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FRØYA SEAWATCH WIND LIDAR BUOY WS 170
PRE-DEPLOYMENT VALIDATION

Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 170 Pre-Deployment Validation at Frøya, Norway

Fugro Norway AS

Report No.: GLGH-4270 17 14462-R-0002, Rev. C
Date: 2017-07-25

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Project name:	Frøya Seawatch Wind LiDAR Buoy WS 170 Pre-Deployment Validation	DNV GL – Energy Renewables Advisory
Report title:	Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 170 Pre-Deployment Validation at Frøya, Norway	GL Garrad Hassan Deutschland GmbH Sommerdeich 14 b 25709 Kaiser-Wilhelm-Koog Germany Tel: +49 4856 901 0
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Date of issue:	2017-07-25	
Project No.:	4270 17 14462	
Report No.:	GLGH-4270 17 14462-R-0002, Rev. C	

Task and objective: 3rd Party Assessment of an Offshore/Nearshore Pre-Deployment Validation of the Fugro/Oceanor SEAWATCH Wind LiDAR Buoy WS 170 at the Island Frøya, Norway

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Keywords:
LiDAR, Floating Lidar Device, Pre-deployment Verification

Reference to part of this report which may lead to misinterpretation is not permissible.

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	2017-04-06	First issue	A. Mark	D. Stein	V. Köhne
B	2017-05-18	Considered client's comments	A. Mark	D. Stein	V. Köhne
C	2017-07-25	Further changes according to client's comments	A. Mark	V. Köhne	V. Köhne

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List of abbreviations

Abbreviation	Meaning
SWLB	Seawatch Wind Lidar Buoy
GH-D	GL Garrad Hassan Deutschland GmbH, part of DNV GL group
FO	Fugro OCEANOR
RLL	Reference Land Lidar
FLD	Floating LiDAR Device
MSL	Mean Sea Level
SL	actual Sea Level
LAT	Lowest astronomical tide
KPI	Key Performance Indicator
AC	Acceptance Criterion
WS	Wind Speed
WD	Wind Direction

1 INTRODUCTION

On 2017-03-22, Fugro OCEANOR AS (FO or the Client) commissioned GL Garrad Hassan Deutschland GmbH ("GH-D"), part of the DNV GL group ("DNV GL") to perform a pre-deployment validation campaign and to provide a validation report for a SEAWATCH Wind LiDAR Buoy (SWLB) unit with the serial number WS 170 moored next to the Island Frøya in the Norwegian Sea.

The pre-deployment validation of this already "Roadmap-Pre-Commercial" staged Floating Lidar Device (FLD) [1] was performed over a period of 18.8 days against a fixed/land based industry accepted Lidar (Reference Land Lidar or RLL), that was used as the only validation reference. This SWLB with the S/N WS170 is considered being of the same type as that SWLB used for the type verification campaign at Ijmuiden [6] which led to "Roadmap-Pre-Commercial" maturity status (see section 4.3).

Data evaluation was performed for specific wind data quality related Key Performance Indicators (KPIs) and Acceptance Criteria (AC) as formulated in the Roadmap towards Commercial Acceptance [2]. DNV GL has not been involved in the data collection. Data from both the SWLB and the RLL were provided by FO.

The Campaign started 2017-03-02 with the deployment of the SWLB at a position South of Frøya in 75 m water depth at Site 1, see Figure 1. The mooring point is about 800 m to the Southwest of the shore of a place called Stabben and approx. 920 m from the "Land Lidar" at Stabben. The campaign was finished by the recovery of the SWLB on 2017-03-21.

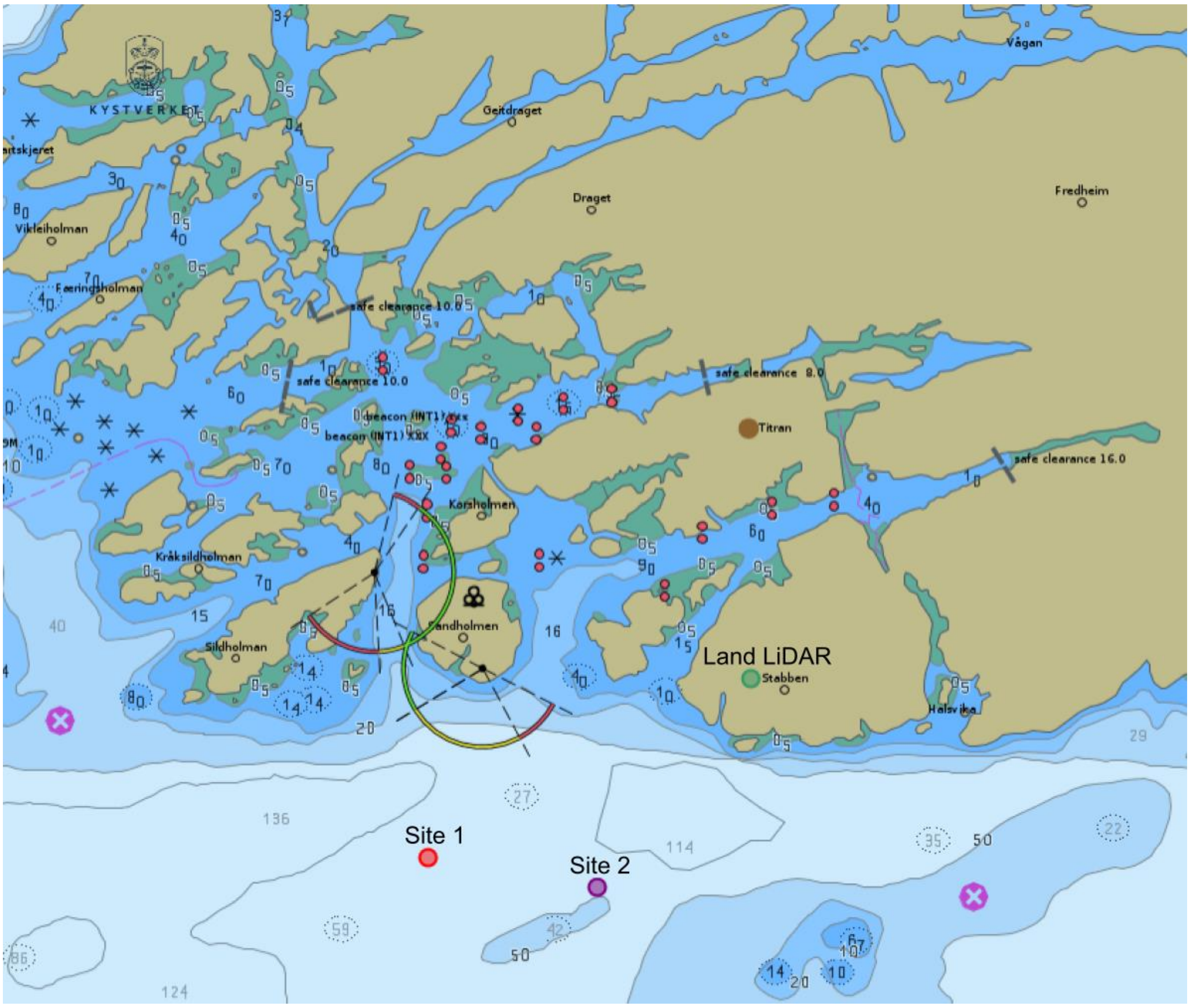


Figure 1: Positions of SWLB (WS170 was deployed at Site 1) and RLL (Land Lidar) near or at the Island Frøya /Stabben.

