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FRØYA SEAWATCH WIND LIDAR BUOY WS 149
POST-DEPLOYMENT VALIDATION

Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 149 Post-Deployment Validation at Frøya, Norway

Fugro Norway AS

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Task and objective: 3rd Party Assessment of an Offshore/Nearshore Post-Deployment Validation of the Fugro/Oceanor SEAWATCH Wind LiDAR Buoy WS 149 at the Island Frøya, Norway

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

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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 2017-03-08, 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 post-deployment validation campaign and to provide a validation report for a SEAWATCH Wind LiDAR Buoy (SWLB) unit with the serial number WS 149 moored next to the Island Frøya in the Norwegian Sea.

WS149 was deployed at Borssele for RVO.nl. This buoy was pre-deployment validated in March 2015 at Frøya and shall now be post validated. This will also act as pre-deployment validation for Hollandse Kust (noord). WS149 is deployed on the same position as of the pre-deployment validated in March 2015.

The post-deployment validation of this already "Roadmap-Pre-Commercial" staged Floating Lidar Device (FLD) [1] was performed over a period of 19.4 days against a fixed/land based industry accepted Lidar (Reference Land Lidar or RLL), that was used as the only validation reference. 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 2017-02-03 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 2017-02-22.

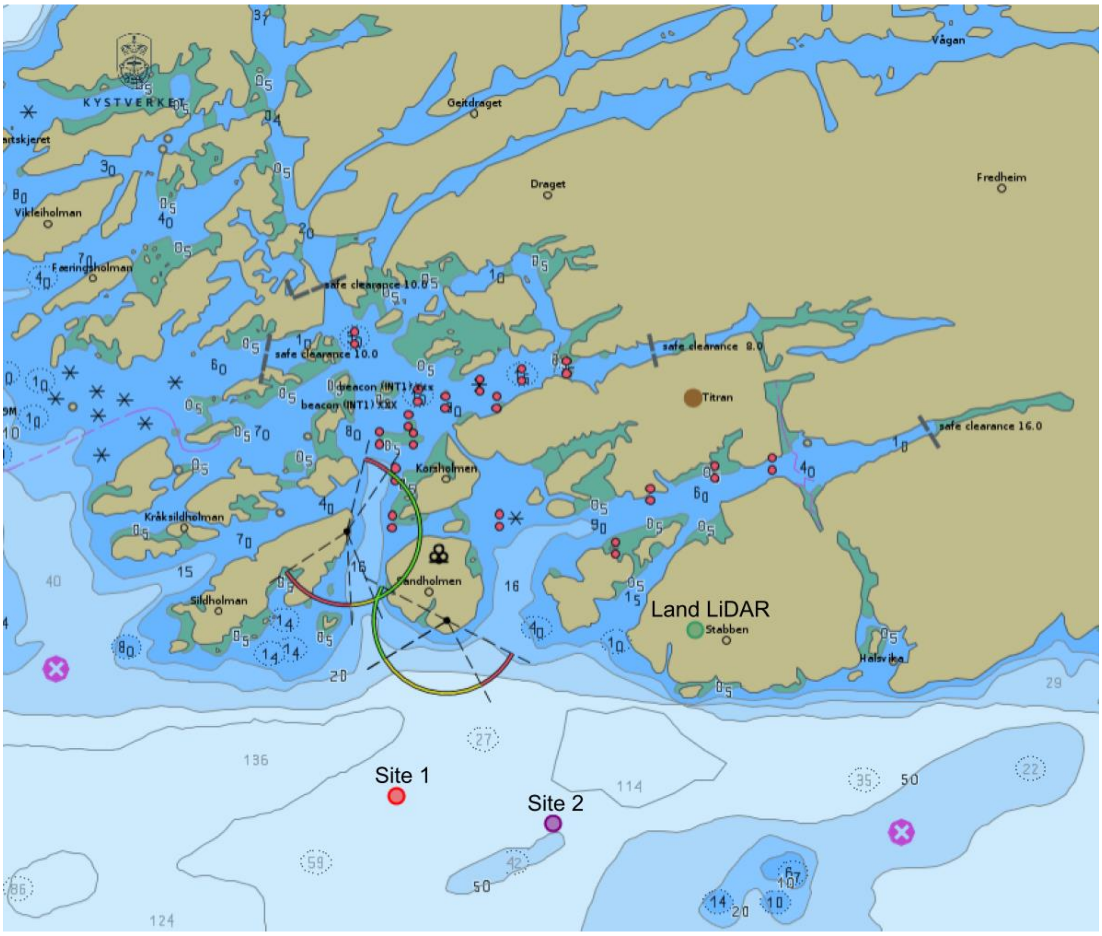


Figure 1: Positions of SWLB (WS149 was deployed at Site 1) and RLL (Land Lidar) near or at the Island Frøya /Stabben.

This report is aimed in documenting the results with respect to the post-deployment validation trial of the Fugro OCEANOR Seawatch Wind Lidar Buoy (SWLB) with S/N WS 149 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 149 employing a ZephIR Lidar with the S/N ZP428) 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 with serial no. WS149 was first deployed at the Borssele Wind Farm Zone (BWFZ) in the Dutch sector of the North Sea on 2015-06-11 with the bottom mooring weight at position 51° 42.41388' N, 3° 2.07708' E. In the remaining 2015 and until 19th January 2016-01-19, the SWLB WS149 was used for wind resource measurements at Borssele. After that it has also been used as onshore spare and deployed at the *Hollandse Kust (zuid)* project until it was finally serviced in Trondheim and then post validated at Froya.

The post deployment validation will also act as pre-deployment validation for *Hollandse Kust (noord)*. WS149 is deployed on the same position as when it was pre-deployment validated in March 2015.

