FUGRO / OCEANOR SEAWATCH WIND LIDAR BUOY

ASSESSMENT OF THE FUGRO / OCEANOR SEAWATCH FLOATING LIDAR VERIFICATION AT RWE IJMUIDEN MET MAST

Fugro / OCEANOR AS

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List of abbreviations

Abbreviation	**Meaning**
SWL Buoy	Seawatch Wind Lidar Buoy
GH-D	GL Garrad Hassan Deutschland GmbH, part of DNV GL group
FO	Fugro/Oceanor
Met Mast	Offshore Meteorological Mast at IJmuiden site
FLD	Floating LiDAR Device
MSL	Mean Sea Level
LAT	Lowest astronomical tide
OPV	Offshore Performance Verification
ECN	Energy research Centre of the Netherlands
RWE	German Utility
KPI	Key Performance Indicator
AC	Acceptance Criterion

1 INTRODUCTION

Fugro OCEANOR AS (FO or the Client) evaluated the performance of a SEAWATCH Wind LiDAR Buoy (SWL Buoy) – a Floating LiDAR Device (FLD) employing a ZephIR 300 type of LiDAR – during an Offshore Performance Verification (OPV) campaign (or Offshore Trial) against an offshore meteorological mast (met mast) in the Dutch North Sea sector. The OPV test site is located some 80 km off the Dutch coast, where a 92 m met mast is operated by ECN on behalf of RWE – known as the IJmuiden Offshore Meteorological Mast site. The met mast served as the reference against which the SWL Buoy, anchored some 150 m from the mast, was tested during this OPV trial. The OPV was performed according to guidelines prepared by DNV GL in a previous task as documented in [1].

FO commissioned GL Garrad Hassan Deutschland GmbH ("GH-D"), part of the DNV GL group ("DNV GL") to perform the data analysis for this OPV campaign and to provide a performance verification report for a SWL Buoy unit installed at the IJmuiden Meteorological Mast against the Roadmap Towards Commercial Acceptance [2]. DNV GL has not been involved in the data collection.

The Campaign started in early January 2014 with the deployment of the SWL Buoy and was finished by the recovery of the SWL Buoy in early November 2014. However, due to a failure of the mooring array after the first few months, only data from the Offshore Trial after the re-deployment in April 2014 are considered for the formal assessment in this report.

1.1 Background

Ground-based LiDAR systems like the ZephIR 300 are frequently used for onshore wind resource assessment, although generally in simple terrain and/or in conjunction with a met mast. Proven-technology LiDARs are indeed known to provide wind speed and direction measurements of high quality and comparable to IEC-compliant met masts under benign conditions. For offshore applications, LiDARs are also being considered as an alternative to installing offshore met masts. The use of floating LiDARs is one of the latest developments in this respect and the buoy-mounted LiDAR developed by FO is one such example. It is expected that a floating system may substantially be cheaper to deploy offshore than met masts and help assess the spatial variation of the wind resource across a site through well-designed relocation scenarios.

Mounting existing (proven-technology) LiDARs on buoys introduces additional uncertainties (mainly due to the motion of the LiDAR on its buoy) in the measurement. Furthermore, reliability, maintainability and power management of the device offshore are additional challenges which need to be addressed. The uncertainties introduced by LiDAR motion lead directly to greater uncertainties in derived properties such as energy production predictions. Therefore, the accuracy of floating LiDAR systems must be demonstrated in actual offshore environments prior to the use of their measurements in formal energy assessments. Assessing the accuracy of the SWL Buoy was the primary objective of this offshore trial. Furthermore, operational experience from the trial are also deemed to be of great interest to potential users – such as offshore wind project developers – willing to understand the risks and challenges of including the SWL Buoy in their offshore wind resource assessment programme.

A general Roadmap towards Commercial Acceptance of FLD technology had originally been issued by DNV GL and the Carbon Trust [3]. The roadmap was adapted to the SWL Buoy's specificities by DNV GL [2]. The roadmap defines the following three stages of technical maturity for the FLDs:

- Baseline: As a pre-requisite, the LiDAR measurement unit itself should have achieved wide-spread acceptance within the onshore wind industry as "proven" in the field of wind resource characterization for non-complex terrain sites at least.
- Pre-commercial: Following a successful pilot validation trial, the floating LiDAR technology may be utilized commercially in limited circumstances - specifically in conditions similar to those experienced during the trial. Elevated measurement uncertainty assumptions may be expected for such application, when benchmarked against the deployment of a conventional fixed offshore meteorological mast.

- Commercial: Following successful further trials and early commercial deployments covering a range of site conditions, a sufficient body of evidence is accumulated to relax the elevated uncertainty assumptions.

This report focuses on the assessment of the SWL Buoy against the Pre-commercial (Stage 2) criteria.

1.2 Aims

The key aims of this verification campaign were:

- to develop sufficient confidence in the SWL Buoy to allow its use in commercial projects, either in conjunction with a met mast or stand-alone, and
- to build a body of independent evidence on reliability and accuracy of the SWL Buoy for an initial Offshore Trial totalling a period of at least six (6) months, in order to increase industry acceptance.

Further future objectives, not explicitly covered in this report, should be:

- to understand and quantify expected measurement uncertainty levels associated with SWL Buoy, including sensitivity to weather, sea state and possibly other important parameters, and
- to gain experience in the issues and challenges of deploying and operating the SWL Buoy.

1.3 Cautionary Note

It is important to note that the verification approach applied for this campaign was designed to focus on the capabilities of floating LiDAR technology (namely in this case for the SWL Buoy technology) to replace met masts in measuring primary wind data, namely wind speed and wind direction. Therefore, while the SWL Buoy currently features additional measurement capabilities and while future developments might add even more comprehensive measurement capabilities, the scope of this document is limited to its primary wind data measurements as a substitute for offshore met masts.

There are other secondary but important parameters required for a comprehensive offshore wind resource assessment such as turbulence intensity, temperature, air density, relative humidity etc. Additionally, complementary oceanographic measurements are also required to achieve a full met-ocean measurement campaign. These will need to be measured independently to complete a comprehensive offshore wind resource and met-ocean measurement campaign.

Also, although system availability is one of the KPIs used in this technical note, this document does not directly address or cover the seaworthiness of the SWL buoy device.

Finally, all conclusions on the capabilities of the FO SWL Buoy drawn from this IJmuiden OPV campaign are valid under sea state and meteorological conditions similar to those experienced during the IJmuiden trial only.

2 FLOATING LIDAR PERFORMANCE ASSESSMENT APPROACH

Recommended guidelines for the setup of this SWL Buoy verification campaign were previously developed by DNV GL as documented in [1]. These were based on the Roadmap for the SWL Buoy towards commercial acceptance [2] and included the verification of the IJmuiden met mast against the IEC standard [4] with respect to wind sensor selection, distribution and mounting. The key features of the assessments of the performance of the FLD under test were based on the following definitions of Key Performance Indicators (KPIs) and Acceptance Criteria (see also Appendix A):

- Key Performance Indicators (KPIs): The parameters derived from analysis of the data gathered, which will specifically be used to assess performance.
- Acceptance Criteria (AC): Specific benchmark values defined for a sub-set of the KPIs which constitute the required minimum level of performance for each floating LiDAR system to be considered as achieving Maturity Level 2 (pre-commercial).

These parameters are divided into two categories: Availability or Reliability of the system; and Accuracy of its measurements.

Generally, it is expected that the KPIs are evaluated for heights representative of a typical state-of-the-art offshore wind turbine covering the full rotor disk. If this is not possible the upper measurement height shall – as a minimum requirement – be representative of a typical offshore hub height, and several other lower heights down to 40 m (if feasible even 30 m) above mean sea level (AMSL) shall also be measured.

