FRØYA SEAWATCH WIND LIDAR BUOY WS 158
PRE-DEPLOYMENT VALIDATION

Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 158 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 158 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 2016-04-15 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 158 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 28 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 2016-04-05 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 2016-05-03.

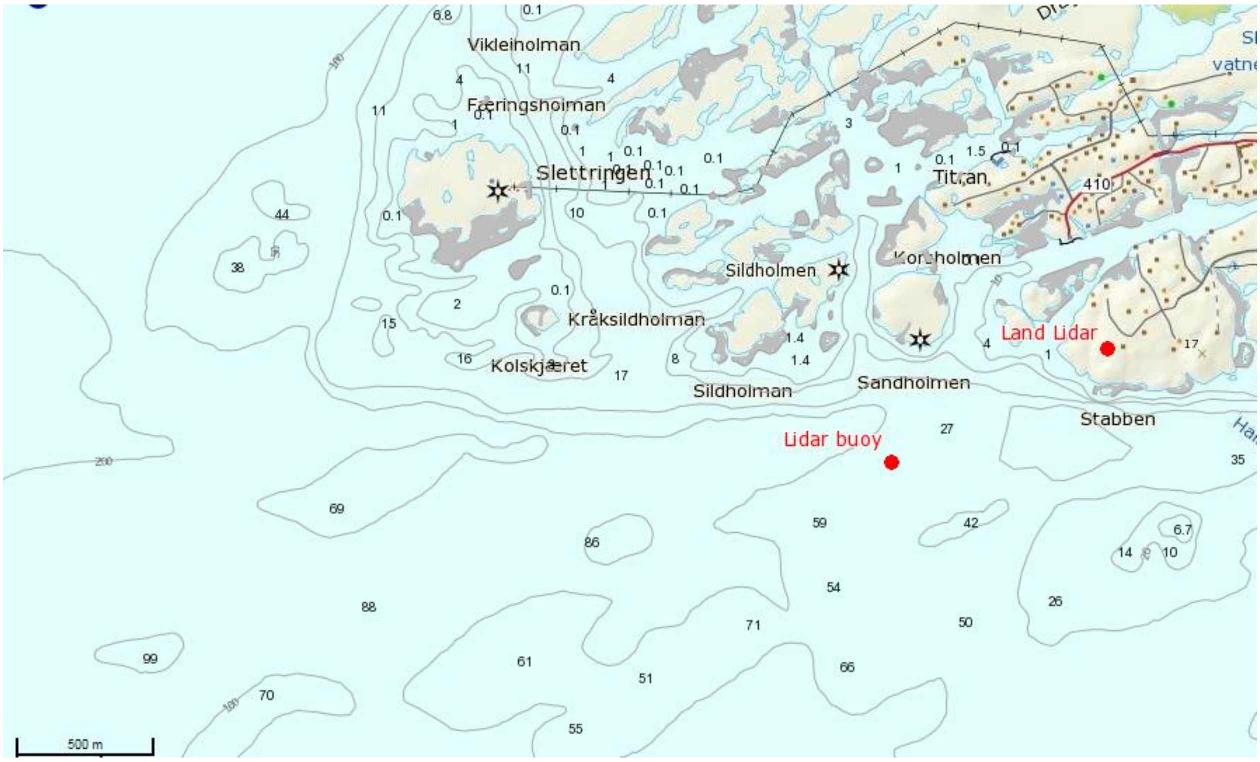


Figure 1: Positions of SWLB (Lidar buoy) and RLL (Land Lidar) near or at the Island Frøya /Stabben.

