FRØYA SEAWATCH WIND LIDAR BUOY WS 140
PRE-DEPLOYMENT VALIDATION

Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 140 Pre-Deployment Validation on Frøya, Norway

Fugro / OCEANOR AS

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Task and objective: 3rd Party Assessment of an Offshore/Nearshore Pre-Deployment Validation of the Fugro/Oceanor SEAWATCH Wind LiDAR Buoy WS 140 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

Fugro OCEANOR AS (FO or the Client) commissioned on 2016-06-30 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 140 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 103.8 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 2016-05-03 with the deployment of the SWLB at a position South of Frøya in 75 m water depth, see Figure 1 “Lidar buoy”. The mooring point is about 820 m to the Southwest of the shore of a place called Stabben and approx. 950 m from the “Land Lidar” at Stabben. The campaign was finished by the recovery of the SWLB on 2016-08-15.

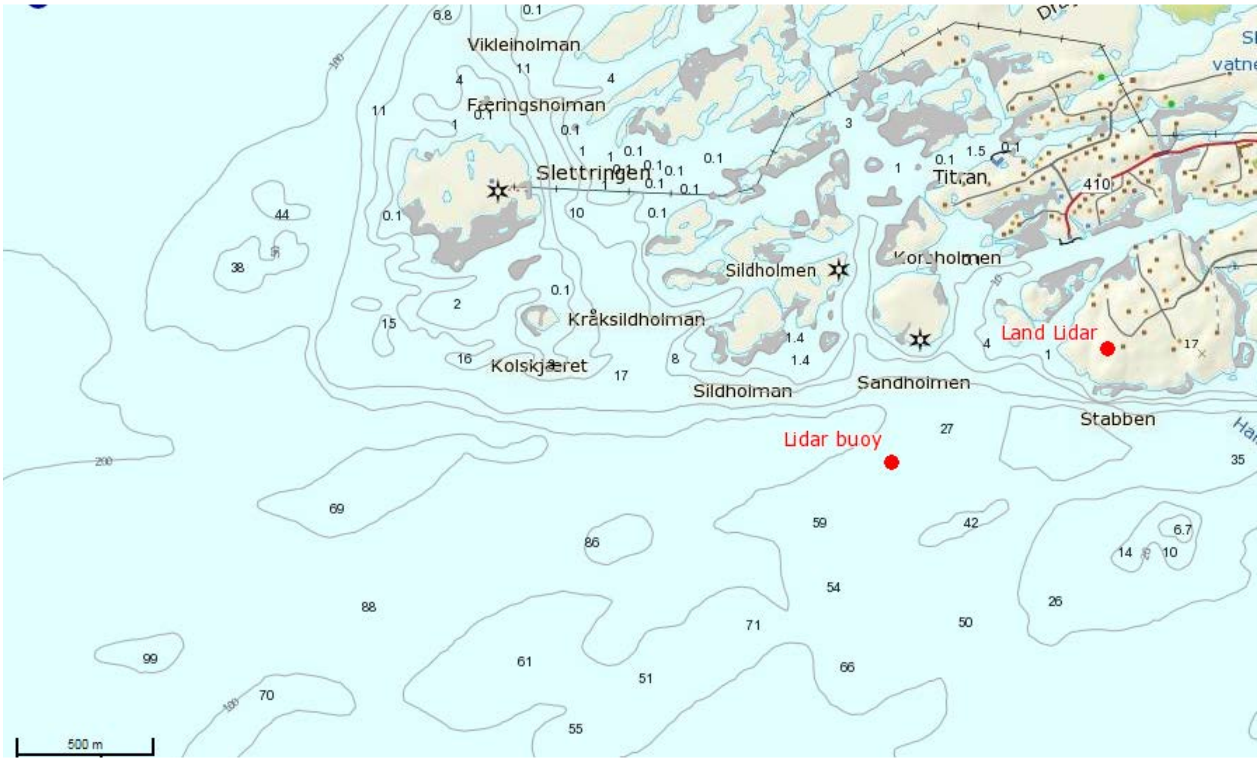


Figure 1: Positions of SWLB (Lidar buoy) and RLL (Land Lidar) near or at the Island Frøya /Stabben.

