About offshore resource assessment with floating lidars with special respect to turbulence and extreme events

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Abstract. Offshore resource assessment with lidars on floating platforms is a flexible and particularly cost-effective alternative to the conventional meteorological mast solution, that is considered as onshore state-of-the-art transferred to offshore sites, and may enable better and more complete wind resource assessments for the growing offshore wind sector. Wind lidar technology, and remote sensing in general, has already been proven to be a very promising technology for resource assessment and power performance testing onshore. For offshore applications and on floating platforms in particular, the motions from the floating base have to be considered in addition, affecting the wind measurements significantly and causing systematic measurement errors.

We have studied the motions and the corresponding influences on lidar measurements generated by different possible offshore platforms – vessels or buoys – both in detailed simulations as well as first validation experiments. In addition to this, we have developed motion compensation algorithms that allow to correct the affected measurements and retrieve the undisturbed wind data. The motions considered and studied comprise rotations as well as translations in all six degrees of freedom.

For the evaluation of the motion-affected and corrected wind data in this paper, special attention is paid to the measurement of turbulence as well as extreme wind events. The research question to be answered is if a lidar device placed on a floating platform is capable of measuring more or less the same statistics of extreme wind events as a fixed lidar device. Quantities to be investigated are: the turbulence intensity as well as the statistics of maximum wind speed values within a 10-min period, but also wind speed increments on different time scales. At this, obviously two issues are to be discussed – the influence of the lidar measurement principle on the recording of extreme wind events, and the additional impact of the superimposed motions of the floating platform.

1. Introduction
1.1. Lidars on floating offshore platforms
Offshore resource assessment with lidars\(^1\) on floating platforms, introduced as flexible and cost-effective alternative to the conventional meteorological (met.) mast solutions, may enable better and more complete wind resource assessments for the growing offshore wind sector. With a floating platform we refer to different sea-based structures, including both vessels – barges or

\(^1\) – i.e. wind measurement instruments based on LiDAR (Light Detection And Ranging) technology, specifically introduced for wind energy applications – as e.g. the commercially available sensors Windcube (Leosphere), ZephIR (Natural Power), Galion (SgurrEnergy) or Vindicator (Catch The Wind), all initially introduced for ground-based application.
ships – and buoys. These different options are related to quite different lidar applications, that may differ not only in the explicit purpose of the measurement but also its duration and the expected accuracy. Resource assessment with a floating lidar system is at this only the superordinate concept, and may be understood as part of a site assessment project but also as part of a monitoring strategy for instance.

Wind lidar technology, and remote sensing in general, has already been proven to be a very promising technology for resource assessment and power performance testing onshore, and a corresponding performance verification and calibration scheme has been developed within the scope of the revision of the IEC 61400-12-1 standard – see [1] and the references herein. However, the motions from a floating base may affect the wind measurements considerably and cause systematic measurement errors.

The market for floating lidar applications comprises already several commercial as well as publicly funded players developing and offering their own systems to the wind industry, following quite different concepts with different commercial lidar sensors integrated and different ways of treating the motions of the complete system due to the sea conditions – see e.g. [2] for an overview. In principle, the motions of the sea can be compensated for either physically through an active or passive stabilization of the system, or with a specifically adapted software correction algorithm – a combination of both is possible as well. Another alternative is not to compensate or correct for the motions at all, or only correct for the motions in part – for this, it has to be checked how significant the impact of the system motions on the lidar measurement is, both in terms of mean values and the variability and extreme values on smaller time scales.

The influence of the lidar measurement principle on the recording of wind data on smaller scales, i.e. smaller than the standard averaging period of 10 min, has been studied in several papers, both theoretically and with lidar-mast comparisons – see e.g. [5] for a study of 3d turbulence quantities, i.e. 10-min variances for $u$, $v$ and $w$ components of the wind vector, and [4] for an initial study on extreme events. In summary, it is found that the averaging due to the large sample volume within that a lidar measures the wind speed in comparison to a cup or sonic anemometer, that are in-situ sensors performing more or less a point measurement, decreases the measured turbulence, whereas a contamination by the cross components of the Reynolds stress tensor may increase the measured turbulence level – cf. [6]. The motions due to floating sea conditions represent a third source of systematic errors affecting not only the variability of the lidar measurement within the 10-min interval but also the recorded mean values.

1.2. List of relevant motions
With a floating platform we may refer to a vessel – barge or ship – or a buoy, i.e. floating structures that exhibit quite different motions. Each of the considered alternatives has its own range of typical motions. The motions considered and studied in this paper comprise rotations as well as translations in all six degrees of freedom. We distinguish between

(i) horizontal tilting, i.e. roll and pitch,
(ii) yaw, or rotation around the vertical axis,
(iii) heave, as vertical displacement above mean sea level together with the corresponding velocity component, and
(iv) horizontal translations, i.e. surge and sway.

