WIND TURBINE TESTING SERVICES

Uncertainty Assessment Fugro OCEANOR SEAWATCH Wind LiDAR Buoy

at RWE Meteomast IJmuiden

11.04.2014 – 27.10.2014

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Date 2 September 2016
Our reference ECN Wind letter

PO Box 1, 1755 ZG PETTEN, The Netherlands

Contact

Dear Reader,

The Fugro OCEANOR SeaWatch Wind LiDAR buoy is used in the Borssele wind farm zone and the Hollandse Kust (zuid) wind farm zone to measure the local wind conditions. In order to perform a thorough wind resource assessment on these measurements it is of utmost importance to understand the uncertainties related the these wind measurements. In the current report Ecofys assesses the uncertainty of the Fugro OCEANOR SeaWatch Wind LiDAR buoy.

ECN has quite a track record on floating LiDAR technology: ECN has validated the EOLOS floating LiDAR, co-validated the Fugro OCEANOR SeaWatch Wind LiDAR buoy, reviews and stores the floating LiDAR measurements from the Borssele and Hollandse Kust (zuid) wind farm zones and was co-author of the OWA/IEA floating LiDAR recommended practices.

Based on the above RVO has requested ECN to validate the current report and as such ECN has used its experience and expertise on the technology in the review process.

ECN agrees with the adopted approach, the assumptions made in the report and the obtained uncertainty values. Therefore, ECN endorses the results of this report.

Kind regards,

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Summary

At the request of RVO, Ecofys WTTS carried out an uncertainty calculation for the SEAWATCH Wind LiDAR Buoy (SWLB, with ZephIR ID Z417) based on a campaign next to the RWE Meteomast IJmuiden located in the Dutch territory of North Sea. RVO has since deployed the SWLB at the Borssele offshore wind farm development zone, and will deploy again at the Hollandse Kust (zuid) zone. A goal of this analysis is to validate the preliminary estimate of 3% uncertainty in wind speed measurements.

The RWE Meteomast IJmuiden is fully IEC compliant and equipped with Thies First Class Advanced cup anemometers mounted at heights of 27 m, 58.5 m, 92 m LAT and with Metek USA-1 sonic anemometers at 85 m. In addition, Thies First Class wind vanes for wind direction measurements are located at 26 m, 58 m and 87 m. The SWLB was collecting wind data at three common heights with the Meteomast IJmuiden cup anemometers. The SWLB verification campaign lasted from 11.04.2014 to 27.10.2014.

All measured data was filtered to ensure entirely valid datasets. The uncertainty analysis is based on the IEC standard 61400-12-1 (ed. 2, draft [2]). For all measurements heights, all 0.5 m/s wind speed bins had sufficient data, the overall data availability is considered very good for the analysis.

Linear regression between the SWLB and Meteomast IJmuiden wind speed recordings showed consistent, highly-correlated measurements with slopes near unity.

The correlation between SWLB and Meteomast IJmuiden binned wind directions is excellent, with an R^2 of greater than 0.98 for all heights, scatter of about ±8° (one standard deviation) and an offset of 6-8° (within the measurement uncertainty). It is important to note that this comparison uses the post-processed LiDAR wind direction, corrected using the buoy's Xsens compass (data post-processing by Fugro OCEANOR AS); Fugro OCEANOR AS now applies this correction for all measurement campaigns.

Sensitivity tests of the wind speed deviation revealed that the wind speed deviation shows no significant linear correlation to the following external conditions: horizontal wind speed, turbulence intensity, rain, significant wave height, maximum wave height and current speed. However, the regression slope with turbulence intensity is relatively large, indicating it is potentially a significant environmental condition; this could be confirmed by a classification analysis of the SWLB.

The calculated uncertainty in the SWLB wind speed measurements is relatively low, in line with high quality anemometry for the majority of the wind speed bins. The calculated uncertainty tables (presented in Section 4.6) can be used directly in wind resource assessments, together with the classification uncertainty and site-specific uncertainty components. An example of the calculation for a future wind measurement campaign results in a weighted total measurement uncertainty of 3.3-3.4%, for campaigns with a mean wind speed between 7-10 m/s at 92 m. The uncertainty tables apply specifically to the tested device (SWLB, with ZephIR ID Z417) although the results should be representative for other Fugro OCEANOR AS SWLB devices, provided the IEA recommended practices are followed for the campaign design [8].

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1 Introduction

RVO requested Ecofys WTTS to perform an uncertainty assessment for the SEAWATCH Wind LiDAR Buoy (SWLB, with ZephIR ID Z417) based on the available parallel measurements against the offshore Meteomast IJmuiden located in Dutch territory of North Sea. These parallel measurements were performed by Fugro OCEANOR AS as a part of the trial campaign of SWLB from 11 April 2014 to 27 October 2014 [6].

1.1 Purpose

RVO has since deployed the SWLB at the Borssele offshore wind farm development zone, and will deploy again at the Hollandse Kust (zuid) zone. The objective of this analysis is to quantify the measurement uncertainty of the SWLB and to validate the preliminary estimate of 3% uncertainty in the resulting wind speed measurements.

Other studies have also been based on the data from this measurement campaign. DNV GL evaluated the performance against several metrics, in terms of stages of maturity defined by the OWA Floating LiDAR Roadmap [5] and "concludes that the FO SWL Buoy has formally qualified for Stage 2 "pre-commercial" in the context of the Floating LiDAR Commercial Roadmap" [6]. ECN has also compared the results of the floating LiDAR verification against the results of a static LiDAR verification (the static LiDAR is mounted on the same monopile as the met mast) [7].

These studies do not provide detailed uncertainty tables; thus this analysis calculates the measurement uncertainty traceable to international standards.

1.2 Scope of the study

This study will assess the uncertainty in wind speed and wind direction measurements obtained from SWLB during the trial campaign performed against Meteomast IJmuiden.

The uncertainty analysis procedure evaluates the accuracy of the floating SWLB measurements based on the international wind industry standards IEC 61400-12-1 verification procedure and uncertainty evaluation [1] [2].

1.3 IEC 61400-12-1 (ed 2)

IEC 61400-12-1 (ed 1 [1]) is the definitive industry-wide standard for high-quality wind measurement campaigns using standard anemometry. The second edition (IEC 61400-12-1 (ed 2)*) also specifies the use of LiDAR, with a detailed procedure (Annex L) that ensures the traceability of the measurements and evaluates associated uncertainty components, which can be applied in wind resource assessments:

* Since the second edition is not yet published, the analysis is based on a Committee Draft [2]

"This test is a comparison of the remote sensing device measurements to those from calibrated cup anemometers mounted on a mast spanning a significant portion of the height range of interest. The purpose of this test is to convey traceability to international standards to this particular device, in the form of an uncertainty. A second result of the verification test is an assessment of the random noise of the device." [2]

The systematic uncertainties in the LiDAR measurements are evaluated for each 0.5 m/s wind speed bin from 4-16 m/s:

- "The standard uncertainty of the reference sensor";
- "The mean deviation of the remote sensing device measurements and the reference sensor measurements";
- "The standard deviation of the measurement of the remote sensing device calculated as the standard deviation of the measurements divided by the square root of the number of data per bin";
- "Uncertainty of the remote sensing device due to mounting effects"; and
- "Uncertainty of the remote sensing device due to non-homogenous flow." [2]

The wind speed dataset should include at least 3 pairs of valid measurements in each wind speed bin between 4 m/s and 16 m/s, and the total amount of valid data should be minimum 180 hours. Wind direction measurements are validated in 5 degree bins by means of regression analysis between the LiDAR and met mast wind vane measurements.

1.4 Structure of the Report

First, the measurement site is described in detail, followed by a description of the uncertainty assessment or verification procedure. Data filtering and data quality are defined and summarised and statistical methods are explained. Results for wind speed and wind direction are presented in the 'Results and discussion' chapter including a small discussion subsection per variable. This chapter also covers on data filtering, and a sensitivity analysis. Finally, conclusions are drawn.

2 Measurement Campaign

A validation campaign of the Fugro OCEANOR AS SWLB was performed at Meteomast IJmuiden as part of the FLOW project initiated by RWE and Eneco. In this project, Fugro OCEANOR AS, owner of the floating LiDAR, and ECN, operator of Meteomast IJmuiden, acted as subcontractors.

2.1 Site Description

The verification of the SWLB was performed at the RWE Meteomast IJmuiden offshore meteorological station, located 85 km from the coast of IJmuiden [6], as depicted in below figure.

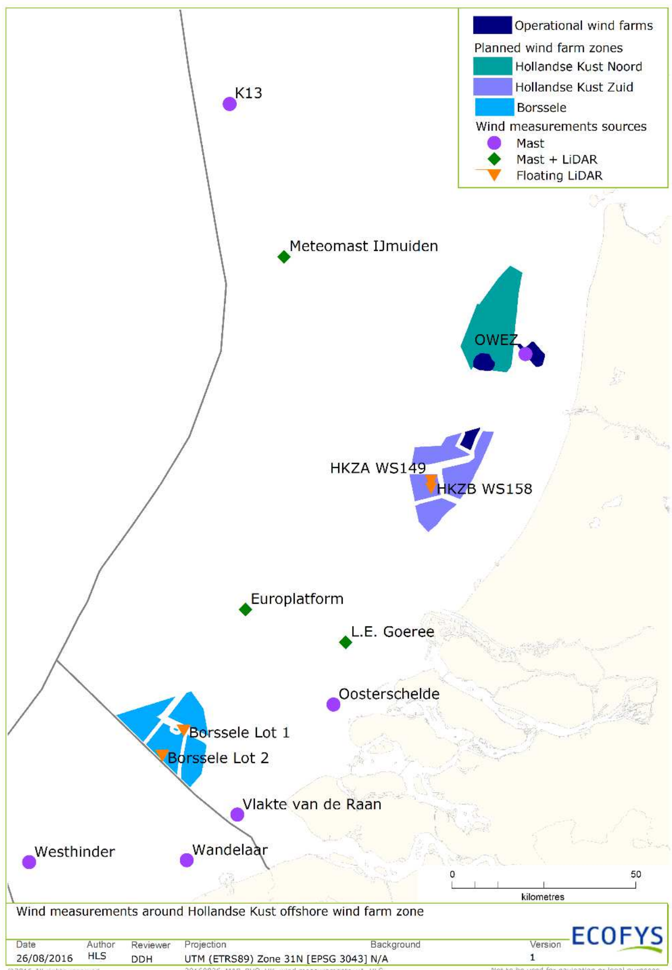

Figure 1: Meteomast IJmuiden location

2.2 Meteomast IJmuiden

Ecofys WTTS obtained measured data of Meteomast IJmuiden from ECN. ECN has been carrying out a wind measurement campaign at Meteomast IJmuiden, an offshore mast built in 2011, approximately 82 km west of the coast of IJmuiden. The Meteomast IJmuiden 92 m is fully IEC compliant with its measuring heights at 27 m, 58.5 m, 85 m and 92 m LAT [4].

The mast was erected on a platform mounted on a monopile. The platform height was 18 m above LAT and the top of the mast is 92 m above LAT. The mast was placed on top of the platform, next to the container [4]. A picture of the offshore meteorological station can be seen in Figure 2. Location of the mast is provided in Table 1 below, with coordinates shown in decimal degrees.

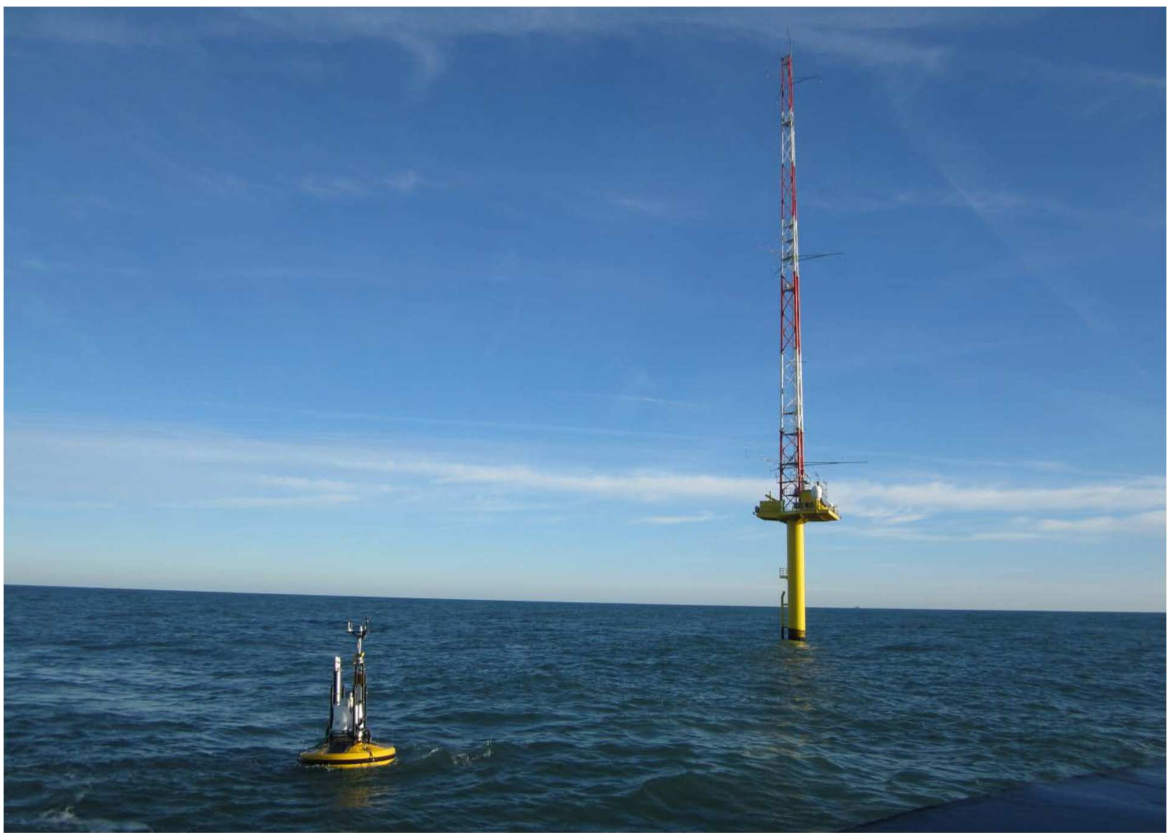

Figure 2: Meteomast IJmuiden along with Fugro OCEANOR SWLB [source: Fugro]

Table 1: Coordinates of Meteomast IJmuiden

	Latitude [ETRS89]	Longitude [ETRS89]
Meteomast IJmuiden	52°41'30.98"	3°01'32.08"

Meteomast IJmuiden was equipped with three cup-anemometers at 27 m and 58.5 m and two at 92 m. Three sonic-anemometers were installed at 85 m. Three wind vanes were installed at each height of 26 m, 58 m and 87 m. Temperature, pressure and relative humidity were sampled at two heights: 21 m and 90 m. Finally, extensive measurements of rain, clouds, fog and visibility took place at 21 m. The data-sources used for this verification are specified in Table 2.

