Date 30 August 2016
Your reference WOZ150011
Our reference ECN-WIND-2016-122

Contact
T +31 224 56 4086
verhoef@ecn.nl

P.O. Box 1, 1755 ZG Petten, The Netherlands
Netherlands Enterprise Agency (RVO.nl)
Croeselaan 15
3521 BJ UTRECHT
THE NETHERLANDS

Subject Supply of Meteorological and Oceanographic data for Borssele Wind Farm Zone Period 15 June – 7 July 2016 (Lot2)

Dear Sir/Madam,

The following two Meteorological and Oceanographic data reports produced by Fugro OCEANOR AS for the newly Lot2 measurement campaign have been reviewed by ECN Wind Energy:

1. Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ) – Lot2 : Monthly Progress Report : 15 June – 7 July 2016.
   Reference No: C75339_Lot2_MPR05_R1
2. Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ) – Lot2 : Validation report : 15 June – 7 July 2016.
   Reference No: C75339_Lot2_VAL05_R1

In this period the buoy was recovered and the measurement period ended for Lot 2 on July 7, 2016

ECN has found that the above referenced reports provide a sufficient detail for potential users of the provided data to perform analysis.

Please note that the provided dataset which has been validated by ECN for Lot 2 (Period 5 , Version 1 dd. 20160811) can be retrieved via the website : www.WindOpZee.net.

.

Yours sincerely,

Hans Verhoef
Project Leader Measurements

Petten
Postbus 1
1755 ZG Petten

Westerduinweg 3
1755 LE Petten
The Netherlands

T +31 88 5 154 949
F +31 88 5 154 480
www.ecn.nl

VAT NL001752625B01
Trade register 41151233

THE NETHERLANDS ENTERPRISE AGENCY (RVO)

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ) - Lot 2
Monthly Progress Report: 15 June - 7 July 2016

Reference No: C75339_Lot2_MPR05_R1
26 August 2016

Fugro OCEANOR AS
Pirsenteret, P.O. Box 1224, Sluppen, N-7462 Trondheim, Norway
Tel: +47 73545200 Fax: +47 73545201, e-mail: trondheim@oceanor.com

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ) - Lot 2: C75339_Lot2_MPR05_R1				
Rev	**Date**	**Originator**	**Checked & Approved**	**Issue Purpose**
0	15.08.2016	Lasse Lønseth	Arve Berg	Draft report for client review
1	26.08.2016	Lasse Lønseth	Arve Berg	Final report

Rev 1 – 26 August 2016	Originator	Checked & Approved
Signed:		

This report is not to be used for contractual or engineering purposes unless the above is signed where indicated by both the originator of the report and the checker/approver and the report is designated 'FINAL'.

TABLE OF CONTENT

SUMMARY

Two Seawatch Wind Lidar buoys are deployed at the Borssele Wind Farm Zone (BWFZ) at positions labelled “Lot 1” and “Lot 2”. This report concerns Lot 2. The buoy WS156 was deployed at Lot 2 on 12 February 2016 at 15:25 UTC. The multicat type workboat Multrasalvor 3 was used for the operation.

Data collection at the Lot 2 location has been completed. The buoy was recovered 7 July 2016 at 11:35 UTC by the vessel “Dutch Power”.

The buoy has delivered data continuously since the deployment. It was agreed to terminate the data collection as soon as the fuel cans where empty. The LiDAR wind profile data end on 22 June 2016 at 18:50 when the LiDAR was shut down due to lack of fuel for the fuel cells. This fifth and last monthly report summarizes the data collected during the period 15 June – 7 July 2016, and presents the data in time series plots.

1. INTRODUCTION

The Seawatch Wind Lidar buoy with serial no. WS156 has been operated at the Borssele Wind Farm Zone (BWFZ) Lot 2 in the Dutch sector of the North Sea. The buoy was deployed on 12 February 2016 at 15:25 with the bottom mooring weight at position 51° 38.778' N, 2° 57.0846' E. The workboat Multrasalvor 3 was used for this operation.

Data collection at the Lot 2 location has been completed. The buoy was recovered 7 July 2016 at 11:35 UTC by the vessel "Dutch Power".

This report presents project progress and results during the period from 15 June 2016 at 07:30 to 7 July 2016 at 11:30, and the data which have been transmitted to shore via the Iridium satellite system in this period. The data recovery percentages for this period are also presented. The period is 22.174 days long, and within this period 7.24 days of good wind profile data were collected by the Lidar buoy. The LiDAR wind profile data end on 22 June 2016 at 18:50 when the LiDAR was shut down because all the fuel for the fuel cells had been spent. This was expected as it was agreed to terminate the data collection as soon as the fuel cans were empty.

The time reference used in this report is UTC.

2. Instrumentation and measurement configuration

The buoy is a Seawatch Wind Lidar Buoy based on the original Seawatch Wavescan buoy design with the following sensors:

- Wavesense: 3-directional wave sensor
- Xsens 3-axes motion sensor
- Gill Windsonic M acoustic wind sensor
- Vaisala PTB330A air pressure sensor
- Vaisala HMP155 air temperature and humidity sensor
- Nortek Aquadopp 600kHz current profiler.
- ZephIR 300S Lidar.

The buoy with mooring as deployed is presented in Figure 2.1.

The measurement setup is detailed in Table 2-1. Details of sensor types and serial number can be found in Appendix A.

Table 2-1 Configuration of measurements by the Seawatch Wind Lidar buoy at Borssele Wind Farm Zone (BWFZ) – Lot 2.

Instrument type	Sensor height (m)	Parameter measured	Sample height[2)] (m)	Sampling interval (s)	Averaging period (s)	Burst interval (s)	Trans-mitted?
Wavesense 3	0	Heave, pitch, roll, heading	0	0.5	Time series duration: 1024 s	600	No
		Sea state parameters (1)	0	600	1024	600	Yes
Xsens		Heave,east,north acceleration, q0,q1,q2,q3 (attitude quaternion)	0	0.5	N/A	3600	No
Gill Windsonic M	4.1	Wind speed, wind direction	4.1	1	600	600	Yes
Vaisala PTB330A	0.5	Air pressure	0.5	30	60	600	Yes
Vaisala HMP155	4.1	Air temperature Air humidity	4.1	5	60	600	Yes
Nortek Aquadopp	-1	Current speed and direction profile, water temperature (at 1 m depth)	-4 -6 … -30 (14 levels)	N/A	600	600	Yes
ZephIR 300S Lidar	2	Wind speed and direction at 10 heights (The 11th level, the so called reference level which is not configurable, is also located at 40 m and referred to as 40.0 Ref.)	30.0 40.0 40.0 ref 60.0 80.0 100.0 120.0 140.0 160.0 180.0 200.0	≈ 17.4 s[1)]	600	600	Yes

1) This is the approximate time between the beginning of one sweep of the profile and the next one, the interval may vary slightly. The ZephIR sweeps one level at a time beginning at the lowest one, and after the top level has been swept it uses some time for calculations and re-focusing back to the lowest level for a new sweep.

2) Height relative to actual sea surface.

Table 2.2 Definitions of wave parameters presented in this report

H	Individual wave height
Hmax	= Max(H): Height of the highest individual wave in the sample, measured from crest to trough
m0, m1, m2, m4, m-1, m-2	Moments of the spectrum about the origin: $\int f^k S(f)df$ where $S(f)$ is the spectral density and the wave frequency, f, is in the range 0.04 - 0.50 Hz
Hm0	Estimate of significant wave height, Hs, $Hm0 = 4\sqrt{m0}$
Tp	Period of spectral peak = $1/f_p$, The frequency/period with the highest energy
Tm01	Estimate of the average wave period; *Tm01 = m0/m1*
Tm02	Another estimate of the average wave period; $Tm02 = \sqrt{\frac{m0}{m2}}$
ThTp	Mean wave direction at the spectral peak (“The direction of most energetic waves”)
Mdir	Wave direction averaged over the whole spectrum
	Directions are given in degrees clockwise from north, giving the direction the waves come from. (0° from north, 90° from east, etc.)

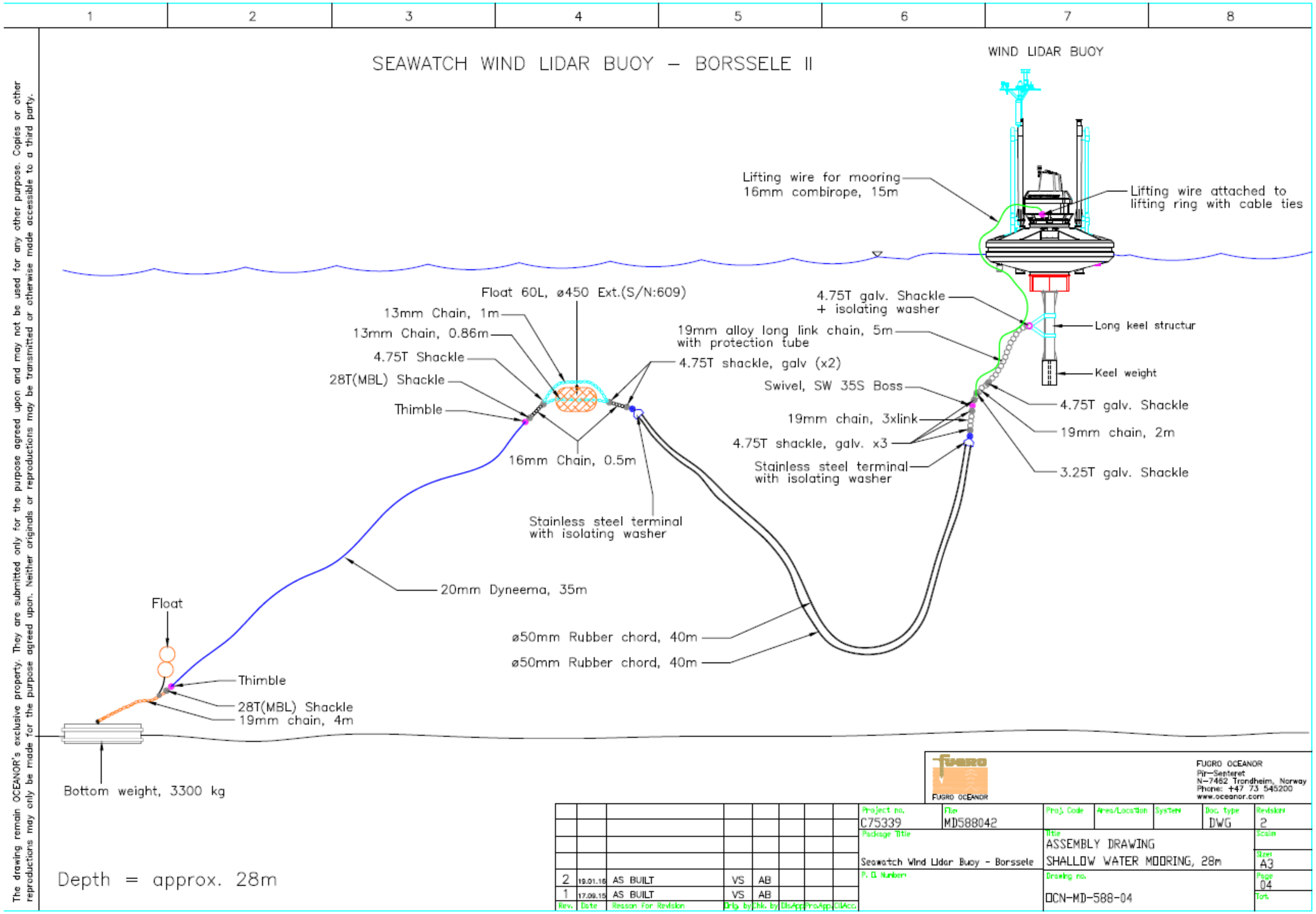

Figure 2.1 Mooring design for the Wind Lidar Buoy as deployed at Borssele Wind Farm Zone (BWFZ) Lot 2.

3. Summary of activities

3.1 Buoy operation

The Seawatch Wind Lidar buoy with serial no. WS156 was deployed at the Borssele Wind Farm Zone (BWFZ) Lot 2 in the Dutch sector of the North Sea. The buoy was deployed on 12 February 2016 at 15:25 with the bottom mooring weight at position 51° 38.778' N, 2° 57.0846' E. The workboat Multrasalvor 3 was used for this operation. The sounder depth was approximately 28 m.