DNV GL understands and assumes that there is agreement between FO and their client *Rijksdienst voor Ondernemend Nederland* (RVO.nl) that a post-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.

All conclusions on the capabilities of the FO SWLB drawn from this Frøya post-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 POST-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 post-deployment verifications of Floating Lidar Devices (FLD).

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.

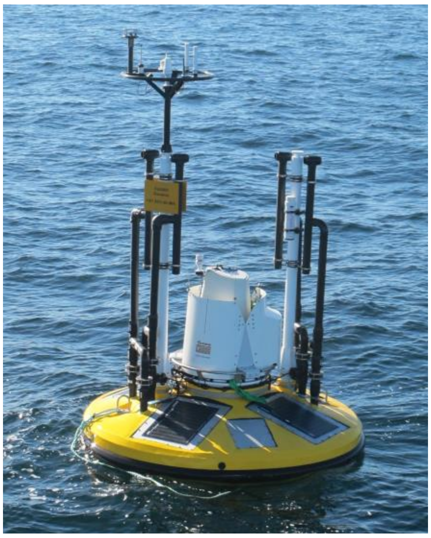


Figure 2: Seawatch Wind Lidar Buoy (left[1]) and Reference Land Lidar as installed near/at Frøya test site.

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

2.2 Settings and Specs of SWLB and RLL Units

SWLB Floating Lidar:

- SWLB S/N WS 149
- ZephIR S/N ZP428
- Height settings[2] 200, 180, 160, 140, 120, 100, 80, 60, 40 m relative to actual sea level

Reference Land Lidar:

- ZephIR S/N ZP495
- Height settings[1] 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].

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

Window Height	Land Reference Lidar Device 14 *meter*		Floating Lidar Device 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 2017-02-03 of SWLB until its decommissioning on 2017-02-22 were taken into account in the overall data processing scheme, regardless of the environmental conditions.

[2] The height settings during the pre-deployment validation [7] were slightly different (200, 170, 150, 130, 110, 90, 70, 55, 35 m).

3 VALIDATION RESULTS

For the post-deployment validation of FO's SWLB against the RLL data from the employed FLD ZephIR 300 LiDAR with the serial number ZP428 and from the RLL ZephIR with the serial number ZP495 were provided by FO for a campaign period lasting 2017-02-03 to 2017-02-22, yielding a duration of 19.4 days.

Compared to the pre-deployment verification of this FLD Lidar unit, carried out at the Froya test site in spring 2015 [7], this campaign yields very similar results, i.e. no significant change in wind data quality relative to the same Reference Land Lidar can be detected (see Appendix D). This shows that the performance of the Lidar has remained stable, in this case over a period of 24 months.

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 21.4 m/s at the lowest comparison level (40 m) and 28.0 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 -4.56°C to +6.50°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 3.16 m, with 18.4 % of the observations above 1.5 m. The experienced maximum wave heights cover a range up to 5.1 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 –1.5 and +1.2 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	21.38	21.80
60	22.00	23.38
80	22.65	24.38
100	23.25	23.55
120	23.65	23.14
140	23.93	23.26
160	24.54	24.67
180	26.23	25.78
200	27.97	23.91

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 not been fulfilled. (15 m/s bin incomplete at 100 to 200 m)

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 shows an overview of the data coverage.

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	109	295	337	356	314	232	170	121	82	49	62	112	71	10	8	0	0	0	0
60	118	274	325	345	296	242	183	117	90	67	65	73	117	9	11	1	0	0	0
80	113	248	343	324	286	234	196	115	86	83	70	45	140	18	11	3	0	0	0
100	89	242	354	340	262	221	193	119	85	91	78	34	139	31	8	9	0	0	0
120	96	231	347	356	257	204	197	124	81	95	84	29	116	63	7	11	0	0	0
140	102	239	336	354	243	189	198	121	87	88	95	28	69	112	9	12	0	0	0
160	111	229	367	318	247	182	185	123	86	83	111	29	39	124	26	9	5	0	0
180	126	240	362	297	248	177	175	115	99	74	118	30	25	115	49	7	8	2	0
200	131	245	354	271	244	190	167	111	101	80	117	30	19	97	72	10	3	7	0

Although the 15m/s bin is not fully complete the data base is considered solid and representative as even a few bins above 16 m/s are filled.

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 100 and 200 m fulfils the best practice acceptance criterion [0.98 > X_{MWS} > 1.02] as given in [1]. However, for the measurement levels 40 to 80 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 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.

These minor deviations from Roadmap minimum criteria at 40 m are assumed to be due to ground friction issues at the RLL site, which are supposedly more pronounced during summer atmospheric conditions for wind sectors from the North East. Hence, these deviations are rather considered to be related to the conditions at the RLL location and hence unrelated and thus insignificant with regards to the performance of the Floating Lidar system.

