Simulation of motion induced measurement errors for wind measurements using LIDAR on floating platforms

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ABSTRACT

Prior to developing future offshore wind parks, knowledge of the local wind conditions is essential. Using met masts for this purpose requires extensive planning and is very expensive, especially in deep water. A solution could be the use of Light Detection and Ranging (LIDAR) systems on floating platforms, like ships or buoys. However, movement of the LIDAR system will influence the obtained values, generating measurement errors and uncertainties.

This paper presents simulations of the measurement errors and uncertainties on LIDAR measurements due to platform motion in 6 degrees of freedom. Generally, the interferences are an additional Doppler-shift due to the platform velocity, a change in measurement location, and a change in the projection of the wind vector to the laser beam due to tilting of the LIDAR system.

Motion measurements from a wave-rider buoy and horizontal wind measurements from ultrasonic anemometers at different heights from met mast FINO1 in the German North Sea are used to simulate the measurement and determine these effects. A comparison between a continuous wave and a pulsed LIDAR system is presented. Possible correction methods for the analysis of raw LIDAR data using position data for the floating platform are also evaluated.

1. INTRODUCTION

In the process of measuring wind velocities via a LIDAR, wind speeds in line of sight (LoS) of the laser beam are measured. This speed is a mean value over the measuring volume and the measuring time. The resulting wind vector can be calculated using at least three LoS-speeds measured for different locations and generally for different points in time. This averaging process of course leads to differences in the results compared to point measuring anemometry like cups or sonic anemometers. For research measurements on ships, special systems were used in the past, which adjusted the beam direction in dependence of ship motion [1].

Due to the complex scanning geometry in combination with the ship motion, it is important to analyze the different influences by simulating the measurement using real input data in combination with different types of scanning modes, e.g. between systems using pulsed or continuous wave laser.

In the first part of the simulation the influences of the different sources of error for the different scanning modes as well as different tilt angles are compared for time resolved data. In a second step, the errors in ten minutes mean values are studied as well as the effect of translational and rotational movement is studied.

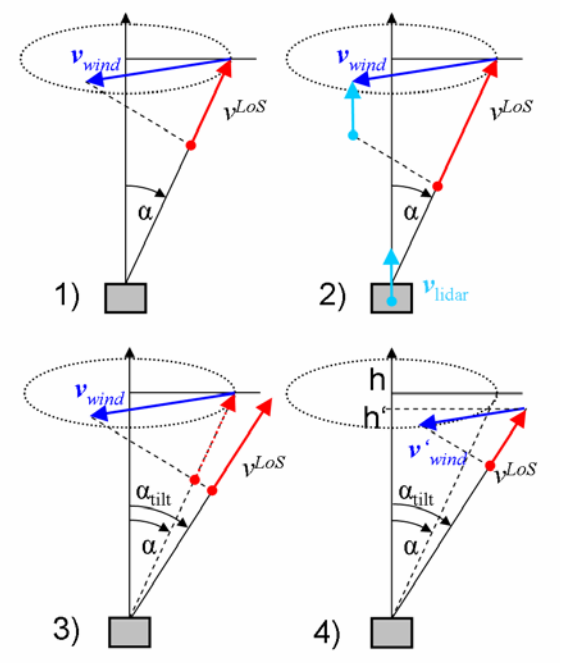

Figure 1. *Shown are wind vectors projected on LoS on a fixed system (1), a vertically moving system (2,) a rotated system taking into account LoS tilting (3) and height displacement (4).*

2. INFLUENCES IN WIND MEASUREMENTS FROM SYSTEM MOTION

In general, movement of a LIDAR-system can generate different kinds of errors, compare figure 1:

1. Errors in the LoS-speed due to the interference of the system velocity.
2. Errors in the LoS-speed due to the tilting of the system and thus a different projection from the wind velocity to the beam vector.
3. Errors to the point of measurement due to the height of the system and the tilting.
4. Combination of the previous errors during temporal averaging process of the scanning.

