Responses to the interactive comment on *"Measuring dynamic wake characteristics with nacelle mounted LiDAR systems" by Inga Reinwardt et al., manuscript number: wes-2019-89*

Responses to the referee: Vasilis Pettas (pettas@ifb.uni-stuttgart.de)
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1. General comments

Thank you very much for the detailed and helpful comments on the paper. We appreciate the work of reviewing it and believe that the quality of the paper significantly gained from the comments.

In the following, we respond to all comments in detail. Particular focus is given to the main comment on more quantitative results and their precise description by introducing further graphs and explanations. The uncertainties are discussed more in detail as well as the data filtering procedure.

2. Specific comments

Title

Is the title reflecting the content? Maybe use a more descriptive one, like for instance: "Calibrating a DWM model with measurements of dynamic wake characteristics using nacelle mounted lidar systems"?

Response*:* A more precise title is reasonable and adjusted to: DWM model calibration using nacelle mounted lidar systems.

Abstract

Specify the objectives of the paper clearly, not only the campaign.

What do we learn by reading the paper?

I would suggest removing lines 4 - 5 as no discussion on the optimization procedure is done in the paper itself.

Response*:* Line 4-5 were removed.

Introduction

L 13: Engineering models like the Frandsen model are intended to calculate mainly the wake deficit and shape and not the wake induced turbulence. It should be clearly stated.

Response*:* As far as we know, the Frandsen model is commonly used in the industry to calculate the wake induced turbulence and is also recommended in the IEC guideline. What kind of model do you mean here?

L 24: What is meant by 2D wind field here?

The lidar can measure 1D (LOS direction only) and 3D in terms of space (have the pulsed technology with range gates). Please clarify.

Response*:* The text passage was rephrased to: "*Especially, the so-called scanning LiDAR systems offer great potential for detailed wake analysis. These LiDARs are capable of scanning a three-dimensional wind field, so that the line of sight (LOS) wind speed can be measured subsequently at different positions in the wake, thus enabling the detection of the wake meandering as well as the shape of the wind speed deficit in the MFR.*"

At the end of the introduction a paragraph should be added stating clearly the objectives of the paper. A small reference on the content and structure of the following sections could also make the work easier to follow.

Response*:* A clear outline of the objectives was added and a small overview of the structure of the following sections was given:

"Thus, a detailed comparison of the predicted degradation of the wind speed deficit between the DWM model and the measurement results is possible. Furthermore, the collected LiDAR measurements are used to recalibrate the DWM model, so that the wake degradation can be modeled more precisely. As a consequence, the calculation of the loads as well as the energy yield of the wind farm can be improved. The remaining document is arranged as follows: in Section 2, the investigated wind farm and the installed measurement equipment are described in detail. Afterwards, in Section 3, an explanation of the data processing and filtering of the measurement results is given. Sections 4, 5, and 6 focus on the description of the theoretical background and a hands-on implementation of the DWM model is introduced. Based on the outlined measurement results, a recalibration of the defined degradation of the wind speed deficit in the DWM model is proposed in Section 6. A summary of the measurement results can be found in Section 7 and a comparison to the original DWM model as well as the recalibrated version is presented in Section 8. Eventually, all findings are concluded in Section 9."

Wind farm

L 67-68: As I understand load measurements are not used in the study, what is the relevance of mentioning the load sensors here

Response*:* The load measurements should be used in a subsequent publication and should be used to further verify the recalibration of the DWM model. A hint to future objectives is added.

L 69: LiDAR system of WTG 1 is installed inside the nacelle and measures through a hole in the rear wall: This is an interesting and uncommon setup. Are there any limitations or benefits using this set up? It could be useful information for future campaign

Response*:* Mounting the device on top of the nacelle of WTG 1 is not possible, as the area is occupied by a recuperator. The reason and the limitations that accompany it are complemented.

L 70: A nacelle mounted GPS is mentioned for the nacelle yaw position tracking. What is the uncertainty of such a system? Did you correlate it with the high frequency SCADA data for nacelle direction?