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	2328	1.026	0.985	7.13	7.33	0.20	2.8%
60	2333	1.022	0.987	7.31	7.49	0.18	2.5%
80	2315	1.021	0.987	7.46	7.64	0.18	2.4%
100	2295	1.019	0.985	7.59	7.77	0.18	2.3%
120	2298	1.019	0.984	7.67	7.85	0.17	2.3%
140	2282	1.016	0.983	7.75	7.91	0.16	2.1%
160	2274	1.014	0.981	7.82	7.97	0.16	2.0%
180	2267	1.009	0.980	7.88	8.01	0.13	1.6%
200	2249	1.010	0.974	7.94	8.07	0.13	1.6%

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. The KPI values for M_{mwd} pass the best practice criterion up to 120m and the minimum criterion up to 180m. The KPI values for R^2_{mwd} pass the best practice criterion up to 100m and the minimum criterion up to 140m. The KPI values for OFF_{mwd} pass the minimum criterion at all tested heights. 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	2328	0.974	0.990	8.49
60	2333	0.974	0.988	8.28
80	2315	0.973	0.976	8.06
100	2295	0.971	0.972	7.72
120	2298	0.972	0.964	7.61
140	2282	0.963	0.953	6.84
160	2274	0.955	0.937	6.31
180	2267	0.954	0.939	6.11
200	2246	0.944	0.927	5.06

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 19.4 days. The test period was sufficient to achieve the required data completeness in most of the required WS bins for data analysis, being compliant to the Roadmap in terms of significance of SWLB wind data accuracy results. The wind speed bin 14 to 16 m/s was not completed for measured heights between 100 and 200, i.e. only approximately 75% of the required database was collected at these heights in this bin, which however is judged non-critical for the significance and good performance in the bins completed below and above.

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 100 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 KPI "Mean Wind Direction – Slope" the Best Practice criterion is passed from 40 m up to 120m and the minimum criterion up to 180m, for the KPI "Mean Wind Direction – Coefficient of Determination" the Best Practice criterion is passed from 40 m up to 100 m and the minimum criterion up to 140 m, and for the KPI "Mean Wind Direction – Offset" the minimum criterion is passed at all comparison heights. This indicates the SWLB's capability of reproducing fixed Lidar wind directions at a high level of accuracy up to 140 m. The discrepancies observed above are supposed to be caused by some marine boundary layer development phenomena, which are considered unrelated to the performance of the SWLB itself.

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: [1.009 to 1.019] Passed at compared heights 100 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: [0.981 to 0.987] Passed at compared heights 40 to 160 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: [0.971 to 0.974] Passed at compared heights 40 to 120 m	0.95 – 1.05 Results: [0.944] Failed at 200 m
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97 Results: [0.972 to 0.990] Passed at compared heights 40 to 100 m	> 0.95 Results: [0.927 to 0.939] Failed at 160, 180 and 200 m

KPI	Definition / Rationale	Acceptance Criteria across total campaign duration	
		Best Practice	**Minimum**
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°	< 10° Results: [5.06 to 8.49] Passed at all compared heights

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 FLD 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 post-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 FLD unit undergoes a pre-deployment verification test no greater than one year prior to commencing the wind resource measurement campaign deployment.

This post-deployment verification is valid for to whatever following campaign that this campaign is started within 12 months after the verification trial assuming representativeness of conditions. From [6] it is recommended that the FLS unit undergoes a FLS Verification Test (see Note 25) no greater than one year prior to commencing the WRA deployment.

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

For the ZephIR 300 unit (ZP428) employed on the SWLB WS 149 buoy DNVGL confirms having seen a report dated 2016-01-26 of an OEM factory repair and service inspection performed on 2016-01-20 and 2016-01-21 at the workshop of Fugro OCEANOR AS, Pir-Senteret, Havnegata 9, N7010 Trondheim, Norway [8]. DNV GL considers this service inspection sufficient to minimize the risk of malfunctions and degradations of the Lidar device ZP 428 during another deployment within a 3 years' period from the Lidar's last factory service.

A post-deployment verification of a FLD 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 FLD measurement system

during wind resource measurement campaign. Otherwise a pre-deployment verification campaign may be considered sufficient (also see [6] chapter 6.8 POST-DEPLOYMENT CHECKS, RP 89).

DNVGL has taken notice of the wind resource measurement campaign reports for the deployment period at Borssele from 2015-06-11 until 2016-01-19 as publicly provided on http://offshorewind.rvo.nl/studiesborssele. During that period the continuous Lidar data collection was interrupted two times over periods of several weeks. The reasons were (a) a failure of the central buoy processor GENI (which was not related to the Lidar device) and (b) a corrosion problem of the On/Off switch on the Lidar. After repairing the GENI problem and solving the corrosion problem of the On/Off switch on the Lidar (by simply bypassing the switch) in Jan/Feb 2016, the Lidar on buoy WS149 continued collecting data normally. With regards to wind data accuracy DNV GL has not found any indication that the quality of the Lidar data was harmed by the mentioned failures.

DNV GL confirms that the results from both the pre- and the post deployment verifications of WS149 are reasonably similar, supporting the buoy's stability in performance and data quality over the spanned period. The similarity between pre- and post-deployment verification results in this case indicate that no post-campaign check is needed for further buoys if the wind resource assessment measurement campaign has been as smooth and seamless as in this example.

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 149 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 3.16 m (and 5.1 m for maximum wave height) were recorded by the Buoy. These wave measures are considered rather representative for the project site in the Borssele area. It needs to be noted that there were higher waves during the pre-deployment verification (see [7]).

The Lidar wind speeds recorded at Frøya covered a range of up to 21.4 m/s at 40 m and 28.0 m/s at 200 m.

The assessments of the Roadmap KPIs for the complete data set (from 2017-02-03 until 2017-02-22) 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 140 m, passing best practice or minimum CT Roadmap acceptance criteria.

The minor deviation from Roadmap minimum criteria for WD slope at 200 m and WD regression coefficient at 160 to 200 m is assumed to be caused by some marine boundary layer development phenomena, which are considered unrelated to the performance of the SWLB itself.

FLD Roadmap related WS bin wise data completeness was achieved for all WS bins up to 14 m/s at all treated comparison heights, and even up to 16 m/s at measurement level between 40 and 80 m.

It is reported by Fugro that the buoy WS149 has had no data quality/accuracy issues during the campaign. This is supported by the monthly data and validation reports published on offshorewind.rvo.nl for Borssele. Although the continuous Lidar data collection was interrupted two times for two different technical failures on the buoy DNV GL has not found any indication that the quality of the Lidar data was harmed by the mentioned failures.