Good data were received from 12 February 2016 at 16:20. This reporting period extends from 15 June 2016 at 07:30 until the end of the data collection at 11.30 on 7 July 2016. During this 22.174 day period 7.24 days of good wind profile data were collected. The LiDAR wind profile data end on 22 June 2016 at 18:50 because the power cell fuel had all been spent, and the LiDAR was shut down due to lack of power.

3.2 Health, Safety and Environment

There were no incidents, near misses or accidents in connection with the recovery operation on 7 July 2016.

4. Results

4.1 Summary of results and data return

The buoy transmitted data continuously from all sensors from 15 June 2016 at 07:30 until 11:30 on 7 July 2016, but the collection of LiDAR wind profiles ended at 18:50 on 22 June due to lack of fuel. There are a few short gaps in the Lidar data where the received data are replaced by the “missing data” flag at all or many heights. The longest gap in the wind profiles occurred from 16:10 to 18:00 on 15 June 2016. In the same period the wave sensor also dropped out.

The number of hours of good data compared to the total obtainable hours of data is presented in Table 4-1.

Table 4-1 Data return during the period 15 June 2016 at 07:30 – 7 July 2016 at 11:30.

Measurement device	Length of data period (days)	Length of data set (days)	Average availability (%)
Lidar wind profile sensor	22.174	7.229	32.57
Wave sensor	22.174	21.881	98.68
Current velocity and direction sensor	22.174	22.049	99.44
Atmospheric pressure sensor	22.174	22.063	99.50
Air temperature sensor	22.174	16.813	75.82

4.2 Presentation of the received data

The following presentations show good data transmitted from the buoy via Iridium satellite during the period 15 June 2016 at 07:30 – 7 July 2016 at 11:30, giving a total wind profile data set of 7.229 days.

4.2.1 Meteorological data

The following plots present the air pressure, air temperature, and sea surface temperature. The sensors performed well in this period.

The water temperature sensor is part of the current profile sensor, Aquadopp, and data recovery for water temperature is the same as for current profile data.

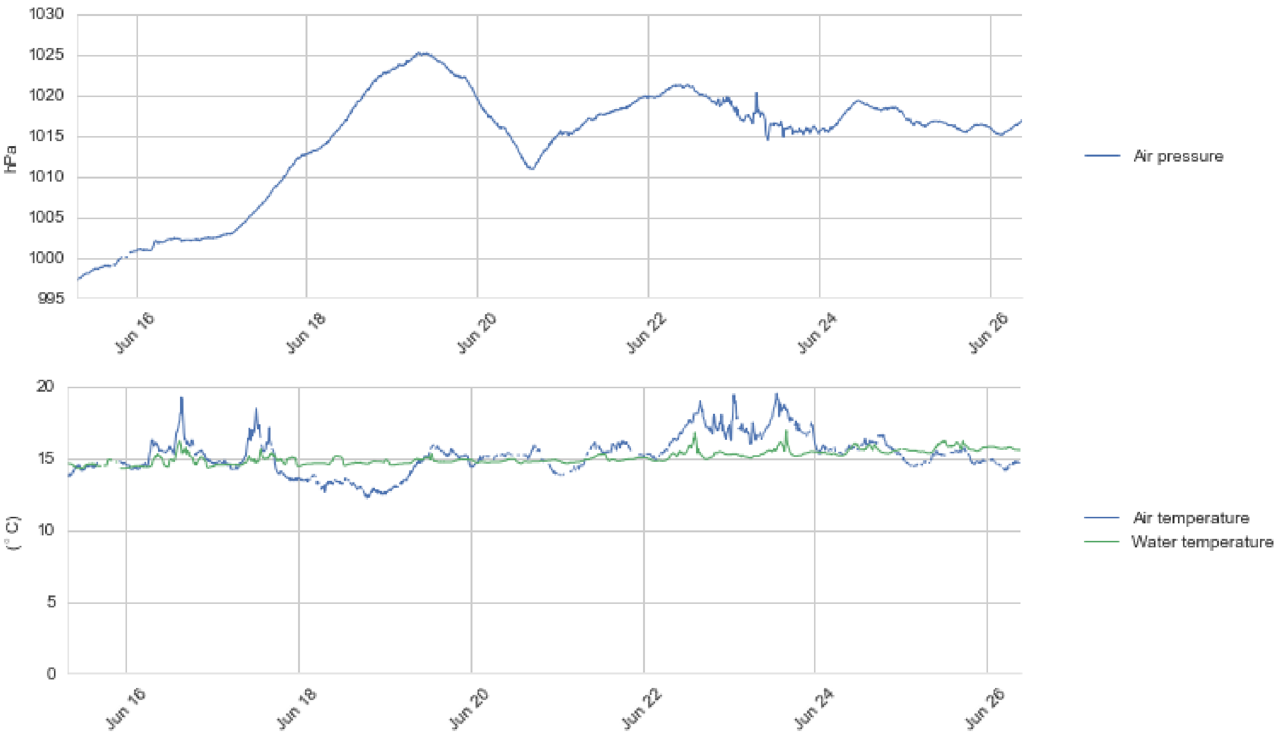

Figure 4.1 Time series plots of air pressure (upper panel), air and water temperature (lower panel), 15 - 26 Jun 2016.

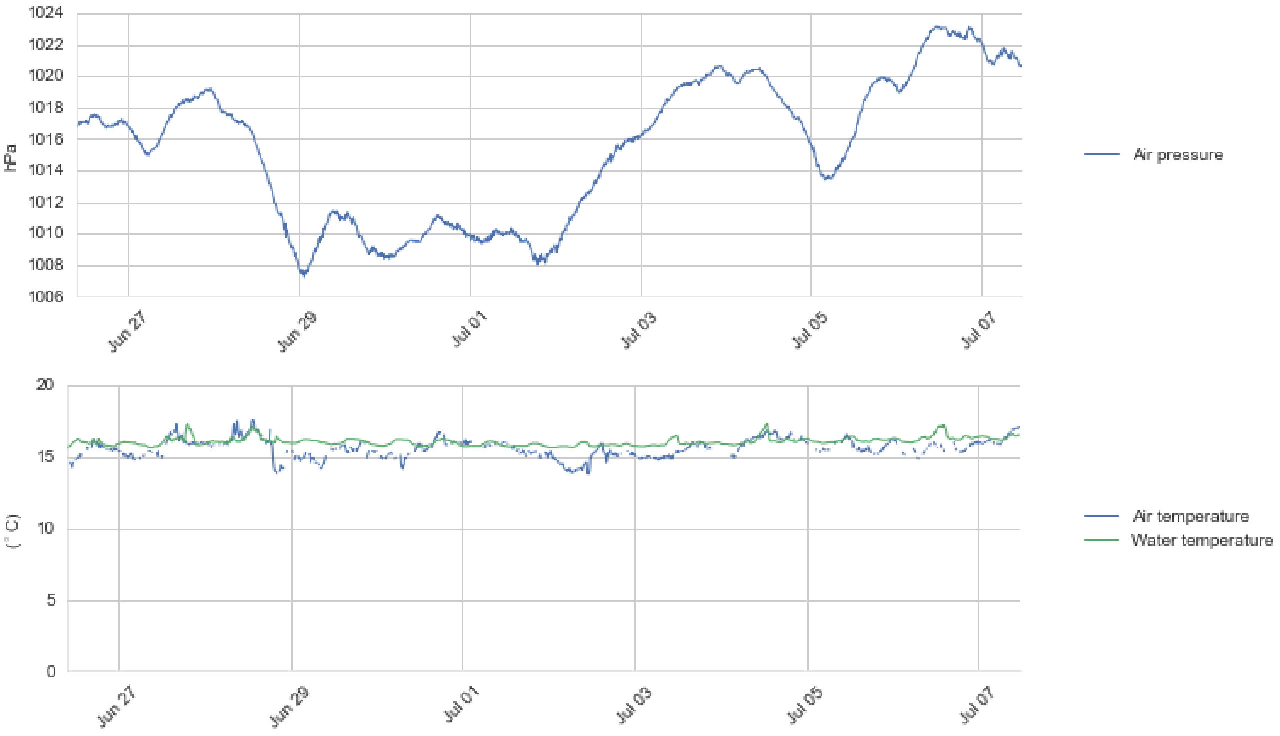

Figure 4.2 Time series plots of air pressure (upper panel), air and water temperature (lower panel), 26 Jun – 7 July 2016.

4.2.2 Wave data

The next plots present wave height, period and direction. The wave sensor has generally functioned well.

The highest significant wave height (Hm0) measured in this period was 2.48 m from a south-westerly direction (235°). This was observed on 1 July 2016 at 22:20-22:30. The highest single wave with a height of 4.63 m was observed at 8:40 on 1 July while Hm0 was 2.32 m.

The variations in wave height agree well with the observed wind speeds. The average wave period parameters Tm01 and Tm02 show semidiurnal variations which can be explained by the shift in frequency when the waves are travelling along with or opposing the current direction, since the tidal current direction varies in a semi-diurnal pattern.

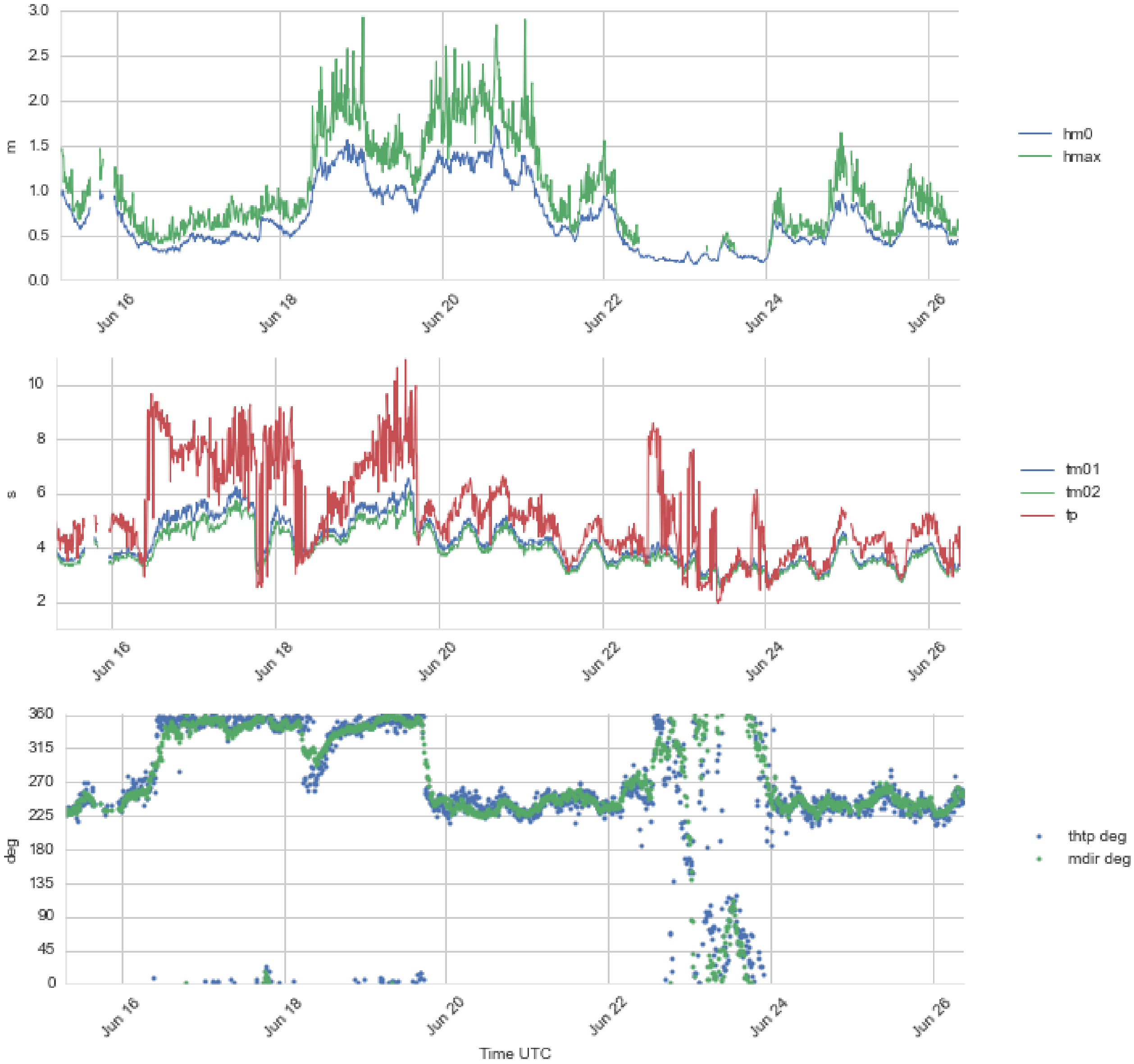

Figure 4.3 Time series plots of wave height (Hm0 and Hmax) (upper panel), wave period (Tm01, Tm02 and Tp) (second panel), and wave direction (ThTp and Mdir) (lower panel), 15 - 26 Jun 2016.

