turbines.

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