D5.10 Mesoscale effects on wind farm energy yield reported

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1. EXECUTIVE SUMMARY

Measurements with a long-range multi-lidar system and a ship-based VAD lidar system have been performed at the offshore test field ‚alpha ventus‘ in the North Sea with the aim of measuring inflow and wake flow near the wind farm. Those datasets are made available for defining test cases which were used to validate meso-scale wake models. The wake model validation is based on three sets of observations:

1) FINO-1 meteorological data,

2) SCADA data from Senvion turbines,

3) ship-based wind lidar data and

three different wake models has been used and compared with the ship-lidar measurements. The comparison of the simulation data with the measurements were performed in two steps. First, a general comparison of static simulations with over the test case time period averaged meteorological conditions was carried out. A second approach, splitting the test case in 10 min inflow averages, was carried out. This single 10min average simulations were interpolated in space and time based on the ship trajectory and ship speed.

2. INTRODUCTION

This report is a summary of the activities and the results done in WP5.2. As part of the WP5, this task deals with the validation of wake models, which are used in the integrated design tool. It addresses the comparison of small scale wake models of the EERA-DTOC partners and ship-lidar measurements in ‚alpha ventus' performed by Fraunhofer IWES and give tentative explanations for the results of the first and second comparison. So far wake models of

DTU, Wind Energy, Denmark (DTU),
Faculty of Engineering, University of Porto (FEUP) and
Fraunhofer IWES, Oldenburg (IWES)

have performed simulations presented in the following. As discussed and agreed in advance within the EERA-DTOC consortium a comparison of mesoscale wake models and scanning lidars will not be part of the report due to the insufficient data availability of the lidar system and turbine production data.

This report describes the defined test cases in section 3.1, focus on the chosen test case in section 3.2, give a brief description of the used wake models in section 3.3 and present the results of the comparisons in section 4. It should be noted that the following results are supposed to validate the wake models and is not considered as a detailed comparison of the simulation results.

3. WAKE MODELLING - SHIP-BASED AND SCANNING LIDAR DATA

The wake modelling described in this part of the report is only based on ship-lidar measurements. No scanning lidar data could be used due to insufficient data availability. The uncertainties of the so far analysed scanning lidar data is to dominant to do a representative comparison with the simulations.

3.1. Case definition

In the context of this report, five test cases have been selected from the performed ship-lidar measurements of Fraunhofer IWES which are described in detail in the section Annex III. Below a brief summary is listed.

Name	Time period	Average wind speed @90m	Average wind direction @90m	Average turbulence intensity @90m	Distance to eastern wind farm edge
Test case 03	05.10.2013 from 08:20h till 09:00h	7.06 m/s	268.42°	4.56%	ca. 1750m - ca. 3500m
Test case 04	05.10.2013 from 09:50h till 10:20h	6.54 m/s	270.23°	4.55%	ca. 2000m - ca. 850m
Test case 05	05.10.2013 from 11:00h till 11:50h	5.88 m/s	270.5°	5.07%	ca. 2800m - ca. 6500m
Test case 06	05.10.2013 from 13:30h till 14:30h	6.43 m/s	285.5°	7.2%	ca. 11000m
Test case 07	05.10.2013 from 08:20h till 09:00h	6.58 m/s	268.42°	4.56%	ca. 800m - ca. 5500m

For time reason, based on the delay of the ‘alpha ventus’ measurement campaign and the pre-discussions of measurement data validation, only one test case could be completed until the completion of this report. Due to the smallest distance and lowest variation in the distance to ‘alpha ventus’ the test case 04 has been selected for the validation of the wake models.

3.2. Test case preparation

In a first consideration averaged inflow conditions, like the wind speed profile at 90m height, wind direction at 90 m height and atmospherically turbulence intensity at 90 m height, measured by the meteorological measurement mast FINO1 in the time from 05.10.2013 9:50h till 10:30h were used as input parameters for the different simulations.

From the figures below it can be seen, that the conditions changed slightly within the 40min of measurement. In this first approach these changes were not taken into account and representative mean values were used instead.

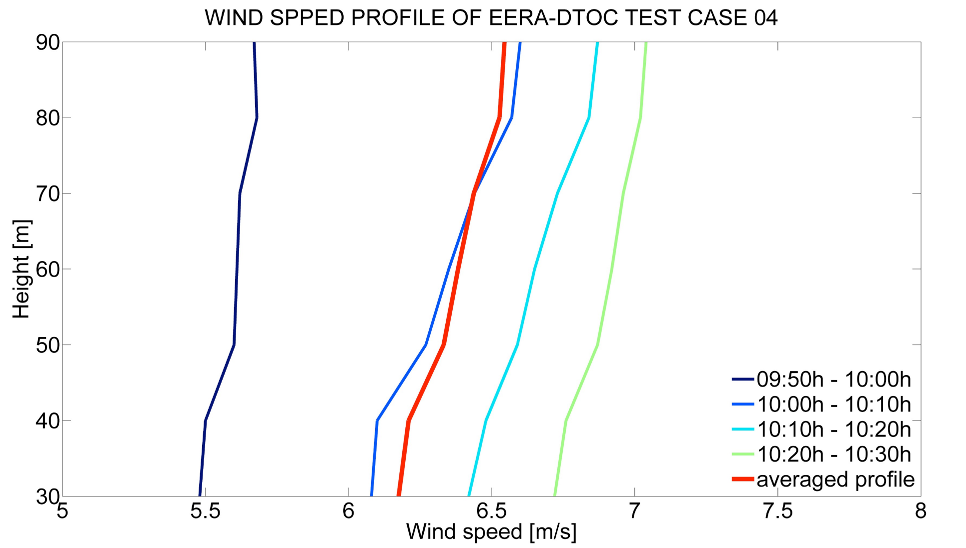


Figure 1: Plots of wind speed profiles in the time period of test case 04 measured by FINO1

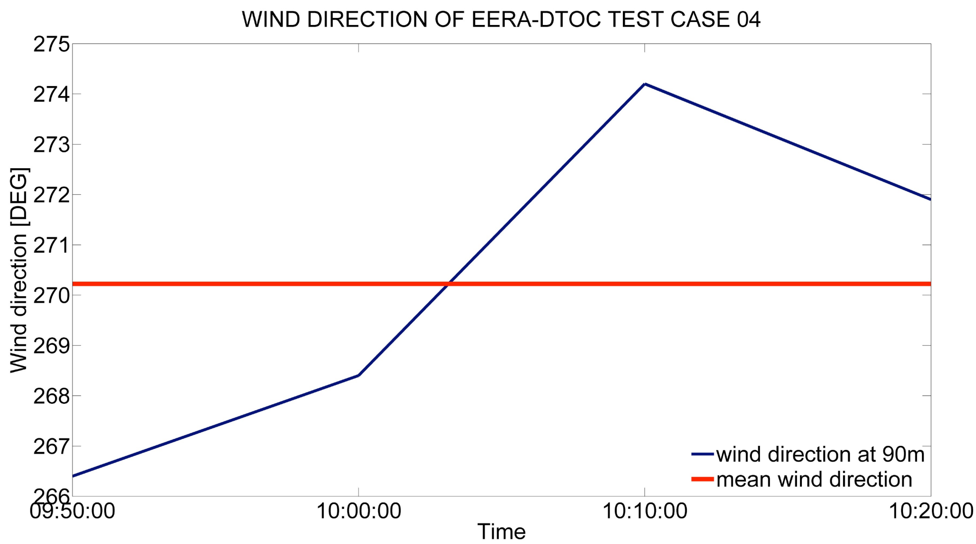


Figure 2: Plots of wind direction in the time period of test case 04 measured by FINO1 at 90 m height

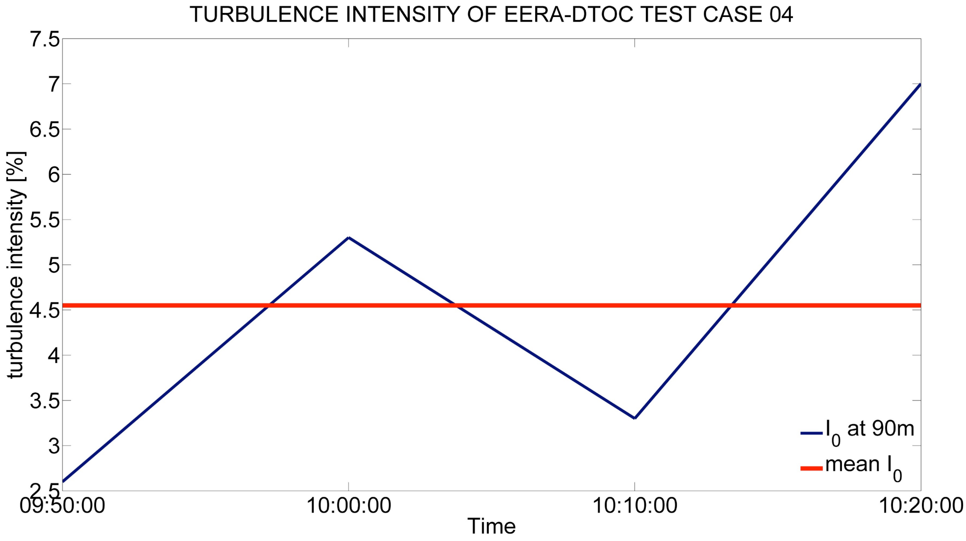


Figure 3: Plots of atmosperical turbulence intensity in the time period of test case 04 measured by FINO1 at 90 m height

In the time period of test case 04 the ship travelled the distance of ca. 4005 m from north east to south east of ‘alpha ventus’ with an average speed of 1.67 m/s as can be seen in the Figure 4.