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 158 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 158 employing a ZephIR Lidar with the S/N Z513) 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 validated 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 independently verified by GL Garrad Hassan [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 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 during loading (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 158
- ZephIR S/N Z513
- 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

	Reference Land Lidar (RLL)		Floating Lidar (SWLB)	
Window Height above sea level (SL)	**14**		2	
Height level #	**True Height above MSL [m]**	**Configured Height [m]**	**True Height above SL [m[**	**Configured Height [m]**
0			4	Gill Sonic
1	30	16	30	28
2	40	26	40	38
3	52	not configurable	40	not configurable
4	60	46	60	58
5	80	66	80	78
6	100	86	100	98
7	120	106	120	118
8	140	126	140	138
9	160	146	160	158
10	180	166	180	178
11	200	186	200	198

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 2016-04-05 of SWLB until its decommissioning on 2016-05-03 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 Z513 and from the RLL ZephIR with the serial number Z495 were provided by FO for a campaign period lasting 2015-04-05 to 2016-05-03, yielding a duration of 28 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 18.5 m/s at the lowest comparison level (40 m) and 23.4 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 +13°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 2.6 m, with 9.9 % of the observations above 1.5 m. The experienced maximum wave heights cover a range up to 4.6 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 –1.4 and +1.3 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	18,47	18,46
60	19,07	18,93
80	19,64	18,87
100	20,02	20,33
120	20,50	19,69
140	21,26	21,09
160	22,15	21,39
180	22,78	22,85
200	23,41	23,26

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 80 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	371	443	561	474	389	359	278	172	141	126	229	99	21	4	0	0
60	332	424	508	448	425	352	313	207	148	127	248	134	17	13	0	0
80	317	414	494	422	423	358	311	209	172	128	257	156	22	18	0	0
100	300	399	484	388	427	369	299	214	181	126	279	151	43	18	1	0
120	279	389	483	384	421	348	301	223	167	149	285	158	51	18	5	0
140	269	366	484	365	401	372	285	211	178	159	286	167	61	16	9	0
160	255	355	474	356	395	361	281	203	184	151	304	175	62	22	8	1
180	245	348	463	356	377	365	283	202	184	143	304	186	63	28	7	3
200	264	338	451	346	375	368	271	204	186	145	303	190	61	33	8	3

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], at 40 m this KPI is within the minimum acceptance criterion [$0.97 > X_{MWS} > 1.03$]. With regards to the Coefficient of Determination (R^2_{mws}) the best practice criterion [$R^2_{mws} > 0.98$] is passed as well at all heights above 40 m, while the minimum acceptance criterion [$R^2_{mws} > 0.97$] is achieved at the lowest measurement level. 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	3667	1,028	0,978	6,71	6,93	0,22	3,3%
60	3696	1,015	0,984	7,00	7,12	0,12	1,8%
80	3701	1,011	0,984	7,16	7,26	0,10	1,4%
100	3679	1,010	0,985	7,31	7,40	0,09	1,3%
120	3661	1,009	0,985	7,43	7,52	0,08	1,1%
140	3629	1,009	0,986	7,54	7,63	0,08	1,1%
160	3587	1,006	0,983	7,64	7,72	0,07	0,9%
180	3557	1,006	0,983	7,71	7,78	0,07	0,9%
200	3546	1,005	0,982	7,75	7,82	0,07	0,9%

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 ynd 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	3665	1,027	0,993	0,66
60	3696	1,027	0,992	0,54
80	3701	1,029	0,992	0,38
100	3678	1,029	0,992	0,43
120	3660	1,026	0,992	0,60
140	3628	1,025	0,993	0,48
160	3586	1,026	0,993	0,47
180	3557	1,027	0,992	0,51
200	3544	1,025	0,991	0,65

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.4 Summary of verification results

3.4.1 Campaign Duration

The campaign duration of 28 days is considered rather short, compared to a typically expected duration of 6 to 8 weeks. However, due to the early spring season this duration 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" and "Mean Wind Speed – Coefficient of Determination" were passed at all heights with a minor exception at 40 m, where the minimum Acceptance Criteria were met.