3. LIDAR SYSTEMS

Two common kinds of wind LIDAR systems were simulated. A pulsed one, using a number of laser pulses in four different directions over four seconds as well as a continuous wave system (cw) using LoS-speed measurements in 50 different directions per second for a period of three seconds. For more information see [2]. The first measures ten heights simultaneously ("pulsed"), whereas the latter one is simulated with scanning one height ("cw1H") as well as six heights sequentially ("cw6H").

Both Systems are measuring the LoS-speeds, but use different methods of calculating the resulting wind velocity. In order to be independent of specific internal calculating methods and algorithms, we use a system of linear equations for obtaining the resulting wind vector:

$$\begin{bmatrix} e_1^x & e_1^y & e_1^z \\ e_2^x & e_2^y & e_2^z \\ e_3^x & e_3^y & e_3^z \\ \vdots & \vdots & \vdots \\ e_n^x & e_n^y & e_n^z \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} v_1^{LoS} \\ v_2^{LoS} \\ v_3^{LoS} \\ \vdots \\ v_n^{LoS} \end{bmatrix} \qquad (1)$$

Using more than three LoS-speeds v_n leads to an overestimated system of linear equations that is solved using a least-square method.

As a first correction method the system movement could be taken into account. The first part is to obtain the system velocity in line of sight and consider it when calculating the wind induced LoS-speeds. Tilting of the system can be considered by using the tilted beam vectors in (1)

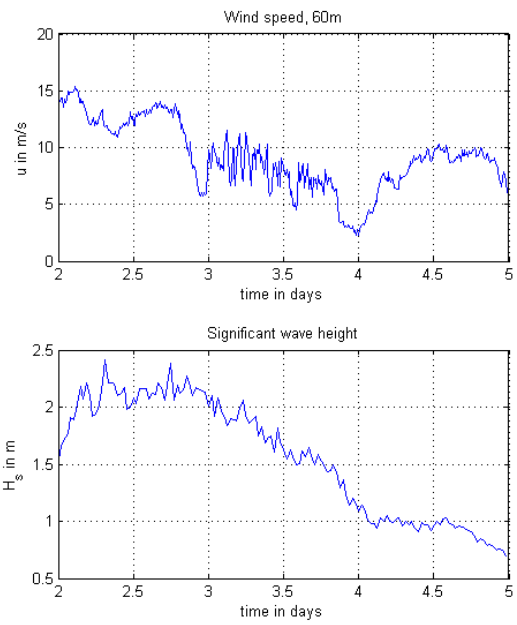

Figure 2. *Overview of the wind speed and wave height for the used time period.*

Further not yet used possibilities are the omitting of LoS-speeds obtained during extreme platform conditions. Another possibility could be the adjustment of the measurement heights in dependance of the system tilting.

4. INPUT DATA

Wind and wave data from the FINO1 met mast was used as input for the simulation. A time period of three days during April 2008 was selected because of the occurrences of different wind velocities and sea states. A plot of the values can be seen in figure 2.

The wind measurement data was acquired by three sonic anemometers located on the heights of 40m, 60m and 80m and contains horizontal wind velocities. The sampling frequency is 10Hz but was resampled to 100Hz to match the simulation time steps of 10ms. The resampling was done using a spline algorithm. During the process of simulation, wind velocities for a certain height were calculated using an interpolation for the heights between 40m and 80m. For heights exceeding this range, a logarithmic wind profile was used.

The wave data consists of three dimensional displacement information measured by a wave rider buoy with a resolution of approximately 1.3Hz in all three dimensions. This data was also resampled to 100Hz using a spline. Due to the lack of tilting information, the tilting angles were approximated by using a linear relation between lateral displacements and tilting angles. Simulations were performed for two tilting modes, whereas a factor of -10°/m (case1) and -20°/m (case2) was chosen.

For the first simulated hour, this leads to a 75.4% probability for the tilting angle in x-direction of being under 5° and a 21.5% probability of between 5° and 10° for case1. For the second simulation (case2) the probabilities are 44.9% and 30.5%.This means that the highest 10% of all tilting occurrences in x-direction exceed 7,2° and 14.4°, respectively.

5. DESCRIPTION OF THE SIMULATION

The simulation takes all geometrical aspects of a LIDAR on a floating vessel into account. The simulation steps were set to 10ms to keep computing time in an acceptable scale. Also higher temporal resolutions would not lead to further information due to the sampling rate of the input data.

