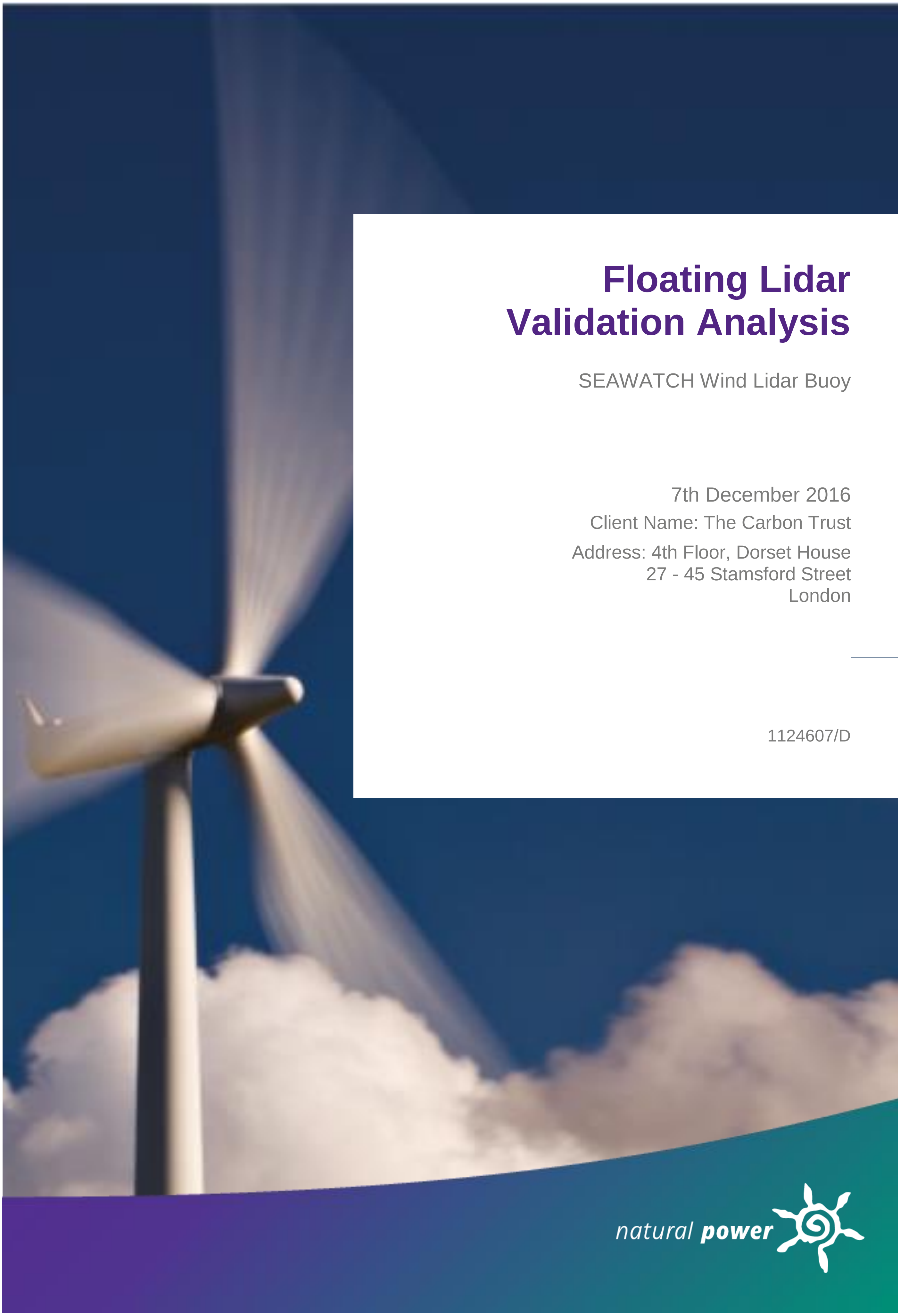

Floating Lidar Validation Analysis

SEAWATCH Wind Lidar Buoy

7th December 2016

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Executive Summary

The Natural Power Consultants Ltd. (Natural Power) was commissioned by The Carbon Trust to validate the performance and suitability of a SEAWATCH Wind LiDAR Buoy device against an offshore meteorological mast, installed at the East Anglia One Wind Farm in the North Sea. The key performance indicators (KPI's) defined within the Offshore Wind Accelerator Floating Lidar Roadmap formed the basis of the validation (Carbon Trust, 11/2013). The following table summarises the project details and findings.

Project Summary		**East Anglia One EA1B mast**
Period of concurrent measurement		26/11/2015 – 06/07/2016
On-site mast		85 m lattice mast installed on 18 m support structure (EA1B)
Measurement heights above mean sea level (m)		103 m, 100 m, 99.5 m, 90 m, 80.3 m, 70.3 m, 59.8 m, 49.7 m, 40.1 m
Mast location (UTM 31N WGS84)		465965 E, 5785000 N
Floating lidar device		FUGRO SEAWATCH Wind Lidar Buoy
Measurement heights above sea level (m)		199 m, 169 m , 149 m, 129 m, 102 m, 99 m, 94 m, 79 m, 59 m, 40 m, 39 m
Central location of floating lidar (UTM 31N WGS84)		465601 E, 5785104 N
KPI Definition – availability	**Minimum availability for all heights (entire period)**	**Maximum availability for all heights (entire period)**
Monthly System Availability, MSA_{1m} (%)	55.3	100.0
Monthly Post Processed Data Availability – 1 month average, $MPDA_{1M}$ (%)	54.8	98.8
Overall Post Processed Data Availability, $OPDA_{CA}$ (%)	85.0	86.5
KPI Definition -Overall System Availability		
Overall System Availability – Campaign Average, OSA_{CA} (%)		88.5
KPI Definition		
Number of Maintenance Visits, MV		0
Number of Unscheduled Outages, UO		1
Uptime of Communication System, CU		N/A
KPI Definition - accuracy	**Minimum accuracy**	**Maximum accuracy**
Mean Wind Speed – Slope, X_{mws} (wind speeds greater than 2 m/s)	0.995	0.997
Mean Wind Speed – Coefficient of Determination, R^2_{mws} (wind speeds greater than 2 m/s)	0.993	0.994
Mean Wind Direction – Slope, M_{mwd}	0.978	0.983
Mean Wind Direction – Offset (absolute value), OFF_{mwd}	5.854	2.070
Mean Wind Direction – Coefficient of Determination, R^2_{mwd}	0.997	0.997
Turbulence Intensity – Slope, X_{TI}	1.797	2.186
Turbulence Intensity – Coefficient of Determination, R^2_{TI}	-0.360	0.058
KPI Definition – shear comparison		
Wind Shear – Shear Exponent, α (EA1B mast)		0.097
Wind Shear – Shear Exponent, α (SEAWATCH Wind LiDAR)		0.097

Green: Meets the best practice acceptance criteria Amber: Meets the minimum acceptance criteria
Red: Does not meet the acceptance criteria **Black**: No acceptance criteria
Note: all wind speed and direction results are based on data where wind speeds are greater than 2 m/s

The validation exercise shows that the SEAWATCH Wind LiDAR Buoy general shows very good performance on the accuracy KPI's but fails on a number of availability KPI's. The minimum requirements were met for all the wind speed and direction accuracy KPI's over the full period of deployment. Performance of the SEAWATCH Wind LiDAR Buoy in wind speed accuracy is excellent with all KPI's surpassing the best practise limits. Wind direction accuracy performed adequately with most measurement heights exceeding best practice with the exception of the wind direction offset at the top two measurement heights where the minimum KPI requirements were met.

Reviewing all the validation results Natural Power considers that the robustness of the SEAWATCH Wind LiDAR Buoy for marine environments has to be improved in order to be able to provide sufficient recovery of data for deployment periods of six months or longer. Once hardware issues are overcome Natural Power is confident that the SEAWATCH Wind LiDAR Buoy can provide accurate wind speed and wind direction measurements, suitable for use in finance grade energy yield assessments without incurring significant uncertainty penalties. The use of ZephIR 300M, a marinised version of the ZephIR 300, is likely to significantly improve the robustness of the system.

1. Introduction

The Natural Power Consultants Ltd ("Natural Power") was commissioned by The Carbon Trust (the "Client") to validate the performance and suitability of a SEAWATCH Wind LiDAR Buoy device against an offshore meteorological mast, installed at the East Anglia One Wind Farm in the North Sea. The key performance indicators (KPI's) as defined in the Offshore Wind Accelerator (OWA) Floating Lidar Roadmap document (Carbon Trust, 11/2013) formed the basis of the validation.

The East Anglia One Wind Farm is located approximately 60 km east of the coast of East Anglia, in the North Sea, England. A map showing the location of the area with respect to the surrounding region is shown in Figure A.1. Data were provided by the Client from a single meteorological mast, Mast EA1B, over the period 8th January 2015 to 6th July 2016 and from a SEAWATCH Wind LiDAR Buoy (the device), combining a ZephIR 300 lidar unit with a SEAWATCH Wavescan Buoy over the period of approximately 26th November 2015 to 6th July 2016.

This report presents details of the analysis undertaken and the key results of the validation exercise.

2. Wind Measurement Review

The wind data were reviewed from the Mast EA1B and the device at the East Anglia One Wind Farm. The following is a brief overview of the wind data review procedure:

1. Raw on-site anemometry data were received on a weekly basis where possible from the Client for Mast EA1B.
2. The raw data from Mast EA1B were processed and validated to identify and remove all suspect data from consideration in the validation study.
3. The raw data from the device were received on a weekly basis where possible from the Client. Filters on the data were applied and the data were processed and validated to identify and remove all suspect data from consideration in the validation study.
4. The raw *.ZPH files from the ZephIR 300 unit were stored on the buoy and recovered during the maintenance visit in March 2016 for the period November 2015 to February 2016, and at the end of the campaign for the period March 2016 to July 2016. These data were compared to the wind data sent by the SEAWATCH Wind LiDAR Buoy for validation.

The following sections contain details of the steps described above.

2.1. Measurement Campaign

The measurement campaign comprised a single 85 m lattice meteorological mast installed on an 18 m AMSL platform, Mast EA1B, and a co-located floating lidar device, a SEAWATCH Wind LiDAR Buoy, the device.

Mast EA1B was installed and maintained by SgurrEnergy and was commissioned in August 2013. The mast measured wind speed at eight different heights and wind direction at seven different heights. Data were provided by the Client for Mast EA1B for the period January 2015 to February 2016 in order for Natural Power to be able to assess the mast data with a fully seasonally balanced dataset prior to the validation study (Natural Power, 2016). On review of the mast and data, Natural Power concluded that the data were deemed to be fit for use within the validation analysis. Filtering of mast data was required to remove tower distortion affected data prior to the validation analysis. The correction of tower distortion in the data is discussed further in Section 2.2.1.

A SEAWATCH Wind LiDAR Buoy, the device, was deployed approximately 400 m to the west of the Mast EA1B for a period of 7 months, between November 2015 and July 2016, in order to collect data for validation purposes. The device deployed at the East Anglia One Wind Farm consists of a ZephIR 300 lidar unit mounted on a standard SEAWATCH Wavescan Buoy which is a low motion autonomous device manufactured by FUGRO OCEANOR AS. The ZephIR 300 lidar unit is installed in the centre of the SEAWATCH Wavescan Buoy 2 m above sea level (ASL). Natural Power has reviewed the lidar and buoy technology prior to the validation study to assess the suitability of the SEAWATCH Wind LiDAR Buoy (Natural Power, 2016). This study concluded that the SEAWATCH Wind LiDAR buoy will have the ability to provide accurate and precise wind measurements.

For the purposes of this validation study, only concurrent data between the mast and the SEAWATCH Wind LiDAR Buoy, spanning the period November 2015 to July 2016, were assessed. Natural Power received the measured data on a weekly basis from the Client for the mast and the SEAWATCH Wind LiDAR Buoy which were reviewed and quality checked.

Table 2.1: Meteorological campaign results summary

	Mast EA1B	SEAWATCH Wind LiDAR Buoy
Location*	465965 E, 5785000 N	465601 E, 5785104 N
Data period of record	26/11/2015 – 06/07/2016	26/11/2015 – 06/07/2016
Wind speed measurement heights (AMSL)	103 m, 100 m, 99.5 m, 90 m, 80.3 m, 70.3 m, 59.8 m, 49.7 m, 40.1 m	199 m, 169 m , 149 m, 129 m, 102 m, 99 m, 94 m, 79 m, 59 m, 40 m, 39 m
Wind direction measurement heights (AMSL)	100 m, 99.5 m, 90 m, 80.3 m, 70.3 m, 59.8 m, 49.7 m, 40.1 m	199 m, 169 m , 149 m, 129 m, 102 m, 99 m, 94 m, 79 m, 59 m, 39 m
Raw data capture	100%	88.5%
Post quality control data capture	99.1% - 99.4%	85.0% - 86.5%
Mean wind shear exponent (50 m – 100 m)	0.09	0.10
Mean turbulence intensity at 100 m measurement height	5.6%	13.3%
Predominant wind direction at 100 m	210°	210°
Mean temperature (°C)	9.7	9.7

Note that none of the values presented in this table are annualised. Coordinates are given in UTM 31 N WGS 84

The SEAWATCH Wind LiDAR Buoy is a floating device anchored by a tether to the sea bed and as such is subject to movement due to waves, currents, tides and winds. The movement of the device around its initial deployment position was examined. Hourly GPS data from the Device and 10-minute data from the ZephIR 300 can be seen in Figure E.17 and Figure E.18 respectively, indicating general agreement in the footprint of the buoy motion. The climate at the site is considered to be typical given the offshore location. The offshore wind climate in the East Anglia region is deemed to be seasonal and with higher than average wind speeds observed in the winter months where weather fronts occur more frequently. Sea state conditions measured from the device can be seen in Figure E.14 to Figure E.16 and in Table E.1 to Table E.3 where the wave significant height ranged from 0.16 m to 5.63 m during the measurement campaign

2.2. Equipment

2.2.1. Mast EA1B

The mast is a triangular mast with a face width of 4.26 m at the platform surface, narrowing to 1.26 m at the 100 m AMSL level. Due to the offshore location, it has open exposure in all direction sectors, with no known obstructions to the wind flow. The mast has been designed to meet the suggested IEC recommendations (IEC 614000:12-1, 2005) for a 0.5% deficit in wind measurement at the top two instruments and 1.0% deficit in wind speed measurements for all other instruments on the mast. Distortion from the mast is important to be taken into consideration as effects of the mast structure, booms and other instruments can adversely affect the measurements from the mast, particularly wind speed data. The setup and photographs of Mast EA1B are presented in Appendix A.

There are two Campbell Scientific CR1000 loggers installed on Mast EA1B and measurements from each height are split between the two loggers. Data are recorded in local time (UTC) with 10-minute averages and the timestamp indicating the period ending.

An overview of the instrumentation on the mast is detailed in Table B.1. Calibration certificates were supplied for each of the anemometers, all of which were calibrated at Deutsche WindGuard GmbH, a MEASNET accredited institute. Calibration factors were cross referenced by Natural Power with those applied in the logger program, and it was found that standard calibration factors had been applied for all of the anemometers. The standard calibration factors were removed from the collected data and the instrument specific calibration values, as documented in the calibration certificates, were applied by Natural Power. The wind vanes installed on the mast were orientated with the north datum aligned along the booms, towards the mast (Wood Group Kenny, 2013). As such, an offset of +60° was applied by Natural Power to the direction data from the mast.

A three day mast maintenance visit took place in May 2016 where each instrument was inspected and several sensors were replaced. The relevant information for the May 2016 maintenance visit can be found in the Table B.3 and was extracted from the mast measurement specification spread sheet (Iberdrola S.A., 05/2016). Based on mast maintenance information provided by the Client, the heights and orientation of the sensors remained the same after each respective replacement. The mast data during the May 2016 maintenance visit were removed from the validation dataset to eliminate potential interference effects. The change in the instrumentation does not constitute a change in the consistency of the dataset.

2.2.2. Floating Lidar Device

The device deployed at the East Anglia One Wind Farm consists of a ZephIR 300 lidar unit mounted on a standard SEAWATCH Wavescan Buoy. The Wavescan Buoy was originally designed as a platform for meteorological and oceanographic data collection use. The ZephIR 300 is a continuous wave coaxial lidar that can measure wind speed and direction data at ten user configurable heights ranging from 10 m to 200 m above the unit. The ZephIR 300 lidar unit used in the device had the firmware version 1.3221 installed. The lidar was positioned in the centre of the SEAWATCH Wavescan Buoy 2 m above sea level (ASL). In addition to the ZephIR 300 lidar, a number of sensors were installed on the buoy itself or on a small 2.2 m vertical mast mounted on the buoy, details of these sensors and their measured parameters are presented in Table 2.2.

Table 2.2: SEAWATCH Wind LiDAR Buoy instrumentation

Device	Mounting	Measured parameters	Reference
Gill Windsonic anemometer	Mast	Wind speed and wind direction	(GILL, 2016)
Vaisala HMP155	Mast	Air temperature	(VAISALA, products: humidity: Pages: HMP155, 2016)
Vaisala PTB330	Mast	Air pressure	(VAISALA, products: pressure: Pages: PTB330)
Nortek Aquadopp profiler	Buoy	Sea current speed and direction at 14 depths	(nortek-as, 2016)
Fugro Wavesense 3 (sensor and data logger)	Buoy	Significant wave height Wave direction Wind wave direction Wave period Heave, yaw, pitch and roll	(Fugro-Oceanor-AS, seawatch: buoys-and-sensor: Oceanor-Wavesense, 2016)
Compass	Buoy	Buoy's rotation relative to north	
GPS	Buoy	Buoy's geographic position	

The ZephIR 300 unit on the buoy was powered by four methanol fuel cells which can provide sufficient power to run the ZephIR 300 lidar autonomously for six months. Four solar panels charging lead acid batteries were installed on the buoy providing power to the other sensors and data logger (Berg, Seawatch Wind LiDAR buoy description for East Anglia ONE Limited, 2015). The full configuration of the SEAWATCH Wind LiDAR Buoy is presented in Appendix C.

Natural Power has carried out a review of the ZephIR 300 lidar technology and concluded that the ZephIR 300 is suitable for use in benign onshore conditions with equivalent performance to that of an IEC compliant mast in the context of wind speed and direction measurements (Natural Power, 2016), these measurements are considered to be of a level of accuracy suitable for use in finance grade energy yield assessments. In offshore conditions, which are also considered to be benign due to the generally uniform flow field found in the offshore environment, it is Natural Power's opinion, based on review of studies and operational experience, that the ZephIR 300 device is suitable for deployment at an offshore location on a fixed platform to provide finance grade wind speed and direction data with equivalent accuracy to an IEC compliant fixed mast. The device is a low motion device and Natural Power is satisfied that the device in a fixed frame of reference can provide accurate and precise wind speed and direction measurements in place of IEC compliant mast data. Performance under free motion in the floating context is subsequently examined in this report.

2.3. Data Review

2.3.1. Mast EA1B

For the purposes of assessing the quality of data from Mast EA1B, measurement data for the period from January 2015 to July 2016 were analysed. All data were processed and quality controlled by Natural Power using internal data validation procedures (Natural Power, 2016). Natural Power observed that the data were of high quality with minimal periods removed as part of the quality control process. The mast anemometers and vanes showed strong correlations when correlated against one another, as shown in Table B.4 and Table B.5.

An assessment of the tower shadow and distortion was conducted due to the boom length/mast face geometry in the context of IEC recommendations (IEC 614000:12-1, 2005). Low levels of shadow effects were observed at 103 m (AMSL) where the "goal post" arrangement is used; however, higher than expected levels of distortion were observed on the lower measurement levels from 100 m to 40 m (AMSL), particularly in the sectors from approximately 240^0 through to approximately 40^0. These effects are considered to be a result of the mast induced distortion effects. The opposing cups should see symmetrical flow for the 30^0 and 210^0 direction sectors. The measurements show agreement for the 210^0 sector and are observed to be well within the 1.0% target value. However, the 30^0 sector shows a discrepancy in excess of 1.0%. This can be mitigated by selective averaging of data and is not considered to be significant in the context of finance grade data.

The Vector A100LK anemometers aligned towards 300° are observed to record slightly higher values (less than 0.1 m/s) than the Thies First class anemometers at 120° for all the heights. Given the small differences, it is not expected to have a significant impact in this validation study.

The influence of the mast is apparent at all measurement heights. The shading effects for all anemometers (with the exception of the top mounted anemometers) is mainly a result of the mast and the fact that the boom length is not sufficient for the anemometers to reach an area of less distorted wind flow. The effect of the mast is clear on the slopes of the single variant linear regression for all the measurement levels around 120° and 300°. The measurements are unexpectedly affected for the sectors from 310° to 10° where the slopes of the regression were expected to be higher and closer to the ones observed for the comparable sectors from 60° to 110°. Assessment of the sector wind speed ratios at each height shows a consistent pattern across the entire mast height with the instruments aligned towards 300° showing an apparent slow down effect from approximately 240°. This slow down effect continues through the mast shadow affected sectors centred on 300° then continuing to approximately 40°. It has been concluded that this slow down effect is due to a large mast structure induced effect. However, a similar effect has been observed at the top level where the instruments should be above the height where significant mast distortion effects are apparent. For the 100 m AMSL measurement level, an increased tower shadow effect was identified in comparison with the lower measurement levels from 90 m to 40 m (AMSL). This effect is probably a result of other sensors installed at the top of the mast and of the external platform which is at the same height as all the sensors at this level.

Typically, when an instrument pair is mounted at the same height on a mast, tower/instrument shadow/distortion effects can be assessed and corrected for in the time series. This was carried out for the mast data by Natural Power using the following means:

- Using only the reading from the unaffected upwind sensor for the direction ranges where one of the instruments experienced shading;
- Averaging the measured data in all other sectors.

The resulting series at each height from the mast has the effects of mast and instrument shading minimised.

The wind speed and direction frequency distributions show similarity across all heights and are generally well represented by fitted Weibull distributions. The data shows predominant winds from the south-west with very little variation of the wind direction across the height of the mast. Assessment of the standard deviation of the wind direction measurements show the mast structure is clearly evident across the wind vane measurement heights.

Turbulence intensity data were reviewed for all the anemometers and the overall turbulence was found to be low and in-line with expectations for the offshore environment where there is low roughness with no obstacles to create turbulence. The average turbulence intensity is higher for the 120° and 300° sectors as a result of the flow distortion from the mast see Figure B.4 to Figure B.9. Wind shear data has been analysed with sector-wise and seasonal binning. Shear is observed to be low and is typical for the offshore environment with uniform shear across the measurement heights.

After quality checking, evaluating and analysing the data from Mast EA1B, Natural Power confirms that the data are of a good quality, suitable for finance grade energy assessments. In addition, the data are deemed to be fit for and can be used for the SEAWATCH Wind LiDAR Buoy validation analysis.

2.3.2. SEAWATCH Wind LiDAR Buoy Data Sources and Filters

Data from the device were provided by the Client. The data were received on a weekly live basis and the further data were recovered at the end of the campaign details of the data received can be found in Appendix C. The ZephIR 300 1-second scan wind data were processed live on the buoy to allow for the buoy bearing / ZephIR 300 direction compensation to be applied. The step by step ZephIR 300 data processing methodology implemented by FUGRO is described in Table 2.3 (Storas, 2016). At the end of the campaign once all the data were provided by the Client, automatic filters had to be applied to the lidar data to take into account fog, rain and contamination.

Table 2.3: SEAWATCH Wind LiDAR Buoy wind data processing methodology

Step	Action	Description
1	Check for new data	The data logger continuously checks the data registered from the ZephIR 300 for updated measurements of horizontal wind speed, vertical wind speed and wind direction on a 1 second basis.
2	Check of validity of the data	Each time the lidar has a new measurement for each height level, the wind direction and wind speed values are checked to be valid compared to FUGRO defined parameters.
3	Wind direction validation and correction	Each wind direction measurement is checked against the instant bearing of the buoy and corrected accordingly to maintain a fixed north datum.
4	Wind direction flipping correction	North corrected wind direction from the lidar is then checked against the direction measured by the sonic anemometer installed on the buoy. If the difference is greater than 135° it is assumed that the direction has an 180° offset and the ZephIR direction measurement is adjusted accordingly.
5	Wind measurement correction	Using the final corrected wind direction, the original wind measurement from the ZephIR 300 is then decomposed to corrected individual vector components (x,y,z) and stored in the logger in a data buffer.
6	Wind measurement averaging	For each 10-minute interval the mean wind speed, wind direction and inflow angles are calculated from the average of the 1 second data. The 10-minute data point is discarded if less than 50% of the averaged 1 second data are considered valid (FUGRO defined parameters). The average values are time-stamped at the end of the 10-minute intervals.

Appendix C describes the data provided once the device was removed from the deployment location during maintenance and at the end of the measurement campaign. As part of this retrieved data, raw *.ZPH files from the ZephIR 300 device containing 10-minute filtered data were collected and processed through the ZephIR Waltz version 4.4 data processing software. These data were used to compare the buoy derived 10-minute averaged data, calculated from the process described in Table 2.3. After comparison of the data from the device and ZephIR 300 filtered data, it was found that the device data had not been filtered for fog, rain and environmental contamination. The amount of data not filtered out through the ZephIR 300 system filtering routine spanned from 105 10-minute time stamps for the 59 m measuring height to 684 10-minute time stamps for the 199 m height. Given that the ZephIR data can be considered to be at stage 3 when the manufacturer’s recommendations are followed, it was deemed mandatory to follow the ZephIR 300 filtering process and filter out these data using the ZPH files processed through the standard Waltz software. As such, the availability from the device was affected by filtering this data, but the effect was relatively small.

2.4. Significant Issues

The device and the mast measured concurrently from 26th November 2015 until the 6th July 2016. During this measurement period, a number of issues occurred with the mast and the device. All significant issues and the associated downtime period are presented in Table 2.4.

Table 2.4: Summary of significant downtime

Event	Device	Period of issue (inclusive)	Description
Loss of communication	SEAWATCH Wind LiDAR Buoy	16/12/2015 - 24/12/2015	Loss of communication from the device. While data were not received during this period, data were logged and retrieved from the device once it was recovered from the site. The measuring systems and sensors remained fully operational during this period. The device came back online automatically at the end of this loss of communication. No reason was identified for this communication loss. As the communication loss downtime was only for one week, only minor implications occurred on the data flow. Further discussion on this significant period of communication downtime is found in Section 2.4
Loss of communication	SEAWATCH Wind LiDAR Buoy	14/01/2016 - 17/02/2016	Loss of communication from the device. While data were not received during this period, data were logged and retrieved from the device once recovered from the site. Two days of corrupted data were detected when the data where retrieved. The reason for the two day data issue could not be identified.
Loss of communication and power	SEAWATCH Wind LiDAR	17/02/2016 – 12/03/2016	Data were not collected during this period due to major corrosion of the cable connectors on the device. Further discussion on this significant period of downtime is found in Section 2.4
Mast maintenance	Mast EA1B	26/05/2016 – 28/05/2016	Maintenance of instruments on Mast EA1B resulting in potential interference of the mast measurements. Data between 8:00 am until 6:10 pm were removed to take this into account

The most significant downtime of the device started on 17th February 2016 where the data received from the buoy system indicated that the ZephIR 300 had lost power and stopped working. Recovery of the buoy for repair and service was carried out as soon as the weather allowed. The device was recovered, replaced with a temporary float and brought to Lowestoft Port on 5th March 2016 for maintenance. The maintenance was carried out by FUGRO and ZephIR engineers.

It was observed during the maintenance of the device that the main cause of the loss of power was found to be a power connection issue. The cables and connectors were replaced. Furthermore, for two of the fuel cells, error messages were found in the log files. The two fuel cells were replaced in order to reduce the risk of failure during the redeployment. The communication issues prior to the loss of power of the device were due to the corrosion on the Ethernet connector. This was replaced during the maintenance of the device. The ZephIR 300 meteorological station was also found to have failed due to the humidity sensor water ingress weakness. This was replaced with a new 200WX IP65 type meteorological station which is more water resistant and deemed to be more appropriate for marine applications. The ZephIR firmware was updated to version 1.3233 from version 1.3221 during the maintenance of the device. The new firmware was installed to support the new met station and it was otherwise identical to the previous one (Fugro Oceanor AS, 03/2016).

The device components were tested separately and the device was re-assembled and tested in the warehouse where the maintenance took place. These tests were also performed outdoors on the dock and with the device deployed in the water. After the tests, the device was found to be in good operational order and it was redeployed on site on 12th March 2016 after being towed to site. The total downtime of the device during this time was 25 days (17th February 2016 – 12th March 2016). Following the redeployment, the device operated normally and provided data regularly until the end of the campaign with no further issues.

During the onshore maintenance described above the missing data due to loss of communication for the periods from 16th December 2015 to 24th December 2015 and from 14th January 2016 to 17th February 2016 were recovered and post processed. System availability for these periods was 100% and 94% respectively.

As a result of the power failure during the deployment, it is recommended that the overall design of the device should be reviewed to ensure the combined system is suitably robust for the harsh marine environment such that consistent measurements and communication of data can be delivered over a deployment period of six months or more.

Future SEAWATCH Wind LiDAR Buoy devices will make use of the ZephIR Z300M device which is essentially the same device as the ZephIR 300 with modifications to the housing, connectors and cooling system specifically for use in the marine environment. These improvements will increase the durability of the system while not affecting the accuracy performance of the system.

3. Validation Dataset

The KPI's as defined in the floating lidar roadmap outline certain conditions for an assessment of accuracy which the device must meet in order to be validated. The preconditions that have to be tested and met for the accuracy assessment can be seen in Table 3.1 and are discussed in more detail in Appendix D.

Table 3.1: Conditions for accuracy assessment

Data condition requirements	Test / Action
Mast data filtered for mast wake effects	A tower shadow corrected series was generated as described in Section 2.3.1
Device data filtered for mast wake effects	Mast wake effect on the device is considered to be negligible due to horizontal seperation compared to mast width.
Exclusion of data from the analysis when the wind speed is lower than 2 m/s	For the data analysis and the validation study, data were taken into account only for wind speeds greater than 2 m/s
Exclusion of wind measurements from the analysis when the air temperature is below 0.5°C	No air temperatures below 0.5°C where recorded during the campaign
Minimum number of 40 10-minute average values per wind speed bin for wind speed measured from the device	More than 40 10-minute average values were recorded per wind speed bin, as described in Appendix D, for all the assessed heights. The exact number of 10-minute records available per wind speed bin per height can be found in Table F.1 to Table F.3

Source: (Carbon Trust, 11/2013)

As wind direction is a circular variable, the beginning and the end of the measuring range coincides with one another. In the case where wind direction measurements from two independent devices are compared, a wrap around effect might ocurr where the magnitude of the measured values can be very different, such as when correlating 1° and 359°. The wrap around effect can affect the results of a linear wind direction correlation. In order for the wind direction correlation between the device and the mast to provide unaffected results, a wrap around methodology described in the Table 3.2 was used.

Table 3.2: Wrap around methodology

Step	Methodology
Step 1	The difference between the mast and the device directions was calculated on a 10-minute basis
Step 2	If the wind direction difference was found to be greater than 300°, then 360° were added to the device 10-minute wind direction value
Step 3	If the wind direction difference was found to be less than -300°, then 360° were subtracted from the device 10-minute wind direction value
Step 4	For all the other cases the device 10-minute wind direction value remained as measured

The data considered for the validation study are shown in Table 3.3. Only the 10-minute time stamps, where valid data were available for all the variables, were taken into account.

Table 3.3: Validation study data set

Period	Measurement levels (m AMSL)
Mast wind speeds (data from both the anemometers and the tower shadow corrected series for each height)	103, 100, 80, 60 and 40
Device wind speeds	102, 99, 79, 59 and 39
Mast wind directions	100, 80, 60 and 40
Device wind directions	102, 99, 79, 59 and 39
Mast EA1B wind turbulence intensity (data from both the anemometers)	103, 100, 80, 60 and 40
Device turbulence intensity	102, 99, 79, 59 and 39
Mast EA1B wind temperature	100, 80, 60 and 40
Device temperature	4
Device (all measured variables from Fugro Wavesense 3)	0
Device sea current speed and direction	-4

The data taken into account for the validation study spanned from 26th November 2015 to 6th July 2016, including the downtime period. The validation exercise was carried out for the period before and after the onshore maintenance work, as well as for the entire period as defined in Table 3.4.

