Park Correction for FINO1-Wind Speed Measurements at alpha ventus

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Abstract

The FINO1-research platform and its 100m-mast were erected in 2003 to perform investigations of the marine atmospheric boundary layer for offshore wind energy projects. Meteorological measurements focus on wind speed and wind direction measured at different heights [1]. After six years of undisturbed measurements between 2004 and 2009, the offshore wind farm alpha ventus influences the wind and turbulence conditions reaching FINO1 from eastern directions. In the wake of a wind turbine the flow is changed such that the turbulence intensity increases while the wind speed decreases. To continue free flow measurements from eastern directions a LiDAR-device was mounted on the alpha ventus converter station in April 2011. The LiDAR measurements are evaluated in comparison with data from FINO1 for the recovery of the undisturbed wind field at FINO1 and to develop a park correction for the FINO1-wind measurement. For the period of May 2011 to September 2012 the park factor (*v_LiDAR/v_FINO1*) for eastern directions is calculated from 10-minute mean values and then averaged for 2 °-wind direction bins, 2 m/s-wind speed bins and three different stability classes for four heights respectively. Only data points were regarded during which all the wind turbines influencing the particular wind direction bin were operating. The park effect increases for lower wind speeds and for heights close to the nacelle with highest values occurring during stable atmospheric stratification.

Introduction

The research platform FINO1 (Forschungsplattformen in Nord- und Ostsee), was installed in 2003 about 45 km north of the island Borkum in the German Bight. Meteorological and oceanographic measurements have been recorded since January 2004. The platform is equipped with a 100-m-mast, from which wind speed and wind direction are measured at eight different heights. Other meteorological measurements include temperature, relative humidity, atmospheric pressure, global and UV radiation and precipitation [1]. The instrumentation for wind measurements is mounted on booms from two opposite sides of the mast. Detailed information is listed in Tab. 1. In 2009 the first German offshore wind park alpha ventus was built east of FINO1 and thus changes the wind field and turbulence conditions reaching FINO1 from eastern directions. Influenced sectors and wind directions are shown in red in Fig. 1. Alpha ventus consists of 6 Repower 5M wind turbines with a rotor diameter of 126 m

Measurement height LAT [m]	Wind speed at FINO1 Instrument	Wind speed at FINO1 Position	Wind direction at FINO1 Instrument	Wind direction at FINO1 Position	LiDAR measurement
249.8	—	—	—	—	available
199.8	—	—	—	—	available
179.8	—	—	—	—	available
159.8	—	—	—	—	available
139.8	—	—	—	—	available
119.8	—	—	—	—	available
103.0	cup-anemometer	top of mast	—	—	available
91.5	cup-anemometer	boom SE	wind vane	boom NW	available
81.5	cup-anemometer	boom SE	Ultra sonic anemometer	boom NW	available
71.5	cup-anemometer	boom SE	wind vane	boom NW	available
61.5	cup-anemometer	boom SE	Ultra sonic anemometer	boom NW	—
51.5	cup-anemometer	boom SE	wind vane	boom NW	—
41.5	cup-anemometer	boom SE	Ultra sonic anemometer	boom NW	—
34.0	cup-anemometer	boom SE	wind vane	boom NW	—

Tab. 1: Measurement heights at FINO1 and the LiDAR at the alpha ventus converter station

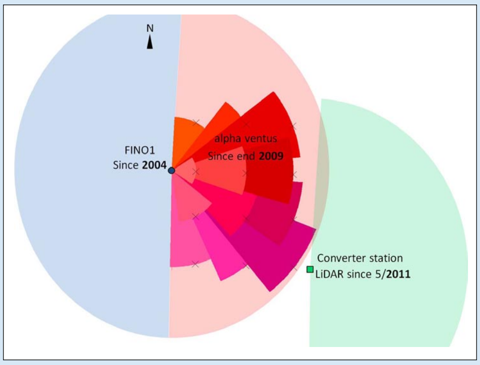

Fig. 1: Layout and location of alpha ventus in the German Bight with FINO1 to the west and the converter station in the south-east. Wind directions from which free wind can be measured at FINO1 are shown in blue. Direction sectors from which the flow is disturbed by individual wind turbines are shown in shades of red. Highlighted in green are wind directions from which the LiDAR at the converter station measures undisturbed wind.