As first part of the simulation, for each simulated moment the vector in the line of sight of the laser beam was calculated. Using the tilt angles, this LoS vector was rotated [3].

Followed by a loop, for each moment the positions of the measurement points for both the tilted and not tilted system were computed and used to acquire the corresponding wind vectors from the measured wind data. To obtain the wind velocity in line of sight, the dot product from wind vector and LoS-vector for the tilted and non-tilted system was calculated. The interference of the system velocity was calculated using the dot product from the system velocity vector and the LoS-vector.

In the last part of the simulation the resulting wind velocity were calculated using the different LoS velocities (fixed system, translated system, rotated system, rotated and translated system) for each system and tilting.

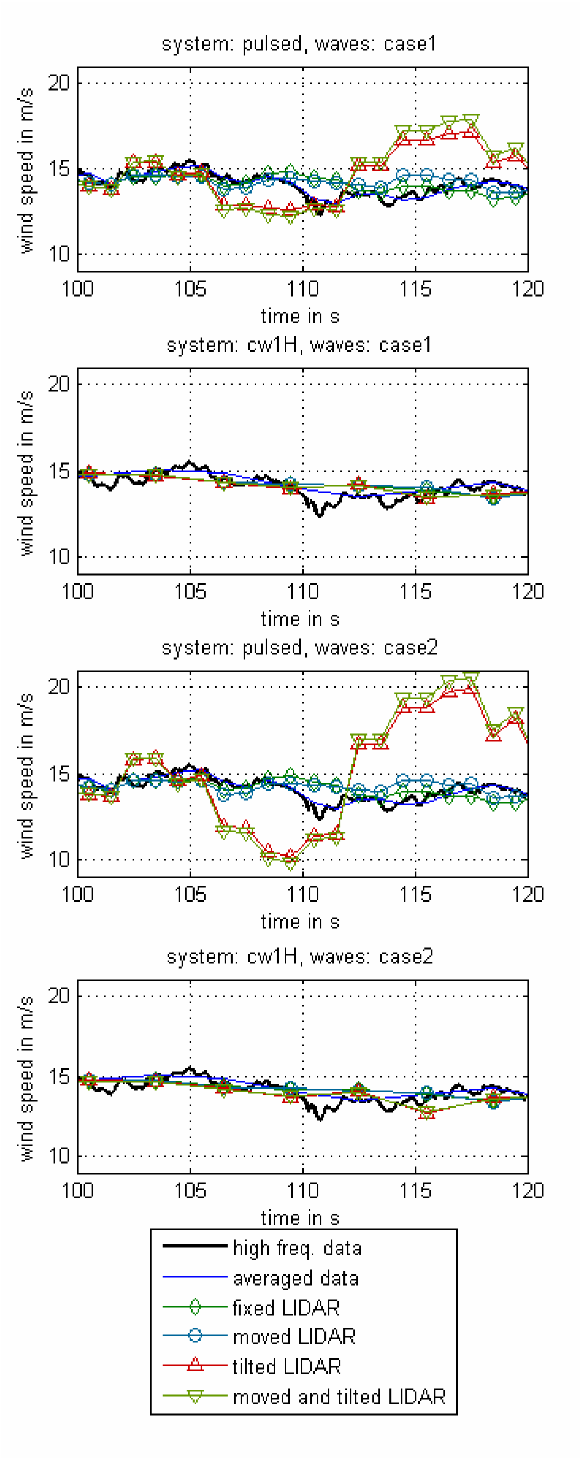

Figure 3.*Plot of 20s example data for both LIDAR-systems and sea states (case1 and case2).*

6. INFLUENCE OF MOVEMENT ON TIME SERIES DATA

To examine the influences from translation movement and tilting as well as the correction methods for time resolved data the first hour of the simulation was analyzed.

The time series for both a pulsed and a cw lidar are shown in figure 3. Because of the higher amount of samples in one direction, the influences on pulsed LIDAR systems are higher, whereas the results from cw lidars are subject to averaging processes due to the higher variability of the beam orientation.