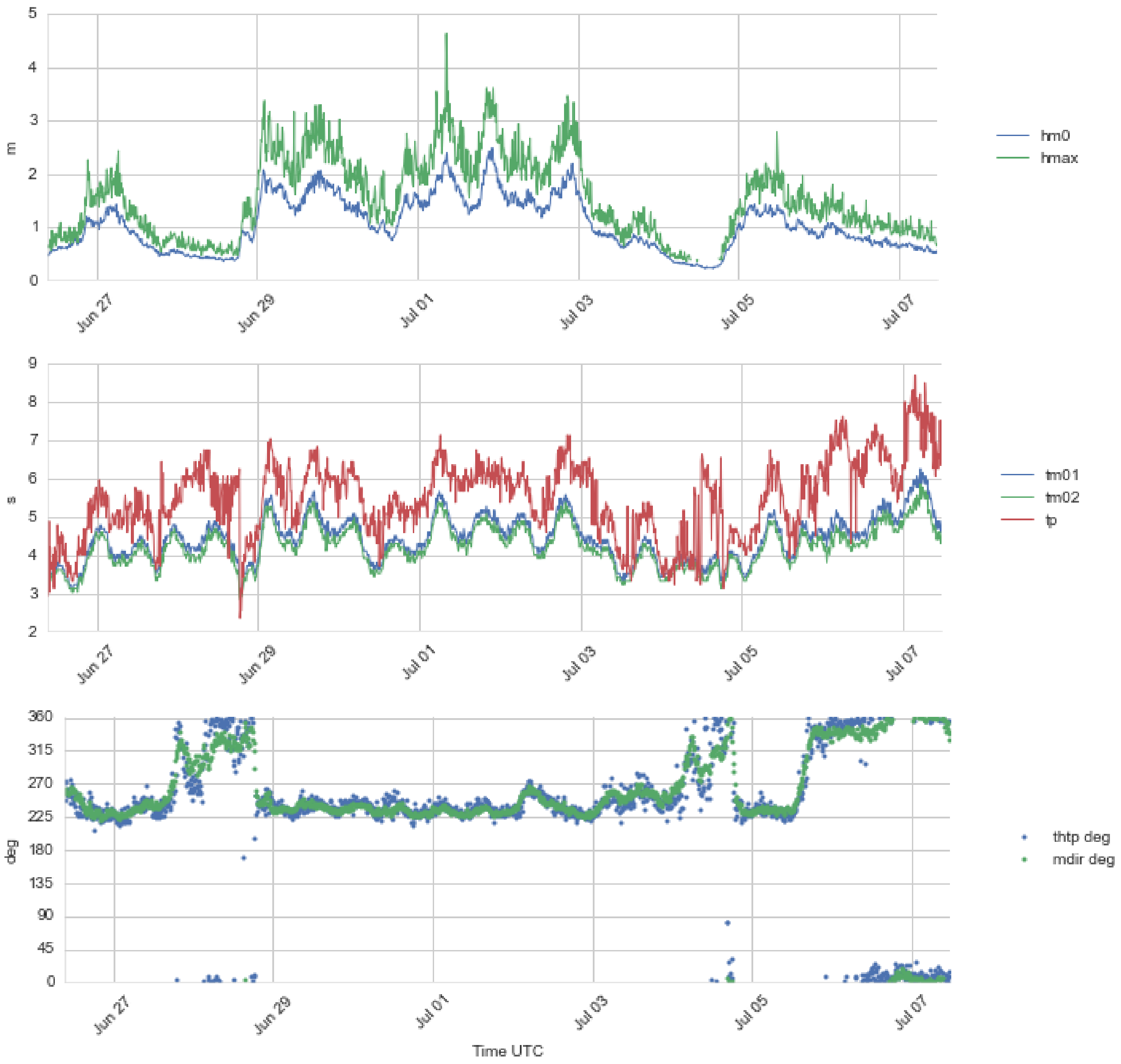

Figure 4.4 Time series plots of wave height (Hm0 and Hmax) (upper panel), wave period (Tm01, Tm02 and Tp) (second panel), and wave direction (ThTp and Mdir) (lower panel), 26 Jun – 7 Jul 2016.

4.2.3 Wind profile data

In the wind and wave direction plots 0° and 360° indicate direction from the north.

The following plots show the wind speed and direction data from the Gill wind sensor mounted at 4 m height on the buoy mast. The data from the Gill sensor are generally good without dropouts. In this period 10 min mean wind speeds up to 12.7 m/s and gusts up to 17.4 m/s were measured at 4 m above the sea surface. The average wind speed at this height was 5.2 m/s.

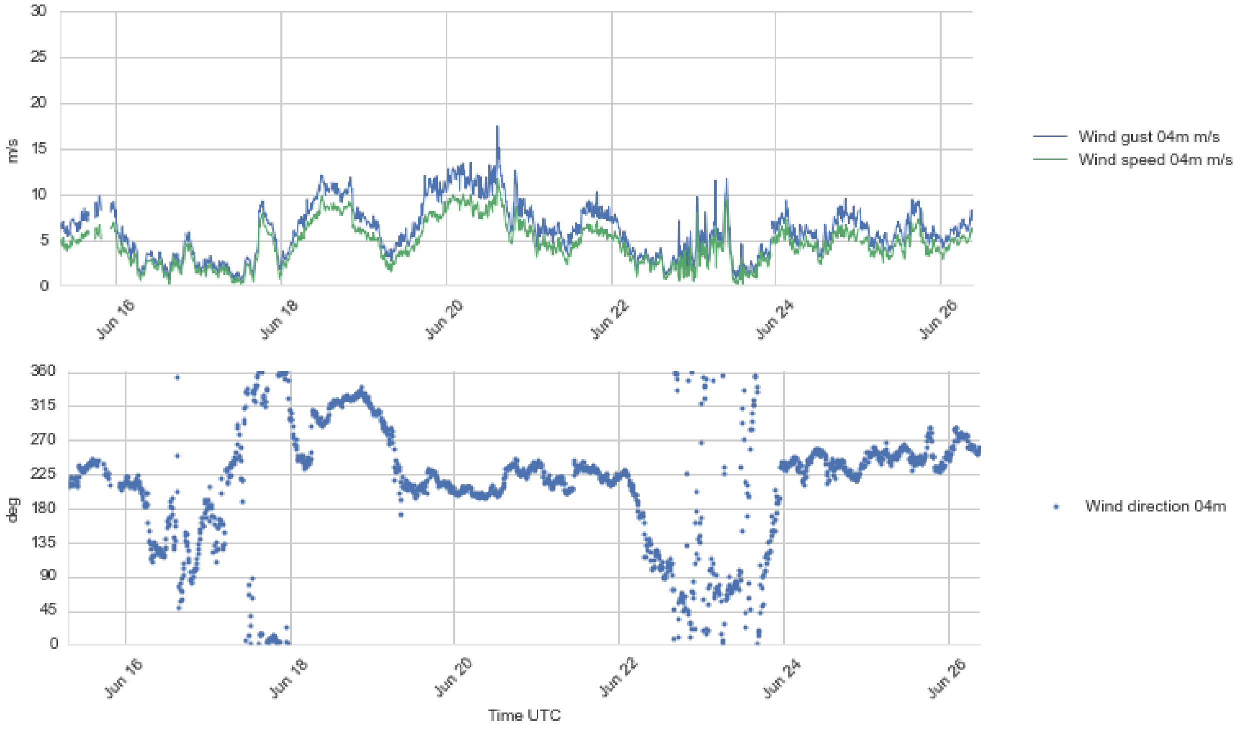

Figure 4.5 Plots of wind speed and gust (upper), and wind direction (lower) at 4 m a.s.l., 15 - 26 Jun 2016.

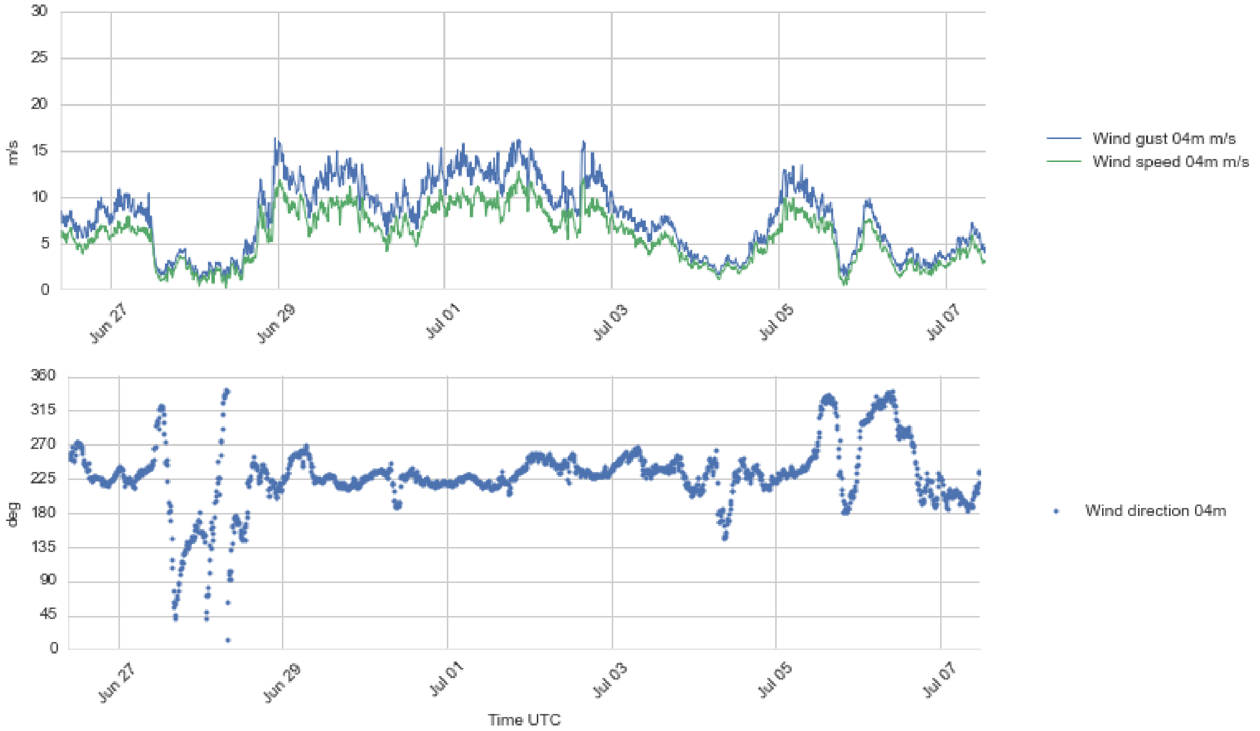

Figure 4.6 Plots of wind speed and gust (upper), and wind direction (lower) at 4 m a.s.l., 26 Jun – 7 Jul 2016.

The wind profiling data from the Lidar are presented in the following plots showing the time series of 10 min. mean wind for each individual level. Plots of the derived parameters Inflow Angle and Turbulence Intensity are also presented[1].

The Inflow Angle (IA) is the angle of the 3-dimensional wind vector based on the ten minute averaged values of the horizontal and vertical wind velocity components. IA can be positive or negative; a positive IA means that the wind vector has an upward directed vertical component. The Turbulence Intensity (TI) is defined as $TI = \sigma/\bar{u}$ where σ is the standard deviation and $\bar{u}$ is the mean of the wind speed for a 10-min period. Note that this definition frequently gives relatively high values in situations with low mean wind speed, which is noticeable in the plots.