Table 3.4: Data periods assessed

Period	Start of data period	End of data period
Entire Period	26/11/2015 11:50	06/07/2016 13:10
Period 1	26/11/2015 11:50	17/02/2016 00:40
Period 2	12/03/2016 12:10	06/07/2016 13:10

4. Floating Lidar Validation

4.1. Data Availability and Accuracy Definition

Data availability is defined as the actual amount of data recorded from a measuring system for a given period compared to the total data that could be collected over that time period. Typically availability is presented in percentage terms. Data availability is important in terms of evaluation of the wind resource of a wind farm as sufficient data should be available in order to provide wind measurements representative of the full range of conditions that the wind farm is expected to operate in. This is of importance if the measurement device is sensitive to particular conditions where measurements are not possible or are of lower quality, leading to potential bias or lack of representativeness of data for the full range of expected conditions. The available data should be of high quality to ensure an accurate assessment in terms of wind resource assessment. Data accuracy is a measure of how precise and correct the data values are and is a parameter used to measure the quality of the measurement campaign. The accuracy of the data has to be checked in order to avoid erroneous results during the data analysis. The OWA roadmap recommends a minimum six month deployment period for the validation of the device. The duration of the validation campaign was approximately 7.5 months. This validation study examines not only the quality of the data provided from the device, but also the robustness of the device/system to record and provide data for all relevant conditions in the harsh marine environment.

4.2. Key Performance Indicators (KPI's)

Through dialogue with industry leaders the Carbon Trust has derived key performance indicators (KPI's) upon which to assess the performance of floating lidar technology. The KPI's have been set out to assess accuracy of wind speed and direction measurements against a reference system, Mast EA1B, which is considered to meet best practise in terms of the incumbent technology for measurement of offshore wind climate. Critical measures are the accuracy of the wind speed and direction measurements across all conditions likely to be experienced at a target offshore wind farm location. While accuracy is a key performance measure, the measurement system must also return suitably high levels of data recovery to enable capture of the full range of expected conditions. High levels of accuracy of the wind speed and direction measurements, combined with high data availability are the main factors to define acceptance of new technology. The KPI's have been specified with these main areas of focus.

The overall and monthly system availability has been assessed for each available measurement height of the device. Post processed data availability has also been assessed overall and on a monthly basis for each available measurement height of the device.

In addition to the availability acceptance criteria, the roadmap also requires that information is provided on the number of maintenance visits, unscheduled outages and communication system. Information pertaining to these measures has been assessed.

Other measures pertinent to the wind climate such as turbulence and shear exponent are included in the KPI's but without any criteria set for these secondary measurements.

Shear comparisons were derived for measurement heights between 40 m and 80 m AMSL from Mast EA1B and 39 m to 79 m AMSL from the device for the whole period, period 1 and period 2. These heights were chosen as they were closest to the 50 m to 90 m range stipulated in the roadmap, and with this height range not being measured from the device, the closest height range was chosen. A power law extrapolation method, equation shown below, was used to calculate the wind shear values.

$$\alpha = \frac{ln\left(\frac{v_1}{v_2}\right)}{ln\left(\frac{h_1}{h_2}\right)}$$

The validation process includes specific KPI's for availability, wind speed accuracy and wind direction accuracy. Each of the parameters from the device was compared to the baseline measurements from the Mast EA1B. The KPI's as defined in the validation exercise are given, with definitions and acceptance criterion, in Table 4.1 to Table 4.6.

Table 4.1: KPI's for system availability

KPI	Definition / Rationale	Acceptance Criteria across six months data
MSA_{1M}	**Monthly system availability – 1 month average** The lidar system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. NaN or 999) for the given month. The Monthly Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (10-minute) data entries including periods of maintenance (regarded as 100%) within the respective month.	≥ 90
OSA_{CA}	**Overall system availability – campaign average** The lidar system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. NaN or 999) for the pre-defined total campaign length. The Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (10-minute) data entries including periods of maintenance (regarded as 100%) within the pre-defined total campaign period.	≥ 95

Table 4.2: KPI's for post processed data availability

KPI	Definition / Rationale	Acceptance Criteria across six months data
$MPDA_{1M}$	**Monthly post processed data availability – 1 month average** The monthly post-processed data availability is the number of those data entries remaining after system internal (unseen) filtering (e.g. – 22dB CNR filter for WC), i.e. excluding (NaN or 999) flagged data entries and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of lidar contractor guidelines relative to the maximum possible number of (10-minute) data entries (regarded as 100%) within the respective month, regardless of the environmental conditions within this period.	≥ 80
$OPDA_{CA}$	**Overall post processed data availability** The overall post-processed data availability is the number of those data entries remaining after system internal (unseen) filtering (e.g. – 22dB CNR filter for WC), i.e. excluding (NaN or 999) flagged data entries and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of lidar contractor guidelines relative to the maximum possible number of (10-minute) data entries (regarded as 100%) within the pre-defined total campaign period regardless of the environmental conditions within this period.	≥ 85

Table 4.3: KPI's for maintenance visits, unscheduled outages and communication system

KPI	Definition / Rationale	Acceptance criteria across six months data
MV	**Number of Maintenance Visits** Number of visits to the floating lidar system by either the supplier or an authorised third party to maintain and service the system. This is to be documented and reported by the supplier and confirmed by The Carbon Trust or their authorised representatives.	n/a
UO	**Number of Unscheduled Outages** Number of unscheduled outages of the floating lidar system in addition to scheduled service outages. Each outage needs to be documented regarding possible cause of outage, exact time / duration and action performed to overcome the unscheduled outage. This is to be reported by the supplier and independently checked and confirmed by The Carbon Trust or their authorised representatives.	n/a
CU	**Uptime of Communication System** To be documented and reported by the supplier and independently checked/confirmed by The Carbon Trust or their authorised representatives.	n/a

Table 4.4: KPI's for wind speed accuracy

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

Table 4.5: KPI's for wind direction and turbulence intensity

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 (absolute value)** (same as for M_{mwd})	< 5^{o}	< 10^{o}
R^2_{mwd}	**Mean wind direction – coefficient of determination** (same as for M_{mwd})	> 0.97	> 0.95
X_{TI}	**Turbulence intensity – slope** Slope co-efficient from single variant regression with the regression analysis constrained to pass through the origin.	n/a	n/a
R^2_{TI}	**Turbulence intensity – correlation co-efficient** Correlation co-efficient returned from single variant regression with the regression analysis constrained to pass through the origin.	n/a	n/a

Table 4.6: KPI’s for wind shear

KPI	Definition / Rationale	Acceptance criteria	
		Best practice	Minimum
α	Wind shear – shear exponent Alpha related to Hellman’s Power law Alpha to be calculated using reference anemometry heights at 50 m and 90 m Mean Alpha values to be compared for different wind speed ranges such as a) 4 m/s – 8 m/s b) 8 m/s – 12 m/s c) 12 m/s – 16 m/s d) All wind speeds above 2 m/s	n/a	n/a

Due to the period of unscheduled maintenance required and the subsequent loss of data, the KPI’s have been assessed for the entire period of data collection and for the period before and after the maintenance period. In the context of the validation study the entire period is deemed valid and the main results have been interpreted as the using this full period of data.

4.3. Validation Results

The validation results are presented within the following sections with commentary where required.

4.3.1. Monthly System Availability – 1 month average (MSA_{1M})

Table 4.7: Device monthly system availability (MSA_{1M})

KPI Definition Acceptance Criteria	Measurement Height (m)	Monthly System Availability (%) */**								
		Nov 2015**	Dec 2015	Jan 2016	Feb 2016	Mar 2016	Apr 2016	May 2016	Jun 2016	Jul 2016**
MSA_{1M} Monthly System Availability 1 Month Average ≥90%	39	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	59	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	79	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	94	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	99	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	102	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	129	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	149	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	169	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9
	199	99.9	99.0	100.0	55.3	62.9	98.8	98.9	98.7	99.9

* ***Green***: *Passes the acceptance criteria* ***Red***: *Fails the acceptance criteria*

*** For the monthly system availabilities, only the days from 26th until the 30th were taken into account for November 2015 and only the days from 1st until the 6th for July 2016*

In general the MSA_{1M} KPI is passed for all heights for all months with the exception of February and March 2016. This was due to the unscheduled shut down as detailed in Section 2.4.

4.3.2. Overall System Availability – Campaign Average (OSA_{CA})

Table 4.8: Device system availability (OSC_{CA})

KPI Definition Acceptance Criteria	**Measurement Height (m)**	**Overall System Availability (%) ***		
		Overall (including downtime)	**Period 1 (26/11/2015 - 17/02/2016)**	**Period 2 (12/03/2016 - 06/07/2016)**
OSA_{CA} Overall System Availability Campaign Average ≥ 95	39	88.5	99.6	98.8
	59	88.5	99.6	98.8
	79	88.5	99.6	98.8
	94	88.5	99.6	98.8
	99	88.5	99.6	98.8
	102	88.5	99.6	98.8
	129	88.5	99.6	98.8
	149	88.5	99.6	98.8
	169	88.5	99.6	98.8
	199	88.5	99.6	98.8

* ***Green***: *Passes the acceptance criteria* ***Red***: *Fails the acceptance criteria*

The device fails the OSA_{CA} KPI for the entire data period. This was due to the unscheduled shut down and subsequent maintenance required, as detailed in Section 2.4. Excluding the down time period and assessing the two continuous periods of data collection it can be seen that the system would pass the OSA_{CA} KPI. Further discussion is given in Section 4.4.

4.3.3. Monthly Post Processed Data Availability – 1 Month Average ($MPDA_{1M}$)

Table 4.9: Device monthly post-processed data availability ($MPDA_{1M}$)

KPI Definition Acceptance Criteria	Measurement Height (m)	Monthly Post-processed Data Availability (%) */**								
		Nov 2015	Dec 2015	Jan 2016	Feb 2016	Mar 2016	Apr 2016	May 2016	Jun 2016	Jul 2016
$MPDA_{1M}$ Monthly Post-processed Data Availability 1 Month Average ≥ 80	39	94.9	97.5	92.8	55.0	61.9	97.6	98.3	97.2	98.8
	59	94.9	97.7	92.9	55.1	62.0	97.9	98.2	97.3	98.8
	79	94.9	97.7	92.8	55.1	62.0	97.8	97.7	96.2	98.8
	94	94.9	97.7	92.8	55.0	62.0	97.7	97.6	94.9	98.8
	99	94.9	97.7	92.8	55.1	62.0	97.6	97.5	94.6	98.8
	102	94.9	97.7	92.9	55.0	61.7	97.5	97.4	94.4	98.6
	129	94.9	97.6	92.8	55.0	62.0	97.6	96.3	92.6	98.8
	149	94.9	97.6	92.8	54.9	62.0	97.6	95.9	91.7	98.6
	169	94.9	97.6	92.8	54.9	62.0	97.4	95.6	90.9	98.6
	199	94.9	97.4	92.8	54.8	62.0	97.5	94.6	90.7	98.8

* ***Green***: *Passes the acceptance criteria* ***Red***: *Fails the acceptance criteria*

*** For the monthly post-processed data availabilities, only the days from 26th until the 30th were taken into account for November 2015 and only the days from 1st until the 6th for July 2016*

In general the $MPDA_{1M}$ KPI is passed for all heights for all months with the exception of February and March 2016. This was due to the unscheduled shut down as detailed in Section 2.4. In general, the $MPDA_{1M}$ measure is lower than MSA_{1M} due to internal filtering of data as applied in the lidar data processing software. This is likely to be due to environmental factors. A general reduction of availability is observed with increasing height and is in line with expectation where fog/cloud or very clear air can lead to reduced Doppler returns at the highest measurement heights.

4.3.4. Overall Post Processed Data Availability ($OPDA_{CA}$)

Table 4.10: Device Period 1, Period 2 and overall post-processed data availability ($OPDA_{1M}$)

KPI Definition Acceptance Criteria	Measurement Height (m)	Overall Post-processed Data Availability (%) *		
		Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
$OPDA_{1M}$ Overall Post-processed Data Availability ≥ 85	39	86.5	96.0	97.9
	59	86.5	96.1	98.0
	79	86.3	96.1	97.5
	94	86.1	96.1	97.1
	99	86.0	96.1	97.0
	102	85.9	96.1	96.8
	129	85.6	96.0	96.2
	149	85.4	96.0	95.8
	169	85.2	96.0	95.5
	199	85.0	95.9	95.2

* ***Green**: Passes the acceptance criteria* ***Red**: Fails the acceptance criteria*

The $OPDA_{CA}$ KPI is passed for all measurement periods.

4.3.5. Number of Maintenance Visits (MV), Unscheduled Outages (UO) and Uptime of Communication System (CU)

Table 4.11: Maintenance, Outages and Communication KPI's

KPI – Definition - Acceptance Criteria	
Number of Maintenance Visits, MV	1
Number of Unscheduled Outages, UO	3
Uptime of Communication System, CU	N/A

During the 7.5 month validation data collection period there were no scheduled maintenance visits carried out, however due the loss of power to the lidar unit an unscheduled maintenance visit was required to recover the device, return it to shore and repair the cause of the failure. Had this unscheduled visit not been carried out, scheduled maintenance was not expected as the unit power reserves are designed for 6 months autonomous operation. Communications loss occurred in December 2015, January and February 2016 as mentioned in Section 2.4, resulting in several periods of data not being transmitted from the device. The missing data periods were recovered directly from the buoy during the maintenance period. The communications system on the device transmits data on a weekly basis; the reasons for the failures are unknown, however out with the periods identified, data were received as expected. The Uptime of Communications Systems (CU) metric is not considered relevant, however it is noted that some data communications issues were experienced.

4.3.6. Mean Wind Speed – Slope (X_{mws})

Table 4.12: Mean wind speed single variant linear regression slope (X_{mws})

KPI Definition Acceptance Criteria	Wind Speed Range	Measurement Height (m)	Mean Wind Speed – Slope * Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
X_{mws} Mean Wind Speed - Slope Best Practice: 0.98 - 1.02 Minimum: 0.97 - 1.03	a) WS 4-16 m/s	103	0.998	1.001	0.995
		100	1.001	1.004	0.999
		80	0.999	1.003	0.996
		60	1.000	1.002	0.997
		40	0.998	0.998	0.997
	b) WS >2m/s	103	0.995	0.995	0.994
		100	0.997	0.997	0.997
		80	0.996	0.995	0.996
		60	0.997	0.996	0.997
		40	0.995	0.994	0.996

* ***Green**: Passes the best practice acceptance criteria* ***Amber**: Passes the minimum acceptance criteria* ***Red**: Fails the acceptance criteria*

The X_{MWS} KPI best practise test is comfortably passed for all measurement periods at all heights and for each of the wind speed ranges specified. The performance of the device in the accuracy test shows excellent results with a maximum deviation of 0.6%. Selected plots of the linear regressions are presented in Appendix F, Figure F.1 to Figure F.4. While not part of the formal KPI’s, the sector performance of the device has been assessed and this is discussed further in Section 4.4.

4.3.7. Mean Wind Speed – Coefficient of Determination (R^2_{mws})

Table 4.13: Mean wind speed single variant linear regression R^2 (R^2_{mws})

KPI Definition Acceptance Criteria	Wind Speed Range	Measurement Height (m)	Mean Wind Speed - Coefficient of Determination * Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
R^2_{mws} Mean Wind Speed - Coefficient of Determination Best Practice: > 0.98 Minimum: > 0.97	a) WS 4-16 m/s	103	0.988	0.986	0.987
		100	0.988	0.985	0.987
		80	0.989	0.984	0.989
		60	0.989	0.983	0.989
		40	0.989	0.983	0.989
	b) WS >2m/s	103	0.994	0.992	0.992
		100	0.994	0.991	0.992
		80	0.993	0.990	0.993
		60	0.993	0.990	0.993
		40	0.993	0.989	0.992

* ***Green**: Passes the best practice acceptance criteria* ***Amber**: Meets the minimum acceptance criteria* ***Red**: Fails the acceptance criteria*

The R^2_{MWS} KPI's passed for all measurement periods, at all heights and for each of the wind speed ranges specified. While not part of the formal KPI's, the sector performance of the device has been assessed, this is discussed further in Section 4.4.

4.3.8. Mean Direction – Slope (M_{mwd}), Offset (absolute value) (OFF_{mwd}) and Coefficient of Determination (R^2_{mwd})

Table 4.14: Mean wind direction linear regression slope, offset and R^2 (M_{mwd}, OFF_{mwd} and R^2_{mwd})

KPI Definition Acceptance Criteria	Measurement Height (m)	Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
M_{mwd} Mean Wind Direction – Slope Analysis applied to all wind directions for all wind speeds above 2 m/s Best Practice: 0.97 - 1.03 Minimum: 0.95 - 1.05	103	0.983	0.961	0.989
	100	0.983	0.961	0.989
	80	0.981	0.958	0.987
	60	0.978	0.952	0.985
	40	0.982	0.956	0.990
OFF_{mwd} Mean Wind Direction - Offset (absolute value) Analysis applied to all wind directions for all wind speeds above 2 m/s Best Practice: < 5° Minimum: < 10°	103	5.854	10.037	5.184
	100	5.632	9.871	4.932
	80	2.070	6.466	1.339
	60	3.044	8.084	2.177
	40	4.812	9.039	4.285
R^2_{mwd} Mean Wind Direction - Coefficient of Determination Analysis applied to all wind directions for all wind speeds above 2 m/s Best Practice: < 0.97 Minimum: < 0.95	103	0.997	0.994	0.998
	100	0.997	0.994	0.998
	80	0.997	0.994	0.998
	60	0.997	0.994	0.998
	40	0.997	0.994	0.998

*** *Green*: *Passes the best practice acceptance criteria* *Amber*: *Meets the minimum acceptance criteria* *Red*: *Fails the acceptance criteria***

The M_{MWD} KPI passes the best practise criterion for all heights for the full data period and the second data period. Minimum KPI's values are achieved for the first period.

The OFF_{MWD} KPI meets the minimum acceptance criterion for the top two measurement heights but exceeds the best practise limits for heights of 80 m and below (when using all data available). For the first period, collected through the winter, the top measurement height fails the minimum KPI and all other heights fail to meet best practice but do achieve the minimum KPI requirement. This is discussed further in Section 4.4.

The R^2_{MWD} KPI comfortably passes the best practise criterion for all height and all data periods.

In general the first period shows poorer performance in terms of the direction KPI's when compared to the second period. A number of investigations were carried out to establish if there was an identifiable reason for this, with inconclusive results. Further discussion on this point is given in Section 4.4. Selected scatter plots for the linear wind direction regressions are presented in Figure F.5 and Figure F.6 for the 99 m AMSL and 59 m AMSL levels respectively.

4.3.9. Turbulence Intensity – Slope (X_{TI}) and Correlation Co-efficient (R^2_{TI})

Table 4.15: Turbulence intensity single variant linear regression slope (Device against Mast EA1B 120° anemometers) (X_{TI})

KPI Definition Acceptance Criteria	Wind Speed Range	Measurement Height (m)	Turbulence Intensity - Slope (EA1B 120°)		
			Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
X_{TI} Turbulence Intensity - Slope (EA1B 120°) N/A	a) WS 4-16 m/s	103	2.119	2.347	1.937
		100	1.701	1.747	1.652
		80	1.875	1.983	1.774
		60	1.749	1.823	1.675
		40	1.883	2.048	1.732
	b) WS >2m/s	103	2.186	2.494	1.888
		100	1.775	1.950	1.582
		80	1.931	2.147	1.703
		60	1.797	1.971	1.607
		40	1.928	2.151	1.691

Table 4.16: Turbulence intensity single variant linear regression R^2 (Device against Mast EA1B 120° anemometers) (R^2_{TI})

KPI Definition Acceptance Criteria	Wind Speed Range	Measurement Height (m)	Turbulence Intensity - Correlation Co-efficient (EA1B 120°)		
			Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
R^2_{TI} Turbulence Intensity - Correlation Co-efficient (EA1B 120°) N/A	a) WS 4-16 m/s	103	-0.015	0.020	-0.493
		100	-0.411	-0.467	-1.157
		80	-0.202	-0.258	-0.762
		60	-0.289	-0.401	-0.846
		40	0.098	-0.028	-0.111
	b) WS >2m/s	103	-0.043	-0.081	-0.299
		100	-0.360	-0.472	-0.807
		80	-0.184	-0.273	-0.562
		60	-0.246	-0.355	-0.632
		40	0.058	-0.053	-0.101

Table 4.17: Turbulence intensity single variant linear regression slope (Device against Mast EA1B 300° anemometers) (X_{TI})

KPI Definition Acceptance Criteria	Wind Speed Range	Measurement Height (m)	Turbulence Intensity - Slope (EA1B 300°) Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
X_{TI} Turbulence Intensity - Slope (EA1B 300°) N/A	a) WS 4-16 m/s	103	2.113	2.323	1.941
		100	1.897	2.032	1.777
		80	1.925	2.043	1.819
		60	1.903	2.025	1.792
		40	1.931	2.136	1.751
	b) WS >2m/s	103	2.177	2.466	1.892
		100	1.951	2.185	1.710
		80	1.982	2.199	1.752
		60	1.942	2.140	1.730
		40	1.958	2.212	1.696

Table 4.18: Turbulence intensity single variant linear regression R^2 (Device against Mast EA1B 300° anemometers) (R^2_{TI})

KPI Definition Acceptance Criteria	Wind Speed Range	Measurement Height (m)	Turbulence Intensity - Correlation Co-efficient (EA1B 300°) Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
R^2_{TI} Turbulence Intensity - Correlation Co-efficient (EA1B 300°) N/A	a) WS 4-16 m/s	103	0.015	0.021	-0.422
		100	-0.260	-0.304	-0.856
		80	-0.175	-0.267	-0.628
		60	-0.116	-0.248	-0.475
		40	0.140	0.031	-0.029
	b) WS >2m/s	103	-0.026	-0.084	-0.251
		100	-0.229	-0.313	-0.596
		80	-0.142	-0.237	-0.486
		60	-0.103	-0.211	-0.382
		40	0.083	-0.008	-0.078

No formal KPI acceptance criterion has been set for the comparison of turbulence values. The result of all analyses show there is significant difference between the turbulence measured using a cup anemometer and turbulence measured by a floating lidar. Further discussion on turbulence is given in Section 4.4.

4.3.10. Wind Shear (α)

Table 4.19: Wind speed shear exponent alpha (α)

KPI Definition Acceptance Criteria	Wind Speed Ranges	Measuring System	Wind Speed Shear (a) - Lidar 39-79 / Mast 40-80		
			Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
Wind Speed Shear - Shear Exponent Alpha related to Hellman's power law. Alpha to be calculated using reference anemometry heights at 50 and 90 m N/A	a) WS 4-8 m/s	EA1B mast	0.080	0.023	0.091
		SEAWATCH Wind Lidar Buoy	0.081	0.030	0.092
	b) WS 8-12 m/s	EA1B mast	0.100	0.049	0.122
		SEAWATCH Wind Lidar Buoy	0.099	0.055	0.119
	c) WS 12-16 m/s	EA1B mast	0.105	0.072	0.155
		SEAWATCH Wind Lidar Buoy	0.104	0.075	0.150
	d) WS > 2m/s	EA1B mast	0.097	0.074	0.121
		SEAWATCH Wind Lidar Buoy	0.097	0.075	0.118

No formal KPI acceptance criterion has been set for the comparison of wind shear exponent values. The result of all analyses show very good agreement, across all considered wind speed ranges, with the shear as measured using a cup anemometry and shear derived from floating lidar wind speed measurements across similar height measurements. This is expected given the very good results of the KPI’s relating to wind speed accuracy across all concurrent measurement heights. Shear exponents were also calculated for heights between 60 m to 100 m AMSL from each measurement system and these were observed to compare equally well.

4.4. Discussion of KPI results

In general the system has performed well over the validation period; a general discussion of pertinent points follows.

4.4.1. KPI Results - Availability

A number of the availability based KPI's failed to meet the minimum requirements, specifically the monthly system availability (MSA_{1M}) and monthly post processed data availability ($MPDA_{1M}$) for the months of February and March, and overall system availability (OSA_{CA}) for the entire data period. Failure of these KPI's is due to the device malfunction on the 17th February 2016, on account of corroded connectors on the device. Despite this unscheduled downtime, the overall post processed data availability ($OPDA_{CA}$) KPI meets the acceptance criteria. On exclusion of the extended downtime period all availability KPI's are achieved. Natural Power considers that improvements in the hardware on the device to marine grade fittings with suitable protection of the lidar unit, is likely to deliver significant benefits such that all KPI's could be achieved over a continuous 6 month period, notwithstanding extreme events.

4.4.2. KPI Results – Wind Speed Accuracy

Accuracy based KPI's on wind speed showed excellent performance throughout the duration of the monitoring campaign and across all heights with wind speed comparisons typically showing similar levels of accuracy to paired cup anemometers mounted on a mast. Maximum deviations from the reference dataset were 0.5% across all specified wind speed ranges at all heights. Scatter in the correlations was low with the lowest R^2_{MWS} of 0.988. In terms of wind speed results the KPI's show that the measurements from the device can be considered to be equivalent to high quality IEC mast/cup anemometer systems.

In addition to the formal KPI accuracy assessment of all wind speeds, a more detailed assessment of the wind speed performance has been carried out in a sector-wise basis. The sector analysis has been assessed for the entire period using the KPI measures X_{MWS} and R^2_{MWS}, results are given in Table F.4 and Table F.7, respectively.

It is observed that the majority of sectors meet the best practise requirements for all heights and for all periods. In the 300° sector the mean wind slope only meets minimum criteria for most heights, with the 80 m results for this sector failing the KPI's for all periods. In this sector only data from the upwind 300° orientated anemometer are used from the mast due to tower shadow effects on the opposing anemometer. Given that the results suggest a higher reading from the device than the mast, the failure of the KPI is considered to be due to distortion effects noted on the mast as discussed in Section 2.2.1. It is also observed that requirements are not met for the coefficient of determination during the period 1 measurement for the 60° sector. After investigation, it was identified that this was due to low coverage at this sector for this period. It is noted that for the whole period and for period 2, this sector meets best practice guidelines for the both mean wind slope and coefficient of determination.

The results of the validation of the wind speed accuracy show the device capable of comparable levels of accuracy to that of first class anemometry on an IEC compliant mast. It could be argued that, due to the lack of the tower induced flow distortion effects in the device dataset, the wind speed measurements are superior to a large lattice mast and cup anemometry system using a dual opposed boom arrangement at each height.

4.4.3. KPI Results – Wind Direction Accuracy

All KPI's for each measurement height meet the best practise requirement for the whole measurement period, apart from the mean wind direction offsets OFF_{MWD} at the top two measurement heights where only the minimum requirements were met. For period 1, it can be observed that the 103 m regression fails narrowly on the OFF_{MWD} minimum requirement. However, it is observed that all other heights meet at least the minimum requirements for all wind direction KPI's. The results of the linear wind direction regressions for period 2 show robust results with all KPI's meeting best practise requirements for all heights apart from the OFF_{MWD} at the top height only meeting minimum requirements. Investigations we carried out to identify if the higher sea states and generally windier conditons during period 1 , as illustrated in Figure E.15 and Figure E.16, affected the direction measurments. It was concluded that the discrepancy in wind directon measurements could not be directly attributed to higher wind and sea conditions. Furthermore, the potential impact of wind direction sectors where the wind vanes on the mast were more frequently within the wake of the mast were investigated, again with no positive conclusion reached. Natural

Power believe the performance at the upper heights is potentially affected by motion of the device while at lower heights the flow distortion is likely to increase with increasing mast face width, as the data suggests.

Linear wind direction regressions were also carried out for the whole period, period 1 and period 2 without the wraparound methodology applied and in the 10° to 350° direction range. The results of these linear regressions are presented in Table F.4 to Table F.9.

It is observed that without the wrap around methodology being applied, the results do not meet the KPI requirements. However, this is not an accurate representation of the direction. The 10° to 350° direction range correlation is a more accurate representation and is in line with results using the wrap around method. As such, this confirms that the wrap around methodology used is appropriate.

The results of the validation of the wind direction accuracy show comparable perfomance of the device and Mast EA1B. It should be noted that due to the short vane boom lengths on the mast that Natural Power consider that the wind vanes on the Mast E1AB are subject to flow distortion effects induced by the mast structure.

4.4.4. KPI Results – Turbulence and Shear Accuracy

Review of the turbulence results show that agreement between the two measurement devices is poor. It is noted from the lidar review Natural Power carried out (Natural Power, 2016) that lidar derived turbulence intensity (Ti) is not considered to be the same as the Ti as measured using cup anemometry. Differences in point and volumetric measurements lead to differences in results and are the subject of further work within the research and development community of lidar developers. While the absolute values of Ti differed significantly between the mast and the device, with data being virtually uncorrelated on a 10 minute averaged basis, Figure F.7, shows that the general Ti versus wind speed plot, typical of IEC turbulence categorisation, shows the characteristic shape expected and in general the Ti versus speed curve is typical of turbulence behaviour, albeit with a bias between the cup and lidar results. This is encouraging as it demonstrates that lidar measured Ti in the floating context shows the expected behaviour with variation of wind speed. Further work is required to understand how fixed frame of reference, and floating, lidar measured turbulence should be treated in the in the context of IEC 61400-12, wind resource assessment and finance grade energy yield assessments.

Attention is drawn to the lower plot in Figure F.7 showing Ti as calculated with the data processing of the buoy device. It is apparent that turbulence measurements as calculated by the buoy are not representative at high wind speeds; further work is required to investigate the processing of the data on the buoy relating specifically to turbulence.

The shear exponents derived from both measurement devices compare very well across a range of shear heights. It is concluded that shear derived from the device is equivalent to shear measured using Class I cup anemometry installed on an IEC compliant mast.

4.5. Sensitivity

In the context of a floating measurement system such as the device under test, the impacts of the weather, tides and waves on how the floating structure moves and what effect this has on the wind measurements are of key interest. A sensitivity analysis was carried out in order to investigate and detect, where possible, any relationship between wind measurements and sea state characteristics to identify any probable patterns or trends. Comparative wind measurements from the mast and the device were checked against the buoy motions and sea state parameters as defined by the met-ocean conditions measured by the device met-ocean sensors. The wind measurements were also checked against the buoy movement. The sensitivity analysis included assessments of the wind speed, wind direction and turbulence intensity measurements checked against the significant wave height, the wave period and the wave direction. In addition the buoy movement parameters were assessed and the main wind measures were investigated with the mast and device measurements reviewed across the range of motions experienced. The list of the sensitivity analysis checks is presented in Table 4.20.

Table 4.20: Sensitivity analysis checks

Dependant variables	Independent variables
Wind speed Wind direction	Significant wave height
	Wave period
	Wave direction
	Sea current speed at 4 m below sea level
	Sea current direction at 4 m below sea level
	Buoy pitch movement
	Buoy roll movement
	Buoy heave movement

The sea states experienced by the device during this campaign were examined. The probability distribution of the significant, and the maximum, wave heights and the amount of data per wind speed bin and significant wave height are presented in Figure E.14 to Figure E.16, and Table E.1 to Table E.3, respectively. High significant wave heights occur during high wind speeds, with these higher sea states inducing higher pitch and roll buoy motions during these periods.

The sensitivity analysis showed the device measurements were generally insensitive to the varying met-ocean conditions and induced buoy motions for the majority of the conditions experienced during the validation period. Comparisons of wind speed and wind direction measurements from the mast and the device were found to be in general agreement for all sea state conditions with errors low across almost the full spectrum of met-ocean conditions. Plots for binned wind speed and wind direction values and associated standard deviations are presented against sea state parameters and buoy motions, presented in Figure E.1 to Figure E.8. The device wind speed error was calculated for different met-ocean conditions and buoy motions by Natural Power. The wind speed errors were shown to remain less than 0.5% across the majority of the motions conditions, presented in Figure E.9 to Figure E.13. Some larger errors were observed particularly with large significant wave height values, and to a lesser degree heave motion. In general the device wind speed error was greater than 0.5%, only where the data coverage was less than 3.5%.

Some degree of movement of the device occurs due to the anchors system and how the device reacts to the action of the weather, tides and waves. The lidar GPS data were checked against the buoy system GPS data. It was found that the device was moving around its mooring with the furthest travel to be approximately 150 m from the anchor location, with general agreement from the two locations logging systems. Maps with the location data recorded from the lidar and the buoy GPS units are presented in Figure E.17 and Figure E.18.

5. Conclusions

The main results of the device validation are given in Table 5.1.