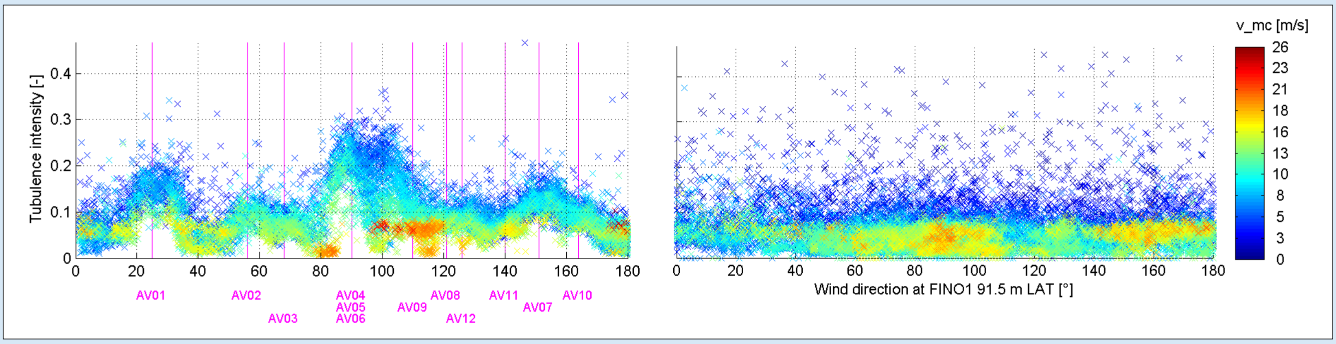

Fig. 2: In the left-hand graph (May 2011 to September 2012) the influence of alpha ventus becomes obvious in turbulence intensity depending on the wind speed depicted in color. Local maxima are related to wind turbines. In the right-hand graph (2008) turbulence intensity was evenly distributed over eastern wind directions.

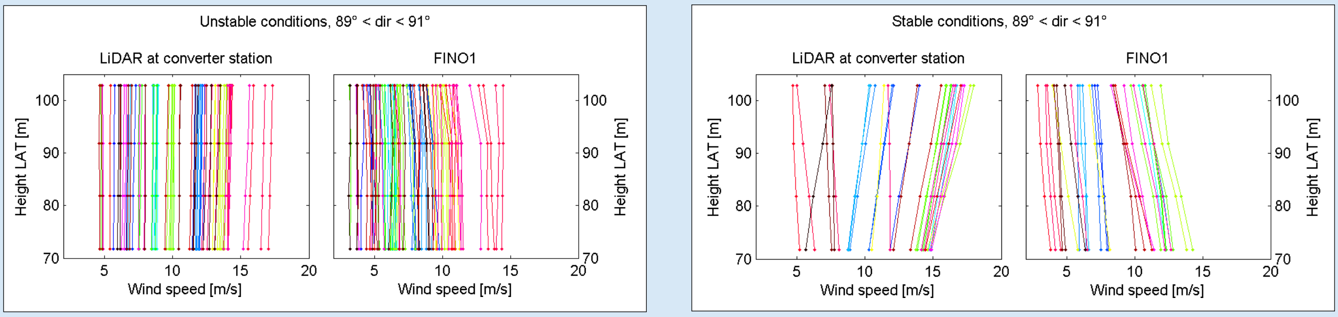

Fig. 3: Wind speed profiles measured during different atmospheric stabilities upstream (LiDAR) and downstream (FINO1) of alpha ventus at common heights. Same colors relate to same times of measurement.

Stable conditions	Unstable conditions	Neutral conditions
$\theta_{34m} - \theta_{Water} > 1$	$\theta_{34m} - \theta_{Water} < -1$	$-1 < \theta_{34m} - \theta_{Water} < 1$

Tab. 2: Relations applied to determine atmospheric stratification.

Stratification	Wind speed bin [m/s]											
	$2 \leq v < 4$	$4 \leq v < 6$	$6 \leq v < 8$	$8 \leq v < 10$	$10 \leq v < 12$	$12 \leq v < 14$	$14 \leq v < 16$	$16 \leq v < 18$	$18 \leq v < 20$	$20 \leq v < 22$	$22 \leq v < 24$	$24 \leq v < 26$
Unstable	4408	15430	16986	15114	11429	6402	4464	2103	1290	183	152	40
Neutral	4269	13885	15733	14124	10193	5497	3190	1432	759	98	76	20
Stable	3781	12777	14241	13374	9902	5791	3896	1829	987	111	76	20
Total	12458	42092	46960	42612	31524	17690	11550	5364	3036	392	304	80

Tab. 3: Number of data sets in each wind speed bin, for unstable, stable and neutral atmospheric stratification.

