Validating a simulation environment for floating lidar systems

O. Bischoff¹, W. Yu¹, J. Gottschall², P. W. Cheng¹
¹Stuttgart Wind Energy (SWE), Allmandring 5B, 70569 Stuttgart, Germany
²Fraunhofer IWES, Am Seedeich 45, 27572 Bremerhaven, Germany

Email: bischoff@ifb.uni-stuttgart.de

Abstract. Assessing the uncertainty of floating lidar systems for different wind and wave climates is a difficult task. One possible solution to close this gap is a validated simulation environment for floating lidar systems. An approach for such a simulation environment is being developed within the German research project MALIBU and will be presented. This paper gives an overview about the simulation model which is being developed and shows ideas and first results regarding the validation aspects for the moving lidar environment. Furthermore an outlook for further steps regarding the validation of the complete simulation model for a floating lidar system (FLS) is being given.

1. Introduction

Reliable offshore wind measurements become more and more important for wind resource assessment and the planning of offshore wind farm projects. In comparison to offshore meteorological (met) masts floating lidar systems (FLS) provide a flexible and cost-effective approach to assess the wind resources at offshore sites. However, buoy motions have an impact on the lidar measurements, and a detailed understanding of this impact is an essential pre-requisite for applying the technology at a fully commercial level. With the growing number of FLS that are currently being developed and tested a method is needed to identify and compensate uncertainties in the wind speed measurement of the lidar due to the wave induced motions. It is already recommended practice to monitor external influences in parallel to a FLS measurement and relate these values to the measurement performance of the system. Today there is a variety of different FLS designs and technical realisations [1], varying in size, buoy type and lidar type among others, which are currently used for wind resource assessment and the first offshore wind projects have been planned on the basis of floating lidar data [2]. Also there are already some guidelines available that support the application of FLS [3], [4]. However there are still a number of open questions regarding the application of FLS for this purpose [1]. One of these gaps is the understanding of the measurement uncertainties from FLS for different wind and wave climates due to buoy and lidar motions. Therefore there is a need for a validated simulation tool for FLS with what it is possible to reduce the uncertainties of FLS measurements in different wind and wave conditions.

The paper is structured as follows: First in section 2 a short overview about the simulation model that is under development is being given. Section 3 describes the two measurement campaigns and the measurement data that is used to carry out first validations for the moving lidar model. Followed by section 4 which shows first results from comparisons of measurement data with simulations. Finally in section 5 an outlook for next validation steps and a conclusion of the first validation results is being given.
2. The floating lidar system simulation model

The full FLS simulation environment will consist of a reduced hydrodynamic buoy model and a model for simulating measurements with a moving lidar system including a wind field reconstruction algorithm. Both models will be validated independently of each other with measurement data collected within various measurement campaigns of the Fraunhofer IWES Wind LiDAR Buoy (see Figure 1) and reference data from stationary lidar systems and offshore masts. In a final step both models will be coupled in order to realize an FLS simulation model to carry out a wide range of parameter studies with limited computational effort. This coupling includes e.g. the transfer of the wave dependent buoy movement to the lidar simulation environment. Additionally an approach for uncertainty assessment with FLS will be integrated to complete the model based approach for FLS wind potential measurements and the determination of uncertainty.

2.1 Simulating a moving lidar system

Earlier works [5], [6] and [7] have already presented methods to simulate a motion affected lidar system measuring the wind parameters with a velocity azimuth display (VAD) trajectory. Within this work a simulation environment is being used that provides the possibility to simulate constant or turbulent wind fields and different motions of the lidar system. The input parameters for the motion of the lidar system can be chosen within the simulation tool. The rotations and translations (6 degrees of freedom (DOF)) of the system can be simulated independently from each other. For example only oscillating pitch or roll movements can be simulated or all 6 DOF simultaneously like it is the case under real offshore conditions [1]. In a simple example for validation purposes the lidar is assumed to follow the wave surface, which is simulated using the Airy wave theory. Based on the simulated lidar raw data and a simplified wind and lidar model, the wind vector can be estimated using a model based wind field reconstruction method [8]. Below in Figure 2 a simple measurement trajectory with only a pitch rotation around the y-axis and a translation in vertical z-direction are being simulated.

