Dependence of Floating LiDAR performance on external parameters – Are existing onshore classification methods applicable?

Gerrit Wolken-Möhlmann and Julia Gottschall
Fraunhofer IWES, Am Seedeich 45, Bremerhaven, Germany
E-mail: gerrit.wolken-moehlmann@iwes.fraunhofer.de

Abstract. Floating LiDAR is a new aspiring technology for replacing offshore meteorological masts for applications like offshore site assessment or power curve measurement. Since the beginning of the development of the first Floating LiDAR Systems (FLS) in the late 2000s, the systems are more and more maturing. The focus of current research is moving from the pure technology development to the application of the obtained data. As a result, procedures for assuring the measurement quality and the assessment of the data quality - or the quantification of estimated measurement uncertainty, respectively - is a key aspect for further increasing the confidence in the data. This is an important pillar for a further distribution of the technology, and for decreasing risks and costs for its application in offshore wind.

In this paper, we introduce the methodologies of FLS verification and classification, with the goal to verify the measurement of individual FLS and study the characteristics of a certain type of LiDAR systems. A classification case study is presented, showing low effects of the buoy motion and sea states on the FLS measurement for the Fraunhofer LiDAR buoy. A detailed study of the interdependencies between influencing parameters and the possible correlations is presented as well.

The robustness and issues of the classification methodology - originally defined for fixed LiDAR systems - is discussed. Especially the non-robustness of the bin-fitting is identified as an issue. Alternative methods for the sensitivity analysis within the classification process are discussed.

1. Introduction
Developments in the past few years have identified Floating LiDAR Systems (FLS) to be the optimal instruments to measure offshore winds, like the Fraunhofer IWES LiDAR buoy, see figure 1. These measurements are an essential input to the wind resource assessment (WRA) for an offshore wind project, while also the application for other purposes, like offshore power curve measurement, is studied these days. Several guidelines were published with the aim of increasing the commercial acceptance of the technology and providing recommendations for conducting and evaluating FLS measurements as part of a WRA study. These include the two versions of the “Carbon Trust Offshore Wind Accelerator (OWA) Roadmap for the Commercial Acceptance of Floating LiDAR Technology” from 2013 [1] and 2018 [4], respectively, and the “IEA Wind Expert Group Report on Recommended Practices 18 on Floating LiDAR Systems” from 2017 [3].
While the first version of the “OWA Roadmap” suggested only some indicative uncertainty ranges for FLS measurements – namely 4\(^{-}\)7\% and 2\(^{-}\)4\%, depending on the maturity of a particular type of system – the later documents have recommended a detailed data-based uncertainty assessment in line with available procedures as the one outlined in the standard IEC 61400-12-1:2017 [6] for wind measurements from mast-mounted anemometers and (ground-based) remote sensing instruments. Such a detailed assessment comprises a device verification, i.e. the direct comparison of the distinct FLS with a suitable reference, as well as a system type classification, which is a detailed analysis of the wind speed deviation between measurement and reference with respect to relevant environmental parameters.

Only the adequate understanding of the respective sensitivities facilitates a practicable and industry-standard application of floating LiDAR technology: this includes the detailed quantification of uncertainties within the WRA process similarly as the pre-deployment assessment of uncertainties that are to be expected for a specific site. With this know-how, FLS types can be, for instance, better selected or adjusted for new sites where no similar campaigns were run before. By following the developed procedures and applying the technology in an optimal way, acceptance of floating LiDAR technology in the industry is further increased with proven uncertainties that are rather at the lower limit of the previously assumed indicative ranges. A detailed review of the IEC 61400-12-1:2017 uncertainty methodology in 2018 [5], as part of that a number of adjustments were suggested by the authors, concluded with the finding that, for the use of FLS in WRA studies, the device class number is an unrealistic high measure for the relevant uncertainties and should not be considered.

The structure of this paper is as follows: first we introduce the concepts of FLS verification and classification. Especially the classification, which is according to [4] required for reaching maturity stage 3 for FLS, will be discussed, based on the methods introduced in [6] that were initially defined for fixed onshore remote sensing devices (RSD). We present a case study that summarizes results for a verification and classification analysis for an FLS trial, conducted in the proximity of the FINO3 met mast located in the German part of the North Sea. Here, a particular focus is set buoy motion variables and oceanographic parameters. Furthermore, the interdependencies of the variables regarded as sensitive are studied. Finally, a number of challenges and possible solutions for the classification of FLS will be discussed.
Figure 2. Exemplary results for verification (left) and classification (right). While a verification is focused on the comparison of wind speed and wind direction differences in between measurement and reference for a specific FLS unit, the classification studies the systematic variation of the relative wind speed deviations corresponding to a number of environmental variables for a type of FLS.