The 180° directional ambiguity in the Lidar wind directions has largely been resolved using a correction with directions from the Gill wind sensor as ground truth.

The highest observed horizontal mean wind speed during this month varies from 13.8 m/s at 30 m to 18.6 m/s at 180 m above the surface. The maxima at all levels were measured in the evening of 30 May 2016 in a situation with north-northwesterly wind and quite homogeneous wind conditions in the profile above 30 m.

[1] TI is not included in the regular Iridium transmissions, and only received through the dialup satellite connection. Consequently, TI is missing for some periods when the dialup connection failed.

Figure 4.7 Plots of wind profile data, 30 – 60 m a.s.l., 15 - 22 Jun 2016.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

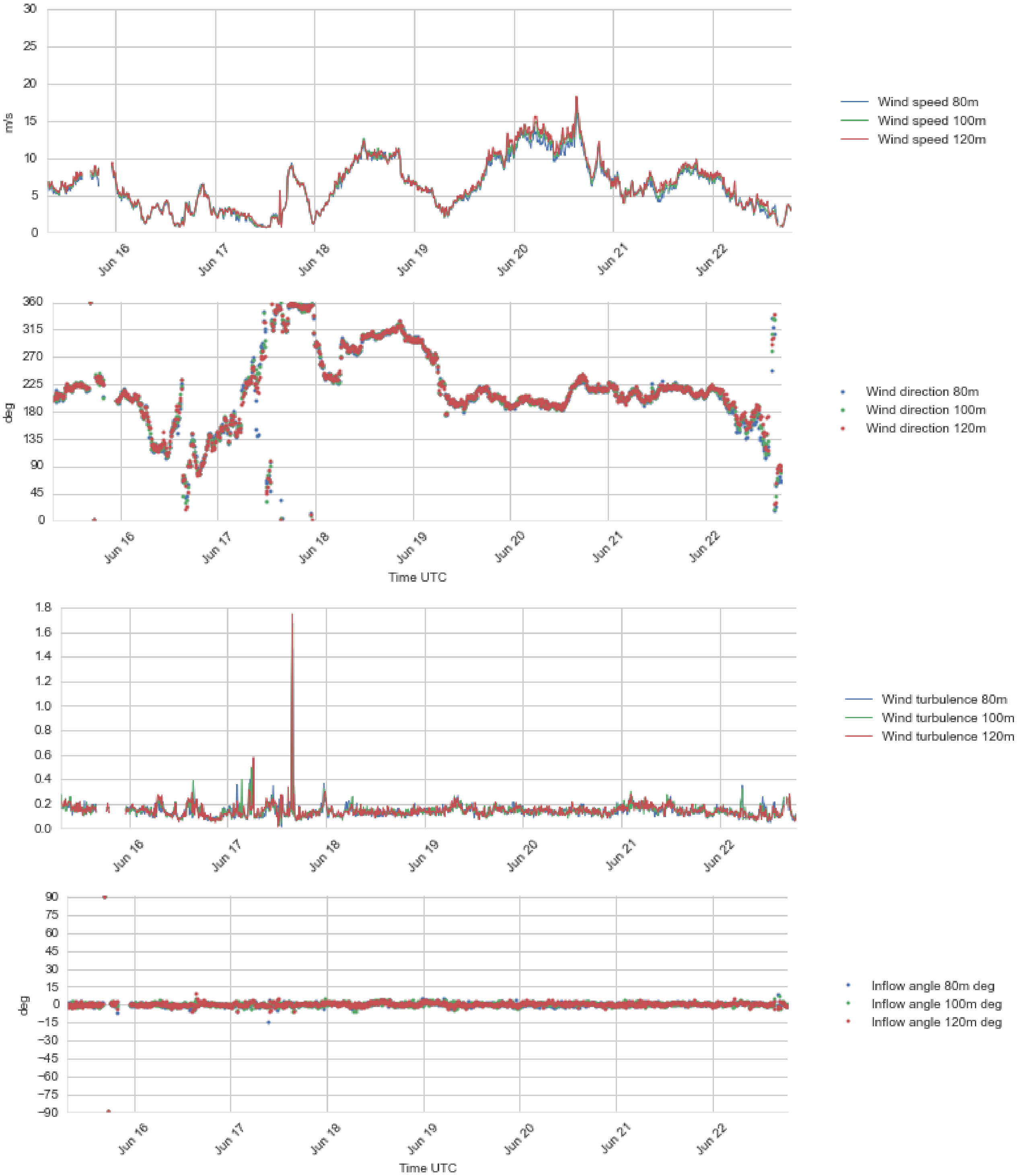

Figure 4.8 Plots of wind profile data, 80 – 120 m a.s.l., 15 - 22 Jun 2016.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

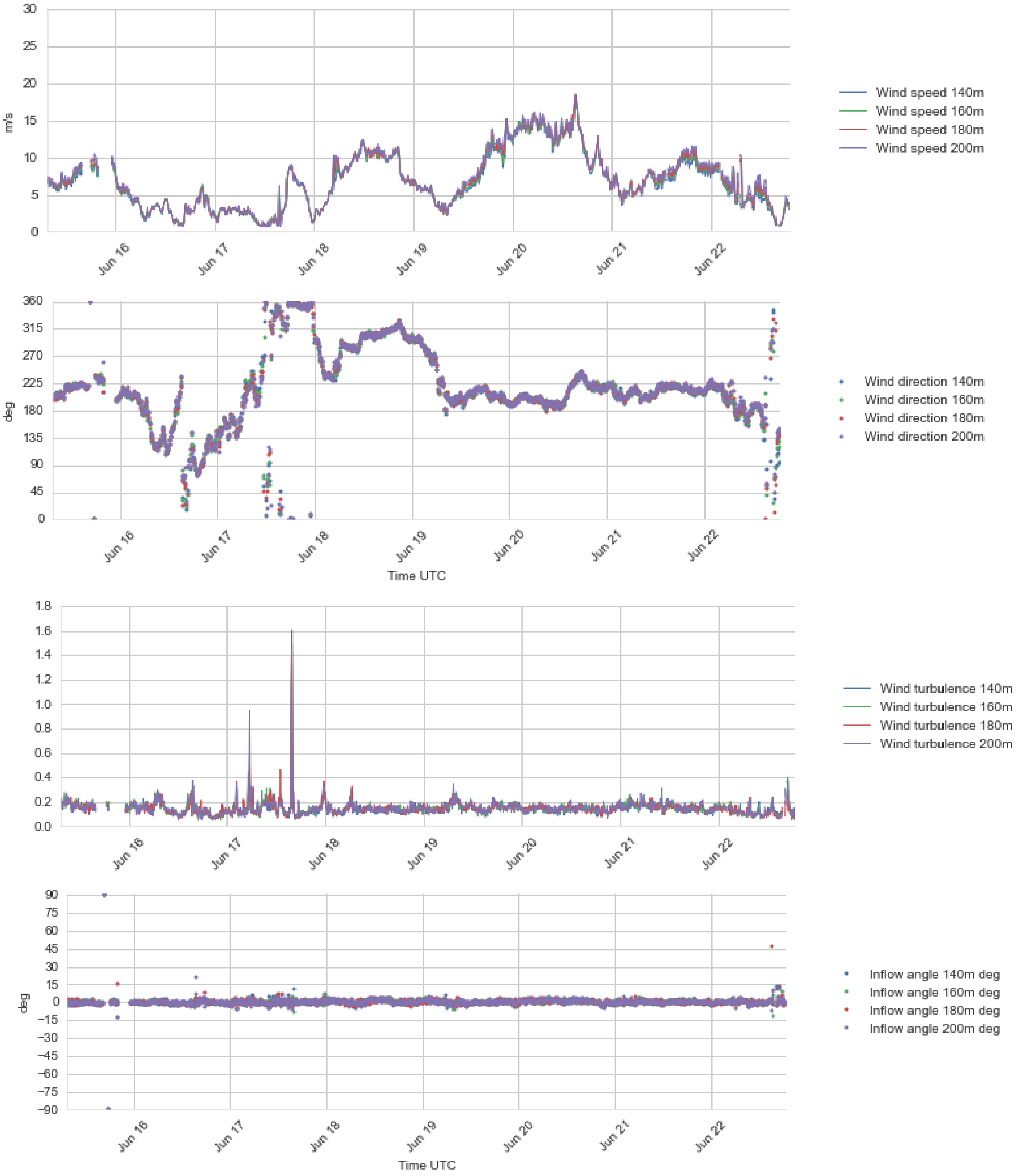

Figure 4.9 Plots of wind profile data, 140 – 200 m a.s.l., 15 - 22 Jun 2016.

From top to bottom: Wind speed, Wind direction, Turbulence Intensity, and Inflow Angle.

4.2.4 Current velocity profile data

The following plots show the current velocity profile time series. In these plots current direction 0° or 360° means that the current flows toward north, 90° indicates flow toward east etc. In general the current profiler has worked well, just a few data points were lost due to buoy restarting, but otherwise the series is continuous.

As expected for this location the current velocity data show a very strong and consistent semi-diurnal tidal current pattern, completing two full rotations of the current vector per day, and four tidal current maxima; two toward south-southwest and two toward north-east. The quarter-diurnal peaks in the current speed vary between 60 – 100 cm/s over the month, depending on the phases of the moon. Duringg this period the current profiler has recorded some higher current velocities, sometimes exceeding 140 cm/s.

The average current speed varies in the profile from 67 cm/s near the surface (6 m depth) to 47 cm/s at 22 m depth The maximum surface current velocity during this period was 149 cm/s toward south-south-west (225°), which was recorded at 6 m depth on at 09:30 on 23 June.

The water depth is about 28 m at this location and current velocities down to 26 m depth are presented. At the lowest level, 26 m, the current speeds are reduced parts of the time when the profiling beam hits the bottom. This usually occurs at every other peak in the current speed; that is when the strong current coincides with relatively low water level.

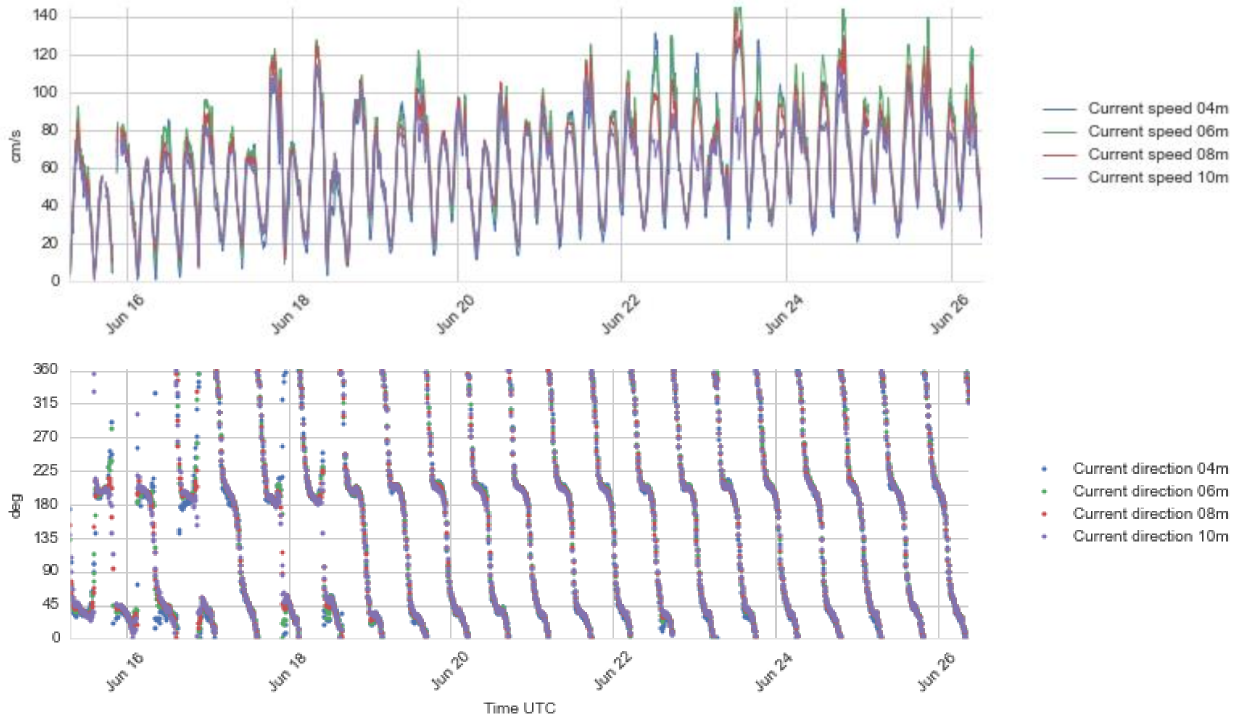

Figure 4.10 Time series plots of current speed (upper) and direction (lower panel), 4 - 10 m depth, 15 -26 Jun 2016