Table 5.1: Summary of results

Project Summary		**East Anglia One EA1B mast**
Period of concurrent measurement		26/11/2015 – 06/07/2016
On-site mast		85 m lattice mast installed on 18 m support structure (EA1B)
Measurement heights above mean sea level (m)		103 m, 100 m, 99.5 m, 90 m, 80.3 m, 70.3 m, 59.8 m, 49.7 m, 40.1 m
Mast location (UTM 31N WGS84)		465965 E, 5785000 N
Floating lidar device		FUGRO SEAWATCH Wind Lidar Buoy
Measurement heights above sea level (m)		199 m, 169 m , 149 m, 129 m, 102 m, 99 m, 94 m, 79 m, 59 m, 40 m, 39 m
Central location of floating lidar (UTM 31N WGS84)		465601 E, 5785104 N
KPI Definition – availability	**Minimum availability for all heights (entire period)**	**Maximum availability for all heights (entire period)**
Monthly System Availability, MSA_{1m} (%)	55.3	100.0
Monthly Post Processed Data Availability – 1 month average, $MPDA_{1M}$ (%)	54.8	98.8
Overall Post Processed Data Availability, $OPDA_{CA}$ (%)	85.0	86.5
KPI Definition -Overall System Availability		
Overall System Availability – Campaign Average, OSA_{CA} (%)		88.5
KPI Definition		
Number of Maintenance Visits, MV		0
Number of Unscheduled Outages, UO		1
Uptime of Communication System, CU		N/A
KPI Definition - accuracy	**Minimum accuracy**	**Maximum accuracy**
Mean Wind Speed – Slope, X_{mws} (wind speeds greater than 2 m/s)	0.995	0.997
Mean Wind Speed – Coefficient of Determination, R^2_{mws} (wind speeds greater than 2 m/s)	0.993	0.994
Mean Wind Direction – Slope, M_{mwd}	0.978	0.983
Mean Wind Direction – Offset (absolute value), OFF_{mwd}	5.854	2.070
Mean Wind Direction – Coefficient of Determination, R^2_{mwd}	0.997	0.997
Turbulence Intensity – Slope, X_{TI}	1.797	2.186
Turbulence Intensity – Coefficient of Determination, R^2_{TI}	-0.360	0.058
KPI Definition – shear comparison		
Wind Shear – Shear Exponent, α (EA1B mast)		0.097
Wind Shear – Shear Exponent, α (SEAWATCH Wind LiDAR)		0.097

Green: Passes best practice acceptance criteria **Amber**: Passes minimum acceptance criteria
Red: Fails the acceptance criteria **Black**: No acceptance criteria
Note: all wind speed and direction results are based on data where wind speeds are greater than 2 m/s

The key points of the validation study are given below:

- Failure of a number of the KPI's relating to availability was observed when the whole period of measurements were considered in its entirety. However, the failures of the availability KPI's was due to an unscheduled outage of the device where a hardware fault resulted in the majority of lost availability. It was noted that, when splitting the measurement periods before and after the unscheduled outage, the availability requirements were met.
- Wind speed accuracy exceeds all best practise KPI's at all measurement heights.
- Direction accuracy KPI's, mean wind direction slope (M_{MWD}) and mean wind direction coefficient of determination (OFF_{MWD}), exceed best practise KPI's at all measurement heights.
- Direction accuracy KPI mean wind direction offset (OFF_{MWD}) KPI exceed best practise KPI's at 80 m and below and satisfy minimum requirements for top two measurement heights.
- Good agreement of shear between mast and device.
- Significant differences exist between mast and device turbulence intensity measurements, with very poor correlations. This is as expected and is a known general issue with all lidar turbulence measurements, with motion of the unit potentially increasing errors. It was noted that the general shape of the turbulence versus speed curves are similar, indicating measurements are closely related when considered in 1 m/s wide bins. Further work is required to enable better understanding of the relationship of lidar measured turbulence to that as measure by cup anemometers.
- It is Natural Power's opinion from this validation study that the device can measure wind speed and wind direction data as accurately as measurements from traditional cup anemometers and wind vanes installed upon an IEC compliant mast, under similar met-ocean conditions experienced in this study. Consequently, the device can be used as a replacement for a mast in finance grade energy yield assessment in similar conditions without a significant uncertainty penalty, and is considered to be pre-commercial in the context of the OWA roadmap.

6. Recommendations

Based on the validation study, Natural Power recommends the following points be considered;

- The design of the device, specifically the power supply/ethernet cables, meteorological station and fuel cell systems, should be reviewed and uprated in order to allow for consistent measurements and communication of data for a period of six months or more in the harsh offshore marine environment. This is not considered to be a significant hurdle for the device, where the further protection of exposed components is expected to be sufficient to allow for the necessary improvements in the availability KPI's. The new marinized ZephIR 300 (Z300M) is specifically designed to resolve the meteorological station, connector corrosion issues with it's design and protection specifically for the marine environment, As existing SEAWATCH Wind Lidar Bouys are serviced, Fugro have confirmed that ZephIR 300 units will be replaced with ZephIR 300M devices. All newly purchased SEAWATCH Wind Lidar Bouys use ZephIR 300M lidar units.
- Further evidence is gathered to demonstrate that the device is capable of six months of continuous autonomous operation with suitable levels of data availability for the period of deployment recommended by the roadmap.
- The device is deployed for a continuous six month period over the winter period in order to assess it's performance in extreme offshore conditions.
- Further validation exercises are carried out across a range of different met-ocean conditions to build an extensive validation dataset in more demanding met-ocean conditions typical of regions suitable for the development of offshore wind farms.
- Further research is undertaken on the derivation of the turbulence intensity from the device, and remote sensing in general, in order to provide an accurate representation of the turbulence as measured by cup anemometers.
- All data are communicated from the device on a live basis in order to assess the conditions and measurements of the buoy. Currently, both the raw ZephIR 300 files and the sea state and motion data, are retrieved once the deployment is finished and the device is back onshore.

7. Bibliography

Berg, A. (11/2015). *Deployment by towing - East Anglia One.* Fugro OCEANOR AS.

Berg, A. (2015). *Seawatch Wind LiDAR buoy description for East Anglia ONE Limited.* FUGRO OCEANOR AS.

Carbon Trust. (11/2013). *Offshore Wind Accelerator roadmap for the commercial acceptance of floating LiDAR technology.*

Carl C AS / KPR Consult AS. (2012, 06). EAOW latice tower (equipment boom type 1 wired). *MET-13-020-030-002867-A-13-EAOW 422_Equipment boom Type 1 wired_Rev A*.

Carl C AS / KPR Consult AS. (2012, 06). EAOW lattice tower (top boom). *MET-13-020-030-002865-A-15-EAOW 420_Top boom_Rev A*.

Carl C AS. (2012, 11). Toppole - 83 m offshore tower - East Anglia. *Toppole-100*.

Fugro Oceanor AS. (03/2016). *Seawatch Wind Lidar buoy at EA ONE service and maintenance March 2016.* Fugro Oceanor AS.

Fugro-Oceanor-AS. (2016). Retrieved from http://www.fugro.com/our-expertise/research-and-development/innovations/seawatch

Fugro-Oceanor-AS. (2016). Retrieved from http://www.oceanor.com/seawatch/buoys-and-sensor/SW_Wind_LiDAR

Fugro-Oceanor-AS. (2016). *seawatch: buoys and sensor: wavescan*. Retrieved from oceanor: http://www.oceanor.no/seawatch/buoys-and-sensor/wavescan

Fugro-Oceanor-AS. (2016). *seawatch: buoys-and-sensor: Oceanor-Wavesense*. Retrieved from oceanor: http://www.oceanor.no/seawatch/buoys-and-sensor/Oceanor-Wavesense

GILL. (2016). *products: anemometer: windsonic*. Retrieved from gillinstruments: http://gillinstruments.com/products/anemometer/windsonic.htm

Iberdrola S.A. (05/2016). *EA1B_wspd_wdir_measurement_specifications_v3.*

IEC 614000:12-1. (2005). *IEC 614000:12-1 - Wind Turbines - Part 12-1: Power performance measurements of electricity producing wind turbines.* IEC.

Natural Power. (2016). *EA1B Mast review report.*

Natural Power. (2016). *Lidar device review.*

nortek-as. (2016). *products: current-profilers: aquadopp-profiler*. Retrieved from nortek: http://www.nortek-as.com/en/products/current-profilers/aquadopp-profiler

SgurrEnergy Ltd. (05/2015). *EA1B Planed maintenance.*

SgurrEnergy Ltd. (09/2015). *EA1B Planed maintenance.*

Storas, O. (2016). *Buoy processing of ZephIR LiDAR measurements.* FUGRO OCEANOR AS.

VAISALA. (2016). *products: humidity: Pages: HMP155*. Retrieved from vaisala: http://www.vaisala.com/en/products/humidity/Pages/HMP155.aspx

VAISALA. (n.d.). *products: pressure: Pages: PTB330*. Retrieved from vaisala: http://www.vaisala.com/en/products/pressure/Pages/PTB330.aspx

Wood Group Kenny. (2013). *EA1B INSTALLATION REPORT.*

ZephIR. (2016). *support: tech-specs*. Retrieved from zephirlidar: http://www.zephirlidar.com/support/tech-specs/

Appendices

A. Location

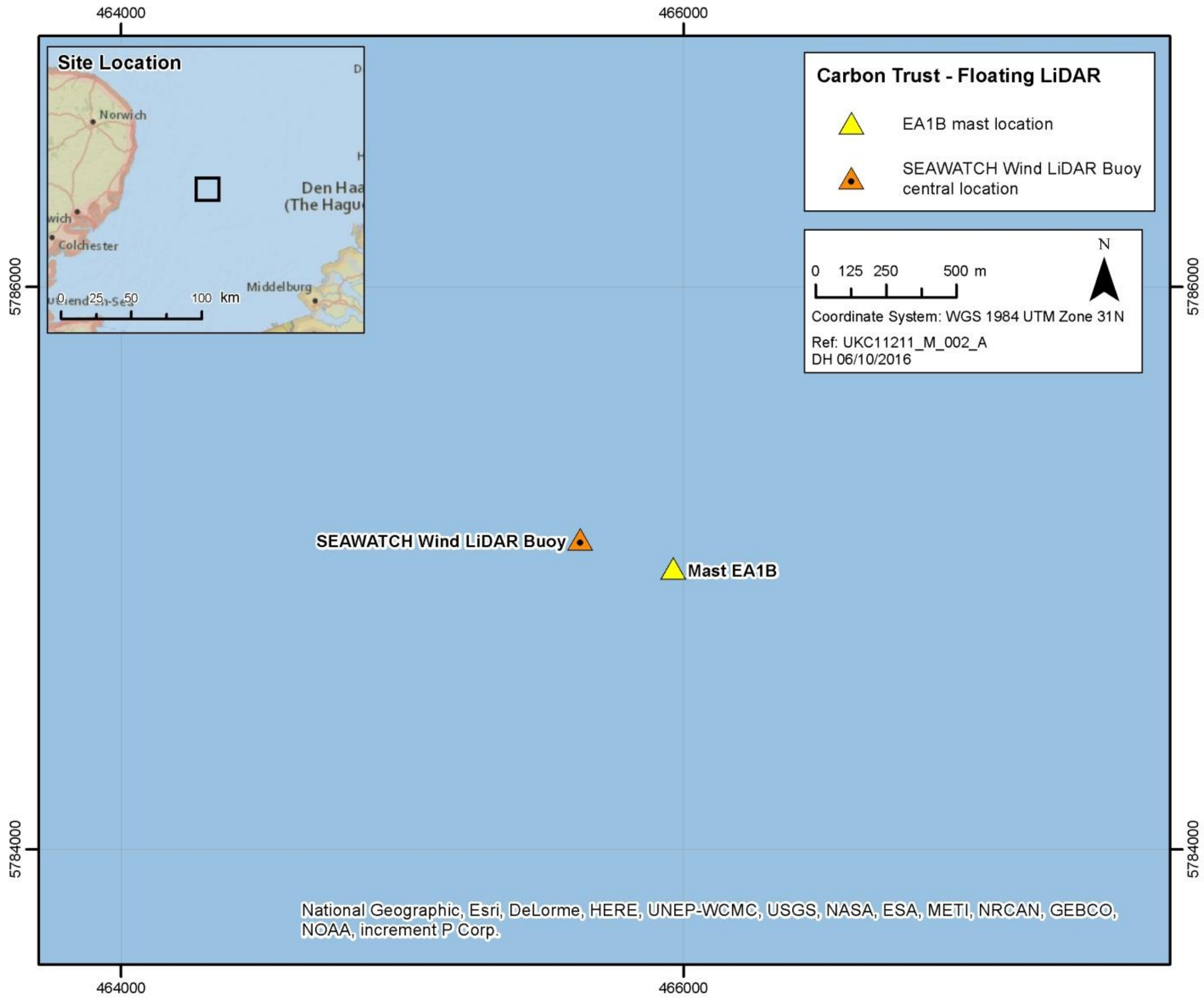


Figure A.1: Regional context map

Table A.1: Measurement point locations*

Turbine ID	Easting	Northing
EA1B mast	465965	5785000
SEAWATCH Wind LiDAR Buoy	465601	5785104

*Coordinates in: WGS 84 UTM zone 31

(Fugro Oceanor AS, 03/2016)

Figure A.2: SEAWATCH Wind LiDAR Buoy and EA1B mast

B. Mast EA1B

Table B.1: Mast EA1B instrumentation

	Anemometry		Wind Vane
Height (m)	120^0 boom orientation	300^0 boom orientation	240^0 boom orientation
103	Thies Clima First Class Advanced	Vector A100LK	
100	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class
90	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class
80	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class
70	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class
60	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class
50	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class
40	Thies Clima First Class Advanced	Vector A100LK	Thies Clima First Class

Source: (Wood Group Kenny, 2013)

Table B.2: Mast EA1B boom dimension summary[1]

Instrument	Boom length (m)		Boom thickness (mm)		Tower width (m)	Boom length/Tower width ratio	Flow distortion target design value[2]	Compliant with IEC 61400-12 vertical length recommendation?
	Horizontal	Vertical	Horizontal	Vertical				
A1	1.5	1.0	50	25	0.06[1]	-	0.5	Yes
A2	1.5	1.0	50	35	0.06[1]	-	0.5	Yes
A3	3.6	1.0	60	25	1.26	2.86	1.0	Yes
A4	3.6	0.9	60	35	1.26	2.86	1.0	Yes
A5	4.4	1.0	60	25	1.45	3.03	1.0	Yes
A6	4.4	0.9	60	35	1.45	3.03	1.0	Yes
A7	5.3	1.2	50	25	1.63	3.25	1.0	Yes
A8	5.3	0.9	50	35	1.63	3.25	1.0	Yes
A9	6.0	1.2	50	25	1.85	3.24	1.0	Yes
A10	6.0	0.9	50	35	1.85	3.24	1.0	Yes
A11	6.7	1.2	50	25	2.27	2.95	1.0	Yes
A12	6.7	0.9	50	35	2.27	2.95	1.0	Yes
A13	7.9	1.4	50	25	2.70	2.93	1.0	Yes
A14	7.9	0.9	50	35	2.70	2.93	1.0	Yes
A15	8.5	1.7	50	25	3.13	2.72	1.0	Yes
A16	8.5	1.0	50	35	3.13	2.72	1.0	Yes

Information derived from the installation report provided by the Client (Wood Group Kenny, 2013)

1. Anemometers A1 and A2 are mounted above the top of the mast and therefore the tower width detailed above is the width of the lightning finial support.

2. Horizontal boom length for anemometers A3 to A16 is not compliant with the IEC 61400-12 standard.

Table B.3: Mast EA1B May 2016 re-instrumentation

Instrument	Model	Initial serial number	Replacement serial number	Calibration certificate number for the replacement anemometers*
A2	Thies Clima First Class Advanced 4.3351.10	5141008	11159405	1610110 (01/2016)
A4	Thies Clima First Class Advanced 4.3351.10	5141009	11159404	1610111 (01/2016)
A6	Thies Clima First Class Advanced 4.3351.10	5140994	11159403	1610112 (01/2016)
A8	Thies Clima First Class Advanced 4.3351.10	5140995	11159402	1610113 (01/2016)
A10	Thies Clima First Class Advanced 4.3351.10	5140996	11159401	1610114 (01/2016)
A12	Thies Clima First Class Advanced 4.3351.10	5140997	11136594	1513837 (07/2015)
A14	Thies Clima First Class Advanced 4.3351.10	5140998	11136595	1513836 (07/2015)
A16	Thies Clima First Class Advanced 4.3351.10	5140999	03132750	1513835 (07/2015)

(Iberdrola S.A., 05/2016)

**Anemometers calibrated from: Deutsche WindGuard GmbH*

(Carl C AS / KPR Consult AS, 2012) (Carl C AS, 2012)

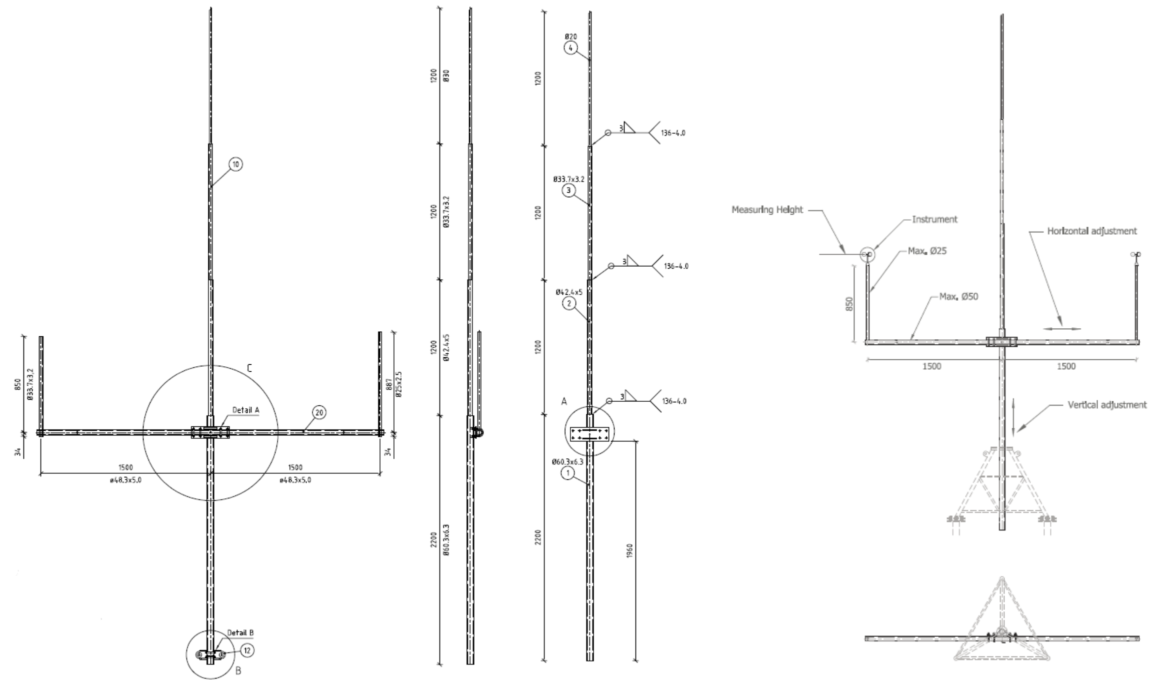


Figure B.1: Indicative drawing of the top section of the mast and 103 m measurement level

(Carl C AS / KPR Consult AS, 2012)

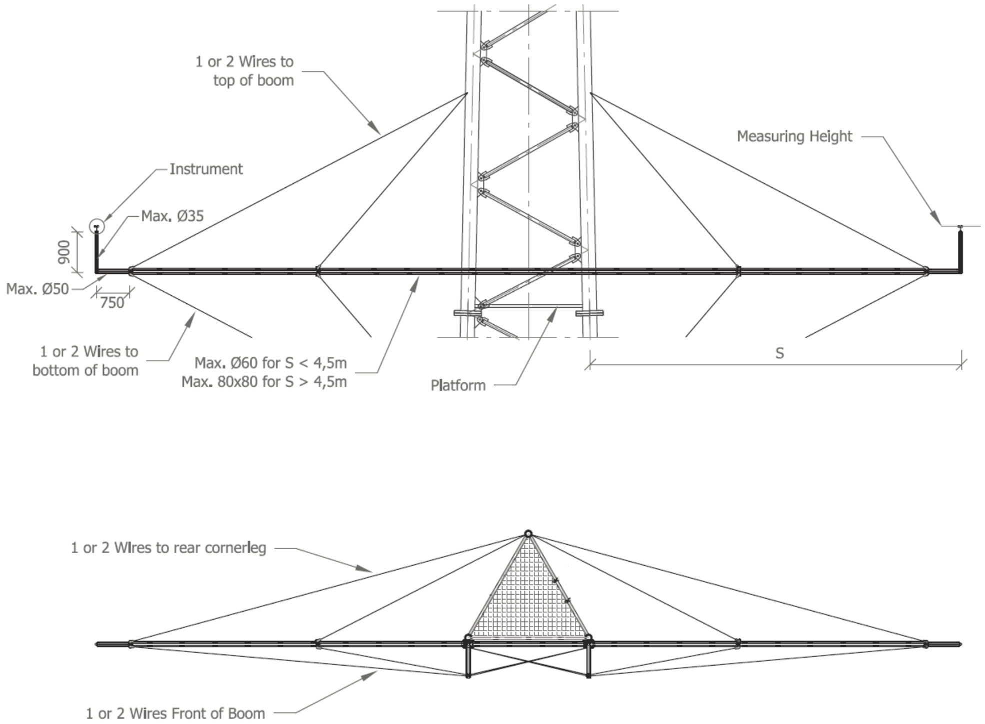


Figure B.2: Indicative drawing of the additional support of anemometer booms

(SgurrEnergy Ltd, 09/2015)

Figure B.3: View of Mast EA1B

Table B.4: Correlations (R^2) values between all vanes for the period 8th January 2015 to 25th February 2016

	V1	V2	V3	V4	V5	V6	V7
V1	-	0.97	0.98	0.97	0.98	0.94	0.94
V2	0.97	-	0.99	0.96	0.96	0.90	0.89
V3	0.98	0.99	-	0.99	0.99	0.94	0.93
V4	0.97	0.96	0.99	-	1.00	0.95	0.94
V5	0.98	0.96	0.99	1.00	-	0.96	0.95
V6	0.94	0.90	0.94	0.95	0.96	-	1.00
V7	0.94	0.89	0.93	0.94	0.95	1.00	-

Table B.5: Correlations (R^2) values between all anemometers for the period 8th January 2015 to 25th February 2016

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
A1	-	1.00	0.99	0.96	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.96	0.97	0.97	0.96	0.96
A2	1.00	-	0.99	0.96	0.99	0.99	0.99	0.98	0.99	0.98	0.98	0.96	0.97	0.97	0.96	0.96
A3	0.99	0.99	-	0.96	1.00	0.98	0.99	0.97	0.99	0.97	0.98	0.96	0.97	0.96	0.97	0.96
A4	0.96	0.96	0.96	-	0.96	0.99	0.95	0.99	0.95	0.98	0.94	0.98	0.94	0.97	0.92	0.95
A5	0.99	0.99	1.00	0.96	-	0.99	1.00	0.98	1.00	0.98	0.99	0.97	0.98	0.97	0.97	0.97
A6	0.99	0.99	0.98	0.99	0.99	-	0.97	1.00	0.98	1.00	0.97	0.99	0.97	0.98	0.96	0.97
A7	0.99	0.99	0.99	0.95	1.00	0.97	-	0.97	0.99	0.97	0.99	0.96	0.98	0.97	0.98	0.97
A8	0.98	0.98	0.97	0.99	0.98	1.00	0.97	-	0.98	1.00	0.97	0.99	0.97	0.99	0.96	0.98
A9	0.99	0.99	0.99	0.95	1.00	0.98	0.99	0.98	-	0.98	1.00	0.97	0.99	0.98	0.99	0.98
A10	0.98	0.98	0.97	0.98	0.98	1.00	0.97	1.00	0.98	-	0.98	1.00	0.98	0.99	0.97	0.99
A11	0.98	0.98	0.98	0.94	0.99	0.97	0.99	0.97	1.00	0.98	-	0.97	1.00	0.98	0.99	0.98
A12	0.96	0.96	0.96	0.98	0.97	0.99	0.96	0.99	0.97	1.00	0.97	-	0.97	1.00	0.96	0.99
A13	0.97	0.97	0.97	0.94	0.98	0.97	0.98	0.97	0.99	0.98	1.00	0.97	-	0.99	1.00	0.99
A14	0.97	0.97	0.96	0.97	0.97	0.98	0.97	0.99	0.98	0.99	0.98	1.00	0.99	-	0.98	1.00
A15	0.96	0.96	0.97	0.92	0.97	0.96	0.98	0.96	0.99	0.97	0.99	0.96	1.00	0.98	-	0.99
A16	0.96	0.96	0.96	0.95	0.97	0.97	0.97	0.98	0.98	0.99	0.98	0.99	0.99	1.00	0.99	-

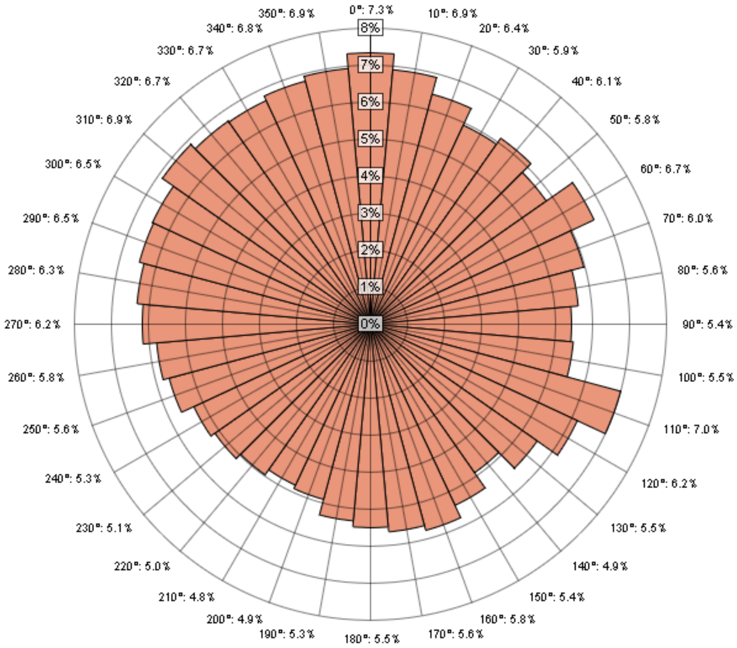


Figure B.4: Turbulence intensity plot for A1 (wind speeds > 2m/s)

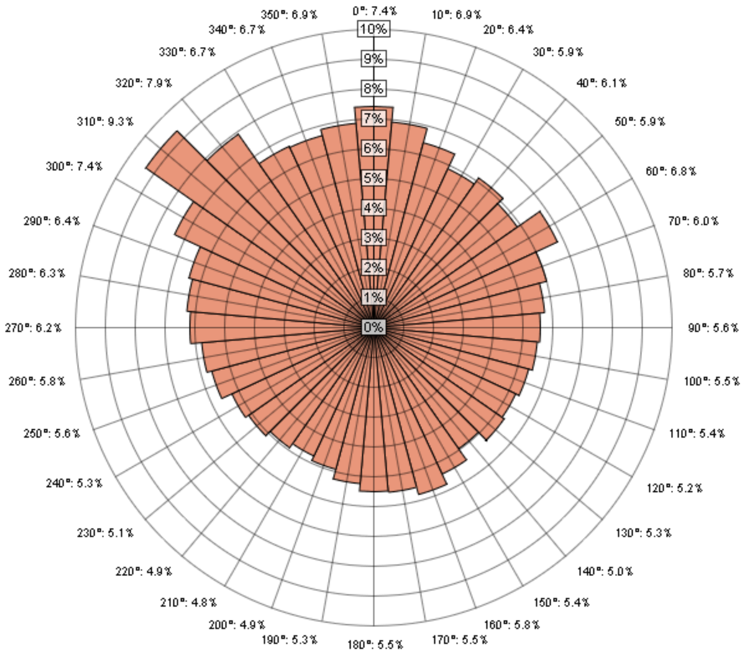


Figure B.5: Turbulence intensity plot for A2 (wind speeds > 2m/s)

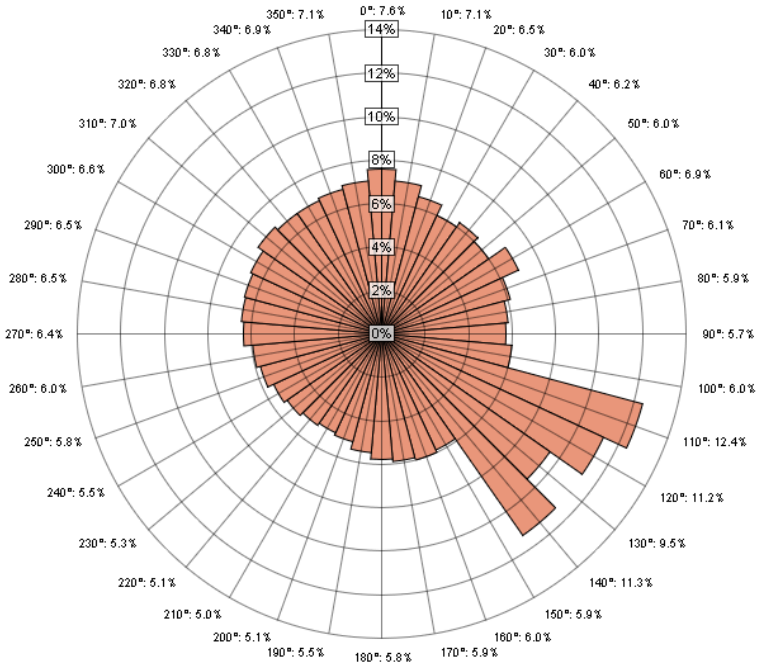


Figure B.6: Turbulence intensity plot for A3 (wind speeds > 2m/s)

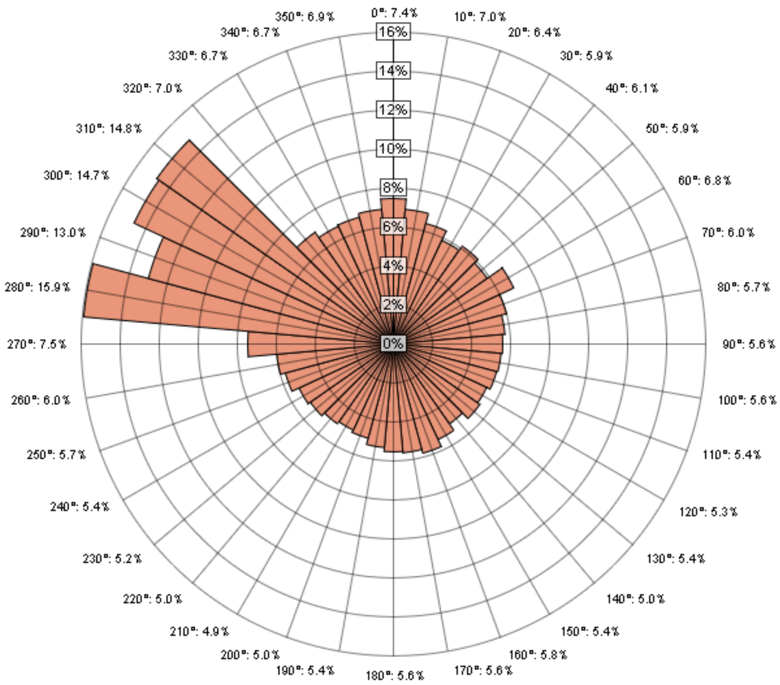


Figure B.7: Turbulence intensity plot for A4 (wind speeds > 2m/s)

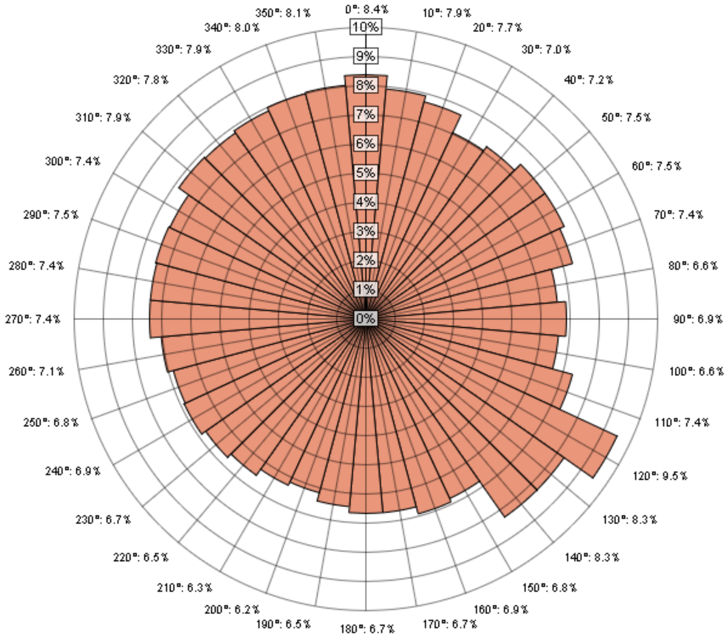


Figure B.8: Turbulence intensity plot for A15 (wind speeds > 2m/s)