The lidar is assumed to follow a wave surface, which is simulated using the Airy wave theory (1), where \( \eta \) is the wave height, \( h_\eta \) is the wave peak-to-peak amplitude, \( k_\eta \) the angular wavenumber and \( T_p \) the wave period.

\[
\eta(x, t) = \frac{h_\eta}{2} \cos(k_\eta x - \frac{2\pi}{T_p} t)
\]  

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Figure 1. Fraunhofer IWES Wind LiDAR Buoy ©IWES

Figure 2. (a) Examplary measurement path for a measurement \((t = 1s)\) with a continuous wave (cw) lidar system due to wave motions [9] (b) Measurement trajectory for a moving cw lidar system (blue) due to linear wave motions with 2 DOF compared with a fixed cw lidar (red) system in VAD measurement mode for \(T_p = 5 s\), \(H_\eta = 4 m\) and \(n = 50\) measurement points per second
2.2 Hydrodynamic buoy model

In parallel a simulation environment for a simplified buoy model based on the complete buoy model of the Fraunhofer IWES Wind LiDAR Buoy (see Figure 3) will be built up in order to allow for fast parameter studies to simulate the motions of the buoy due to a large number of sea states with reasonable computational effort. Furthermore the simplified buoy model gives the possibility to simulate different buoy configurations e.g. with a different center of mass or different dimensions of the buoy. The hydrodynamic model is based on the potential flow theory and Morison’s Equation. To solve the linearized hydrodynamic radiation and diffraction problems for the interaction of surface waves, a three-dimensional numerical-panel method in frequency domain is used. Elements using Morison’s equation will be added to capture the non-linear drag forces. The mooring system is solved by using a quasi-static simplification, which means the loads from the mooring lines are only dependent on the line configuration.

3. Measurement data for the validation of the simulation environment

In order to validate the simulation environment, measurement data from a controlled environment i.e. controlled motions of the lidar system is needed. For a first approach measurement data from two measurement campaigns with two different lidar types has been chosen. In both campaigns the lidar devices were placed on so called motion tables with which controlled movements i.e. rotations in pitch and roll direction could be performed.

The first data set comes from a measurement campaign carried out 2013 by Fraunhofer IWES within the FP7-MARINET project at the Danish National Test Centre for Large Wind Turbines in Høvsøre/Denmark. Within this campaign the measurement setup included a motion table capable of simulating 2D tilting motions in pitch and roll direction on top of which the lidar device (in this case a Leosphere WindCube V2 offshore edition, WLS7-119) is fixed (see Figure 4) on the motion table which is connected to an inertial measurement unit (IMU) that records the motions with high resolution. For reference wind measurements a 114 m tall met mast with cup and ultra sonic anemometry instrumentation in six measurement heights plus additional sensors for wind direction, temperature, pressure and other meteorological parameters as well as a ground based WindCube V2 (WC139) were available. The motion platform is a 2 DOF custom-manufactured actuation system. The size of the upper table of the platform (on that the devices may be installed) is 1.0 m x 1.2 m, and it can be loaded with up to 80 kg. In roll and pitch direction angles of about +/- 25° can be reached, the max. angular velocity is 10°/s and the max. acceleration is 15°/s². The motion platform is fixed to a trailer. The total height of the table surface above ground is approx. 1.2 m. Within this experiment static tilting and dynamic tilting motions in one or two degrees of freedom have been emulated. A static tilting motion pattern is defined by a constant tilt angle in roll or/and pitch direction. Dynamic tilting motion patterns are described by one simple or several superimposed sinusoidal functions, defined by an amplitude, an angular frequency, and optionally an offset and a phase shift. Furthermore within this experiment a so called ‘yaw spinning’ was included to rotate the programmed (horizontal) tilting in different steps clockwise, i.e. with different relative directions to the inflow direction, within a certain time. In total 61 different motion patterns (some are repeated) with a duration of more than 60 minutes have been simulated. All with a short calibration period i.e. fixed position of the lidar on the motion platform.
The second experiment was carried out 2012/13 within the KIC-Neptune project [9] and [11] at the Universidad Politécnica de Catalunya (UPC). In this experiment a continuous wave (cw) Doppler lidar unit (ZephIR 300) is installed on a motion table and a fixed ZephIR 300 installed on the ground nearby (see Figure 5). The motion platform was designed to simulate dynamic tilting rotations in pitch and roll direction and was fitted with IMUs to capture the rotational motion parameters. Within this experiment different various angular dynamic tilting motions have been emulated. Pitch and roll motions with periods of $T = 3s, 6s, 12s$ and pitch angles of $\theta = 10^\circ, 16^\circ, 25^\circ$ have been applied to the motion platform. Within this experiment no controlled yaw motion has been simulated. For every motion simulation both devices were kept fixed for a certain time to allow for calibration.