Table 2: Partial sensor list of Meteomast IJmuiden

Sensor	Height	Orientation - Position
Thies First Class Advanced anemometer	92 m	North East leg of mast
Thies First Class Advanced anemometer	92 m	South West leg of mast
Vaisala PTB210 air pressure sensor	90 m	North East side of top platform
Vaisala HMP155D	90 m	North West side of top platform
Thies First Class Wind vane	87 m	46.5°
Thies First Class Wind vane	87 m	166.5°
Thies First Class Wind vane	87 m	286.5°
Metek USA-1 sonic anemometer	85 m	46.5°
Metek USA-1 sonic anemometer	85 m	166.5°
Metek USA-1 sonic anemometer	85 m	286.5°
Thies First Class Advanced anemometer	58.5 m	46.5°
Thies First Class Advanced anemometer	58.5 m	166.5°
Thies First Class Advanced anemometer	58.5 m	286.5°
Thies First Class Wind vane	58 m	46.5°
Thies First Class Wind vane	58 m	166.5°
Thies First Class Wind vane	58 m	286.5°
Thies First Class Advanced anemometer	27 m	46.5°
Thies First Class Advanced anemometer	27 m	166.5°
Thies First Class Advanced anemometer	27 m	286.5°
Thies First Class Wind vane	26 m	46.5°
Thies First Class Wind vane	26 m	166.5°
Thies First Class Wind vane	26 m	286.5°
Thies Disdro laser precipitation sensor	21 m	Railing of container, South side
Vaisala HMP155D	21 m	Railing of container, North side
Vaisala PTB210 air pressure sensor	21 m	Railing of container, North side

2.3 SEAWATCH Wind LiDAR Buoy

The SEAWATCH Wind LiDAR Buoy (SWLB) consists of a LiDAR ZephIR 300S mounted and integrated with the SEAWATCH Wavescan. Manufactured by Fugro OCEANOR AS, the SWLB has been designed especially for offshore environment. The SEAWATCH Wavescan was designed in 1985 as a directional wave buoy and multi-purpose metocean platform. According to Fugro OCEANOR AS, it has had numerous deployments and a proven track-record in the most hostile offshore environments.

The SWLB has been moored 150 m from Meteomast IJmuiden, with the coordinates shown in Table 3.

Table 3: Coordinates of SWLB measurement position

LiDAR ID	Latitude [ETRS89]	Longitude [ETRS89]
ZephIR 300S	52°50’53.48”	3°26’02.18”

Fugro OCEANOR AS provided Ecofys WTTS with the SWLB data of 10-minute mean wind speed at 12, 27, 40, 48, 58, 70, 85, 92, 120, 150 and 190 m (above sea surface). These heights match with the available measurement heights of the Meteomast IJmuiden. Fugro OCEANOR AS also provided 10-minute mean wind direction at 25, 55 and 90 m. According to Fugro OCEANOR AS, the wind direction data was post-processed with the Xsens as compass, in line with the revised algorithm for future deployments.

Other meteorological parameters were provided separately, including air temperature, air pressure and humidity. In addition to the meteorological data, Fugro OCEANOR AS also provided Ecofys WTTS with metocean parameters (wave and current). Full details of the dataset are shown in Table 4. Note that the periods of each dataset are different, with less data available in the metocean dataset and Xsens-corrected wind directions.

The design of the floating LiDAR campaign is in line with the recommended practices of the IEA Task 32 working group [8].

Table 4: Details of the SWLB during verification campaign

Parameters	
Test ID	ZephIR 300S
System serial number	Z417
Measurement range	12, 27, 40, 48, 58, 70, 85, 92, 120, 150 & 190 m (LiDAR) 0, -3, -5, -10, -15, -20, -25 & -27 m (metocean)
Beam angles	30°
Timestamp interval	10 min (LiDAR) 30min (metocean)
Timestamp	UTC
Data period	11/04/2014 to 28/10/2014 (wind speed) 11/04/2014 to 08/08/2014 (wind direction) 11/04/2014 to 12/06/2014 (metocean data)
LiDAR data	Mean horizontal wind speed, Mean wind direction, Air temperature, Air pressure, Humidity
Metocean data	Current speed, Current direction, Significant wave height, Maximum wave height, Wave direction, Wave period, Peak spectral period & Water temperature

2.4 Valid Wind Direction Sectors

The design of the Meteomast IJmuiden and data processing techniques ensure high data quality. Flow distortion due to the tower is minimised by installing anemometers on three different booms at each height (two at the mast top). Each boom was pointing in another wind direction, so that data can be selected only from relatively undisturbed sensors. ECN had verified the data quality in several ways. The measurement computer checked sensor connection and if recordings exceed minimum and maximum thresholds. Subsequently the data was checked manually. Only valid data was kept in the provided raw data files. Missing values are indicated with blanks.

Data from the derived wind speed and direction were calculated according to the methods described by ECN for three anemometers at each height [4], modified by Ecofys WTTS to include periods with only a single undisturbed wind vane.

No information is given regarding the recommended filters for the derived wind speed for the top measurement height where there are only two anemometers. Therefore, Ecofys WTTS designed its own interpolation method based on disturbed sectors. The location of the two anemometers was identified based on the instrumentation report [4] and the mast layout shown in Figure 3 and the location of the lightning rod was confirmed by ECN. An intercomparison of the two measured wind speeds confirmed flow disturbances in the expected sectors, and the directional filters in Table 5 were defined.

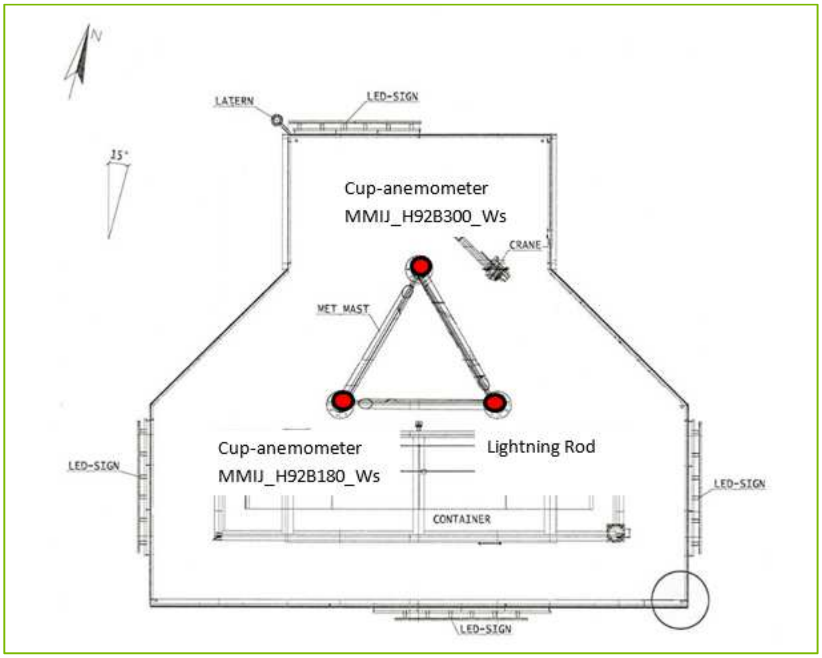

Figure 3: Top view of 92 m top section of Meteomast IJmuiden (source: [4]) with the location of the two cup-anemometers and the lightning rod indicated.

Table 5: Summary of directional filters for 92 m measurement height

Disturbed sector [°]	Blockage effects	Valid data
10-30	MMIJ_H92B180_Ws affected by MMIJ_H92B300_Ws	MMIJ_H92B300_Ws
60-100	MMIJ_H92B180_Ws affected by Lightning rod	MMIJ_H92B300_Ws
125-160	MMIJ_H92B300_Ws affected by Lightning rod	MMIJ_H92B180_Ws
185-210	MMIJ_H92B300_Ws affected by MMIJ_H92B180_Ws	MMIJ_H92B180_Ws

2.4.1 Final Valid Wind Direction Sectors

A single wind data time series was derived at each height, based on the multiple measurements at each height. All sectors are considered to be valid for performing an uncertainty assessment of the floating SWLB against RWE Meteomast IJmuiden. A limited amount of wind direction data at all heights was filtered out, for wind directions close to North, to remove misleading comparisons between directions slightly above 0° and below 360°.

3 Procedure

The LiDAR data was compared to the reference anemometry data on the basis of 10-minute averages.

To increase the accuracy and repeatability of the uncertainty assessment, the datasets are filtered. The filtered data forms the basis for the data analysis, founded on the IEC 61400-12-1 verification procedure and uncertainty evaluation [1] [2]. The full procedure is described in Appendix B, including filtering, statistical tests and uncertainty calculation.

The uncertainty resulting from the LiDAR verification test is divided into 5 separate uncertainties, as summarised below, and shown in Table 6:

1. Reference uncertainty (in anemometry)
   a. Wind tunnel calibration*
   b. Cup anemometer effects according to the anemometer classification
   c. Cup anemometer mounting effects
      i. Mast shadowing
      ii. Boom distortion
      iii. Lightning rod distortion
   d. Uncertainty of any applied mast correction
2. Mean deviation of the LiDAR measurements and the reference anemometry measurements
3. Standard deviation of the measurement of the LiDAR
4. Uncertainty in mounting effects
5. Uncertainty of the LiDAR due to non-homogeneous flow within the measurement volume and variation in flow across the site, during the verification test

The uncertainties are combined as the square root of the sum of squares:

$$Utotal = \sqrt{U1^2 + U2^2 + U3^2 + U4^2 + U5^2}$$

The calculated uncertainty refers to the uncertainty in the performance verification test. The total uncertainty for future wind measurement campaigns will also include components relating to site-specific mounting and flow condition on-site, and uncertainty resulting from the classification of the LiDAR (sensitivity to environmental variables). These uncertainties should be assessed as part of the wind resource assessments.

* *Calibration certificates of Meteomast Ijmuiden presented in Appendix A are the property of ECN, any use of these calibration certificates without written permission from ECN is strictly prohibited.*

Table 6: Uncertainties for Meteomast IJmuiden used for the SWLB verification

Uncertainty category	Uncertainty subcategory	Parameter	Value
Reference uncertainty (in anemometry)			See uncertainty table, defined per wind speed bin of 0.5 m/s
	Wind tunnel calibration	Calibration standard error in linear fit and the wind tunnel accuracy for k=1	Defined per wind speed bin of 0.5 m/s Sensor # 6042: 0.008m/s at 92 m and 0.025m/s Sensor # 6043: 0.015m/s at 92 m and 0.025m/s Sensor # 6045: 0.015m/s at 58.5 m and 0.025m/s Sensor # 6046: 0.009m/s at 58.5 m and 0.025m/s Sensor # 6047: 0.015m/s at 58.5 m and 0.025m/s Sensor # 6106: 0.012m/s at 27 m and 0.025m/s Sensor # 6107: 0.018m/s at 27 m and 0.025m/s Sensor # 6108: 0.014m/s at 27 m and 0.025m/s
	Cup anemometer effects according to the anemometer classification	k	0.9
	Cup anemometer mounting effects	Uncertainty	0.3% for mast distortion 0.5% for boom distortion 0.1% for data acquisition system
	Uncertainty of any applied mast correction		0.0%
Mean deviation of the LiDAR measurements and the reference anemometry measurements			See uncertainty table, defined per wind speed bin of 0.5 m/s
Standard deviation of the measurement of the LiDAR			See uncertainty table, defined per wind speed bin of 0.5 m/s
Uncertainty in mounting effects at the verification test		Uncertainty	0.5%
Uncertainty of the LiDAR due to non-homogeneous flow within the measurement volume, during the verification test		Uncertainty	0.0%
Uncertainty due to variation in flow across the site		Uncertainty	Defined per height, based on the separation distance between met mast and remote sensing device: 1.63% (at 92 m) 2.59% (at 58.5 m) 5.56% (at 27 m)

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4 Verification Analysis

The results for the SWLB verification campaign are presented below. The data coverage is shown, followed by a linear regression of the wind speed and direction measurements. A sensitivity analysis is shown against several environmental factors and finally the uncertainty numbers are presented.

4.1 Data Coverage

The data filtering (described in the previous chapter) reduced the number of data points, as shown in Table 7 and Table 8. The disabled data was primarily because of wind direction processing, as well as some SWLB data that was flagged as low signal to noise conditions; more detail can be found in Appendix C.

Table 7: Number of data points and data coverage before and after filtering for wind speed

Height [m]	Number of data points			
	Before **filtering**		***After*** **filtering**	
	SWLB	**Meteomast IJmuiden**	**SWLB**	**Meteomast IJmuiden**
27	26,202	28,540	26,160	26,028
58/58.5	26,198	28,542	26,160	26,025
92	26,199	28,543	26,160	26,027

Table 8: Number of data points and data coverage before and after filtering for wind direction

Height [m]	Number of data points			
	Before **filtering**		***After*** **filtering**	
	SWLB	**Meteomast IJmuiden**	**SWLB**	**Meteomast Ijmuiden**
27/26	27,719	28,539	24,884	25,019
58	27,719	28,541	24,806	25,039
92 / 87	27,719	28,542	25,653	24,995

4.2 Wind Speed Verification

The mean wind speed measured by the SWLB is compared to the concurrent Meteomast IJmuiden measurements in a scatter plot (see Figure 4 to Figure 6) and a single parameter Ordinary Least Squares (OLS) linear regression is applied. The slope of the linear regression and the corresponding coefficients of determination are shown. The plots show excellent correlation between the SWLB and Meteomast IJmuiden wind speed measurements.