For the IJmuiden SWL Buoy campaign the four (4) available comparison heights followed this recommendation – see Table 1. The top level was at 92 m AMSL and the lowest height was at 26 m AMSL. DNV GL notes that the wind data quality at the lowest level may suffer from its proximity to the somewhat bulky platform deck components just a few meters below, possibly causing flow distortions.

Table 1: List of relevant heights for wind data comparisons between SWL Buoy and met mast, including type and levels of all meteorological sensors and SWL Buoy sensing heights

Level AMSL [m]	Parameter	Sensor type	Mast height AMSL [m]	FLD level, above sea surface [m]
91	Wind speed	Thies First Class Advanced cup anemometer	91.4	92
84	Wind speed	Metek USA-1 sonic anemometer	84.4	85
58	Wind speed	Thies First Class Advanced cup anemometer	57.9	58
26	Wind speed	Thies First Class Advanced cup anemometer	26.4	26
86	Wind direction	Thies First Class wind vane	86.4	85
58	Wind direction	Thies First Class wind vane	57.4	58
26	Wind direction	Thies First Class wind vane	26.4	26

The assessment of the KPIs and their respective acceptance criteria regarding Availability and Accuracy were done at each reference level, that is:

- Four (4) met mast levels for wind speed (91, 84, 58 and 26 m), and
- Three (3) met mast levels for wind direction (86, 58 and 26 m) - see Table 2.

Further details on measurement levels and general layout of the campaign are provided in [1].

All data collected from the deployment and final commissioning on 2014-04-12 of SWL Buoy until its decommissioning on 2014-11-28 were taken into account in the overall data processing scheme, regardless of the environmental conditions.

The duration of the campaign was also considered. A total of six (6) months' worth of data was gathered across 2 separate campaign phases, interrupted by a 14-day service period dedicated to a refit of the fuel cells in the power supply system. Despite this short interruption, DNV GL considers that the trial duration was sufficient to provide confidence in the measured KPIs for Reliability and Accuracy as reported in the next Section and, in more detail, in Appendix A.

It is noted that the conclusions are valid for the met-ocean conditions experienced during the trial. Longer trials would have increased the probability of experiencing harsher sea states and therefore extending the range of validity of the current results.

3 OPV RESULTS

For formal Offshore Performance Verification of FO's SWL Buoy against the RWE IJmuiden reference mast data from the employed ZephIR 300 LiDAR with the serial number Z417 and from the met mast were provided by FO and ECN, respectively, for a measurement campaign period from 2014-04-11 to 2014-10-27, yielding a total net duration of 6 months. The deployment was interrupted from 2014-06-12 until 2014-06-27 due to an intermittent recovery of the buoy for maintenance services as noted above. Table 3 presents the SWL Buoy's operational period's details and the monthly breakdown used for the KPIs reported herein.

Table 2: Periods of available data for both periods of the trial (1 and 2) and for the individual months M1 to M6 treated for KPIs and ACs in the availability and reliability assessment

P1		11.4.14 13:50	12.6.14 18:50
	M1	11.4.14 13:50	11.5.14 13:50
	M2	11.5.14 13:50	11.6.14 13:50
P2		27.6.14 9:50	27.10.14 23:50
	M3	27.6.14 9:50	27.7.14 9:40
	M4	27.7.14 9:50	27.8.14 9:40
	M5	27.8.14 9:50	27.9.14 9:40
	M6	27.9.14 9:50	27.10.14 9:40
Total Period		11.4.14 13:50	27.10.14 23:50

3.1 Data transfer and processing

The Following remarks and reservations with respect to data transfer, traceability and processing are noted:

- Valid data provided and accepted for analysis totalled a net measurement period of 6 months.
- Reference met mast data were provided for the whole campaign period by the mast operator ECN, directly. However, all data from the reference met mast were also known by and available to FO from the beginning and throughout the campaign. In that sense, this trial cannot be strictly described as a blind test to FO.
- LiDAR wind statistics were provided by the central controller unit (called GENI) installed on the SWL Buoy. This unit collected the 1-sec raw data from the ZephIR 300 to calculate the 10 minute wind data statistics. DNV GL considers this as a deviation from default ZephIR data handling, as the 10 minute averaging is usually performed by the LiDAR internally including a proven data filtering scheme. Hence, this external data processing bears some potential risk of not excluding spurious wind data.
- Wind direction (WD) data are reported to be post-processed by FO for:
    a. the buoy orientation, using bearing data from the ZephIR, which are based on its internal compass; and
    b. the 180° WD ambiguity (a particular feature related to the CW laser approach used by the ZephIR LiDAR) using WD data from a buoy mounted Sonic anemometer as reference.

  DNV GL was able to verify the buoy orientation compensation based on the ZephIR internal compass. The correction for the 180° ambiguity could not be verified by DNV GL. However, some indirect evidence for the consistent applications of WD correction being independent from the reference data has been delivered. That makes DNV GL comfortable with the validity and trustworthiness of the correction approach.

3.2 Wind and sea state conditions during the IJmuiden offshore trial

The verification of the SWL Buoy was undertaken over the period from April 2014 to November 2014 where the device encountered a wide range of wind conditions facing 10 minute average wind speeds of up to 24 m/s at the lowest comparison level (26 m) and 26 m/s at the mast top level (91 m) – see Table 4.

During this period the SWL Buoy experienced a full range of sea states with significant wave heights of up to 5.8 m and maximum wave heights of up to 9.8 m – see time series in Figure 1 (further details on wave height frequency distribution and wave periods can be found in Appendix D). The wave measurements were recorded by the SWL Buoy under trial using a 30 min data acquisition and processing interval (further specs on the wave parameters recorded can be found in [1]).

Table 3: Maximum 10 min averaged wind speeds measure at the mast (cups) and by the SWL Buoy FLD across the total campaign period.

Level	Max WS 10 min. average	
	Cup	FLD
26 m	23,2	23,9
58 m	24,8	24,8
85 m	25,2	25,8
91 m	25,9	26,3

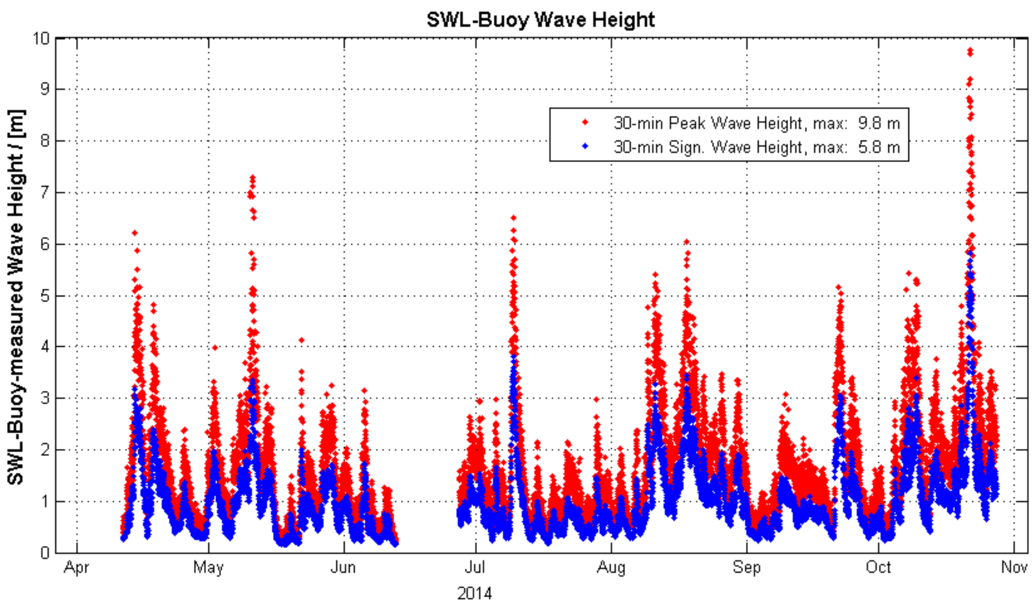


Figure 1: Peak wave height and significant wave height as measured by the SWL Buoy itself, across the Offshore Trial period.