While the ship moved southwards, the VAD measurement was slicing the eastwards oriented multiple wakes of the wind farm.

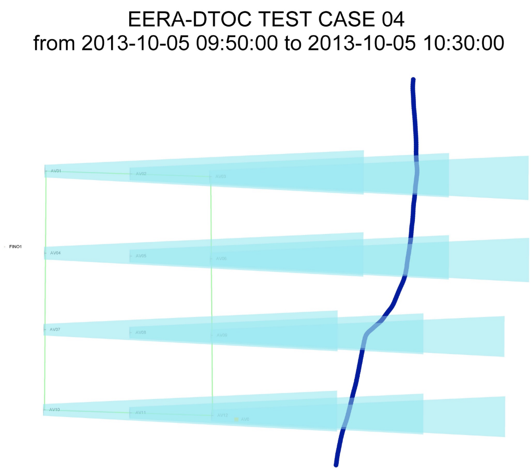


Figure 4: Visualisation of the the ship lidar trajectory in ‚alpha ventus' in the time period of test case 04.

The figures show that all models may reflect that wake effect seen in the measurements. Since not all models used a vertical velocity profile, but a constant inflow for all heights, or used different extrapolations of the wind speed for heights above 90m, the simulated wind speeds were normalised with the free flow at the edges of the simulations respectively of the ship measurements.

3.3. Wake models

A precise description of the model, can be found in the report of the project internal performed wake benchmark.

3.3.1. The modified Park model by DTU

A modified version of the Park wake model (Katic et al., 1986), also implemented in the Wind Atlas Analysis and Application Program (WAsP) (Mortensen et al., 2007), is here used for wake calculations. The main difference between this modified version and that in WAsP is that the former does not take into account the effects of the 'ground reflecting back wakes' and so it only takes into account the shading rotors both directly upstream and sideways.
The Park wake model is based on the wake deficit suggested by Jensen (1983), who derived a mass conservation-like equation for the velocity immediately before a turbine u_1, which is affected by a wake,

$$u_1=u_{free}(1-a/(1+kw\ x/r)^2)$$

where u_{free} is the upstream wind speed non-disturbed by the turbine (free), a the induction factor ($a = 1\text{-sqrt}(1-c_T)$), which is a function of the thrust coefficient (c_T), kw the wake decay coefficient, x the downstream distance, and r the turbine's rotor radius. Katic et al. (1986) further suggested that the square of the total wake deficit should be the sum of the square of all contributing wake deficits and introduced the effect of the mirrored rotors.

The used model was implemented in a Matlab script, which allows to compute wake deficits in any given point and can be easily compared to the location and path of the ship. Here a $k_w = 0.03$ was used for wake computations but it should be noted that kw is a function of turbulence intensity. For further comparisons a much lower k_w values (as the turbulence intensity is very low for all test cases) which will increase the wake deficits measured at the ship positions.

3.3.2. flapFOAM by Fraunhofer IWES

The flapFOAM model is intended to be used for wind farm modelling and layout optimisation. It is the aim to provide an extendable modelling platform that is able to represent as much of this as possible, and to perform wind farm calculations and layout optimisation for various distributions of inflow conditions. flapFOAM is based on OpenFOAM libraries and fully programmed in C++. All implemented models are run-time selectable, and the code is easily extendable by new models. Similar to what is done in other wind farm modelling software, the local wind velocity at a point inside the wind farm is obtained by overlapping a background wind field and the wake deficits that arise from upstream turbines. Each turbine is equipped with a wake model, and various models from the literature have been implemented.

3.3.3. FEUP

The CFD code, VENTOS®/2, is a finite volume implicit solver for the Reynolds averaged Navier-Stokes (RaNS) equations for non-stratified flows, with a two equation k-e turbulence model. It is geared specifically towards the solution of wind flow problems over complex terrain. It is based on the SIMPLE algorithm for non-collocated grids to solve the velocity pressure coupling. Each fundamental equation is integrated in control volumes to produce an algebraic system of equations, solved by a TDMA (Tri-Diagonal Matrix Algorithm) solver. Upwind, second and third-order interpolations are used for the discretisation. It uses structured terrain-following meshes to accurately capture topography-induced effects. Modelling the momentum drag associated with the presence of a wind turbine is done implicitly in VENTOS®/2, using a uniformly loaded Actuator Disk model. The wind turbine rotor's span is first described in a fine cylindrical coordinate mesh, from which a smooth Actuator Disk is produced in the domain mesh by tri-linear extrapolation.

3.4. 'alpha ventus'

As an input for the simulations FINO1 data from test case 04 was used to represent atmospheric conditions. For the simulation of ‚alpha ventus' the in Annex I described coordinates of the wind turbines were used to represent the wind farm with a averaged hub height of 91m for Senvion and AREVA turbines with a rotor diameter of 122m. To avoid unnecessary extensions of the difficult discussion about the confidentiality of turbine data and to comply with the strict obligations by the manufacturer all turbines were described by one representative type of wind turbine.

This type of turbine is characterised by its adapted thrust coefficient curve which satisfies the behaviour of Senvion and AREVA turbines without providing any conclusions about the original thrust coefficient curves. It has been obtained by modification of a thrust curve from aero-elastic simulations of the NREL 5MW wind turbine and is describes in detail in Annex II.

4. RESULTS

4.1. First comparison – 40min average approach

The three mentioned models were use to simulate the measured wake situation in test case 04. On the basis of the ship trajectory and from the measured heights from 40 m to 140 m altitude, the wind speed was extracted from the corresponding points of the simulations. A comparison of the ship-lidar measurements and the simulations can be found in the following graphs for different heights. To represent lower tip height, hub height and upper tip height graphs for 40 m, 90 m and 140 m were elected to be compared.

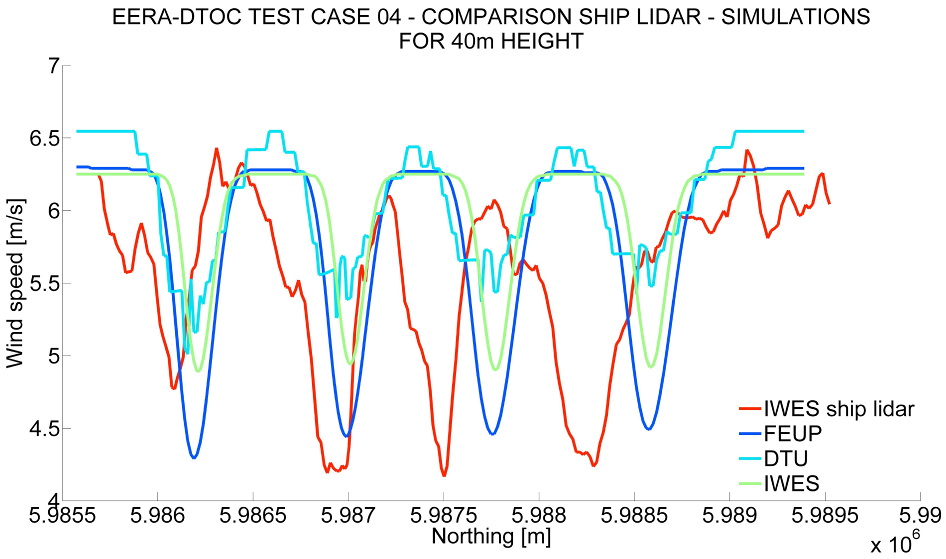


Figure 5: Comparison of wind speed at 40 m height in the wake of ‚alpha ventus' for test case 04 inflow condition.

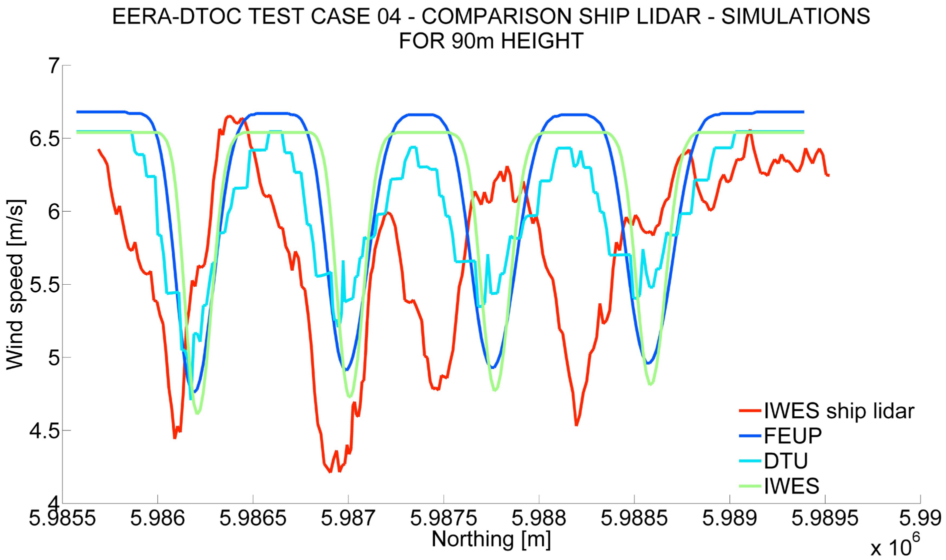


Figure 6: Comparison of wind speed at 90 m height in the wake of ‚alpha ventus' for test case 04 inflow condition.