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 90 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: [1.005 to 1.015] Passed at compared heights 60 to 200 m	0.97 – 1.03 Results: [1.028] Passed at compared height 40 m
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Assessed for wind speed range [all above 2 m/s]	>0.98 Results: [0.982 to 0.986] Passed at compared heights 60 to 200 m	>0.97 Results: [0.978] Passed at compared height 40 m
M_{mwd}	**Mean Wind Direction – Slope** Assessed for wind speed range [all above 2 m/s]	0.97 – 1.03 Results: [1.025 to 1.029] 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: [0.38 to 0.66] Passed at all compared heights	< 10°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97 Results: [0.991 to 0.993] 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 treated heights between 40 m and 200 m a 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 excellent. They are indicating that non-synchronicity at the mentioned distance between SWLB and RLL of approx. 950 m is 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 WS158

During the course of the validation campaign DNV GL has been informed by FO that this buoy WS 158 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 Z531 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 158 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 > 2.6 m (and > 4.5 m for maximum wave height) were recorded by the Buoy. The Lidar wind speeds recorded at Frøya covered a range of up to 18.5 m/s at 40 m and 23.4 m/s at 200 m.

The assessments of the Roadmap KPIs for the complete data set (from 2016-04-05 until 2016-05-03) show that all FLD-Roadmap Acceptance Criteria are met at all relevant heights between 40 and 200 m above MSL for wind speed and wind direction related Key Performance Indicators (KPI), passing best practice Roadmap acceptance criteria in almost all cases, with a minor exception for wind speed at 40 m where the minimum criteria are met.

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 100 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 ZP513" dated 2015-06-09.

[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.

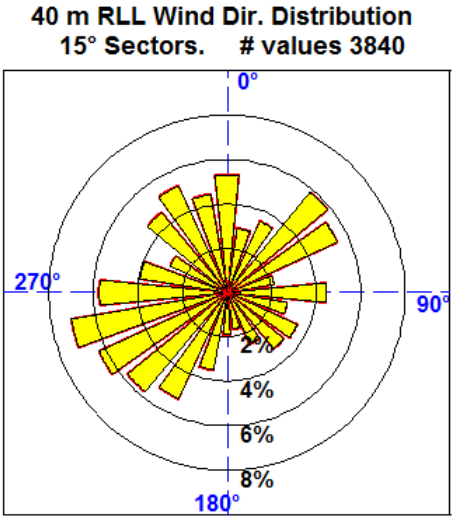
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

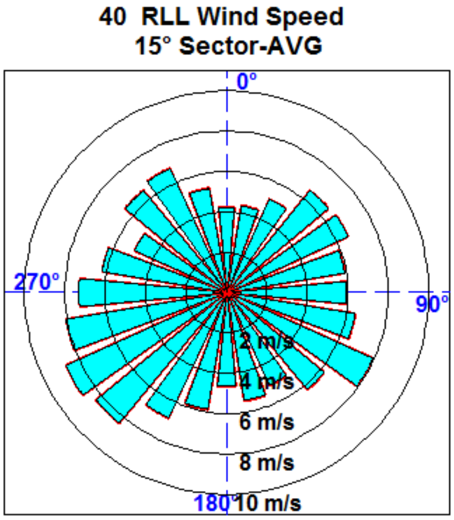
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed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

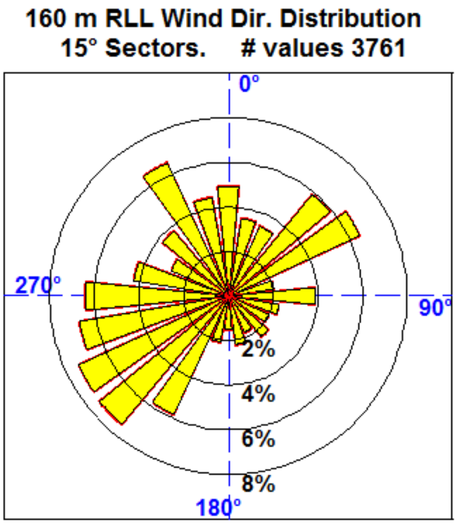
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of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