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 140 against a Reference Land Lidar (RLL) of type ZephIR with the S/N Z495 at the FO test site near and on the Norwegian Island Frøya at a place call 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 140 employing a ZephIR Lidar with the S/N Z417) 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 in the Dutch offshore wind planning area Hollandse Kust (zuid) 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.

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 950 m and over the full height range as shown in this report and from three (3) previously performed validations (one of which lasting 3+ months), 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).

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 63° 39’ 46.60’’ N, 008° 18’ 35.50’’ E.

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

- The SWLB is deployed at a position of 63° 39’ 29.40” N, 008° 17’ 39.10” E.
- 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 820 m from the shore of a place called Stabben and approx. 950 m to the South West of the RLL position.

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 after deployment off Frøya (left) 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 140
- ZephIR S/N Z417
- 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 Z495
- 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].

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 2016-05-03 of SWLB until its decommissioning on 2016-08-15 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 Z417 and from the RLL ZephIR with the serial number Z495 were provided by FO for a campaign period lasting 2016-05-03 to 2016-08-15, yielding a duration of 103.8 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 17.2 m/s at the lowest comparison level (40 m) and 21.8 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 +2°C to +27.5°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 2.3 m, with 3.4 % of the observations above 1.5 m. The experienced maximum wave heights cover a range up to 4.2 m. Compare Appendix C for wave statistics as provided by FO. The wave measurements were recorded by the SWLB under trial itself using a 30 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	17.15	16.70
60	18.02	17.75
80	19.19	20.10
100	20.25	20.39
120	20.93	21.15
140	21.45	21.21
160	21.66	21.21
180	21.64	20.74
200	21.83	21.56

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.

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, the Roadmap related WS bin wise data completeness – to include more than 40 values per bin – was achieved for all WS bins between 2 and 16 m/s (as demanded by a and b) at all treated comparison heights, and up to 18 m/s at all levels above 120 m (compare Table 3).

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
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
Level / [m]	RLL number of 10 min data entries per WS bin - AFTER filtering for data to be used for regression analysis															
40	992	1479	1844	1740	1463	1254	798	461	320	196	198	54	4	0	0	0
60	880	1339	1621	1701	1455	1264	980	583	375	261	252	85	12	1	0	0
80	798	1264	1554	1624	1429	1278	971	702	410	303	309	117	18	4	0	0
100	785	1202	1494	1524	1452	1200	997	711	483	341	338	152	25	7	2	0
120	791	1159	1463	1484	1392	1172	957	777	508	353	372	176	38	13	2	0
140	813	1112	1433	1445	1343	1145	960	773	549	360	390	191	55	10	5	0
160	818	1083	1406	1401	1293	1137	954	788	564	359	399	192	76	11	5	0
180	817	1068	1377	1358	1270	1108	953	792	539	388	403	202	90	11	8	0
200	827	1035	1362	1301	1241	1074	955	754	541	390	358	199	111	14	9	0

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 for the data period considered here KPIs for slope at heights between 60 and 200 m fall within the best practice acceptance criterion [$0.98 > X_{MWS} > 1.02$] as given in [1]. However, for the 40 m measurement level the slope exceeds the minimum acceptance criterion [$0.97 > X_{MWS} > 1.03$] with 1.035 slightly.

With regards to the Coefficient of Determination (R^2_{mws}) the minimum acceptance criterion [$R^2_{mws} > 0.97$] is passed at all heights above 40 m, while the lowest measurement level slightly fails the minimum acceptance criterion [$R^2_{mws} > 0.97$]. 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	10803	1.035	0.963	5.97	6.19	0.21	3.6%
60	10809	1.016	0.971	6.29	6.39	0.10	1.6%
80	10781	1.009	0.974	6.50	6.56	0.06	1.0%
100	10713	1.006	0.977	6.64	6.68	0.05	0.7%
120	10657	1.004	0.977	6.74	6.78	0.04	0.6%
140	10584	1.004	0.978	6.81	6.85	0.04	0.6%
160	10486	1.004	0.976	6.87	6.91	0.04	0.6%
180	10384	1.003	0.976	6.92	6.95	0.03	0.5%
200	10171	1.003	0.971	6.92	6.96	0.04	0.6%