A comparison between the Pre- and Post-Deployment validation results also shows that the slopes and regression coefficients do not deviate significantly between both validations (see Appendix D). This affirms that a general conclusion can be made towards the trustworthiness of the measurement campaign data.

As of recommended practice this offshore post-campaign 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. Furthermore DNV GL recommends that Lidar OEM’s service intervals, i.e. at maximum of 3 years for ZP428 are to be followed.

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 ZP428" dated 2013-11-12.

[6] 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 (https://www.ieawind.org/index_page_postings/whatsNEW/IEA_Wind_Task32_StateOfArtFloatingLIDAR_Feb2016.pdf)

[7] DNV GL Report GLGH-4275 13 10378-R-0004-A, "Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy Pre-Deployment Validation at Frøya, Norway", March 2015.

[8] ZEPHIR REPAIR REPORT – Unit 428 – Fitted to Buoy WS149, 2016-01-26

APPENDIX A – APPLIED KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA FOR FLD POST-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.

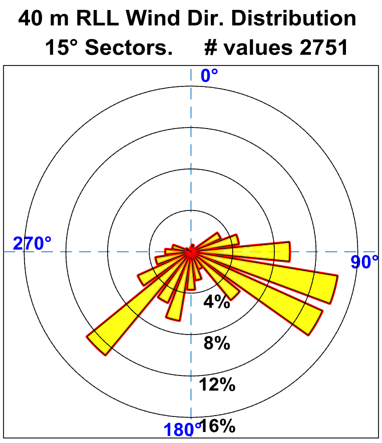
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

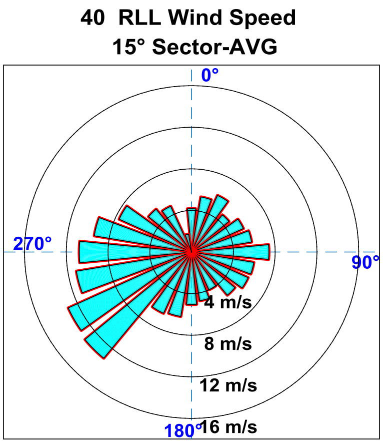
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind 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

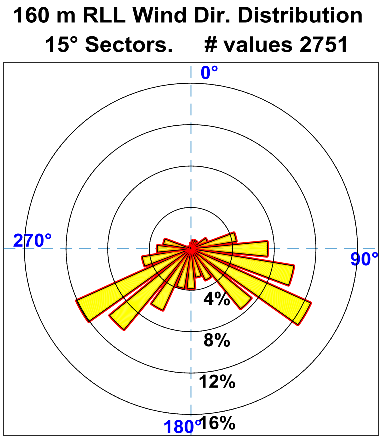
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of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

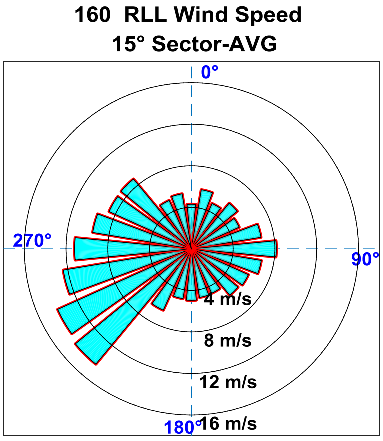
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