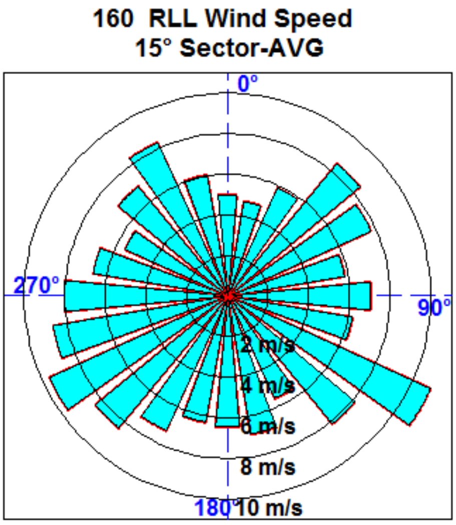
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

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

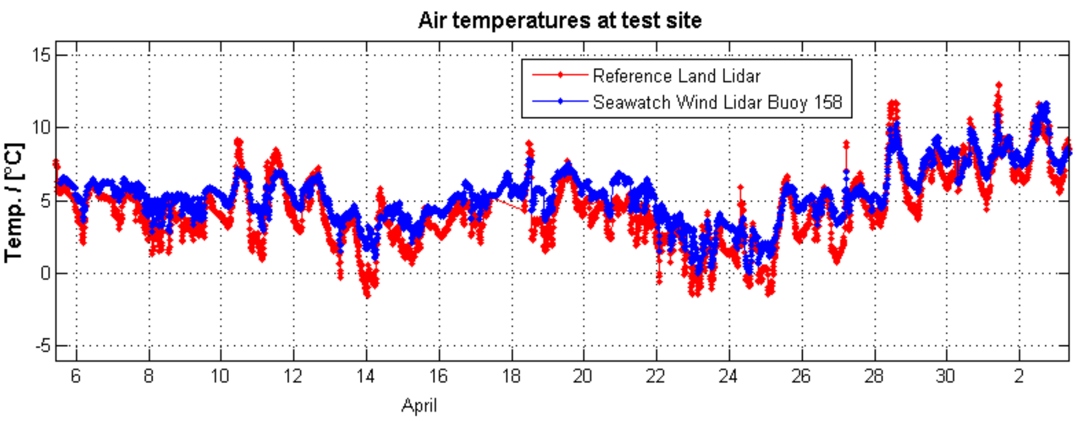




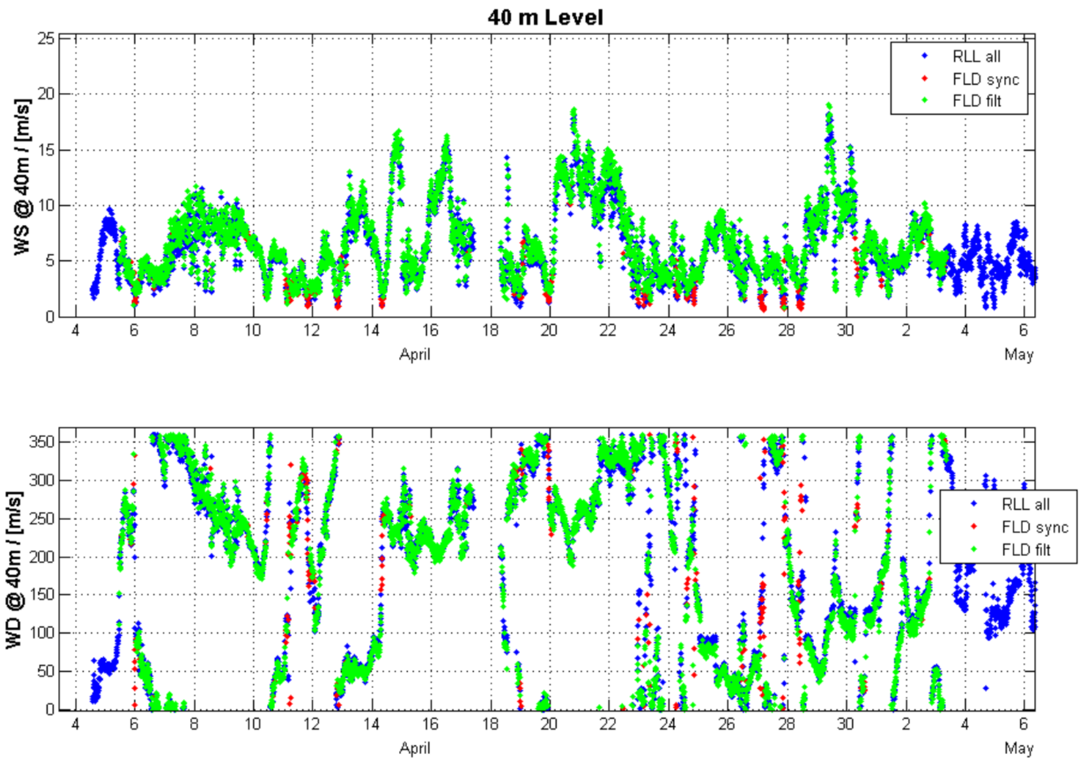


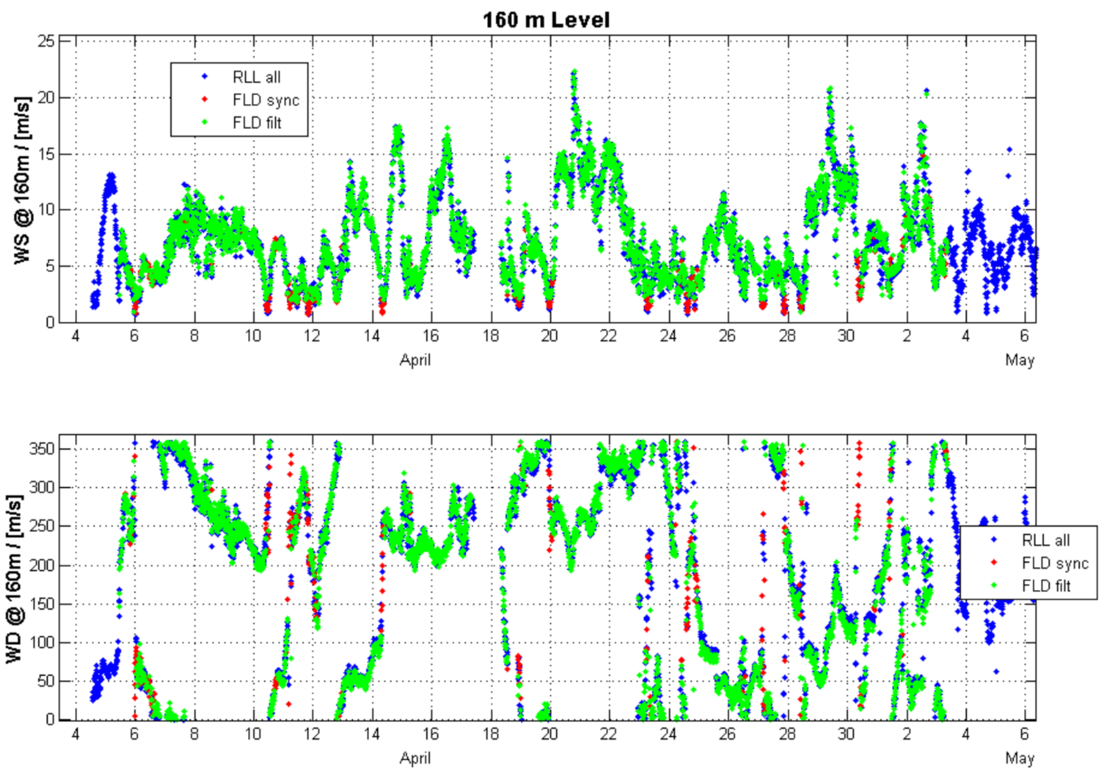


Time series of air temperature at RLL location and on SWLB:



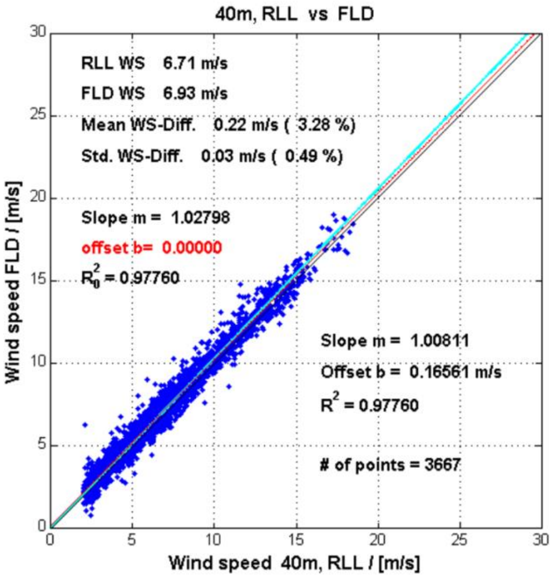
Wind speed and wind directions time series for 40 m and 160 m comparison heights:

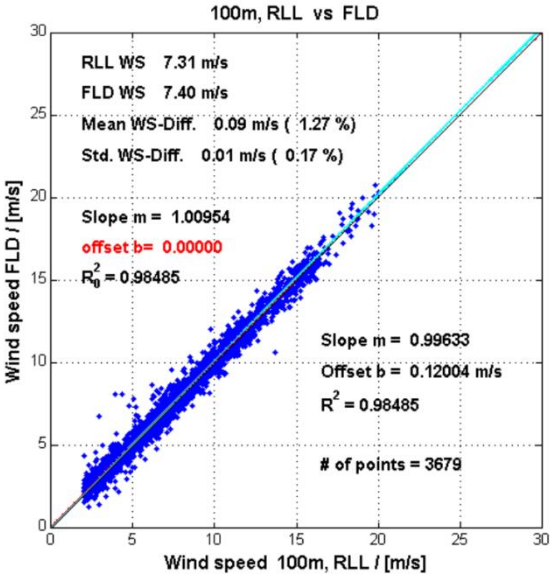


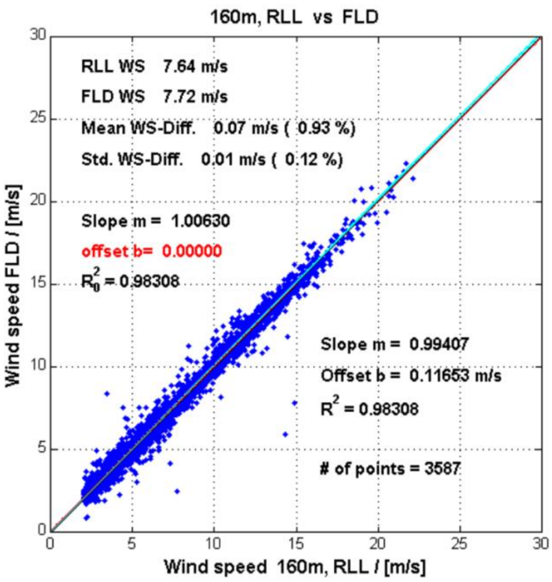


WS regression plots for four (4) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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.