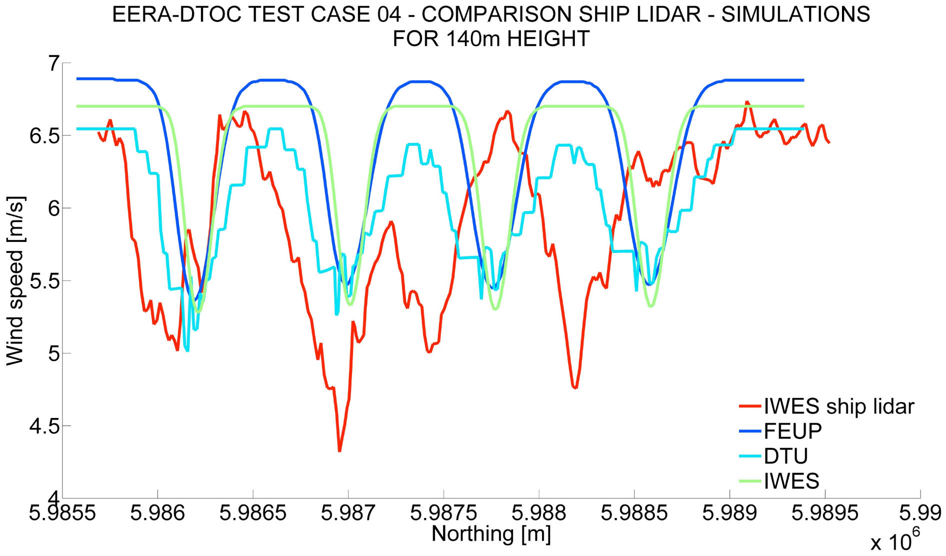


Figure 7: Comparison of wind speed at 140 m height in the wake of ‚alpha ventus' for test case 04 inflow condition.

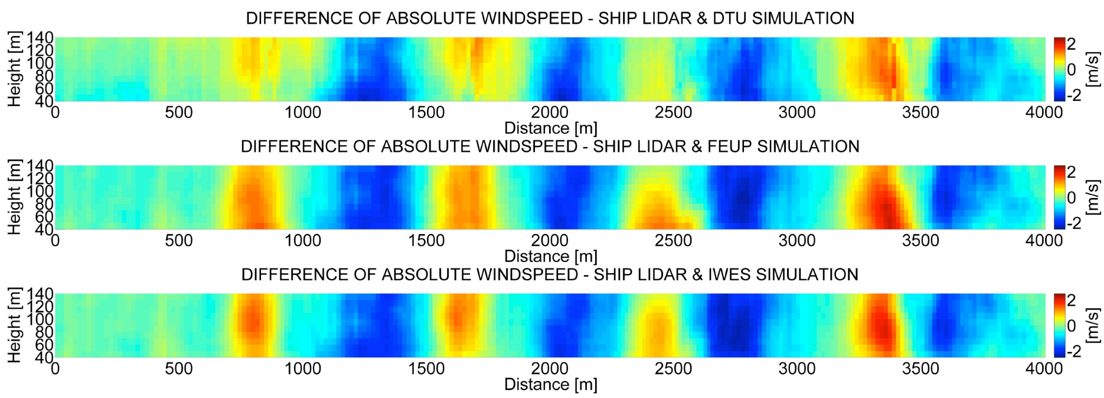


Figure 8: Visualisation of difference in absolute wind speed from simulations based on ship-lidar measurements for heights from 40 m to 140 m.

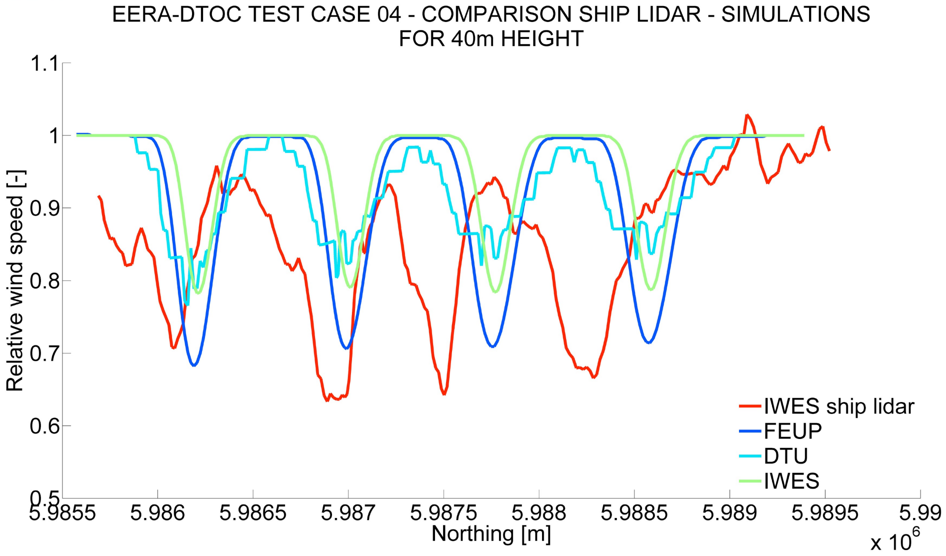


Figure 9: Comparison of relative wind speed at 40 m height in the wake of ‚alpha ventus' for test case 04 inflow condition.

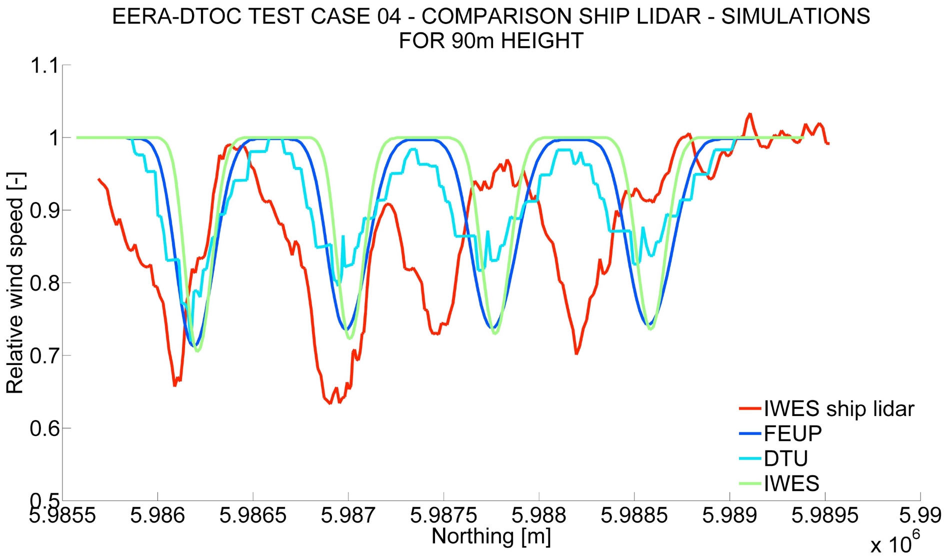


Figure 10: Comparison of relative wind speed at 90 m height in the wake of ‚alpha ventus' for test case 04 inflow condition

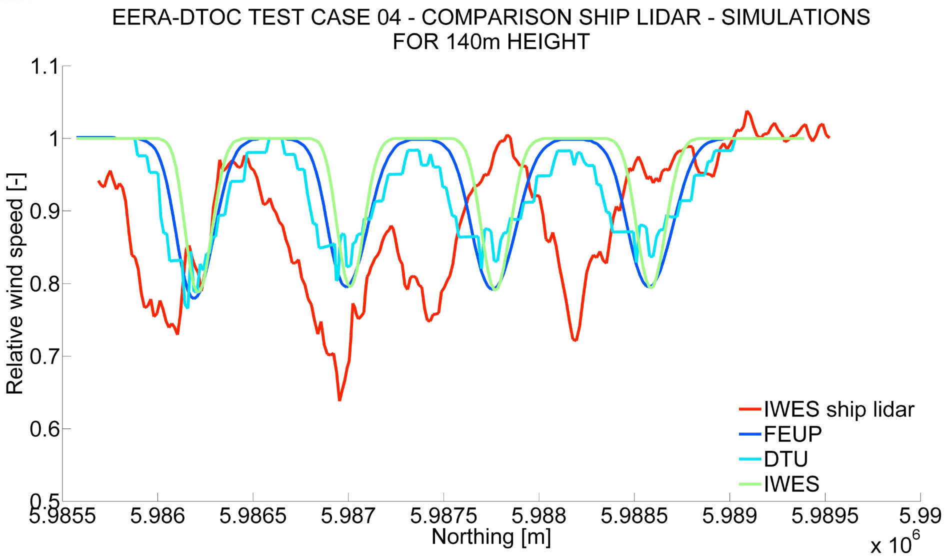


Figure 11: Comparison of relative wind speed at 140 m height in the wake of ‚alpha ventus' for test case 04 inflow condition.