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

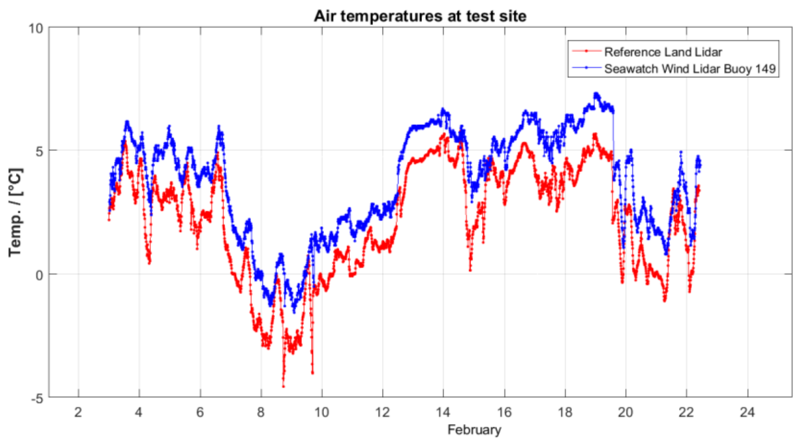




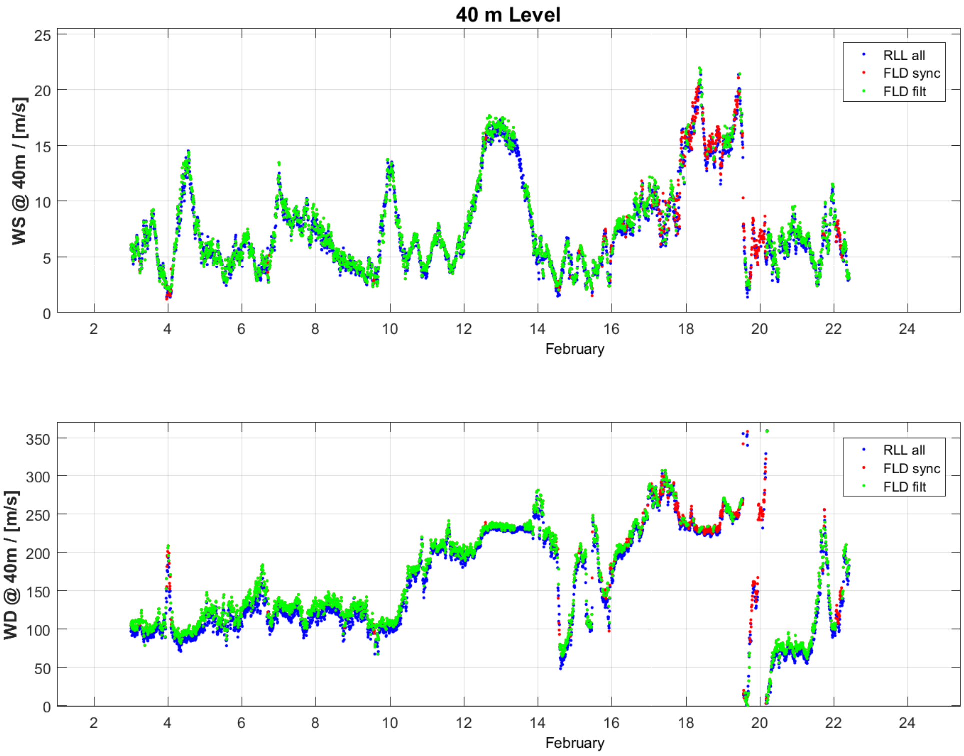


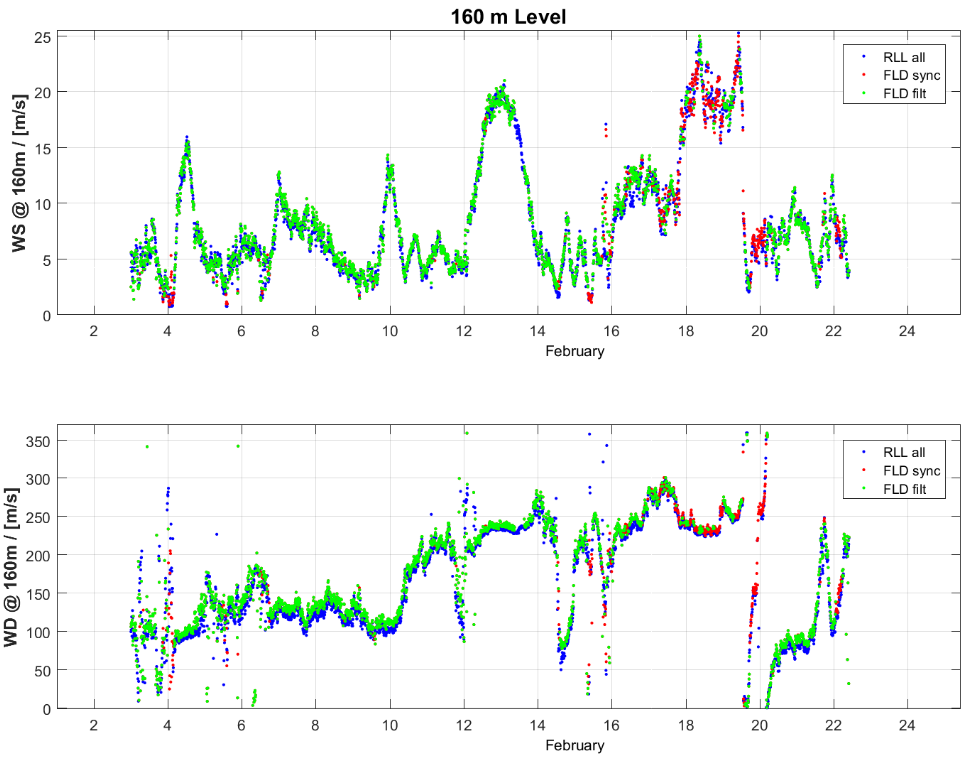


Time series of air temperature at RLL location and on SWLB:



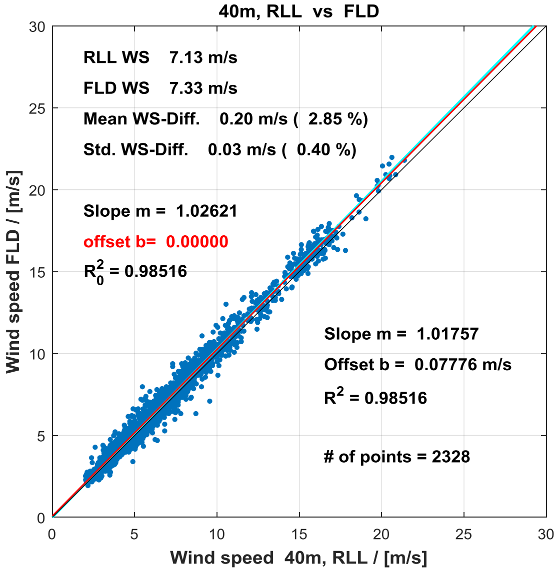
Wind speed and wind directions time series for 40 m and 160 m comparison heights:

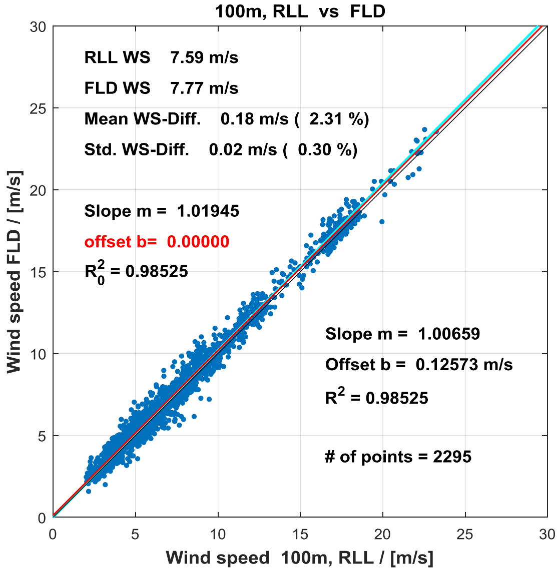


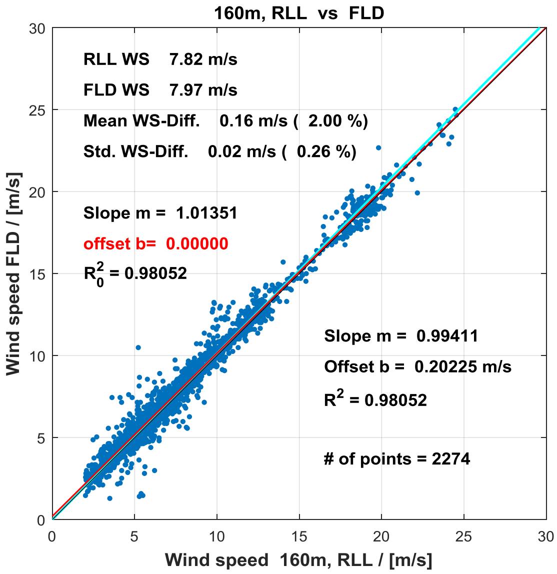


WS regression plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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.

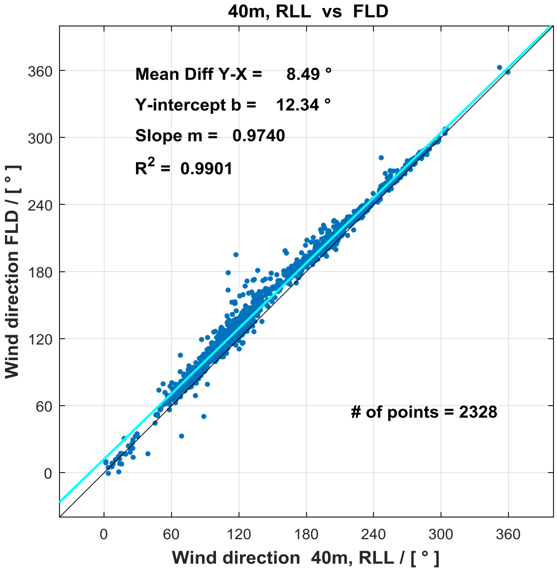


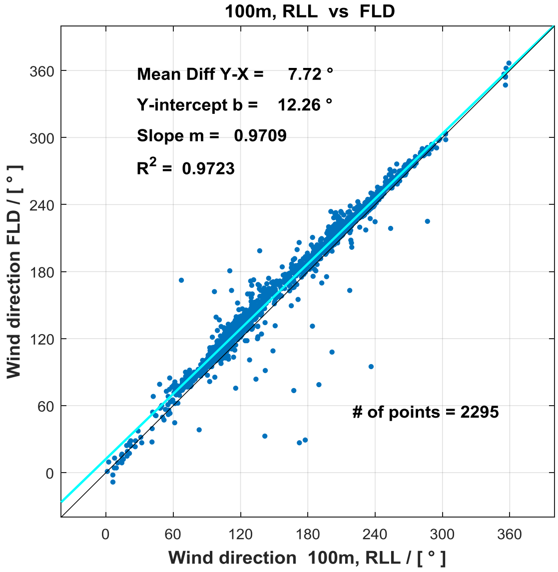


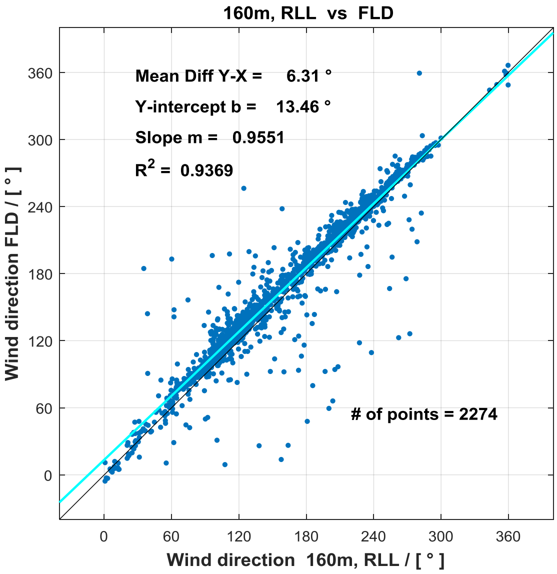


WD correlation plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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 : 2017.02.03 11:00 - 2017.02.22 08:09

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													0	0	0	0				
0.5 - 1.0		8	283	354	399	249	44						1337	49.3	1337	0.49281	3.7	6	8.7	1.1
1.0 - 1.5			140	207	203	194	125	8					877	32.3	2214	0.81607	4	6.5	9.8	1.3
1.5 - 2.0			61	66	46	24	7	1					205	7.6	2419	0.89163	4.3	5.8	9.2	1.1
2.0 - 2.5			4	201	18								223	8.2	2642	0.97383	4.9	5.6	6.8	0.3
2.5 - 3.0				40	20								60	2.2	2702	0.99595	5.6	5.9	6.4	0.2
3.0 - 3.5				2	8								10	0.4	2712	0.99963	6	6.1	6.2	0.1
>= 3.5													0	0	2712	0.99963				
------------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	------	--------	--------	-------	-------	-------	-------
SUM	0	8	488	870	694	467	176	9	0	0	0	0	2712	100	2712	0.99963	0	6.1	9.8	1.14
% OF TOTAL	0	0.3	18	32.1	25.6	17.2	6.5	0.3	0	0	0	0	100							
SUM ACCUM.	0	8	496	1366	2060	2527	2703	2712	2712	2712	2712	2712	2712							
CUM. PROB.	0	0.0029	0.1828	0.5035	0.7593	0.9314	0.9963	0.9996	0.9996	0.9996	0.9996	0.9996	0.99963							
MIN. VALUE		0.66	0.53	0.53	0.57	0.61	0.76	1.21					0							
AVE. VALUE		0.78	1.04	1.4	1.08	1.02	1.14	1.32					1.17							
MAX. VALUE		0.86	2.03	3.05	3.16	1.97	1.56	1.52					3.16							
STD. DEV.		0.06	0.33	0.65	0.5	0.25	0.19	0.11					0.51							
------------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	------	--------	--------	-------	-------	-------	-------