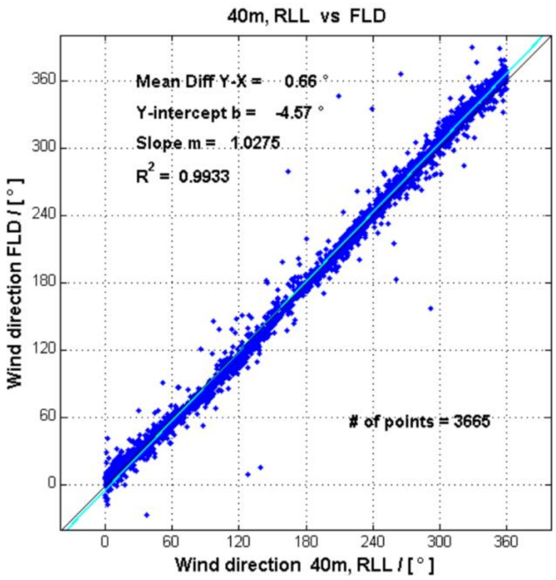


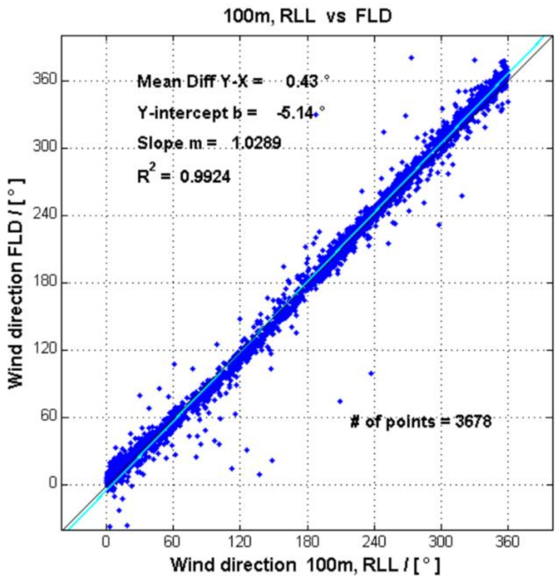


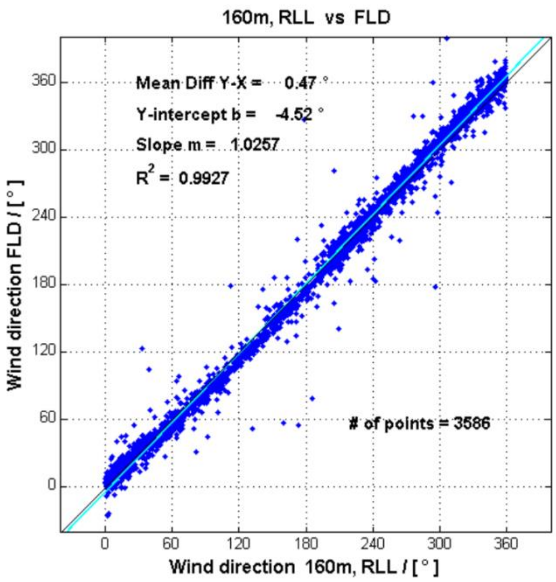


WD correlation plots for four (4) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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, Lidar buoy WS158
Hm0 Significant wave height (m) Slettringen, Lidar buoy WS158

Measuring depth : 0.00 m
Water depth : 75.00 m
Sampling interval: 9,9
Period : 2016.04.05 11:10 - 2016.05.03 08:59

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	6	296	298	577	280	26							1483	37,1	1483
0.5 - 1.0	7	88	359	209	325	66	50	6					1110	27,8	2593
1.0 - 1.5		7	258	148	287	250	40	19	1				1010	25,3	3603
1.5 - 2.0			87	69	117	77	22						372	9,3	3975
2.0 - 2.5			2	17			1						20	0,5	3995
2.5 - 3.0				4									4	0,1	3999
>= 3.0													0	0	3999
SUM	13	391	1004	1024	1009	419	113	25	1	0	0	0	3999	100	3999
% OF TOT/	0,3	9,8	25,1	25,6	25,2	10,5	2,8	0,6	0	0	0	0	100		
SUM ACCI	13	404	1408	2432	3441	3860	3973	3998	3999	3999	3999	3999	3999		
CUM. PRO	0,0033	0,101	0,352	0,608	0,8602	0,965	0,9933	0,9995	0,9998	0,9998	0,9998	0,9998	0,99975		
MIN. VALI	0,31	0,25	0,18	0,18	0,25	0,39	0,51	0,74	1,19				0		
AVE. VALI	0,48	0,46	0,84	0,69	0,89	1,23	1,16	1,07	1,19				0,83		
MAX. VAL	0,64	1,21	2,07	2,62	1,99	1,95	2,07	1,29	1,19				2,62		
STD. DEV.	0,1	0,17	0,45	0,49	0,45	0,34	0,38	0,13	0				0,47		