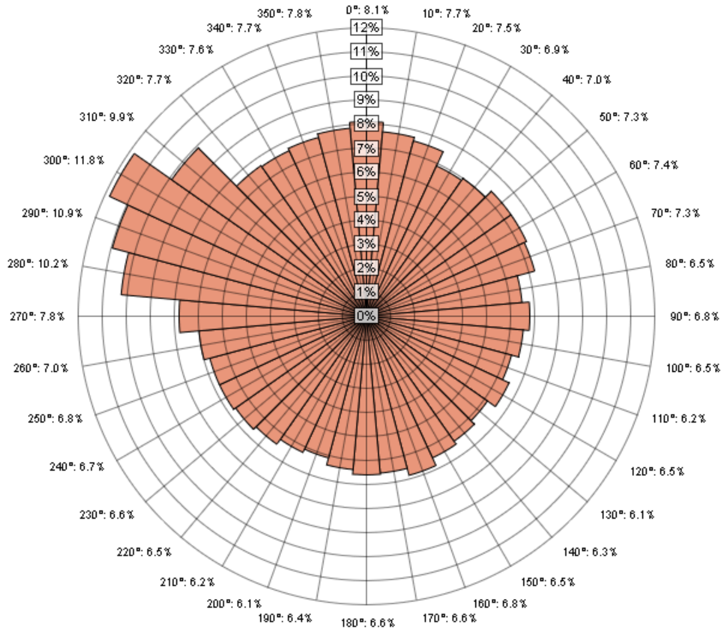


Figure B.9: Turbulence intensity plot for A16 (wind speeds > 2m/s)

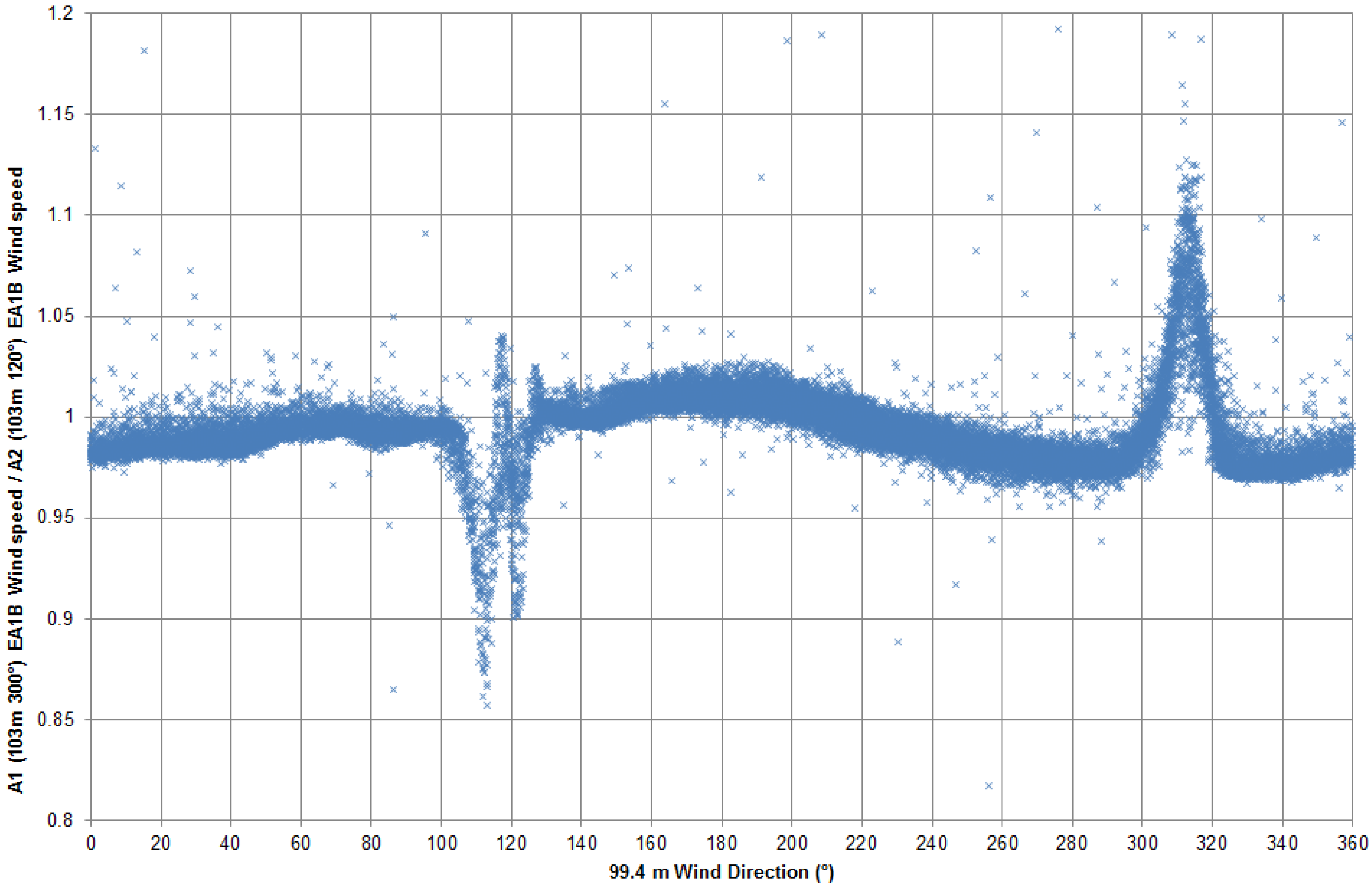


Figure B.10: Mast EA1B tower shadow plot for the 103 m measurement level

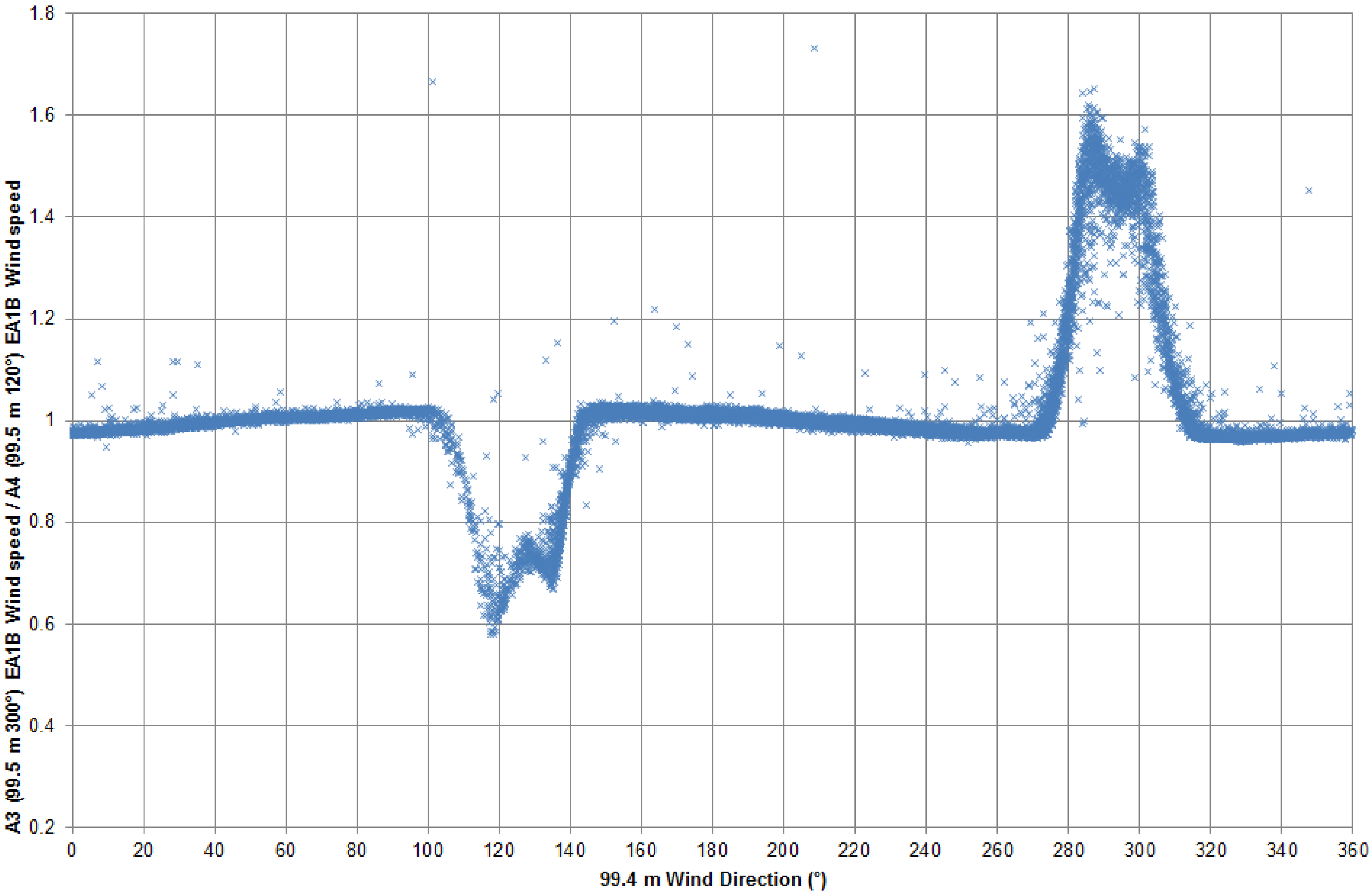


Figure B.11: Mast EA1B tower shadow plot for the 100 m measurement level

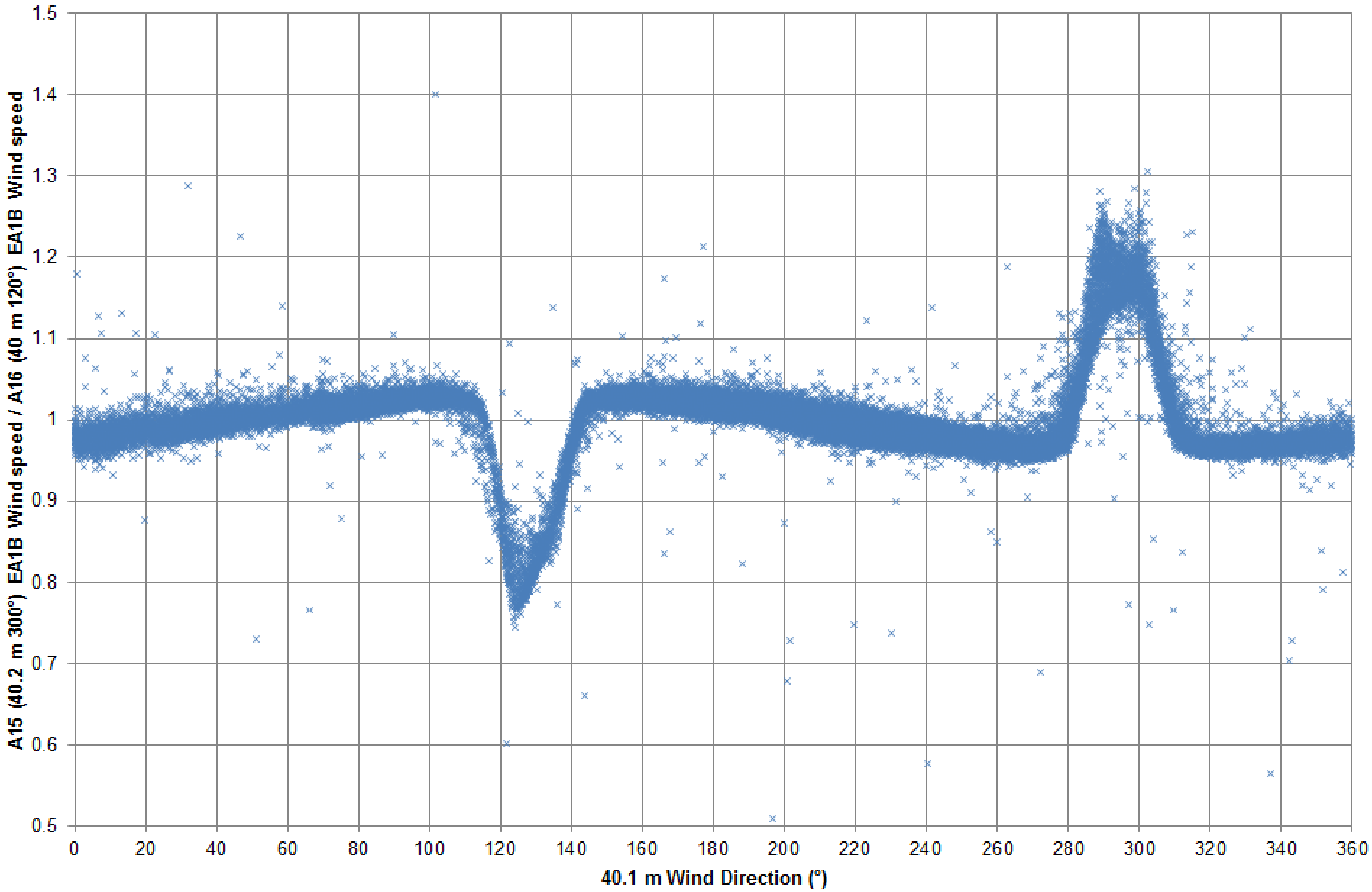


Figure B.12: Mast EA1B tower shadow plot for the 40 m measurement level

C. SEAWATCH Wind LiDAR Buoy

The East Anglia One SEAWATCH Wind LiDAR Buoy consists of a ZephIR 300 lidar unit and a SEAWATCH Wavescan Buoy.

- The ZephIR 300 lidar unit deployed at East Anglia One is a standard ZephIR 300 unit using the ZephIR firmware 1.3.221.
- The SEAWATCH Wavescan Buoy used at East Anglia One is a tailored SEAWATCH Wavescan Buoy which has been configured in order to be deployed in conjunction with a ZephIR 300 to serve wind measurement purposes.

The tailored SEAWATCH Wavescan Buoy has a floating body with horizontal diameter of 2.7 m and a total height of 3.5 m from the lifting ring to the bottom of the keel weight. The buoy weighs approximately 925 kg and has a net buoyancy of 2700 kg (Berg, Seawatch Wind LiDAR buoy description for East Anglia ONE Limited, 2015) (Berg, Deployment by towing - East Anglia One, 11/2015). The setup of the device is shown in Figure C.1. A representation of a ZephIR 300 measuring cone when it is deployed on a SEAWATCH Wavescan Buoy can be seen in Figure C.2.

(Berg, Seawatch Wind LiDAR buoy description for East Anglia ONE Limited, 2015)

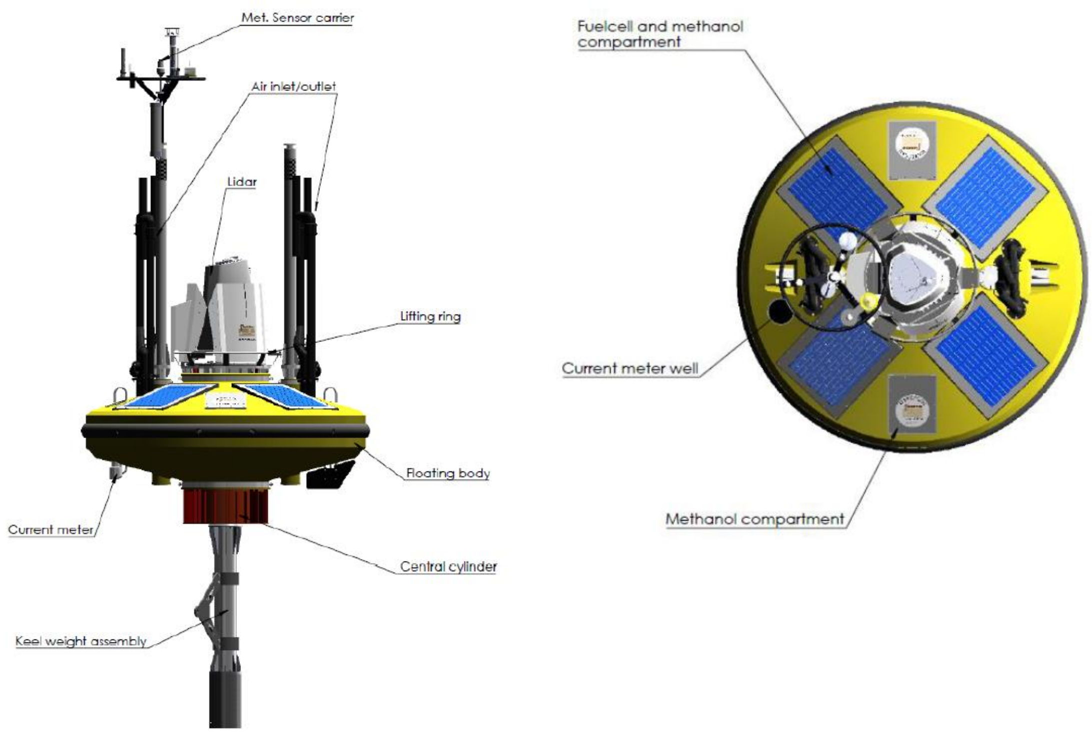


Figure C.1: SEAWATCH Wind LiDAR Buoy at East Anglia One

(Fugro-Oceanor-AS, 2016)

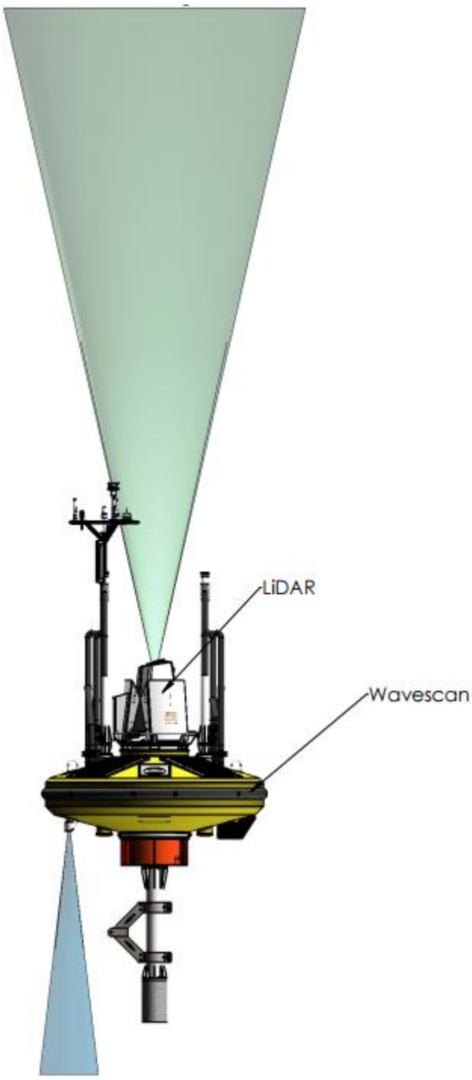


Figure C.2: Representation SEAWATCH Wind LiDAR Buoy and the ZephIR 300 mesuring cone

- The mooring system used for the device at East Anglia One consists of a bottom weight of 4,300 kg at approximately 42.0 m in depth and a sub-surface float buoyancy of 60 L.
- The buoy is connected to the sub-surface float buoyancy through a chain and a rubber chord with total length of 45.5 m.
- The sub-surface float buoyancy is connected to the bottom weight by an offshore mooring rope and a chain with total length of 57.5 m.
- The maximum excursion is estimated to be 95.0 m from the drop point (sea bed location) without taking into account the possible extension of the rubber chord (Berg, Deployment by towing - East Anglia One, 11/2015). The mooring system of the device is shown in Figure C.3.

- The total weight of the buoy with all the measuring equipment and full fuel cartridges is approximately 1800 kg (Berg, Deployment by towing - East Anglia One, 11/2015).

(Berg, Deployment by towing - East Anglia One, 11/2015)

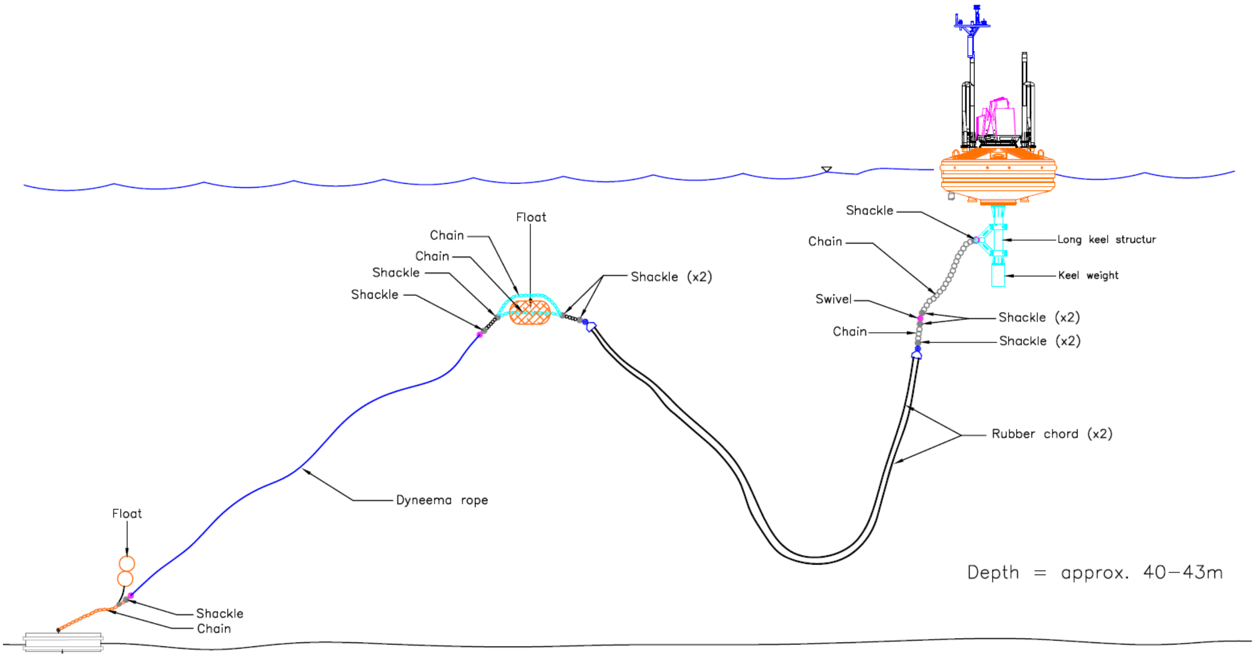


Figure C.3: SEAWATCH Wind LiDAR Buoy mooring system at East Anglia One

C.1. ZephIR 300 measured parameters

The ZephIR 300 can measure at ten user configurable heights ranging from 10 m to 200 m above the unit. The data measured from the ZephIR 300 are listed below (ZephIR, 2016):

- Horizontal wind speed (mean, min, max and std. dev.)
- Vertical wind speed
- Horizontal wind direction
- Turbulence intensity
- Battery voltage
- Generator voltage
- Upper and lower unit temperature
- Unit humidity
- GPS location
- Unit bearing with regards to true north
- Tilt away from vertical plane
- Air temperature
- Air pressure
- Air humidity
- Horizontal wind speed at the unit level
- Horizontal wind direction at the unit level

ZephIR 300 takes approximately 35 1-second scan measurements per height per 10-minute period when it is configured to measure at 10 heights. Measurements are also taken at the reference heights at the beginning and end of each measuring cycle. The 1-second data are stored and averaged to make up the 10-minute data. The validation and filtering of the data is done on a 10-minute basis. If use of the 1-second data is required it is important to note that internal ZephIR 300 firmware validation and filtering have not been carried out. In this case, it is prudent to check the 10-minute values coming from the processed 1-second data compare well to the 10-minute data as produced directly from the raw ZephIR 300 data files processed by the validated firmware.

C.2. SEAWATCH Wavescan LiDAR Buoy measured parameters

The device is equipped with several sensors and measurement devices:

- a ZephIR 300 lidar
- a windsonic anemometer
- a temperature sensor
- a pressure sensor at approximately 3.5 m ASL installed
- a sea current sonar profiler
- a combined data logger/wave sensor
- an internal compass
- a GPS

The ZephIR 300 lidar is set up to measure at ten heights (39 m, 59 m, 79 m, 94 m, 99 m, 102 m, 129 m, 149 m, 169 m and 199 m above mean sea level (AMSL)). The 1-second data from the ZephIR are used in order to check and correct the wind direction according to the buoy movement. The 10-minute sampled post-processed ZephIR 300 data sent from the buoy data communication system are detailed in Table C.1.

Table C.1: 10-min sampled data from buoy data communication system

ZephIR 300 (post processed)	SEAWATCH Wind Lidar Buoy
Horizontal wind speed, mean value, for all heights	Wind speed, direction and gust from the windsonic anemometer
Horizontal wind direction for all heights	Current speed and direction from the sea current profiler for the depths -4 m, -6 m, -8 m, -10 m, -12 m, -14 m, -16 m, -18 m, -20 m, -22 m, -24 m, -26 m, -28 m and -30 m below mean sea level
Inflow angle based on ten minute averaged values of horizontal and vertical wind speed for all the heights	Air temperature
Turbulence intensity for all the heights	Air pressure
Horizontal wind speed at the reference level of 40 m AMSL	Water temperature
	Significant wave height, significant wave height for the low and upper frequency band, and maximum wave height
	Mean wave direction, mean wave direction for the low and upper frequency band, wind wave direction, wave direction at peak period and directional spread at peak period
	Mean wave period, max wave period, peak wave period, mean wave period for the lower and upper frequency band

Also received from the SEAWATCH Wind Lidar Buoy at a 1-hour sampling are the GPS coordinates, the charge and discharge of the lead battery and the discharge of the lithium battery.

Apart from the data sent from the SEAWATCH Wind Lidar Buoy via the data communication system, the data that can be collected only during a visit or when the system is decommissioned are:

- Raw 1 second and 10 minute "ZPH" files from the ZephIR 300
- 30 second sampled direction from the SEAWATCH Wind Lidar Buoy internal compass
- 10 minute sampled heave, yaw, pitch and roll motion data
- 1 hour sampled data for the energy provided by fuel cells, the fuel cells current and voltage, the remaining level of methanol in fuel cells, the solar panels voltage and the internal temperature of the buoy.

D. Road Map Key Performance Indicators

The Carbon Trust Offshore Wind Accelerator (OWA) is a joint industry project involving nine developers representing over three-quarters of the UK's licenced capacity. The purpose of this joint project is to present a roadmap for floating LiDARs to become commercially accepted as a source of data to support financial investment decisions. The OWA roadmap was published in the UK in November 2013 (Carbon Trust, 11/2013).

It is important to note that the roadmap was designed to focus on the capabilities of floating LiDAR technology in measuring primary wind data, namely wind speed and wind direction. There are other secondary but important parameters required for a comprehensive offshore wind resource assessment such as hub-height turbulence intensity, temperature, air density, relative humidity. Additionally, complementary oceanographic measurements are also required to achieve a full met-ocean measurement campaign.

Recommended guidelines for the assessment of the performance of the floating LiDAR units under test are based on the following definitions:

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

Generally, it is expected that the KPI's are evaluated for heights being representative for a typical state-of-the-art offshore wind turbine covering a height range over the full rotor disk and as minimum requirement the primary measurement height is representative of a typical offshore hub height.

The performance assessment of the given KPI's and respective acceptance criteria regarding availability and accuracy shall be executed at each reference level present, in this case at each of the Mast EA1B and SEAWATCH Wind LiDAR Buoy concurrent levels. All data collected from the date of commissioning of the SEAWATCH Wind LiDAR Buoy until its decommissioning shall be taken into account in the overall data processing scheme, regardless of the environmental conditions. It is recommended that at least six months of offshore data are available to provide confidence with respect to the measured KPI's. Additionally, although system availability is one of the KPI's used in the roadmap does not directly address or cover the seaworthiness of the floating lidar devices.

All comparisons and regression analysis are to be based on 10-minute average values. The data from both the lidar and the mast are to be filtered for external parameters such as:

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

The requirements on data coverage are based on 10-minute average values as returned from the floating lidar system after the quality check and filtering is finalised.

1. 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 m/s and 12 m/s.

2. Minimum number of 40 data points required in each 2 m/s bin wide reference wind speed bin centred on 13 m/s and 15 m/s, i.e. covering a range 12 m/s and 16 m/s.
3. 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.

In order to assess the accuracy a statistical linear regression approach has been selected.

4. A two variant regression y = mx+b (with m slope and b offset) to be applied to wind direction data comparisons between floating instrument and reference mast; or,
5. A single variant regression, with the regression analysis constrained to pass through origin (y = mx+b; b = 0) to be applied to wind speed, turbulence intensity and wind shear data comparisons between floating instrument and reference mast.