The wind speed deviation is defined as the SWLB mean wind speed minus the Meteomast IJmuiden mean wind speed. This is also plotted (in m/s) in the scatter plots below. The statistical distribution of the wind speed deviations has been derived, as shown in Table 9.

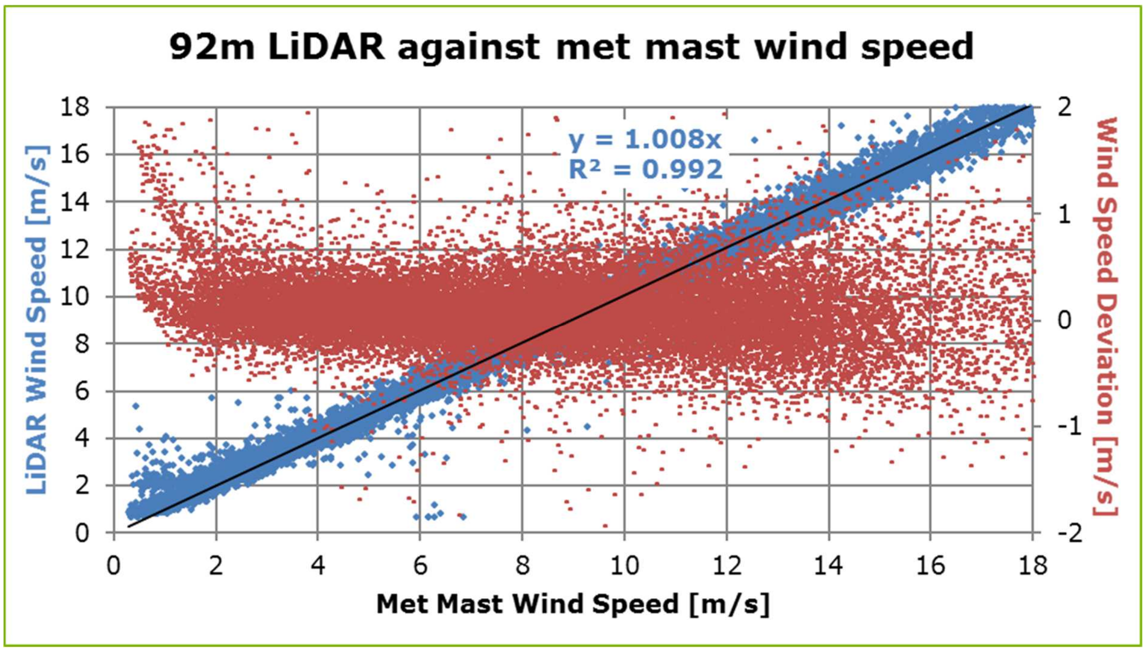


Figure 4: Linear regression of mean wind speed at 92m for SWLB

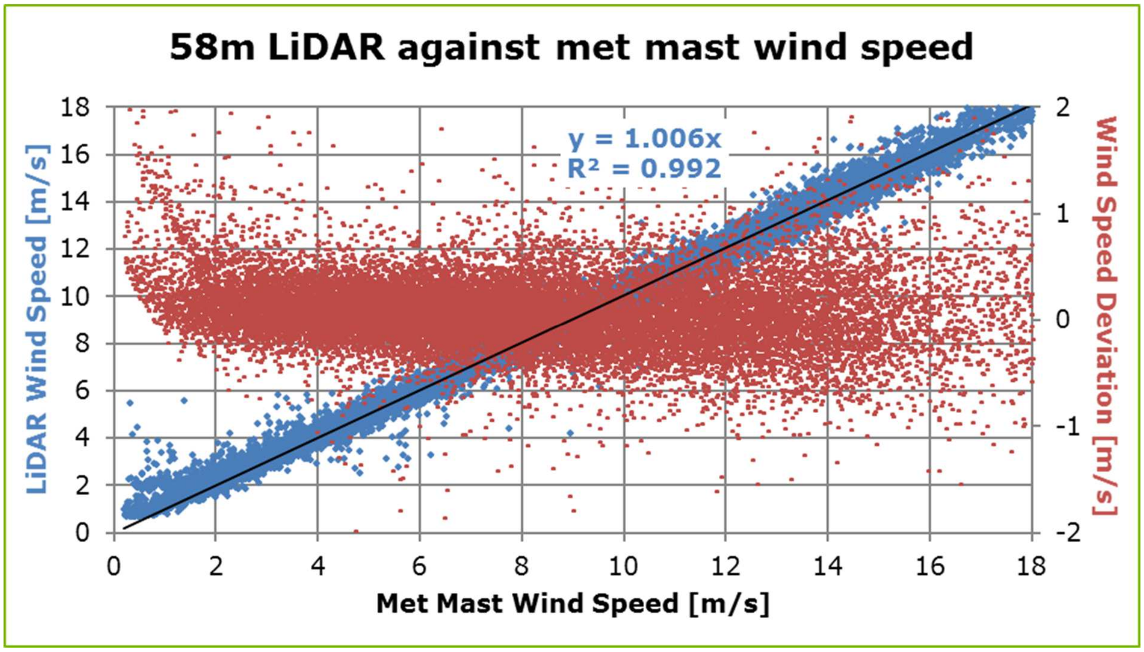


Figure 5: Linear regression of mean wind speed at 58m for SWLB

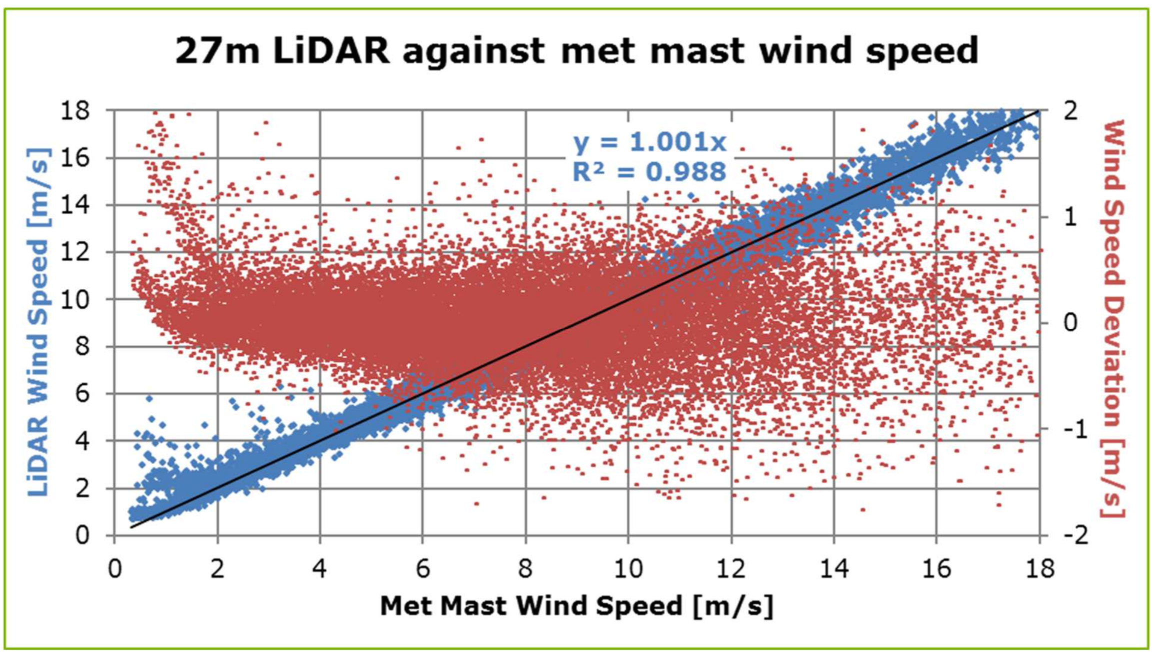


Figure 6: Linear regression of mean wind speed at 27 m for SWLB

Table 9: Statistical parameters of wind speed at each reference height for SWLB

Height [m]	Mean of Wind Speed Deviations [m/s]	Standard Deviation of Wind Speed Deviations [m/s]	Coefficient of determination [R^2]
27	0.027	0.415	0.988
58	0.095	0.360	0.992
92	0.101	0.375	0.992

4.3 Wind Direction Verification

Similarly, a linear fit is applied to scatter plots of the wind direction, as shown in the below figures. A two-parameter Ordinary Least Squares linear regression is used, in order to identify any offset from zero, with slopes, offsets and coefficients of determination (plotted in the graphs).

The correlation between SWLB and Meteomast IJmuiden binned wind directions is excellent, with an R^2 of greater than 0.98 for all heights, scatter of about ±8° (one standard deviation) and an offset of 6-8° (within the measurement uncertainty). It is important to note that this comparison uses the post-processed LiDAR wind direction, corrected using the buoy's Xsens compass (data post-processing by Fugro OCEANOR AS); Fugro OCEANOR AS now applies this correction for all measurement campaigns.

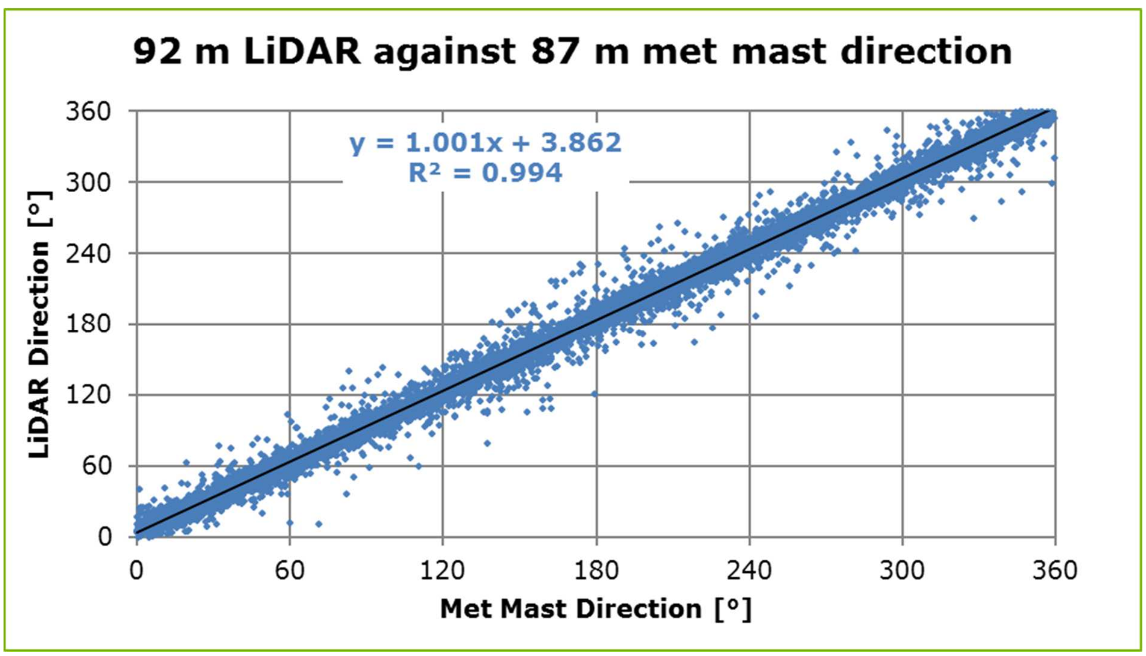


Figure 7: Linear regression of mean wind direction at 87 m and 92 m for SWLB.

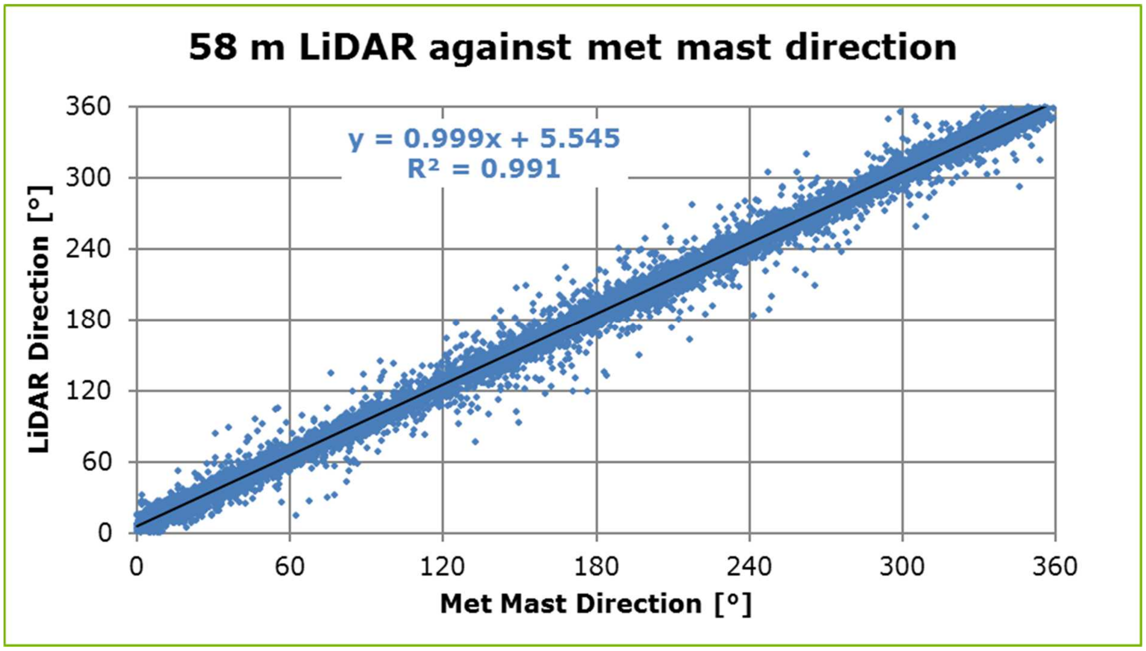


Figure 8: Linear regression of mean wind direction at 58.5 m and 56 m for SWLB.