This report is aimed in documenting the results with respect to the pre-deployment validation trial of the Fugro OCEANOR Seawatch Wind Lidar Buoy (SWLB) with S/N WS 170 against a Reference Land Lidar (RLL) of type ZephIR with the S/N ZP495 at the FO test site near and on the Norwegian Island Frøya at a place called Stabben, in the Norwegian Sea.

1.1 Clarification Note

It is important to note that the validation approach applied for this campaign focusses on the capabilities of floating LiDAR technology (namely in this case for the SWLB with the buoy's S/N WS 170 employing a ZephIR 300 Lidar with the S/N ZP585) measuring primary wind data, namely wind speed and wind direction. Therefore, while the SWLB currently features additional measures the scope of this document is limited to its primary wind data measurements.

DNV GL understands that the tested SWLB Floating Lidar unit is planned to be deployed at *Hollandse Kust (noord)* in the Dutch North Sea sector, and that this campaign serves as the according pre-deployment validation.

DNV GL understands and assumes that there is agreement between FO and their client *Rijksdienst voor Ondernemend Nederland* (RvO) that a pre-deployment validation of an already "Roadmap-Pre-Commercial" staged FLD against a fixed/land based industry accepted Lidar to be used as the only validation reference (Reference Land Lidar, RLL) is acceptable.

It is further understood that the following conditions have to be fulfilled in this validation context:

- The RLL has successfully been validated against an IEC compliant onshore met mast:
→ this is fulfilled by a Lidar validation performed at the ZephIR site in Pershore, UK, independently verified by DNV GL [4]
- The ZephIR Lidar mounted on the SWLB has successfully been validated against an IEC compliant onshore met mast→ this is fulfilled by a Lidar validation performed at the ZephIR site in Pershore, UK, which was reviewed by DNV GL [5]
- The suitability of Frøya test site, i.e. given comparativeness of wind conditions between locations of Reference Land Lidar (RLL) and SWBL
- Setup of RLL in compliance with industry best practice
→ confirmed by installation report from DNV GL [3]
- The wind speed data coverage and bin wise completeness according to the Roadmap [1] is achieved.
- The wind speed and wind direction comparison results yielded according to relevant Roadmap KPIs and ACs meet at least the Roadmap minimum Acceptance Criteria.

The representativeness of wave conditions experienced at the Frøya test site for the projected deployment site should ideally be shown, but the range of conditions may not always be attained for a shorter trial duration and the comparatively calm season in this case. In general, the test site has conditions which are representative for the Dutch site *Hollandse Kust (noord)*. From the SWLB type verification trial at Ijmuiden [6] and further historical evidence DNV GL is confident that the performance of the SWLB device WS170 as shown in this shorter pre-deployment verification campaign can be transferred to more demanding wave conditions than seen in this short verification period at Frøya.

All conclusions on the capabilities of the FO SWLB drawn from this Frøya pre-deployment validation campaign are valid under sea state and meteorological conditions similar to those experienced during the campaign duration, only.

2 SETUP OF THE SWLB PRE-DEPLOYMENT VALIDATIONS

DNV GL has performed a site visit at the Stabben/Frøya site on 2015-03-25 [3] in order to inspect the suitability to serve as a test site for FLD validations. In addition to this, substantial evidence has now been collected by

1. acknowledging the information provided by FO to DNV GL on the side upfront,
2. seeing the generally consistent resemblance between SWLB and RLL at the given spatial separation of 920 m and over the full height range as shown in this report and
3. from the site inspection itself, considering the terrain as rather benign.

With this DNV GL considers Stabben/Frøya test site is suitable for pre-deployment verifications of Floating Lidar Devices (FLD).

In general, DNV GL recommends to regularly re-verify and factory service the RLL – in this case ZP 495 – unit against a suitable onshore reference and to factory service the device in intervals of no longer than 3 (three) years according to OEM recommendations to prove its suitability and validity to serve as reliable reference.

The RLL ZP495 as used in this campaign had been manufactured in early 2015 shortly before it got onshore verified against a reference onshore met mast on the OEM's test site in February 2015. DNV GL has provided an independent assessment report for this initial unit verification in March 2015, see [4].

In conclusion DNV GL confirms that the test site setup was suitable and all used equipment valid for an offshore Floating Lidar verification during this campaign.

2.1 Positions of Installed SWLB and RLL Units

Position of ZephIR Reference Land Lidar (RLL), see Figure 2, right:

- The location is called Stabben on the Island Frøya and the RLL is placed at 14 m above sea level (mean sea level or MSL).
- The GPS position of the RLL is Latitude 63.662920°, Longitude 8.310100°

Position of Seawatch Wind Lidar Buoy (SWLB) Floating Lidar Device, see Figure 2, left:

- The SWLB is deployed at position Latitude 63.658500°, Longitude 8.294400°
- It is moored in 75 m of water depth and the mooring array allows a horizontal sway freedom of movement around the anchor of about 115 m.
- The mooring point is about 800 m from the shore of a place called Stabben and approx. 920 m to the South West of the RLL position, see Figure 1.

These positions were confirmed during a site visit and RLL inspection by DNV GL, on 2015-03-25 [3] (for the RLL) and from direct GPS recordings in the FLD data.

Figure 2: Seawatch Wind Lidar Buoy (left[1]) and Reference Land Lidar as installed near/at Frøya test site.

2.2 Settings and Specs of SWLB and RLL Units

<u>SWLB Floating Lidar:</u>

- SWLB S/N WS 170
- ZephIR S/N ZP585
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 40 m relative to actual sea level

<u>Reference Land Lidar:</u>

- ZephIR S/N ZP495
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 40 m above mean sea level

These specs and height settings are confirmed from

- original ZephIR product data (ZPH-files) for both units provided by FO, and
- during the site visit and RLL inspection by DNV GL, on 2015-03-15 [3].

[1] The shown LiDAR buoy is similar to the validated one

Table 1: List of heights relevant for wind data comparisons between SWLB and RLL (green shading, targeted heights above MSL/SL

	Land Reference Lidar Device		Floating Lidar Device	
Window Height	14 *meter*		2 *meter*	
Height Index	**Height AMSL [m]**	**Configured height [m]**	**Height AMSL [m]**	**Configured height [m]**
0			4	**Gill sensor**
1	200	**186**	200	**198**
2	180	**166**	180	**178**
3	160	**146**	160	**158**
4	140	**126**	140	**138**
5	120	**106**	120	**118**
6	100	**86**	100	**98**
7	80	**66**	80	**78**
8	60	**46**	60	**58**
9	40	**26**	40	**38**
10	30	**16**	30	**28**
11	**52**	**(Non-configurable)**	**40**	**(Non-configurable)**

The assessment of the KPIs and their respective Acceptance Criteria regarding wind data accuracy was performed at height levels between 40 m and 200 m as mentioned in Table 1.