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. 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	10800	0.973	0.995	0.71
60	10805	0.974	0.996	0.35
80	10776	0.973	0.996	0.50
100	10711	0.973	0.995	0.38
120	10652	0.974	0.995	0.17
140	10579	0.975	0.995	0.02
160	10480	0.973	0.994	-0.28
180	10378	0.974	0.994	0.15
200	10165	0.973	0.992	0.02

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 103.8 days. The test period was sufficient to achieve the required data completeness in useable 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 60 and 200 m. For both KPI's the lowest measurement level (40 m) slightly fails the minimum acceptance criterion. As mentioned above these minor deviations at the lowest comparison height are considered insignificant with regards to the performance of the Floating Lidar system

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 103 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: [1.003 to 1.016] Passed at compared heights 60 to 200 m	0.97 – 1.03 Results: [0.963] Missed at 40 m
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Assessed for wind speed range [all above 2 m/s]	>0.98 Results:	>0.97 Results: [0.971 to 0.978] Passed at compared heights 60 to 200 m
M_{mwd}	**Mean Wind Direction – Slope** Assessed for wind speed range [all above 2 m/s]	0.97 – 1.03 Results: [0.973 to 0.975] Passed at all compared heights	0.95 – 1.05 Results:
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: [0.02 to 0.71] Passed at all compared heights	< 10°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97 Results: [0.992 to 0.996] Passed at all compared heights	> 0.95

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 above 40 m 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. 950 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.

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 WS140

During the course of the validation campaign DNV GL has been informed by FO that this buoy WS 140 has received design changes compared to the unit trialled in the FLS type verification at IJmuiden in 2014/2015 [6] with regards to using a marinized version of the employed Z300 type Lidar (1) and by adding extra buoyancy to the buoy assembly (2).

(1) The ZP-Lidar Z417 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 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.

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 140 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 > 2.3 m (and > 3.6 m for maximum wave height) were recorded by the Buoy. The Lidar wind speeds recorded at Frøya covered a range of up to 17.2 m/s at 40 m and 21.8 m/s at 200 m.

The assessments of the Roadmap KPIs for the complete data set (from 2016-05-03 until 2016-08-15) show that all FLD-Roadmap Acceptance Criteria are met at heights between 60 and 200 m above MSL for wind speed and wind direction related Key Performance Indicators (KPI), passing best practice or minimum CT Roadmap acceptance criteria.

The minor deviation from Roadmap minimum criteria for WS slope at 40 m is 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. This deviation is considered to be related to the conditions at the RLL location rather than to the FLS itself and thus insignificant with regards to the performance of the Floating Lidar System.

FLD Roadmap related WS bin wise data completeness was achieved for all WS bins up to 16 m/s at all treated comparison heights, and even up to 18 m/s at measurement level between 140 and 200 m.

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 ZP417” dated 2016-03-31.

[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

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.

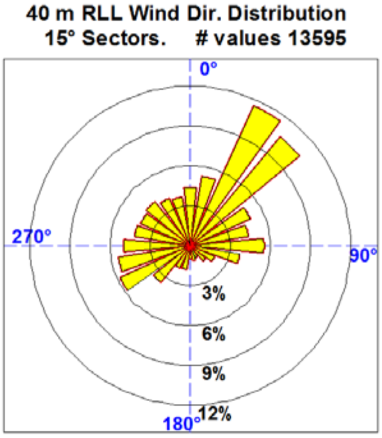
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

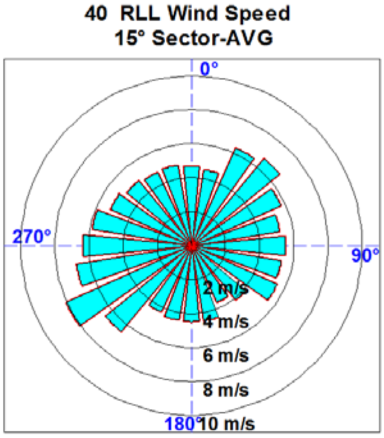
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed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