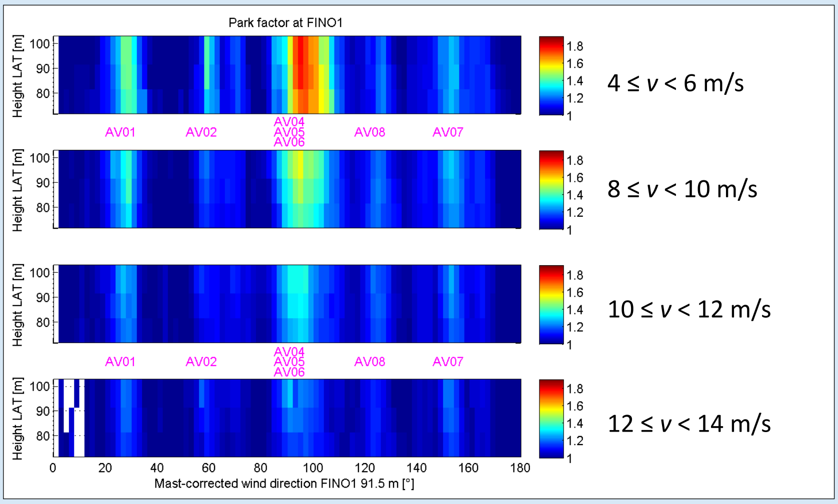

Fig. 4: Average park correction factor between 2 heights shown in color above wind direction for 4 different wind speed bins.

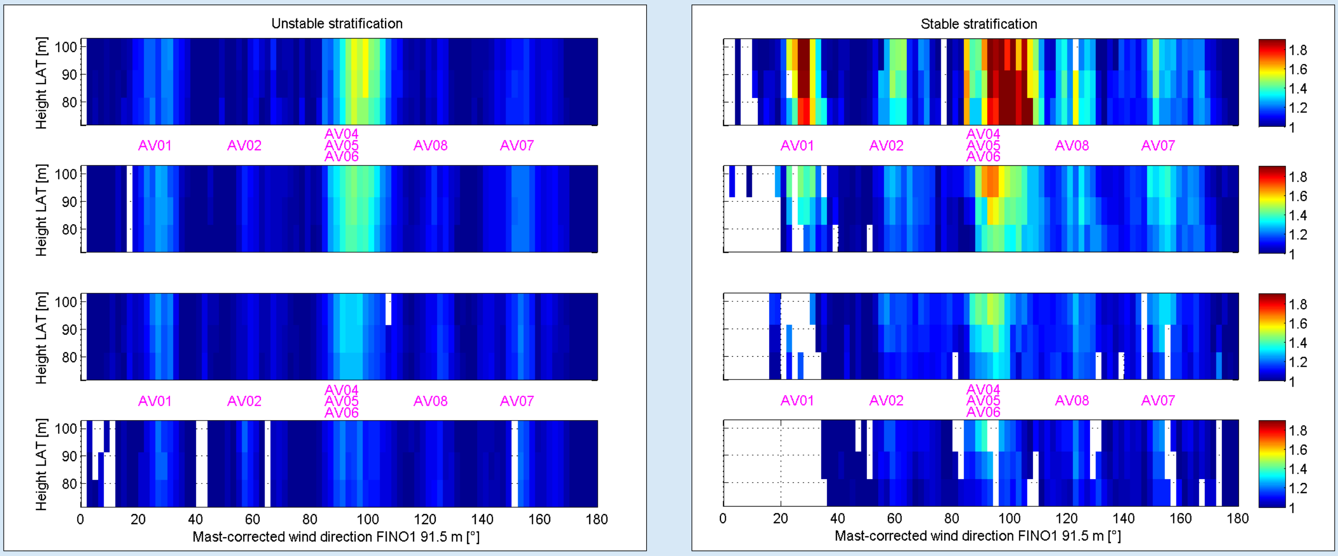

Fig. 5: Park correction factor for different heights shown in color above wind direction for 4 different wind speed bins (as in Fig. 4) for unstable stratification in the left-hand graph and for stable stratification in the right-hand graph.

(AV01-AV06) and 6 AREVA M5000 wind turbines with a rotor diameter of 116 m (AV07-AV12). As the closest wind turbine is only 405 m away from FINO1 wake effects are measured. In order to continue measurements of the free wind from eastern directions (green in Fig. 1), in April 2011 a *Windcube* LiDAR from *Leosphere* was installed on the alpha ventus converter station which is located again on the eastern side of alpha ventus. Now measurements of the free wind as well as detailed investigations on how the wind conditions are modified by the wind park can be performed for any wind direction. For the period from May 2011 to September 2012 the LiDAR measurements are compared with those from the cup-anemometers (Vector A100 marine version) at FINO1. As it can be seen in Tab. 1 the wind speed is measured by FINO1 and the LiDAR on the alpha ventus converter station at 4 common heights (71.5 m LAT, 81.5 m LAT, 91.5 m LAT and 103.0 m LAT).