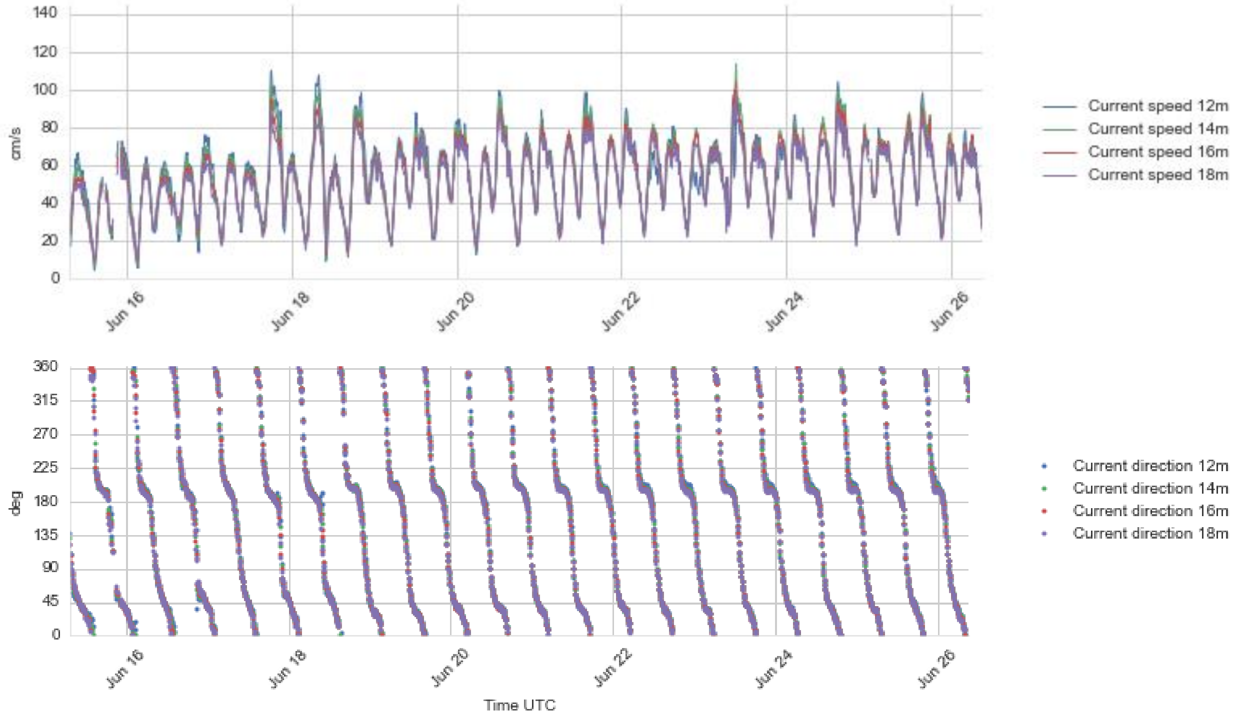

Figure 4.11 Time series plots of current speed (upper) and direction (lower panel), 12 - 18 m depth, 15 -26 Jun 2016.

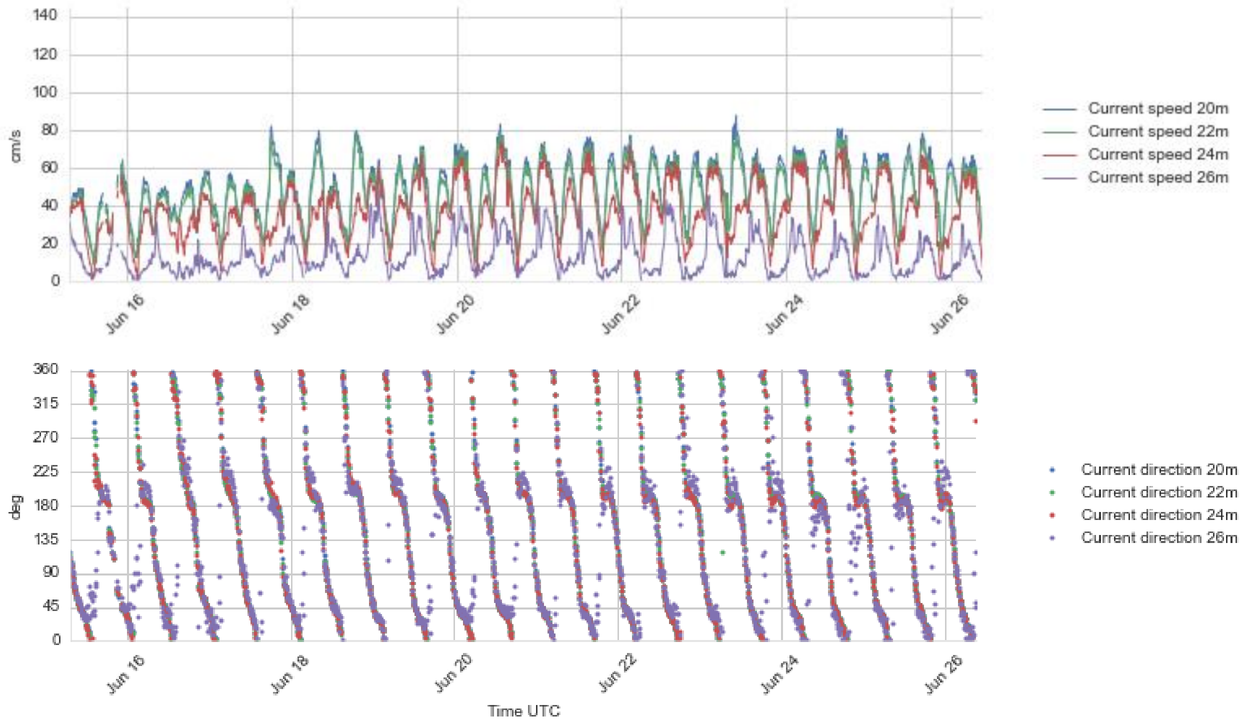

Figure 4.12 Time series plots of current speed (upper) and direction (lower panel), 20 - 26 m depth, 15 -26 Jun 2016.

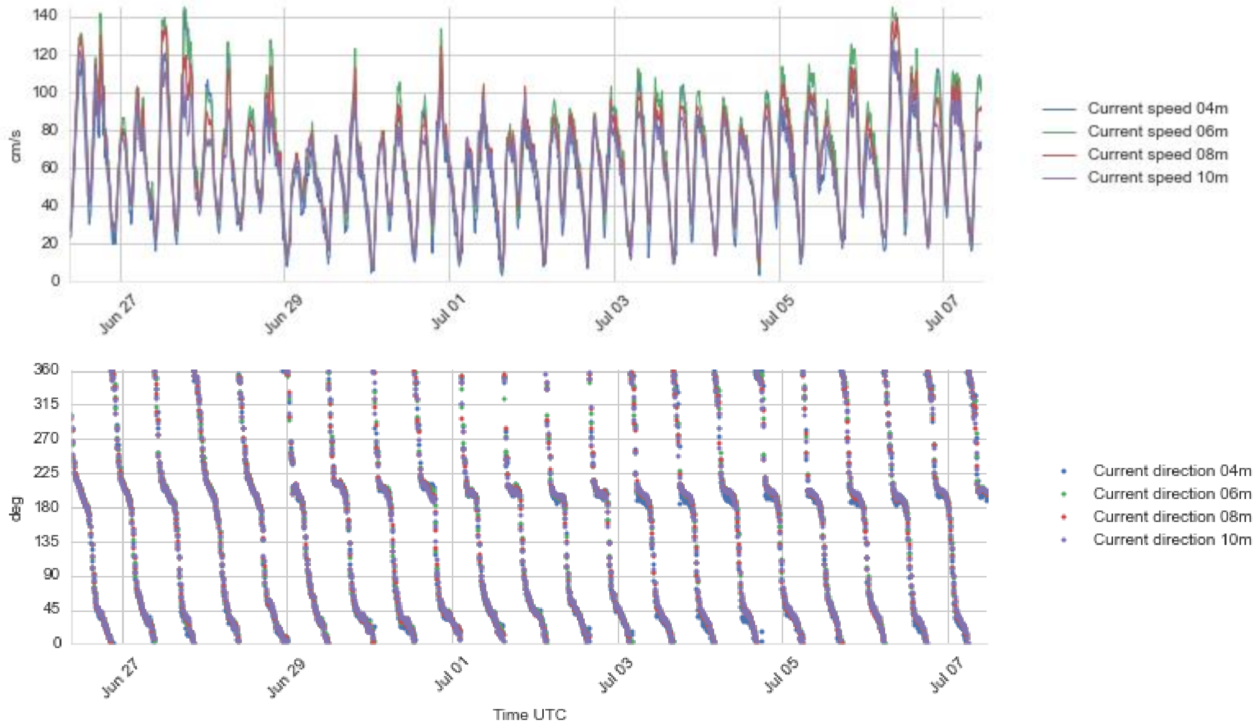

Figure 4.13 Time series plots of current speed (upper) and direction (lower panel), 4 - 10 m depth, 26 Jun – 7 Jul 2016.

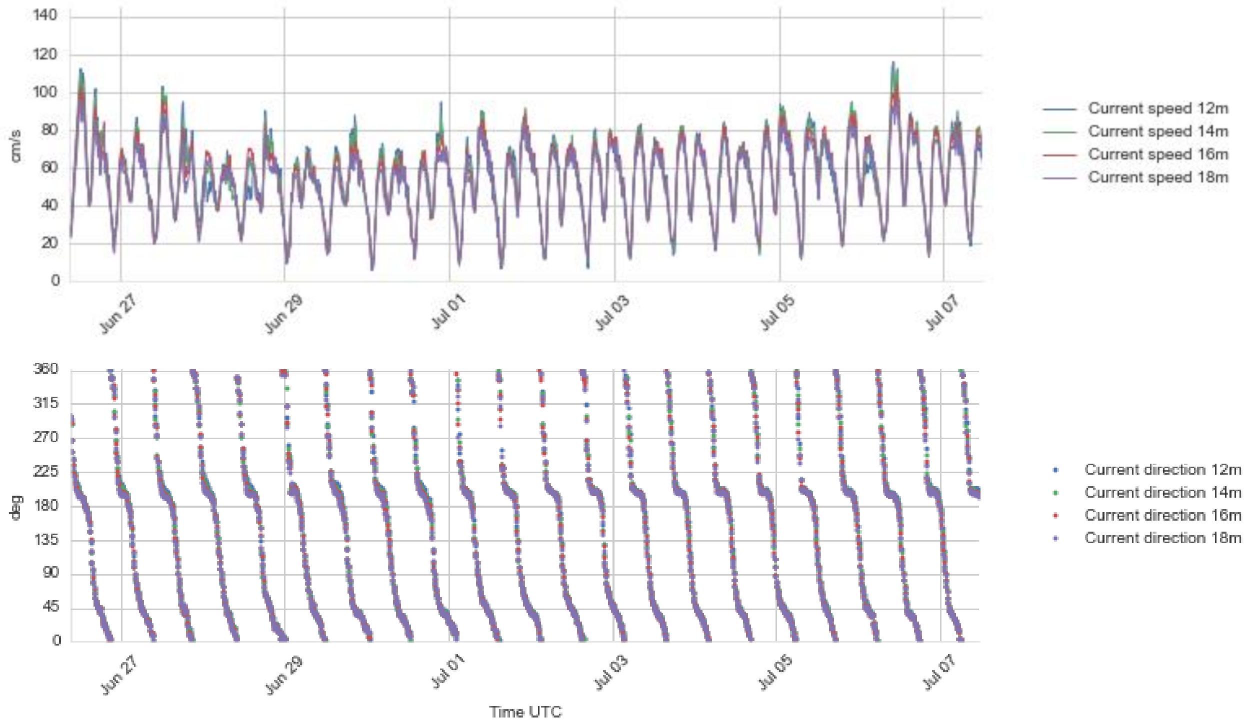

Figure 4.14 Time series plots of current speed (upper) and direction (lower panel), 12 -18 m depth, 26 Jun – 7 Jul 2016.