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

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

E. Sensitivity Analysis

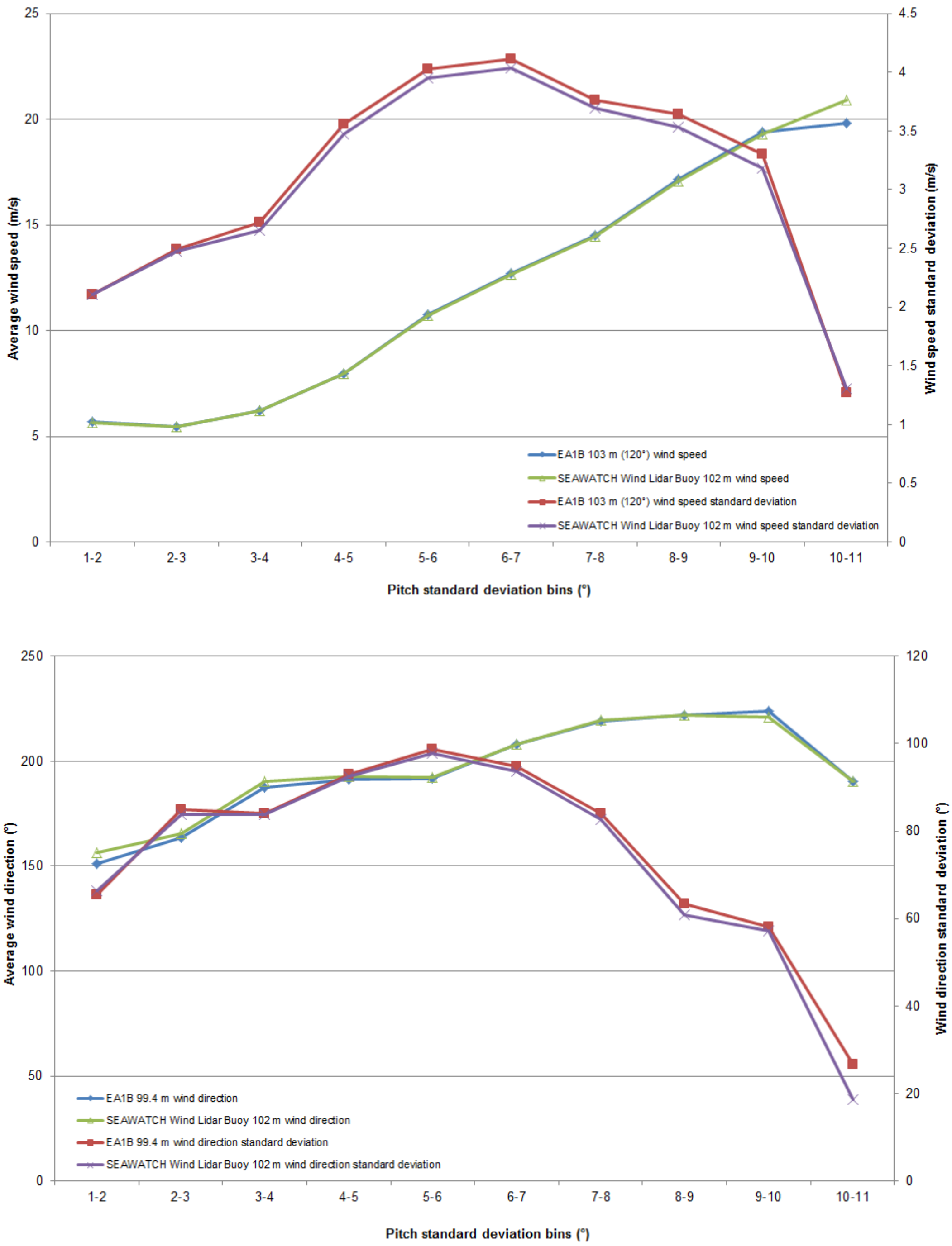
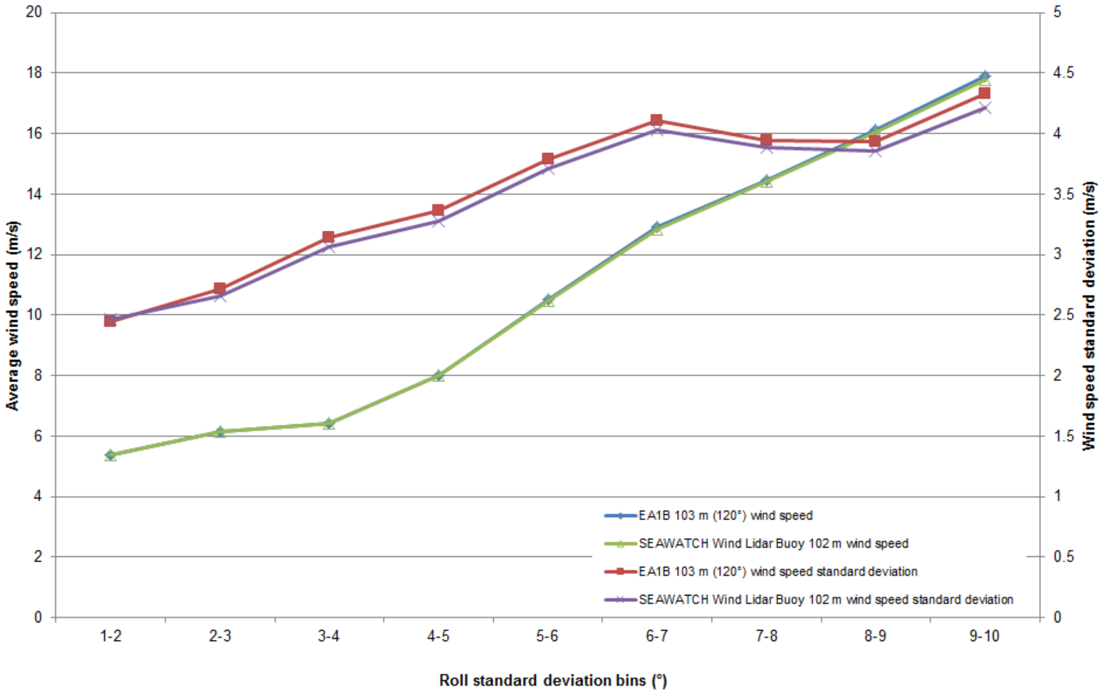


Figure E.1: Mast EA1B 103 m (120°) wind speed and standard deviation, Mast EA1B 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against Pitch standard deviation (entire period)



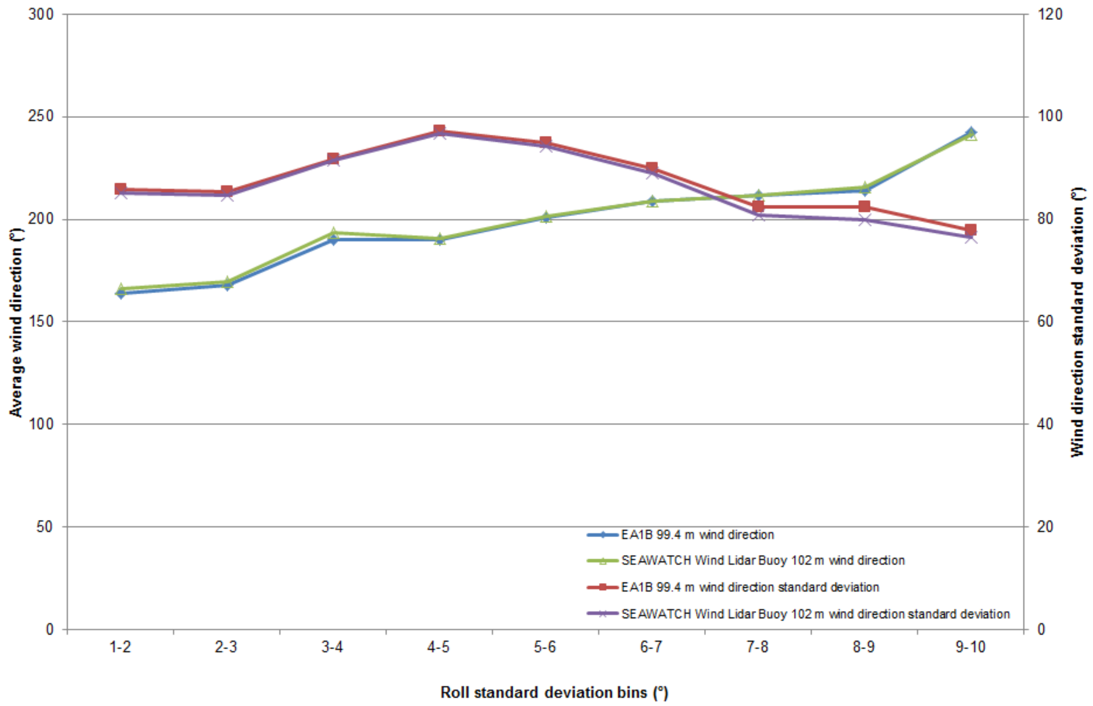
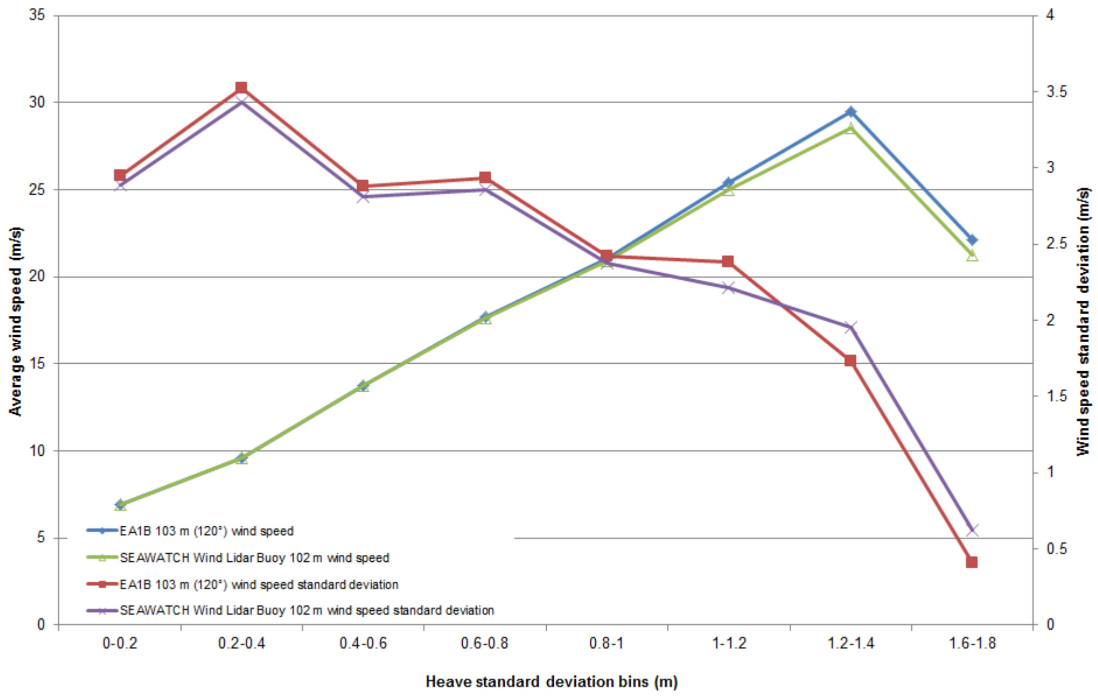


Figure E.2: **Mast EA1B 103 m (120°) wind speed and standard deviation, Mast EA1B 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against Roll standard deviation (entire period)**



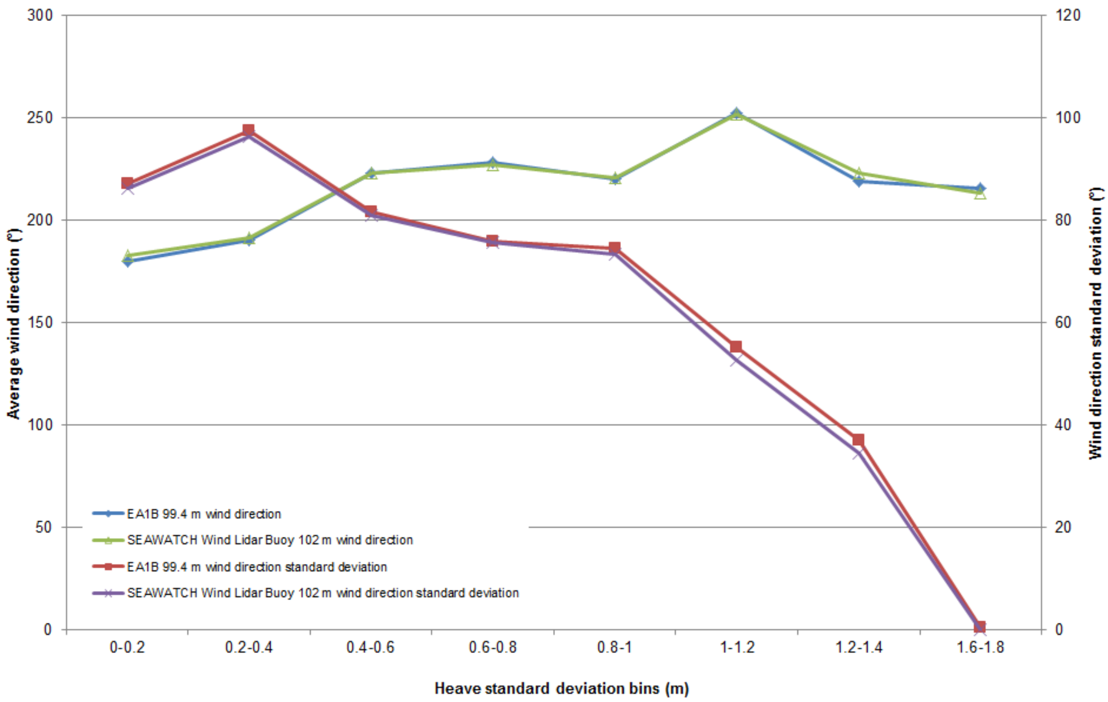
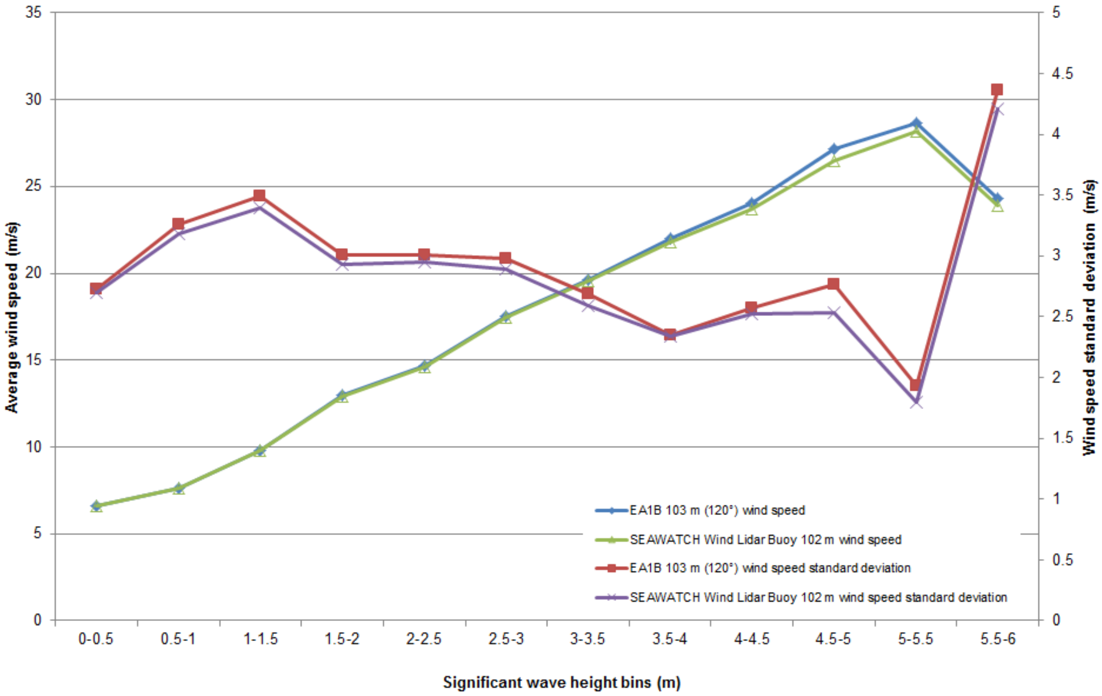


Figure E.3: Mast EA1B 103 m (120°) wind speed and standard deviation, Mast EA1B 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against Heave standard deviation (entire period)



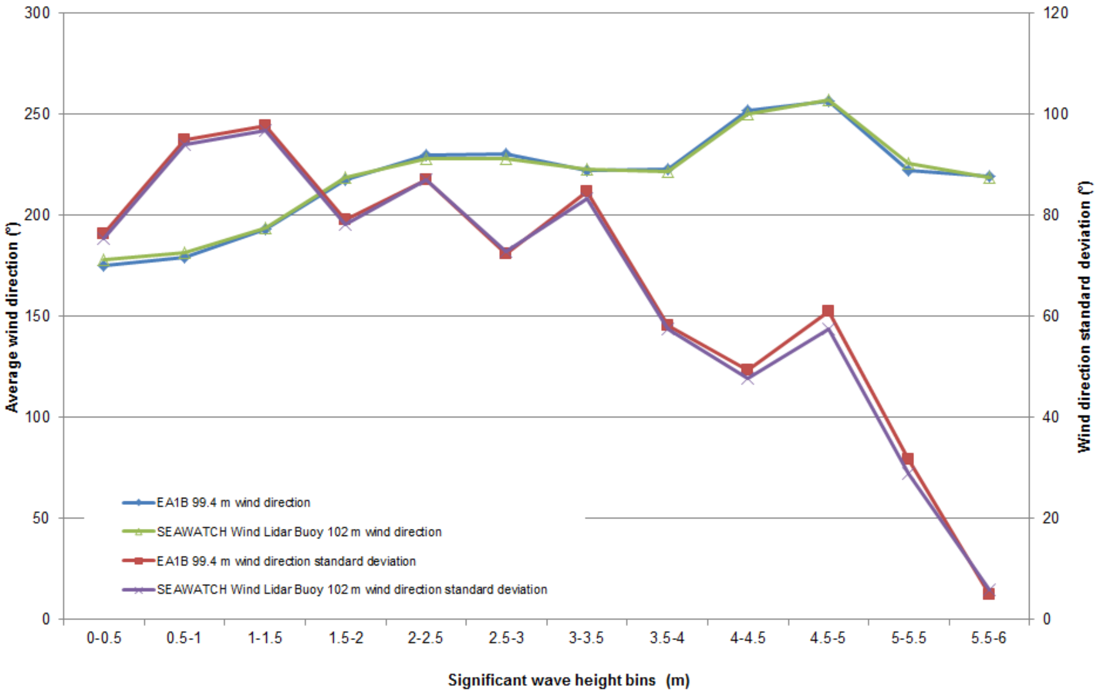
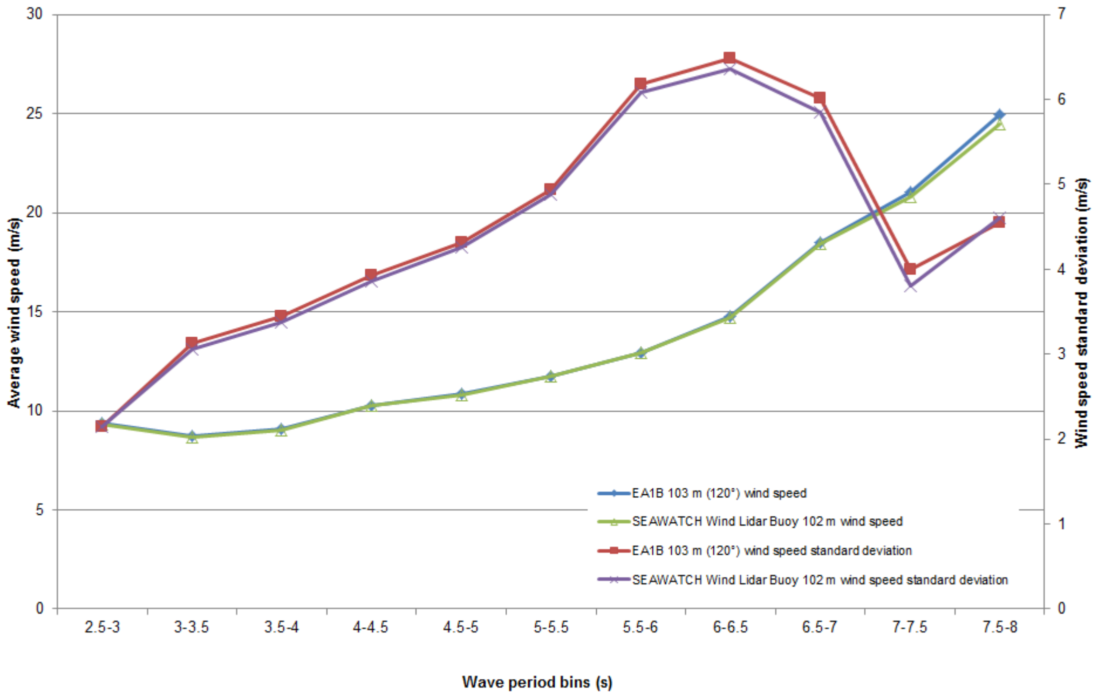


Figure E.4: EA1B mast 103 m (120°) wind speed and standard deviation, EA1B mast 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against significant wave height (entire period)



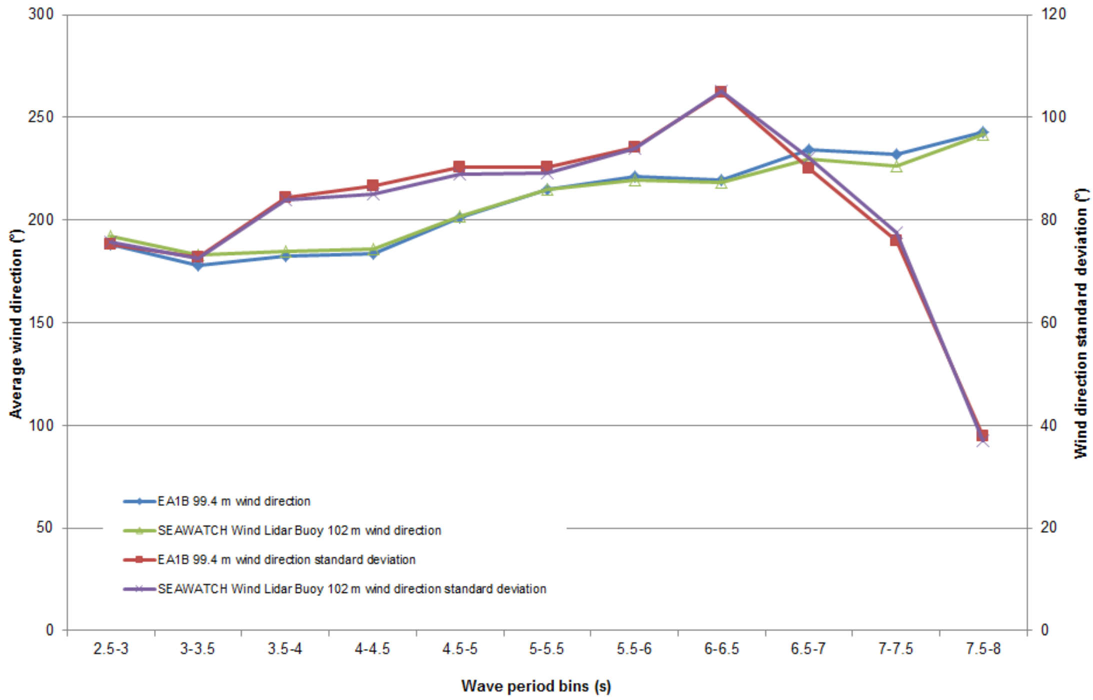
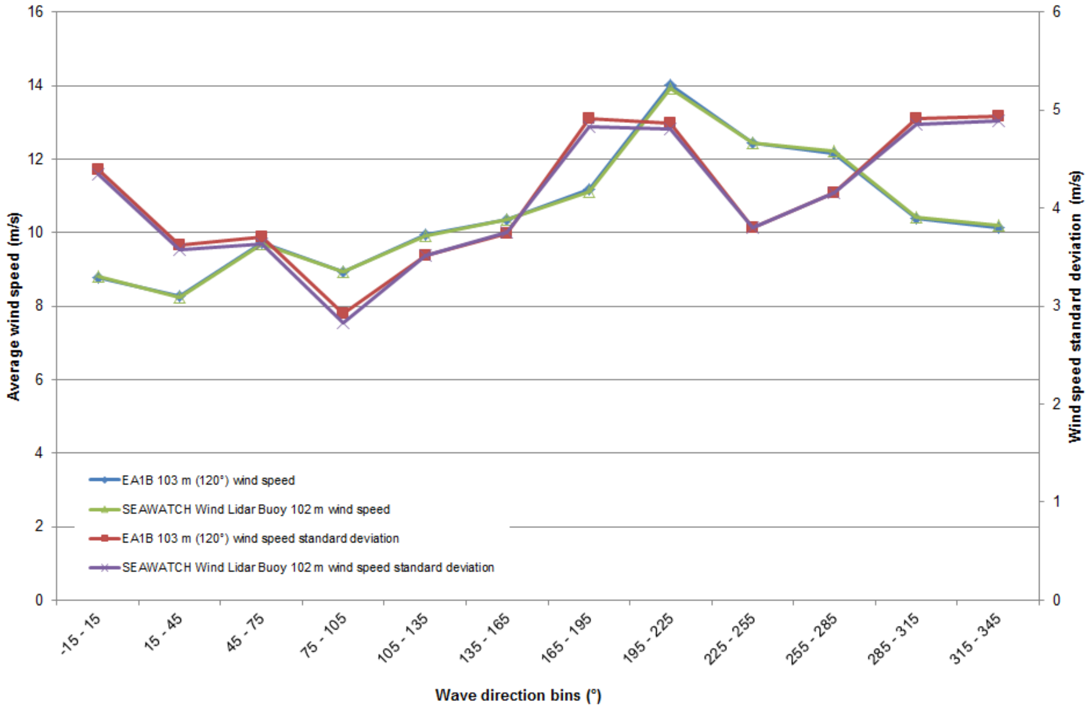


Figure E.5: **EA1B mast 103 m (120°) wind speed and standard deviation, EA1B mast 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against wave period (entire period)**



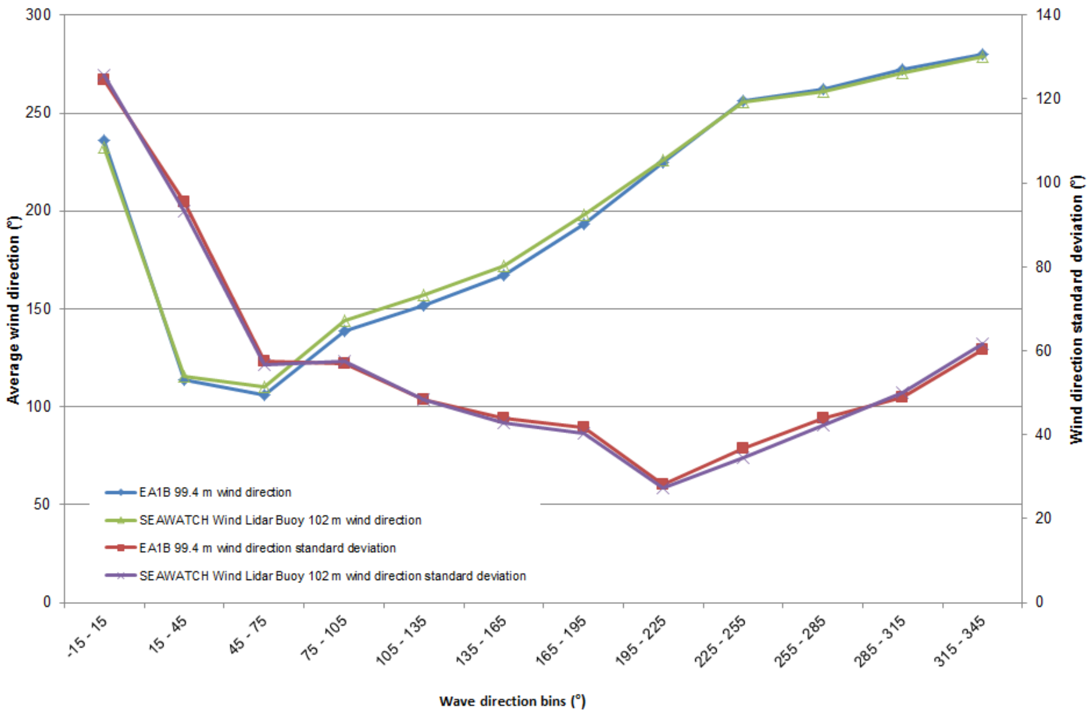
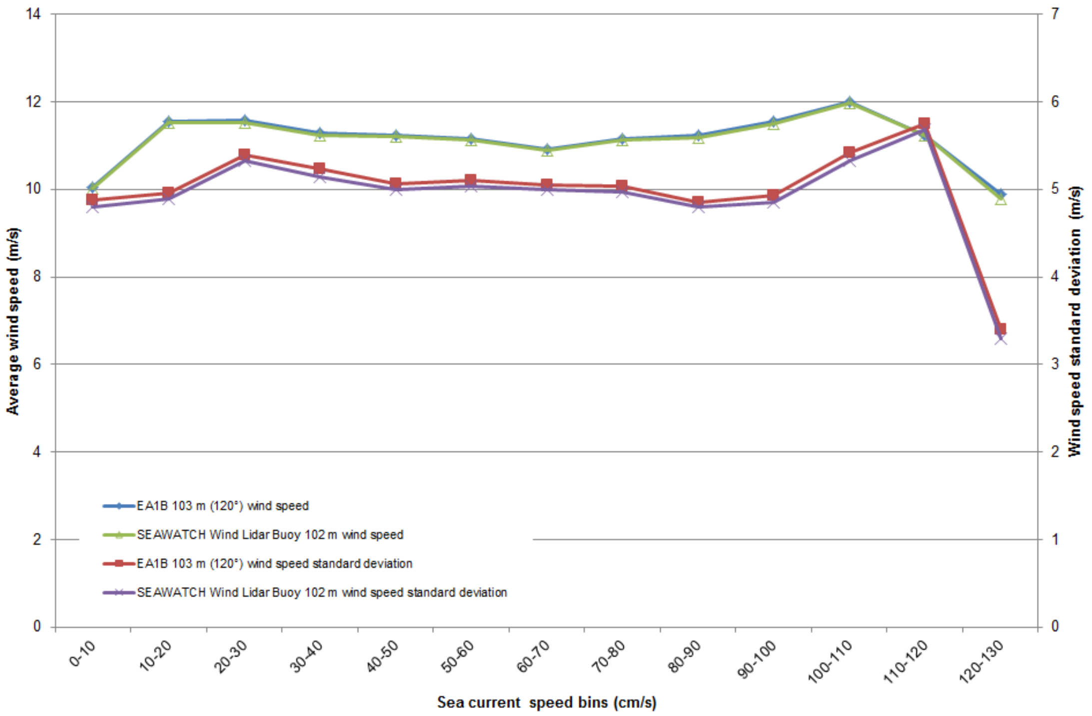


Figure E.6: EA1B mast 103 m (120°) wind speed and standard deviation, EA1B mast 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against wave direction (entire period)



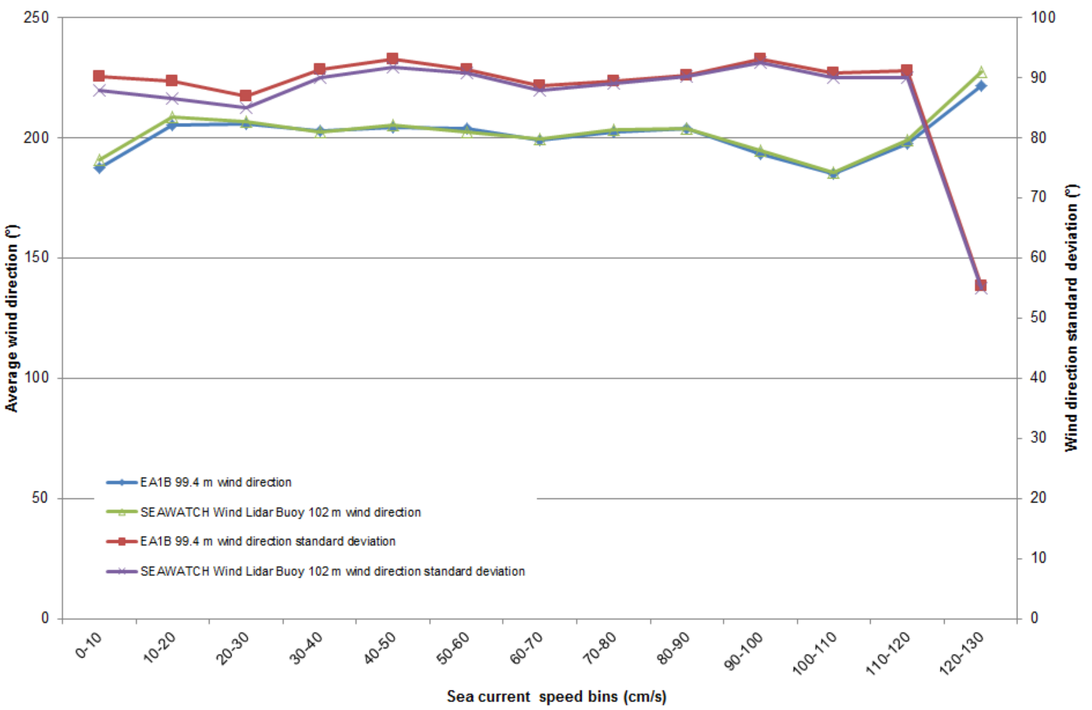
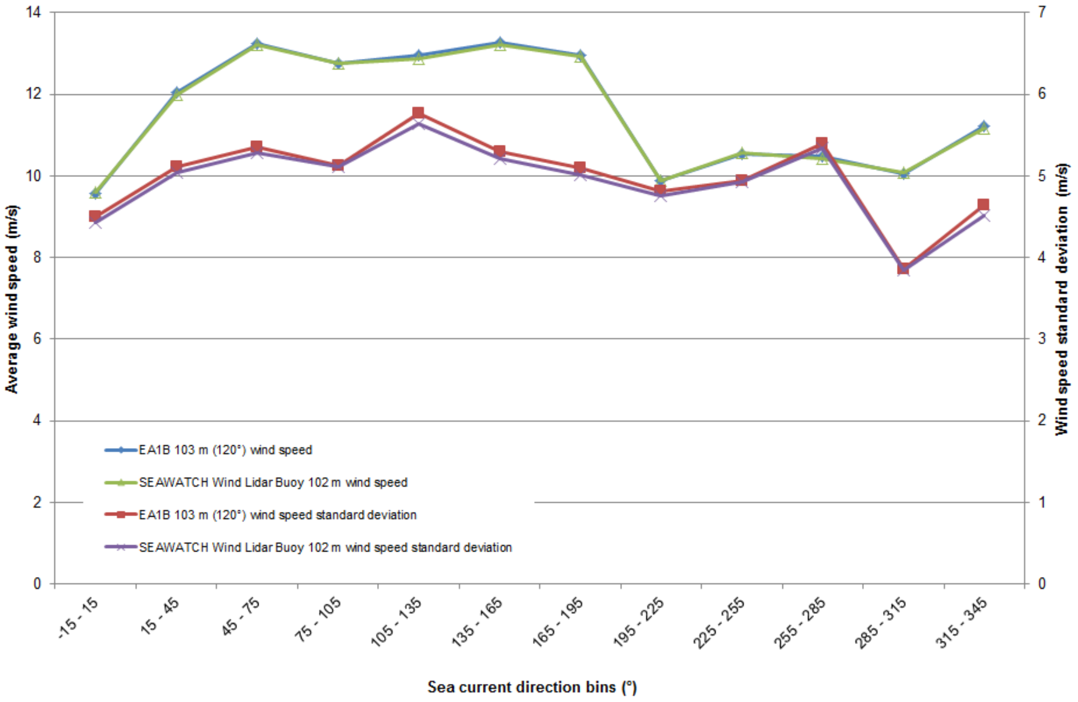


Figure E.7: EA1B mast 103 m (120°) wind speed and standard deviation, EA1B mast 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against sea current speed (entire period)