Is there any data filtering based on SCADA or gps nacelle position in order to make sure that the turbines were not yawing often during the accepted time intervals?

Response*:* The differential GPS system measures in centimetre range. A comparison between the SCADA data nacelle direction has been done. This comparison has shown that the measured nacelle direction of the SCADA system has a non-negligible offset of more than 10° at some turbines. This error in measuring the nacelle direction occurs frequently at common wind turbines, wherefore we decided to install the GPS systems. The GPS systems are used to ensure that the turbines are not yawing during the used time intervals. This is also mentioned in Section 4.

L 78 - 80: The Richardson number is mentioned here. It is not mentioned how it was used to filter the data or how it is used in general in the study.
Stability is only mentioned again in L 216 where it is stated that it is not considered. Am I missing something?
L 79:State the heights of measurements used for the calculation of the Richardson number
Response: First, we divided the data set into stable and instable measurements, but in the end, we used all data sets for the recalibration of the DWM model. Therefore, the Richardson number calculation was removed. Furthermore, in L216, in the description of the DWM-Keck model, it is explicitly pointed out that no atmospheric stability is included in the model, as the referred author of this model version developed a model with atmospheric stability included and to clarify that this approach is not used here.

How many rays are used in each pulse for the campaign?
Response: The pulse repetition rate of the LiDAR system is 15 kHz and the ray update rate is about 1Hz, so it averages over approximately 15,000 pulses (depending on the atmospheric conditions). The sample frequency is 100 MHz. Considering the speed of light, we get a point length of 1.5 m. The range gate length is 30 m, thus 20 points are used per range gate. This explanation was also added to the paper.

Are the SCADA data used 10min averages or high frequency?
Response: The SCADA data is only used to determine if the turbine operates under normal power production conditions and to affirm no yaw misalignment. For this purpose, the statistics of the 10-min time series are used. All other data filtering is done with the metmast and the GPS systems.

L 73-88: A lot of information in this paragraph. Would be clearer to add a table with all the filtering as well as the amount of total data and data kept after filtering. This way it will be easier to identify sources of bad measurements and provide a condensed overview.
Response: The paragraph was restructured, and a workflow was added to clarify the filtering procedure. The amount of data after filtering has already been given in Table 2 in the results section.

L 85-88: Give more details on the final setup of the lidar campaign. What was the sampling rate per scan/ray? Which range gates were used (as 750m exceeds the distance of the downwind turbines and usually this type of devices cannot measure below 50-100m)? Exact information on the campaign can be very useful for future research.
Response: The sampling rate as well as the range gates were added in the section (see also previous comment). The range gates used for the validation of the DWM model and the recalibration can vary between each used time series because not all range gates fulfill the filtering criteria. Nevertheless, the used range gates for all data sets are illustrated in Figures 6, 7, and 8. Further distances, which are not illustrated in these graphs, are not considered.

L89-94: Is there any uncertainty in that? According to the misalignment of the nacelle to the main direction, the tilt or yaw flows and the lidar angle, the uncertainty can be significant. Is there a way to quantify that? What are the angles used and how small are they?
Response: A discussion and estimation of the error made by yaw misalignments was supplemented as follows: *"…if there is yaw misalignment, this could have an impact on the overall results. To decrease the uncertainties based on yaw misalignments, the measurement*

data has accordingly been filtered. The yaw misalignment has the biggest impact at the largest scan opening angles, so that a misalignment of 6° at an opening angle of 20° leads to an overestimation of the wind speed of less than 5%.”.

Wind speed deficit in MFR calculation

L 107-108: “However… campaign” This is a good example of more concise language and argumentation needed in the paper. What does highly improbable mean (especially when only 1 10min data set is used for some TI bins later on)? What does very robust mean? Please be more specific in the arguments used to validate assumptions.