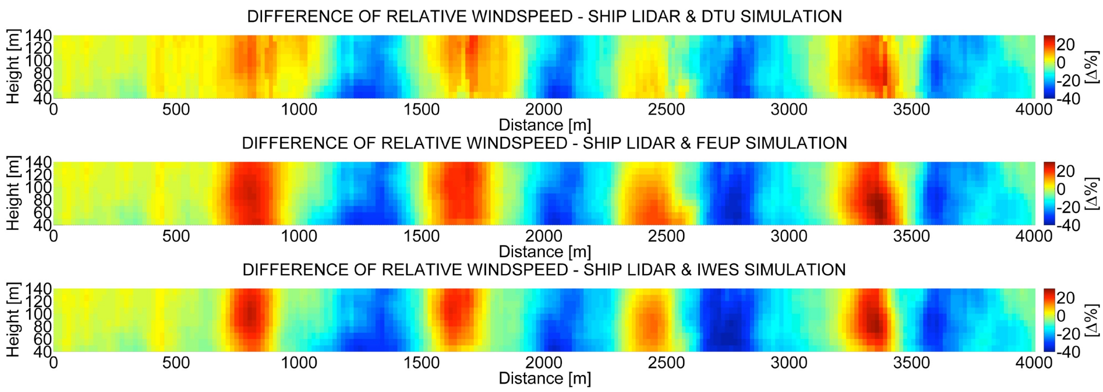


Figure 12: Visualisation of difference of relative wind speed from simulations based on ship-lidar measurements for heights from 40 m to 140 m.

While the magnitude of the deficit can be simulated in average within a tolerance of 7% for 40 m and 90 m heights, there are larger deviations at 140 m height. The position of the wakes from the simulations show a trend for the AREVA turbines to match the measurements in a better manner than for the Senvion turbines. This deviation first concluded a systematic error in the ship's coordinates, which turned out as not applicable.

It can be assumed that by the continuous movement of the ship and the associated measurement time of 40 minutes, the change of wind direction measured at FINO1 has a heavier impact on the positioning of the wakes than assumed in advance.

Since the first simulations of the test case 04 was an estimation and a check of plausibility, effects that could influence the wake deflection, such as yaw-offset of the wind turbines were not taken into account yet.

4.2. Second comparison - time weighted 10min dataset

After the first consideration of the test cases with average environmental conditions for the entire measurement period of 40 minutes a second iteration of the comparison was carried out with individual simulations. Therefore the time interval was divided into four 10 minutes segments for which each had input information based on the meteorological mast FINO1. Four different vertical wind speed profiles, wind direction at 90m height and atmospherically turbulence intensity at 90m height were given to the modellers. The detailed conditions can see Figure 1, Figure 2 and Figure 3.

To generate a single comparable data set from the four individual simulations which corresponds to the time-variant ship measurements a weighted interpolation was applied to these simulations. The temporal midpoints of each 10 minutes time interval were starting- and endpoint for the linear weighting functions of each simulations. The transfer of the weighting function, which is based on time, as can be seen in Figure 13, to the spatial ship trajectory was carried out on the basis of the ship speed (Figure 14).

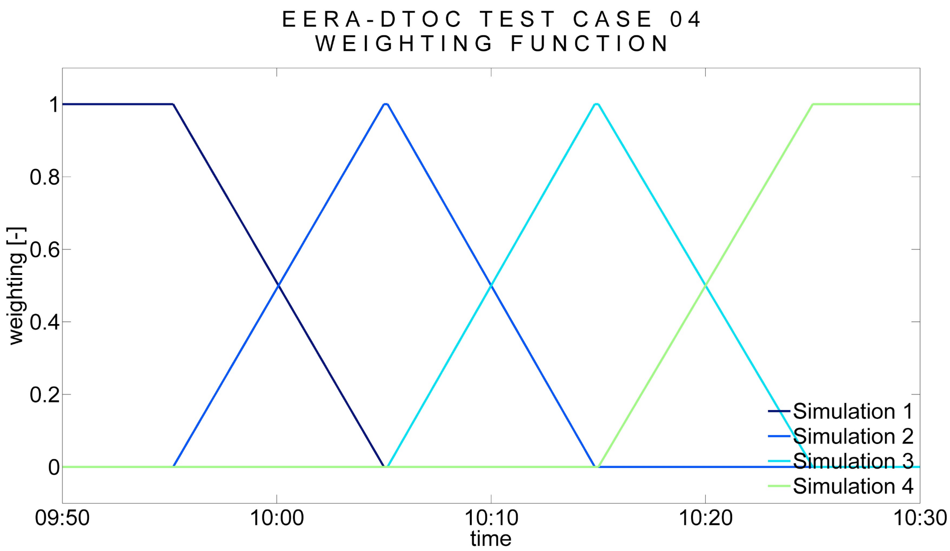


Figure 13: Weighting function of single static 10min simulation for test case 04 over time.

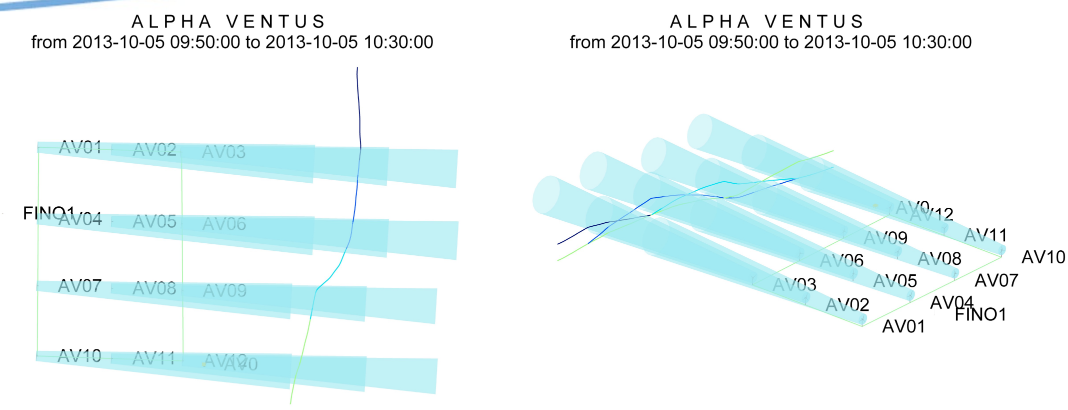


Figure 14: Weighting function of single static 10min simulation for test case 04 projected to spatial ship trajectory.

To represent lower tip height, hub height and upper tip height, graphs for 40 m, 90 m and 140 m were again selected to be compared.

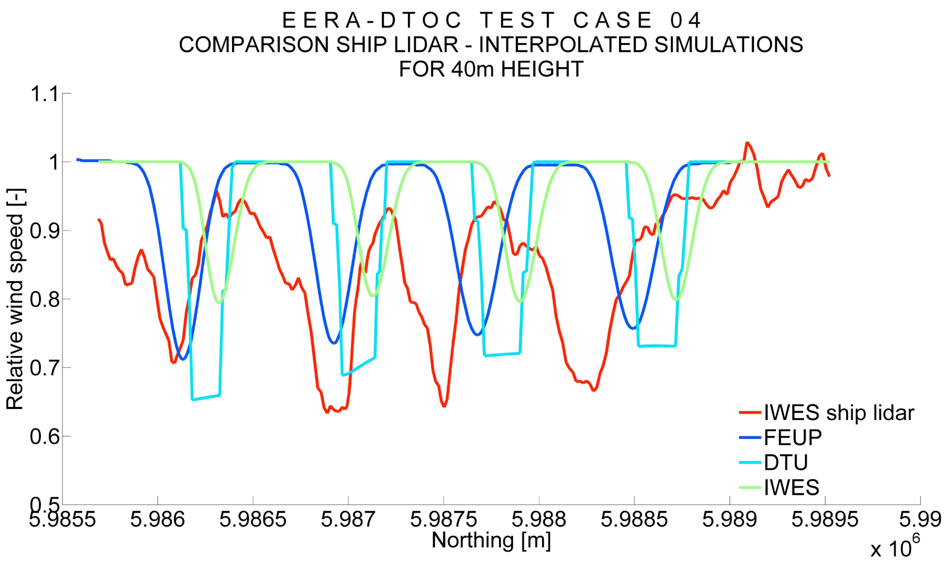


Figure 15: Comparison of relative wind speed based on time interpolated data set at 40 m height in the wake of ‚alpha ventus' for test case 04 10min averaged inflow conditions.