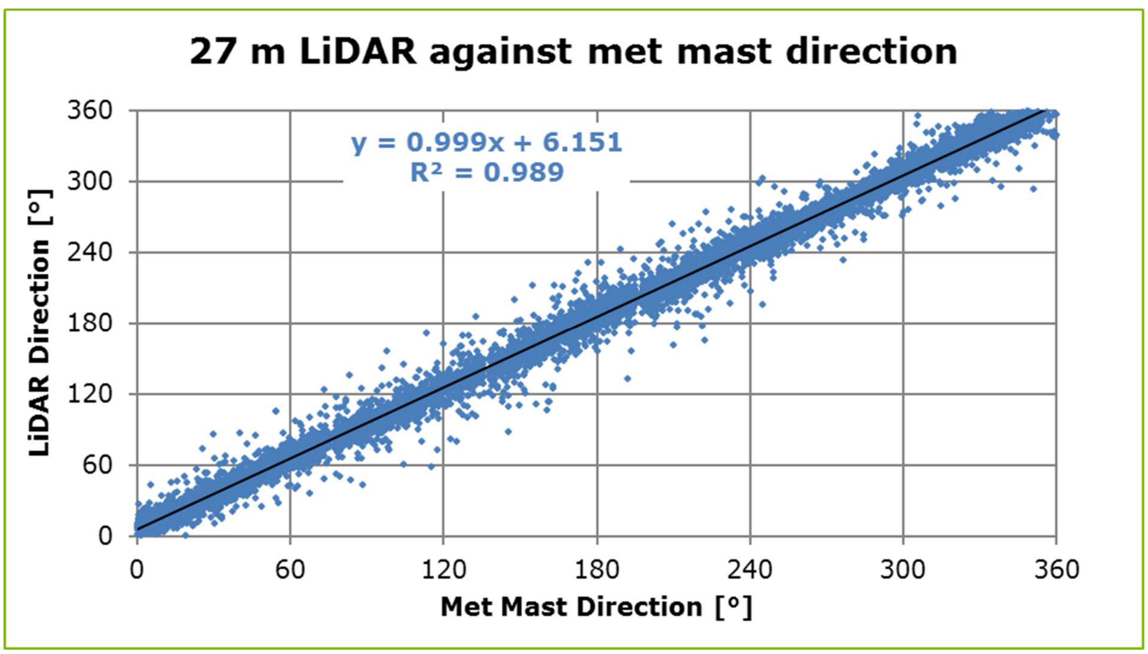
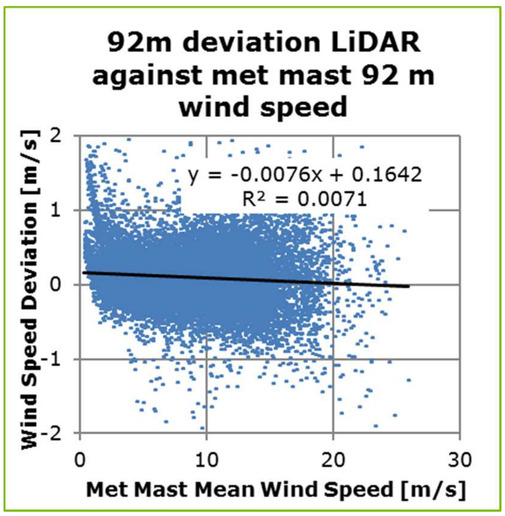


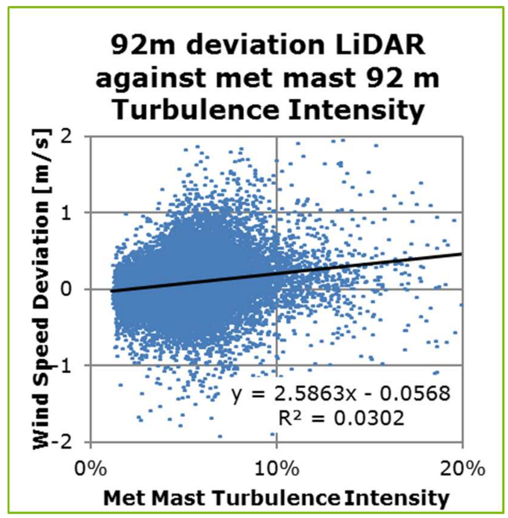
Figure 9: Linear regression of mean wind direction at 26 m and 27 m for SWLB.

4.4 Sensitivity Tests

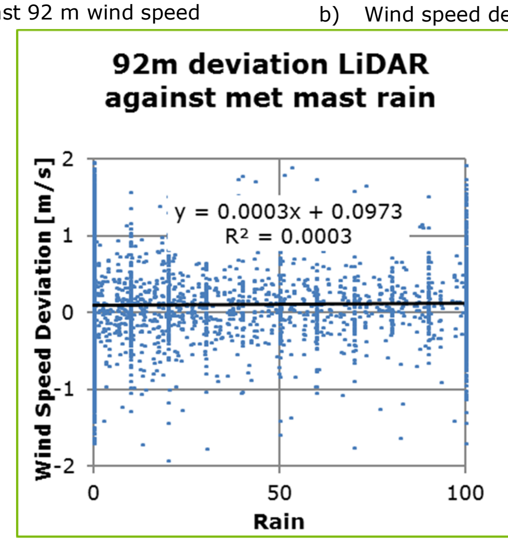
Several sensitivity tests are run to find possible relationships between wind speed deviation and external conditions. The wind speed deviation at 92 m is plotted against Meteomast IJmuiden mean wind speed, turbulence intensity and precipitation as seen in Figure 10. Metocean parameters are shown in Figure 11. All plots show negligible correlation with the wind speed deviation at 92 m and same observed at heights, indicating that the SWLB is relatively insensitive to these factors at all heights. However, the slope of the regression with turbulence intensity is relatively large, which may indicate a significant relationship (as noted by ECN in their separate study [7]); this could be confirmed by a classification analysis of the SWLB.



a) Wind speed deviation against 92 m wind speed

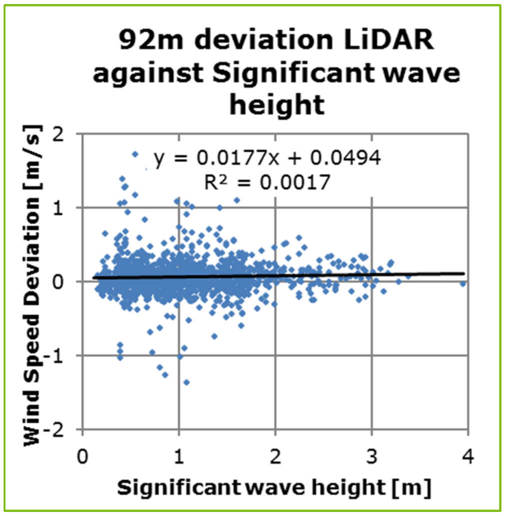


b) Wind speed deviation against Turbulence intensity

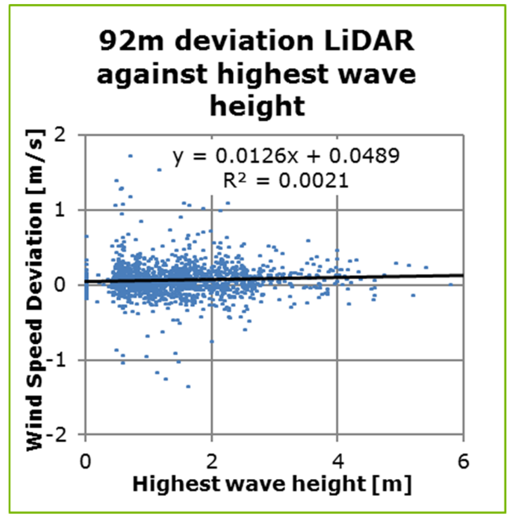


c) Wind speed deviation against rain

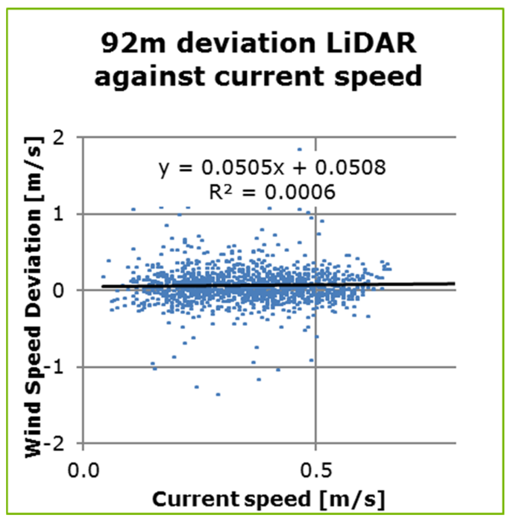
Figure 10: Sensitivity tests of wind speed deviation at 92 m plotted against other meteorological factors for SWLB



a) Wind speed deviation significant wave height



b) Wind speed deviation against highest wave height



c) Wind speed deviation against current speed at -3m

Figure 11: Sensitivity tests of wind speed deviation at 92 m plotted against metocean factors for SWLB

4.5 Verification Uncertainty Graphs

For each height, an uncertainty calculation was performed for each wind speed bin of 0.5 m/s between 4 and 16 m/s. For all of the bins, a sufficient number of valid data points were collected.

This analysis shows a low uncertainty in the SWLB wind speed measurements, as seen in Figure 12 to Figure 14. The full uncertainty analysis is documented in the tables in the next section. The deviations between LiDAR and met mast wind speeds are generally of the same order of magnitude as the reference anemometer uncertainty, coupled with statistical uncertainty.

In particular, the verification uncertainty at a measurement height of 92 m is about 2% and shows a high consistency across wind speed bins.

The total verification uncertainty is higher for lower measurement heights and this is largely due to the component of uncertainty due to variation in flow across the site, from Meteomast IJmuiden to SWLB. As per the IEC standard, this component of uncertainty is defined as 1% of the ratio between measurement height and distance (i.e. 1.6% at 92 m and up to 5.6% at 27 m). These results are in strict accordance with the IEC standard, although Ecofys WTTS believes that a lower uncertainty is justified for this component of flow uncertainty, which would reduce the calculated uncertainty at lower heights.