Response*:* Results of the calculation of the position of the wind speed deficit at 200 m based on the DWM model simulation has been added to clarify the very low probability (“*e.g., the DWM model predicts the wind speed deficit’s probability at the horizontal position of 200 m to be $2*10^{-22}$ for an ambient wind speed of 6.5 m/s and an ambient turbulence intensity of 8 %*”).

What is meant by “especially when only 1 10min data set is used for some TI bins later on”? Are you suggesting that too much data is filtered out due to the 200 m criterion? Based on the simulation results given from the DWM model, this is not the case.

L 118-120: Maybe I am missing something, but it is not clear to me how this plausibility check works. Can you explain it more?

Response*:* After averaging the wind speed deficits in the MFR and FFR, the calculated minimum mean wind speed in the MFR is compared to the minimum mean wind speed in the FFR. In theory, the wind speed deficit in the MFR should be more pronounced than the measured one in the FFR. This comparison is used as a plausibility check.

Lidar simulation

This section needs a lot of work, with a lot of missing information. More information is needed in order to ensure reproducibility. How is the lidar simulator working? How are the wind fields created and how is the DWM model incorporated? Are you using Turbsim or Mannbox generator or some other turbulence generator? How is the LOS speed reconstruction done? Do you consider perfect lidar measurements? How are the range gates and probe volume averaging considered?

Response*:* The LiDAR simulations are very simple and basic to ensure that the meandering as well as the wind speed deficit in the MFR could be captured with the used devices and to check if the selected scan pattern is usable. The wind field with wake effects is generated with an in-house Python tool. A detailed description of the model implementation is given in Section 6 and is not repeated here. A hint to the next section has already been given. There, it is explained that the Veers model is used instead of the Mannbox. The simulations assume perfect LiDAR measurements, so that no probe volume averaging is considered and the LiDAR directly measures the horizontal wind speed. The wind field is simulated at midway of the range gate.

L 129-131: This is the only reference through the paper to the optimization study to find an optimal pattern. It results to a simple horizontal scan of 11 equispaced points. It is very general and does not explain the procedure. I think it should either omitted from the paper and only state the used trajectory or add a dedicated section with more details and figures.

Response*:* L129-131 has been rephrased. The LiDAR simulation are only used to check if the scan pattern could be used in the campaign and only manual iteration processes with different angle increments have been carried out. To avoid further misunderstandings, the term “optimization” has been replaced in the description. Graphs with results of simulation and simulated “measurements” are given in Figure 3.

L 136: What does very well mean in this context? Can it be quantified e.g. with error metrics or R^2?
Response*:* The coefficient of determination is given in Figure 3 (R^2=0.93). A hint in the text was added, too.

L 144-146: What does optimal operating conditions mean? Does it mean it operated on max CP, CT which in turn produce the highest deficit? Please be more specific. Maybe a dimensionless CP-CT vs wind speed curve would be useful here but also for the argumentation in L 299 about thrust being constant.
Response*:* Yes, optimal operating conditions means operating at maximum CP, where the highest or most pronounced deficit is generated. CP and CT curves are added in the section “wind farm”.

Dynamic wake meandering model
Sections 6.1 and 6.2: Nice, thorough description of the models. Can you explain how you generated the wind fields (tools, models, parameters, discretization) and how you implemented the variations of the DWM models? Is this an in-house tool or a commercial/open source tool? Can the codes be shared with others so that such validations can be repeated with other data sets?
Response*:* The wind fields are generated with an in-house Python tool, as mentioned in Section 6 and described in Section 6.1. The discretization in axial and radial direction for solving the thin shear layer equations is 0.2D and 0.0125. The information was added to the description. The axial induction factor, which is needed for calculating the boundary conditions, cannot be shared because these are confidential data of the turbine manufacturer. All other parameters are given. The source code can be requested by the authors as explained at the end of the paper in the provided section “Code and data availability”.

Section 6.3: As stated, the wake induced turbulence in the DWM model is not used in this study. I suggest to remove this section as it does not add something to the purpose of the paper.
Response*:* The section was removed.