3.3 Availability and reliability

DNV GL reviewed the KPIs and Acceptance Criteria relating to the availability of the SWL Buoy unit [2]. An overview of the findings for each KPI is included below and summarized in Table 5.

System availability:
The table below presents the Monthly System Availability (MSA_{1M}, M1 to M6) and Overall System Availability (OSA_{CA}) for the floating LiDAR unit measurement campaign. It is clear that the acceptance criteria for MSA_{1M} and OSA_{CA} as given in [2] are met.

Table 4: Monthly and Overall System Availabilities to exceed 90% and 95%, respectively.

Period name	Start	End	System availability		
			#-val ref.	#-val	
P1	11.4.14 13:50	12.6.14 18:50	8960	8949	99,9%
M1	11.4.14 13:50	11.5.14 13:50	4322	4318	99,9%
M2	11.5.14 13:50	11.6.14 13:50	4466	4458	99,8%
P2	27.6.14 9:50	27.10.14 23:50	17654	17635	99,9%
M3	27.6.14 9:50	27.7.14 9:40	4321	4318	99,9%
M4	27.7.14 9:50	27.8.14 9:40	4465	4462	99,9%
M5	27.8.14 9:50	27.9.14 9:40	4465	4458	99,8%
M6	27.9.14 9:50	27.10.14 9:40	4321	4312	99,8%
Overall	11.4.14 13:50	27.10.14 23:50	26614	26584	99,9%

Post-processed data availability:

No post-processing filters were applied to the floating LiDAR data for this trial, so the internal and post-processed data availabilities are the same. Other filters based on met mast instrumentation accuracy are irrelevant when assessing the reliability of the LiDAR, so the filtered data availability was not considered here.

Table 6 below shows the Monthly Post-processed Data Availability ($MPDA_{1M}$) and Overall Post-processed Data Availability ($OPDA_{CA}$) for the SWL Buoy unit verification campaign. The Roadmap [2] states that the assessment of the KPIs and their Acceptance Criteria should be performed at each available reference level, in this case at each of the IJmuiden met mast's reference anemometry levels, highlighted in orange. As a result, it is shown that all acceptance criteria for Post-processed Data Availability are met. Table 6 shows that the acceptance criteria for $MPDA_{1M}$ and $OPDA_{CA}$ given in [2] are actually met beyond the requirements of the roadmap and at all SWL Buoy measurement heights and for each individual month.

Table 5: Monthly and Overall Post-processed data availability. Orange shading marks wind value comparison levels.

Overall and monthly data availability per height level											
Height [m]	12	27	40	48	58	70	85	92	120	150	190
P1	95,4%	95,8%	95,8%	95,8%	95,8%	95,8%	95,8%	95,8%	95,8%	95,8%	95,8%
M1	99,3%	99,7%	99,7%	99,7%	99,7%	99,7%	99,7%	99,7%	99,7%	99,7%	99,7%
M2	92,0%	92,4%	92,4%	92,4%	92,4%	92,4%	92,4%	92,4%	92,4%	92,4%	92,4%
P2	98,8%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%
M3	96,5%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
M4	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
M5	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%	99,6%
M6	99,1%	99,1%	99,1%	99,1%	99,1%	99,1%	99,1%	99,1%	99,1%	99,1%	99,1%
Overall	97,7%	98,4%	98,4%	98,4%	98,4%	98,4%	98,4%	98,4%	98,4%	98,4%	98,4%

3.4 Accuracy

DNV GL has analysed the wind data against the KPIs and Acceptance Criteria as given in Appendix A relating to the accuracy of the SWL Buoy unit.

In accordance with conditions outlined in Appendix A, the comparisons in this section are based on ten-minute average values at both the floating LiDAR unit and met mast. For the analysis conducted in this section, a low wind speed cut-off of 2 m/s has been applied for the wind speed comparison and a cut-off of 3 m/s for the wind directions comparison.

Data coverage requirements for accuracy assessment

In accordance with the data coverage requirements outlined in Appendix A, DNV GL assessed the data coverage of the floating LiDAR system at the four measurement heights considered. This has been conducted according to the following requirements:

a) Minimum number of 40 data points required in each 1 m/s bin wide reference wind speed bin centred between 2.5 m/s and 11.5 m/s, i.e. covering a range between 2 and 12 m/s.
b) Minimum number of 40 data points required in each 2 m/s bin wide reference wind speed bin centred on 13 m/s and 15 m/s, i.e. covering a range 12 m/s to 16 m/s.
c) Minimum number of 40 data points in each 2 m/s bin wide reference wind speed bin centred on 17 m/s and above, i.e. covering a range above 16 m/s only if such number of data is available. This is not mandatory.

For the period considered in this report, requirements a) and b) are met for measurements at the four considered heights. Requirement c) is also met at these heights for wind speeds from 16 m/s up to 22 m/s for the lower two comparison heights and up to 24 m/s for the upper two heights – see green-shaded cells in Table 4.

Table 6: Summary of data coverage per WS bin, complete bins with at least 40 values are marked in green.

WS Bins [m/s]	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 14	14 to 16	16 to 18	18 to 20	20 to 22	22 to 24	24 to 26
Bin Center [m/s]	2,5	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	13	15	17	19	21	23	25
91m [#]	1365	1814	2071	2379	2410	2144	2057	1920	1769	1793	2772	1274	574	248	81	41	12
84m [#]	1372	1800	2095	2379	2428	1994	1235	844	666	528	796	394	149	70	64	41	4
58m [#]	1427	1893	2161	2557	2539	2266	2262	2097	2018	1637	2233	850	473	153	60	34	3
26m [#]	1367	1956	2280	2389	2381	2255	2244	2057	1444	1122	1459	597	338	77	50	5	0

3.4.1 Wind speed accuracy

A summary of the findings for each wind-speed-related KPI is presented in Table 8. The wind speed accuracy assessment has been conducted at four heights (26 m, 58 m, 84 m and 91 m AMSL), as detailed below, where the SWL Buoy and the met mast measurement heights are comparable. It is noted that the heights are within 1.0 m of each other, and the differences are seen as negligible in the context of the movement of the device relative to MSL due to the tidal water level movements. The tide-induced sea level variations were reported to be within +/- 2 m, excluding storm surge.

The slopes (X_{MWS}) and Coefficient of Determination (R^2_{mws}) are presented for all 4 compared heights. It can be seen that these fall within the best practice acceptance criteria [0.98 > X_{MWS} > 1.02] as given in [1] for the data period considered here. Plots for WS regression results together with WS time series plots can be found in Appendix B.