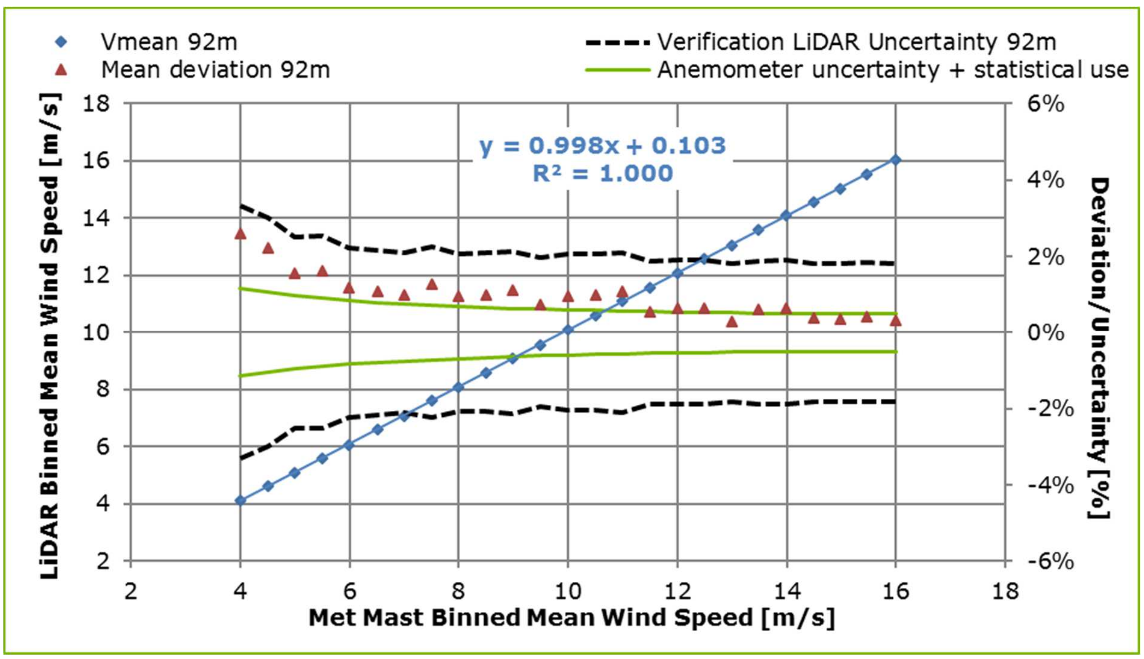


Figure 12: Uncertainty analysis of SWLB wind speed measurements at 92 m for SWLB

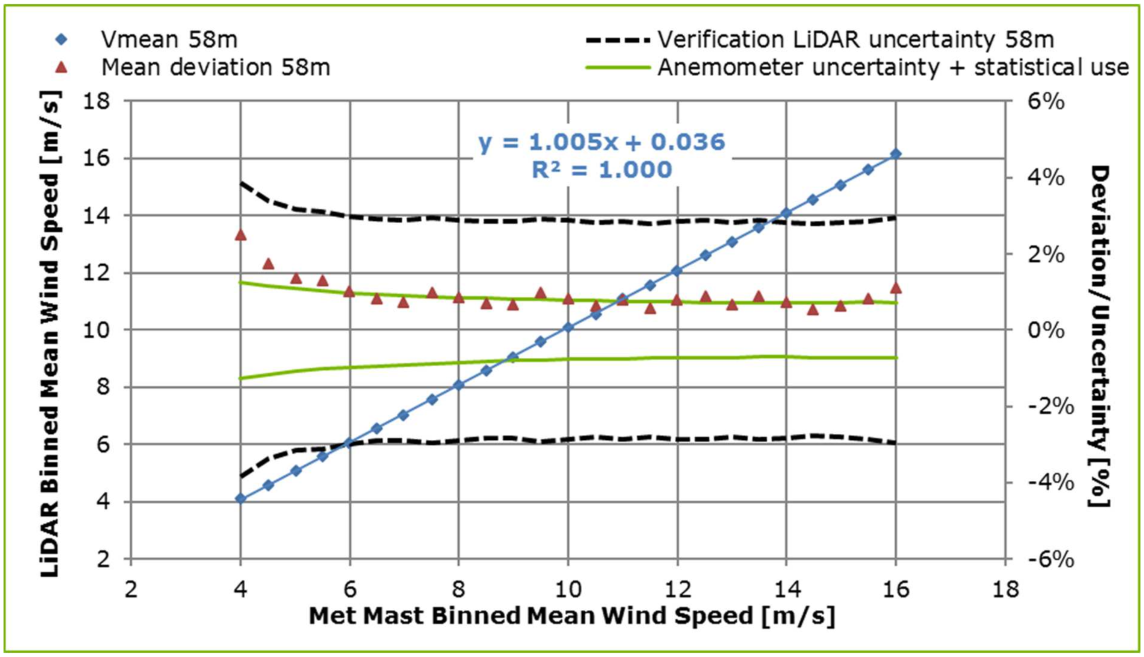


Figure 13: Uncertainty analysis of SWLB wind speed measurements at 58 m for SWLB

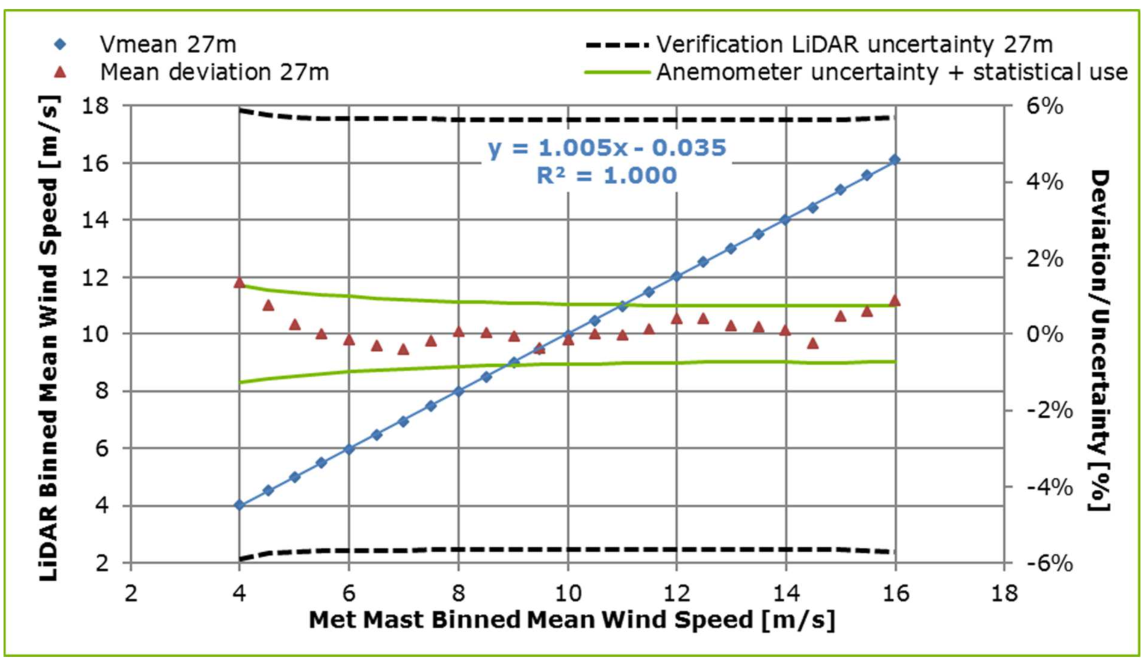


Figure 14: Uncertainty analysis of SWLB wind speed measurements at 27 m for SWLB.

4.6 Uncertainty tables

The detailed results of the uncertainty calculations, based on the IEC 61400-12-1 methods, are presented below. The uncertainty values in the tables below are based on a coverage factor of 1 which implies that the level of confidence is 68%.

Table 10: Uncertainty analysis at 92 m for SWLB

Bin	V_{cup}	V_{RSD}	Number of datasets	V_{RSD} max	V_{RSD} min	V_{RSD}-std	V_{RSD}-std/√n	Mean deviation	V_{cup} uncertainty	Mounting uncertainty	Flow uncertainty	V_{RSD} uncertainty
4	4.010	4.114	943	5.74	2.87	0.284	0.009	2.6%	1.1%	1.0%	1.6%	3.4%
4.5	4.507	4.607	999	5.80	2.87	0.267	0.008	2.2%	1.0%	1.0%	1.6%	3.1%
5	4.994	5.072	1136	6.45	2.46	0.290	0.009	1.6%	1.0%	1.0%	1.6%	2.6%
5.5	5.498	5.588	1174	6.56	2.87	0.263	0.008	1.6%	0.9%	1.0%	1.6%	2.7%
6	5.994	6.064	1242	7.44	2.99	0.321	0.009	1.2%	0.8%	1.0%	1.6%	2.4%
6.5	6.510	6.580	1231	9.67	3.16	0.317	0.009	1.1%	0.8%	1.0%	1.6%	2.3%
7	6.991	7.060	1135	8.09	4.92	0.285	0.008	1.0%	0.7%	1.0%	1.6%	2.3%
7.5	7.501	7.595	1057	11.60	6.33	0.349	0.011	1.3%	0.7%	1.0%	1.6%	2.4%
8	7.996	8.072	1045	9.84	4.34	0.345	0.011	1.0%	0.7%	1.0%	1.6%	2.2%
8.5	8.500	8.584	1014	10.55	7.21	0.338	0.011	1.0%	0.7%	1.0%	1.6%	2.3%
9	8.987	9.086	1021	12.07	7.15	0.357	0.011	1.1%	0.6%	1.0%	1.6%	2.3%
9.5	9.495	9.565	969	12.19	4.51	0.418	0.013	0.7%	0.6%	1.0%	1.6%	2.1%
10	9.997	10.094	975	11.72	7.44	0.363	0.012	1.0%	0.6%	1.0%	1.6%	2.2%
10.5	10.504	10.608	855	13.30	7.44	0.435	0.015	1.0%	0.6%	1.0%	1.6%	2.2%
11	10.999	11.117	864	14.59	8.56	0.402	0.014	1.1%	0.6%	1.0%	1.6%	2.3%
11.5	11.498	11.560	917	13.48	10.25	0.390	0.013	0.5%	0.5%	1.0%	1.6%	2.1%
12	11.994	12.069	835	13.89	10.66	0.366	0.013	0.6%	0.5%	1.0%	1.6%	2.1%
12.5	12.493	12.572	734	16.64	9.84	0.431	0.016	0.6%	0.5%	1.0%	1.6%	2.1%
13	12.995	13.034	763	14.65	9.96	0.414	0.015	0.3%	0.5%	1.0%	1.6%	2.0%
13.5	13.490	13.574	598	15.06	12.48	0.432	0.018	0.6%	0.5%	1.0%	1.6%	2.1%
14	13.993	14.084	560	16.00	12.89	0.469	0.020	0.7%	0.5%	1.0%	1.6%	2.1%
14.5	14.496	14.550	428	17.23	13.24	0.491	0.024	0.4%	0.5%	1.0%	1.6%	2.0%
15	14.990	15.043	328	16.70	12.48	0.486	0.027	0.4%	0.5%	1.0%	1.6%	2.0%
15.5	15.476	15.541	249	17.64	14.18	0.549	0.035	0.4%	0.5%	1.0%	1.6%	2.0%
16	15.993	16.044	191	17.34	12.656	0.548	0.040	0.3%	0.5%	1.0%	1.6%	2.0%

Table 11: Uncertainty analysis at 58 m for SWLB

Bin	V_{cup}	V_{RSD}	Number of datasets	V_{RSD} max	V_{RSD} min	V_{RSD}-std	V_{RSD}-std/√n	Mean deviation	V_{cup} uncertainty	Mounting uncertainty	Flow uncertainty	V_{RSD} uncertainty
4	4.008	4.108	993	5.27	3.22	0.253	0.008	2.5%	1.3%	1.0%	2.6%	4.0%
4.5	4.502	4.581	1058	5.45	3.28	0.252	0.008	1.7%	1.2%	1.0%	2.6%	3.5%
5	5.007	5.075	1180	6.15	4.10	0.251	0.007	1.4%	1.1%	1.0%	2.6%	3.3%
5.5	5.503	5.575	1232	6.62	3.63	0.261	0.007	1.3%	1.1%	1.0%	2.6%	3.2%
6	5.991	6.051	1297	8.38	4.92	0.274	0.008	1.0%	1.0%	1.0%	2.6%	3.1%
6.5	6.498	6.551	1309	7.73	4.57	0.287	0.008	0.8%	1.0%	1.0%	2.6%	3.1%
7	6.983	7.036	1148	11.37	4.69	0.329	0.010	0.7%	1.0%	1.0%	2.6%	3.0%
7.5	7.500	7.575	1137	10.02	6.56	0.320	0.009	1.0%	0.9%	1.0%	2.6%	3.1%
8	7.993	8.061	1097	10.37	6.21	0.342	0.010	0.8%	0.9%	1.0%	2.6%	3.0%
8.5	8.498	8.558	1145	9.90	7.15	0.332	0.010	0.7%	0.9%	1.0%	2.6%	3.0%
9	8.989	9.050	1125	11.84	7.62	0.336	0.010	0.7%	0.9%	1.0%	2.6%	3.0%
9.5	9.496	9.591	1110	11.66	8.44	0.372	0.011	1.0%	0.9%	1.0%	2.6%	3.1%
10	10.000	10.082	1006	12.72	8.67	0.380	0.012	0.8%	0.8%	1.0%	2.6%	3.0%
10.5	10.496	10.565	1023	12.25	9.08	0.357	0.011	0.7%	0.8%	1.0%	2.6%	3.0%
11	10.997	11.085	950	14.36	9.96	0.396	0.013	0.8%	0.8%	1.0%	2.6%	3.0%
11.5	11.496	11.563	853	13.24	10.14	0.401	0.014	0.6%	0.8%	1.0%	2.6%	2.9%
12	11.986	12.083	705	14.82	10.84	0.422	0.016	0.8%	0.8%	1.0%	2.6%	3.0%
12.5	12.506	12.617	654	14.59	9.79	0.445	0.017	0.9%	0.8%	1.0%	2.6%	3.0%
13	12.994	13.080	572	15.00	11.78	0.448	0.019	0.7%	0.8%	1.0%	2.6%	3.0%
13.5	13.487	13.609	525	15.06	12.42	0.435	0.019	0.9%	0.8%	1.0%	2.6%	3.0%
14	13.990	14.090	382	15.88	12.54	0.466	0.024	0.7%	0.8%	1.0%	2.6%	3.0%
14.5	14.481	14.561	275	16.41	12.36	0.535	0.032	0.6%	0.8%	1.0%	2.6%	2.9%
15	14.975	15.072	221	17.05	13.42	0.539	0.036	0.6%	0.8%	1.0%	2.6%	3.0%
15.5	15.491	15.620	181	17.58	12.31	0.618	0.046	0.8%	0.8%	1.0%	2.6%	3.0%
16	15.985	16.165	144	17.52	14.766	0.512	0.043	1.1%	0.7%	1.0%	2.6%	3.1%

Table 12: Uncertainty analysis at 27 m for SWLB

Bin	V_{cup}	V_{RSD}	Number of datasets	V_{RSD} max	V_{RSD} min	V_{RSD}-std	V_{RSD}-std/√n	Mean deviation	V_{cup} uncertainty	Mounting uncertainty	Flow uncertainty	V_{RSD} uncertainty
4	3.998	4.053	1209	6.15	3.11	0.273	0.008	1.4%	1.3%	1.0%	5.6%	6.0%
4.5	4.511	4.545	1192	5.74	3.28	0.268	0.008	0.8%	1.2%	1.0%	5.6%	5.8%
5	5.005	5.018	1306	6.04	4.22	0.272	0.008	0.3%	1.1%	1.0%	5.6%	5.8%
5.5	5.500	5.501	1404	8.56	4.28	0.315	0.008	0.0%	1.1%	1.0%	5.6%	5.7%
6	5.992	5.984	1340	7.56	4.75	0.323	0.009	-0.1%	1.0%	1.0%	5.6%	5.7%
6.5	6.495	6.475	1416	8.32	5.10	0.314	0.008	-0.3%	1.0%	1.0%	5.6%	5.7%
7	6.990	6.961	1349	10.61	5.33	0.382	0.010	-0.4%	1.0%	1.0%	5.6%	5.7%
7.5	7.493	7.480	1257	8.85	6.15	0.364	0.010	-0.2%	0.9%	1.0%	5.6%	5.7%
8	7.996	8.001	1228	10.14	6.74	0.370	0.011	0.1%	0.9%	1.0%	5.6%	5.7%
8.5	8.503	8.505	1173	11.37	6.68	0.383	0.011	0.0%	0.9%	1.0%	5.6%	5.7%
9	9.008	9.004	1212	11.02	7.44	0.404	0.012	0.0%	0.9%	1.0%	5.6%	5.7%
9.5	9.489	9.453	1183	11.48	7.97	0.435	0.013	-0.4%	0.9%	1.0%	5.6%	5.7%
10	10.001	9.987	961	12.25	8.56	0.446	0.014	-0.1%	0.8%	1.0%	5.6%	5.7%
10.5	10.496	10.498	799	14.24	8.97	0.480	0.017	0.0%	0.8%	1.0%	5.6%	5.7%
11	10.998	10.997	691	14.41	9.14	0.523	0.020	0.0%	0.8%	1.0%	5.6%	5.7%
11.5	11.490	11.506	657	12.95	10.08	0.492	0.019	0.1%	0.8%	1.0%	5.6%	5.7%
12	12.002	12.052	594	14.00	9.49	0.511	0.021	0.4%	0.8%	1.0%	5.6%	5.7%
12.5	12.488	12.539	501	14.06	10.61	0.524	0.023	0.4%	0.8%	1.0%	5.6%	5.7%
13	12.981	13.010	448	14.77	11.43	0.571	0.027	0.2%	0.8%	1.0%	5.6%	5.7%
13.5	13.501	13.529	339	14.88	11.95	0.533	0.029	0.2%	0.8%	1.0%	5.6%	5.7%
14	13.986	14.000	265	15.65	12.31	0.571	0.035	0.1%	0.8%	1.0%	5.6%	5.7%
14.5	14.491	14.456	189	16.35	12.25	0.624	0.045	-0.2%	0.8%	1.0%	5.6%	5.7%
15	14.987	15.058	175	16.64	11.95	0.655	0.049	0.5%	0.8%	1.0%	5.6%	5.7%
15.5	15.487	15.584	154	17.46	14.12	0.597	0.048	0.6%	0.8%	1.0%	5.6%	5.7%
16	15.995	16.141	170	19.10	14.59	0.665	0.051	0.9%	0.7%	1.0%	5.6%	5.8%

4.7 Application of Uncertainty On-Site (example)

The calculated verification uncertainty (shown in the above sections) can be used directly in wind resource assessments with this device, together with the classification uncertainty and site-specific uncertainty components. An example at a measurement height of 92 m is presented in Table 13, for a campaign at a similar site to the Meteomast IJmuiden site. The classification uncertainty is based on an assumed final class of 4, although no classification tests results have yet been published for ZephIR 300S or SWLB, so this value may change as more information is made available.