L 258-259: What does relatively good agreement mean in this context? Please be more precise and avoid using such expressions.
Response*:* The sentence was rephrased.

The results with high shear and low TI (and vice versa) suggest some kind of stability based filtering in the results. Is this done somehow? Would this be an important parameter on how well the DWM models and the parameter fitting perform?
Response*:* There is no stability filtering included in the results. Previously, a filtering according to atmospheric stability was implemented, but since this drastically decreases the amount of data, it was discarded and only a sorting according to turbulence intensity bins has been carried out. Moreover, the used eddy viscosity description in the DWM model,

which is calibrated, only depends on the turbulence intensity, thus atmospheric stability is only partially and indirectly considered in the model description, which is why a classification into turbulence intensity bins is more valuable in this application.

L 270-271: Can't this (along with the observation that the center of the wake in the MFR is not exactly at the 0 point) correlated to the rotational direction of the rotor too?
Response*:* The movement of the wake is based on the assumption that the wake behaves as a passive tracer in a turbulent ambient wind field, so the movement is driven by large scale turbulences and not by the rotational direction of the rotor. Furthermore, if the displacement would be correlated to the rotational direction of the rotor, this behaviour should be visible in all data sets, which is not the case.

L 277-280: This discussion is interesting and would be more relevant if it could quantify the trade-offs. As mentioned in a previous comment this could fit in the numerical study of the optimization.
Response*:* A quantitative discussion of the possibility of increasing the number of scan points was added: *"According to Equation (18), the meandering is correlated to frequencies lower than approximately 0.028 Hz considering a wind speed of 6.5 m/s and a rotor diameter of 117 m. This means that, considering the Nyquist–Shannon sampling theorem, the scan time must be longer than half of the reciprocal of 0.028 Hz, which results in a necessary scan time of less than 18 s. The scan time for the current usage of 11 scan points is already at about 16 s (depending on the visibility conditions), which is close to the limit of 18 s, so with an increased number of scan points it is no longer ensured that the meandering can be captured."*

L 293-298: and L 305 and L 311-314: The data for bins of TI higher than 12 seem very sparse with 1 or 2 data sets each. Are these sufficient to extract conclusions about the models and fit parameters? I would suggest a more thorough argumentation for using them or removing values higher than 12 from the analysis.
Response*:* The agreement between the measurements and the simulations is already good in the higher turbulence intensity bins, so the recalibration affects only the lower turbulence intensity bins with larger amounts of data, while the influence of the calibration on higher turbulence intensities is negligible. Therefore, it would not make any difference to exclude the data from the model fit. This explanation is added at the end of Section 7.

Table 2: Could it include also shear values? Or maybe a plot can be added showing the joint probabilities of shear and TI. This will help to give a better overview of the conditions to the reader.
Response*:* A scatterplot of shear and TI was added.

Figure 2 is hard to read. I recommend plotting it again with thicker lines and playing with line style, markers and size
Response*:* The authors think that the method description in Figure 2 is sufficient.

L298-301: As mentioned earlier, a CP-CT curve vs wind speed would be more clear for this argument.
Response*:* CP-CT curves were added and referred to.

L 314-318: The argumentation here is weak. More quantitative results are needed and more concise language in order to validate the assumptions.
Response*:* A more detailed description about the uncertainties related to the determination of the ambient conditions as well as a description, why it is acceptable to use the higher turbulence intensity bins for the recalibration (see also comment to line L 293-298: and L 305 and L 311-314 above), was added as follows: *"The farthest distance between the metmast and the measured wind speed with the LiDAR system, which can occur in the analyzed sectors, is about 1200 m. With an ambient wind speed of 6.5 m/s, this leads to a wake advection time of 185 s, thus even at worst conditions, the measured ambient conditions at the metmast should be valid for the measured wakes from the LiDAR system most of the time. Furthermore, there is no complex terrain at the site, so it can be assumed that the conditions do not change with the wind direction. In addition, the agreement between measurements and simulations is already good in the higher turbulence intensity bins, so the recalibration affects only the lower turbulence intensity bins with larger amounts of data, while the influence of the calibration on higher turbulence intensities is negligible (see Figure 14)."*

Comparison between measurements and DWM model simulation
L 323: Which are the distances used in the simulations?
Response*:* As explained, the simulated distances correspond to the center of the range gate.