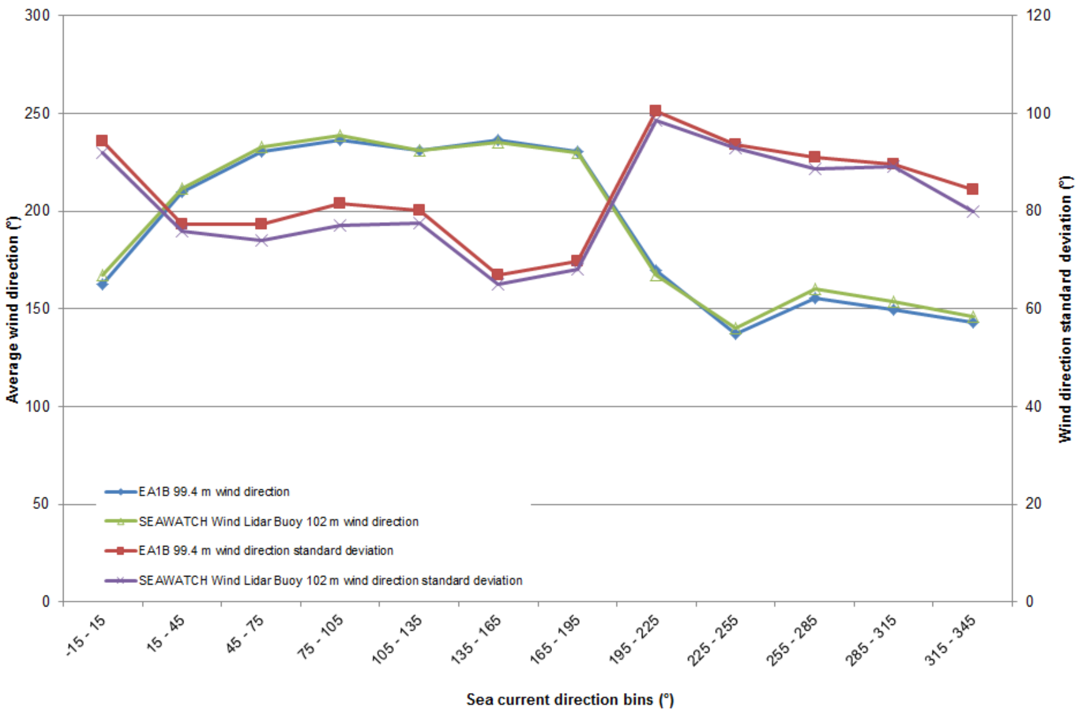


Figure E.8: **EA1B mast 103 m (120°) wind speed and standard deviation, EA1B mast 99.4 m wind direction and standard deviation, SEAWATCH Wind Lidar Buoy 102 m wind speed, wind direction and standard deviations against sea current direction (entire period)**

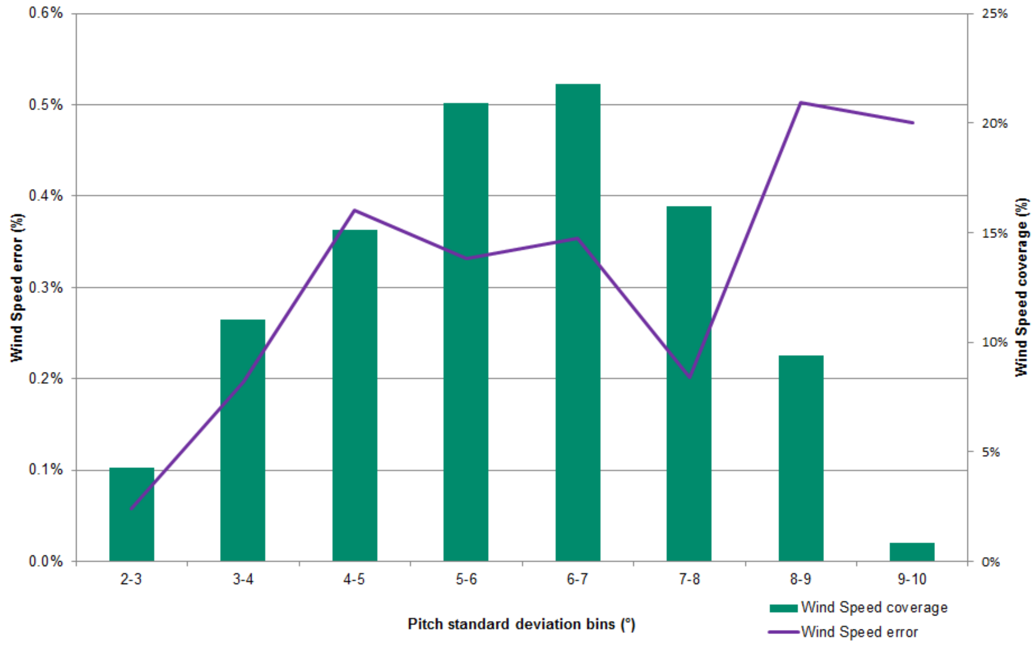


Figure E.9: SEAWATCH Wind Lidar Buoy 102 m wind speed error dependent on pitch standard deviation

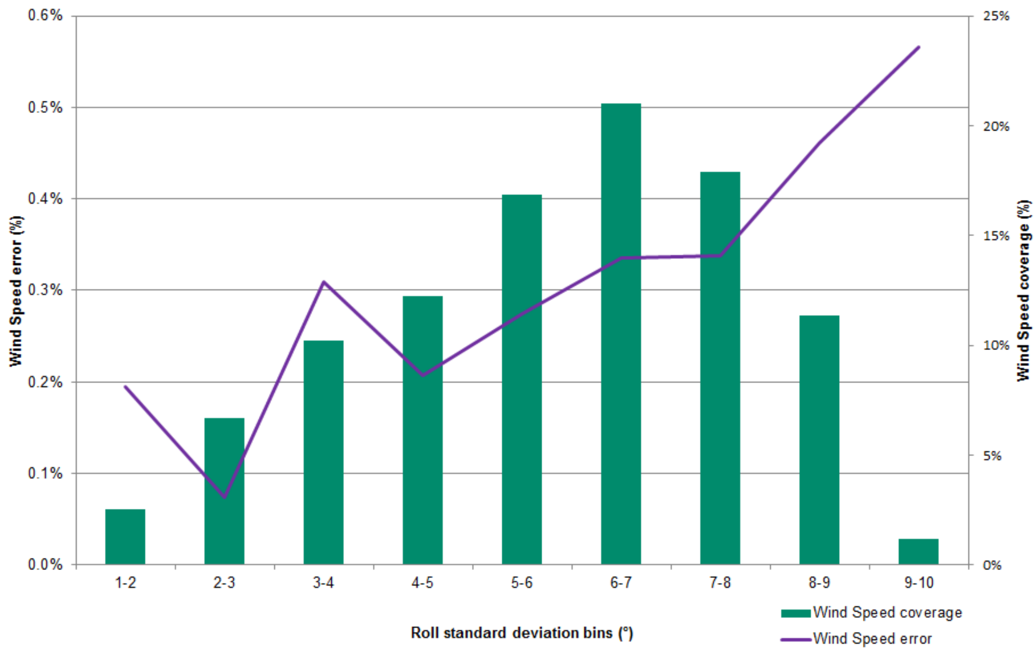


Figure E.10: SEAWATCH Wind Lidar Buoy 102 m wind speed error dependent on roll standard deviation

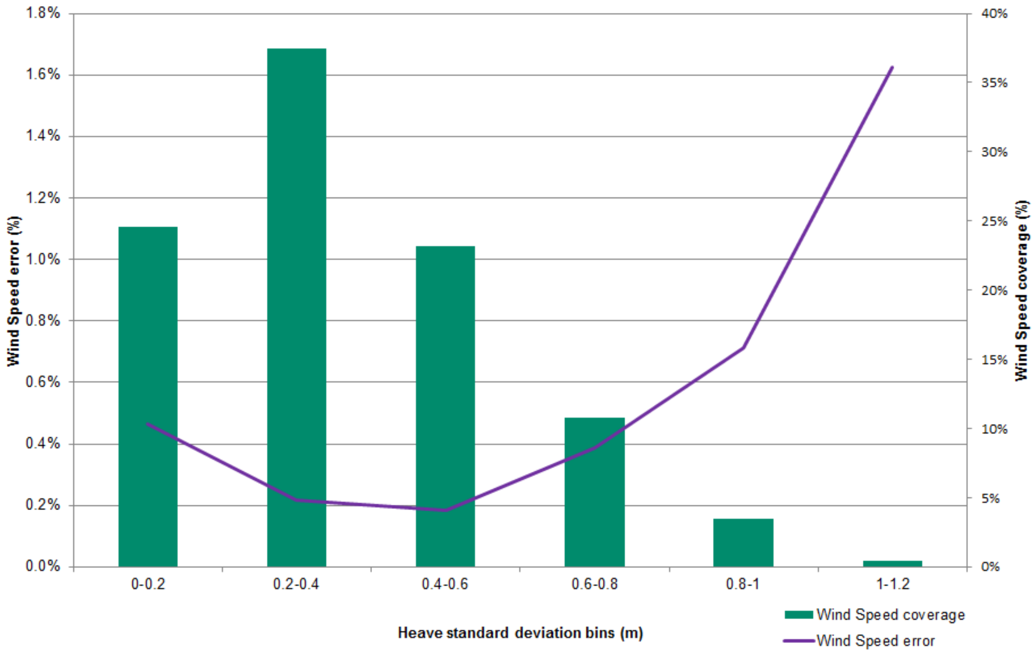


Figure E.11: SEAWATCH Wind Lidar Buoy 102 m wind speed error dependent on heave standard deviation

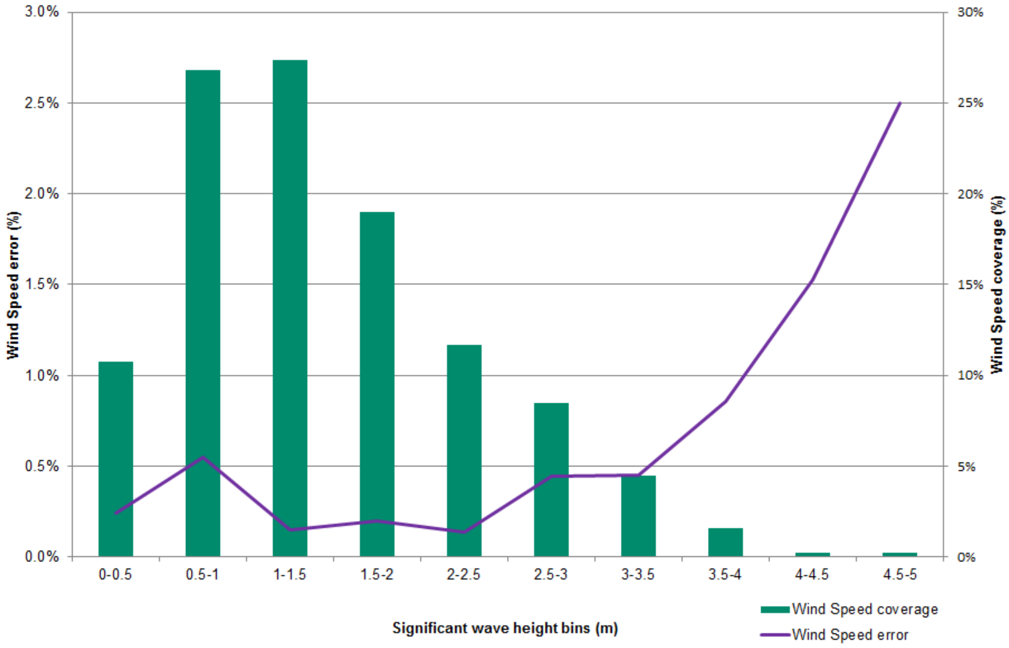


Figure E.12: SEAWATCH Wind Lidar Buoy 102 m wind speed error dependent on significant wave height

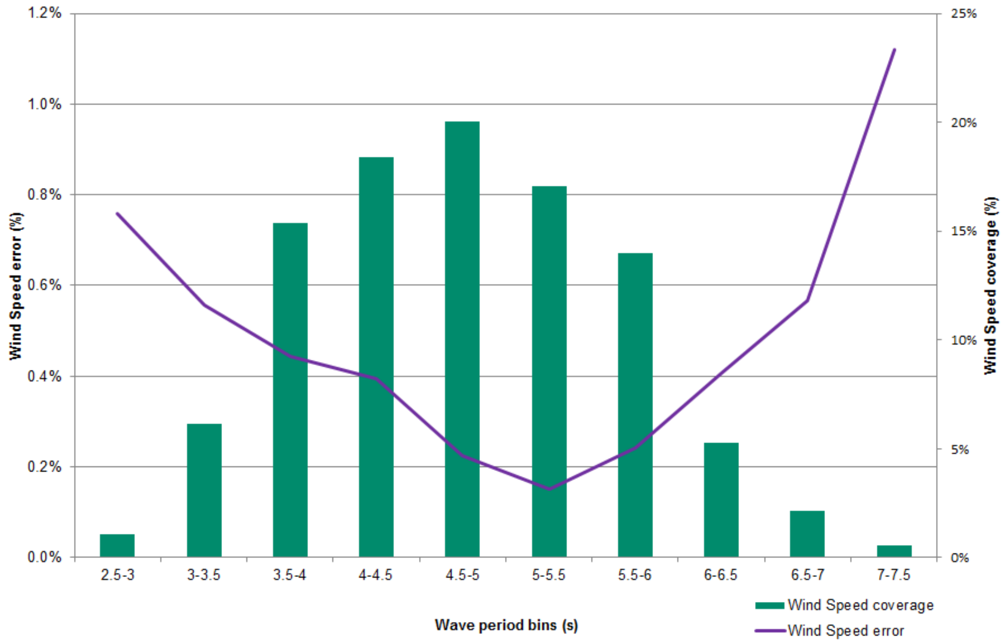


Figure E.13: SEAWATCH Wind Lidar Buoy 102 m wind speed error dependent on wave period

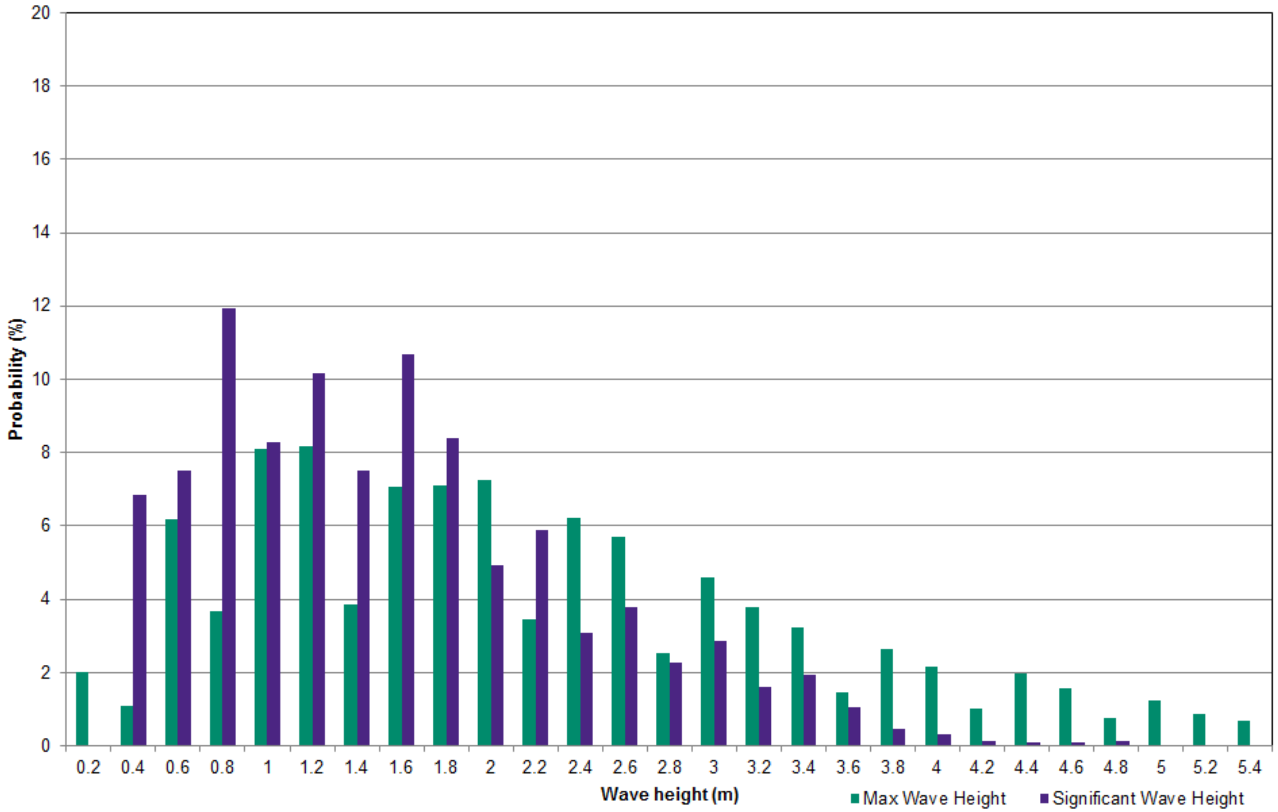


Figure E.14: Probability distribution of maximum wave height and significant wave height (entire period)

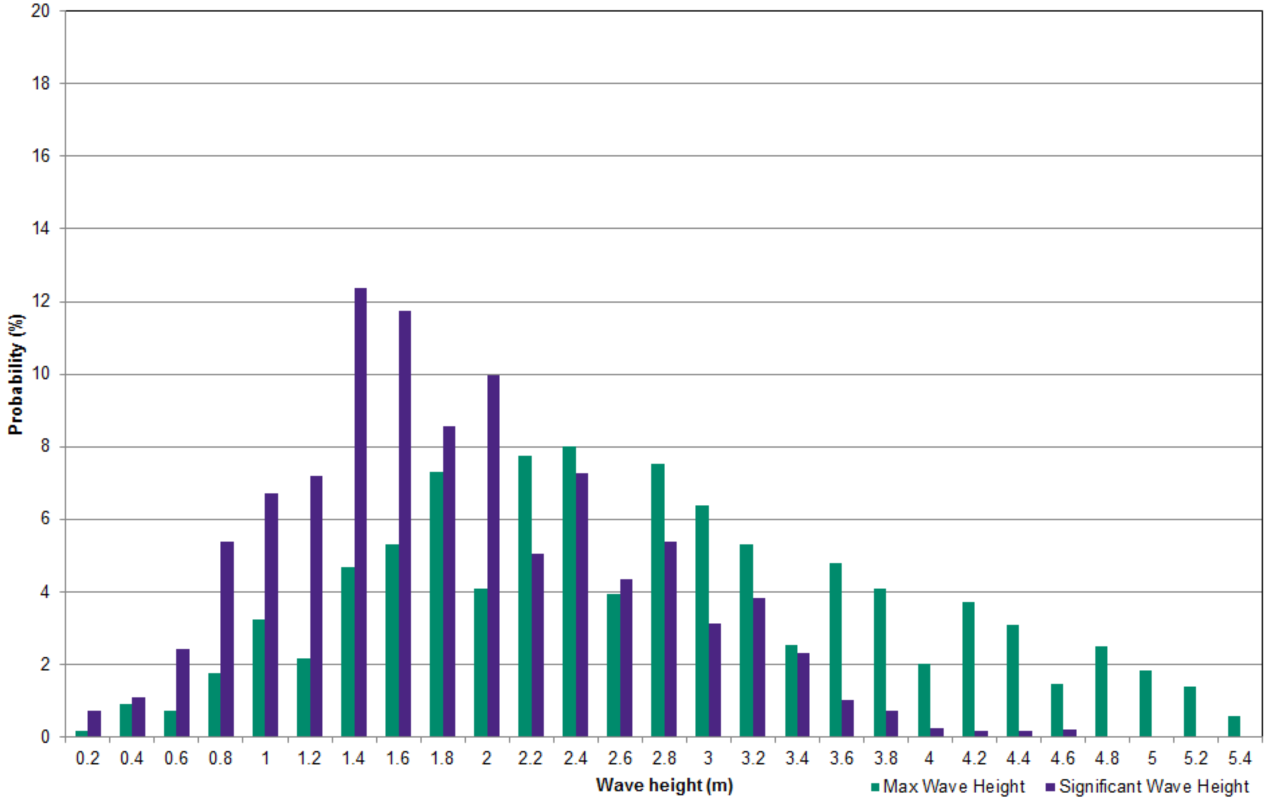


Figure E.15: Probability distribution of maximum wave height and significant wave height (period 1)

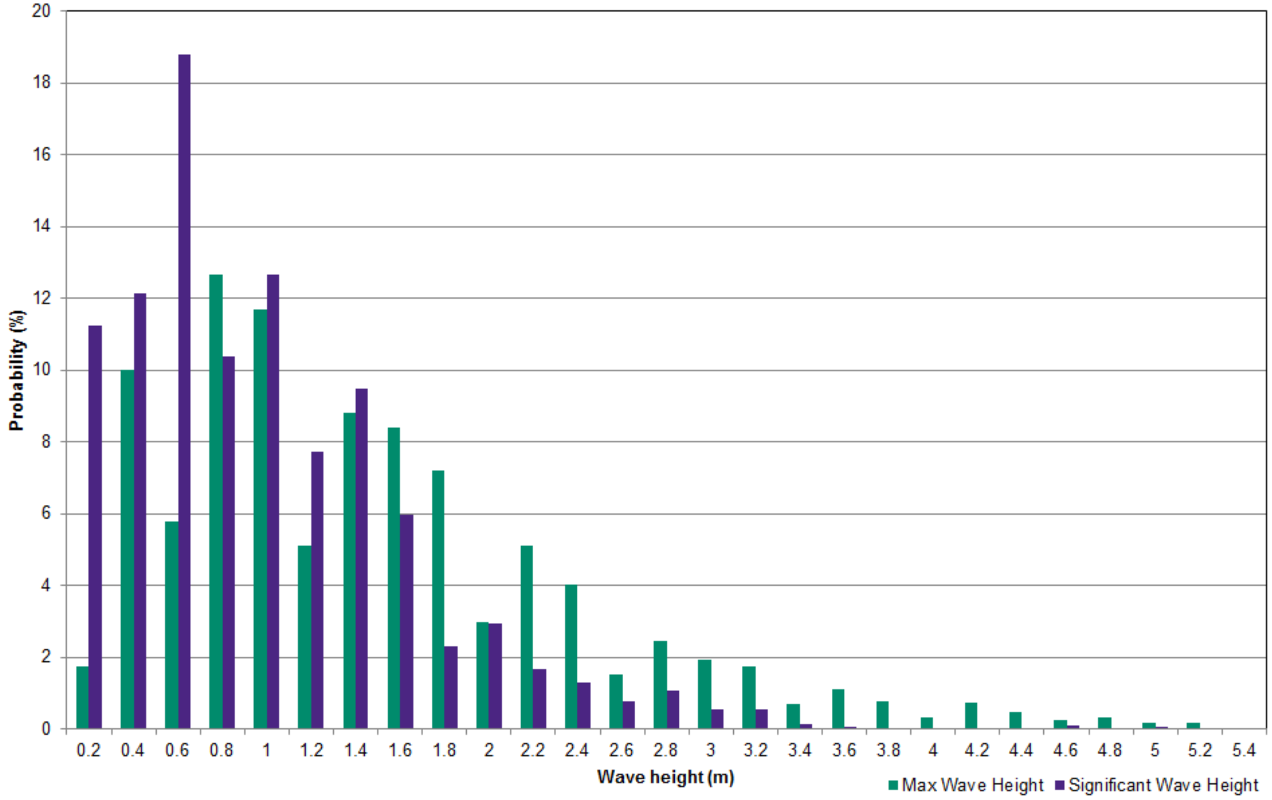


Figure E.16: Probability distribution of maximum wave height and significant wave height (period 2)

Table E.1: Amount of data per wind speed bin* and significant wave height bin (entire period)

Wind speed bins (m/s) Significant wave height bins (m)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
5.5 - 6.0	-	-	-	-	-	-	-	-	-	-	2	-	-	-	1
5.0 - 5.5	-	-	-	-	-	-	-	-	-	-	-	1	3	8	3
4.5 - 5.0	-	-	-	-	-	-	-	-	1	1	6	4	22	12	7
4.0 - 4.5	-	-	-	-	-	-	-	1	2	10	18	19	14	1	-
3.5 - 4.0	-	-	-	-	-	-	-	4	21	49	87	150	54	14	1
3.0 - 3.5	-	-	-	-	3	4	23	94	157	249	346	172	26	3	-
2.5 - 3.0	-	-	1	6	31	66	160	277	497	605	330	59	10	-	-
2.0 - 2.5	-	-	-	28	169	367	564	719	594	282	67	12	1	1	-
1.5 - 2.0	-	26	104	158	405	787	1,301	1,180	466	110	13	12	-	-	-
1.0 - 1.5	145	363	478	801	1,539	1,543	1,090	581	170	7	-	-	-	-	-
0.5 - 1.0	238	632	1,163	1,712	1,478	873	340	142	69	28	-	-	-	-	-
0.0 - 0.5	118	347	656	799	446	248	63	15	2	-	-	-	-	-	-

***** Wind speed bins: Mast EA1B 103 m wind speed tower shadow corrected series.

Table E.2: Amount of data per wind speed bin* and significant wave height bin (period 1)

Wind speed bins (m/s) Significant wave height bins (m)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
5.5 - 6.0	-	-	-	-	-	-	-	-	-	-	2	-		-	-
5.0 - 5.5	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1
4.5 - 5.0	-	-	-	-	-	-	-	-	1	1	3	3	21	6	-
4.0 - 4.5	-	-	-	-	-	-	-	1	1	8	18	18	9		-
3.5 - 4.0	-	-	-	-	-	-	-	4	11	43	83	150	50	10	1
3.0 - 3.5	-	-	-	-	3	3	20	43	102	192	338	172	21	1	-
2.5 - 3.0	-	-	1	5	19	32	97	146	398	548	324	53		-	-
2.0 - 2.5	-	-	-	19	70	167	377	555	494	258	53	5	1	1	-
1.5 - 2.0	-	6	29	75	149	401	903	801	332	103	4	-	-	-	-
1.0 - 1.5	7	86	170	260	440	575	591	270	69	7	-	-	-	-	-
0.5 - 1.0	10	50	198	252	258	143	44	22	-	-	-	-	-	-	-
0.0 - 0.5	1	53	31	27	-	-	-	-	-	-	-	-	-	-	-

***** Wind speed bins: Mast EA1B 103 m wind speed tower shadow corrected series.

Table E.3: Amount of data per wind speed bin* and significant wave height bin (period 2)

Wind speed bins (m/s) / Significant wave height bins (m)	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	16-18	18-20	20-22	22-24	24-26	26-28	28-30
5.5 - 6.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
5.0 - 5.5	-	-	-	-	-	-	-	-	-	-	-	-	1	2	7
4.5 - 5.0	-	-	-	-	-	-	-	-	-	-	-	3	1	1	6
4.0 - 4.5	-	-	-	-	-	-	-	-	-	1	2	-	1	5	1
3.5 - 4.0	-	-	-	-	-	-	-	-	10	6	4	-	4	4	-
3.0 - 3.5	-	-	-	-	-	1	3	51	55	57	8	-	5	2	-
2.5 - 3.0	-	-	-	1	12	34	63	131	99	57	6	6	2	-	-
2.0 - 2.5	-	-	-	9	99	200	187	164	100	24	14	7	-	-	-
1.5 - 2.0	-	20	75	83	256	386	398	379	134	7	9	12	-	-	-
1.0 - 1.5	138	277	308	541	1,099	968	499	311	101	-	-	-	-	-	-
0.5 - 1.0	228	582	965	1,460	1,220	730	296	120	69	28	-	-	-	-	-
0.0 - 0.5	117	294	625	772	446	248	63	15	2	-	-	-	-	-	-

***** Wind speed bins: Mast EA1B 103 m wind speed tower shadow corrected series.

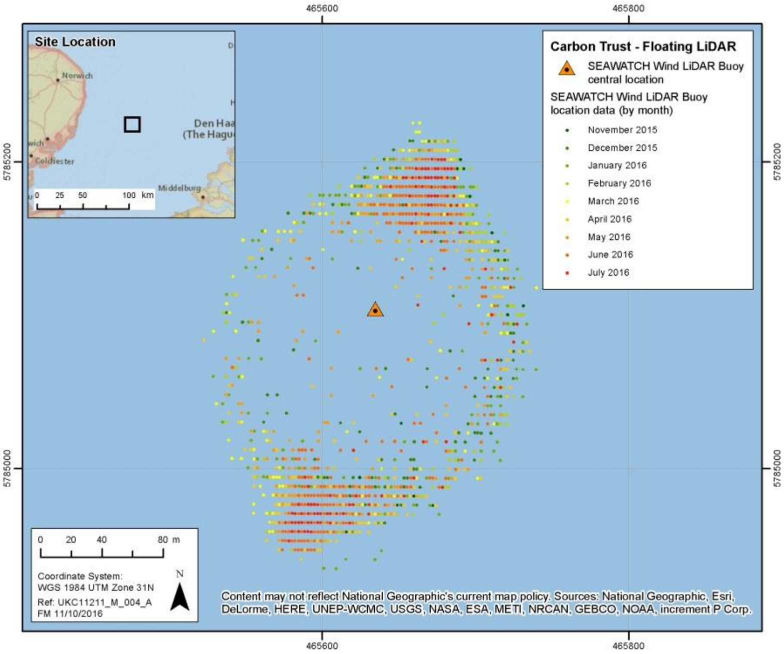


Figure E.17: Movement of the SEAWATCH Wind Lidar Buoy using the using the 1-hour data from the embedded GPS

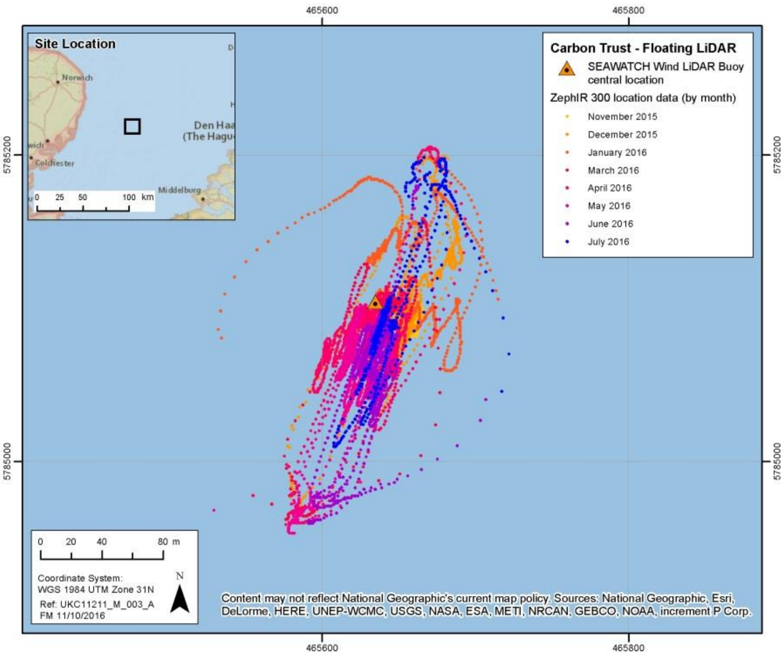


Figure E.18: Movement of the SEAWATCH Wind Lidar Buoy ZephIR 300 10-minute data

F. Wind Measurement Analysis

Table F.1: Data coverage per wind speed bin for the entire period (26/11/2016 – 06/07/2016)

Wind Speed Bin	Number of 10-min records used for the validation study per measurement height				
	39 m	59 m	79 m	99 m	102 m
1	578	553	551	548	566
2	1,051	926	879	877	881
3	1,323	1,202	1,186	1,152	1,156
4	1,757	1,507	1,343	1,272	1,245
5	2,022	1,900	1,719	1,707	1,721
6	2,136	1,982	1,979	1,842	1,800
7	2,251	2,172	2,061	1,999	1,987
8	2,290	2,210	2,065	2,086	2,102
9	2,273	2,197	2,205	1,970	1,965
10	1,989	2,066	1,964	2,013	1,987
11	3,504	3,690	3,682	3,538	3,522
12	2,338	2,592	2,932	3,068	3,069
13	1,659	1,700	1,727	1,931	1,973
14	936	1,132	1,298	1,346	1,346
15	413	578	702	828	834
16	101	187	265	351	368
17	70	69	88	105	111
18	17	37	40	48	52
19	1	5	15	19	15
20	0	1	1	3	7
Total number of 10-min data per height	**26,709**	**26,706**	**26,702**	**26,703**	**26,707**

Table F.2: Data coverage per wind speed bin for period 1 (26/11/2015 - 17/02/2016)

Wind Speed Bin	Number of 10-min records used for the validation study per measurement height				
	39 m	59 m	79 m	99 m	102 m
1	51	51	47	43	40
2	147	149	145	140	141
3	203	196	193	192	199
4	246	227	230	241	230
5	327	321	293	277	275
6	379	362	365	352	362
7	535	461	461	442	444
8	628	595	514	521	507
9	796	688	628	511	512
10	1,044	944	859	823	801
11	2,305	2,251	2,144	2,028	2,021
12	1,799	1,813	1,883	1,908	1,907
13	1,431	1,426	1,397	1,444	1,463
14	904	1,045	1,162	1,179	1,177
15	402	565	672	783	779
16	88	177	252	332	350
17	48	52	68	91	92
18	3	16	26	30	35
19	0	0	0	3	4
20	0	0	0	0	0
Total number of 10-min data per height	**11,336**	**11,339**	**11,339**	**11,340**	**11,339**

Table F.3: **Data coverage per wind speed bin for period 2 (12/03/2016 - 06/07/2016)**