Table 7: Overview of linear regression analysis results for wind speed comparisons between the SWL Buoy and the reference mast at the four available comparison levels in two different wind speed ranges. Colour shading indicates the compliance with the prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

	26 m level	# Values	Slope	R^2	WS-avg Cup	WS-avg Lid	Mean diff.	Mean diff.
		-	-	-	[m/s]	[m/s]	[m/s]	[%]
	WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
a	All > 2 m/s	22021	1,018	0,991	7,66	7,81	0,15	2,0%
b	4 - 16 m/s	18228	1,018	0,986	8,23	8,38	0,15	1,8%

	58 m level	# Values	Slope	R^2	WS-avg Cup	WS-avg Lid	Mean diff.	Mean diff.
		-	-	-	[m/s]	[m/s]	[m/s]	[%]
	WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
a	All > 2 m/s	24663	1,015	0,993	8,15	8,29	0,14	1,7%
b	4 - 16 m/s	20620	1,015	0,989	8,63	8,76	0,14	1,6%

	84 m level	# Values	Slope	R^2	WS-avg Cup	WS-avg Lid	Mean diff.	Mean diff.
		-	-	-	[m/s]	[m/s]	[m/s]	[%]
	WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
a	All > 2 m/s	16859	1,012	0,992	6,94	7,05	0,11	1,6%
b	4 - 16 m/s	13359	1,011	0,988	7,56	7,65	0,09	1,3%

	91 m level	# Values	Slope	R^2	WS-avg Cup	WS-avg Lid	Mean diff.	Mean diff.
		-	-	-	[m/s]	[m/s]	[m/s]	[%]
	WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
a	All > 2 m/s	24724	1,011	0,992	8,53	8,65	0,11	1,3%
b	4 - 16 m/s	20589	1,011	0,988	8,93	9,04	0,11	1,2%

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.4.2 Wind direction accuracy:

The direction data comparison was conducted for measurements at 26 m, 58 m and 86 m AMSL at the met mast and SWL Buoy unit, respectively. DNV GL notes that wind directions measured by the SWL Buoy were post-processed by FO to compensate the misalignment induced by buoy rotation through the tidal cycle. As reported by FO the buoy orientation is recorded by the ZephIR, which uses the bearing measured on its magnetic compass to correct the wind direction measurements for buoy heading. From direct access to the original ZephIR data DNV GL was able to verify that this correction was based on the bearing data as provided by the ZephIR LiDAR standard output.

In the future a more accurate motion and heading sensor (called Xsens) will be continuously available for buoy orientation correction instead of the ZephIR internal compass. The capability of the Xsens-based algorithm has been verified by DNV GL for a shorter part (4 months) of the 6 month long campaign, yielding SWL Buoy wind directions meeting best practice criteria. Hence, the results from the ZephIR-compass-corrected SWL Buoy wind direction comparisons are regarded as provisional. For future verification campaigns – employing Xsens- based corrections – WD comparisons are expected to yield improved results.

The results for the wind direction comparison are presented in Table 9 where the Wind Direction Regression Slope (M_{mwd}), the Mean Offset (OFF_{mwd}) and the Coefficient of Determination (R^2_{mwd}) are presented. The slope values for the upper and lower heights and the offset for the upper height fall within the best practice acceptance criteria given in [2] for the data period considered here. All other values meet the minimum criteria. Plots for WD regression results can be found in Appendix C.

Table 8: Overview of linear regression results for WD comparisons between SWL Buoy and reference mast at the three (3) WD comparison levels. Colour shading indicates compliance with prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

WD Level	KPI M_{mwd} slope	KPI OFF_{mwd} mean offset	KPI R^2_{mwd} corr.-coeff.	# points used after filtering
86 m	0,970	3,08	0,960	23235
58 m	0,969	5,11	0,961	23234
26 m	0,973	5,83	0,966	20929

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.5 Summary of verification results

3.5.1 Campaign Duration

In the campaign layout document prepared by DNV GL [1] and in the Roadmap [2] a six (6) month minimum total campaign duration was prescribed in order to allow the tested unit to experience different season-related sea states and other environmental conditions. It is understood that the campaign was interrupted twice:

(a) In February 2014 for some 2 months due to a malfunction of the mooring array in Feb 2014 resulting in a braking away of the buoy, that required a repair, refit and re-deployment
(b) In June 2014 for two weeks to address an issue with the fuel cells that requires a recovery and re-deployment of the buoy for service.

However, considering

- the overall offshore deployment period which started in January 2014,
- the level of information provided for the corrective maintenance for both interruptions, and
- the amount of data gathered since re-deployment April 2014,

DNV GL considers that the overall deployment period that started mid April 2014 and ended in end of October 2014 fulfils the 6-month requirement.

3.5.2 System and Data Availability

System and data availability were above those prescribed in the Roadmap document as best practice [2]. The detailed results are given in Table 10 below.

Table 9: Summary of achievement of 6 months net campaign data for prescribed campaign KPIs and Acceptance Criteria with respect to the availability and reliability assessment

KPI	Definition / Rationale	Acceptance Criteria across total of six (6) months net data period;
MSA_{1M}	**Monthly System Availability – 1 Month Average**	≥90% Results: [99.8 to 99.9 %] Passed
OSA_{CA}	**Overall System Availability – Campaign Average**	≥95% Results: [99.9 %] Passed for the net period of the six months available Not considering the 15 days of maintenance gap
$MPDA_{1M}$	**Monthly Post-processed Data Availability – 1 Month Average**	≥80% Results: [92.0 to 99.9 %] Passed for all compared heights No FLD system internal quality filters were available or applied in the data analysis
$OPDA_{CA}$	**Overall Post-processed Data Availability**	≥85 Results: [97.7 to 98.4 %] Passed for all compared heights Not considering the 15 days maintenance interruption No FLD system internal quality filters were available or applied in the data analysis

3.5.3 Wind Measurement Accuracy

The wind speeds of both the SWL Buoy and the reference met mast (cups/sonic) at all comparison heights correlated very well, showing a low level of scatter and an excellent agreement between SWL Buoy wind speeds and those of cups/sonic in terms of linear regression analyses. This comparison campaign indicates that the SWL Buoy is able to reproduce cup anemometer wind speeds at a high level of accuracy. The Best Practice criteria for the KPIs "Mean Wind Speed – Slope" and "Mean Wind Speed – Coefficient of Determination" were passed.

For wind direction Best Practice criteria (or in a few instances at least the Minimum criteria) were passed for the KPIs "Mean Wind Direction – Slope", "Mean Wind Direction – Coefficient of Determination" and "Mean Wind Direction – Offset", indicating the SWL Buoy's capability of reproducing vane and sonic wind directions at a good level of accuracy.

DNV GL notes that the sea states faced by the FLD system during the Offshore Trial were relatively benign when compared to harsher conditions (though covering significant wave heights up to almost 6 m), notably those which might be experienced in the more central or northern North Sea over the winter season. So findings presented here are limited to the sea conditions experienced. It is expected that future trials in harsher conditions will shed additional light on the performance of the SWL Buoy in more demanding met-ocean conditions.

The detailed results with respect to KPIs and ACs for wind speed and wind direction comparisons are given in Table 11, below.

Table 10: Summary of achievement after 6 months wrt KPIs and Acceptance Criteria for data accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria across total of six (6) months net data period	
		Best Practice	**Minimum**
X_{mws}	**Mean Wind Speed – Slope**	0.98 – 1.02 Results: [1.011 to 1.018] Passed for all WS ranges and at all compared heights	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination**	>0.98 Results: [0.986 to 0.993] Passed for all WS ranges and at all compared heights	>0.97
M_{mwd}	**Mean Wind Direction – Slope**	0.97 – 1.03 Results: [0.970 to 0.973] Passed for comparison heights at 86m and 26m	0.95 – 1.05 Results: [0.969] Passed for comparison height at 58m
OFF_{mwd}	**Mean Wind Direction – Offset, in terms of the mean WD difference over the total campaign duration**	< 5° Results: [@ 86m, 3.08°] Passed for comparison height at 86m	< 10° Results: [@ 58m, 5.11°] [@ 26m: 5.83°] Passed for comparison heights at 58m and 26m

KPI	Definition / Rationale	Acceptance Criteria across total of six (6) months net data period	
		Best Practice	**Minimum**
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97 not passed at any level	> 0.95 Results: [@ 86m, 0.960] [@ 58m, 0.961] [@ 26m: 0.966] Passed for all comparison heights
X_{TI}	**Turbulence Intensity – Slope**	Not analysed, yet	Not analysed, yet
R^2_{TI}	**Turbulence Intensity – Correlation Co-efficient**	Not analysed, yet	Not analysed, yet
A	**Wind Speed Shear**	Not analysed, yet	Not analysed, yet

4 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

Offshore wind farms have high capital costs and therefore when employing relatively new technology for a purpose as vital as predicting the future energy output of a large wind farm, particular care should be exercised to reduce, to the extent possible, prediction uncertainty. While some sources of uncertainty apply irrespective of the nature or the maturity of the selected measurement technology; other risks are directly related to the specific measurement equipment and of these, measurement accuracy and system / data availability are the most significant. New technologies and devices must prove, through track record and on-site deployments, that they meet or exceed current industry standards to gain wide-spread acceptance. This track record ensures that enough scientific and engineering knowledge and experience has been gained for the technology to be used with confidence within well understood limits.