2. Floating LiDAR verification and classification
In this section, we introduce the basic concepts of FLS verification and classification. Both are important steps for assessing an uncertainty budget [5] covering the uncertainty of FLS measurements.

2.1. Verification
Corresponding to the verification of onshore RSD, an offshore verification trial for an FLS is performed in the proximity of a reference measurement system, like an offshore met mast or a fixed reference LiDAR. Key performance indicators (KPI) for evaluating a verification are, for example, the regression parameters when investigating the the wind speed and wind direction correlations between reference and FLS data, compare figure 2, left. For the individual altitudes studied, the slope, offset (only for wind direction) and coefficient of determination $R^2$ have to satisfy well-defined acceptance criteria.

The environmental conditions during the verification trial, like sea state parameters, and meteorological conditions beside wind speed and direction, are documented. A detailed analysis of effects on the measurement is not part of the verification, but is a central element of the classification.
Two different kinds of verification trials are defined, pilot validation trials and verification trials in connection to a specific deployment or application (including pre- and post-deployment as well as in-situ verifications). The pilot validation trial is covering a period of six months and is an essential requirement for reaching the stage-2 pre-commercial or stage-3 full commercial status for a buoy type. Corresponding to the trial duration, the FLS has to prove the reliability for the FLS type. On the other hand, verification trials should be conducted before, during or after a measurement campaign for the employed FLS unit, compare [3]. Here the focus is set on the of traceability of corresponding measurement uncertainties and the measurement quality, respectively, requiring only a shorter trial duration.

2.2. Classification
The classification assesses the sensitivity of a type of FLS and its performance to environmental variables (EV). This is evaluated based on the systematic relative wind speed deviation between reference and RSD measurement. The wind speed deviation is plotted versus all variables which might have an effect on the measurement - cf. figure 2, right. If there is a systematic effect, derived by applying typically linear regression methods, the FLS is sensitive to this EV.

In [6], an RSD classification methodology was introduced for RSD applied onshore and based on ground. Suggested relevant EV comprise meteorological variables and LiDAR system variables like internally recorded carrier-to-noise ratios. For FLS measurements, the buoy motions like roll, pitch or heave need to be additionally taken into account and must be tested for sensitivity. In relation to this, at least two specific challenges arise: First, it is unclear how explicitly the buoy motion parameters should be considered as EV, possible candidates are e.g. mean values, standard deviations or minimum/maximum ranges. Second, using commonly used motion exciting oceanographic EV (cf. figure 3) like significant wave height Hs instead of the motions itself may be preferable. These variables are accessible through external sources, like reference measurements or existing model data and could be used for an uncertainty estimation for future campaign sites, which may require them to be used also in the classification test.

![Figure 3. Flow chart of the relationship of wind, sea state and buoy motion effects, and the buoy set-up on the obtained wind data.](image)

A summary of the main steps of the classification procedure according to [6] are as follows:

(i) Selection of valid wind direction sectors showing low or negligible directional effects on the reference anemometer by e.g. mast effects.

(ii) Identification of environmental variables (EV) from met-ocean data, buoy motion data and LiDAR quality parameters, if these were not already filtered out. Definition of
corresponding binnings for each variable for the following bin-fitting process.

(iii) Conduction of a two-parameter fitting on both the filtered 10-minutes mean data as well as the binned data. Within the bin-fitting process, only bins with a required minimum number of events are considered, to avoid effects from rare or extreme events. Main results are the slope $m$ from the bin-fitting, the EV’s standard deviation $std$ and the coefficient of determination $R^2$ for the fitting of all filtered 10-minutes mean data.

(iv) Calculation of the variable sensitivity $S = m \cdot std$, as well as $S \cdot R$.\(^1\) An EV is defined as sensitive if $|S| > 0.5$ or $|S \cdot R| > 0.1$.

(v) Identification of the sensitive variables: a variable is sensitive if at least one of the before mentioned thresholds is exceeded for at least one altitude.