All data collected from the deployment 2017-03-02 of SWLB until its decommissioning on 2017-03-21 were taken into account in the overall data processing scheme, regardless of the environmental conditions.

3 VALIDATION RESULTS

For the pre-deployment validation of FO's SWLB against the RLL data from the employed FLD ZephIR 300 LiDAR with the serial number ZP585 and from the RLL ZephIR with the serial number ZP495 were provided by FO for a campaign period lasting 2017-03-02 to 2017-03-21, yielding a duration of 18.8 days.

3.1 Data provision

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

- RLL and SWLB data were provided to DNV GL for the whole campaign period by FO, directly.
- SWLB LiDAR wind statistics were returned by the central controller unit (called GENI) installed on the SWLB. This unit collected the 1-sec raw data from the on-board ZephIR 300 Lidar to calculate the 10 minute wind data statistics.

3.2 Meteorological and sea state conditions during the trial

During the validation period of the SWLB the device encountered a wide range of wind conditions facing 10 minute averaged wind speeds at the RLL of up to 23.6 m/s at the lowest comparison level (40 m) and 28.3 m/s at the upper most level (200 m) – see Table 2. The air temperatures covered during the campaign at the RLL location and on the SWLB buoy range from -3.4°C to +7.9°C, related time series are displayed in Appendix B.

The significant wave heights observed during the trial period at Frøya were in a range up to 5.6 m, with 29.8 % of the observations above 1.5 m. The experienced maximum wave heights cover a range up to 9.2 m. Compare Appendix C for wave statistics as provided by FO. The wave measurements were recorded by the SWLB under trial itself using a 10 min data acquisition and processing interval.

The tidal or water level as observed during the campaign at a place in the North of Frøya called Mausund varies between –1.2 and +1.5 m over MSL. See related time series plot in Appendix C.

Table 2: Maximum 10 min averaged wind speeds measure at the RLL and by the SWLB across the total campaign period.

WS Max	RLL	SWLB
Level / [m]	WS [m/s]	
40	23.60	23.32
60	24.70	21.62
80	25.58	25.72
100	25.99	25.90
120	26.68	26.66
140	27.26	26.37
160	27.81	27.01
180	28.07	27.48
200	28.26	27.48

3.3 Accuracy

DNV GL has analysed the wind data against the relevant KPIs and Acceptance Criteria given in [1] and in Appendix A which are related to the WS and WD accuracy of the SWLB unit.

The comparisons in this section are based on ten-minute average values at both the floating LiDAR unit and the RLL. For the analysis conducted in this section, a low wind speed cut-off of 2 m/s has been applied for the wind speed comparisons and for the wind direction comparisons.

3.3.1 Data coverage requirements for accuracy assessment

In accordance with the data coverage requirements outlined in the Roadmap [1], DNV GL has assessed the data coverage of the floating LiDAR system at the nine (9) 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.
→ This criterion has been fulfilled.

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.
→ This criterion has been fulfilled.

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 criterion is not mandatory.

Table 3 gives an overview of the data coverage. It shows that for all probing levels all WS bins up to 18 m/s have sufficiently been filled.

Table 3: Wind speed data coverage per WS bin. Bins including at least 40 values 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	26 to 28	28 to 30
Bin Center	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	27	29
Level / [m]	RLL number of 10 min data entries per WS bin - AFTER filtering for data to be used for regression analysis																		
40	153	194	244	308	283	176	141	111	100	62	177	98	84	51	44	12	0	0	0
60	156	179	226	301	285	149	155	139	108	70	169	95	97	38	51	29	4	0	0
80	162	183	208	300	282	144	142	156	102	82	165	106	90	36	52	41	9	0	0
100	159	174	195	303	270	152	135	149	121	93	162	111	88	44	40	48	17	0	0
120	153	173	196	304	246	154	137	122	137	101	164	115	94	43	39	50	23	2	0
140	151	172	185	314	236	149	131	129	119	108	180	112	96	49	36	56	26	4	0
160	149	183	188	302	225	148	128	122	119	94	193	119	93	60	32	58	29	10	0
180	149	176	206	291	218	136	128	112	114	86	200	123	108	63	38	56	35	10	1
200	151	174	202	304	199	137	125	107	113	79	203	123	116	68	40	54	44	10	2

3.3.2 Wind speed accuracy

A summary of the findings for each wind-speed-related KPI is presented in Table 4. The wind speed accuracy assessment has been conducted at nine heights between 40 and 200 m above MSL.

The slopes (X_{mws}) and Coefficient of Determination (R^2_{mws}) are presented for all compared heights. It can be seen that the KPI for slope at heights between 60 and 200 m fulfils the best practice acceptance criterion [0.98 > X_{MWS} > 1.02] as given in [1]. However, for the measurement level 40 m, the slope is still within the minimum acceptance criterion [0.97 > X_{MWS} > 1.03].

With regards to the Coefficient of Determination (R^2_{mws}) the best practice acceptance criterion [R^2_{mws} > 0.98] is fulfilled for the heights 40 to 140 m. The minimum acceptance criterion [R^2_{mws} > 0.97] is passed at all heights. Plots for WS regression results together with WS time series plots selected for a few comparison levels can be found in Appendix B.

Table 4: Overview of linear regression analysis results for wind speed comparisons between the SWL Buoy and the reference Lidar at all available comparison levels. Colour shading indicates the compliance with the prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

WS comparison		slope	regr. coeff.	WS RLL avg	WS FLD avg	WS diff.	relative WS diff.
		KPIs					
Level / [m]	#	X_{mws}	R^2_{mws}				
40	2238	1.025	0.987	8.22	8.42	0.21	2.5%
60	2251	1.016	0.989	8.47	8.61	0.15	1.7%
80	2260	1.014	0.989	8.62	8.76	0.14	1.6%
100	2261	1.015	0.988	8.77	8.92	0.16	1.8%
120	2253	1.017	0.984	8.92	9.09	0.17	1.9%
140	2253	1.016	0.983	9.05	9.22	0.17	1.9%
160	2252	1.013	0.976	9.17	9.33	0.16	1.7%
180	2250	1.010	0.978	9.32	9.46	0.13	1.4%
200	2251	1.010	0.972	9.46	9.60	0.14	1.5%

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.3.3 Wind direction accuracy:

The wind direction data comparison was conducted at the same nine (9) heights between 40 and 200 m above MSL.

The results for the wind direction comparison are shown in Table 5 where the Wind Direction Regression Slope (M_{mwd}), the Mean Offset (OFF_{mwd}) and the Coefficient of Determination (R^2_{mwd}) are presented. All KPI values for R^2_{mwd}, OFF_{mwd} and M_{mwd} fall within the best practice acceptance criteria. Plots for WD regression results selected for a few heights can be found in Appendix B.

Table 5: Overview of linear regression results for WD comparisons between SWLB and reference Lidar at the nine (9) WD comparison levels. Colour shading indicates compliance with prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

WD comparison		slope	regr. Coeff.	mean diff.
		KPIs		
Level / [m]	#	M_{mwd}	R^2_{mwd}	OFF_{mwd}
40	2238	0.992	0.995	-1.20
60	2251	0.993	0.993	-1.25
80	2260	0.992	0.993	-1.27
100	2261	0.994	0.993	-1.42
120	2253	0.994	0.993	-1.34
140	2253	0.993	0.993	-1.36
160	2252	0.995	0.992	-1.58
180	2249	0.995	0.992	-1.67
200	2251	0.993	0.984	-1.60

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.4 Summary of verification results

3.4.1 Campaign Duration

The duration of the verification campaign was 18.8 days. The test period was sufficient to achieve the required data completeness in all required WS bins for data analysis, being compliant to the Roadmap in terms of significance of SWLB wind data accuracy results.