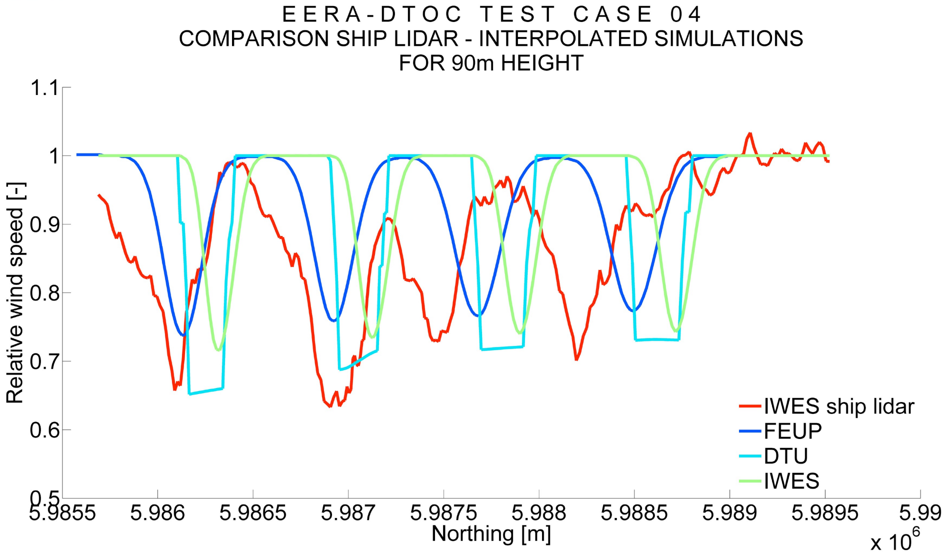


Figure 16: Comparison of relative wind speed based on time interpolated data set at 90 m height in the wake of ‚alpha ventus' for test case 04 10min averaged inflow conditions.

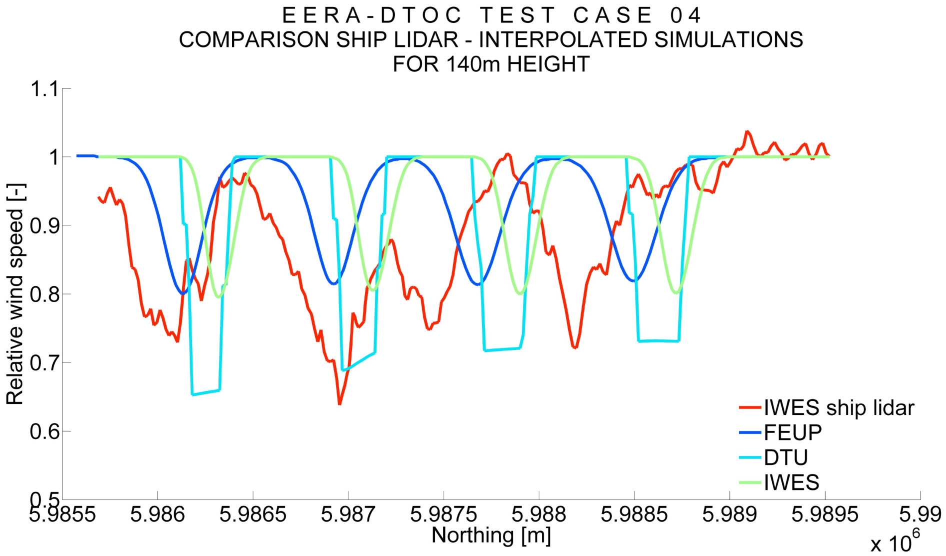


Figure 17: Comparison of relative wind speed based on time interpolated data set at 140 m height in the wake of ‚alpha ventus' for test case 04 10min averaged inflow conditions.

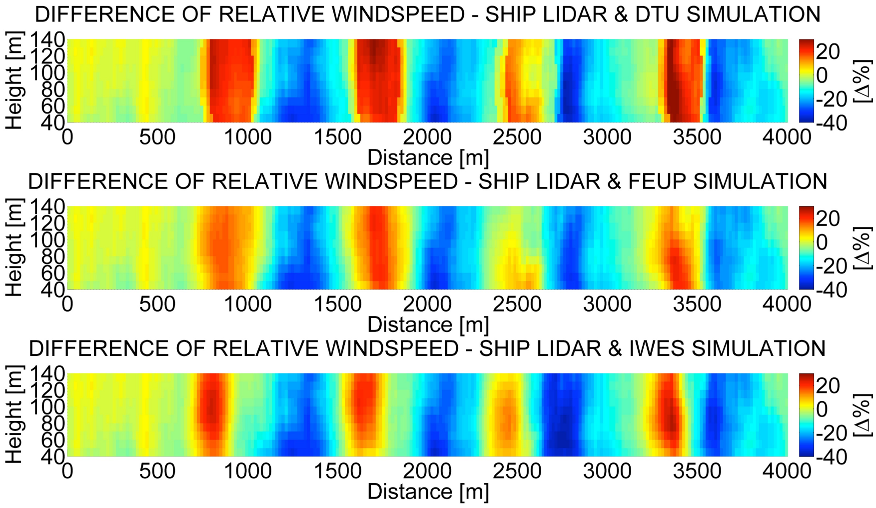


Figure 18: Visualisation of difference of relative wind speed based on time interpolated data set from simulations with ship-lidar measurements for heights from 40 m to 140 m.

Again, it can be seen that the differences of the used models with regard to the position of the wakes, show no major differences, however, they vary more than in the first comparison. The wake centres for 40 m and 90 m height have a good match for the southern two rows of turbines, whereas the northern two turbine rows show a clear north shift for 40 m and 90 m height.

To investigate this behaviour, the azimuth angles of all the ‚alpha ventus' turbine were compared with the wind direction. The yaw-activity in the measurement period corresponds to the behaviour of the wind direction change, whereby an offset based on a wake deflection by yaw errors can be excluded.

With respect to the first comparison the second comparison indicates that the conformity of strength is the deficits become worse. In both simulation methods (40 minutes averaged and time weighted) no model can depict the flow velocity between the wake centres from 40 m to 90 m height in an appropriate way.

The sobering results of the second comparison led to a re-review of the meteorological inflow data. These have been checked and were time shifted based on the spatial difference of FINO1 and the ship position. A cross correlation of the wind speed and wind direction time series of FINO1 and ship measurements pointed out an almost twice as large time offset as was calculated in advance(Figure 19 & Figure 20). Both correlations revealed an offset of nearly 19.5min.

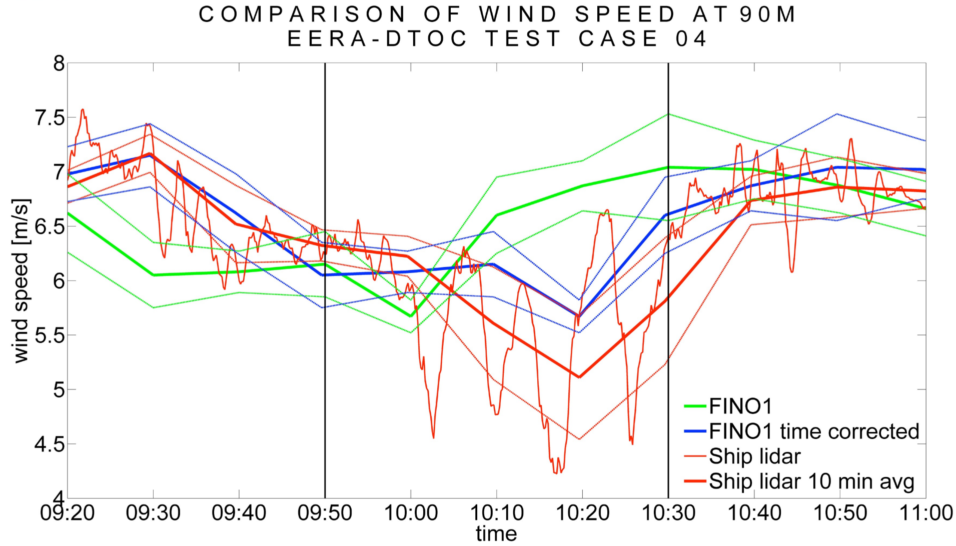


Figure 19: Comparison of measured wind speed at 90 m height by FINO1 and ship based VAD measurements. Black lines are indicating test case 04 time period.

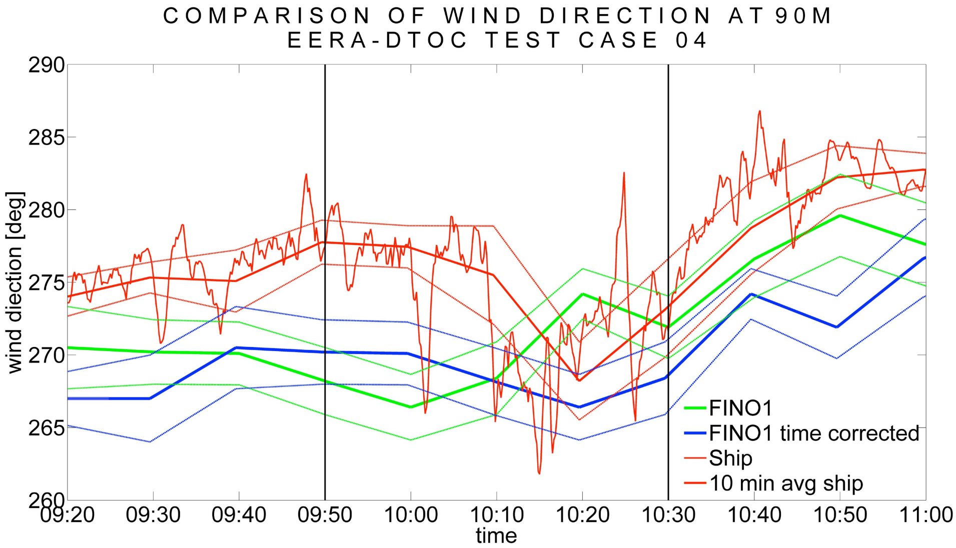


Figure 20: Comparison of measured wind direction at 90 m height by FINO1 and ship based VAD measurements. Black lines are indicating test case 04 time period.