Measurement of Park Effects

Park effects are noticeable in the turbulence intensity, which is the ratio of standard deviation and mean wind speed, measured at FINO1 and displayed in Fig. 2 left for eastern directions. It increases in the wake of a wind turbine. Depending on the distance between FINO1 and the wind turbine the sector with increased turbulence intensity has a certain width. It is broadest for the nearest wind turbine AV04 and considerably smaller for the wake of the AV01 which is about 900 m away. Natural turbulence and turbulence introduced by the wind park contribute to this increase of turbulence intensity depending on the wind speed, which is indicated by the color of the marker. Before alpha ventus, for example in 2008 the turbulence intensity is even for any eastern direction as shown in Fig. 2 right. It can also be seen that the wind farm introduces the highest level of turbulence just before reaching the rated power wind speed (8-10 m/s), for high wind speeds above 18 m/s the contribution is small. The wind speed profiles for the common heights upstream and downstream of the wind farm are shown in Fig. 3 for a narrow wind direction sector in the wake of the nearest wind turbine AV04 (between 89 ° and 91 °). In any case a wind speed reduction is obvious especially during unstable atmospheric stratification as in Fig. 3 left. During stable stratification as shown in Fig. 3 right the wind speed usually increases with height as measured by the LiDAR upstream of alpha ventus. Downstream, after the wind flow has passed the turbine field, wake losses cause an opposite picture with decreasing wind speeds up to the tower height of 100 m.

Park Correction Method and Conditions

For each wind turbine the sector of disturbance was calculated from the angular view of FINO1 according to IEC61400-12-1 standards [2]. The wind measurements from wind directions in the green sector in Fig. 1 are used to complement the free wind measurements in the blue sector west of FINO1 in Fig. 1. As the mast itself on FINO1 influences the observation of the free wind [3], the data from FINO1 is corrected for mast effects using the *Unifom Ambient flow Mast correction scheme* [4]. The park factor is then calculated for eastern wind directions as the ratio of the free wind speed measured at the converter station (green sector in Fig. 1) and the disturbed wind speed reaching FINO1 after passing through one or more influenced sectors of the alpha ventus wind turbines (shades of red in Fig. 1). The data set from May 2011 to September 2012 was scanned for FINO1-cup and LiDAR wind speed measurements at corresponding heights for which the following conditions apply:

- The wind is coming from eastern directions between 0 ° and 180 °.
- All the wind turbines whose sector of disturbance overlaps with the measured wind direction are operating [5].
- The availability of LiDAR scans for the 10-minute average is 100 %.

The resulting park factors which depend on wind direction, wind speed, height and atmospheric stratification

$$\langle Corr(dir, v, h, \theta)\rangle = \langle v_{LiDAR}(dir, v, h, \theta)/v_{FINO1}(dir, v, h, \theta)\rangle$$

were averaged by 2 °-wind direction bins and 2 m/s-wind speed bins for each of the four common heights and for unstable, neutral and stable atmospheric stratification respectively. Stability conditions are summarized in Tab. 2. If the water temperature is lower than the air temperature we assume stable stratification. If the water is warmer than the air we usually encounter unstable stratification. Temperature differences between air and sea that are relatively small result in neutral stratification.

Resulting Park Correction

The number of data sets as listed in Tab. 3 was found to match the conditions that are explained above. There is well enough data for wind speeds lower than 12 m/s but only roughly a tenth of that for wind speeds greater than 16 m/s. Stable conditions naturally appear less than unstable. The resulting park factor is shown in color for different heights and for a selection of wind speed bins in Fig. 4. Clearly the factor is largest in the immediate wake as seen in the top 2 graphs. Naturally the affected wind direction sector becomes wider closer to hub height at around 90 m. Profiles of the park factor in Fig. 4 show little vertical dependency. The park factor increases with height as the influenced sector becomes wider close to hub height. The two graphs of Fig. 5 show the park correction factors during unstable and stable conditions. For unstable conditions the factor is generally smaller which is most significant for wind speeds lower than 10 m/s.

Conclusions and Outlook

At FINO1 the wind farm alpha ventus is responsible for a turbulence intensity increase and a wind speed reduction of up to 50 %. The described park correction matrix depends on wind speed, direction and stability. The park factor is highest for low wind speeds between 4 m/s and 8 m/s during stable atmospheric conditions, which is reasonable. However, for high wind speeds and stable stratification the correction matrix still needs to be completed. As a next step thorough uncertainty assessment shall be performed. Main sources of uncertainty are the limited correlation of the two measurement points with a distance 2.5 km and the lack of knowledge regarding the actual park status for some periods. First application followed by energy yield assessment is intended in the near future. It is known, that the wind direction is also disturbed by the wind farm. This effect which is regarded to have a minor influence however shall be further investigated in the future.

Acknowledgements
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