(vi) Due to possible interdependencies between different EV and a multiple consideration of a sensitivity which can be traced back to one general environmental characteristic, the sensitive EV must be further studied. An example is the boundary layer stability which may be connected to the turbulence intensity TI, the temperature difference (or Richardson number) and the wind shear, amongst others.

The resulting sensitive EV, after taking possible interdependencies into account, are then considered for the classification uncertainty analysis. An RSD class number may be calculated from the resulting sensitive EV. The RSD class number is based on the regression slope and the range for each remaining EV to assess the maximum deviation, see [6]. The range may be taken from the earlier defined bins, the difference between the EV’s minimum and maximum value, or the difference between quantiles like P99-P01. Therefore, the results may vary significantly. In [5] it is suggested, as an alternative approach which is also included in [6], not to use the class number directly due to the too conservative description of the uncertainty, even if the use of a class number is more simple than considering the individual EV.

Finally, it should be noted that the classification only focuses on bin mean values for the wind speed deviation, but not on the standard deviation or on the EV impact on other measures, like wind direction or turbulence intensity TI.

3. Case study
Fraunhofer IWES has successfully implemented the Fraunhofer IWES LiDAR buoy with both Leopshere’s WindCube V2 or ZX Lidars’ ZX 300M, formally known as Zephyr LiDAR. The here presented verification and classification results are based on a trial conducted from November 26th, 2016 to June 18th, 2017 in the proximity of the FINO3 meteorological (met.) mast. The trial covers a period of approx. 204 days with a system availability of approximately 99.5% and a data availability of 97.9% after post-processing for a measurement height of 100 m. With this, all reliability best-practice acceptance criteria according to the stage-2 requirements in [5] were reached.

3.1. Verification
The results of the verification - here as a pre-condition for the later classification - are displayed in figure 4 for wind speed and wind direction. For a measurement height of 100m, both $m = 0.994$ and $R^2 = 0.994$ are clearly within the best practice acceptance criteria of $0.98 < m < 1.02$ for the slope and $R^2 > 0.98$ for the coefficient of determination, respectively. The results for the wind direction are similarly satisfying the best practice requirements, showing a slope of $m = 0.996$, an offset of $b = 1.3^\circ$ and $R^2 = 0.998$.

\(^1\) Note that the correlation coefficient $R$ is used instead of the coefficient of determination $R^2$. 

3.2. Classification
Within the classification, an extensive number of meteorological, oceanographic and buoy motion variables may be sensitive variables and could have a potential effect on the wind speed deviation, compare table 1.

For the buoy motions, roll and pitch time series were used to receive both tilting and angular velocity time series. As resulting variables used for the classification, mean values, standard deviation and variable ranges within the 10-minutes interval were considered. The oceanographic reference data was taken from the FINO database\(^2\). The significant wave height $H_s$ was obtained by a Datawell Mark III wave rider buoy. Water level and current could not be checked due to extensive data gaps. Also the variables visibility range, fog and mist were not available.

As an example, results for the wind shear exponent $\alpha$ and significant wave height $H_s$ are

\[^2\]http://fino.bsh.de/
displayed in figure 5 and figure 6, respectively. Both the fits - based on all 10-minutes data points (green) as well as the bin-averaged fit (red, dashed) are displayed. The valid bins, containing a sufficient relative number of samples, are marked red. Additionally to the fitting parameters, $R^2$ values for both fits are shown. Finally, the corresponding magnitude of the resulting sensitivity and sensitivity $\cdot R$ are stated. For the shear exponent, the resulting sensitivity $S$ is 0.974%, while the $S \cdot R$ is 0.334%. Hence both values do exceed the threshold and mark the wind shear as a sensitive variable. In contrast, there is no significant sensitivity for the significant wave height $H_s$ with resulting values 0.101% and 0.001%, respectively.