This leads to the assumption that wind speed and wind direction changes within a wind farm may not follow Taylors hypothesis of frozen turbulence based on the wind farms average wind speed.

In a third comparison, which will not be part of this report, additional simulation in a wider time frame will be made.

5. ANNEX I – ALPHA VENTUS

Wind farm coordinates WGS84

Corner	Latitude	Longitude
Top right	54° 1.6' N	6° 37.3' E
Top left	54° 1.6' N	6° 34.4' E
Bottom left	54° 0.0' N	6° 34.4' E
Bottom right	54° 0.0' N	6° 37.4' E

Wind turbine coordinates in UTM 32

Object	East coordinate [m]	North coordinate [m]	Turbine
FINO 1	341941	5987859	
AV 01	342351	5988612	Senvion 5M
AV 02	343192	5988584	Senvion 5M
AV 03	343978	5988557	Senvion 5M
AV 04	342346	5987796	Senvion 5M
AV 05	343191	5987767	Senvion 5M
AV 06	343984	5987740	Senvion 5M
AV 07	342341	5987035	AREVA M5000
AV 08	343189	5987006	AREVA M5000
AV 09	343990	5986979	AREVA M5000
AV 10	342336	5986237	AREVA M5000
AV 11	343188	5986208	AREVA M5000
AV 12	343996	5986181	AREVA M5000
Substation	318664	5989018	

6. ANNEX II – WIND TURBINE CHARACTERSITICS

Technical specifications of the turbines

SENVION 5M

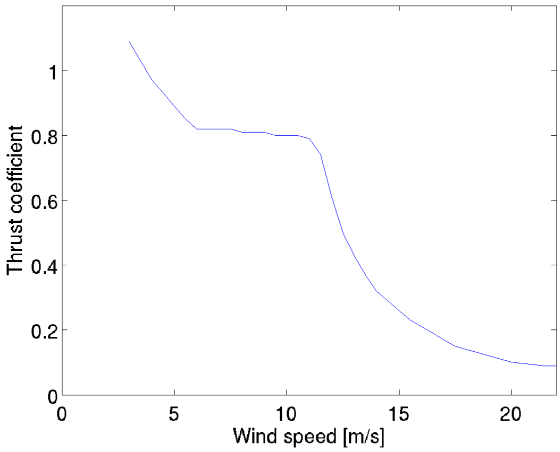
Rotor diameter	126 m
Hub height	92 m
Rated power	5 MW
Speed	Rotor: 6.9 to 12.1 U/min Generator: 670-1170 U min
Cut-in	3.5 m/s (storm force 3)
Rated wind speed	13 m/s (storm force 6)
Cut -out	30 m/s (storm force 11)
Max. tip speed	80 m/s at rotor speed 12.1 U/min
Design life	20 years
Weight of nacelle without rotor and hub	~290 t
Weight of nacelle with rotor and hub	~410 t
Weight tower	~210 t

AREVA M5000

Rotor diameter	116 m
Hub height	90 m
Rated power	5 MW
Speed	Rotor: 6.9 to 12.1 U/min
Cut-in	3.5 m/s (storm force 3)
Rated wind speed	12.5 m/s (storm force 6)
Cut -out	25 m/s (storm force 11)
Max. tip speed	90 m/s
Weight of nacelle without rotor and hub	~200 t
Weight of nacelle with rotor and hub	~309 t
Weight tripod, tower, nacelle	~1000 t

Thrust curve

The thrust coefficient curve is a generalized curve to be used for both turbine types at alpha ventus. It has been obtained by modification of a thrust curve from aero-elastic simulations of the NREL 5MW wind turbine.



7. ANNEX III – AVAILABLE CASES FOR PHASE 2

Working report - Microscale modelling test cases / Ship-LIDAR measurements
Gerrit Wolken-Möhlmann / Fraunhofer IWES

Using ‚alpha ventus' wind farm for measuring and simulating wind turbine wakes, there is a number of special scenarios due to the geometry and the small number of turbines. Generally speaking these cases are an even distribution of all single wind turbines as well as interferences that leads to double, triple or quadruple wakes, dependent on the inflow wind direction.
Therefore a geometrical analysis was performed using the original ‚alpha ventus' wind turbine coordinates. For an estimation of the resulting wake pattern, each single wake was modelled using a Gaussian distribution with sigma = 60m. In a second step, all Gaussian distributions were summed up. The so calculated resulting pattern describes a cut through the wind farm wake perpendicular to the inflow direction.
The geometrical position of the wakes and the corresponding wake pattern is displayed in Figure 13 and Figure 14. An overview of the occurrences of the different wake configurations/patterns is shown in Table 1. Interesting test cases could be inflow angles of 270°, as well as 197° and 206°. The later ones should show a number of double wakes, measurements exist for different distances.
Furthermore plots for some special cases are attached.

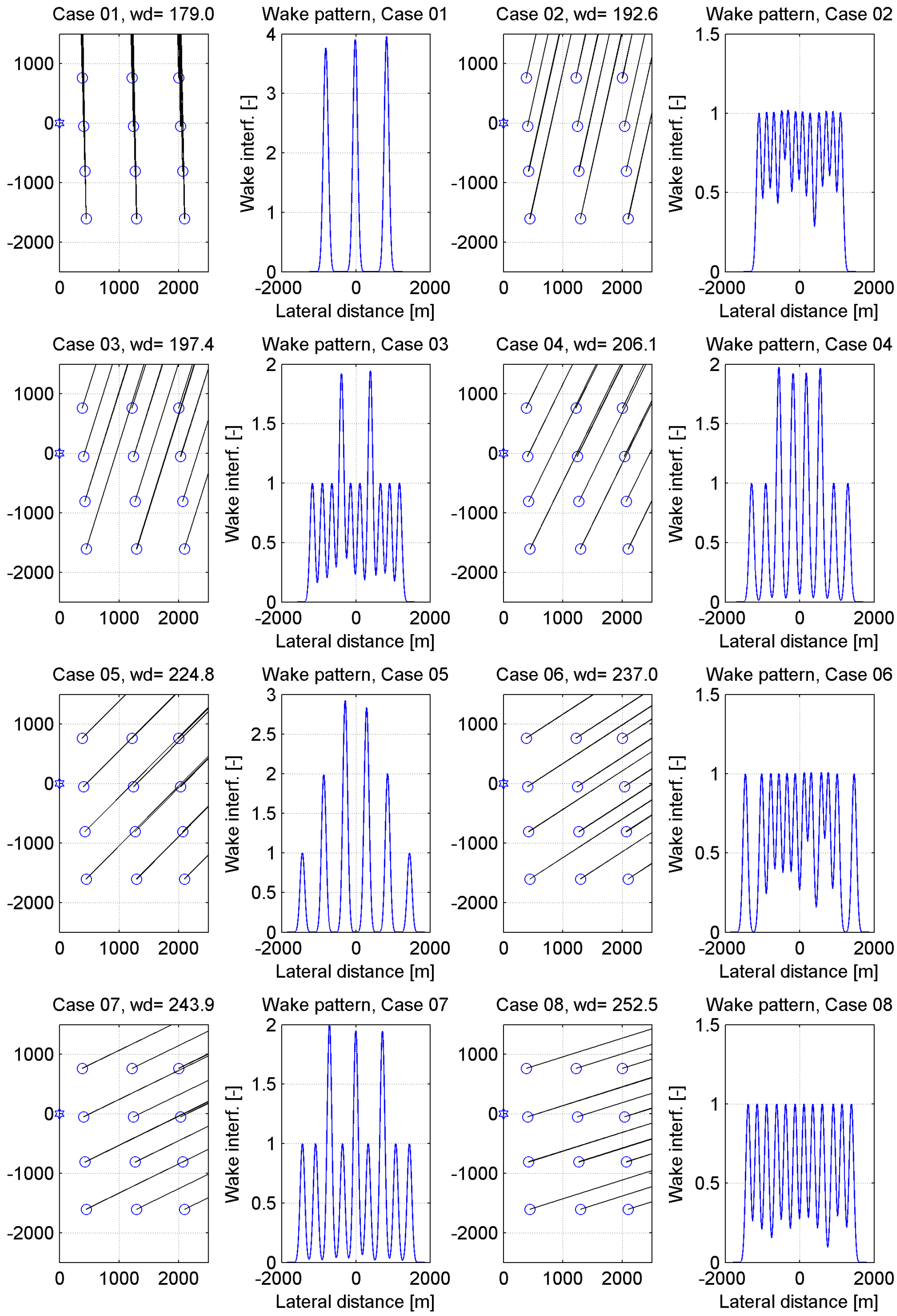


Figure 13: Plots of special Alpha Ventus wake configurations for wind direction from 179°-252°