Wind Speed Bin	Number of 10-min records used for the validation study per measurement height				
	39 m	59 m	79 m	99 m	102 m
1	527	502	504	505	526
2	904	777	734	737	740
3	1,120	1,006	993	960	957
4	1,511	1,280	1,113	1,031	1,015
5	1,695	1,579	1,426	1,430	1,446
6	1,757	1,620	1,614	1,490	1,438
7	1,716	1,711	1,600	1,557	1,543
8	1,662	1,615	1,551	1,565	1,595
9	1,477	1,509	1,577	1,459	1,453
10	945	1,122	1,105	1,190	1,186
11	1,199	1,439	1,538	1,510	1,501
12	539	779	1,049	1,160	1,162
13	228	274	330	487	510
14	32	87	136	167	169
15	11	13	30	45	55
16	13	10	13	19	18
17	22	17	20	14	19
18	14	21	14	18	17
19	1	5	15	16	11
20	0	1	1	3	7
Total number of 10-min data per height	**15,373**	**15,367**	**15,363**	**15,363**	**15,368**

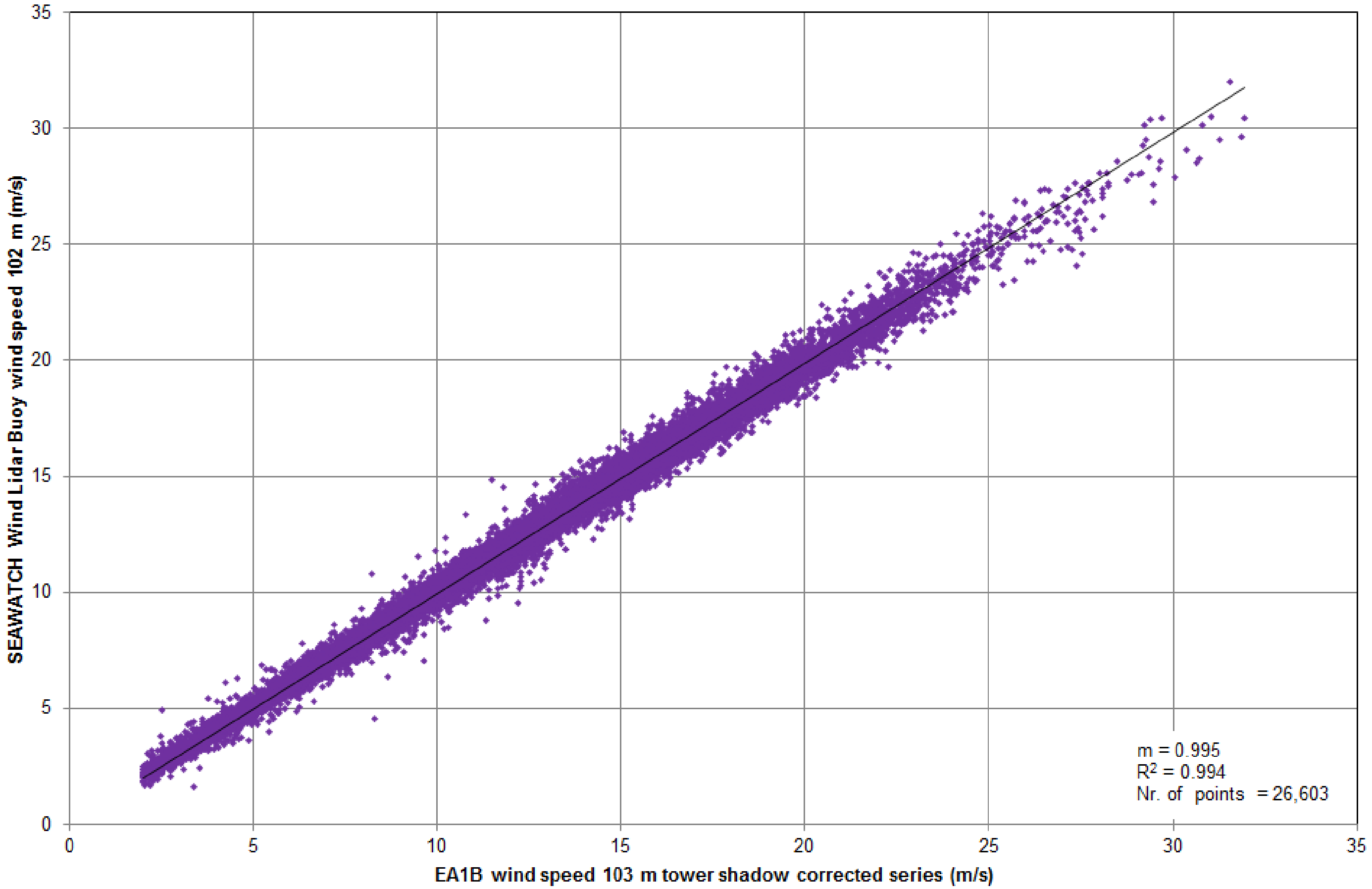


Figure F.1: Correlation plot of 10-minute horizontal wind speed SEAWATCH Wind Lidar Buoy 102 m vs EA1B Mast 103 m tower shadow corrected series for wind speeds greater than 2 m/s (entire period)

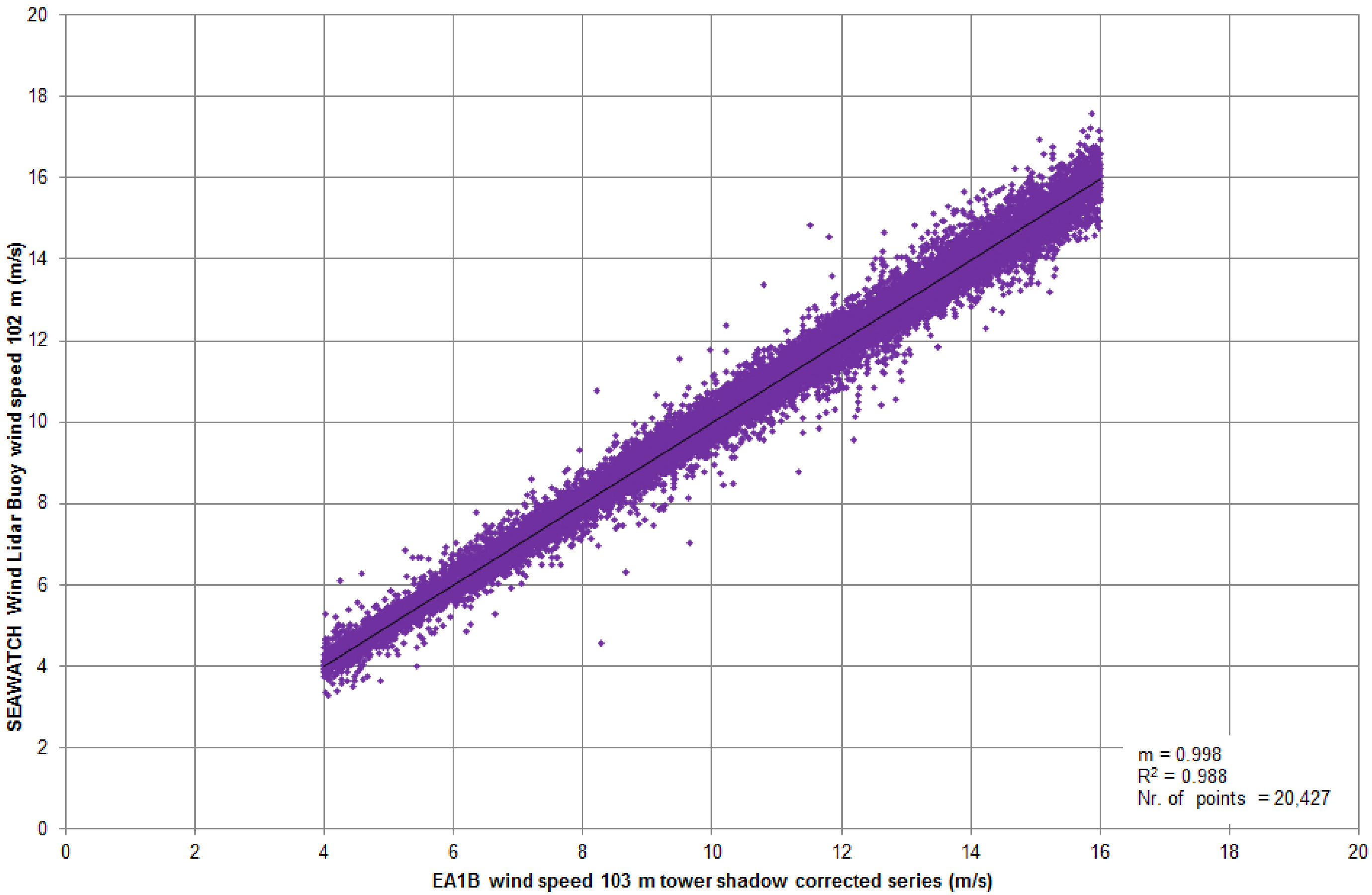


Figure F.2: Correlation plot of 10-minute horizontal wind speed SEAWATCH Wind Lidar Buoy 102 m vs EA1B Mast 103 m tower shadow corrected series for wind speeds between 4 m/s and 16 m/s (entire period)

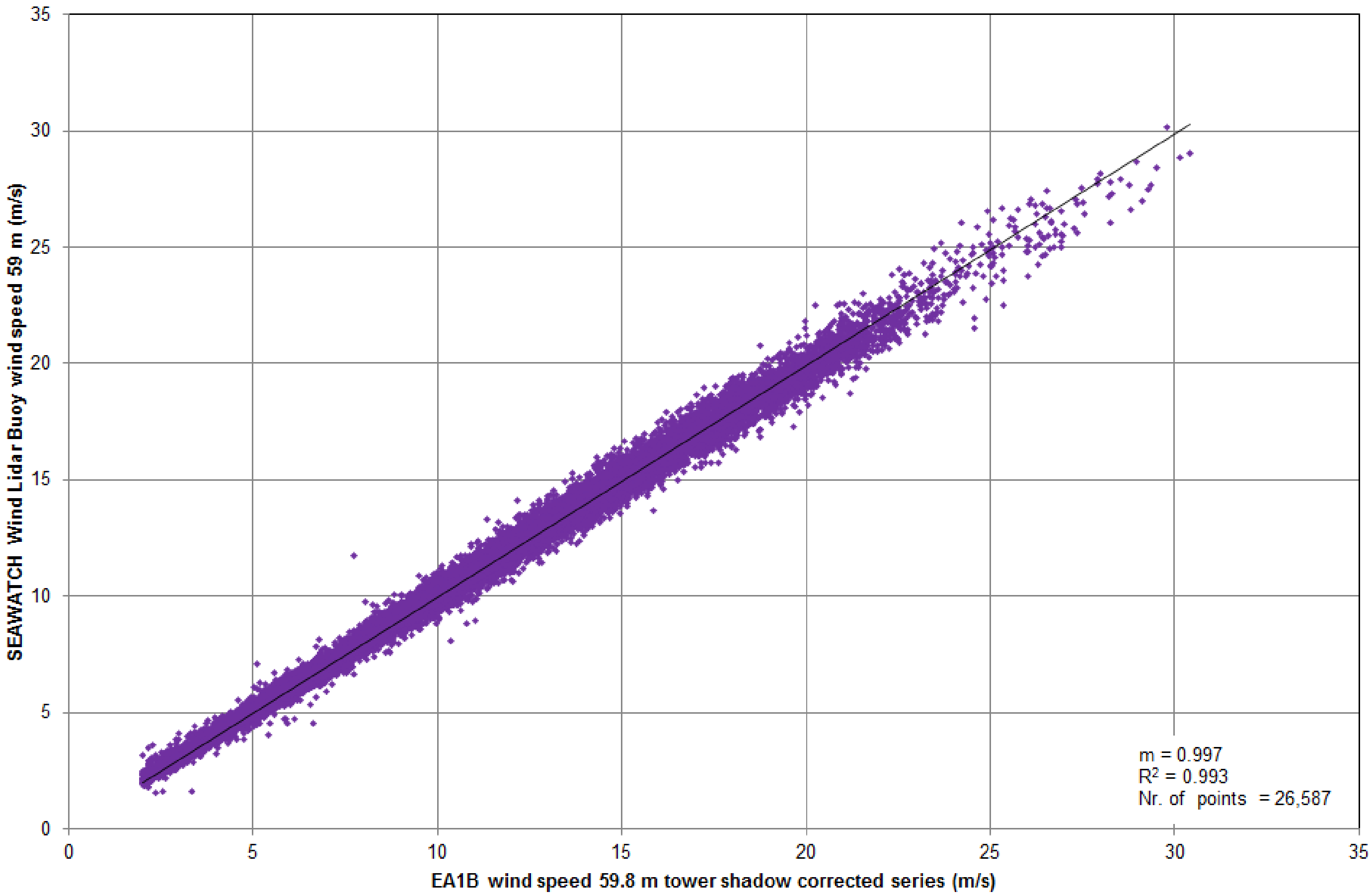


Figure F.3: Correlation plot of 10-minute horizontal wind speed SEAWATCH Wind Lidar Buoy 59 m vs EA1B Mast 59.8 m tower shadow corrected series for wind speeds greater than 2 m/s (entire period)

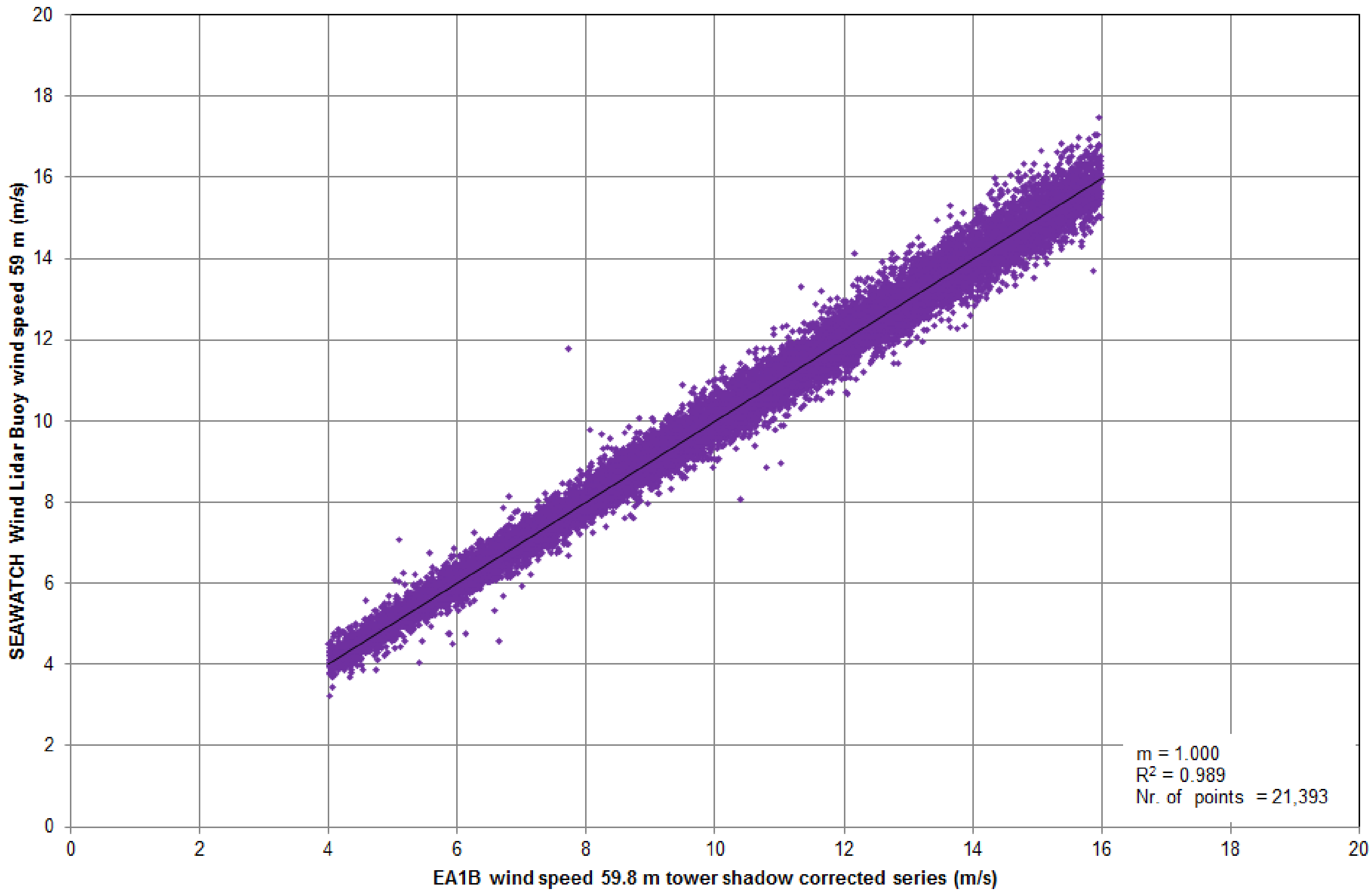


Figure F.4: Correlation plot of 10-minute horizontal wind speed SEAWATCH Wind Lidar Buoy 59 m vs EA1B Mast 59.8 m tower shadow corrected series for wind speeds between 4 m/s and 16 m/s (entire period)

In the Table F.4 to Table F.10 there are values that due to rounding seem to pass the best practice acceptance criteria or meet the minimum acceptance criteria but are marked as they meet the minimum or fail the acceptance criteria respectively.

Table F.4: Sectorwise mean wind speed single variant linear regression slope for the entire period (12 sectors) (X_{mws})

Wind Speed Range	Measurement Height (m)	Sector Wise Mean Speed - Slope (X_{mws}) Overall (including downtime)*											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.992	1.000	0.997	0.997	0.998	1.005	0.994	0.994	0.998	1.002	1.011	1.004
	100	0.997	1.006	0.999	0.998	1.010	1.011	0.997	0.995	0.997	1.013	1.023	1.005
	80	0.998	0.997	0.994	0.995	1.004	1.013	0.998	0.990	0.993	1.009	1.032	1.009
	60	0.997	0.998	0.995	0.994	1.008	1.011	0.998	0.992	0.993	1.010	1.029	1.010
	40	0.999	0.998	0.996	0.996	1.011	1.006	0.992	0.990	0.992	1.009	1.022	1.002
b) WS >2m/s	103	0.995	0.996	0.995	0.995	0.996	1.003	0.990	0.991	0.995	1.001	1.008	1.000
	100	0.999	1.002	0.997	0.996	1.007	1.007	0.993	0.992	0.993	1.012	1.020	1.000
	80	0.999	0.995	0.994	0.995	1.002	1.011	0.995	0.988	0.990	1.007	1.027	1.004
	60	0.997	0.997	0.995	0.994	1.009	1.010	0.995	0.989	0.991	1.009	1.026	1.005
	40	0.998	0.998	0.996	0.997	1.012	1.004	0.991	0.987	0.991	1.009	1.020	0.999

* ***Green***: *Passes the best practice acceptance criteria* ***Amber***: *Meets the minimum acceptance criteria* ***Red***: *Fails the acceptance criteria*

Table F.5: Sectorwise mean wind speed single variant linear regression slope for period 1 (12 sectors) (X_{mws})

Wind Speed Range	Measurement Height (m)	Sector Wise Mean Speed - Slope (X_{mws}) Period 1 (26/11/2015 - 17/02/2016) *											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.996	1.007	1.004	1.011	1.007	1.008	0.997	0.998	0.998	1.004	1.012	1.007
	100	1.003	1.012	1.006	1.011	1.018	1.013	0.999	0.998	0.996	1.015	1.025	1.009
	80	1.001	1.007	1.000	1.008	1.023	1.014	1.000	0.993	0.993	1.011	1.032	1.016
	60	1.000	1.005	0.992	1.005	1.022	1.012	1.000	0.993	0.993	1.012	1.030	1.014
	40	0.997	1.001	0.996	0.993	1.015	1.005	0.993	0.990	0.994	1.012	1.022	1.001
b) WS >2m/s	103	0.998	1.000	1.004	1.012	1.006	1.004	0.992	0.992	0.994	1.002	1.007	0.994
	100	1.001	1.006	1.007	1.012	1.017	1.008	0.995	0.992	0.992	1.013	1.020	0.994
	80	1.002	0.996	1.001	1.008	1.024	1.011	0.996	0.988	0.990	1.008	1.026	0.998
	60	1.000	0.996	0.993	1.005	1.021	1.010	0.996	0.989	0.991	1.010	1.025	0.999
	40	0.995	0.998	0.996	0.994	1.015	1.003	0.991	0.987	0.992	1.011	1.019	0.994

* ***Green***: *Passes the best practice acceptance criteria* ***Amber***: *Meets the minimum acceptance criteria* ***Red***: *Fails the acceptance criteria*

Table F.6: Sectorwise mean wind speed single variant linear regression slope for period 2 (12 sectors) (X_{mws})

Wind Speed Range	Measurement Height (m)	Sector Wise Mean Speed - Slope (X_{mws}) Period 2 (12/03/2016 - 06/07/2016) *											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.992	0.999	0.996	0.996	0.994	0.996	0.989	0.990	0.998	0.997	1.009	1.004
	100	0.997	1.005	0.999	0.997	1.006	1.004	0.993	0.991	0.998	1.009	1.020	1.004
	80	0.998	0.995	0.993	0.993	0.998	1.010	0.994	0.988	0.992	1.004	1.030	1.007
	60	0.997	0.997	0.995	0.993	1.002	1.010	0.994	0.991	0.991	1.004	1.029	1.008
	40	0.999	0.998	0.995	0.997	1.009	1.007	0.992	0.990	0.989	1.001	1.021	1.002
b) WS >2m/s	103	0.995	0.995	0.993	0.994	0.991	0.997	0.984	0.989	0.996	0.997	1.010	1.004
	100	0.999	1.001	0.996	0.995	1.002	1.005	0.990	0.991	0.996	1.009	1.021	1.004
	80	0.999	0.995	0.993	0.993	0.996	1.011	0.992	0.987	0.990	1.004	1.030	1.007
	60	0.997	0.997	0.995	0.993	1.003	1.011	0.992	0.990	0.990	1.004	1.028	1.009
	40	0.998	0.998	0.996	0.997	1.009	1.006	0.991	0.988	0.989	1.001	1.023	1.001

* ***Green***: *Passes the best practice acceptance criteria* ***Amber***: *Meets the minimum acceptance criteria* ***Red***: *Fails the acceptance criteria*

Table F.7: Sectorwise mean wind speed single variant linear regression R^2 for the overall period (12 sectors) (R^2_{mws})

Wind Speed Range	Measurement Height (m)	Sector Wise Mean Wind Speed - Coefficient of Determination (R^2_{mws}) Overall (including downtime)*											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.977	0.983	0.986	0.990	0.990	0.992	0.991	0.989	0.986	0.991	0.990	0.987
	100	0.979	0.984	0.986	0.991	0.990	0.992	0.991	0.989	0.987	0.990	0.991	0.987
	80	0.986	0.986	0.986	0.991	0.989	0.993	0.992	0.988	0.988	0.991	0.991	0.988
	60	0.986	0.985	0.986	0.992	0.988	0.992	0.992	0.989	0.989	0.989	0.991	0.987
	40	0.985	0.985	0.987	0.992	0.988	0.991	0.991	0.989	0.989	0.990	0.990	0.988
b) WS >2m/s	103	0.986	0.989	0.989	0.993	0.994	0.994	0.995	0.994	0.993	0.995	0.995	0.992
	100	0.987	0.989	0.989	0.993	0.993	0.994	0.995	0.994	0.994	0.994	0.995	0.992
	80	0.991	0.990	0.989	0.993	0.992	0.995	0.995	0.993	0.994	0.994	0.995	0.993
	60	0.991	0.990	0.989	0.994	0.991	0.994	0.995	0.993	0.993	0.994	0.995	0.992
	40	0.990	0.989	0.991	0.993	0.991	0.994	0.994	0.993	0.993	0.994	0.995	0.993

* *Green: Passes the best practice acceptance criteria Amber: Meets the minimum acceptance criteria Red: Fails the acceptance criteria*

Table F.8: Sectorwise mean wind speed single variant linear regression R^2 for period 1 (12 sectors) (R^2_{mws})

Wind Speed Range	Measurement Height (m)	Sector Wise Mean Wind Speed - Coefficient of Determination (R^2_{mws}) Period 1 (26/11/2015 - 17/02/2016) *											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.987	0.992	0.976	0.993	0.995	0.990	0.986	0.980	0.979	0.983	0.987	0.990
	100	0.984	0.992	0.978	0.994	0.995	0.990	0.986	0.981	0.981	0.982	0.987	0.991
	80	0.983	0.990	0.980	0.993	0.994	0.991	0.986	0.981	0.980	0.983	0.984	0.989
	60	0.984	0.988	0.973	0.993	0.992	0.989	0.986	0.980	0.982	0.981	0.983	0.987
	40	0.984	0.990	0.967	0.993	0.990	0.988	0.983	0.980	0.983	0.982	0.983	0.989
b) WS >2m/s	103	0.989	0.993	0.989	0.995	0.995	0.991	0.991	0.989	0.989	0.991	0.994	0.992
	100	0.989	0.993	0.990	0.995	0.995	0.991	0.991	0.989	0.990	0.991	0.993	0.992
	80	0.988	0.992	0.991	0.995	0.994	0.993	0.989	0.989	0.989	0.990	0.993	0.992
	60	0.988	0.992	0.989	0.995	0.993	0.991	0.989	0.987	0.988	0.989	0.993	0.992
	40	0.986	0.992	0.987	0.994	0.992	0.990	0.988	0.986	0.988	0.988	0.992	0.993

* *Green: Passes the best practice acceptance criteria Amber: Meets the minimum acceptance criteria Red: Fails the acceptance criteria*

Table F.9: Sectorwise mean wind speed single variant linear regression R^2 for period 2 (12 sectors) (R^2_{mws})

Wind Speed Range	Measurement Height (m)	Sector Wise Mean Wind Speed - Coefficient of Determination (R^2_{mws}) Period 2 (12/03/2016 - 06/07/2016) *											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.976	0.980	0.986	0.990	0.987	0.991	0.992	0.991	0.986	0.992	0.989	0.986
	100	0.978	0.981	0.986	0.990	0.987	0.990	0.991	0.991	0.986	0.991	0.991	0.986
	80	0.986	0.984	0.986	0.991	0.989	0.990	0.994	0.990	0.989	0.992	0.992	0.988
	60	0.986	0.983	0.986	0.993	0.987	0.989	0.994	0.990	0.988	0.992	0.992	0.987
	40	0.985	0.982	0.988	0.992	0.983	0.987	0.993	0.991	0.988	0.992	0.991	0.988
b) WS >2m/s	103	0.986	0.987	0.989	0.992	0.993	0.995	0.996	0.994	0.991	0.994	0.994	0.990
	100	0.986	0.987	0.989	0.993	0.993	0.994	0.996	0.994	0.991	0.993	0.994	0.990
	80	0.991	0.987	0.989	0.993	0.992	0.992	0.997	0.993	0.993	0.994	0.994	0.991
	60	0.991	0.987	0.989	0.994	0.990	0.992	0.997	0.993	0.993	0.994	0.994	0.991
	40	0.989	0.986	0.991	0.993	0.989	0.993	0.996	0.993	0.993	0.994	0.994	0.991

* ***Green***: *Passes the best practice acceptance criteria* ***Amber***: *Meets the minimum acceptance criteria* ***Red***: *Fails the acceptance criteria*

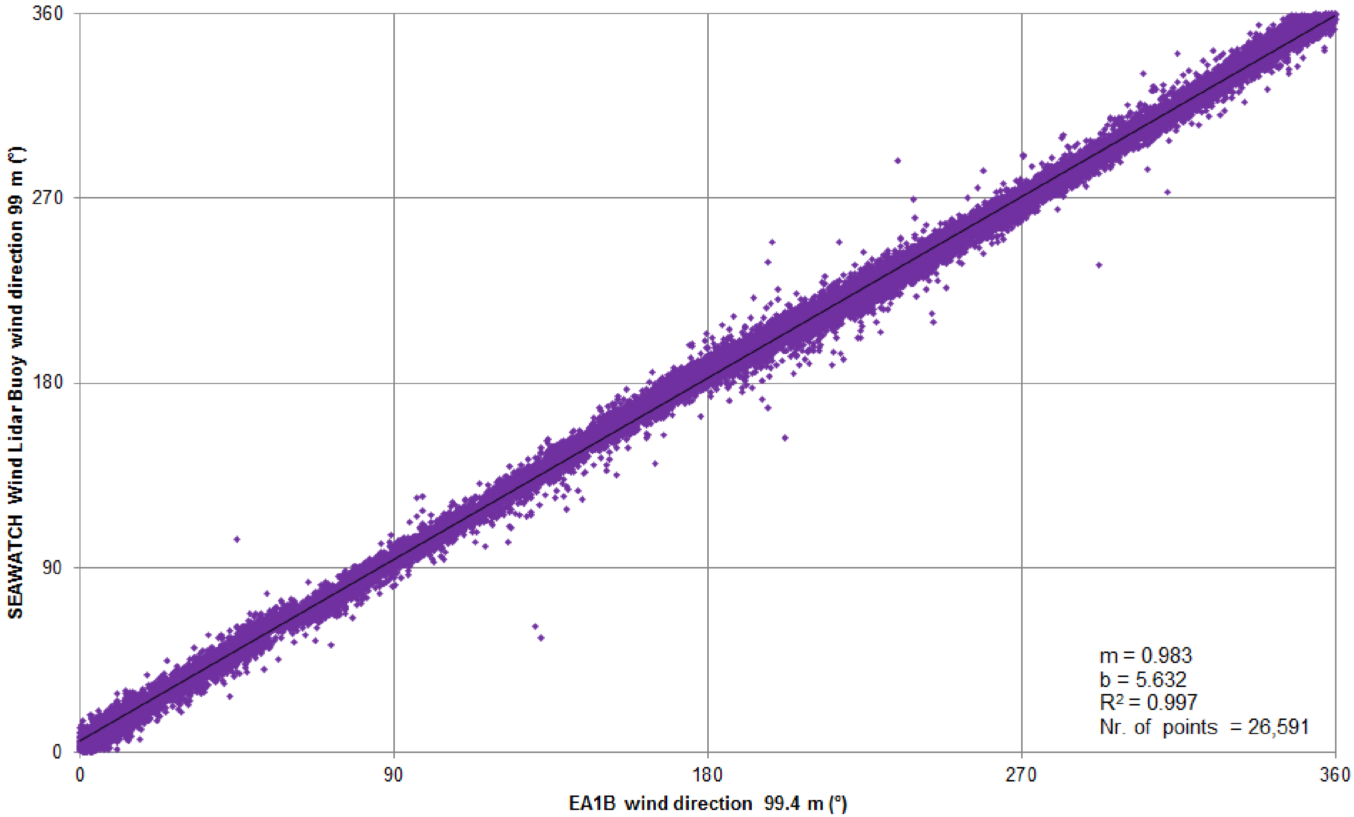


Figure F.5: Correlation plot of 10-minute horizontal wind direction SEAWATCH Wind Lidar Buoy 99 m vs EA1B Mast 99.4 m for wind speeds greater than 2 m/s (entire period)