Horizontal translations, as the principal motions affecting a vessel, for instance, appear as an added velocity to the wind velocity vector in the lidar measurement. A heave affects the measured vertical velocity component but primarily falsifies the measured wind speed through a wrong measurement height, resulting in a systematic error that is depending on the wind shear.

2 in general – as well as the different more detailed concepts, as the continuous wave (cw) or pulsed approach
Corrected lidar rtd data may refer to another sampling rate than the LoS data and include some kind of averaging. But still the sampling rate is in the range of seconds whereas the statistical data are averaged over 10 min.

Yaw confuses the measured wind direction. And finally, horizontal tilting (roll and pitch) results in a changed projection of the wind velocity vector with respect to the lidar line of sight (LoS) direction, leading to wrong velocity estimates and also wrong assumed measurement heights.

We believe that (ii)–(iv) can be controlled separately to a sufficient degree, and have not to be discussed in much detail. Therefore our main emphasis in this paper lies on (i).

1.3. Principle of motion correction algorithm

The essential requirement for a motion compensation, based on a correction algorithm that manipulates the lidar data after recording, is a precise measurement of the motions of the system. The compensation can be only as accurate as these measurements are.

Figure 1 summarizes the concept of the motion correction algorithm we refer to in this paper. Lidar real time LoS data and the corresponding motion data are combined to calculate the corrected lidar real time data – either as 3d wind velocity vector $\mathbf{v}$ with $x$-, $y$- and $z$-component, or as horizontal wind speed $v_{\text{Hor}}$, wind direction $\phi$ and vertical wind speed $v_z$. These data are then averaged to lidar sta (statistical) data, i.e. basically the mean values and standard deviations with respect to 10-min intervals or the corresponding turbulence intensity, resp.

1.4. Structure of paper

This paper is structured as follows: following the introduction in this section, where we have introduced the basic concepts for our study, we enlarge on the simulation approach and framework for motion-affected lidar measurements in section 2. At this, we concentrate on a few issues, which we have found relevant for evaluating the more general impact of typical sea motions on different floating lidar designs. In section 3, we present a first experimental onshore validation. Special attention is paid to a comparison of the turbulence and extreme value statistics of the measurements from a fixed and a tilted lidar (in 3.2). The paper is completed with a discussion (section 4) and a closing section summarizing the main conclusions of the study (section 5).
2. Simulation approach and framework

2.1. General remarks
The simulation approach we follow in this study is summarized in figure 2. As input we use a synthetic 3d wind field, simulated with the NREL code TurbSim [7], with typical offshore settings, the lidar design and configuration to be modelled – either based on cw or pulsed lidar technology – and the assumed superimposed motions. We focus on the modelling of geometrical effects, more detailed physical effects as e.g. backscattering mechanisms, the detection of the Doppler effect or the spectral analysis are not further taken into account. Depending on whether a fixed or a tilted lidar is considered and if for the latter case a motion correction is taken into account, we produce the following datasets: the reference wind velocity $v_{\text{ref}}$, the fixed lidar wind velocity $v_{\text{fixed}}$, the tilted lidar wind velocity $v_{\text{tilted}}$, and the tilted and corrected lidar wind velocity $v_{\text{tiltCor}}$.

2.2. Static and dynamic tilting, and cw versus pulsed lidar
A first simulation study of motion-induced lidar measurement errors was presented in [8], considering both cw and pulsed lidar technology. It was found that the motions of the system had a non-negligible influence on the respective lidar measurements, and a motion correction was successfully applied. Tilting motions were identified as predominant source of error.

In [3] the effect of horizontal tilting, i.e. roll and pitch, was studied in more detail – but only for measurements of a pulsed lidar modelled on the measurement principle of a Leosphere Windcube v2 with five beams in one measurement block. Essentially, it was found that static tilting, i.e. a constant angle for roll or pitch caused a bias in the lidar measurements with respect to a fixed reference, and dynamic tilting increased the RMSE (Root Mean Squared Error) or the variability in the real time data, resp. The magnitude of bias and increased RMSE but also the performance of the applied correction depends on the amount and direction of the tilting as well as the direction of the wind vector. In this sense, it is helpful to define a relative wind direction, describing the direction of tilting with respect to the direction the wind is coming from.