4. Validation of the lidar simulation environment and first results

Before being able to use the simulation environment, the different modules need to be validated as thoroughly as possible. The full validation process takes into account statistical data sets i.e. 10min data and also at a later stage high resolution data. Measurement data from experiments (as outlined above) with lidar systems installed on a motion table movable in 2 DOF alongside with reference systems are used to verify the assumptions within the lidar simulation model. The reference systems are either a fixed lidar plus a meteorological mast or a fixed lidar only. In order to carry out first validation steps for the simulation environment, a number of datasets i.e. use cases from both measurement campaigns have been selected. In both campaigns the motion tables have been moved with a defined rotation around one axis i.e. one degree of freedom with constant tilt angles and rotational frequencies for the same use case.

An overview about the selected use cases is given in Table 1 and Table 2. Within the simulation environment the same movements have been simulated for a virtual lidar device. The rotation of the lidar with the tilt angle $\theta$ (rotation around one axis) is simulated, analogously to the realized motions, within the different experiments in order to create comparable conditions. The tilt angle $\theta$ can be calculated according to Equation (2) which is the negative derivative of Equation (1).

$$\tan(\theta(t)) = \frac{h_{\theta}k_{\eta}}{2} \sin\left(-\frac{2\pi}{T_p} t\right)$$

On the basis of the measurements from the fixed reference devices, suitable TurbSim wind fields according to the range of the measured mean wind speeds $v_{mean}$ and turbulence intensities $TI$ of the reference system, have been created. These are used in order to simulate the lidar wind measurement as realistic as possible. The wind fields used for the simulation have a duration of 10min. Wind fields for 6 different wind seeds with a wind speed range of $v = 4−12$ m/s and a turbulence intensity range of $TI = 6−24\%$ have been used. The assessment of the validity of the model has been carried out by comparing the different test cases i.e. measurements from the experiments and the reconstructed wind field estimation with the following simple statistical parameters. The first one is the so called wind speed bias (3), which is in this case defined as the difference between the measured horizontal wind speed of the moving lidar $HWS_{Mov}$ and the measured horizontal wind speed of the reference system $HWS_{Fixed}$.

$$HWS_{Bias} = HWS_{Mov} - HWS_{Fixed}$$

The second one is the quotient $HWS_{rel}$ of both measured wind speeds (4). Both will be used to categorize and evaluate the simulation model for the different motions and wind conditions.

$$HWS_{rel} = \frac{HWS_{Mov}}{HWS_{Fixed}}$$
4.1 Comparison of measurement data from campaign 1 (Windcube V2) to the simulation

As mentioned before, within the first measurement campaign a Leosphere Windcube V2 had been installed on a motion table. Four different motion patterns (see Table 1) have been selected for validation purposes.

Table 1. Overview of different motion table test cases

| Period | Angle | 10° | 15° |
|--------|-------|-----|-----|
|        |       | 43  | 47  |
|        | 10s   | 47  | 54  |

Within this experiment a so-called yaw spinning of 120 deg/hour was included to rotate the programmed (horizontal) tilting in different steps clockwise. For a first validation this will be neglected in the simulation routine due to the fact that there was no yawing included in the second measurement campaign. Figure 6 shows a comparison of the measured horizontal wind speeds for the two tilting angles $\theta = 10^\circ$ and $\theta = 15^\circ$. Each point in the scatterplots refers to the mean horizontal wind speeds of one 10 min time series. Due to the fact that there are only a limited number of data sets available there is some scattering and the coefficients of determination are below $R^2 = 0.92$ for both testing scenarios. For the larger tilt angle with $\theta = 15^\circ$ the scattering seems to get more intense with $R^2 = 0.84$.

Figure 6. Scatterplot of Windcube V2 measured horizontal wind speeds at a measurement height of $H = 100m$ for (a) $\theta = 10^\circ$ and (b) $\theta = 15^\circ$

Figure 7 shows the results for the simulated Windcube V2. Each point refers to the simulation of one windfield for the different seeds, velocities and turbulence intensities simulated. It can be noticed that there is almost no scattering in the results and very high values of $R^2 > 0.99$ for both scenarios. But also here the scattering gets a bit more intense for larger tilting angles $\theta$.