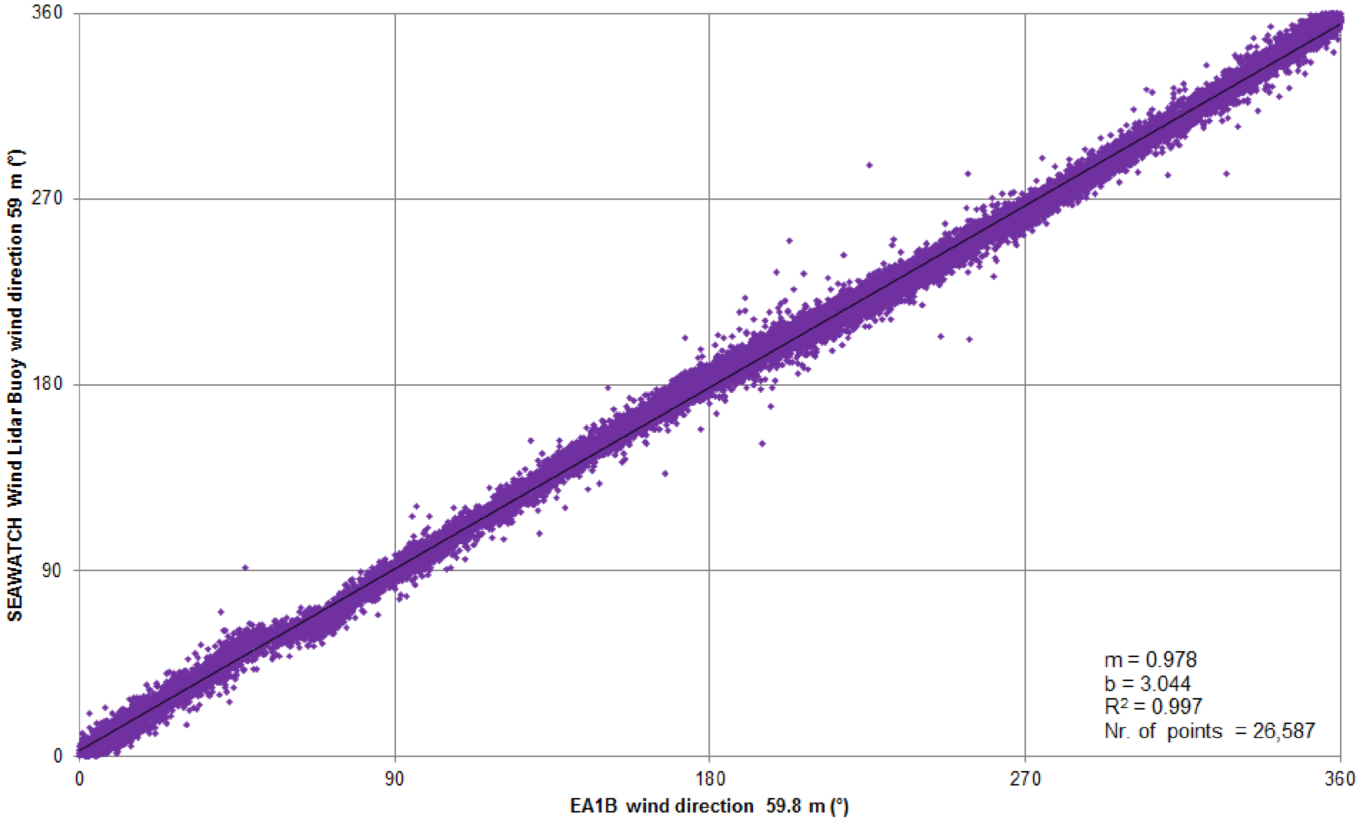


Figure F.6: **Correlation plot of 10-minute horizontal wind direction SEAWATCH Wind Lidar Buoy 59 m vs EA1B Mast 59.8 m for wind speeds greater than 2 m/s (entire period)**

Table F.10: Mean wind direction two variant linear regression slope, offset and R^2 (wind directions with wraparound from 0° to 360° and from 10° to 350°) (M_{mwd}, OFF_{mwd}, R^2_{mwd})

KPI Definition Acceptance Criteria	Measurement Height (m)	WS>2 m/s Sectors 0 - 360			WS>2 m/s Sectors 10 - 350		
		Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)	Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
M_{mwd}	103	0.912	0.923	0.907	0.977	0.954	0.985
Mean Wind Direction – Slope	100	0.910	0.923	0.905	0.979	0.957	0.986
Analysis applied to all wind directions for all wind speeds above 2 m/s	80	0.912	0.920	0.911	0.976	0.954	0.984
	60	0.902	0.910	0.901	0.972	0.947	0.980
Best Practice: 0.97 - 1.03 Minimum: 0.95 - 1.05	40	0.901	0.915	0.894	0.976	0.952	0.985
OFF_{mwd}	103	18.612	17.716	18.427	6.994	11.394	6.049
Mean Wind Direction - Offset (absolute value)	100	18.677	17.079	18.690	6.552	10.720	5.659
Analysis applied to all wind directions for all wind speeds above 2 m/s	80	17.279	14.808	17.883	2.975	7.312	1.999
	60	19.733	17.194	20.364	4.245	9.106	3.132
Best Practice: < 5° Minimum: < 10°	40	17.755	17.090	17.284	5.845	9.950	5.062
$R2_{mwd}$	103	0.852	0.910	0.837	0.993	0.990	0.994
Mean Wind Direction - Coefficient of Determination	100	0.849	0.903	0.834	0.995	0.994	0.996
Analysis applied to all wind directions for all wind speeds above 2 m/s	80	0.869	0.923	0.854	0.996	0.994	0.997
	60	0.856	0.914	0.840	0.996	0.993	0.997
Best Practice: < 0.97 Minimum: < 0.95	40	0.828	0.898	0.810	0.993	0.994	0.993

* ***Green****: Passes the best practice acceptance criteria* ***Amber****: Meets the minimum acceptance criteria* ***Red****: Fails the acceptance criteria*

Table F.11: Sectorwise Turbulence intensity single variant linear regression slope for the overall period (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 120° anemometers) (X_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Slope (EA1B 120°) (X_{TI}) Overall (including downtime)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	2.139	2.137	2.226	2.001	1.797	1.886	2.033	2.243	2.325	2.445	2.001	1.854
	100	2.104	2.107	2.214	2.022	1.811	1.892	2.027	2.228	2.291	1.323	1.083	1.974
	80	2.107	2.044	2.200	2.035	1.786	1.810	2.051	2.178	2.246	2.097	1.168	1.933
	60	2.073	2.035	2.056	2.034	1.685	1.781	2.048	2.143	2.190	1.757	1.036	1.863
	40	1.994	1.921	1.939	1.884	1.676	1.818	1.931	1.989	2.150	1.972	1.404	1.890
b) WS >2m/s	103	2.165	2.122	2.236	1.918	1.750	1.836	2.117	2.432	2.495	2.407	1.940	1.941
	100	2.122	2.098	2.220	1.918	1.755	1.830	2.106	2.405	2.433	1.327	1.083	2.042
	80	2.114	2.052	2.132	1.925	1.722	1.747	2.047	2.325	2.415	2.072	1.187	1.989
	60	2.096	2.049	2.031	1.880	1.646	1.739	2.063	2.268	2.344	1.750	1.034	1.928
	40	2.015	1.883	1.912	1.748	1.624	1.770	1.948	2.132	2.297	1.919	1.430	1.980

Table F.12: Sectorwise Turbulence intensity single variant linear regression slope for the period 1 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 120° anemometers) (X_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Slope (EA1B 120°) (X_{TI}) Period 1 (26/11/2015 - 17/02/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	2.729	2.272	2.290	2.154	1.881	2.106	2.089	2.376	2.511	2.673	2.347	2.224
	100	2.621	2.178	2.276	2.261	1.915	2.108	2.077	2.370	2.486	1.363	1.218	2.535
	80	2.840	2.082	2.322	2.115	1.912	2.025	2.139	2.295	2.459	2.206	1.248	2.339
	60	2.726	2.159	2.061	2.014	1.849	1.974	2.109	2.293	2.368	1.833	1.120	2.244
	40	2.754	2.092	2.091	2.077	1.761	1.899	2.023	2.144	2.347	2.109	1.521	2.409
b) WS >2m/s	103	2.837	2.267	2.055	1.816	1.713	2.107	2.281	2.656	2.888	2.625	2.233	2.611
	100	2.709	2.190	2.037	1.887	1.754	2.104	2.272	2.622	2.823	1.431	1.218	2.846
	80	2.896	2.120	2.071	1.760	1.733	2.013	2.260	2.507	2.797	2.209	1.288	2.537
	60	2.837	2.183	1.846	1.712	1.667	1.946	2.208	2.459	2.652	1.859	1.133	2.404
	40	2.825	2.054	1.855	1.723	1.602	1.875	2.077	2.363	2.532	2.075	1.584	2.694

Table F.13: Sectorwise Turbulence intensity single variant linear regression slope for the period 2 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 120° anemometers) (X_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Slope (EA1B 120°) (X_{TI}) Period 2 (12/03/2016 - 06/07/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	2.002	2.080	2.210	1.952	1.695	1.487	1.915	2.087	2.115	2.009	1.715	1.777
	100	1.984	2.078	2.199	1.948	1.689	1.496	1.922	2.061	2.065	1.206	0.924	1.865
	80	1.965	2.029	2.170	2.014	1.671	1.390	1.879	2.034	1.980	1.860	1.052	1.826
	60	1.946	1.990	2.055	2.039	1.544	1.378	1.926	1.968	1.942	1.579	0.910	1.765
	40	1.836	1.862	1.908	1.832	1.591	1.598	1.765	1.796	1.842	1.671	1.267	1.789
b) WS >2m/s	103	2.014	2.054	2.290	1.960	1.794	1.503	1.813	1.997	1.909	1.979	1.679	1.761
	100	1.991	2.055	2.275	1.931	1.756	1.496	1.800	1.982	1.852	1.107	0.940	1.832
	80	1.966	2.022	2.151	1.983	1.710	1.400	1.704	1.963	1.784	1.779	1.062	1.801
	60	1.952	1.994	2.091	1.936	1.626	1.405	1.793	1.909	1.770	1.515	0.913	1.761
	40	1.842	1.821	1.926	1.756	1.646	1.564	1.707	1.710	1.813	1.606	1.263	1.789

Table F.14: Sectorwise Turbulence intensity single variant linear regression R^2 for the overall period (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 120° anemometers) (R^2_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Correlation Co-efficient (EA1B 120°) (R^2_{TI}) Overall (including downtime)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.143	0.298	-0.025	-0.198	-0.057	0.069	-0.268	-0.230	-0.058	0.032	-0.096	-0.308
	100	0.137	0.263	0.028	-0.105	-0.001	0.018	-0.240	-0.172	-0.050	-0.599	-0.166	-0.226
	80	0.218	0.223	0.175	-0.225	0.009	-0.033	-0.123	-0.150	-0.024	-0.136	-0.237	-0.200
	60	0.240	0.322	0.179	-0.093	0.104	-0.120	-0.033	-0.042	-0.001	-0.398	-0.172	-0.268
	40	0.365	0.366	0.341	0.203	0.308	0.237	0.081	0.085	0.049	-0.106	-0.234	-0.076
b) WS >2m/s	103	0.103	0.200	-0.011	-0.216	-0.144	-0.056	-0.282	0.005	-0.033	-0.049	-0.142	-0.129
	100	0.096	0.161	0.009	-0.166	-0.094	-0.105	-0.269	0.030	-0.051	-0.703	-0.117	-0.105
	80	0.150	0.141	0.087	-0.246	-0.023	-0.095	-0.233	0.016	-0.008	-0.243	-0.175	-0.148
	60	0.201	0.212	0.068	-0.088	-0.002	-0.058	-0.114	0.080	0.011	-0.461	-0.155	-0.156
	40	0.281	0.249	0.214	0.053	0.182	0.265	0.037	0.122	0.102	-0.215	-0.144	0.031

Table F.15: Sectorwise Turbulence intensity single variant linear regression R^2 for the period 1 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 120° anemometers) (R^2_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Correlation Co-efficient (EA1B 120°) (R^2_{TI}) Period 1 (26/11/2015 - 17/02/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.487	0.044	-0.083	-1.019	-0.306	-0.096	-0.386	-0.236	-0.191	0.004	0.006	0.036
	100	0.509	-0.032	0.120	-0.667	-0.481	-0.229	-0.366	-0.209	-0.100	-0.700	-0.128	0.084
	80	0.584	-0.026	-0.080	-1.455	-0.512	0.013	-0.284	-0.192	-0.052	-0.243	-0.305	0.035
	60	0.481	0.044	0.141	-1.706	-0.681	-0.293	-0.231	-0.098	-0.053	-0.546	-0.215	0.048
	40	0.558	0.010	0.253	-0.635	-0.514	-0.010	-0.124	-0.013	-0.033	-0.229	-0.228	0.183
b) WS >2m/s	103	0.430	-0.165	-0.278	-1.596	-0.715	-0.112	-0.413	-0.048	-0.053	-0.111	-0.174	-0.105
	100	0.459	-0.258	-0.068	-1.250	-0.832	-0.221	-0.408	-0.036	-0.034	-0.799	-0.141	-0.029
	80	0.505	-0.206	-0.285	-1.994	-0.734	0.011	-0.316	-0.052	0.039	-0.366	-0.314	-0.159
	60	0.405	-0.152	-0.017	-2.153	-0.848	-0.027	-0.235	0.018	0.051	-0.631	-0.246	-0.175
	40	0.493	-0.143	0.011	-1.273	-0.659	0.193	-0.127	0.067	0.059	-0.342	-0.190	0.044

Table F.16: Sectorwise Turbulence intensity single variant linear regression R^2 for the period 2 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 120° anemometers) (R^2_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Correlation Co-efficient (EA1B 120°) (R^2_{TI}) Period 2 (12/03/2016 - 06/07/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	-1.020	-0.238	-0.456	-0.532	-1.030	0.062	-1.096	-1.177	-0.148	-0.451	-0.900	-1.119
	100	-0.945	-0.244	-0.415	-0.477	-0.811	0.098	-1.018	-1.008	-0.383	-2.436	-1.459	-1.006
	80	-0.783	-0.314	-0.110	-0.453	-0.700	-0.610	-0.583	-1.095	-0.371	-0.857	-0.937	-1.107
	60	-0.489	-0.128	-0.082	-0.228	-0.186	-0.758	-0.387	-0.783	-0.255	-1.482	-0.718	-1.324
	40	-0.204	0.093	0.154	-0.004	0.158	0.010	-0.117	-0.343	-0.046	-0.672	-0.948	-0.685
b) WS >2m/s	103	-0.610	-0.282	-0.080	-0.356	-0.366	0.012	-0.682	-0.842	-0.176	-0.262	-0.322	-0.705
	100	-0.613	-0.236	-0.084	-0.364	-0.390	0.003	-0.631	-0.625	-0.355	-1.729	-0.610	-0.787
	80	-0.513	-0.237	-0.057	-0.256	-0.384	-0.213	-0.466	-0.717	-0.439	-0.729	-0.119	-0.878
	60	-0.365	-0.086	0.006	-0.080	-0.106	-0.286	-0.391	-0.584	-0.577	-1.122	-0.185	-0.868
	40	-0.144	0.006	0.146	-0.032	0.112	0.107	-0.081	-0.364	-0.062	-0.532	-0.398	-0.501

Table F.17: Sectorwise Turbulence intensity single variant linear regression slope for the overall period (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 300° anemometers) (X_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Slope (EA1B 300°) (X_{TI}) Overall (including downtime)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	2.092	2.113	2.188	1.969	1.538	1.852	1.980	2.191	2.290	2.420	2.306	1.985
	100	2.075	2.081	2.160	1.911	0.844	1.274	1.964	2.168	2.254	2.399	2.277	1.991
	80	2.061	2.004	2.112	2.011	1.045	1.188	1.974	2.107	2.183	2.332	2.268	1.996
	60	2.016	1.993	2.021	2.006	1.001	1.225	1.977	2.084	2.125	2.293	2.216	1.934
	40	1.957	1.880	1.898	1.871	1.245	1.607	1.895	1.971	2.123	2.280	2.095	1.874
b) WS >2m/s	103	2.115	2.094	2.206	1.897	1.538	1.817	2.066	2.385	2.459	2.364	2.138	2.064
	100	2.088	2.073	2.182	1.816	0.844	1.270	2.046	2.347	2.389	2.341	2.122	2.075
	80	2.070	2.019	2.094	1.912	1.019	1.198	2.004	2.250	2.350	2.293	2.111	2.073
	60	2.037	2.008	1.923	1.877	0.965	1.232	2.021	2.205	2.273	2.248	2.053	2.021
	40	1.970	1.848	1.875	1.731	1.179	1.587	1.923	2.080	2.244	2.188	2.014	1.955

Table F.18: Sectorwise Turbulence intensity single variant linear regression slope for the period 1 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 300° anemometers) (X_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Slope (EA1B 300°) (X_{TI}) Period 1 (26/11/2015 - 17/02/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	2.704	2.311	2.282	2.123	1.646	2.058	2.024	2.314	2.475	2.647	2.560	2.521
	100	2.607	2.186	2.253	2.108	0.943	1.360	2.002	2.287	2.443	2.604	2.515	2.678
	80	2.785	2.055	2.270	2.114	1.072	1.270	2.041	2.196	2.378	2.514	2.427	2.568
	60	2.691	2.153	2.069	1.960	1.021	1.316	2.029	2.211	2.294	2.465	2.376	2.494
	40	2.732	2.071	2.126	2.099	1.361	1.699	1.980	2.115	2.336	2.463	2.277	2.470
b) WS >2m/s	103	2.791	2.273	2.062	1.819	1.546	2.059	2.218	2.601	2.843	2.578	2.386	2.895
	100	2.678	2.193	2.052	1.764	0.924	1.399	2.192	2.547	2.744	2.539	2.358	2.969
	80	2.849	2.106	2.059	1.782	1.064	1.293	2.191	2.409	2.680	2.491	2.305	2.743
	60	2.775	2.167	1.843	1.720	0.995	1.329	2.148	2.375	2.550	2.419	2.232	2.653
	40	2.785	2.029	1.883	1.733	1.265	1.700	2.054	2.324	2.500	2.360	2.220	2.716

Table F.19: Sectorwise Turbulence intensity single variant linear regression slope for the period 2 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 300° anemometers) (X_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Slope (EA1B 300°) (X_{TI}) Period 2 (12/03/2016 - 06/07/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	1.952	2.032	2.166	1.921	1.425	1.477	1.887	2.047	2.075	1.967	2.053	1.883
	100	1.952	2.038	2.139	1.847	0.750	1.086	1.884	2.025	2.025	1.971	2.037	1.863
	80	1.921	1.985	2.073	1.984	1.017	1.000	1.843	1.994	1.926	1.973	2.067	1.855
	60	1.886	1.937	2.009	2.019	0.978	1.004	1.872	1.932	1.879	1.943	2.014	1.804
	40	1.793	1.815	1.855	1.811	1.134	1.374	1.743	1.787	1.788	1.875	1.903	1.759
b) WS >2m/s	103	1.966	2.012	2.247	1.929	1.531	1.507	1.778	1.963	1.886	1.941	1.895	1.858
	100	1.958	2.019	2.220	1.838	0.763	1.089	1.768	1.948	1.842	1.936	1.889	1.855
	80	1.925	1.981	2.104	1.956	0.973	1.037	1.689	1.925	1.772	1.909	1.887	1.859
	60	1.896	1.945	1.946	1.928	0.934	1.053	1.778	1.877	1.743	1.898	1.846	1.823
	40	1.799	1.784	1.873	1.731	1.104	1.374	1.682	1.643	1.737	1.831	1.792	1.759

Table F.20: Sectorwise Turbulence intensity single variant linear regression R^2 for the overall period (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 300° anemometers) (R^2_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Correlation Co-efficient (EA1B 300°) (R^2_{TI}) Overall (including downtime)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.165	0.323	0.021	-0.166	0.081	0.108	-0.214	-0.215	-0.042	0.051	-0.038	-0.201
	100	0.154	0.278	0.070	-0.138	-0.225	-0.464	-0.183	-0.155	-0.011	0.102	-0.061	-0.100
	80	0.238	0.246	0.159	-0.185	-0.294	-0.475	-0.072	-0.120	0.021	0.039	-0.259	-0.075
	60	0.266	0.346	0.219	-0.034	-0.002	-0.588	-0.010	-0.003	0.046	0.065	-0.238	-0.118
	40	0.377	0.389	0.342	0.231	0.294	0.118	0.098	0.127	0.067	0.115	-0.146	-0.014
b) WS >2m/s	103	0.117	0.220	0.015	-0.171	-0.021	-0.009	-0.238	0.008	-0.025	-0.032	-0.192	-0.090
	100	0.115	0.178	0.044	-0.210	-0.091	-0.502	-0.218	0.044	-0.016	0.006	-0.201	-0.044
	80	0.163	0.167	0.127	-0.208	-0.215	-0.450	-0.170	0.040	0.035	-0.045	-0.278	-0.055
	60	0.217	0.224	0.031	-0.040	0.039	-0.415	-0.067	0.100	0.048	-0.034	-0.326	-0.047
	40	0.314	0.270	0.229	0.064	0.239	0.194	0.057	0.115	0.101	-0.002	-0.184	0.057

Table F.21: Sectorwise Turbulence intensity single variant linear regression R^2 for the period 1 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 300° anemometers) (R^2_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Correlation Co-efficient (EA1B 300°) (R^2_{TI}) Period 1 (26/11/2015 - 17/02/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	0.492	0.070	-0.047	-0.919	-0.190	-0.054	-0.320	-0.213	-0.181	0.022	-0.054	0.053
	100	0.506	-0.036	0.155	-0.697	-0.362	-1.256	-0.298	-0.210	-0.078	0.065	-0.092	0.139
	80	0.586	-0.015	-0.058	-1.322	-1.307	-0.897	-0.213	-0.170	-0.021	-0.025	-0.422	0.130
	60	0.477	0.054	0.161	-1.642	-1.128	-1.298	-0.196	-0.069	-0.010	-0.020	-0.387	0.087
	40	0.563	0.038	0.263	-0.544	-0.244	-0.135	-0.110	0.016	0.003	0.039	-0.249	0.214
b) WS >2m/s	103	0.443	-0.136	-0.231	-1.425	-0.429	-0.075	-0.370	-0.050	-0.053	-0.095	-0.279	-0.010
	100	0.474	-0.233	-0.004	-1.255	-0.278	-1.230	-0.362	-0.031	-0.023	-0.053	-0.267	0.040
	80	0.509	-0.162	-0.225	-1.811	-0.925	-0.972	-0.262	-0.038	0.051	-0.118	-0.392	-0.012
	60	0.414	-0.131	-0.012	-1.989	-0.797	-0.880	-0.195	0.027	0.065	-0.140	-0.430	-0.005
	40	0.499	-0.153	-0.005	-1.260	-0.353	0.095	-0.102	0.084	0.084	-0.113	-0.232	0.098

Table F.22: Sectorwise Turbulence intensity single variant linear regression R^2 for the period 2 (12 sectors) (SEAWATCH Wind Lidar Buoy against EA1B 300° anemometers) (R^2_{TI})

Wind Speed Range	Measurement Height (m)	Sector Wise Turbulence Intensity - Correlation Co-efficient (EA1B 300°) (R^2_{TI}) Period 2 (12/03/2016 - 06/07/2016)											
		0	30	60	90	120	150	180	210	240	270	300	330
a) WS 4-16 m/s	103	-0.956	-0.191	-0.378	-0.504	-0.668	0.089	-1.009	-1.145	-0.116	-0.509	-0.768	-0.836
	100	-0.881	-0.206	-0.351	-0.538	-1.326	-0.105	-0.947	-0.935	-0.310	-0.421	-0.726	-0.752
	80	-0.699	-0.243	-0.147	-0.414	-0.994	-0.801	-0.514	-0.928	-0.305	-0.442	-0.674	-0.840
	60	-0.413	-0.057	-0.014	-0.150	-0.276	-1.148	-0.355	-0.670	-0.183	-0.333	-0.620	-0.875
	40	-0.146	0.147	0.170	0.037	0.069	-0.167	-0.083	-0.227	-0.029	-0.218	-0.448	-0.567
b) WS >2m/s	103	-0.573	-0.235	-0.058	-0.323	-0.270	0.043	-0.616	-0.810	-0.129	-0.222	-0.398	-0.587
	100	-0.568	-0.203	-0.055	-0.431	-1.037	-0.108	-0.544	-0.569	-0.256	-0.218	-0.486	-0.561
	80	-0.472	-0.200	-0.014	-0.240	-1.025	-0.351	-0.391	-0.651	-0.326	-0.347	-0.319	-0.641
	60	-0.307	-0.064	-0.051	-0.036	-0.278	-0.424	-0.309	-0.504	-0.397	-0.312	-0.386	-0.580
	40	-0.075	0.068	0.167	-0.017	0.039	0.055	-0.057	-0.519	-0.146	-0.129	-0.472	-0.413

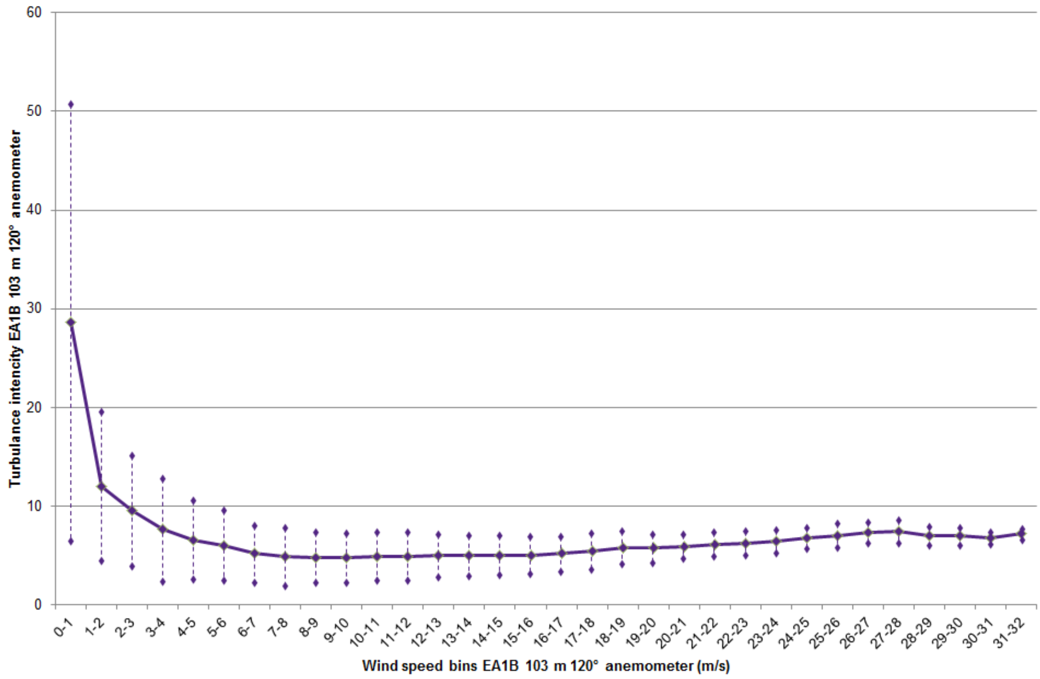


Figure F.7: Turbulence intensity from Mast EA1B 103 m (120°) anemometer against the 1 m/s wind speed bins from Mast EA1B 103 m (120°) anemometer

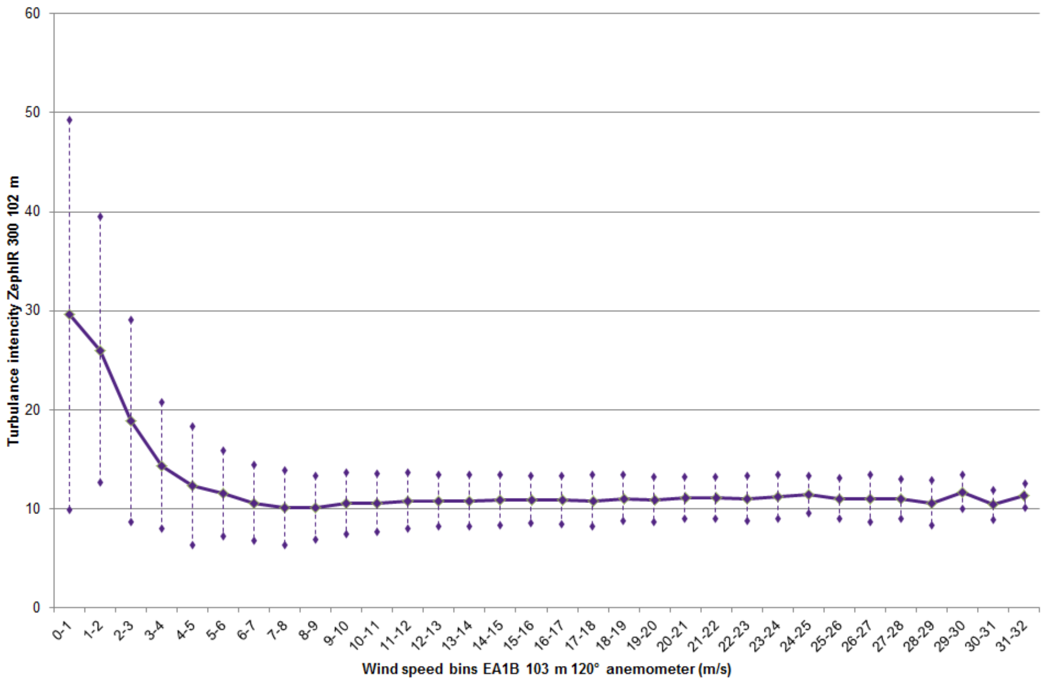


Figure F.8: Turbulence intensity from the ZephIR 300 102 m (raw ZPH) against the 1 m/s wind speed bins from Mast EA1B 103 m (120°) anemometer

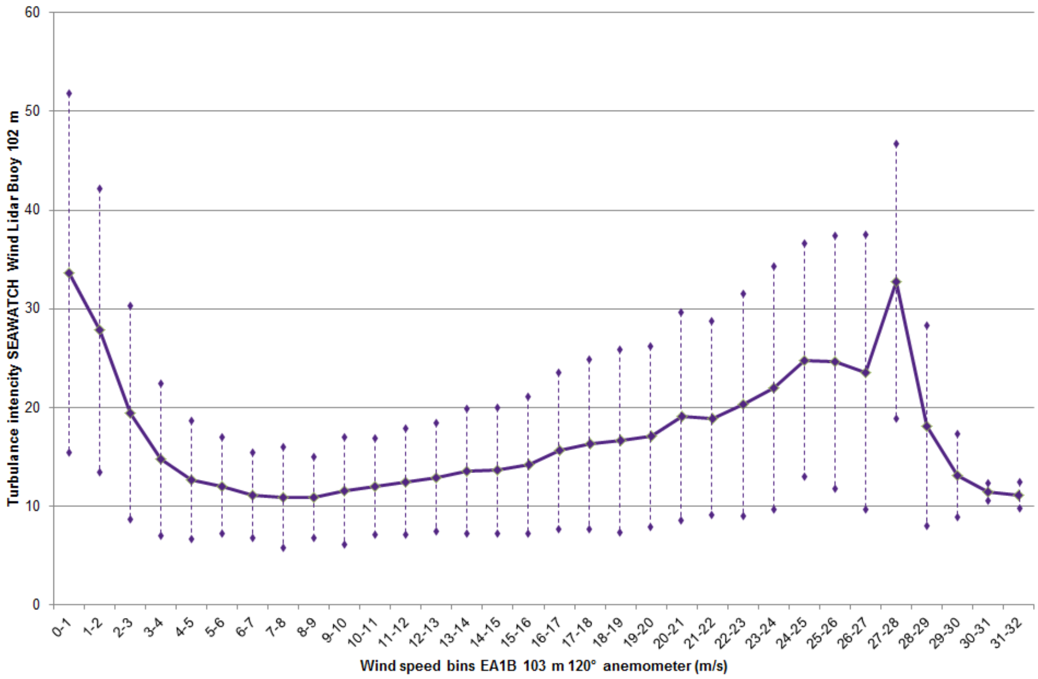


Figure F.9: Turbulence intensity from the SEAWATCH Wind Lidar Buoy against the 1 m/s wind speed bins from Mast EA1B 103 m (120°) anemometer

Table F.23: Wind speed shear exponent alpha (α)

Wind Speed Ranges	Measuring System	Wind Speed Shear (α) - Lidar 59-99 / Mast 60-100			Wind Speed Shear (α) - Lidar 59-102 / Mast 60-103		
		Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)	Overall (including downtime)	Period 1 (26/11/2015 - 17/02/2016)	Period 2 (12/03/2016 - 06/07/2016)
a) WS 4-8 m/s	Mast EA1B	0.047	0.029	0.051	0.053	0.035	0.057
	SEAWATCH Wind Lidar Buoy	0.050	0.025	0.054	0.048	0.025	0.052
b) WS 8-12 m/s	Mast EA1B	0.086	0.050	0.102	0.091	0.057	0.105
	SEAWATCH Wind Lidar Buoy	0.089	0.050	0.104	0.086	0.049	0.101
c) WS 12-16 m/s	Mast EA1B	0.109	0.078	0.154	0.112	0.082	0.157
	SEAWATCH Wind Lidar Buoy	0.108	0.077	0.154	0.107	0.078	0.151
d) WS > 2m/s	Mast EA1B	0.093	0.080	0.107	0.098	0.083	0.111
	SEAWATCH Wind Lidar Buoy	0.093	0.080	0.108	0.092	0.079	0.106

What We Do

Natural Power is a leading independent renewable energy consultancy and products provider. The company offers proactive and integrated consultancy, management and due diligence services, backed by an innovative product range, across the onshore wind, offshore wind, wave, tidal, renewable heat, solar pv and hydro sectors, whilst maintaining a strong outlook on other new and emerging renewable energy sectors.

Established in the mid 1990s, Natural Power has been at the heart of many groundbreaking projects, products and portfolios for more than two decades, assisting project developers, investors, manufacturers, research houses and other consulting companies. With its iconic Scottish headquarters, The Green House, Natural Power has expanded internationally and now employs more than 330 renewable energy experts.

Our Global Expertise

Natural Power delivers services and operates assets globally for our clients, with eleven offices across Europe and North America and agencies active in South America and AsiaPac.

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