L 325-326: "However, the wind speed gradient in axial direction is relatively low and almost linear in the observed downstream distances, so that a fair comparison between simulation and measurements is carried out". The phrasing relatively low and almost linear are not making an argument for the assumptions. Please explain why you consider this valid. Moreover, it is not clear what is meant by fair comparison in this context.
Response*:* The following explanation was added: *"The wind speed gradient in axial direction is low and almost linear in the observed downstream distances, so even in the DWM model, the discretization in downstream direction is 23.4 m (equivalent to 0.2D), which is in the same magnitude as the range gate of 30 m. Therefore, a valid comparison between simulation and measurements is carried out."*

L329 Avoid the phrase 'it is obvious',
Response*:* Phrase was removed.

L320-336 In general the analysis here is only descriptive and qualitative. Can the convergence be quantified and the discrepancies of the model to the measurements explained based on their assumptions and detail level?
Response*:* A graph with the RMSE between the simulations and models was added as well as a comparison of the deviations to the measurement uncertainties that are related to yaw misalignments and measuring the LOS wind speed itself.

L 342 How were the simulations performed? What code was used, what type of spatial and temporal discretization? Give more details.
Response*:* A detailed explanation of the simulations is given in Section 6. It is done with an in-house python tool. The spatial and temporal resolution were also added in this section.

L345 It is not clear to me what does this weighting mean. Can you explain it a bit more along with the reasoning?
Response*:* To calculate a mean value of the simulated minimum wind speed and thus allow a comparison with the measurement results collected at two different turbine types, simulations with both turbine types are carried out for each turbulence intensity bin and weighted in accordance with the number of measurement results per turbine listed in Table 2. Thus, for example at the ambient turbulence intensity bin of 4 %, the mean value of the simulated minimum wind speed consists of the sum of the simulated minimum wind speed weighted by 0.451 and 0.549, the weighting factors for WTG1 and WTG2, respectively. Nevertheless, this weighting has only a marginal influence on the overall results, because the axial induction in the considered wind speed range (5 m/s – 8 m/s) is very small for these two turbine types (see also thrust and power curves in Figure 3). A more detailed explanation was also added in the paper.

L 346 It is stated that the calibrated model "coincides very well with the measurements". Can you quantify this improvement by comparing with the level of agreements of the previous models?
Response*:* A graph with the RMSE between measurements and simulations for all turbulence intensity bins was added to provide a better quantification of the improvements.

L 350 - 362 In this paragraph the differences between the models described based on Figure 10. Can you add some explanation on why the models behave differently? What is the driver of this behavior?
Response*:* The difference between the models was explained in detail in Section 6.1 and repeated in Section 8. The DWM-Egmond model and the DWM-Keck model differ in the definition of the boundary conditions for solving the thin shear layer equations as well as the eddy viscosity definition, which is used to calculate the expansion downstream. The DWM-Keck and the recalibrated DWM-Keck-c model differ in the definition of the eddy viscosity. The faster degradation of the wind speed deficit in the recalibrated model version is caused by introducing the function F_{amb} in the eddy viscosity definition in Equation (21) as explained in Section 6.1. The function increases the eddy viscosity for lower turbulence intensities and thus increases the wind speed deficit degradation in downstream direction.

Conclusions
L 366 As commented earlier the part about deriving an optimal scan pattern is not discussed at all through the paper. I would suggest you either add a section on this optimization procedure or remove it from the text.
Response*:* The sentence was rephrased.

L374 comparably good agreement: This is not clear as a conclusion. As stated earlier I think more concise language and quantitative results are needed
Response*:* The sentence was rephrased.

3. Minor comments
Response*:* All minor comments were adopted in the paper.