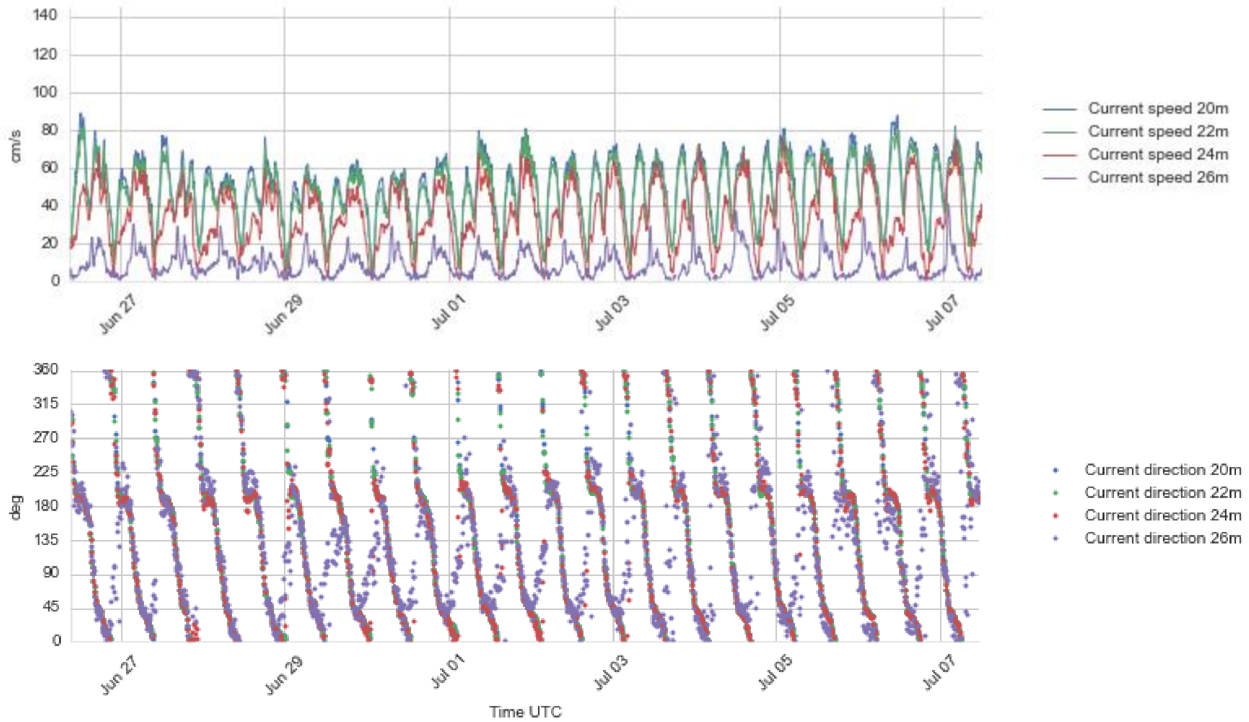

Figure 4.15 Time series plots of current speed (upper) and direction (lower panel), 20 – 26 m depth, 26 Jun – 7 Jul 2016.

Appendix A

Buoy deployment record

DEPLOYMENT/RECOVERY SHEET

Project Name:	**WS lidar buoy to Borssele-nederland**		
Project no:	C75339	Latitude:	51°38.7780'N (y=5,721,704)
Station name:	Borssele – Lot 2	Longitude:	2°57.0846'E (x=496,638)
WS buoy no:	WS156	Approx. depth:	30m
PFF numbers:	33920 – 33926	Buoy marking:	

Buoy module/sensor	**Serial number/ID**
Wavesense 3 data logger	279
XSense	0770017B
PMU	346
Vaisala PTB330	K2740014
Compass	1039696
Iridium modem	IMEI: 300125060202800 SIM: 8988169514001092381 MSISDN: 881623489332 MSISDN-C: 881692788814
UHF service radio Adeunis ARF7940BA	B142500101 Addr:11562
UHF service radio Adeunis ARF7940BA	B142500109 Addr: 11570
L3 AIS	Ser.no: ? MMSI. 992572061
Gill wind sensor	14360066
Vaisala air HMP155 temperature/humidity	L3050100
Buoytracker	ID: 730307 Name: Borssele 2 WS156
LIDAR ZephIR300	501
Flashlight	329387
Nortek Current meter	AQP6691/AQD8621
Fuel Cell 1	**efoy : 302306-1536-36837** **stack: 151010086--00092**
Fuel Cell 2	**efoy : 302306-1536-36834** **stack: 151010086--00088**
Fuel Cell 3	**efoy : 302305-1444-34726** **stack: 151010084--01192**
Fuel Cell 4	**efoy : 302305-1443-34636** **stack: 151010084--01171**

CONFIGURATION

Data transmission interval:	Continuous mode. ‘
Listening window	NA

POWER OPTIONS

Lead batteries type	**4 x 62Ah**
Lithium batteries:	**6 x 272Ah**
Fuel cells	**4 fuel cells with 10 methanol cartridges 28 litres each.**

DEPLOYMENT HISTORY

	YEAR	MONTH	DATE	GMT

First measurement	2016	February	12	14:10
First measurement in position	2016	February	12	16:20
Out of measuring position	2016	July	7	11:35
Last measurement				

Comments:

Deployment vessel: Multrasalvor 3	Recovery vessel: Dutch Power
Deployed by: Edvard M. Elgsæther	Recovered by: Ole Kristian Høiby

THE NETHERLANDS ENTERPRISE AGENCY (RVO)

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ) - Lot 2
Validation report: 15 June - 7 July 2016

Reference No: C75339_Lot2_VAL05_R1
26 August 2016

Fugro OCEANOR AS
Pirsenteret, P.O. Box 1224, Sluppen, N-7462 Trondheim, Norway
Tel: +47 73545200 Fax: +47 73545201, e-mail: trondheim@oceanor.com

Supply of Meteorological and Oceanographic data at Borssele Wind Farm Zone (BWFZ) - Lot 2: C75339_Lot2_VAL05_R1				
Rev	**Date**	**Originator**	**Checked & Approved**	**Issue Purpose**
0	15.08.2016	Lasse Lønseth	Arve Berg	Draft report for client review
1	26.08.2016	Lasse Lønseth	Arve Berg	Final report

Rev 1 – 26 August 2016	Originator	Checked & Approved
Signed:	Lasse Lønseth	Arve Berg

This report is not to be used for contractual or engineering purposes unless the above is signed where indicated by both the originator of the report and the checker/approver and the report is designated 'FINAL'.

TABLE OF CONTENT

SUMMARY

Two Seawatch Wind Lidar buoys are deployed at the Borssele Wind Farm Zone (BWFZ) at positions labelled “Lot 1” and “Lot 2”. This report concerns Lot 2.

The buoy WS156 was deployed at Lot 2 on 12 February 2016 at 15:25 UTC. Data collection at the Lot 2 location has been completed. The buoy was recovered 7 July 2016 at 11:35 UTC by the vessel “Dutch Power”.

The buoy has delivered data continuously since the deployment. The LiDAR wind profile data end on 22 June 2016 at 18:50 because the fuel cell fuel had all been spent and the LiDAR was shut down due to lack of power. This report presents an evaluation of the wind and wave data collected during the period 15 June – 7 July 2016, comparing the buoy data to data from two fixed measurement stations in the region. The reference station for wave measurements is a Waverider buoy at Schouwenbank (station SCHB), and the reference for wind measurements is the platform at Vlakte van de Raan (VR).

Although the reference stations are some 25 – 27 km away from the buoy location we see good agreement between the buoy and references.

1. INTRODUCTION

The Seawatch Wind Lidar buoy with serial no. WS156 has been deployed at the Borssele Wind Farm Zone (BWFZ) Lot 2 in the Dutch sector of the North Sea. The buoy was deployed on 12 February 2016 at 15:25 with the bottom mooring weight at position 51° 38.778' N, 2° 57.0846' E. The data collection at the Lot 2 location has been completed. The buoy was recovered 7 July 2016 at 11:35 UTC by the vessel "Dutch Power".

The wind and wave data collected during the period 15 June – 7 July 2016 are presented in the data presentation report ref. C75339_Lot2_MPR05_R1. This report presents an evaluation of the wind and wave data by comparing the buoy data to data from fixed measurement stations in the area. Intercomparisons between the data from the two Lidar buoys will be handled separately outside of this report. The reference stations used in this report are the Waverider buoy at Schouwenbank (station SCHB) for waves, and a platform with a wind sensor at Vlakte van de Raan (VR) for wind measurements. The comparisons are shown in time series and scatter plots.

The time reference used in this report is UTC.

2. Instrumentation and measurement configuration

The buoy is a Seawatch Wind Lidar Buoy based on the original Seawatch Wavescan buoy design with the following sensors:

- Wavesense: 3-directional wave sensor
- Xsens 3-axes motion sensor
- Gill Windsonic M acoustic wind sensor
- Vaisala PTB330A air pressure sensor
- Vaisala HMP155 air temperature and humidity sensor
- Nortek Aquadopp 600kHz current profiler.
- ZephIR 300S Lidar.

The buoy with mooring as deployed is presented in Figure 2.1.

The measurement setup is detailed in Table 2.1. Detail information such as sensor types and serial numbers can be found in the deployment record in Appendix A.

Table 2.1 Configuration of measurements by the Seawatch Wind Lidar buoy at Borssele Borssele Wind Farm Zone (BWFZ) – Lot 2.

Instrument type	Sensor height (m)	Parameter measured	Sample height[2)] (m)	Sampling interval (s)	Averaging period (s)	Burst interval (s)	Trans-mitted?
Wavesense 3	0	Heave, pitch, roll, heading	0	0.5	Time series duration: 1024 s	600	No
		Sea state parameters (1)	0	600	1024	600	Yes
Xsens		Heave,east,north acceleration, q0,q1,q2,q3 (attitude quaternion)	0	0.5	N/A	3600	No
Gill Windsonic M	4.1	Wind speed, wind direction	4.1	1	600	600	Yes
Vaisala PTB330A	0.5	Air pressure	0.5	30	60	600	Yes
Vaisala HMP155	4.1	Air temperature Air humidity	4.1	5	60	600	Yes
Nortek Aquadopp	-1	Current speed and direction profile, water temperature (at 1 m depth)	-4 -6 … -30 (14 levels)	N/A	600	600	Yes
ZephIR 300S Lidar	2	Wind speed and direction at 10 heights (The 11th level, the so called reference level which is not configurable, is also located at 40 m and referred to as 40.0 Ref.)	30.0 40.0 40.0 ref 60.0 80.0 100.0 120.0 140.0 160.0 180.0 200.0	≈ 17.4 s[1)]	600	600	Yes

1) This is the approximate time between the beginning of one sweep of the profile and the next one, the interval may vary slightly. The ZephIR sweeps one level at a time beginning at the lowest one, and after the top level has been swept it uses some time for calculations and re-focusing back to the lowest level for a new sweep.
2) Height relative to actual sea surface.

Table 2.2 Definitions of wave parameters presented in this report

H	Individual wave height
Hmax	= Max(H): Height of the highest individual wave in the sample, measured from crest to trough
m0, m1, m2, m4, m-1, m-2	Moments of the spectrum about the origin: $\int f^k S(f)df$ where $S(f)$ is the spectral density and the wave frequency, f, is in the range 0.04 - 0.50 Hz
Hm0	Estimate of significant wave height, Hs, $Hm0 = 4\sqrt{m0}$
Tp	Period of spectral peak = $1/f_p$, The frequency/period with the highest energy
Tm01	Estimate of the average wave period; $Tm01 = m0/m1$
Tm02	Another estimate of the average wave period; $Tm02 = \sqrt{\frac{m0}{m2}}$
ThTp	Mean wave direction at the spectral peak (“The direction of most energetic waves”)
Mdir	Wave direction averaged over the whole spectrum
	Directions are given in degrees clockwise from north, giving the direction the waves come from. (0° from north, 90° from east, etc.)