Table 13: Example of total uncertainty analysis for future campaign at 92 m for SWLB

Wind speed bin [m/s]	Verification uncertainty [%]	Classification uncertainty (assumed) [%]	Non-homogenous flow uncertainty (assumed) [%]	Mounting uncertainty (assumed) [%]	Total measurement uncertainty [%]
4	3.4%	2.3%	0.0%	0.5%	4.2%
4.5	3.1%	2.3%	0.0%	0.5%	3.9%
5	2.7%	2.3%	0.0%	0.5%	3.6%
5.5	2.7%	2.3%	0.0%	0.5%	3.6%
6	2.4%	2.3%	0.0%	0.5%	3.4%
6.5	2.4%	2.3%	0.0%	0.5%	3.3%
7	2.3%	2.3%	0.0%	0.5%	3.3%
7.5	2.4%	2.3%	0.0%	0.5%	3.4%
8	2.3%	2.3%	0.0%	0.5%	3.3%
8.5	2.3%	2.3%	0.0%	0.5%	3.3%
9	2.3%	2.3%	0.0%	0.5%	3.3%
9.5	2.2%	2.3%	0.0%	0.5%	3.2%
10	2.2%	2.3%	0.0%	0.5%	3.3%
10.5	2.3%	2.3%	0.0%	0.5%	3.3%
11	2.3%	2.3%	0.0%	0.5%	3.3%
11.5	2.1%	2.3%	0.0%	0.5%	3.2%
12	2.1%	2.3%	0.0%	0.5%	3.2%
12.5	2.1%	2.3%	0.0%	0.5%	3.2%
13	2.0%	2.3%	0.0%	0.5%	3.1%
13.5	2.1%	2.3%	0.0%	0.5%	3.2%
14	2.1%	2.3%	0.0%	0.5%	3.2%
14.5	2.0%	2.3%	0.0%	0.5%	3.1%
15	2.0%	2.3%	0.0%	0.5%	3.1%
15.5	2.0%	2.3%	0.0%	0.5%	3.1%
16	2.0%	2.3%	0.0%	0.5%	3.1%

The total LiDAR wind speed uncertainty decreases slightly at higher wind speeds. In order to estimate the overall measurement uncertainty for a full measurement campaign, the bin-wise uncertainty is weighted according to various Rayleigh wind speed distributions, as shown in Table 14. For a mean wind speed between 7-10 m/s at 92 m, the weighted total measurement uncertainty is 3.3-3.4%.

Table 14: Example of weighted total uncertainty analysis for future campaign at 92 m for SWLB for different Rayleigh wind speed distributions

Example site mean wind speed [m/s]	Rayleigh scale factor (equivalent to Weibull scale factor with a shape factor of 2) [m/s]	Weighted total measurement uncertainty [%]
7	7.9	**3.4%**
8	9.0	**3.4%**
9	10.2	**3.3%**
10	11.3	**3.3%**

5 Conclusions

At the request of RVO, Ecofys WTTS carried out an uncertainty calculation for the SEAWATCH Wind LiDAR Buoy (SWLB, with ZephIR ID Z417) based on a campaign next to the RWE Meteomast IJmuiden located in the Dutch territory of North Sea. RVO has since deployed the SWLB at the Borssele offshore wind farm development zone, and will deploy again at the Hollandse Kust (zuid) zone. A goal of this analysis is to validate the preliminary estimate of 3% uncertainty in wind speed measurements.

The RWE Meteomast IJmuiden is fully IEC compliant and equipped with Thies First Class Advanced cup anemometers mounted at heights of 27 m, 58.5 m, 92 m LAT and with Metek USA-1 sonic anemometers at 85 m. In addition, Thies First Class wind vanes for wind direction measurements are located at 26 m, 58 m and 87 m. The SWLB was collecting wind data at three common heights with the Meteomast IJmuiden cup anemometers. The SWLB verification campaign lasted from 11.04.2014 to 27.10.2014.

All measured data was filtered to ensure entirely valid datasets. The uncertainty analysis is based on the IEC standard 61400-12-1 (ed. 2, draft [2]). For all measurements heights, all 0.5 m/s wind speed bins had sufficient data, the overall data availability is considered very good for the analysis.

Linear regression between the SWLB and Meteomast IJmuiden wind speed recordings showed consistent, highly-correlated measurements with slopes near unity.

The correlation between SWLB and Meteomast IJmuiden binned wind directions is excellent, with an R^2 of greater than 0.98 for all heights, scatter of about ±8° (one standard deviation) and an offset of 6-8° (within the measurement uncertainty). It is important to note that this comparison uses the post-processed LiDAR wind direction, corrected using the buoy’s Xsens compass (data post-processing by Fugro OCEANOR AS); Fugro OCEANOR AS now applies this correction for all measurement campaigns.

Sensitivity tests of the wind speed deviation revealed that the wind speed deviation shows no significant linear correlation to the following external conditions: horizontal wind speed, turbulence intensity, rain, significant wave height, maximum wave height and current speed. However, the regression slope with turbulence intensity is relatively large, indicating it is potentially a significant environmental condition; this could be confirmed by a classification analysis of the SWLB.

The calculated uncertainty in the SWLB wind speed measurements is relatively low, in line with high quality anemometry for the majority of the wind speed bins. The calculated uncertainty tables (presented in Section 4.6) can be used directly in wind resource assessments, together with the classification uncertainty and site-specific uncertainty components. An example of the calculation for a future wind measurement campaign results in a weighted total measurement uncertainty of 3.3-3.4%, for campaigns with a mean wind speed between 7-10 m/s at 92 m. The uncertainty tables apply specifically to the tested device (SWLB, with ZephIR ID Z417) although the results should be representative for other Fugro OCEANOR AS SWLB devices, provided the IEA recommended practices are followed for the campaign design [8].

References

[1] IEC 61400-12-1 (ed 1.0), ‘Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines’, 2005

[2] IEC, IEC 61400-12-1 Ed. 2 (642/DCV) ‘Committee Draft - Power performance measurements of electricity producing wind turbines’, 2013

[3] Deutsche WindGuard, 2008, ‘Summary of cup-anemometer classification according to IEC 61400-12-1 (2005-12) Classification scheme’, AK081662.01S

[4] ECN, Offshore meteorological mast IJmuiden abstract of instrumentation report, ECN-Wind-Memo-12-010, February 2012

[5] OWA, ‘Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LiDAR technology’, CTC819, Version 1.0, 21 November 2013

[6] GLGH-4257 13 10378-R-0003, Rev. B: Assessment of the Fugro/Oceanor Seawatch Floating Lidar Verification at RWE Ijmuiden Met Mast, 30 January 2015

[7] Wagenaar JW, Wouters DAJ and Verhoef JP: Ring analysis floating LiDAR, static LiDAR and offshore meteorological mast. ECN-M--15-047, 15 December 2015

[8] IEA Wind Annex 32 'Work Package 1.5 - State-of-the-Art Report: Recommended Practices for Floating Lidar Systems’, Issue 1.0, 2 February 2016

Appendix A Anemometer Calibration Certificates

Top cup-anemometer at 92 m, sensor # 6042 (Orientation 180 degree)

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15780
D-K-
15140-01-00
09/2012

Kalibrierergebnis:
Result:

File:	15780	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
84.822	4.125	0.05
127.350	6.079	0.05
167.537	7.932	0.05
207.793	9.771	0.05
250.228	11.725	0.05
292.625	13.682	0.05
335.795	15.646	0.05
312.677	14.610	0.05
271.977	12.725	0.05
229.097	10.738	0.05
186.871	8.832	0.05
145.507	6.922	0.05
107.758	5.177	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europas sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

The DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

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Wind Tunnel Services GmbH, Varel

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Annex

15780

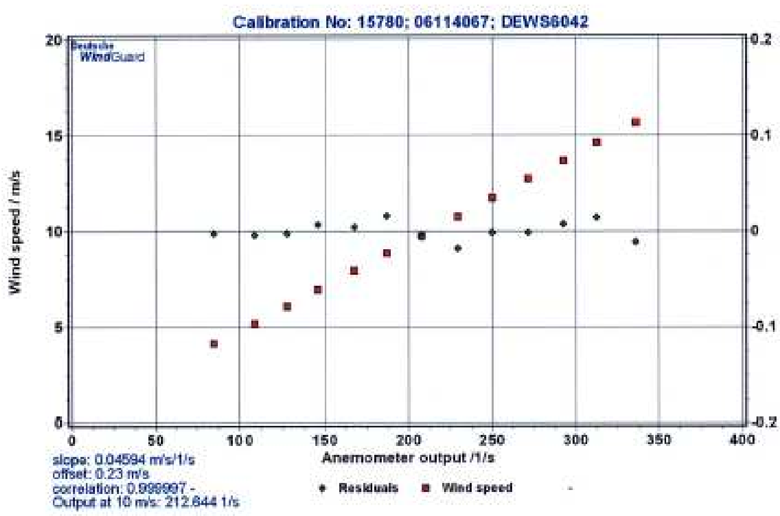
1 Detailed Calibration Results

DKD calibration no.	15780
Serial no. 1	06114067
Serial no. 2	DEWS6042
Date	12.09.2012
Air temperature	21.7 °C
Air pressure	1010.8 hPa
Humidity	50.4 %

Linear regression analysis

Slope	0.04594 (m/s)/(1/s) ±0.00004 (m/s)/(1/s)
Offset	0.2301 m/s ±0.008 m/s
St.err(Y)	0.008 m/s
Correlation coefficient	0.999997

Remarks no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Deutsche WindGuard

Top cup-anemometer at 92 m, sensor # 6043 (Orientation 300 degree)

15783
D-K-15140-01-00
09/2012

Kalibrierergebnis:
Result:

File:	15783	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
85.203	4.118	0.05
127.518	6.079	0.05
167.817	7.932	0.05
208.245	9.760	0.05
250.946	11.723	0.05
292.870	13.685	0.05
335.318	15.640	0.05
312.608	14.600	0.05
271.767	12.707	0.05
228.573	10.727	0.05
186.504	8.805	0.05
145.174	6.918	0.05
106.492	5.132	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

The DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

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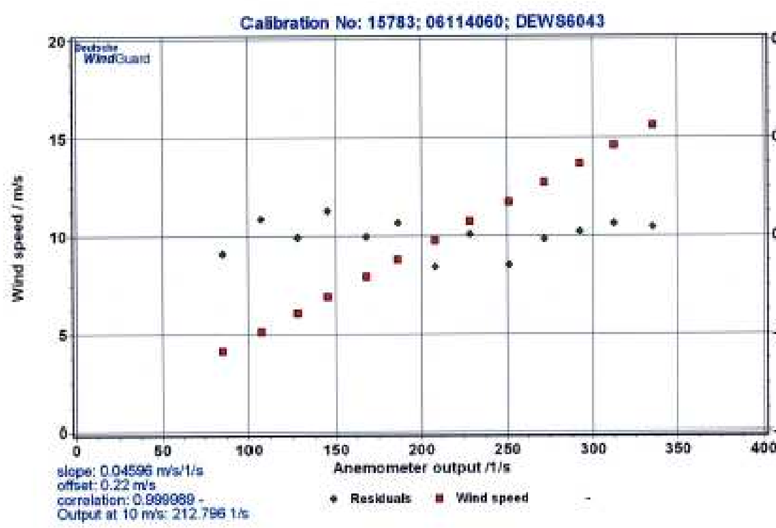
Annex

15783

1 Detailed Calibration Results

DKD calibration no.	15783
Serial no. 1	06114060
Serial no. 2	DEWS6043
Date	12.09.2012
Air temperature	22.1 °C
Air pressure	1010.3 hPa
Humidity	51.1 %
Linear regression analysis	
Slope	0.04596 (m/s)/(1/s) ±0.00006 (m/s)/(1/s)
Offset	0.2201 m/s ±0.014 m/s
St.err(Y)	0.015 m/s
Correlation coefficient	0.999989
Remarks	no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Cup-anemometer at 58.5 m, sensor # 6045 (Orientation 0 degree)

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15785
D-K-15140-01-00
09/2012

Kalibrierergebnis:
Result:

File:	15785	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
84.756	4.117	0.05
126.648	6.053	0.05
167.826	7.934	0.05
207.748	9.763	0.05
250.957	11.708	0.05
293.742	13.684	0.05
335.759	15.638	0.05
314.493	14.599	0.05
272.898	12.709	0.05
228.973	10.739	0.05
187.119	8.806	0.05
145.307	6.918	0.05
106.751	5.138	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

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Deutsche WindGuard

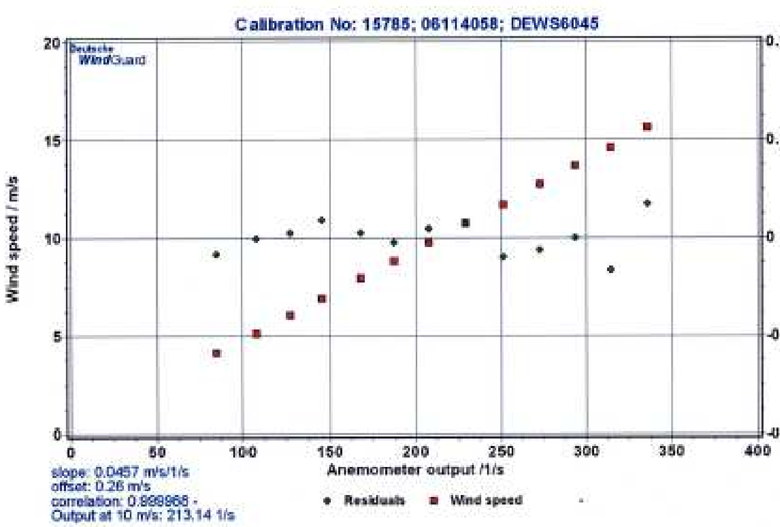
1 Detailed Calibration Results

DKD calibration no.	15785
Serial no. 1	06114058
Serial no. 2	DEWS6045
Date	12.09.2012
Air temperature	22.4 °C
Air pressure	1010.6 hPa
Humidity	50.2 %