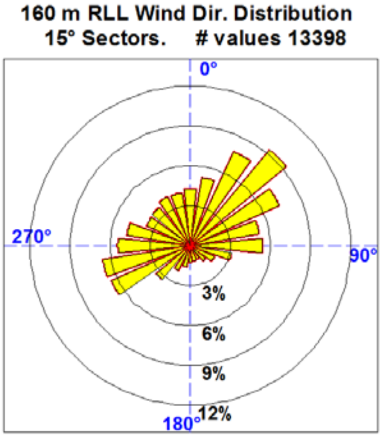
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of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

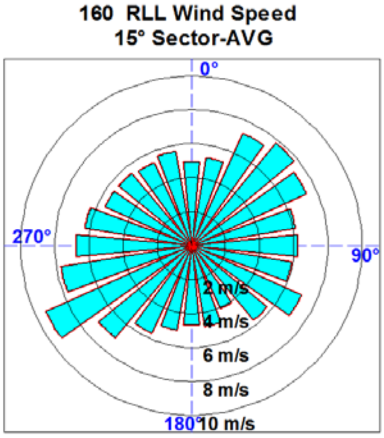
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

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

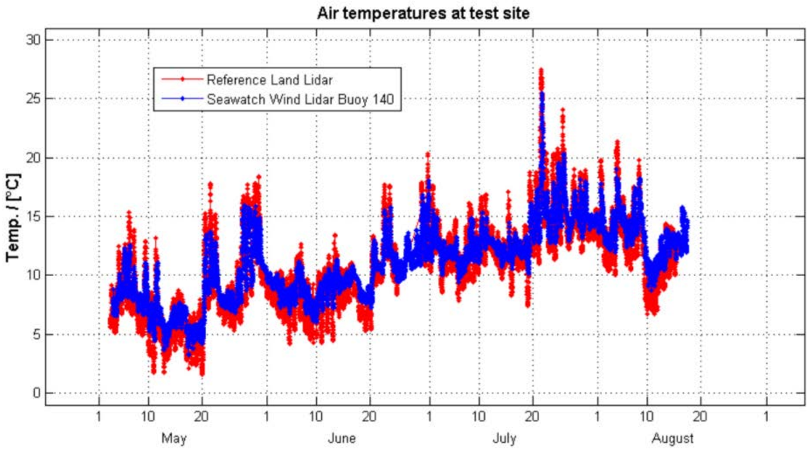




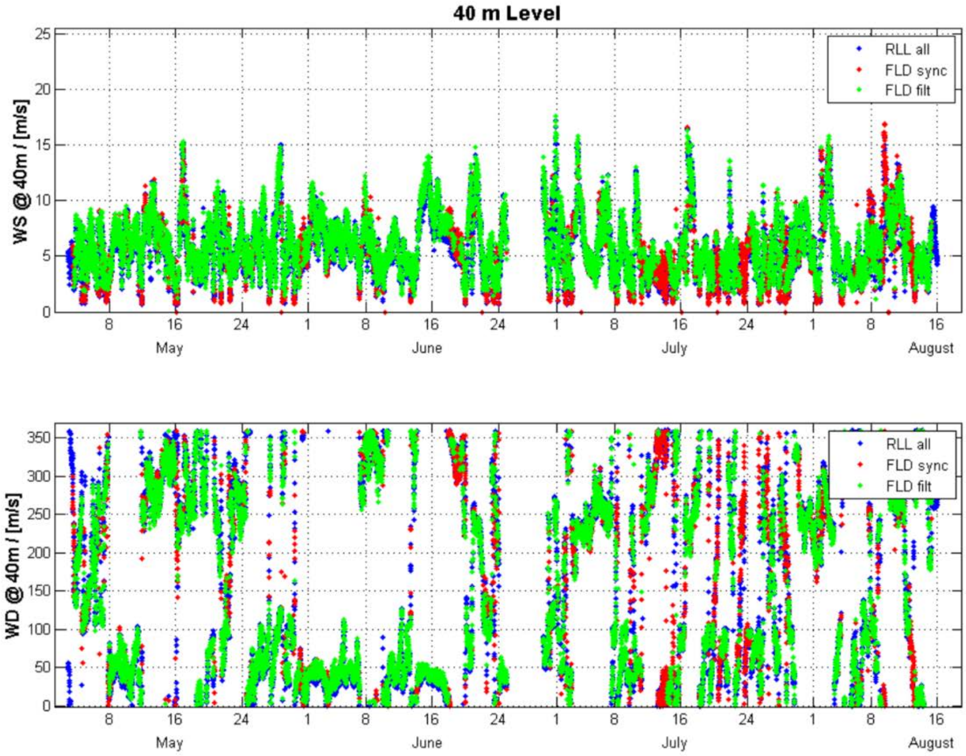


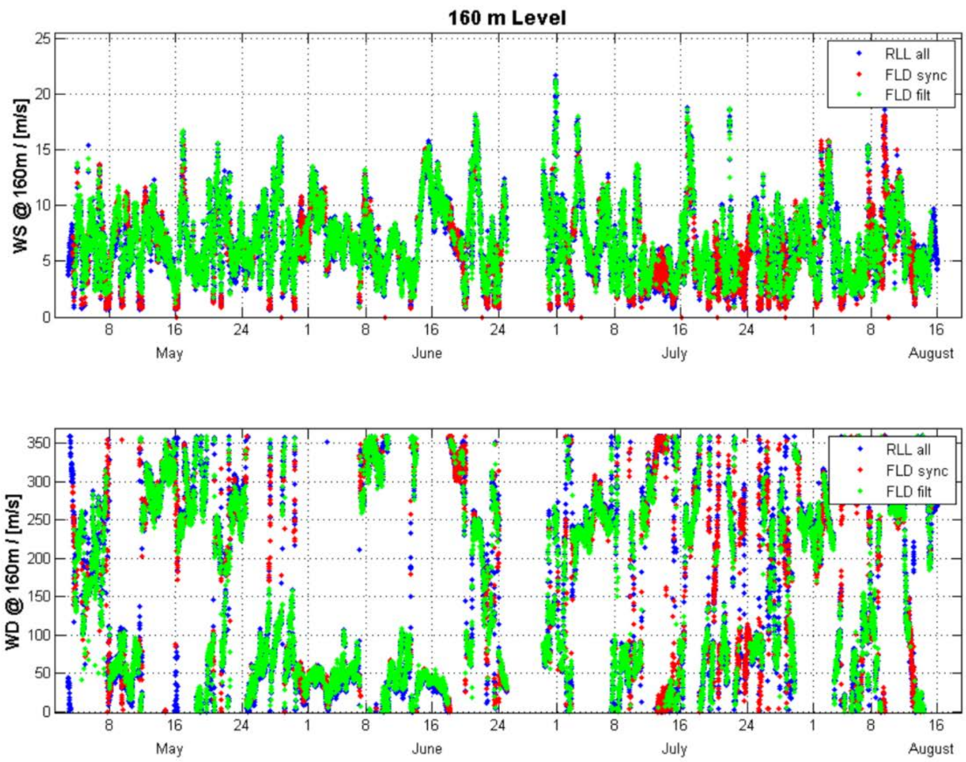


Time series of air temperature at RLL location and on SWLB:



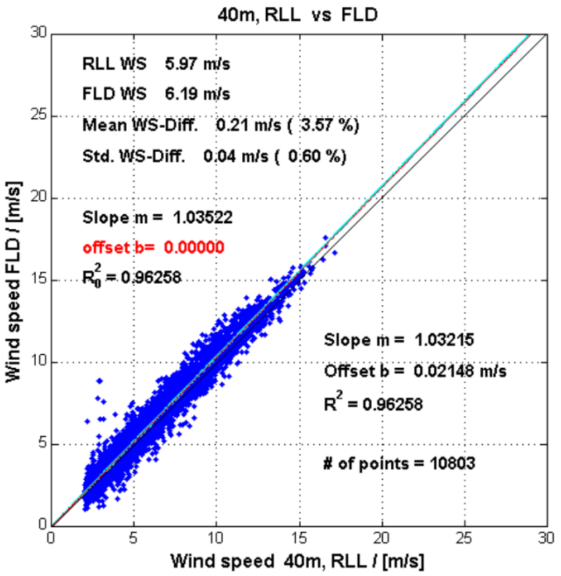
Wind speed and wind directions time series for 40 m and 160 m comparison heights:

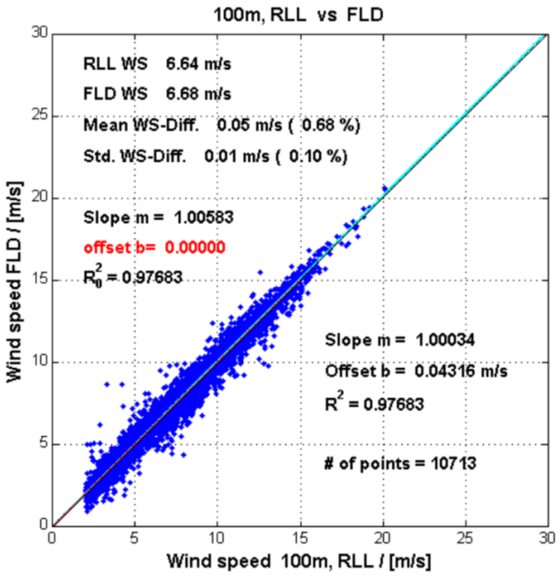


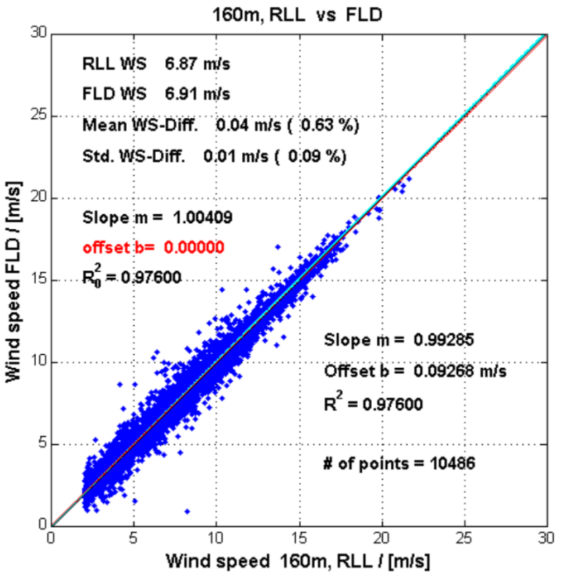


WS regression plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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.