The three stages of maturity defined by the Floating LiDAR Commercial Roadmap [2] are designed to help build the above-described track record. The Roadmap notably defines and uses KPIs to help gauge objectively the level of maturity of floating LiDAR technologies for offshore wind resource assessment against defined milestones.

An evaluation of the Fugro/Oceanor SWL Buoy floating LiDAR system was completed by comparing its measurements against data from the IEC-compliant IJmuiden met mast. Sufficient data were collected to allow an assessment in line with the Roadmap.

In the IJmuiden offshore trial very encouraging results were indeed obtained. DNV GL concludes that the FO SWL Buoy system has demonstrated its capability to produce accurate wind speed and direction data across the range of sea states and meteorological conditions experienced in this trial (i.e. up to about 5.8 m significant wave height and 9.8 m maximum wave height and 10 min averaged wind speeds up to 26 m/s). Furthermore, it has recorded excellent availability throughout the 6 month period and demonstrated structural survivability in the met-ocean conditions present from early spring until mid-autumn.

The assessment of the Roadmap KPIs for the complete data set (from April 12th until Oct 27th 2014, excluding the 15 days service interruption in June 2014) shows that in almost all cases the best practice criteria as prescribed above are met for SWL Buoy system availability, data availability and wind data accuracy. Only in a few instances the wind direction comparisons only meet the prescribed minimum Acceptance Criterion to reach Roadmap Stage 2 ("pre-commercial"). For all other KPIs the best practice Acceptance Criteria are met.

Hence, accepting that the knowledge and availability of reference met mast data to FO had no influence on the final data post processing (in particular with respect to the wind direction compensation) and having verified a consistent application of the wind direction correction algorithm used in offline post processing, DNV GL concludes that the FO SWL Buoy has formally qualified for Stage 2 "pre-commercial" in the context of the Floating LiDAR Commercial Roadmap.

5 REFERENCES

[1] DNV GL Report GLGH-4257 13 10378 267-P-0001 Issue C, "OFFSHORE VERIFICATION OF SEAWATCH FLOATING LIDAR AT RWE IJMUIDEN MET MAST", dated 2014-03-21.

[2] DNV GL Report GLGH-4257 13 10378 266-R-0002 Issue B , "A ROADMAP FOR THE COMMERCIAL ACCEPTANCE OF THE FUGRO/OCEANOR SEAWATCH WIND LIDAR BUOY", dated 2015-01-29.

[3] Offshore Wind Accelerator Roadmap for the commercial acceptance of floating lidar technology. The Carbon Trust, 21 November 2013.

[4] IEC 61400-12-1, "Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines", 2005.

APPENDIX A – KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA FOR FLD OFFSHORE PERFORMANCE VERIFICATION

Availability / Reliability

The KPIs and Acceptance Criteria relating to availability, all of which are applicable to all measurement heights under consideration, are defined as follows:

KPI	Definition / Rationale	Acceptance Criteria across total of six (6) months data
MSA_{1M}	**Monthly System Availability – 1 Month Average** The LiDAR system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the given month. The Monthly Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10 minute) data entries including periods of maintenance (regarded as 100%) within the respective month.	≥90%
OSA_{CA}	**Overall System Availability – Campaign Average** The LiDAR system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the pre-defined total campaign length. The Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10 minute) data entries including periods of maintenance (regarded as 100%) within the pre-defined total campaign period.	≥95%
$MPDA_{1M}$	**Monthly Post-processed Data Availability – 1 Month Average** The Monthly Post-processed Data availability is the number of those data entries remaining • after system internal (unseen) filtering, i.e. excluding (NaN or 999) flagged data entries • and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of LiDAR Manufacturer guidelines relative to the maximum possible number of (here 10 minute) data entries (regarded as 100%) within the respective month, regardless of the environmental conditions within this period.	≥80%

KPI	Definition / Rationale	Acceptance Criteria across total of six (6) months data
$OPDA_{CA}$	**Overall Post-processed Data Availability** The Overall Post-processed Data availability is the number of those data entries remaining • after system internal (unseen) filtering, i.e. excluding (NaN or 999) flagged data entries • and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of LiDAR Manufacturer guidelines relative to the maximum possible number of (here 10 minute) data entries (regarded as 100%) within the pre-defined total campaign period regardless of the environmental conditions within this period.	≥85%
MV	**Number of Maintenance Visits** Number of Visits to the floating LiDAR system by either the supplier or an authorized third party to maintain and service the system. This is to be documented and reported by the Manufacturer.	N/A
UO	**Number of Unscheduled Outages** Number Unscheduled Outages of the floating LiDAR system in addition to scheduled service outages. Each outage needs to be documented regarding possible cause of outage, exact time / duration and action performed to overcome the Unscheduled outage. This is to be reported by the supplier and independently confirmed and checked by Fugro OCEANOR AS or their authorized representatives.	N/A
CU	**Uptime of Communication System** To be documented and reported by the supplier and independently checked/confirmed by Fugro OCEANOR AS or their authorized representatives.	N/A

In the above table, during periods of maintenance; the system is deemed unavailable.

Preconditions for accuracy assessment

All comparisons and regression analysis are to be based on 10-minute average values returned from sensors installed on the reference mast such as MEASNET calibrated cup anemometers, wind vanes and other meteorological instruments.

The data from both the LiDAR and the mast are to be filtered for external parameters such as:

- wind direction in order to avoid non-valid wind speed measures from sectors where either the cups at the reference mast or the floating LiDAR itself is influenced by mast wake effects. Final valid sectors are to be defined by taking into account:
    - boom directions for the side mounted cup anemometry at the mast;
    - any lightning protection components that may wake effect top mounted cups on the mast; and,
    - each floating LiDAR position relative to the mast.
- wind speed: application of clipping below 2 m/s. The rational for such low wind speed cut-off is that remote sensing techniques are known to suffer from weak signals in low wind speed conditions. Therefore, such wind speeds should be excluded from the analysis to prevent the relation between floating LiDAR and reference being biased in a rather unimportant wind speeds range.
- air temperature in order to avoid unpredictable conditions like icing of cups that could violate the representativeness of the reference measurements. Hence the data should be clipped for temperature with $T < 0.5°C$.

To avoid bias in the wind speed relationships, the reference data from the mast are expected to be corrected in order to account for tidal water level variations.

Data coverage requirements for accuracy assessment

The data coverage requirements set-out below, prescribes the minimum required number of valid data points after the final filtering for allowable conditions required for data quality assessment, i.e. after clipping for wake affected wind direction sectors, low wind speeds and low temperatures. By defining such data coverage requirements it shall be assured that results from the performance assessment are statistically relevant.
The requirements on data coverage are based on 10-minute average values as returned from the floating LiDAR system.

The following data coverage definitions are prescribed as follows:

a) minimum number of 40 data points required in each 1 m/s bin wide reference wind speed bin centred between 2.5 m/s and 11.5 m/s, i.e. covering a range between 2 and 12 m/s.

b) minimum number of 40 data points required in each 2 m/s bin wide reference wind speed bin centred on 13 m/s and 15 m/s, i.e. covering a range 12 m/s and 16 m/s.

c) minimum number of 40 data points in each 2 m/s bin wide reference wind speed bin centred on 17 m/s and above, i.e. covering a range above 16 m/s only if such number of data is available. This is not mandatory.