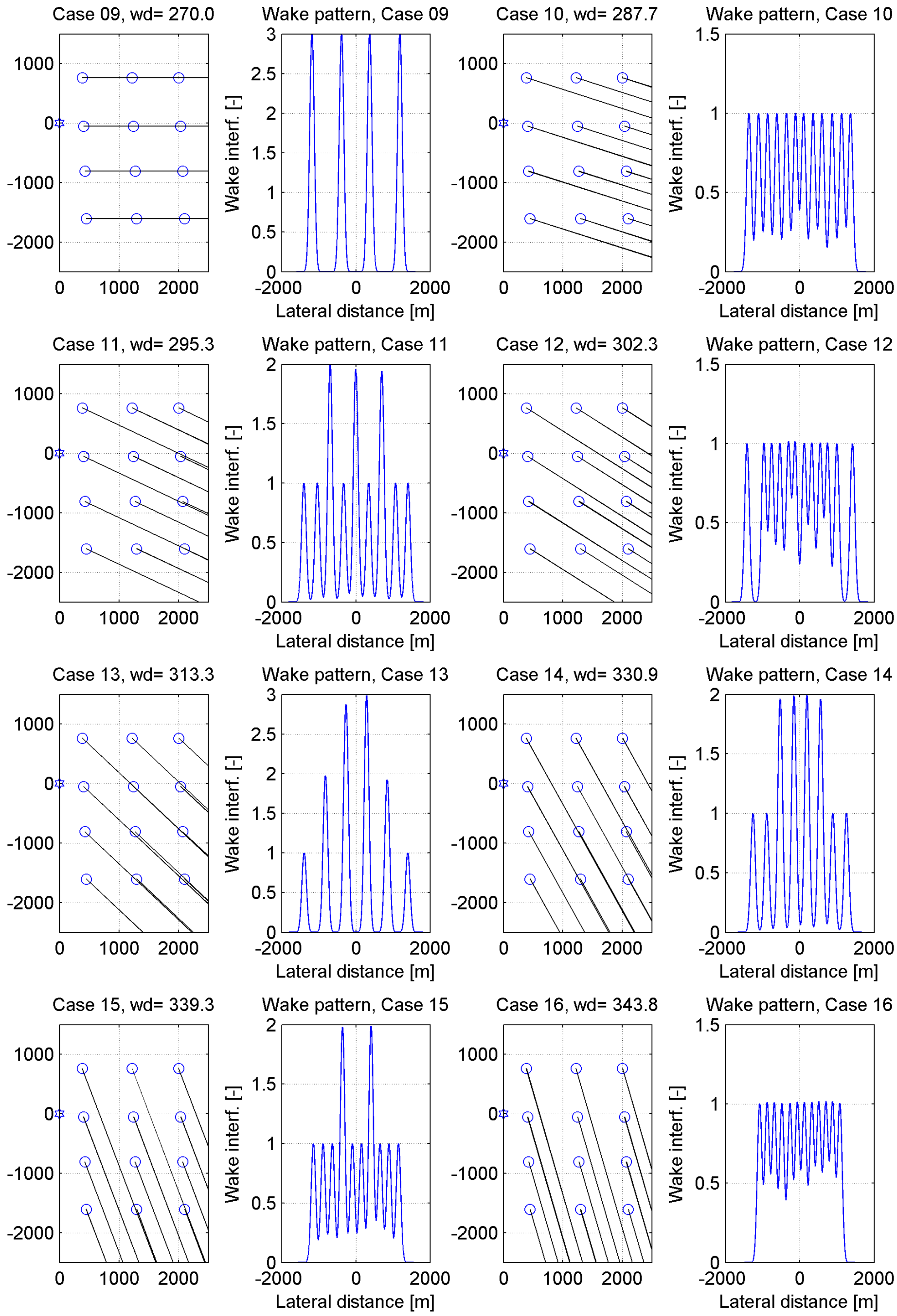


Figure 14: Plots of special Alpha Ventus wake configurations for wind direction from 270°-343°

Table 1: Overview of different wake configurations and occurrences during the measurement. Measurements with downwind distances over 6000 Meter or downwind distances with variations over 1000 Meter during a measurement are marked red.

Condition Nr.	Inflow direction	Single Wakes	Double Wakes	WT distance	Tripple Wakes	WT distance	Quadruple Wakes	WT distance	Meas. Nr.
1	178.0						3	800m/	
2	192.6	12							#26;#27
3	197.4	8	2	2500					#20;#22;#23;#25
4	206.1	4 4	4	1750					#15;#18;#19;#24;#28
5	224.8	2	2	1150	2	1150			#13;#30;
6	237,0	12							#32;#33
7	243.9	6	3	1800					
8	252.5	12							#31;
9	270.0				3	800			#3;#4;#5;
10	287.7	12							#6;#12;
11	295.3	6	3	1850					
12	302.3	12							#7;
13	313.3	2	2	1200	2	1200			#8;
14	330.9	4	4	1800					
15	339.3	8	2	2550					
16	343.8	12							
17	358.0								
Else	#1; #2;#9;#10;#11;#14;#16;#17;#21;#29;#34;#35;#36								