3.4.2 Wind Measurement Accuracy

The wind speeds of both the SWLB and the RLL at all comparison heights correlated very well, showing a low level of scatter and good agreement in terms of linear regression analyses. This comparison campaign indicates that the SWBL is able to reproduce fixed Lidar wind speeds at a high level of accuracy. The Best Practice criteria for the KPI "Mean Wind Speed – Slope" were passed at heights between 60 and 200 m. The "Mean Wind Speed – Coefficient of Determination" passed the minimum acceptance criterion at heights between 40 and 200 m.

For wind direction Best Practice criteria for the KPIs "Mean Wind Direction – Slope", "Mean Wind Direction – Coefficient of Determination" and "Mean Wind Direction – Offset" were passed at all comparison heights, indicating the SWLB's capability of reproducing fixed Lidar wind directions at a very high level of accuracy.

The detailed results with respect to KPIs and ACs for wind speed and wind direction comparisons are given in Table 6 below.

Table 6: Summary of achievement after 19.4 days with regards to KPIs and Acceptance Criteria for the data accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria across total campaign duration	
		Best Practice	**Minimum**
X_{mws}	**Mean Wind Speed – Slope** Assessed for wind speed range [all above 2 m/s]	0.98 – 1.02 Results: [1.010 to 1.017] Passed at compared heights 60 to 200 m	0.97 – 1.03 Results: Passed at all compared heights
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Assessed for wind speed range [all above 2 m/s]	>0.98 Results: [0.983 to 0.987] Passed at compared heights 40 to 140 m	>0.97 Results: Passed at all compared heights
M_{mwd}	**Mean Wind Direction – Slope** Assessed for wind speed range [all above 2 m/s]	0.97 – 1.03 Results: [0.992 to 0.995] Passed at all compared heights	0.95 – 1.05
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97 Results: [0.984 to 0.995] Passed at all compared heights	> 0.95
OFF_{mwd}	**Mean Wind Direction – Offset, in terms of the mean absolute WD difference over the total campaign duration** (same as for M_{mwd})	< 5° Results: [-1.60 to -1.20] Passed at all compared heights	< 10°

4 REMARKS AND LIMITATIONS

4.1 General

The presented results have to be regarded under the following reservations and limitations:

- Both data sets, (a) the one for the Reference Land Lidar (RLL) and (b) the one for the SWLB were visible to Fugro/OCEANOR (FO), i.e. they've had full access to the data from the tested device and from the reference data. However, with regards to (a) DNV GL has had direct access to the respective ZephIR RLL unit and has downloaded the data directly. The FLD data set (b) – stemming directly from the buoys original raw data – was sent to DNVGL in a single batch. Hence, DNV GL has no doubts in the integrity of reference and FLS data.
- In the WS regressions for the heights between 40 m and 200 m a slight decrease (improvement) of the slope towards unity with increasing height can be detected. This indicates a slight ground friction effect on the RLL data which tends to decrease with height. However, all "forced" (through the origin) regression slopes are within the Roadmap allowance, i.e. below 1.03. And the yielded coefficients of determination are above 0.97. They are indicating that non-synchronicity at the mentioned distance between SWLB and RLL of approx. 920 m seems to be no issue.
- All conclusions on the capabilities of the SWLB drawn from this Frøya pre-deployment verification campaign are valid under sea states and meteorological conditions similar to those experienced during this trial, only.

4.2 Pre- and Post-Deployment Verification

DNV GL recommends in general that a FLS unit undergoes a pre-deployment verification test no greater than one year prior to commencing the wind resource measurement campaign deployment.

Furthermore, DNVGL confirms manufacturers recommendation (OEM in this case ZephIR Ltd.) of a three years' factory service interval for ZephIR 300 type Lidar. DNV GL recommends following such service intervals in order to sufficiently minimizes the risk of malfunctions and degradations of a Lidar device during a deployment period.

A post-deployment verification of a FLS can be necessary, in case of e.g.

- inconsistencies in the data time series or the operation of the buoy being observed
- known or assumed incidents to the buoy or FLS measurement system

during wind resource measurement campaign. Otherwise a pre-deployment verification campaign may be considered sufficient.

4.3 Design Specifics of WS170

During the course of the validation campaign DNV GL has been informed by FO that this buoy WS 170 has received design changes (now version 2.0) compared to the unit (design version 1.0) trialled in the FLS type verification at IJmuiden in 2014/2015 [6] with regards to (1) using a marinized version of the employed Z300 type Lidar, (2) adding extra buoyancy to the buoy assembly and (3) adding another 6 methanol fuel tanks to the already existing 10 tanks, i.e. increasing the maximum weight of the buoy by 325 kg when completely fuelled.

(1) The ZP-Lidar Z585 used on the buoy is a marinized version of the Z300 type Lidar with improved connectors, i.e. more corrosion resistant materials have been used compared to the standard onshore type. DNV GL considers that this will have no effect on quality of wind data measured by the Lidar.

(2) The buoy assembly has been supplied with an extra buoyancy ring. DNV GL has performed a high-level desktop assessment of the change in buoy design (from version 1.0 to 1.5) with regards to motion in response to waves and currents, based on drawings of the new buoy design provided by FO [7]. As a result based on this documentation DNV GL considers the change negligible for motion types like rotation, pitch and role. The motion damping actually seems to be improved. Based on the documentation of the change available to DNV GL and noticing that the anchoring and mooring array design has properly been adapted and reviewed by FO in response to changes of weight, total buoyancy and size, and therefore for wave loadings as documented in FO's internal mooring design report no. C75342-02-03 [8], DNV GL considers that the statements with regards to wind data quality and data availability given for the former (original) buoy design in relation to the Roadmap related achievements [1, 6] should as well hold for the new buoy design.

(3) The number of fuel tanks has been increased from 10 to 16, the fuel cell compartments have been adopted and PV cell mounting has changed. These measures increase the total weight of the buoy when completely fuelled by 325 kg. DNV GL has performed a high-level desktop assessment of this further change in buoy design version 2.0 (compared to version 1.0 and 1.5) with regards to motion in response to waves and currents. This assessment was based on a drawing together with information on the change of centre of gravity and change in natural frequency due to the increase of weight of the new buoy design 2.0 provided by FO [10]. From this DNV GL concludes that the expected behaviour of the buoy (with the latest design) in response to wave excitation is going to be well within the envelope as set by both previous buoy designs, i.e. the one with the original floater (version 1.0 as type verified at IJmuiden[6]) and the one with increased buoyancy (version 1.5, as verified at East Anglia [10]). Hence, DNV GL considers that the statements with regards to wind data quality and data availability given for the original buoy design (1.0) with regards to the Roadmap related achievements [1, 6] should as well hold for the latest buoy design (2.0) of SWLB WS170.