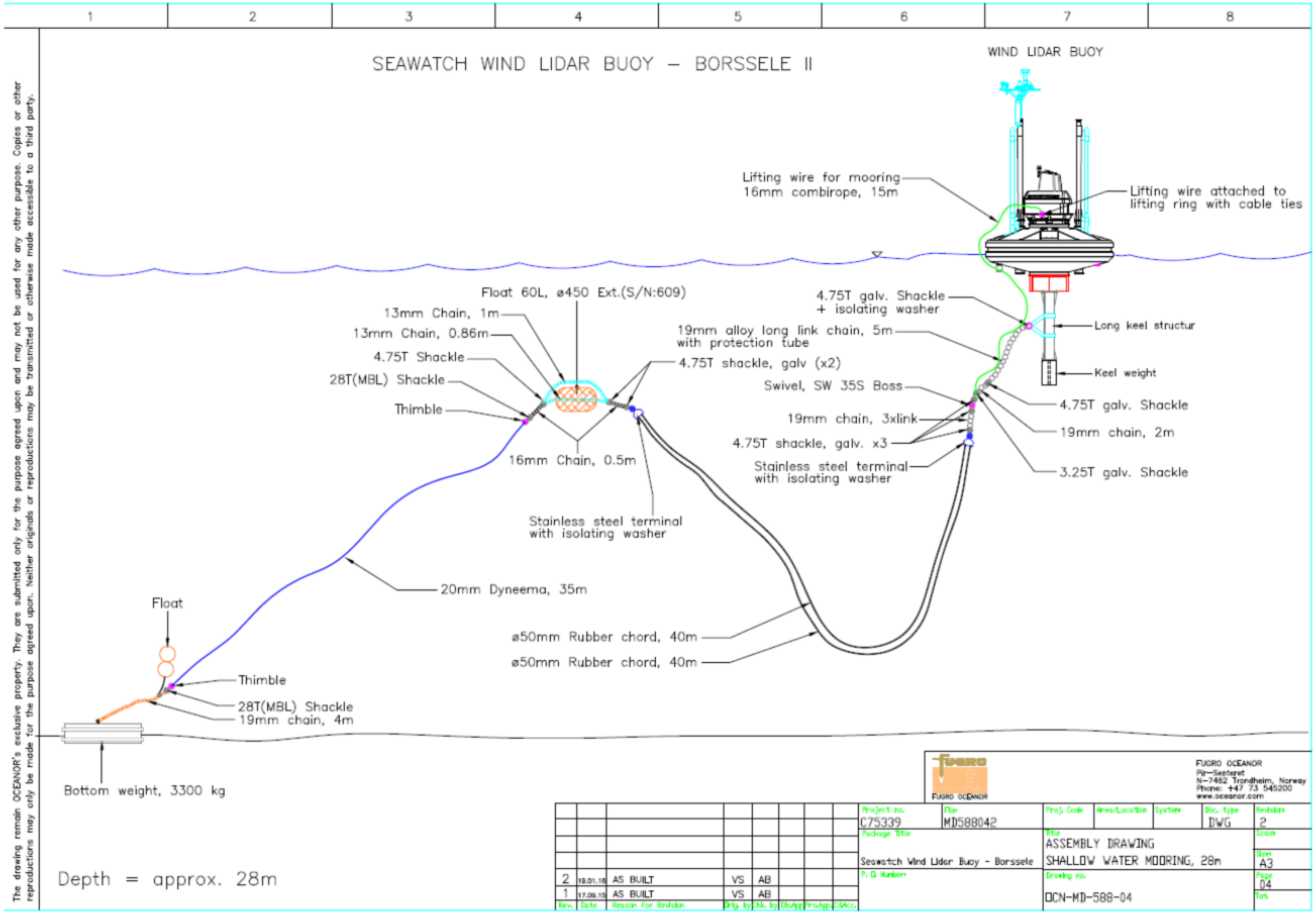

Figure 2.1 Mooring design for the Wind Lidar Buoy as deployed at Borssele Wind Farm Zone (BWFZ) – Lot 2.

3. Results

3.1 Data recovery

The buoy transmitted data continuously from all sensors from 15 June 2016 at 07:30 until 11:30 on 7 July 2016, but the collection of LiDAR wind profiles ended at 18:50 on 22 June due to lack of fuel. There are a few short gaps in the Lidar data where the received data are replaced by the “missing data” flag at all or many heights. The longest gap in the wind profiles occurred from 16:10 to 18:00 on 15 June 2016. In the same period the wave sensor also dropped out.

The number of days of good data compared to the total length of the data collection period is presented in Table 3.1, which is copied from the data presentation report (ref. C75339_Lot2_MPR05_R1).

Table 3.1 Data return during the period 15 June 2016 at 07:30 – 7 July 2016 at 11:30.

Measurement device	Length of data period (days)	Length of data set (days)	Average availability (%)
Lidar wind profile sensor	22.174	7.229	32.57
Wave sensor	22.174	21.881	98.68
Current velocity sensor	22.174	22.049	99.44
Atmospheric pressure sensor	22.174	22.063	99.50
Air temperature sensor	22.174	16.813	75.82

3.2 Reference stations

3.2.1 Positions and distances

Two public reference stations are used in the validation of the data. The reference for the wave measurements is a Waverider buoy at Schouwenbank (SCHB). For wind the reference is the station at Vlakte van de Raan (VR). The positions of the stations are given in Table 3.2, which gives an overview of the locations and distances. Intercomparisons between the Lot 1 and Lot 2 buoys will be the subject of a separate analysis report.

Table 3.2 Positions of the Lidar buoy and the reference stations used in the evaluation of the buoy data.

Station	Latitude	Longitude	Distance from the Lidar buoy	Shortest distance from land
Borssele Lidar buoy – Lot 2	51° 38.78' N	2° 57.08' E		32.5 km
Schouwenbank Waverider buoy (SCHB)	51° 44.8' N	3° 18.3' E	26.5 km	22.0 km
Vlakte van de Raan (VR)	51° 30.0' N	3° 15.0' E	25.7 km	12.2 km

With another validated buoy also on location it would have been possible to validate this second buoy in the BWFZ against the first one. However, it is chosen to validate each buoy using independent data sources as the “ground truth”, and not make the validity of one buoy dependent on the other. This is analogous to the validation of each new buoy against an independent data source which is done before any buoy is delivered for use in an actual measurement campaign. However, a comparison between the conditions at the two buoy locations in the BWFZ is of interest in itself and will be treated separately from the data validation.

3.2.2 Schouwenbank

The wave measuring buoy at Schouwenbank (SCHB station) is a directional ("2D") Datawell Waverider buoy. This buoy measures the wave height and directional spectrum using 3-axis accelerometers.

The SCHB station should be expected to have lower heights of wind sea (locally wind generated waves) than the Borssele Lidar buoy location in southerly to north-easterly winds due to the more limited fetch distance in those directions. In situations with wind sea from north-east to north-west, and situations dominated by northerly swells the two buoy should be exposed to approximately the same wave heights.

Figure 3.1 Google Earth image with indication of the Lidar buoy position and reference stations. (The Borssele Lot 2 Lidar buoy which is validated in this report is marked by the orange coloured pin.)

3.2.3 Vlakte van de Raan

The Vlakte van de Raan (VR) station is measuring wind speed and wind direction. Figure 3.2 shows a photo of the wind mast. Wind speed is measured with the KNMI cup-anemometer. Cup diameter is 105 mm and the distance between the centre of the cups to the rotation axis is 100 mm. Wind direction is measured with the KNMI wind vane. Distance between axis and the outer side of the vane is 535 mm. The anemometer and wind vane are located 13.9 m above the mean sea level. The azimuth of the wind vane plugs at the tip of the booms are determined with a camera relative to distant objects at close to the horizon. The instruments are logged with the KNMI wind SIAM. Wind gusts are determined from a running 3 sec mean value.

Figure 3.2 The wind measuring station at Vlakte van de Raan.

Calibration of the cup anemometers is done in the wind tunnel of KNMI. Wind vanes are balanced and the direction of the vane is tested. Sensors are replaced after 26 month. The cup anemometer contains a photo-chopper with 32 slits. The accuracy is 0.5 m/s. The treshold velocity is 0.5 m/s. The resolution is

0.1 m/s. The response length is 2.5 m. The wind vane contains a code disk. Accuracy is 3°. Resolution is 1°. [ref. Chapter 5 "Handbook for the Meteorological Observation. Koninklijk Nederlands Meteorologisch Instituut KNMI, De Bilt September 2000.]

The VR station is located only 12 km from the coast and much closer to land than the Lidar buoy, and that is expected to have some effect on the winds, both speed and direction, especially for wind with direction from shore; directions from south-southwest to east-northeast in particular. This means that there can be considerable differences in wind speed and direction at any given time, while the long term overall averages are expected to be approximately the same.

3.3 Evaluation of the collected data

3.3.1 Wave data

The wave data from the Lidar buoy are compared to data from the Waverider at Schouwenbank in time series and scatter plots. The distance of about 20 km between the two locations and the different distance from shore is expected to cause some differences in these shallow waters.

The time series plot in Figure 3.3 and scatter plot in Figure 3.4 compare the significant wave height (Hm0). All peaks in the time series occur at almost exactly the same time, showing good coherence. The average Hm0 values are 0.87 m at the Lidar buoy compared to 0.91 m at Schouwenbank. The difference as well as the scatter with R^2 = 0.924 may be attributed to differences between the locations. The water depth is different at the two locations, with SCHB being the shallower, and this would explain why the wave height is systematically lower at SCHB compared to the Lot 2 buoy at higher sea states, while they are the same at low sea states. The different distance from shore would give lower waves at SCHB when there is wind from shore due to the more limited fetch. Keeping this in mind we see that the Lidar buoy data compares remarkably well to the reference.

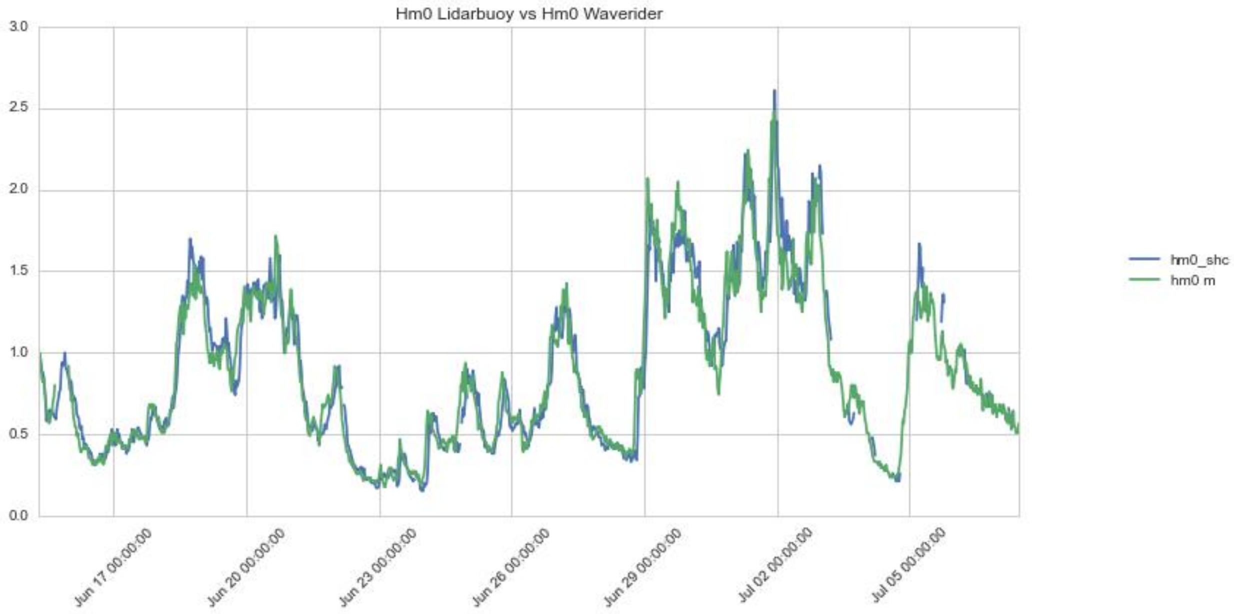

Figure 3.3 Time series plot of significant wave height (Hm0) from the Lidar buoy (green curve) and the Schouwenbank Waverider buoy (blue).