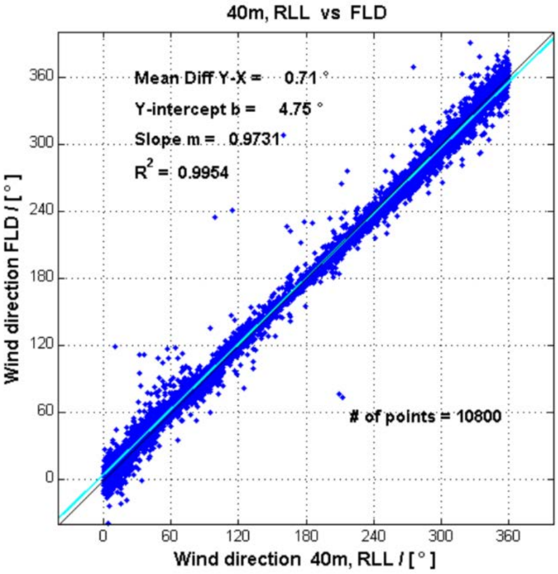


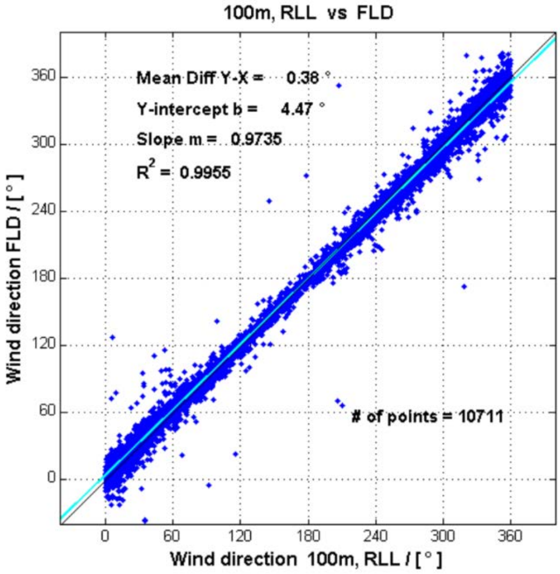


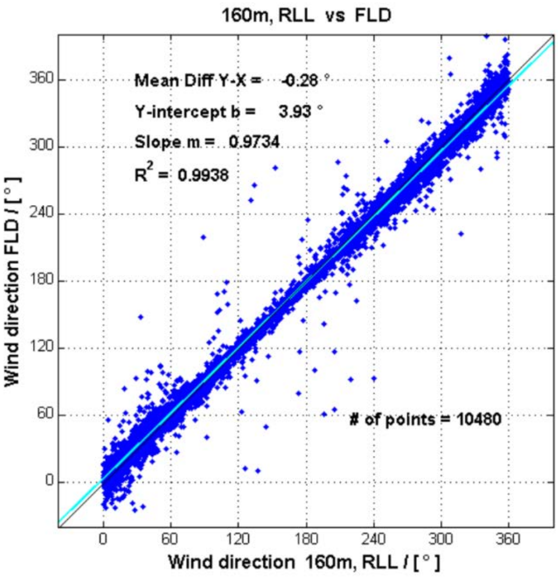


WD correlation plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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 : 2016.05.03 13:30 - 2016.08.15 07:49

Tm02 (s)	2	3	4	5	6	7	8	9	10	11	12 >=		SUM	% OF	SUM
Hm0 (m)	3	4	5	6	7	8	9	10	11	12	13	13		TOTAL	ACC.
0.0 - 0.5	322	1235	2878	2230	1190	490	73	9					8427	56.7	8427
0.5 - 1.0	1	722	1485	788	627	649	89	12	2				4375	29.5	12802
1.0 - 1.5		42	433	292	355	296	109	14					1541	10.4	14343
1.5 - 2.0			86	69	36	191	81	26					489	3.3	14832
2.0 - 2.5					3	12	1	4					20	0.1	14852
>= 2.5													0	0	14852
SUM	323	1999	4882	3379	2211	1638	353	65	2	0	0	0	14852	100	14852
% OF TOTAL	2.2	13.5	32.9	22.8	14.9	11	2.4	0.4	0	0	0	0	100		
SUM ACCUM.	323	2322	7204	10583	12794	14432	14785	14850	14852	14852	14852	14852	14852		
CUM. PROB.	0.0217	0.1563	0.485	0.7125	0.8614	0.9717	0.9954	0.9998	0.9999	0.9999	0.9999	0.9999	0.99993		
MIN. VALUE	0.2	0.14	0.12	0.14	0.14	0.14	0.33	0.37	0.53				0		
AVE. VALUE	0.29	0.46	0.52	0.48	0.58	0.82	1.05	1.29	0.55				0.56		
MAX. VALUE	0.51	1.31	1.82	1.99	2.21	2.27	2.01	2.3	0.57				2.3		
STD. DEV.	0.05	0.23	0.33	0.35	0.38	0.46	0.5	0.52	0.02				0.38		