5

5 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

An evaluation of the Fugro/OCEAN Seawatch Wind Lidar Buoy floating LiDAR system was completed by comparing its measurements against data of a Reference Land Lidar installed on the Island Frøya in the Norwegian Sea. Sufficient data in terms of WS data completeness and coverage were collected to allow an assessment in line with the Roadmap for commercialization of Floating Lidar Devices [1].

DNV GL concludes that the FO SWBL unit with the S/N 170 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. significant wave heights of > 5.6 m (and > 9.2 m for maximum wave height) were recorded by the Buoy. The Lidar wind speeds recorded at Frøya covered a range of up to 23.6 m/s at 40 m and 28.3 m/s at 200 m.

The assessments of the Roadmap KPIs for the complete data set (from 2017-03-02 until 2017-03-21) show that all FLD-Roadmap Acceptance Criteria for wind speed are met at heights between 40 and 200 m and all FLD-Roadmap Acceptance Criteria for wind directions are met at heights between 40 and 200 m, passing best practice or minimum CT Roadmap acceptance criteria.

FLD Roadmap related WS bin wise data completeness was achieved for all WS bins up to 18 m/s at all treated comparison heights.

DNV GL considers that the statements on Lidar type commercial maturity with regards to wind data quality and data availability given for the original buoy design (1.0) with regards to the Roadmap related maturity stage 2 [1, 6] is as well valid for the current buoy design (2.0) of SWLB WS170.

Finally, DNV GL emphasizes that according to recommended practice this offshore Floating Lidar verification can serve as a pre-deployment verification if the time from the end of this campaign until the following deployment is no longer than 12 months. In this context DNV GL recommends complying with Lidar OEM’s suggested service intervals, i.e. at a maximum of 3 years for this ZephIR 300 type Lidar with the S/N ZP585.

6 REFERENCES

[1] Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology. CTC 819 Version 1.0, The Carbon Trust, 21 November 2013.

[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] DNV GL Report GLGH-4275 13 10378 271-T-0003-A, Draft, "Technical note for inspection of Reference Land Lidar at Frøya", May 2015.

[4] DNV GL Report GLGH-4257 13 11068 267-R-0021-A, "ZP495 Independent analysis and reporting of ZephIR Lidar performance verification executed by ZephIR Ltd. At their test site and reference mast in Pershore, UK", dated 2015-03-27

[5] ZephIR Lidar Ltd. internal report "Functional test & full performance verification of ZephIR 300 Lidar ZP585" dated 2016-11-14.

[6] DNV GL Report GLGH-4257 13 10378 266-R-0003 Issue B , "ASSESSMENT OF THE FUGRO/OCEANOR SEAWATCH FLOATING LIDAR VERIFICATION AT RWE IJMUIDEN MET MAST", dated 2015-01-30.

[7] Arve Berg, Fugro OCEANOR Report , "EXTRA BUOYANCY LIDAR BUOY - IMPLEMENTATION", dated 2015-05-05.

[8] Fredrik Dessen, Fugro OCEANOR Mooring design report No. C75342-02-03, "Lidar for Carbon Trust Wavescan hull with extra buoyancy", dated 2015-06-12

[10] Fugro drawing of SWL double hull (16 fuel cans) - General Dimensions as pdf document, dated 2016-10-27

APPENDIX A – APPLIED KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA FOR FLD PRE-DEPLOYMENT VALIDATION

Wind Data 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 the reference ; and,

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 the reference.

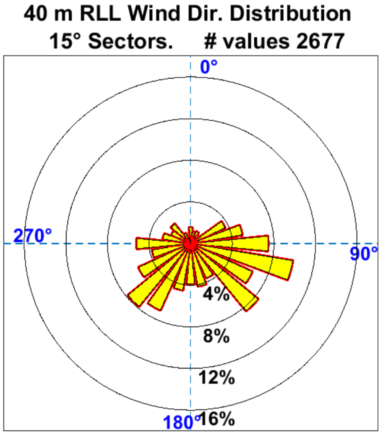
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

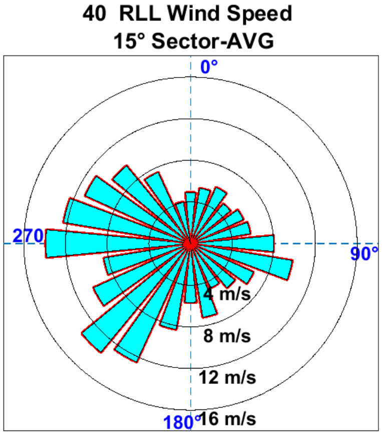
KPI	**Definition / Rationale**	**Acceptance Criteria**	
		Best Practice	**Minimum**
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed range a) 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** Coefficient returned from single variant regression A tolerance is imposed on the Coefficient value. Analysis shall be applied to wind speed range a) all above 2 m/s given achieved data coverage requirements.	>0.98	>0.97

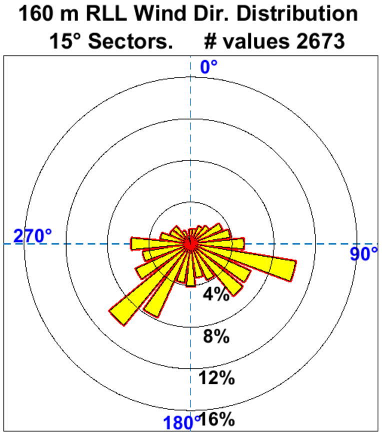
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of 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

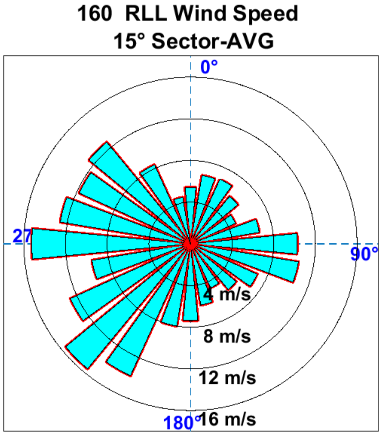
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

Polar plots of wind directions and wind speed for 40 m and 160 m comparison heights:

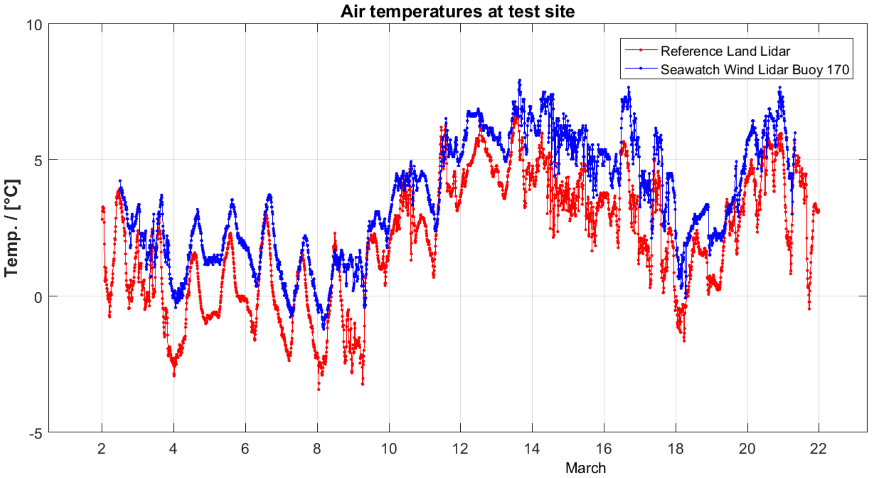




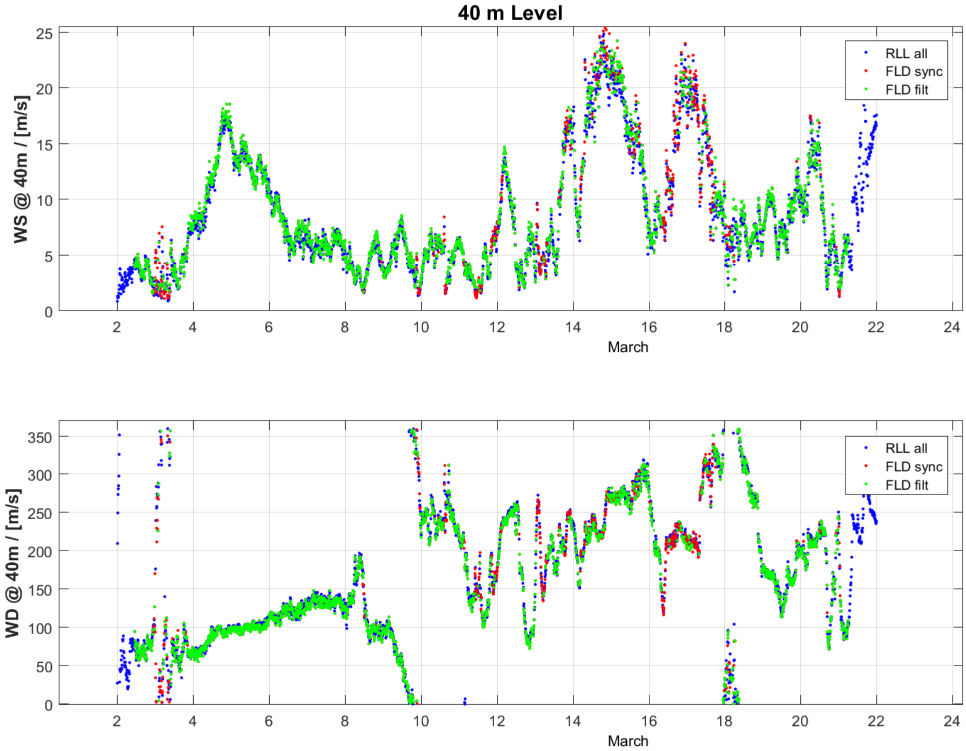


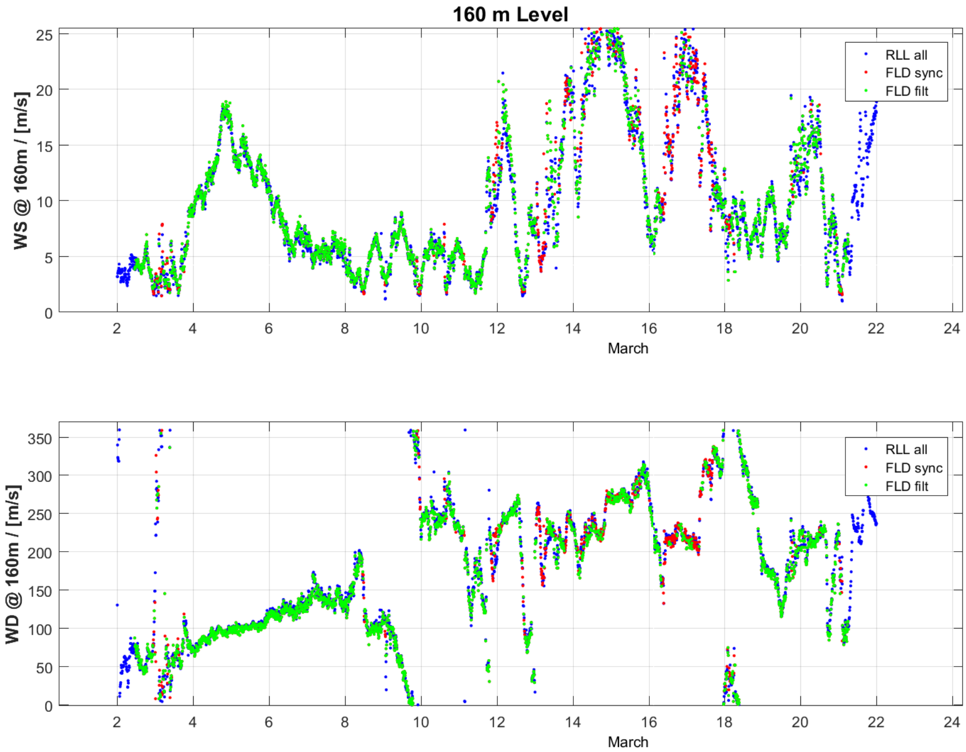


Time series of air temperature at RLL location and on SWLB:



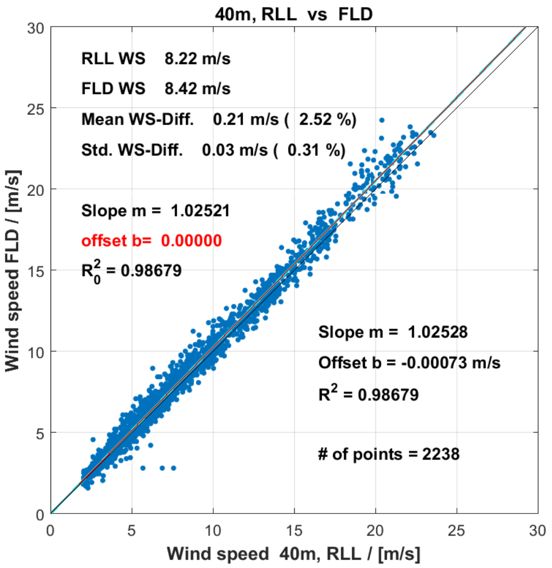
Wind speed and wind directions time series for 40 m and 160 m comparison heights:

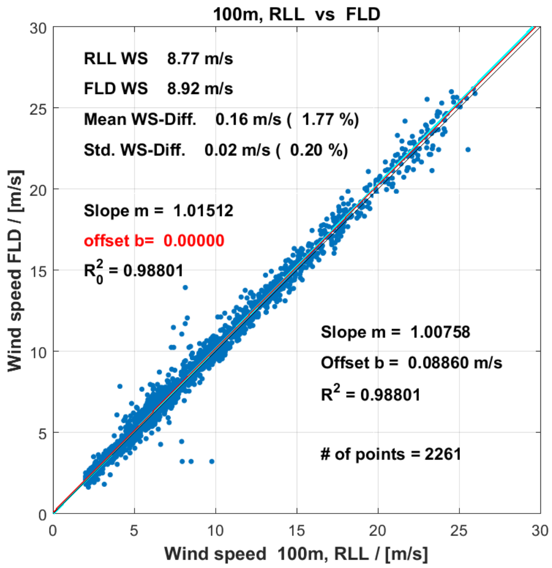


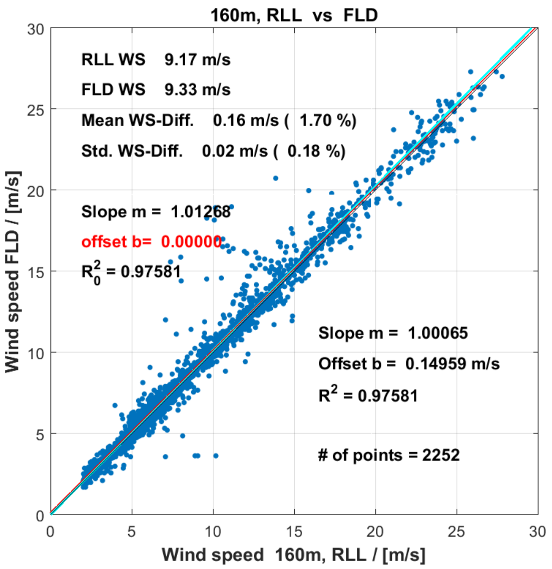


WS regression plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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

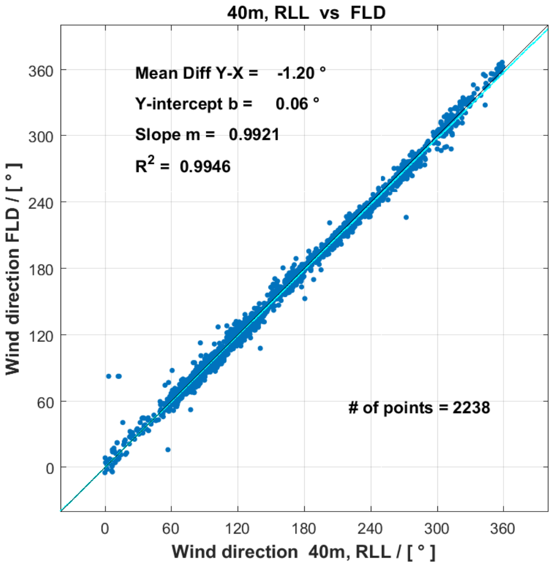


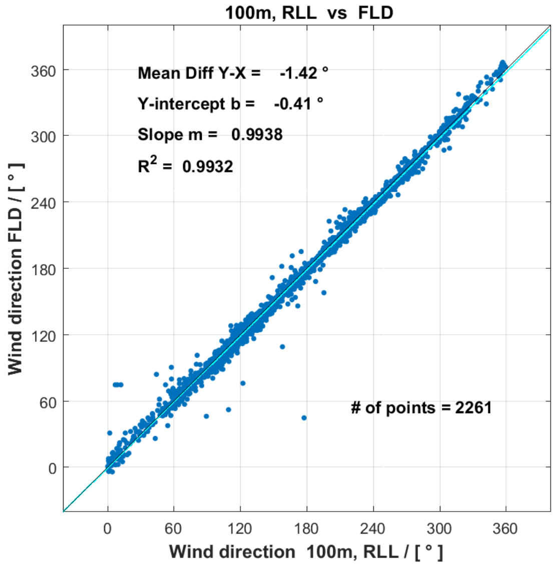


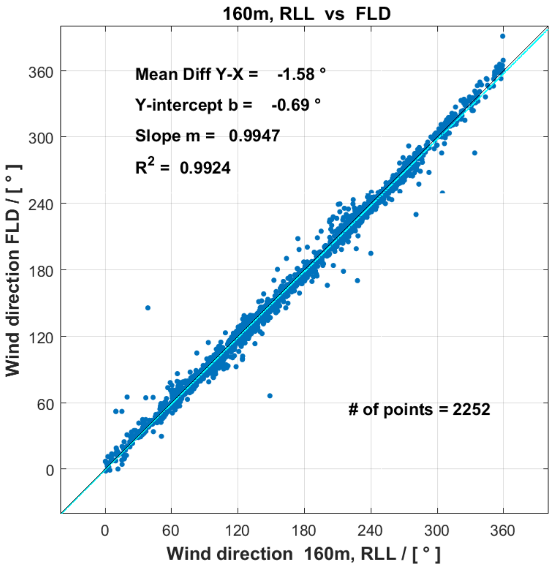


WD correlation plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

Shown are results for linear “un-forced” WD regressions “un-forced” linear WS regressions, yielding as well the WD offset in terms of intercept of the regression line of the y-axis and in terms of the mean WD difference.







APPENDIX C – WAVES AND TIDES

Mean wave period and significant wave height distribution across total campaign period:

Tm02 Mean wave period (Tm02) (s) Slettringen, Wavescan buoy
Hm0 Significant wave height (m) Slettringen, Wavescan buoy

Measuring depth : 0.00 m
Water depth : 75.00 m
Sampling interval:
Period : 2017.03.02 12:00 - 2017.03.21 08:29

Tm02 (s)	2	3	4	5	6	7	8	9	10	11	12	>=	SUM	% OF	SUM	CUM	MIN.	AVE.	MAX.	STD.
Hm0 (m)	3	4	5	6	7	8	9	10	11	12	13	13		TOTAL	ACC.	PROB.				DEV.
0.0 - 0.5	92	68	31	139	60								390	14.4	390	0.1440	0	4.6	6.7	1.3
0.5 - 1.0	55	150	132	253	260	89	38	10					987	36.5	1377	0.508	2.7	5.5	9.7	1.5
1.0 - 1.5		3	55	101	171	120	36	36	2				524	19.4	1901	0.702	3.3	6.7	10.2	1.3
1.5 - 2.0			44	79	84	37	20						264	9.8	2165	0.799	4.7	6.2	9	1.1
2.0 - 2.5				40	32	36							108	4	2273	0.839	5.1	6.4	7.9	0.8
2.5 - 3.0				18	26	49	18						111	4.1	2384	0.880	5.5	7	8.3	0.9
3.0 - 3.5					74	35	15						124	4.6	2508	0.926	6.1	7	8.4	0.7
3.5 - 4.0					43	14	18						75	2.8	2583	0.954	6.3	7.2	8.7	0.7
4.0 - 4.5					2	30	20						52	1.9	2635	0.973	6.8	7.7	8.9	0.5
4.5 - 5.0						11	27						38	1.4	2673	0.987	7.4	8.3	8.9	0.4
5.0 - 5.5							28	3					31	1.1	2704	0.998	8	8.7	9.2	0.3
5.5 - 6.0								2					2	0.1	2706	0.999	9.1	9.1	9.2	0
>= 6.0													0	0	2706	0.99963				
SUM	147	221	262	630	752	421	220	51	2	0	0	0	2706	100	2706	0.999	0	6	10.2	1.58
% OF TOTAL	5.4	8.2	9.7	23.3	27.8	15.6	8.1	1.9	0.1	0	0	0	100							
SUM ACCUM.	147	368	630	1260	2012	2433	2653	2704	2706	2706	2706	2706	2706							
CUM. PROB.	0.0543	0.1359	0.2327	0.4655	0.7433	0.8988	0.9801	0.9989	0.9996	0.9996	0.9996	0.9996	0.99963							
MIN. VALUE	0.33	0.29	0.39	0.31	0.31	0.55	0.61	0.84	1.41				0							
AVE. VALUE	0.49	0.64	1	1.04	1.51	1.99	2.87	1.55	1.43				1.41							
MAX. VALUE	0.68	1.04	1.93	2.97	4.12	4.98	5.49	5.64	1.45				5.64							
STD. DEV.	0.08	0.2	0.43	0.59	0.98	1.16	1.65	1.28	0.02				1.1							