After applying this procedure, sensitive variables for this classification trial are the CNR signal quality, wind shear, wind veer, wind speed, turbulence intensity TI and the temperature gradient
Table 2. List of sensitive variables. Furthermore the oceanographic variables significant wave height \( H_s \) and peak period \( T_p \) as well as the buoy motion parameter heave range are stated.

| Independent variable | No. 10-min means after filter | avg (independent variable) | std (independent variable) | Sensitivity \( S \) \( (\text{m x std}) \) | \( S \cdot R \) | Sensitivity |
|----------------------|-----------------------------|---------------------------|---------------------------|--------------------------|----------|----------------|
| CNR signal quality   | 6592                        | -6.54                     | 5.90                      | -0.65                    | 0.01     | -0.06 yes     |
| Wind shear exponent  | 6592                        | 0.12                      | 0.11                      | -0.97                    | 0.12     | -0.33 yes     |
| Wind veer            | 6585                        | 0.10                      | 0.13                      | -0.66                    | 0.04     | -0.23 yes     |
| Wind speed           | 6592                        | 10.47                     | 3.16                      | -0.20                    | 0.06     | -0.15 yes     |
| Turbulence intensity Tl | 6592                     | 4.55                      | 2.27                      | 0.81                     | 0.05     | 0.18 yes     |
| Temperature gradient | 6592                        | 0.00                      | 0.01                      | -1.09                    | 0.01     | -0.13 yes     |
| Significant wave height \( H_s \) (Buoy) | 6384                 | 1.53                      | 0.72                      | -0.14                    | 0.00     | 0.00 no     |
| Peak period \( T_p \) (Buoy) | 6384                 | 7.07                      | 2.29                      | 0.03                     | 0.00     | 0.00 no     |
| Heave range          | 6590                        | 1.31                      | 0.57                      | -0.22                    | 0.12     | 0.00 no     |

- cf. table 2 and figure 7, left plot. On the other hand, no sensitivities could be identified for the extensive list of oceanographic variables or buoy motion variables. Nevertheless, the results for the significant wave height \( H_s \), peak period \( T_p \) and heave range are stated for comparison.

Similar results were obtained for further classification trials using the Fraunhofer IWES LiDAR buoy equipped with a ZX LiDAR. Sensitivities could only be detected for meteorological variables but for none of the buoy motion or oceanographic variables. Note that these results are specific to the studied type of buoy and may be different for another buoy design and type of FLS, respectively. Furthermore, sensitivities are possible for motion and ocean conditions exceeding the range of the yet experienced conditions at sites in the North Sea and Irish Sea.

3.3. Analysis of interdependencies of sensitive variables
The IEC 61400-12-1 standard emphasizes the need for considering the interdependencies between as sensitive identified EV but does not state an explicit method for this. One possible approach is to study the correlations between the different EV and form groups of correlated variables [2]. Due to the number of possible EV for FLS, the here presented method is derived from the method stated in IEC 61400-12-1 for considering reference anemometer sensitivity: from the number of sensitive variables stated before in table 2, we chose one and adjust the relative wind speed deviation according to the slope \( m \) and offset. In the next step, the sensitivity analysis is repeated, including the calculation of the results for the sensitivity \( S \) and \( S \cdot R \). We assume that, if environmental variables are correlated, the adjustment of the initial EV distinctly decreases the sensitivities for all other being in this group.

For this classification, relative wind speed deviation was adjusted considering the wind shear. As a result, the \( S \) and \( S \cdot R \) drop significantly for the variables CNR, veer, wind speed, turbulence intensity TI and the temperature difference - cf. figure 7, middle plot - and form a group of dependent variables. Veer slightly exceeds the threshold for the sensitivity and may be defined as independent sensitive variable. Adjusting the relative wind speed deviation for both shear and veer, all parameters are below the thresholds - cf. figure 7, right plot.

It must be noted that the sensitivity results for the oceanographic variables and buoy motion variables are rising with the consideration of shear as well as veer and shear. A reason for this behavior could be that effects of the oceanographic variables and buoy motions may be distorted or counteracted by other EV.

3.4. Standard implementation issues
There is a number of ambiguities in implementing the classification described in IEC 61400-12-1 Annex L:
Environmental variables: a specification of offshore environmental variables is important to avoid to miss sensitive variables. If variables are known for being potentially sensitive, especially from existing previous classification trials or from other experience, this should also be considered in case the variable is not available for a distinct trial.

The process of calculating the sensitivity $S$ is not robust: the slope of the bin fit - and thus the resulting uncertainty - strongly depends on the binning itself and includes some randomness. The effect of the binning - to exclude rare extreme values within the EV - could be reached by using the valid bin criteria to select a valid EV range and apply a fit on the 10-minute mean values within this valid range to receive robust results. Furthermore, considering the median instead of the mean may have an effect on the robustness, but was not implemented yet.