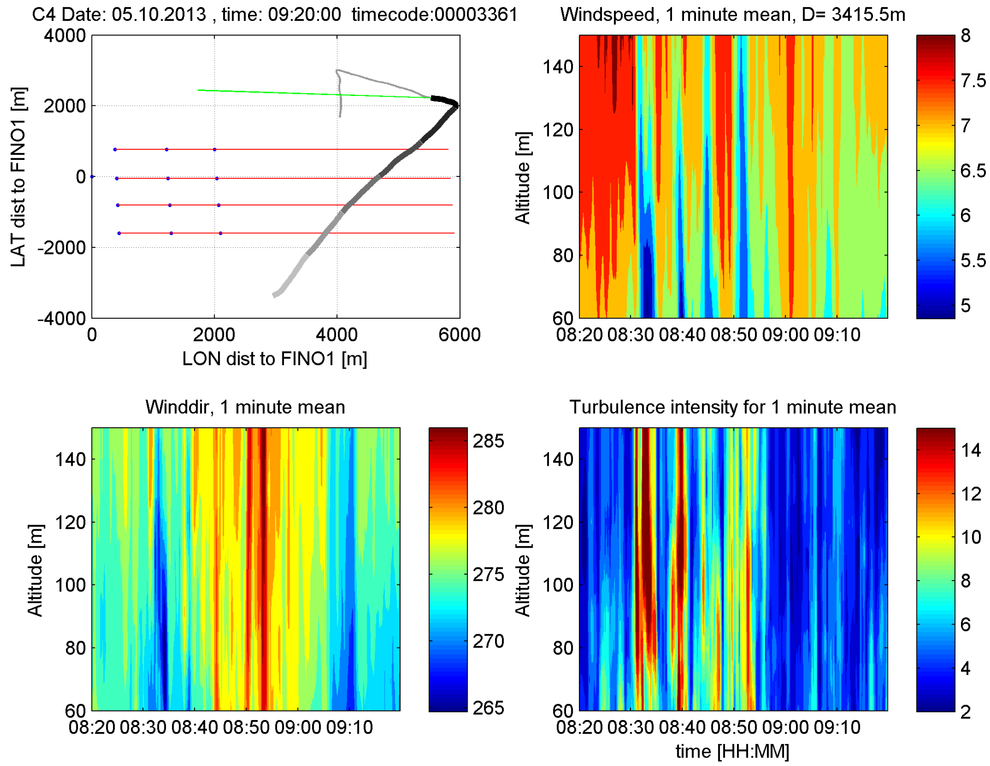


Figure 15: Measurement nr. 3

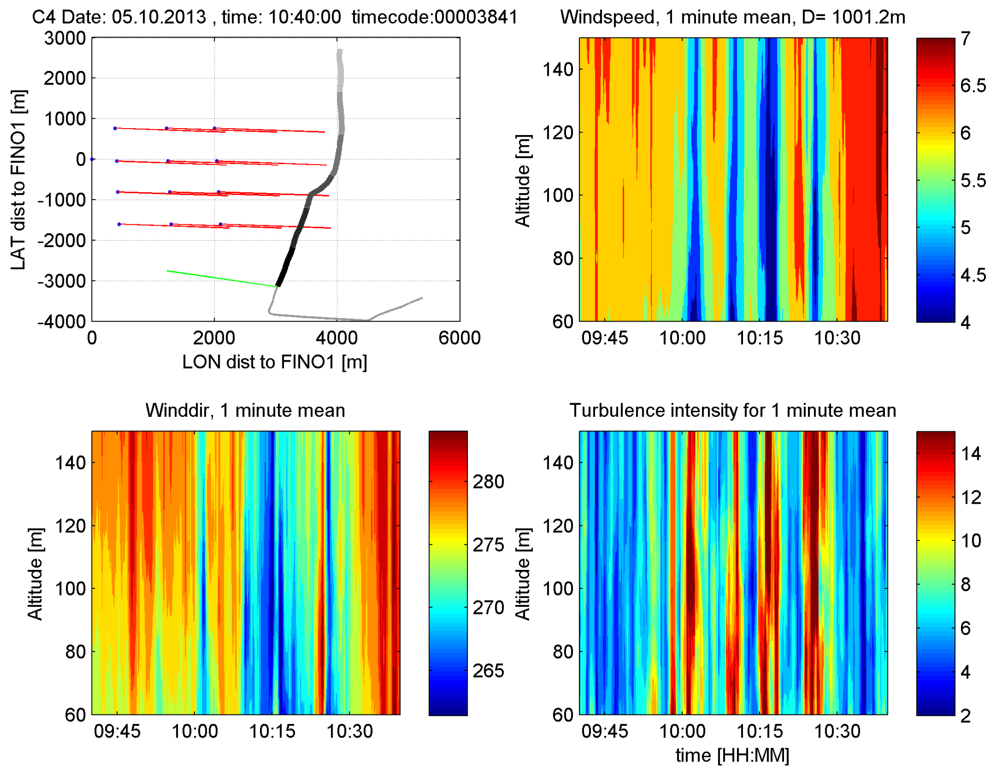


Figure 16: Measurement nr. 4

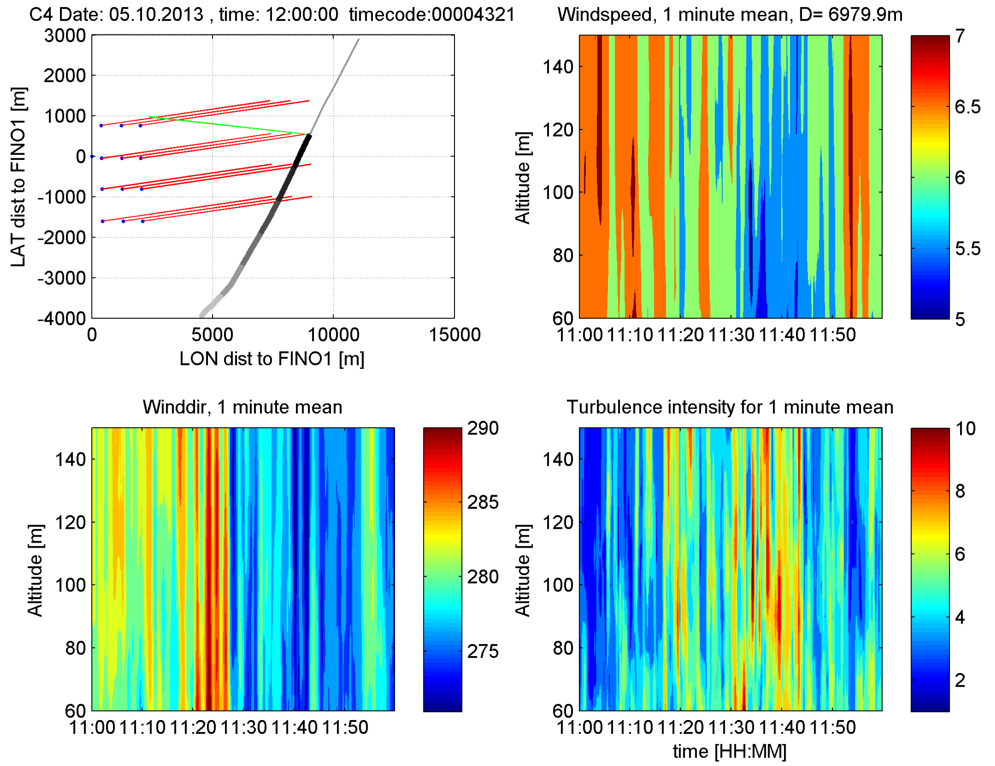


Figure 17: Measurement nr. 5. Strong variation of wind direction in the 1-min-mean data, so the plotted wakes have to be corrected for time of flight, which is approx. (7000m / 6m/s =) 20 Minutes.

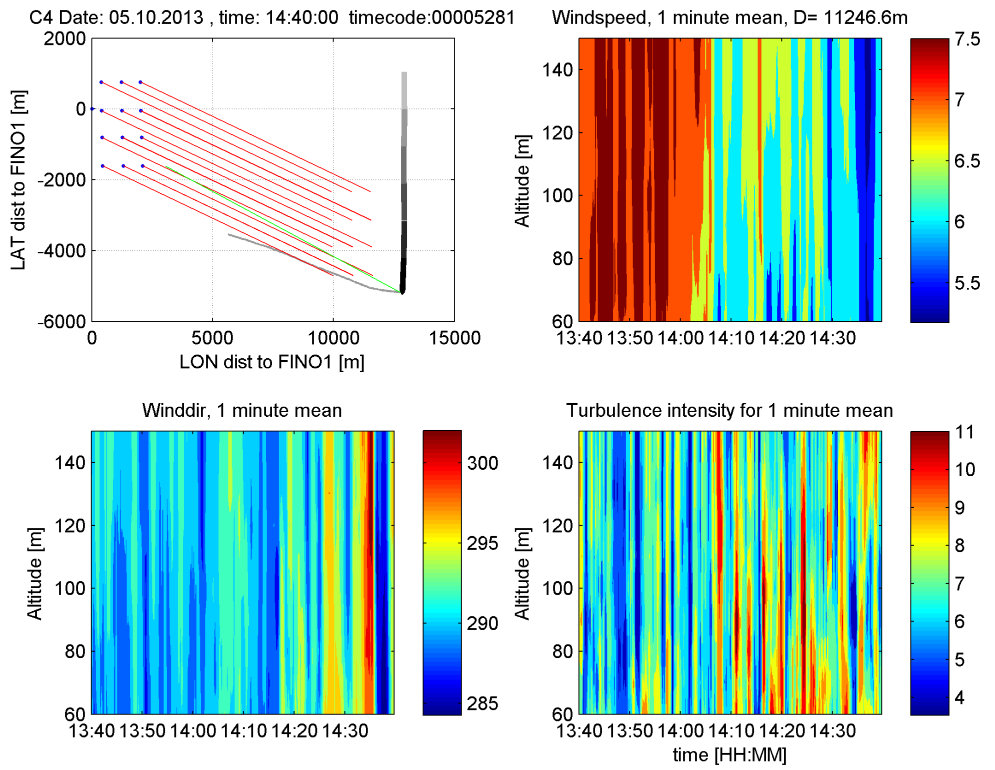


Figure 18: Measurement nr. 6

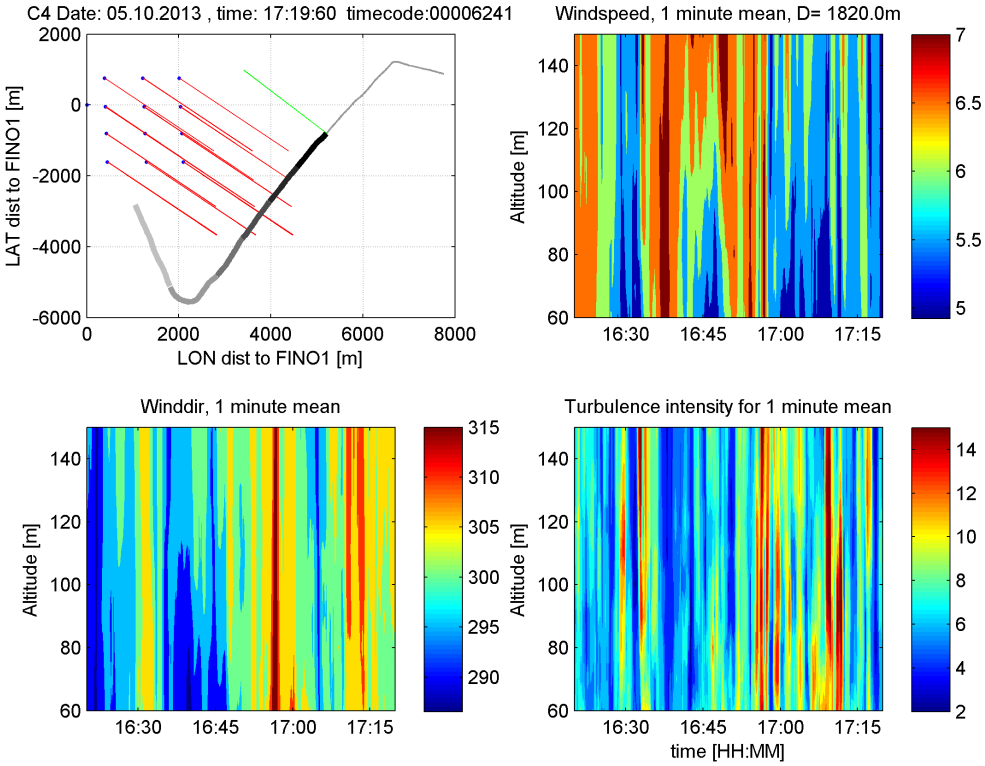


Figure 19: Measurement nr. 7