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

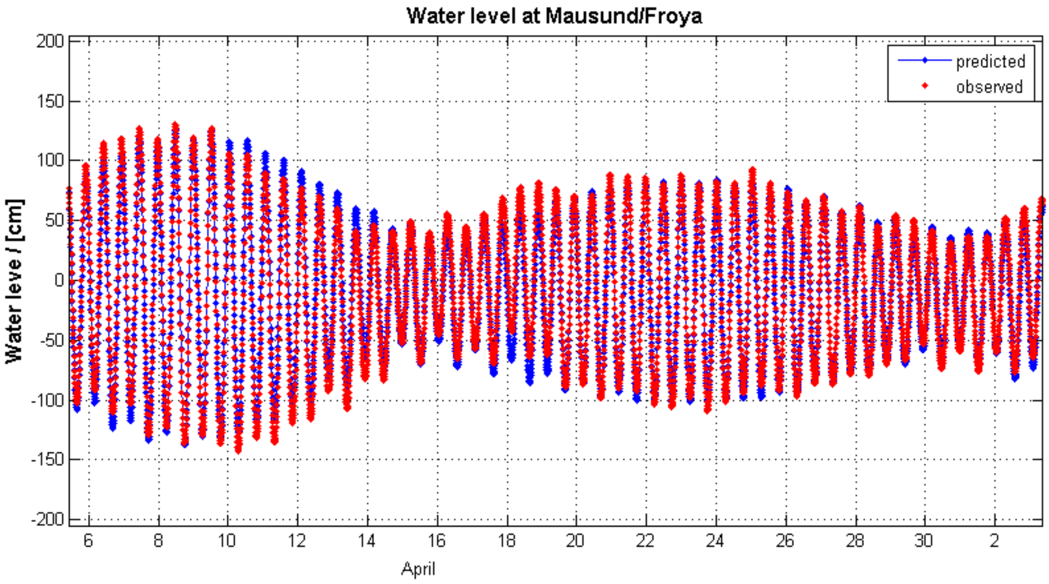
Hmax Maximum wave height (m) Slettringen, Lidar buoy WS158

Measuring depth : 0.00 m
Water depth : 75.00 m 18,7
Sampling interval:
Period : 2016.04.05 11:10 - 2016.05.03 08:59

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		1		3	26	52	63	41	33	18	21	116	374	10,2	374
0.5 - 1.0	2	29	16	43	172	310	327	100	37	51	57	109	1253	34,3	1627
1.0 - 1.5		7	15	25	82	209	157	43	24	11	27	87	687	18,8	2314
1.5 - 2.0			22	53	76	98	118	92	51	35	28	80	653	17,9	2967
2.0 - 2.5			10	55	58	68	99	86	42	27	18	46	509	13,9	3476
2.5 - 3.0			3	23	22	17	38	24	8	2	3	4	144	3,9	3620
3.0 - 3.5				3	7	6	6	1	1				24	0,7	3644
3.5 - 4.0					3	1							4	0,1	3648
4.0 - 4.5					3		1						4	0,1	3652
4.5 - 5.0							1						1	0	3653
>= 5.0													0	0	3653
SUM	2	37	66	205	449	761	810	387	196	144	154	442	3653	100	3653
% OF TOTAL	0,1	1	1,8	5,6	12,3	20,8	22,2	10,6	5,4	3,9	4,2	12,1	100		
SUM ACCUM.	2	39	105	310	759	1520	2330	2717	2913	3057	3211	3653	3653		
CUM. PROB.	0,0005	0,0107	0,0287	0,0848	0,2077	0,416	0,6377	0,7436	0,7972	0,8366	0,8788	0,9997	0,99973		
MIN. VALUE	0,56	0,44	0,53	0,41	0,38	0,38	0,35	0,41	0,38	0,38	0,38	0,35	0,35		
AVE. VALUE	0,57	0,89	1,52	1,72	1,36	1,18	1,24	1,46	1,41	1,27	1,17	1,1	1,28		
MAX. VALUE	0,59	1,26	2,96	3,31	4,07	3,69	4,57	3,02	3,19	2,55	2,75	2,64	4,57		
STD. DEV.	0,01	0,18	0,6	0,68	0,75	0,62	0,7	0,74	0,72	0,68	0,63	0,63	0,7		

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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