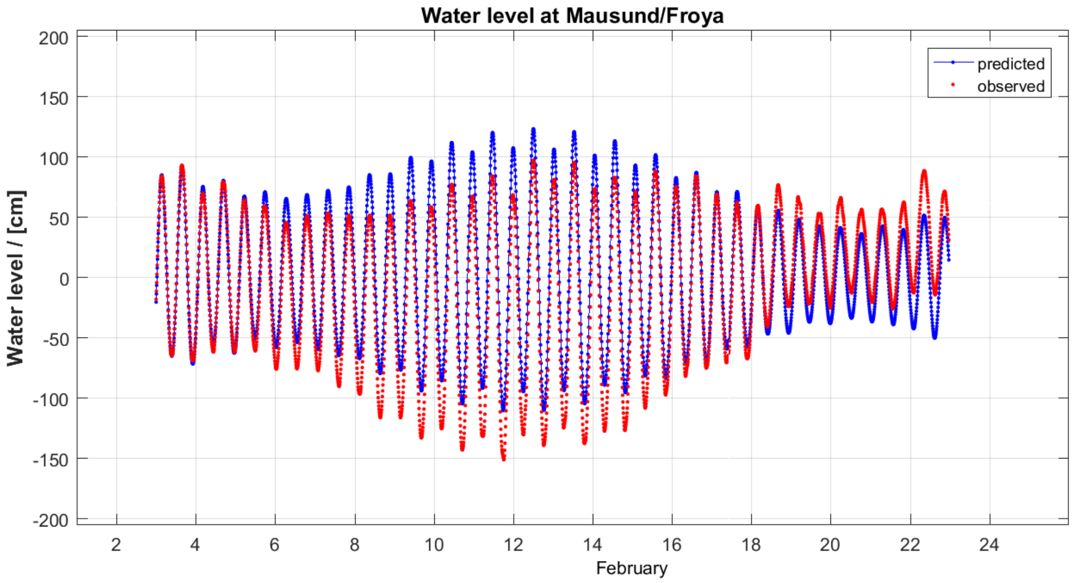
Highest wave period and maximum wave height distribution across total campaign period:

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 : 2017.02.03 11:00 - 2017.02.22 08:09

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.
------------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	------	--------	--------	-------	-------	-------	-------
0.5 - 1.0				2	8	47	85	63	35	15	7	4	266	9.8	266	0.09805	5.7	9.1	14.4	1.4
1.0 - 1.5			18	72	83	124	250	230	160	127	76	18	1158	42.7	1424	0.52488	4	9.2	15.2	2
1.5 - 2.0			8	21	87	96	40	67	62	95	109	108	693	25.6	2117	0.78032	4.6	10.1	17.6	2.7
2.0 - 2.5			5	22	24	29	22	32	21	12	14	22	203	7.5	2320	0.85514	4.6	9.1	16.2	2.7
2.5 - 3.0				22	42	38	21	6	6				135	5	2455	0.9049	5.2	7.3	10.8	1.3
3.0 - 3.5				18	37	46	23	5		1			130	4.8	2585	0.95282	5.3	7.2	11	1
3.5 - 4.0				5	33	39	11	2					90	3.3	2675	0.98599	5.6	7.2	9.1	0.8
4.0 - 4.5					6	18	3	2					29	1.1	2704	0.99668	6.1	7.4	9.3	0.7
4.5 - 5.0					2	3	2						7	0.3	2711	0.99926	6.6	7.4	9	0.8
5.0 - 5.5								1					1	0	2712	0.99963	9.1	9.1	9.1	0
>= 5.5													0	0	2712	0.99963				
------------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	------	--------	--------	-------	-------	-------	-------
SUM	0	0	31	162	322	440	457	408	284	250	206	152	2712	100	2712	0.99963	4	9.1	17.6	2.29
% OF TOTAL	0	0	1.1	6	11.9	16.2	16.9	15	10.5	9.2	7.6	5.6	100							
SUM ACCUM.	0	0	31	193	515	955	1412	1820	2104	2354	2560	2712	2712							
CUM. PROB.	0	0	0.0114	0.0711	0.1898	0.352	0.5205	0.6708	0.7755	0.8677	0.9436	0.9996	0.99963							
MIN. VALUE			1.05	0.67	0.73	0.76	0.73	0.73	0.67	0.76	0.85	0.82	0.67							
AVE. VALUE			1.54	1.97	2.21	2.08	1.53	1.43	1.4	1.47	1.58	1.74	1.71							
MAX. VALUE			2.49	3.96	4.8	4.86	4.95	5.1	2.81	3.02	2.34	2.37	5.1							
STD. DEV.			0.37	0.78	0.93	1.03	0.77	0.54	0.4	0.33	0.29	0.28	0.77							
------------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	/-------	------	--------	--------	-------	-------	-------	-------