Linear regression analysis

Slope	0.04570 (m/s)/(1/s) ±0.00007 (m/s)/(1/s)
Offset	0.2599 m/s ±0.015 m/s
St.err(Y)	0.015 m/s
Correlation coefficient	0.999988

Remarks no



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Cup-anemometer at 58.5 m, sensor # 6046 (Orientation 120 degree)

15786
D-K-15140-01-00
09/2012

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Page

Kalibrierergebnis:
Result:

File:	15786	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
85.094	4.122	0.05
126.548	6.047	0.05
167.634	7.931	0.05
207.183	9.751	0.05
250.106	11.717	0.05
293.369	13.680	0.05
336.017	15.640	0.05
313.611	14.604	0.05
271.745	12.705	0.05
228.363	10.725	0.05
187.144	8.828	0.05
145.813	6.916	0.05
107.160	5.154	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

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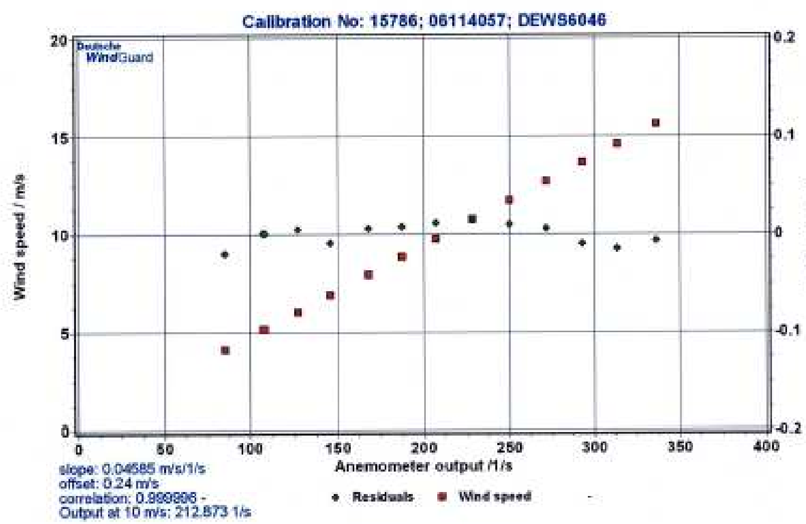
1 Detailed Calibration Results

DKD calibration no.	15786
Serial no. 1	06114057
Serial no. 2	DEWS6046
Date	12.09.2012
Air temperature	22.6 °C
Air pressure	1010.8 hPa
Humidity	50.4 %

Linear regression analysis

Slope	0.04585 (m/s)/(1/s) ±0.00004 (m/s)/(1/s)
Offset	0.2400 m/s ±0.009 m/s
St.err(Y)	0.009 m/s
Correlation coefficient	0.999996
Remarks	no



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Cup-anemometer at 58.5 m, sensor # 6047 (Orientation 240 degree)

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Kalibrierergebnis:
Result:

File:	15782	
Test item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
84.453	4.124	0.05
126.714	6.052	0.05
167.923	7.935	0.05
207.586	9.764	0.05
249.759	11.727	0.05
293.205	13.684	0.05
336.403	15.644	0.05
313.623	14.596	0.05
271.112	12.706	0.05
228.333	10.731	0.05
186.802	8.828	0.05
145.748	6.923	0.05
106.738	5.139	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

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Anhang
Annex

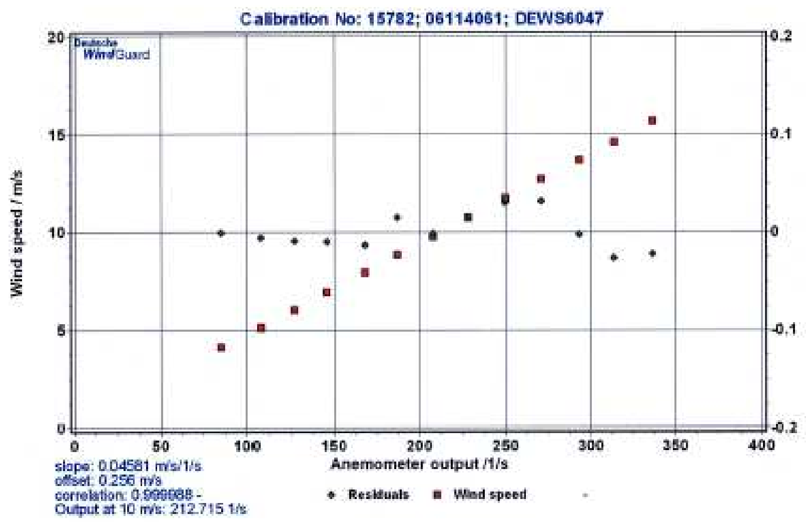
15782

1 Detailed Calibration Results

DKD calibration no.	15782
Serial no. 1	06114061
Serial no. 2	DEWS6047
Date	12.09.2012
Air temperature	22.0 °C
Air pressure	1010.7 hPa
Humidity	50.7 %

Linear regression analysis

Slope	0.04581 (m/s)/(1/s) ±0.00007 (m/s)/(1/s)
Offset	0.2562 m/s ±0.015 m/s
St.err(Y)	0.015 m/s
Correlation coefficient	0.999988
Remarks	no



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Cup-anemometer at 27 m, sensor # 6106 (Orientation 0 degree)

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12852
D-K-15140-01-00
04/2012

Kalibrierergebnis:
Result:

File:	12852	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
84.303	4.106	0.05
126.597	6.074	0.05
167.591	7.935	0.05
208.158	9.769	0.05
250.066	11.716	0.05
292.371	13.683	0.05
335.625	15.639	0.05
312.703	14.610	0.05
271.650	12.705	0.05
228.092	10.733	0.05
186.732	8.826	0.05
145.040	6.910	0.05
107.072	5.152	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

The DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

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12852

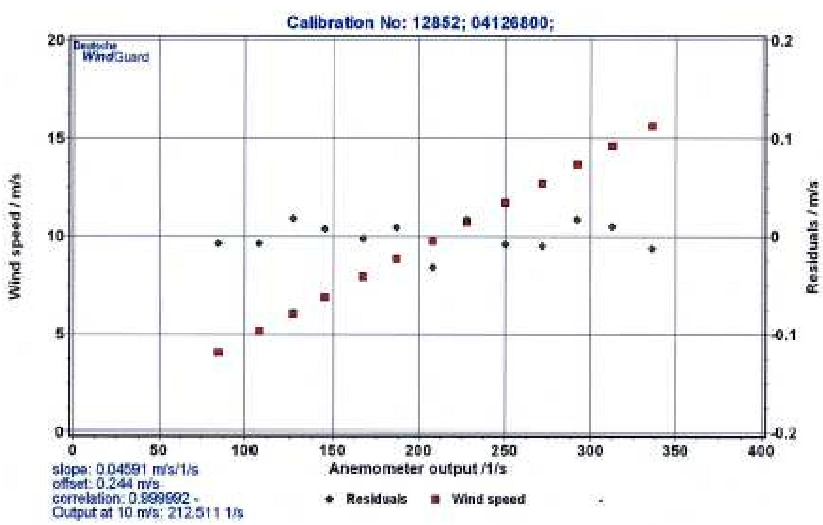
1 Detailed Calibration Results

DKD calibration no.	12852
Body no.	04126800
Cup no.	
Date	25.04.2012
Air temperature	22.6 °C
Air pressure	998.3 hPa
Humidity	37.8 %

Linear regression analysis

Slope	0.04591 (m/s)/(1/s) ±0.00005 (m/s)/(1/s)
Offset	0.2440 m/s ±0.012 m/s
St.err(Y)	0.012 m/s
Correlation coefficient	0.999992

Remarks no



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Cup-anemometer at 27 m, sensor # 6107 (Orientation 120 degree)

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Page

12853
D-K-15140-01-00
04/2012

Kalibrierergebnis:
Result:

File:	12853	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
84.038	4.113	0.05
126.766	6.078	0.05
167.434	7.933	0.05
207.655	9.769	0.05
250.443	11.725	0.05
292.469	13.687	0.05
334.878	15.645	0.05
314.176	14.606	0.05
271.843	12.713	0.05
229.063	10.741	0.05
186.465	8.826	0.05
145.113	6.910	0.05
106.916	5.157	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

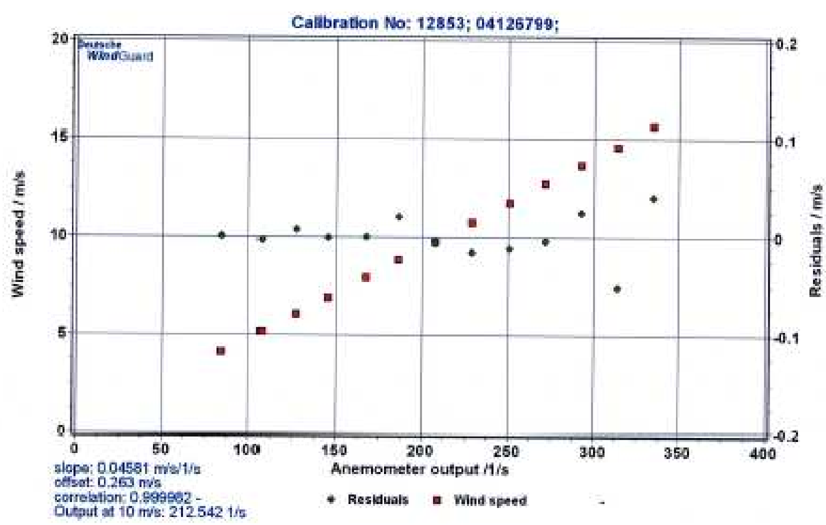
Deutsche WindGuard

1 Detailed Calibration Results

DKD calibration no.	12853
Body no.	04126799
Cup no.	
Date	25.04.2012
Air temperature	22.5 °C
Air pressure	998.0 hPa
Humidity	38.1 %

Linear regression analysis

Slope	0.04581 (m/s)/(1/s) ±0.00008 (m/s)/(1/s)
Offset	0.2626 m/s ±0.018 m/s
St.err(Y)	0.018 m/s
Correlation coefficient	0.999982
Remarks	no



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Cup-anemometer at 27 m, sensor # 6108 (Orientation 240 degree)

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12848
D-K-15140-01-00
04/2012

Kalibrierergebnis:
Result:

File:	12848	
Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
84.698	4.117	0.05
127.092	6.084	0.05
167.841	7.942	0.05
207.881	9.769	0.05
250.555	11.721	0.05
293.194	13.684	0.05
335.780	15.642	0.05
312.470	14.599	0.05
272.222	12.714	0.05
228.240	10.736	0.05
187.007	8.831	0.05
144.776	6.919	0.05
106.821	5.163	0.05

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Anhang
Annex

12848

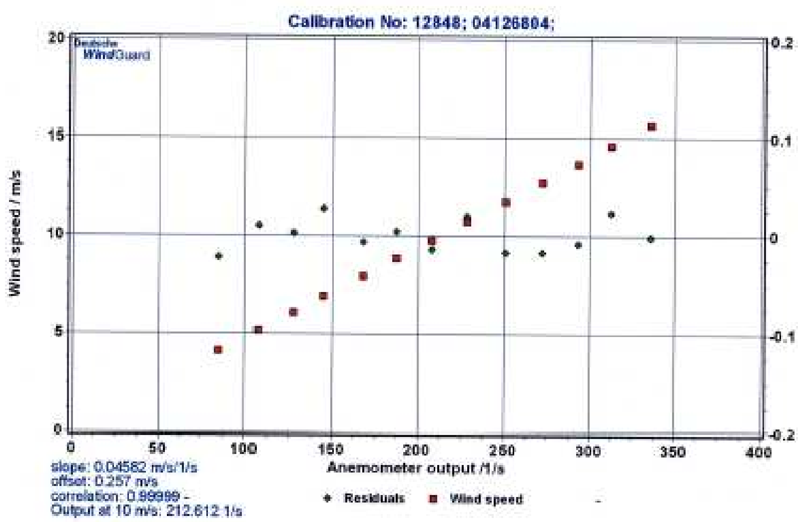
1 Detailed Calibration Results

DKD calibration no.	12848
Body no.	04126804
Cup no.	
Date	25.04.2012
Air temperature	22.2 °C
Air pressure	999.1 hPa
Humidity	38.2 %

Linear regression analysis

Slope	0.04582 (m/s)/(1/s) ±0.00006 (m/s)/(1/s)
Offset	0.2575 m/s ±0.014 m/s
St.err(Y)	0.014 m/s
Correlation coefficient	0.999990

Remarks	no



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Appendix B Procedure for Filtering, Statistical Tests and Uncertainty Calculation

The filtering is carried out in Windographer using flag rules to disable data.

Meteomast IJmuiden Data Filtering

The Meteomast IJmuiden dataset is filtered according to the following protocols:

System non-availability

This category covers power outages, maintenance and other external issues. During these periods, no data is recorded, so data does not need to be flagged or disabled. This category is defined to explain any missing data due to external issues.

Wind direction recordings

There is no wind direction measurement at 92 m, therefore wind vane of 87 m is linked with wind speed measurements of 92 m. The wind vane of 58 m is linked to wind speed of 58.5 m and wind vane of 26 m is linked to wind speed of 27 m.

Excluded wind sectors

All excluded sectors are filtered out, according to the valid sectors identified in Section 2.4. This category combines mast shadowing of mast instrumentation and disturbed sectors. All wind data is disabled if either wind vane is within an excluded sector, and flagged as 'Excluded sectors.'

LiDAR Data Filtering

Ecofys WTTS received processed wind data time series of wind speed and wind direction from Fugro.

System non-availability

This category covers power outages, maintenance and other external issues. During these periods, no data is recorded, so data does not need to be flagged or disabled. This category is defined to explain any missing data due to external issues.

Low signal to noise conditions

The LiDAR will not sample the wind accurately when the signal is weak compared to background noise, which could be due to atmospheric conditions (e.g. fog) and flow distortions (e.g. wakes). For the provided SWLB data, the data logger on the buoy only calculate the average values, if there are more than 50% valid measurements during measurement interval. The LiDAR flags these measurements as invalid by using codes 9999 or 9998.These data points are filtered out during post-processing.