Those data coverage requirements are regarded as achievable for the planned 6 months deployment period.

Accuracy assessment

The KPIs and Acceptance Criteria relating to accuracy are defined in the following table. To assess the accuracy a statistical linear regression approach has been selected which is based on:

a) a two variant regression y = mx+b (with m slope and b offset) to be applied to wind direction data comparisons between floating instrument and reference mast; or,

b) a single variant regression, with the regression analysis constrained to pass through origin (y = mx+b; b = 0) to be applied to wind speed, turbulence intensity and wind shear data comparisons between floating instrument and reference mast.

In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on correlation coefficients returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

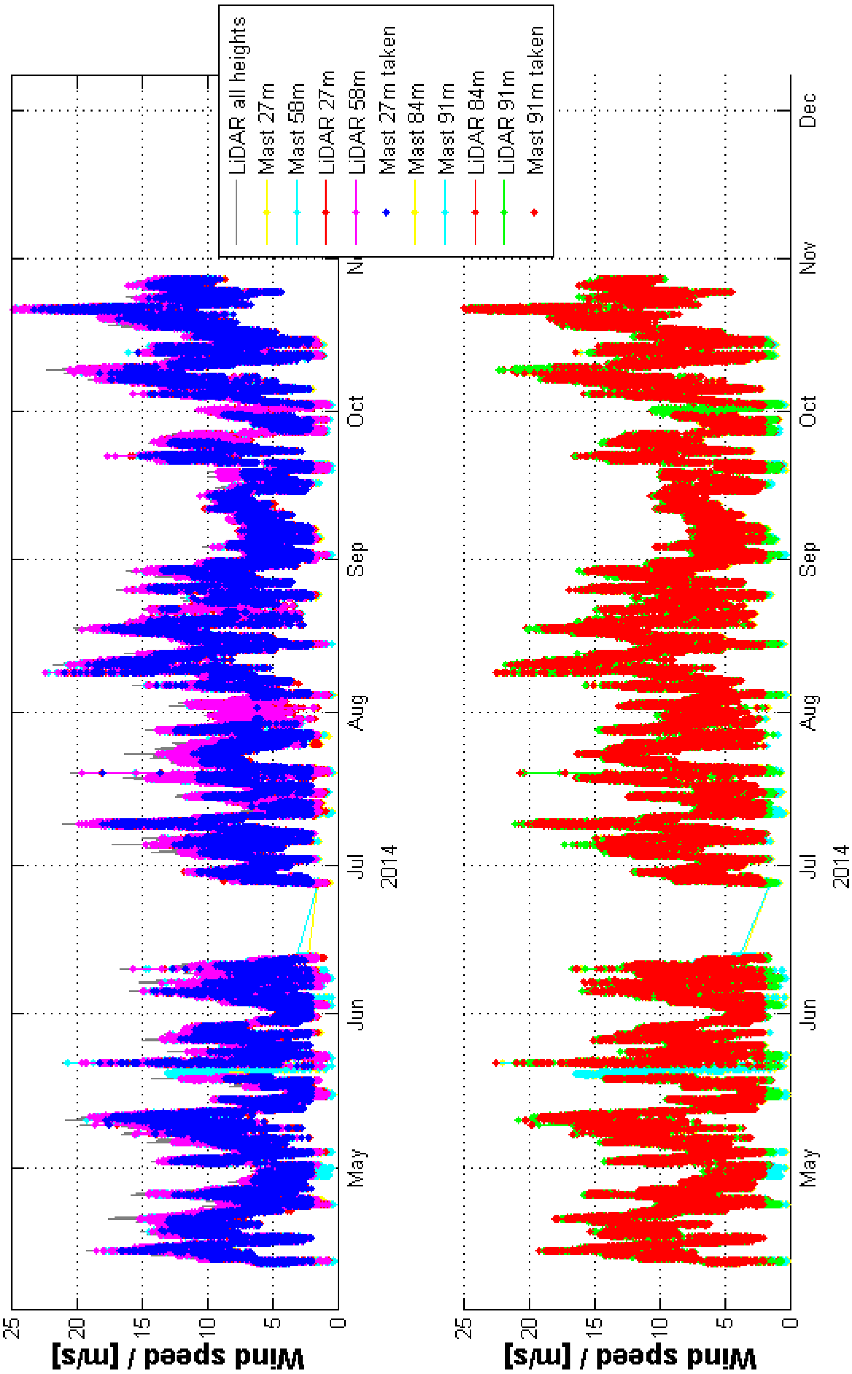
The level of accuracy parameters of secondary importance as measured (wind shear and turbulence intensity) is defined as KPIs below, but without Acceptance Criteria.

KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Correlation Co-efficient returned from single variant regression A tolerance is imposed on the Correlation Co-efficient value. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	>0.98	>0.97

KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of coverage requirements.	0.97 – 1.03	0.95 – 1.05
OFF_{mwd}	**Mean Wind Direction – Offset, in terms of the mean WD difference over the total campaign duration** (same as for M_{mwd})	< 5°	< 10°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97	> 0.95
X_{TI}	**Turbulence Intensity – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin.	N/A	N/A
R^2_{TI}	**Turbulence Intensity – Correlation Co-efficient** Correlation Co-efficient returned from single variant regression with the regression analysis constrained to pass through the origin.	N/A	N/A
Α	Wind Speed Shear – Shear Exponent Alpha related to Hellman's power law. Alpha to be calculated using reference anemometry heights at 58 m and 91 m Mean Alpha values to be compared for different wind speed ranges such as a) 4 to 8 m/s b) 8 to 12 m/s c) 12 to 16 m/s d) all wind speeds above 2 m/s	N/A	N/A

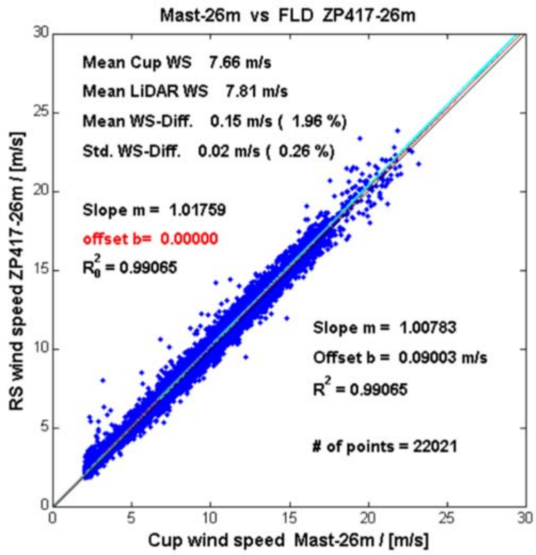
APPENDIX B – WS TIME SERIES AND CORRELATION PLOTS

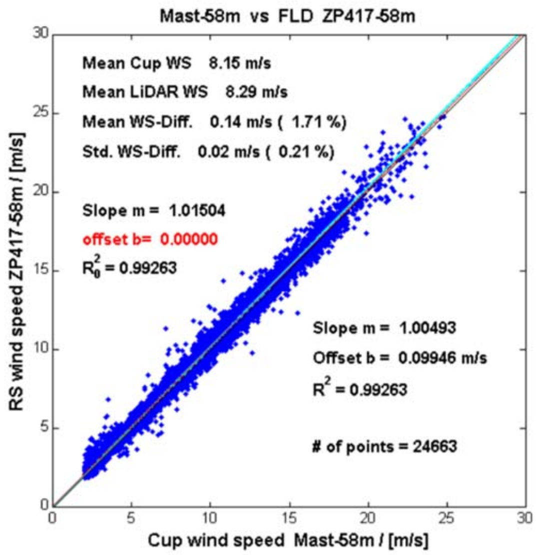
WS time series for all comparison heights:

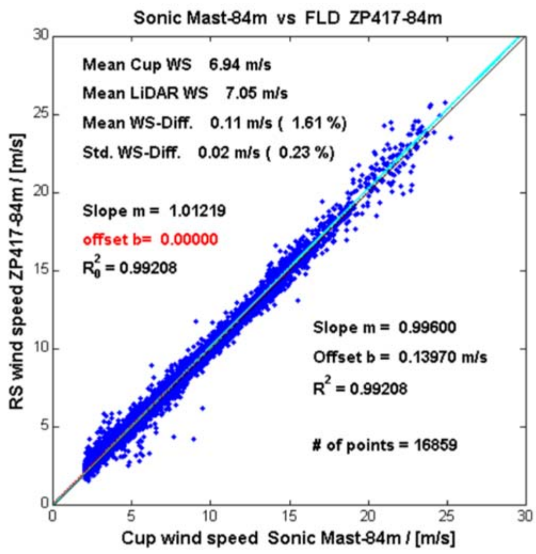


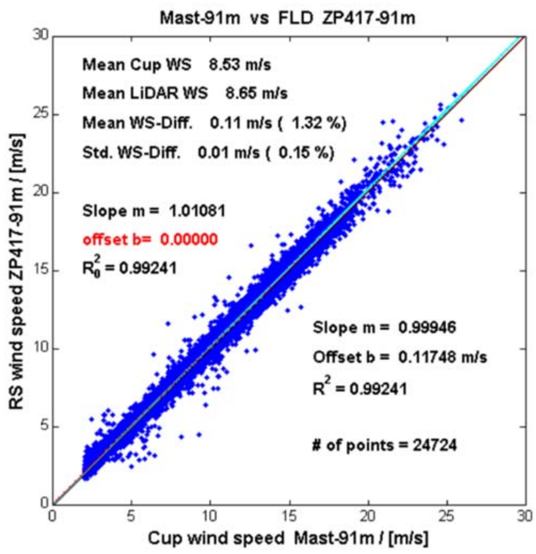
WS regression plots for all comparison heights.

Shown are results for linear regressions “forced” through the origin as discussed above, and for information “un-forced” linear regressions, yielding as well the WS offset in terms of intercept of the regression line of the y-axis.