The thresholds for defining EV as sensitive is not reasoned within the IEC 61400-12-1. This was already noted in [5]. An alternative is the sorting of the EV for the calculated sensitivities. A fraction of the highest EV sensitivity may be used as a minimum threshold for the further sensitive variables.

The number of measurement heights: if a variable shows the sensitivity on an individual altitude, it should be treated sensible for all altitudes. As a result, an additional (lower) altitude considered within the classification with stronger reference mast wake effects on the anemometer affects the uncertainty on the other altitudes.

For FLS verification, two wind speed ranges are defined, 4m/s - 16m/s and over 2m/s. For the classification, no wind speed range is defined, nevertheless the results differ for the

---

**Figure 7.** Display of the $|S|$ and $|S \times R|$ for different environmental variables for the initial results (left), relative wind speed adjustment considering shear (middle) as well as shear and veer (right).
different ranges.

4. Conclusion and outlook
We presented the results of a classification trial for a Fraunhofer IWES LiDAR buoy with a Leosphere Windcube V2 at the FINO3 site in the North Sea. Sensitivities exist for a number of meteorological parameters like wind speed, shear, veer etc. The analysis for environmental variables interdependencies show a correlation between these variables, forming a group of correlating variables. These variables must not be considered at the same time for the uncertainty to avoid an over estimation. Furthermore, no sensitivities could be detected for neither the buoy’s motion variables nor the oceanographic variables. This corresponds to the results of further classifications using the Fraunhofer IWES LiDAR buoy with a ZX LiDAR in the North Sea and Irish Sea. It is not yet clear if this insensitivity for buoy motions and oceanographic variables is the results for all locations. Future results of the MALIBU project should deliver further insights into the buoy motion induced uncertainties using a simulation environment. This would also be favorable due to the effort in time and costs for performing classification trials and assess the behavior for sites which environmental conditions are not yet completely covered by existing trials.

During the application of the classification process, ambiguity within the standard IEC 61400-12-1 were found for application on FLS. This includes the possible environmental variables, the method of calculating the sensibility and the criteria for being a sensitive or not sensitive variables. A clarification within the standard would be an important improvement for the standardization of the classification process.

5. Acknowledgements
The here presented work was conducted within the research project MALIBU which is a cooperation with Stiftungslehrstuhl Windenergie SWE Stuttgart, funded by the German Federal Ministry For Economics Affairs and Energy (BMWi) under Grant number 0324197B, as well as the support of Project Management Jülich (PTJ). Furthermore, the reference data was acquired by the FINO-Platforms, also funded and supported by the BMWi and PTJ. The FINO-data is provided by the FINO-Datenbank, operated by the German Bundesamt für Seeschifffahrt und Hydrographie (BSH).

References
[1] Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology, Version 1.0, November 2013.
[2] Barker et. al. Correlation effects in the field classification of ground based remote sensors, Conference proceeding, EWEA 2014, Barcelona, Spain (http://publica.fraunhofer.de/documents/N-351481.html accessed Mai 13th 2020)
[3] IEA Wind, Expert Group Report on Recommended Practices, 18.Floating LiDAR Systems, First Edition 2017. O. Bischoff, I. Würth, J. Gottschall, B. Gribben, J. Hughes, D. Stein, H. Verhoef (https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=99ec44ff-4493-4493-4493-4493-4493-4493 accessed Mai 13th 2020)
[4] Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology, Version 2.0, October 2018. (https://prod-drupal-files.storage.googleapis.com/documents/resource/public/Roadmap%20for%20Commercial%20LiDAR%20Technology%20%202018.pdf accessed Mai 13th 2020)
[5] Carbon Trust Offshore Wind Accelerator Lidar Uncertainty Standard Review Methodology Review and Recommendations, OWA Report 2017-001, June 2018. (https://prod-drupal-files.storage.googleapis.com/documents/resource/public/owa-w-lusr_nov-2018.pdf accessed Mai 13th 2020)
[6] IEC 61400-12-1:2017 Wind energy generation systems -Part 12-1: Power performance measurements of electricity producing wind turbines, Annex L: The application of remote sensing technology (https://www.vde-verlag.de/iec-normen/224299/iec-61400-12-1-2017.html accessed Mai 13th 2020)