Coming back to the comparison of cw and pulsed lidar technology, and their interference with floating motions, it becomes evident that also the different time scales are of major importance: the time scale(s) of the considered motions, characteristic scales of the wind field both in time and space, and time scales that are characteristic of the lidar measurement principle.
Figure 3. Simulated wind speed time series for cw (top) and pulsed (bottom) lidar subjected to dynamic tilting ($\alpha = 10 \cdot \sin(2\pi \cdot 0.1)\text{[deg]}$ in pitch direction). Reference time series (TurbSim; 50 Hz reference frequency) as dotted black line. Fixed lidar data in blue, tilted lidar data in red, and tilted and corrected lidar data in green.

A Leosphere Windcube v2 – as an example for a pulsed lidar device – measures with five beams, each of them standing for a particular LoS direction, with one beam measurement taking approximately 0.7 s. All measurement heights (typically around ten) are scanned simultaneously. A new wind velocity vector may be acquired after each new measurement, i.e. every 0.7 s. A ZephIR by Natural Power – as a cw lidar device – in standard configuration scans one circle consisting of 50 individual measurements along 50 LoS directions in 1 s, repeats this measurement two more times for one measurement height, and then focuses at the next height. With typically five measurement heights and some extra time for signal processing, it takes about 20 s until a new velocity vector for one particular height is acquired.

Figure 3 shows simulated time series for a cw and a pulsed lidar system that is exposed to a dynamic tilting. For the pulsed lidar a clear increase in the variability and associated turbulence intensity of the data is observed when the system is tilted dynamically, which is however compensated quite well by the correction algorithm. For the cw lidar, such an increased turbulence cannot be observed – simply due to the fact that the modelled device cannot resolve the structures on comparable scales. Table 1 quantifies the findings in terms of bias and RMSE values.

2.3. Degraded homogeneity through dynamic tilting
Using the velocity azimuth display (VAD) technique to retrieve the 3d velocity vector from a certain number of lidar LoS measurements that emerge from one point and then span a volume in the atmosphere, the assumption of at least horizontal homogeneity for the covered volume...
Table 1. Bias and RMSE values for the time series presented and compared in figure 3.

|            | BIAS [m/s] | RMSE [m/s] |
|------------|------------|------------|
|            | fixed      | tilted     | tiltCor    | fixed    | tilted    | tiltCor    |
| cw lidar   | -0.0242    | -0.2149    | -0.1049    | 0.8162   | 0.8808    | 0.8517     |
| pulsed lidar | -0.1000  | -0.1453    | -0.1280    | 0.7645   | 1.6665    | 0.9276     |

is essential. We have seen that a superimposed dynamic tilting causes an increased measured turbulence – in fact the tilting degrades the homogeneity seen by the laser beams. It may be argued that the increased lack of homogeneity, i.e. an increased inhomogeneity of the seen wind field, violates the applicability of the VAD technique. For now, a certain threshold indicating if the technique may be applied or not has not been identified, and we assume that the degraded homogeneity may be treated in the same way as the increased turbulence is corrected with the appropriate correction algorithm. Considering the different lidar principles, it is again a question of time scales that have to be taken into account and opposed to each other.

2.4. Consideration of horizontal and vertical translations

As stated above, the correction for superimposed translatory motions is rather straightforward – both in the simulations and with respect to the development of a corresponding compensation algorithm. Crucial is at this the precision of the motion measurements. The consideration of horizontal translations (surge and sway motions) is most notably relevant for a ship-based lidar application. A more detailed discussion of this kind of application can be found in [9].

3. Experimental validation

3.1. Description of Tauche measurement campaign – setup and purpose

In December 2011 we initiated a measurement campaign at the test site Tauche near Berlin, evaluating the measurements from two Windcube v2 lidar units, one placed on a motion table and the other as fixed reference unit, and a 100 m tall reference met. mast – see figure 4 for a picture of the measurement setup. The motion table is a controllable platform that performs tilting motions with two degrees of freedom (roll and pitch). Attached to the lidar unit on the platform has been a motion sensor (inertial measurement unit, or IMU) that synchronously measured the motions of the system with a resolution of 10 Hz.

During the 12 days of the measurement campaign, we run a series of pre-defined motion patterns, including static and dynamic tilting in one and two tilting directions. With investigating static and dynamic tilting separately, we could confirm the conclusions from our simulations for pulsed lidars quite satisfactorily – cf. the results presented in [3].

For the second part of the campaign, we then run a few more realistic motion patterns, combining superpositions of different sinusoidal signals for roll and pitch direction and constant offsets – with the aim of getting an idea how these motions affect the lidar measurements in terms of mean values as well as turbulence quantities and maximum values as a first – even though rather limited – hint to extreme events. The corresponding statistical evaluation is given in the following section.

3.2. Evaluation of turbulence quantities and extreme events

The data analysed in this section cover a continuous measurement period of 47 hours – only the data from the two lidar units are considered, and no data filtering is applied. Figure 5 gives an idea of the run motion patterns – we selected two quite similar patterns, each run for 22 hours.
with three calibration phases in between for that the motion platform was stopped and fixed to zero position with a total length of three hours.