Highest wave period and maximum wave height distribution across total campaign period:

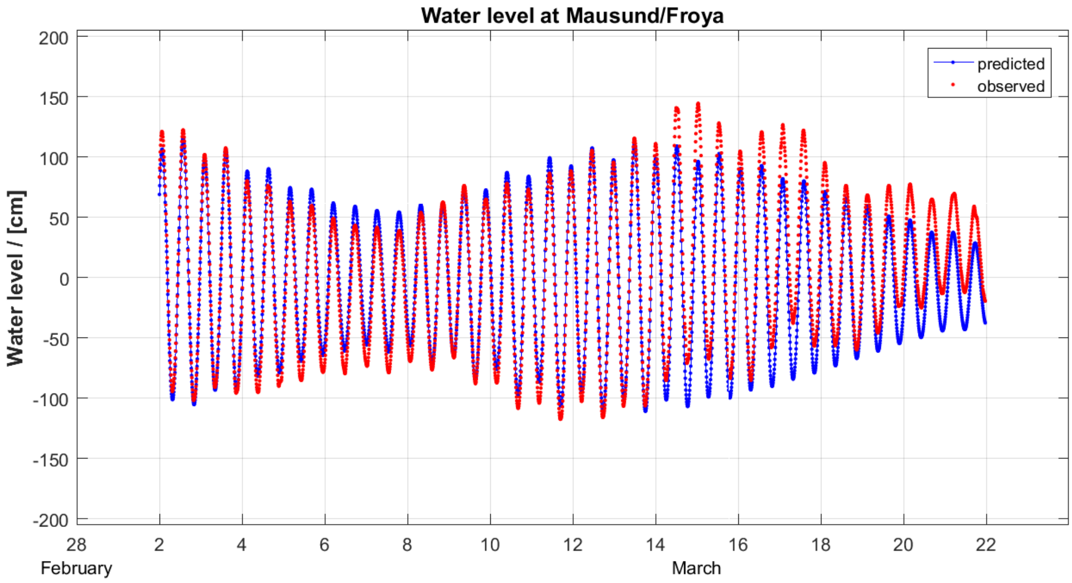
THmax Period of highest wave (s) Slettringen, Wavescan buoy
Hmax Maximum wave height (m) Slettringen, Wavescan buoy

Measuring depth : 0.00 m
Water depth : 75.00 m
Sampling interval:
Period : 2017.03.02 12:00 - 2017.03.21 08:29

THmax (s)	2	3	4	5	6	7	8	9	10	11	12	>=	SUM	% OF	SUM	CUM.	MIN.	AVE.	MAX.	STD.
Hmax (m)	3	4	5	6	7	8	9	10	11	12	13	13		TOTAL	ACC.	PROB.				DEV.
0.0 - 0.5	5	7	5	3	8	6	19	13	5	5	5	33	114	4.2	114	0.04213	2.7	10.9	24.9	5.9
0.5 - 1.0	15	92	11	25	41	63	118	79	59	54	38	42	637	23.5	751	0.27753	2.7	8.5	24.7	3.5
1.0 - 1.5		30	11	10	20	65	104	126	136	77	34	69	682	25.2	1433	0.52956	3.3	9.8	18.8	2.6
1.5 - 2.0				3	14	54	67	94	74	48	15	11	380	14	1813	0.66999	5.2	9.6	16.5	1.7
2.0 - 2.5			1	4	19	39	48	23	37	22	8	4	205	7.6	2018	0.74575	5	9.1	13.9	1.8
2.5 - 3.0			2	8	18	18	28	18	23	14	14	5	148	5.5	2166	0.80044	4.8	9.1	13.4	2.1
3.0 - 3.5				2	6	18	13	13	23	3	1	4	83	3.1	2249	0.83112	5.9	9.2	14.6	1.8
3.5 - 4.0				2	5	11	10	17	19	11	4	3	82	3	2331	0.86142	5.8	9.6	14.3	1.9
4.0 - 4.5					1	9	10	14	26	19	3	4	86	3.2	2417	0.8932	6.7	10.2	14.9	1.6
4.5 - 5.0					4	7	10	12	17	14	9	3	76	2.8	2493	0.92129	6.4	10.1	13.3	1.8
5.0 - 5.5					2	7	3	9	7	13		1	42	1.6	2535	0.93681	6.2	9.8	13.1	1.7
5.5 - 6.0					2	1	3	14	13	6	7	3	49	1.8	2584	0.95491	6.7	10.5	14.9	1.8
6.0 - 6.5							3	3	10	11	6	2	35	1.3	2619	0.96785	8.6	11.1	15	1.4
6.5 - 7.0							3	4	8	11	11	3	40	1.5	2659	0.98263	8.7	11.3	13.7	1.3
7.0 - 7.5						2		1	3	6	3	3	18	0.7	2677	0.98928	7.1	11.4	15.9	2.1
7.5 - 8.0								4	8	5		2	19	0.7	2696	0.9963	9.1	11	15.3	1.4
8.0 - 8.5									1	3	1		5	0.2	2701	0.99815	10.9	11.8	12.6	0.5
8.5 - 9.0										1			1	0	2702	0.99852	11.7	11.7	11.7	0
9.0 - 9.5												3	3	0.1	2705	0.99963	13.4	13.8	14	0.3
>= 9.5													0	0	2705	0.99963				
SUM	20	129	30	57	140	300	439	444	469	323	159	195	2705	100	2705	0.99963	2.7	9.5	24.9	2.85
% OF TOTAL	0.7	4.8	1.1	2.1	5.2	11.1	16.2	16.4	17.3	11.9	5.9	7.2	100							
SUM ACCUM	20	149	179	236	376	676	1115	1559	2028	2351	2510	2705	2705							
CUM. PROB.	0.0074	0.0551	0.0661	0.0872	0.139	0.2498	0.412	0.5761	0.7494	0.8688	0.9276	0.9996	0.99963							
MIN. VALUE	0.44	0.44	0.35	0.41	0.35	0.44	0.38	0.38	0.38	0.41	0.44	0.35	0.35							
AVE. VALUE	0.56	0.83	1.06	1.39	1.82	1.96	1.75	2.07	2.45	2.69	2.57	1.77	2.05							
MAX. VALUE	0.73	1.35	2.93	3.87	5.89	7.12	6.83	7.68	8.38	8.55	8.06	9.23	9.23							
STD. DEV.	0.08	0.22	0.64	0.96	1.24	1.26	1.24	1.54	1.75	2.07	2.13	1.9	1.65							

Note that the number of Hmax observations is lower than the number of Hm0 observations. As of FO this is because the single waves can’t be identified properly in nearly calm sea states.

Time series of tidal/water level at Mausund, Frøya over total campaign period:



End of report

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.