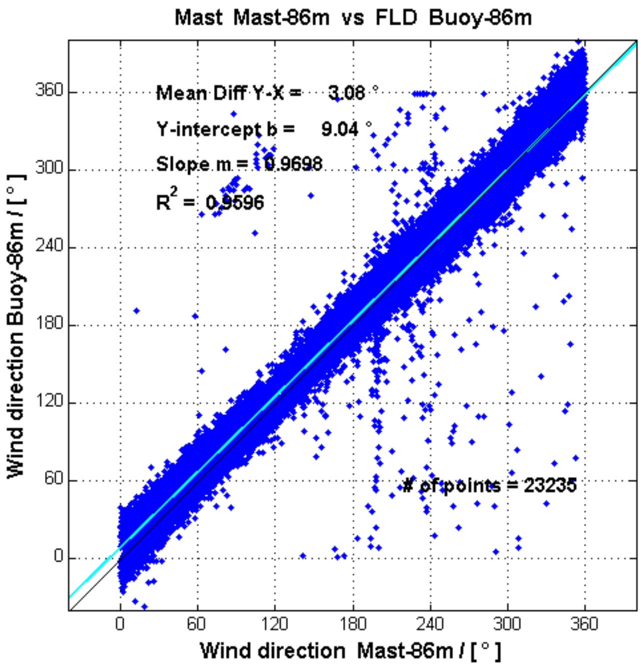


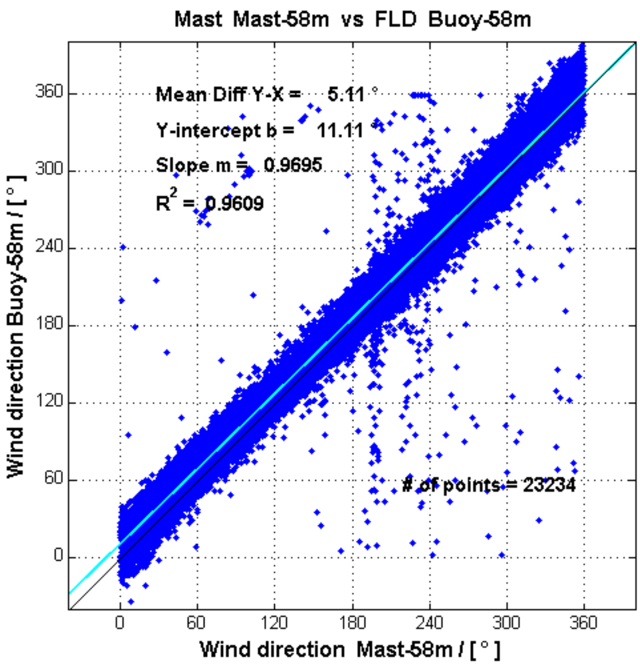


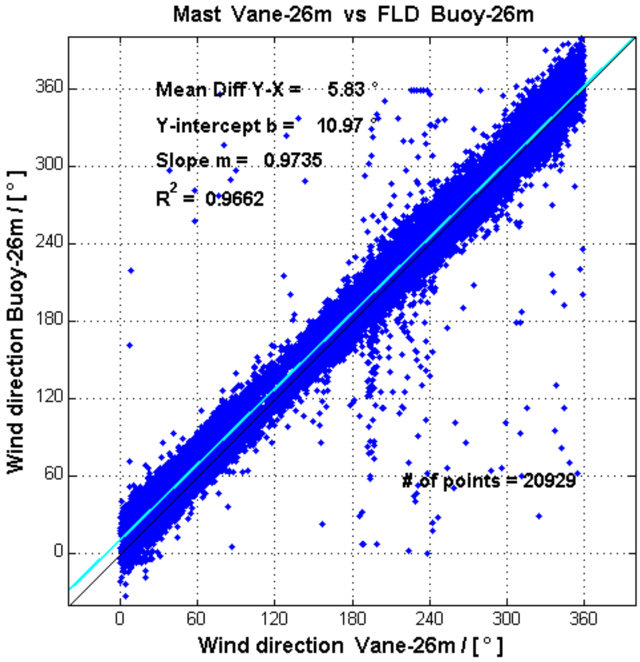


APPENDIX C – WD CORRELATION PLOTS

WD correlation plots for all three comparison heights

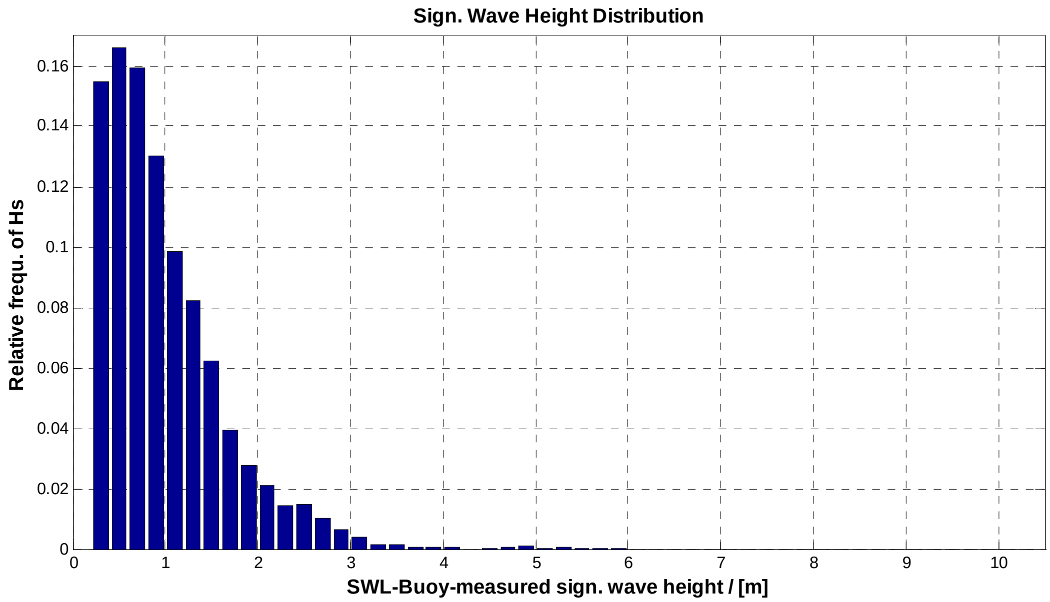


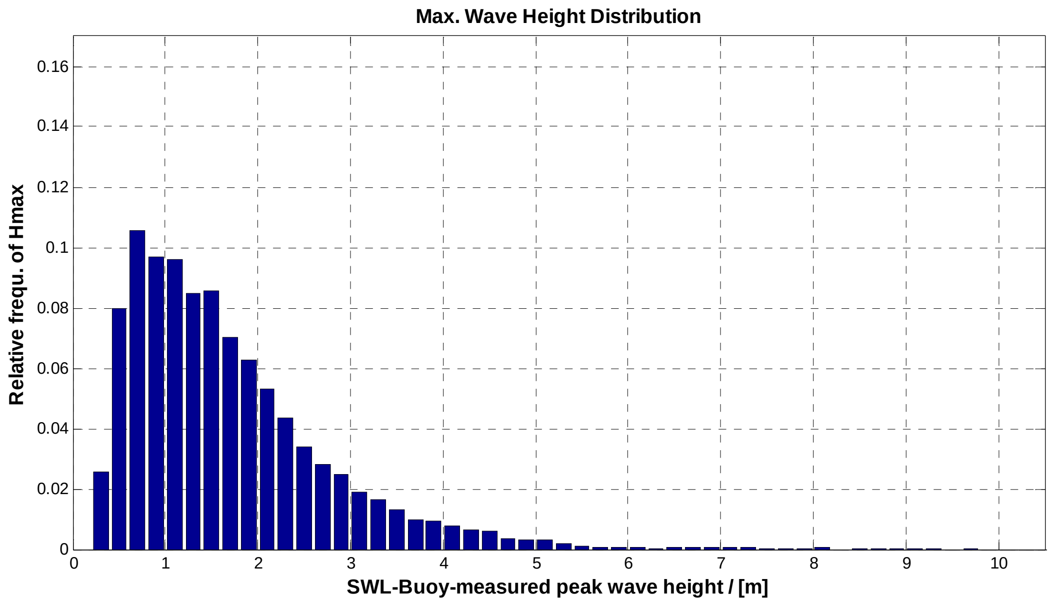



Mast Vane-26m vs FLD Buoy-26m
Mean Diff Y-X = 5.83 °
Y-intercept b = 10.97 °
Slope m = 0.9735
R2 = 0.9662
# of points = 20929
Wind direction Buoy-26m / [°]
Wind direction Vane-26m / [°]
0
60
120
180
240
300
360

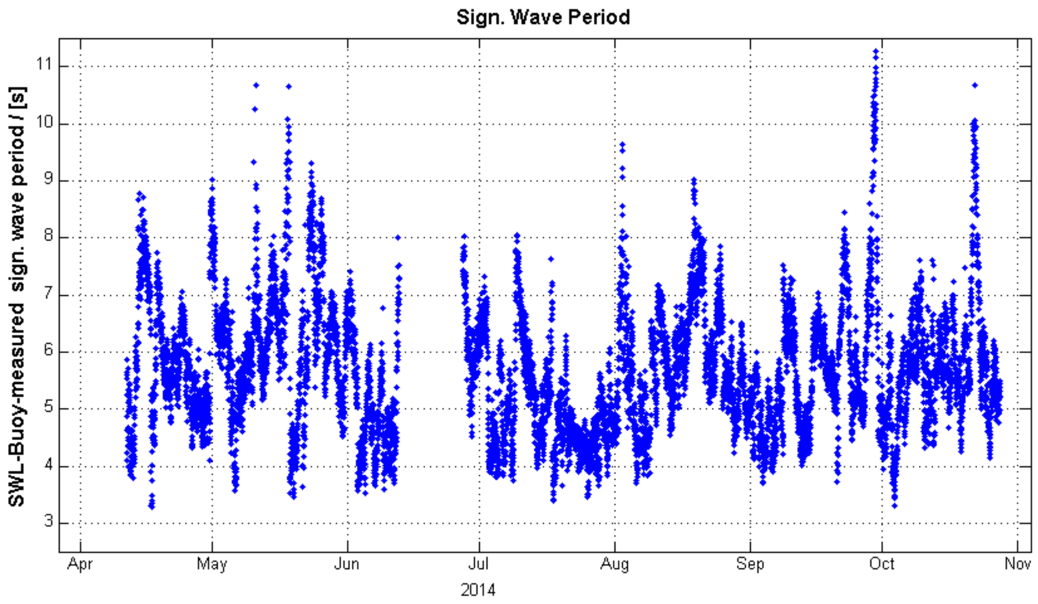
APPENDIX D – WAVE DATA PLOTS

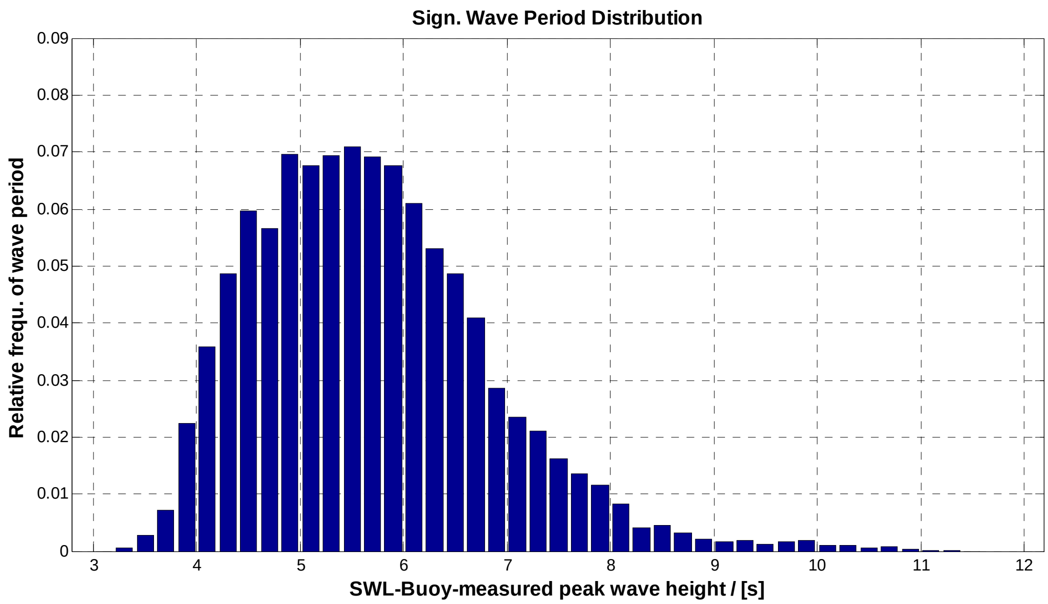
Plots of significant and maximum (peak) wave height distribution





Plots of significant wave period time series and distribution





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