The influences of the translative and rotationary movement are studied using the RMSE. For the results, see table 1. Displayed are values for a non moving system (fixed), a translated system (trans.), a rotated/tilted system (rot.) as well a system with translative and rotational motion (moved). The last row shows the wind speed by using the movement and tilting information (corr.).

It can clearly be seen that the influence of the rotation is predominant, see figure 3. The pulsed system is much more influenced by the movement than the cw-system. This can be explained as mentioned before by the bigger amount of different scanning directions from the cw-system that works like a low pass filter for the wave movement.

It has to be stated that the temporal resolution is lower.

Table 1: *RMSE values for the simulated systems and both sea states for a height of 80m. The reference is a point measurement over the system.*

case1	**RMSE in m/s**		
	pulsed	cw1H	cw6H
fixed	0,535	0,364	0,343
trans.	0,579	0,370	0,353
rot.	1,481	0,386	0,364
moved.	1,655	0,388	0,367
corr.	0,537	0,372	0,353

case2	**RMSE in m/s**		
	pulsed	cw1H	cw6H
fixed	0,535	0,364	0,343
trans.	0,579	0,370	0,353
rot.	2,734	0,566	0,505
moved.	2,902	0,570	0,508
corr.	0,578	0,430	0,398

An advanced analysis show different RMSE, see table 1. As stated before, the pulsed system is much more influenced from the movement. The error due to the tilting is predominant compared to the error due to translation movement.

It can also be deduced that taking the movement into account for calculating the wind speed improves the results for all three scaning modes, especially if it has to be kept in mind that, simulating the pulsed system, not single beam measurement can be corrected but a block of measurement taken over 0.5s.

7. EXAMINATION OF MOVEMENT ON 10 MINUTES AVERAGED DATA

For the use of floating LIDAR the influence on averaged data was studied. Due to over as well as underestimation of the wind speeds by the measurement, results are not obvious for a wind speed mean for a day.

Table 2: *Diurnal mean values for wave state case2 and the different systems.*

case2	**mean velocity day 1 in m/s**		
	pulsed	cw1H	cw6H
reference	12,534	12,534	12,534
fixed	12,533	12,531	12,534
moved	12,601	12,311	12,308
corr.	12,466	12,439	12,443

Table 3: *RMSE for ten minute values for both case1 and case2. The simulated height is 80m.*

case1	**10 min RMSE in m**		
	pulsed	cw1H	cw6H
fixed	0,015	0,003	0,031
moved	0,093	0,067	0,079
corr.	0,034	0,032	0,042

case2	**10 min RMSE in m**		
	pulsed	cw1H	cw6H
fixed	0,015	0,003	0,031
moved	0,180	0,230	0,242
corr.	0,077	0,100	0,102

Therefore again the RMSE of ten minutes mean values were calculated for a measurement heigth of 80m, see table 3. Under the condition of a fixed system, the cw6H shows the best result. If the system is used by scanning different heights, the RMSE increases.

The results for the moved systems vary dependent on the wave height. Especially for case2, the error is not negligible. For both systems the correction by using the movement and heading information improves the results signifiantly.

8. CONCLUSION AND OUTLOOK

It was shown in this paper that system motion has a not negligible influence on pulsed and cw LIDAR-systems. These influences vary for the different components of the complex motion and also depend on the LIDAR-systems, but it can be clearly stated that the influence of tilting is predominant.

For all simulated systems a correction was successfully used. Main part of this correction is the knowledge of the heading of the system and thus the changed beam directions.

In further simulations the simulated time period will be extended. Also the estimation of the tilting angles will be improved by the simulation of different floating platforms like buoys or ships. Furthermore the uncertainties of measurement of inertial sensors as well as offsets in the tilting angles will be considered.

9. RESTRICTIONS TO SIMULATION RESULTS

The simulation just considers geometrical aspects of wind lidar measurement. The measuring process was treated as a point measurement. Only wind velocity data for three heights without vertical components were available. Wave motion could only be approximated, because the real movement characteristics are strongly dependent on Problems based on specifics of the measurement techniques, like the cloud correction for cw-systems, could not be considered.

10. ACKNOWLEDGEMENTS

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