In figures 6–8, we compare 10-min mean values of horizontal wind speed, corresponding turbulence intensities (defined as \( \text{TI} \equiv \sigma_v/\bar{v} \), with \( \bar{v} \) the mean wind speed and \( \sigma_v \) the standard deviation) and maximum values within a 10-min interval for the tilted (WC119) and the fixed reference lidar unit (WC161). While the mean values agree quite well, turbulence and extreme (maximum) values of the tilted lidar are increased with respect to the reference. Figure 9 shows a comparison of the gust factors \( G^3 \), again calculated for each 10-min interval, for the tilted and the reference lidar. As expected, also the gust factors show increased values for the tilted lidar.

Figure 10 represents an alternative approach to investigating the small-scale structures of the wind data – namely in terms of increment statistics (cf. e.g. [10] and the references herein). The

\[ G^3 = (v_{\text{max}} - \bar{v}) \cdot (\sigma_v)^{-1} \]
Figure 6. Comparison of mean values of horizontal wind speed – for 60 m, 100 m, and 140 m measurement height (from left to right).

Figure 7. Comparison of turbulence intensity (TI) values – for 60 m, 100 m, and 140 m measurement height (from left to right).

Figure 8. Comparison of maximum values of horizontal wind speed – for 60 m, 100 m, and 140 m measurement height (from left to right).

The plot shows the pdf (probability density function – but here as discrete points) of the increments

\[ \text{incr}(v_{\text{Hor}}) \equiv v_{\text{Hor}}(t + \tau) - v_{\text{Hor}}(t) \]

for different values of the time increment \( \tau \). Again it can be seen that the data of the tilted lidar are characterized by a higher variability on all considered scales, i.e. a higher virtual turbulence, leading to larger wind speed increments, or a higher probability for the larger wind speed increments, resp.
4. Discussion
The measurements from lidars on floating platforms are affected by systematic measurement errors due to the motions of the system. Depending on the type of platform – if it is a vessel or a buoy – different kinds of motion are relevant, and a compensation may be necessary or not. In this paper, the main emphasis was put on tilting motions – which may lead to both, a bias and an increased turbulence in the recorded lidar data. If the increased turbulence, in any circumstance, needs to be corrected for is arguable – in particular, since turbulence measurements from lidars even if they are fixed have not been found as fully reliable yet in comparison to reference turbulence measurements from in-situ sensors as sonic or cup anemometers (cf. [5]). But a systematic bias should definitely be compensated, or it must be made sure that the tilting of the device is balanced around zero, resp. Another influence that cannot be neglected is the yawing of the system, resulting in a confused wind direction measurement.

If a respective motion is relevant or not – i.e. if it affects the lidar measurement considerably, or if the effect is rather negligible – particularly depends on the involved time scales: the time
scales of the respective motion pattern as tilting frequency or frequency of wave motions, the velocity of the occurring translations, the characteristic scales of the wind field and not least the turbulence length scale, and finally the time scales characterizing a specific lidar technology, ie the time needed for one measurement as well as the time between two measurements at the same height. Similarly relevant is the relative direction between the motion (tilting, or translatory motion) and the mean wind speed, or the LoS direction of the lidar’s laser beam. The respective relations can be studied and evaluated quite efficiently with the introduced simulation tools.

Further work is needed with regard to experimental testing – onshore with the help of motion platforms that simulate typical sea motions, and offshore with the final applications, lidars on vessels and buoys – to confirm the findings obtained from our simulation tools, and to validate the developed motion correction algorithms.

5. Conclusions
In this paper and previous studies, we have investigated the motions and the corresponding influences on the lidar measurements that originate from different possible offshore platforms – vessels or buoys – both in detailed simulations as well as first validation experiments. In addition to this, we introduced a motion compensation algorithm that allows to correct the affected measurements and retrieve the undisturbed wind data. The motions considered and studied comprise rotations as well as translations in all six degrees of freedom.

For the evaluation of the motion-affected and corrected wind data in this paper, special attention has been paid to the measurement of turbulence as well extreme wind events. The research question to be answered has been if a lidar device placed on a floating platform – or a floating lidar, respectively – is capable of measuring more or less the same statistics of extreme wind events as a fixed lidar device. Quantities that have been investigated are: the turbulence intensity as well as the statistics of maximum wind speed values within a 10-min period, but also wind speed increments on different time scales. The results show a systematically increased turbulence or data variability on small scales for the data of the tilted lidar with respect to a fixed reference, that however may be controlled by the developed compensation algorithm quite well if this is needed.

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