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

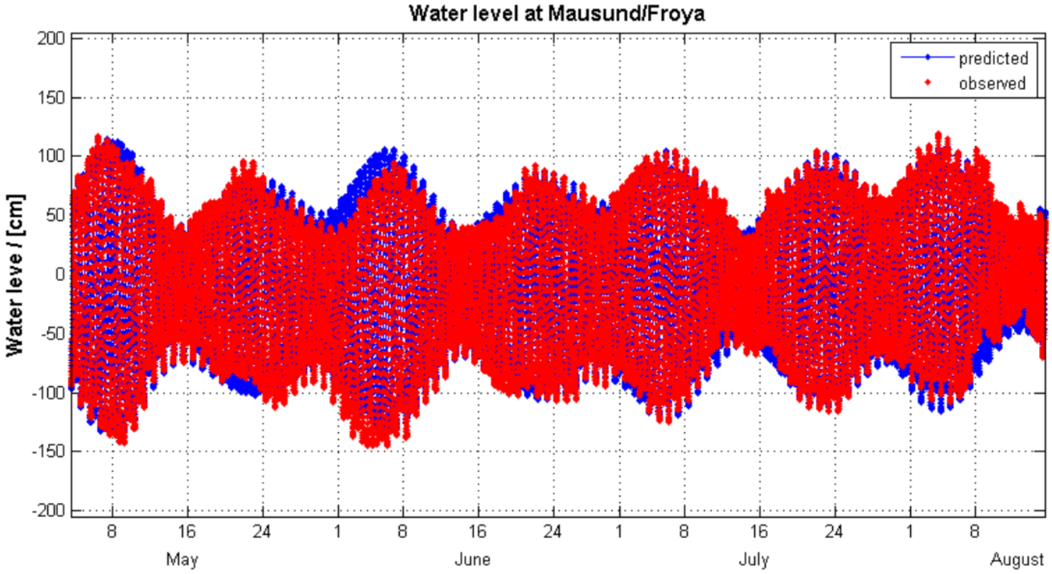
THmax Period of highest wave (s) Slettringen, Wavescan buoy
Hmax Maximum wave height (m) Slettringen, Wavescan buoy

Measuring depth : 0.00 m
Water depth : 75.00 m
Sampling interval:
Period : 2016.05.03 13:30 - 2016.08.15 07:49

THmax (s)	2	3	4	5	6	7	8	9	10	11	12 >=		SUM	% OF	SUM
Hmax (m)	3	4	5	6	7	8	9	10	11	12	13	13		TOTAL	ACC
0.0 - 0.5		5	19	44	76	187	250	160	91	65	60	374	1331	13.3	1331
0.5 - 1.0	1	67	279	509	810	990	1142	532	197	116	86	155	4884	48.8	6215
1.0 - 1.5		10	230	224	323	405	326	224	99	17	2	2	1862	18.6	8077
1.5 - 2.0			80	116	164	209	191	153	170	63	20		1166	11.6	9243
2.0 - 2.5			22	54	47	68	106	116	83	46	16	6	564	5.6	9807
2.5 - 3.0			4	18	17	8	25	43	25	16	6	1	163	1.6	9970
3.0 - 3.5				1	4	2	6	9	8	3			33	0.3	10003
3.5 - 4.0				1				2	1	1			5	0	10008
4.0 - 4.5								2					2	0	10010
>= 4.5													0	0	10010
SUM	1	82	634	967	1441	1869	2046	1241	674	327	190	538	10010	100	10010
% OF TOT/	0	0.8	6.3	9.7	14.4	18.7	20.4	12.4	6.7	3.3	1.9	5.4	100		
SUM ACCI	1	83	717	1684	3125	4994	7040	8281	8955	9282	9472	10010	10010		
CUM. PRO	0.0001	0.0083	0.0716	0.1682	0.3122	0.4989	0.7032	0.8272	0.8945	0.9272	0.9462	0.9999	0.9999		
MIN. VALU	0.53	0.38	0.35	0.38	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.32	0.32		
AVE. VALU	0.53	0.77	1.11	1.1	1.03	0.99	0.98	1.15	1.31	1.21	0.9	0.52	1.03		
MAX. VAL	0.53	1.35	2.78	3.63	3.19	3.28	3.4	4.16	3.6	3.54	2.87	2.75	4.16		
STD. DEV.	0	0.2	0.43	0.53	0.48	0.47	0.52	0.66	0.71	0.77	0.66	0.24	0.56		

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

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