Data processing issues

Data is disabled in the event the data processing software fails to remove erroneous data. The SWLB wind direction measurements are compared with Meteomast IJmuiden wind direction recordings (before filtering) and evident deviations in wind direction recordings are flagged and disabled. In the case of flagged data, wind data is disabled at all heights.

Wind direction processing

It was confirmed from Fugro that the provided wind direction data has been post-processed to account for the buoy orientation and the 180° wind direction ambiguity of ZephIR 300S.

Statistical Tests

A number of statistical methods are applied to the filtered datasets, based on the requirements of IEC 61400-12-1 [2]. All data analyses techniques are performed in Excel.

Scatter plot

The measurements of the LiDAR are plotted against the measurements of the reference anemometer, also showing the deviations between the LiDAR and reference anemometer. The wind speed deviation is defined as the deviation between LiDAR and Meteomast IJmuiden mean wind speeds at the same height. The mean deviation and standard deviation of deviations is also calculated.

Bin averaged analysis

A bin averaging procedure is used to compare the LiDAR measurements and the reference anemometers, using wind speed bins of 0.5 m/s between 4-16 m/s. The bin-wise deviation between the LiDAR and reference measurements is the key result. Each wind speed bin should contain at least 3 valid pairs of data to ensure a representative SWLB verification [2].

Linear regression analysis is applied in order to evaluate the relationship in terms of horizontal mean wind speed and mean wind direction with zero and non-zero constants at each height. Also the coefficient of determination (R^2) of the linear regression is given. Below the formula are given for each parameter that is analysed.

Two-parameter linear regression

The two-parameter Ordinary Least Squares regression equation is:

$$y = C + kx$$

Coefficient of determination

The coefficient of determination (R^2) of the linear regression is calculated as:

$$R^2 \equiv 1 - \frac{SS_{err}}{SS_{tot}}$$

$$SS_{err} = \sum_i (y_i - f_i)^2$$

$$SS_{tot} = \sum_i (y_i - \bar{y})^2$$

where f_i is the modelled value and $\bar{y}$ is the mean of the observed data.

Wind speed deviation

The mean and standard deviation of the wind speed deviation is also calculated for each wind speed bin of 0.5 m/s.

Wind direction

A two-parameter Ordinary Least Squares linear regression is used, in order to identify any offset from zero.

Sensitivity tests

Several sensitivity tests are run to find any possible relationship with external conditions, including Meteomast IJmuiden mean wind speed, turbulence intensity and precipitation.

Reference Uncertainty

The uncertainty calculations are based on IEC 61400-12-1 (ed 2) which is still in draft [2]. If information is absent in the draft, formulas and definitions were taken from the first edition [1]. The following uncertainty components are considered for the evaluation of the Meteomast IJmuiden anemometer uncertainty.

Wind tunnel calibration

The uncertainty in wind tunnel calibration is defined as the root sum square of standard error in linear fit in the calibration certificates of the Meteomast IJmuiden and the wind tunnel accuracy.

Cup anemometer effects according to the anemometer classification

This uncertainty relates to the sensitivity of the cup anemometer to ranges of environmental parameters per terrain class. Valid ranges of environmental variables are defined for Class A and B in Annex I of [1], as shown in Table 15. Meteomast IJmuiden meets all of the criteria of a Class A site, unless temperatures drop below 0 or turbulence intensity is incidentally exceeding the Class A thresholds.

Table 15: Influence parameter ranges (based on 10 min average) of Classes A and B [1]

	Class A Terrain meets requirements in Annex B		Class B Terrain does not meets requirements in Annex B	
	Min	Max	Min	Max
Wind speed range to cover [m/s]	4	16	4	16
Turbulence intensity	0.03	0.12 + 0.48/V	0.03	0.12 + 0.96/V
Turbulence structure σ_u / σ_v / σ_w	1/0.8/0.5 (non -isotropic turbulence)		1/1/1 (isotropic turbulence)	
Air temperature (°C)	0	40	-10	40
Air density (kg/m^3)	0.9	1.35	0.9	1.35
Average flow inclination angle (°)	-3	3	-15	15

The sensitivity of several cup anemometer models was calculated in the Deutsche Windguard study [3]. For a Thies First Class cup anemometer (as used at Meteomast IJmuiden), in Class A conditions, the class number *k* equals to 0.9, and in Class B conditions (such as periods with temperatures below zero), *k* is 3.0. This class number *k* is inserted into the following equation to derive the standard uncertainty due to cup-anemometer type and environmental conditions during the verification test:

$$u_{V2,i} = (0{,}05\, m/s + 0{,}005 \cdot U_i) \cdot k/\sqrt{3}$$

Cup anemometer mounting effects

The cup anemometers are influenced by flow distortion of the Meteomast IJmuiden's components:

For the top anemometer: lightning rod distortion ((\and interference with each other)

- For the cup anemometers below top: mast distortion and boom distortion

Mast distortion depends upon the type of mast and its solidity, the drag of the individual members, the orientation of the wind and the separation of the measurement point from the mast. Therefore, in Annex G.4 of [2], mast distortion functions are defined for different mast types. Based on Meteomast IJmuiden design drawings, RWE Meteomast IJmuiden has an approximate solidity of 0.15 and an R/L (roughly boom length over leg distance) of 5.2 which results in a C_t of 0.27. Entering these values into the equation below results in a standard uncertainty of about 0.3% of the measured 10 min wind speed at every time interval.

$$U_d = 1 - (0.062C_t^2 + 0.076C_t) \cdot \left(\frac{L}{R} - 0.082\right)$$

The flow distortions due to the booms equals 0.5% as this IEC-compliant Meteomast IJmuiden was designed such that its boom distortion is kept below 0.5%.

Lightning rod distortion can be ignored if the following conditions are met [2]:

1. The top cup-anemometer is separated horizontally at least 30 times the lightning rod diameter from the lightning rod.
2. The cup-anemometer is not in the wake of the lightning rod. As the top height has two anemometers, no wind data disturbed by the lightning rod is in the dataset anymore.

Uncertainty of any applied mast correction

This uncertainty defines any uncertainties in applied mast corrections. Since no correction factors were used for the wind speed data, this uncertainty is excluded.

Mean deviation of the LiDAR and the reference anemometry

This refers to the mean deviation of the remote sensing device measurements and the reference sensor measurements for each bin of 0.5 m/s as defined in Annex L4.2.1 of [2]. The standard uncertainty is derived from the difference between remote sensing device mean wind speed and Meteomast IJmuiden mean wind speed. To obtain a percentage, the standard uncertainty is divided by the Meteomast IJmuiden mean wind speed. Therefore, the mean deviation uncertainty tends to be higher at lower wind speeds.

Precision of the measurement of the LiDAR

The precision of the measurement of the remote sensing device is calculated as the standard deviation of the measurements for every 0.5m/s bin, divided by the square root of the number of data points per bin as defined in Annex L4.2.1 of [2].

Uncertainty in mounting effects at the verification test

This uncertainty is related to non-ideal levelling of the device and shall be estimated by Ecofys WTTS according to Annex L4.5 in [2]. This includes the uncertainty due to mounting on a moving buoy. Fugro OCEANOR AS has previously published research showing that the movement of the buoy does not significantly affect the LiDAR accuracy. This is also evident in the sensitivity analysis in Section 4.4.

Flow Uncertainty

This includes the uncertainty due to non-homogenous flow through the measurement volume. It is assumed that this uncertainty is negligible.

This also includes an uncertainty due to variation of flow conditions between the centre of the remote sensing device and the met mast. According to L4.2.1 in [2], this can be calculated as 1% times the separation distance divided by the measurement height.

Appendix C Data Filtering and Coverage

During this verification campaign, Meteomast IJmuiden was fully available for measurements. The breakdown of the data points flagged by each filtering criteria is shown in Table 16. The same data point can be flagged for different criteria. Therefore, the sum of all criteria exceeds the total number of data points possible within the measurement period. All flagged data was disabled and excluded from the verification.

The conditions specific to this verification campaign affect the count of several categories and are therefore not necessarily representative of the long-term. System non-availability for instance is affected by external power outages, while low signal to noise conditions can be because of offshore condition (waves, turbulence).

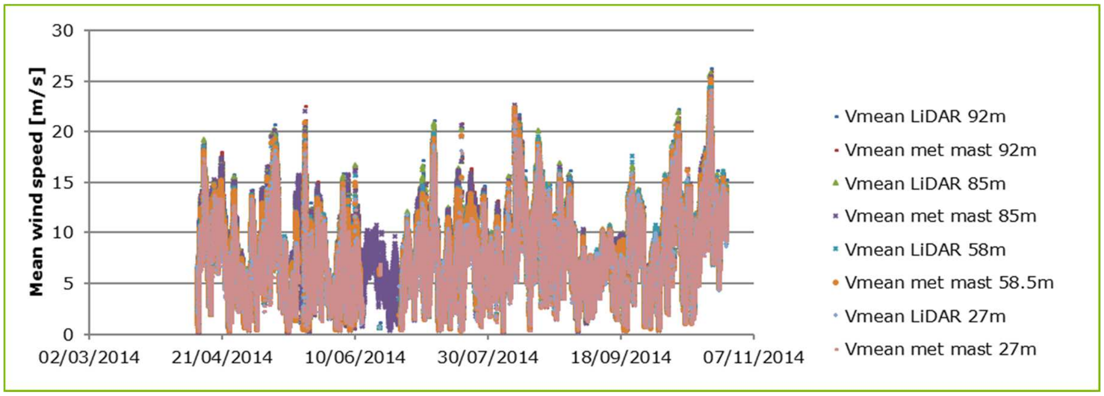
The two filtering criteria 'Data processing issues' and 'Conditions outside operational envelope' summarise characteristics intrinsic to other SWLB models. The 'Data processing issues' category encompasses all malfunctioning of data processing software during operation

Table 16: Number of data points flagged for each filtering criteria for each height

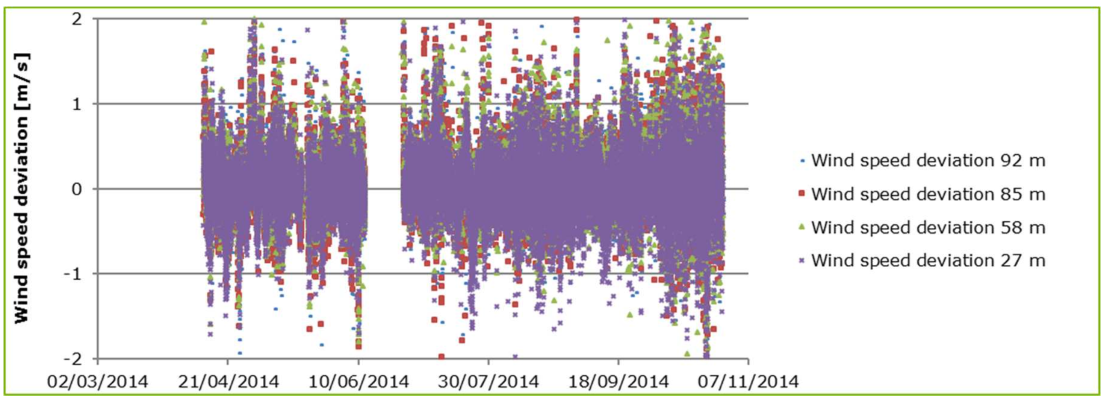
Height [m]	Wind speed		Wind direction		Low signal to noise conditions		Data processing issues (Total)		Conditions outside operational	
	SWLB	Met mast	SWLB	Met mast	SWLB	Met mast	SWLB	Met mast	SWLB	Met mast
27	174	2512	2835	3520	43	0	2877	6032	0	0
58/58.5	173	2517	2913	3502	43	0	2951	6019	0	0
85/87	368	0	2918	3547	43	0	2957	3547	0	0
92	172	2516	2066	0	43	0	2105	2516	0	0

After filtering, all wind speed bins should have at least the required amount of wind data (3 valid data points per bin). If certain bins do not meet these criteria, then from the two adjacent bins that have 3 or more data points, the overall uncertainty could be interpolated. Otherwise no uncertainty is shown for the entire wind speed bin.

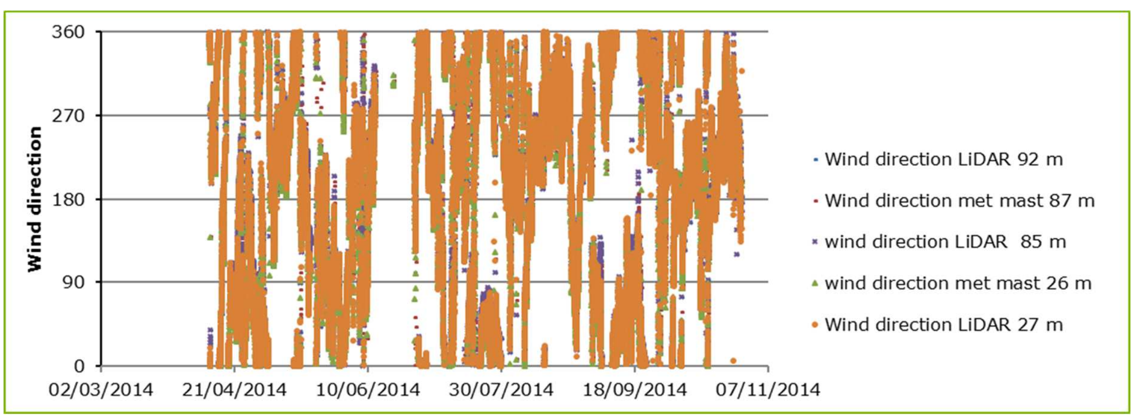
Time series of the valid data, in terms of mean wind speed, wind speed deviation and wind direction are plotted in Figure 15.



a) Time series of SWLB and Meteomast IJmuiden mean wind speed at 92, 85, 58.5, 58 and 27m.



b) Time series of wind speed deviation at 92, 85, 58.5 and 27m.



c) Time series of SWLB and Meteomast IJmuiden mean wind direction at 92, 87, 85, 27 and 26m.

Figure 15: Time series of (a) mean wind speed, (b) wind speed deviation & (c) wind direction for SWLB and Meteomast IJmuiden

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