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



APPENDIX D – COMPARISON BETWEEN PRE- AND POST DEPLOYMENT VALIDATION RESULTS

Pre-Deployment Results

WS comparison		slope	regr. coeff.	WS RLL avg	WS FLD avg	WS diff.	relative WS diff.
		KPIs					
Level / [m]	#	X_{mws}	R^2_{mws}				
35	1504	0.993	0.991	8.41	8.38	-0.03	-0.3%
55	1515	1.019	0.994	8.89	9.08	0.19	2.1%
70	1520	1.014	0.994	9.13	9.28	0.15	1.6%
90	1511	1.011	0.994	9.42	9.54	0.13	1.3%
110	1498	1.011	0.994	9.66	9.79	0.12	1.3%
130	1491	1.011	0.994	9.85	9.98	0.13	1.3%
150	1491	1.009	0.994	10.03	10.15	0.12	1.2%
170	1490	1.006	0.993	10.22	10.32	0.10	1.0%
200	1484	0.999	0.990	10.50	10.56	0.07	0.6%

WD comparison		slope	regr. Coeff.	mean diff.
		KPIs		
Level / [m]	#	M_{mwd}	R^2_{mwd}	OFF_{mwd}
35	1504	0.976	0.985	-5.35
55	1513	0.963	0.980	-6.51
70	1519	0.975	0.985	-4.45
90	1510	0.975	0.982	-4.89
110	1498	0.977	0.980	-4.97
130	1491	0.975	0.977	-4.69
150	1491	0.972	0.975	-4.74
170	1489	0.962	0.965	-3.62
200	1483	0.963	0.972	-3.71

Post-Deployment Results

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	2328	1.026	0.985	7.13	7.33	0.20	2.8%
60	2333	1.022	0.987	7.31	7.49	0.18	2.5%
80	2315	1.021	0.987	7.46	7.64	0.18	2.4%
100	2295	1.019	0.985	7.59	7.77	0.18	2.3%
120	2298	1.019	0.984	7.67	7.85	0.17	2.3%
140	2282	1.016	0.983	7.75	7.91	0.16	2.1%
160	2274	1.014	0.981	7.82	7.97	0.16	2.0%
180	2267	1.009	0.980	7.88	8.01	0.13	1.6%
200	2249	1.010	0.974	7.94	8.07	0.13	1.6%

WD comparison		slope	regr. Coeff.	mean diff.
		KPIs		
Level / [m]	#	M_{mwd}	R^2_{mwd}	OFF_{mwd}
40	2328	0.974	0.990	8.49
60	2333	0.974	0.988	8.28
80	2315	0.973	0.976	8.06
100	2295	0.971	0.972	7.72
120	2298	0.972	0.964	7.61
140	2282	0.963	0.953	6.84
160	2274	0.955	0.937	6.31
180	2267	0.954	0.939	6.11
200	2246	0.944	0.927	5.06

Difference Of Results (Post - Pre)

Level / [m]	slope	regr. coeff.	WS RLL avg	WS FLD avg	WS diff.	relative WS diff.
	KPIs					
	X_{mws}	R^2_{mws}				
40	0.033	-0.006	-1.29	-1.05	0.23	3.2%
60	0.003	-0.007	-1.58	-1.59	-0.01	0.3%
80	0.007	-0.007	-1.67	-1.64	0.03	0.8%
100	0.009	-0.008	-1.82	-1.77	0.05	1.0%
120	0.008	-0.010	-1.99	-1.94	0.05	1.0%
140	0.005	-0.011	-2.10	-2.07	0.03	0.8%
160	0.005	-0.014	-2.21	-2.18	0.04	0.8%
180	0.002	-0.013	-2.34	-2.31	0.03	0.6%
200	0.011	-0.016	-2.56	-2.50	0.06	1.0%

Level / [m]	slope	regr. Coeff.	mean diff.
	KPIs		
	M_{mwd}	R^2_{mwd}	OFF_{mwd}
40	-0.002	0.005	13.84
60	0.011	0.007	14.79
80	-0.001	-0.009	12.50
100	-0.004	-0.010	12.61
120	-0.005	-0.015	12.58
140	-0.012	-0.024	11.53
160	-0.017	-0.038	11.05
180	-0.008	-0.026	9.73
200	-0.019	-0.045	8.77

Ratio Of Results (Post / Pre)

Level / [m]	slope	regr. coeff.	WS RLL avg	WS FLD avg	WS diff.	relative WS diff.
	KPIs					
	X_{mws}	R^2_{mws}				
40	1.034	0.994	0.847	0.874	-7.068	-8.344
60	1.003	0.993	0.823	0.825	0.941	1.144
80	1.007	0.993	0.817	0.823	1.192	1.459
100	1.009	0.992	0.806	0.814	1.393	1.728
120	1.008	0.990	0.794	0.802	1.403	1.767
140	1.005	0.989	0.786	0.792	1.249	1.588
160	1.004	0.986	0.779	0.786	1.300	1.668
180	1.002	0.987	0.771	0.776	1.244	1.613
200	1.011	0.984	0.756	0.764	1.926	2.547

Level / [m]	slope	regr. Coeff.	mean diff.
	KPIs		
	M_{mwd}	R^2_{mwd}	OFF_{mwd}
40	0.998	1.005	-1.587
60	1.011	1.008	-1.271
80	0.999	0.991	-1.812
100	0.996	0.990	-1.580
120	0.995	0.984	-1.532
140	0.987	0.976	-1.461
160	0.983	0.961	-1.331
180	0.991	0.973	-1.689
200	0.980	0.953	-1.365

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.