Figure 7. Scatterplot of simulated Windcube V2 horizontal wind speeds at a measurement height of $H = 100m$ for (a) $\theta = 10^\circ$ and (b) $\theta = 15^\circ$

The differences between the measured data and the simulated data can also be seen in Figure 8 and Figure 9 where the bias of the horizontal wind speeds and the relative difference of both horizontal wind speeds are shown. The biases of the measured wind speeds $HW_{Bias}$ are up to ten times higher than the
ones of the simulation. The relative difference $HWS_{rel}$ is also up to 50% higher. For $\theta = 10^\circ$ the trend seems to agree for the measurement and the simulation whereas for $\theta = 15^\circ$ the trend deviates significantly and shows different slopes. Due to the limited measurement data it is although difficult to figure out if the behaviour for the different tilting periods $T_p = 5s$ and $T_p = 10s$ correlates for the measurement and the simulations.

![Image](image1.png)

**Figure 8.** Scatter plots for (a) $HWS_{Bias}/HWS_{Fixed}$, $\theta = 10^\circ$ (b) $HWS_{Bias}/HWS_{Fixed}$, $\theta = 15^\circ$ (c) $HWS_{rel}/HWS_{Fixed}$, $\theta = 10^\circ$ (d) $HWS_{rel}/HWS_{Fixed}$, $\theta = 15^\circ$ of Windcube V2 measured data

![Image](image2.png)

**Figure 9.** Scatter plots for (a) $HWS_{Bias}/HWS_{Fixed}$, $\theta = 10^\circ$ (b) $HWS_{Bias}/HWS_{Fixed}$, $\theta = 15^\circ$ (c) $HWS_{rel}/HWS_{Fixed}$, $\theta = 10^\circ$ (d) $HWS_{rel}/HWS_{Fixed}$, $\theta = 15^\circ$ of Windcube V2 simulation data

The comparison of the measurement results and the simulation results of a Windcube V2 show a significant difference. This can be for example due to the disregarding of the wind direction and vertical wind shear i.e. not adjusting the simulation routine to the measured wind direction and wind shear. Another reason might be the limited amount of measurement data considered in this first validation trial.
4.2 Comparison of measurement data from campaign 2 (ZephIR 300) to the simulation

The second measurement campaign was carried out with a ZephIR 300 lidar, installed on a motion table as outlined in chapter 3. More information on this experiment can be found in [11]. For this experiment six different motion patterns (see Table 2) have been selected for validation purposes.

| Angle | 10° | 16° |
|-------|-----|-----|
| Period | Number of 10min data sets |
| 3s    | 45  | 48  |
| 6s°   | 42  | 46  |
| 12s   | 15  | 26  |

Also for this use case the horizontal wind speeds for the moving lidar $HWS_{Mov}$ and the stationary lidar $HWS_{Fixed}$ are compared to each other. Figure 10 shows the scatterplots i.e. comparisons for the 10-min mean values of the measurements. Figure 11 shows the results of the simulated movements for tilting angles $\theta = 10^\circ$ and $\theta = 16^\circ$ and tilting periods of $T_p = 3\,s$, $T_p = 6\,s$ and $T_p = 12\,s$ for the different simulated wind fields as outlined above.

It can be noticed that for this use case there is a much better agreement of simulation and measurement data. The coefficients of determination agree very well for the measurement and the simulation with values of $R^2 > 0.99$. Also it can be seen that there is a similar behaviour for the different tilting angles with $R^2$ degrading similar in the measurement and the simulation for the larger tilting angle $\theta = 16^\circ$.

Due to the limited number of datasets it is more difficult to conclude a similar behaviour for the biases and the relative differences. However it can be seen in Figure 12 and Figure 13 that, besides some outliers, the values are within the same boundaries. Only the trend for higher tilting angles $\theta$ and higher
wind velocities differs to some extent. Although this can’t be verified due to the absence of larger wind speeds in the measurement data.

![Figure 12](image1.png)

**Figure 12.** Scatterplots for (a) $\text{HWS}_{\text{Bias}} / \text{HWS}_{\text{Fixed}}, \theta = 10^\circ$ (b) $\text{HWS}_{\text{Bias}} / \text{HWS}_{\text{Fixed}}, \theta = 15^\circ$ (c) $\text{HWS}_{\text{rel}} / \text{HWS}_{\text{Fixed}}, \theta = 10^\circ$ (d) $\text{HWS}_{\text{rel}} / \text{HWS}_{\text{Fixed}}, \theta = 16^\circ$ of ZephIR 300 measured data

![Figure 13](image2.png)

**Figure 13.** Scatterplots for (a) $\text{HWS}_{\text{Bias}} / \text{HWS}_{\text{Fixed}}, \theta = 10^\circ$ (b) $\text{HWS}_{\text{Bias}} / \text{HWS}_{\text{Fixed}}, \theta = 15^\circ$ (c) $\text{HWS}_{\text{rel}} / \text{HWS}_{\text{Fixed}}, \theta = 10^\circ$ (d) $\text{HWS}_{\text{rel}} / \text{HWS}_{\text{Fixed}}, \theta = 15^\circ$ of ZephIR simulation data

For this campaign also high resolution data (1 Hz) for the moving system and the reference system is available. This allows it to perform a deeper analysis of the simulation tool i.e. to analyse the motion effects on the wind measurements not only statistically and to verify correct implementation of these effects within the simulation environment. Figure 14 shows some first preliminary results. A measured and simulated time series for the moving and fixed lidar system are being compared for the same tilting angle $\theta$ and oscillation period $T_p$ with similar wind speed and turbulence intensities. It can be seen that in both cases the wind speed of the moving lidar system is oscillating around the wind speed of the fixed
reference system. This oscillating behaviour is being generated due to the changing tilt angle for every single wind speed measurement. However a deeper analysis, which is out of the scope of this work, must follow to verify that the simulation model shows the same behaviour for different motion conditions and wind conditions.

Figure 14. (a) Measured 10-min time series with $\theta = 16^\circ$ and $T_p = 12$ s with $v_{\text{mean,Fixed}} = 8.2$ m/s and $T_{\text{I,Fixed}} = 0.19$ (b) Simulated 10-min time series with $\theta = 16^\circ$ and $T_p = 12$ s with $v_{\text{mean,Fixed}} = 7.9$ m/s and $T_{\text{I,Fixed}} = 0.18$

Figure 15 shows the scatterplots for the same data sets as in Figure 14. It can be seen that the simulation model shows less scattering and hence a higher agreement of $HWS_{\text{Mov}}$ and $HWS_{\text{Fixed}}$ than the measurement data. It has to be remarked that those are two different data sets. Therefore the next steps will include an analysis of a larger number of high resolution data sets and also efforts to use the real measured wind fields as input for the simulation routine in order to simulate the same conditions and to allow for a better comparison.

Figure 15. Scatter plot for (a) Measured 10-min time series with $\theta = 16^\circ$ and $T_p = 12$ s with $v_{\text{mean,Fixed}} = 8.2$ m/s and $T_{\text{I,Fixed}} = 0.19$ and (b) Simulated 10-min time series with $\theta = 16^\circ$ and $T_p = 12$ s with $v_{\text{mean,Fixed}} = 7.9$ m/s and $T_{\text{I,Fixed}} = 0.18$

5. Conclusion

The first validation results outlined above show that there are differences regarding the agreement of the simulation with the measurements for the two lidar systems. It has to be analysed where these differences come from. One reason might be that it is due to the limited amount of data i.e. motion patterns that have been used for validation purposes so far, especially for the first analysed lidar system the Windcube V2. But it could also be that simulation model i.e. the wind field reconstruction method that is implemented in the simulation routine needs to be adapted to account for the differences that have been found for the different lidar systems. The measurement data needs also to be analysed deeper in order to filter out data sets that don’t fit to general applicable criteria such as disturbed wind directions or unusual occurrences in the wind field itself that are yet not taken account for in the simulation model. Nevertheless the results are also promising due to the fact that it could be shown that the simulation method shows especially for the second lidar system the ZephIR 300 good agreements with the measurements.
6. Outlook

The next validation steps will include a deeper analysis of the high resolution data from the motion table experiments, taking into account wind direction and wind shear and different motion patterns not analyzed yet in this work. Furthermore measurement data from real FLS trials with the IWES Wind LiDAR Buoy and the FINO III met mast will be used for comparisons between the model and the moving lidar system. The validation of the buoy module will be carried out in parallel. The final coupled model will then be used to estimate and forecast measurement uncertainties for FLS at arbitrary offshore sites (see Figure 16) for different buoy designs taking into account wave probability tables and uncertainty information such as sensitivities and classifications for an FLS. Furthermore it is also planned to test various buoy configurations and hence to present optimisation methods for FLS for different wind and wave climates.

Acknowledgment

This work is part of the research project “MALIBU” which is funded by the German Ministry for Economic Affairs and Energy under the code number 0324197. Measurement data has been provided from works within the FP7-MARINET and KIC-NEPTUNE projects.

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Figure 16. Exemplary parameter study for different wave heights and wave periods.