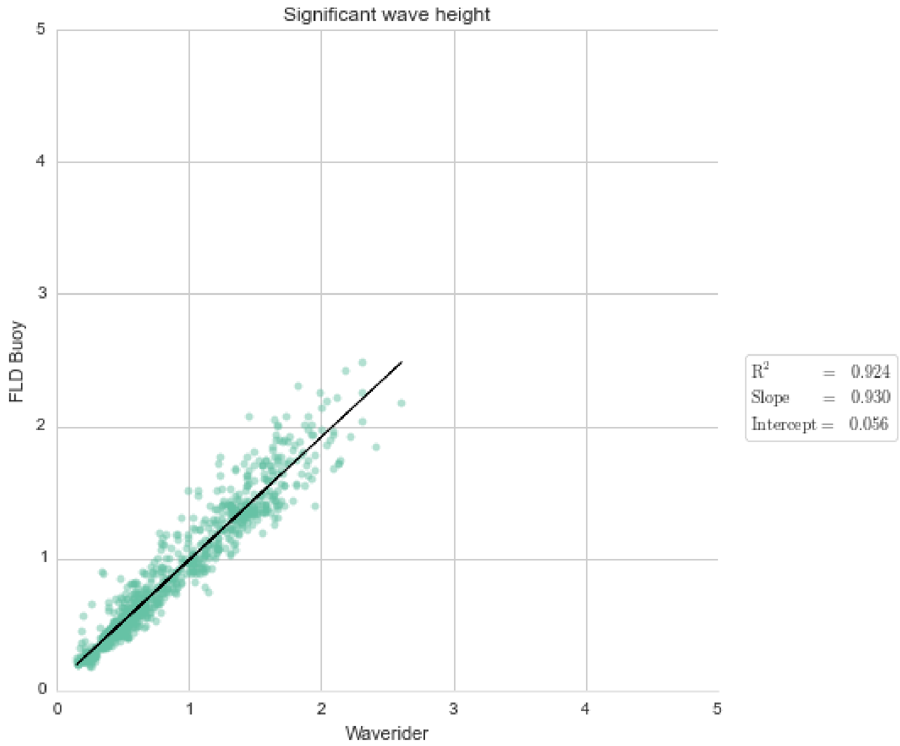

Figure 3.4 Scatter plot comparing Hm0 measured by the Lidar buoy to Hm0 from the Schouwenbank Waverider buoy.

The mean wave period (Tm02) from the Lidar buoy is compared to the Waverider Tm02 in the time series plot in Figure 3.5 and the scatter plot in Figure 3.6. The time series plot shows good coherence and the values appear very similar. The scatter plot shows R^2 = 0.798. Some scatter must be expected due to the distance between the stations. The average values of Tm02 are almost equal, 4.06 s at the Lidar buoy and 4.03 s at the Waverider.

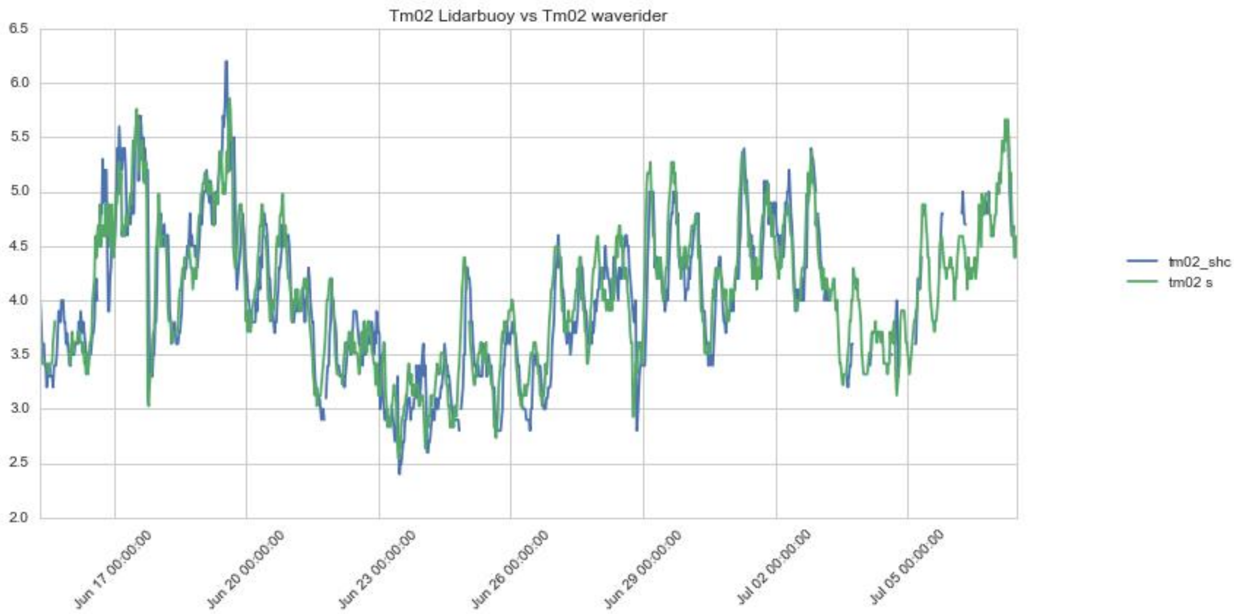

Figure 3.5 Time series plot of mean wave period (Tm02) from the Lidar buoy (green curve) and the Schouwenbank Waverider buoy (blue).

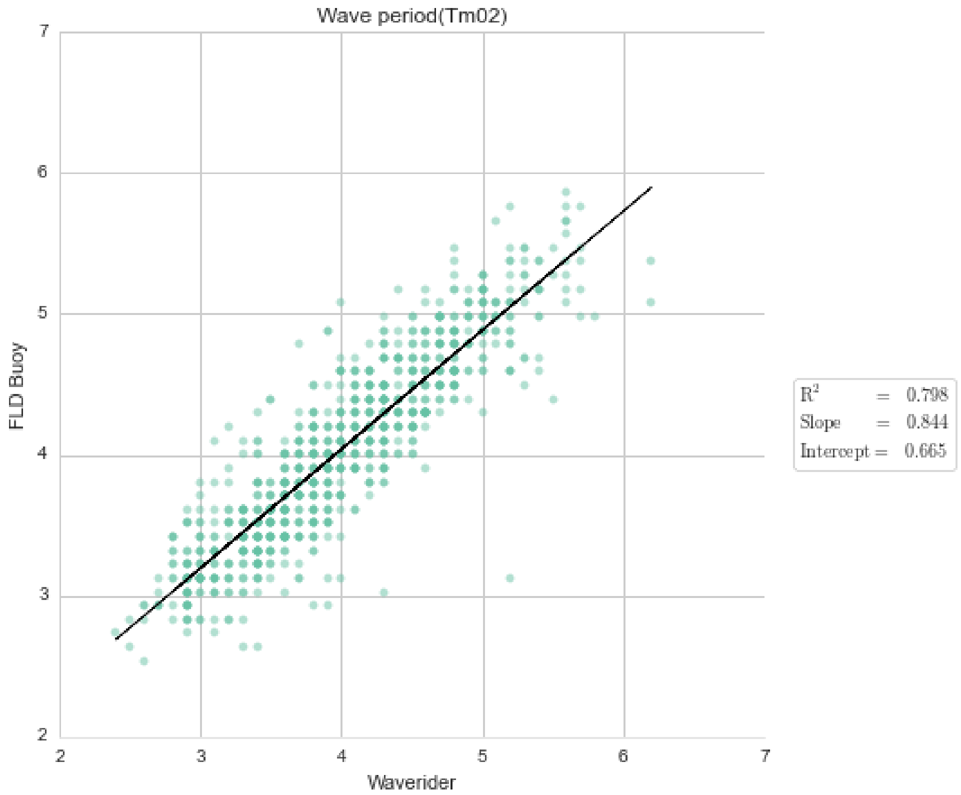

Figure 3.6 Scatter plot comparing Tm02 measured by the Lidar buoy toTm02 from the Schouwenbank Waverider buoy.

3.3.2 Wind data

The Vlakte van de Raan (VR) wind station is located about 26 km away from the BWFZ Lot 2 Lidar buoy, and closer to shore. The VR station is about 12 km from the nearest shore, while the buoy is 32.5 km from land. The wind speeds measured at anemometer height, 13.9 m above the mean sea level, have been reduced to 10 m above mean sea level by a factor of 0.95[1]. The horizontal Lidar wind speed data from the lowest cell, at 30 m above the sea surface, have been compared to the wind data from VR adjusted from 10 m to 30 m height by a factor of 1.15. The data series presented in Figure 3.7 show good agreement in general terms; the maxima in wind speed at both locations appear at the same time, showing good coherence. In average the data compare well with a 30 m average speed of 5.74 m/s at the buoy compared to 6.98 m/s in average at the VR station. The velocities differ particularly during the period 20-21 June with higher velocities at VR compared to the buoy. During that period the wind was south-westerly, and the reduction in wind may be explained by the lee effects of the wind farms to the SW of the buoy. The data from the Lot 1 buoy further east did not show the same kind of reduced wind speed in this period.[2]

The scatter plot in Figure 3.8 compares the wind speeds when the VR station speeds exceed 2 m/s. The correlation is seen clearly, although the scatter is quite large at wind speeds below 10-12 m/s, partly due to the distance between the stations and the differences in the way land effects influence the local wind,

[1] Determined from the ratio of the wind speed at 10 m height to the wind speed measured at anemometer height as given in the original data from Rijkswaterstaat.
[2] Report ref. C75339_VAL09_R1.

and partly due to lee effects from neighbouring wind farms to the SW. This confirms that there is no reason to suspect that the Lidar has not measured the wind speed correctly.

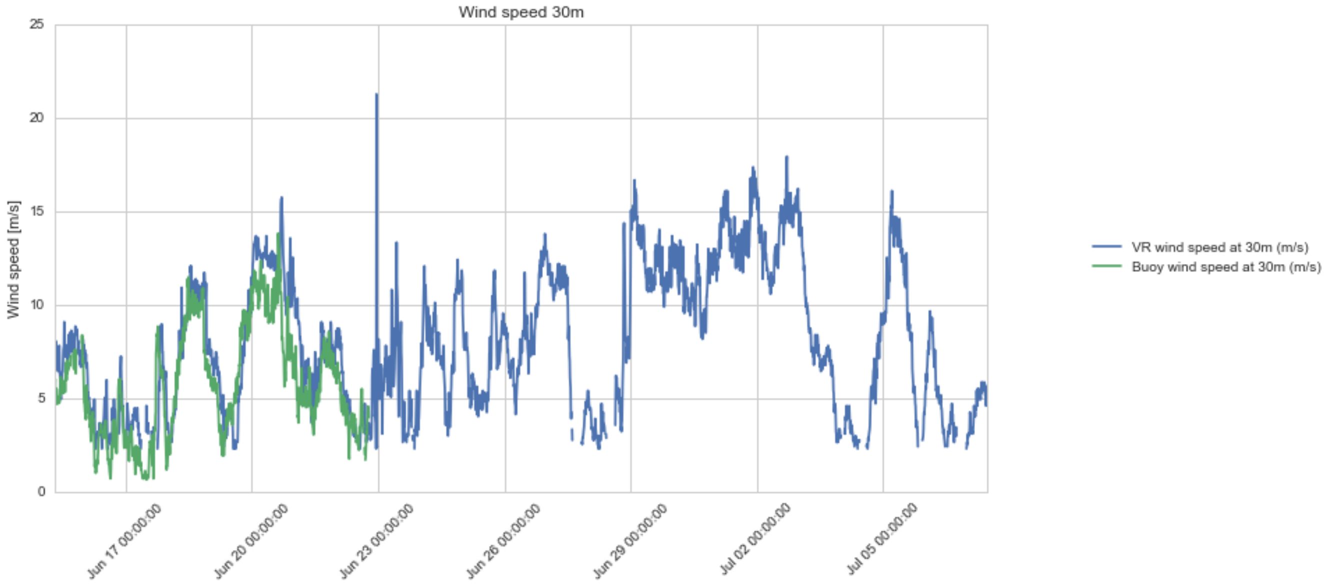

Figure 3.7 Wind speed at 30 m above sea level measured by the Lidar buoy (green curve) compared to wind speed at Vlakte van de Raan adjusted to 30 m (blue).

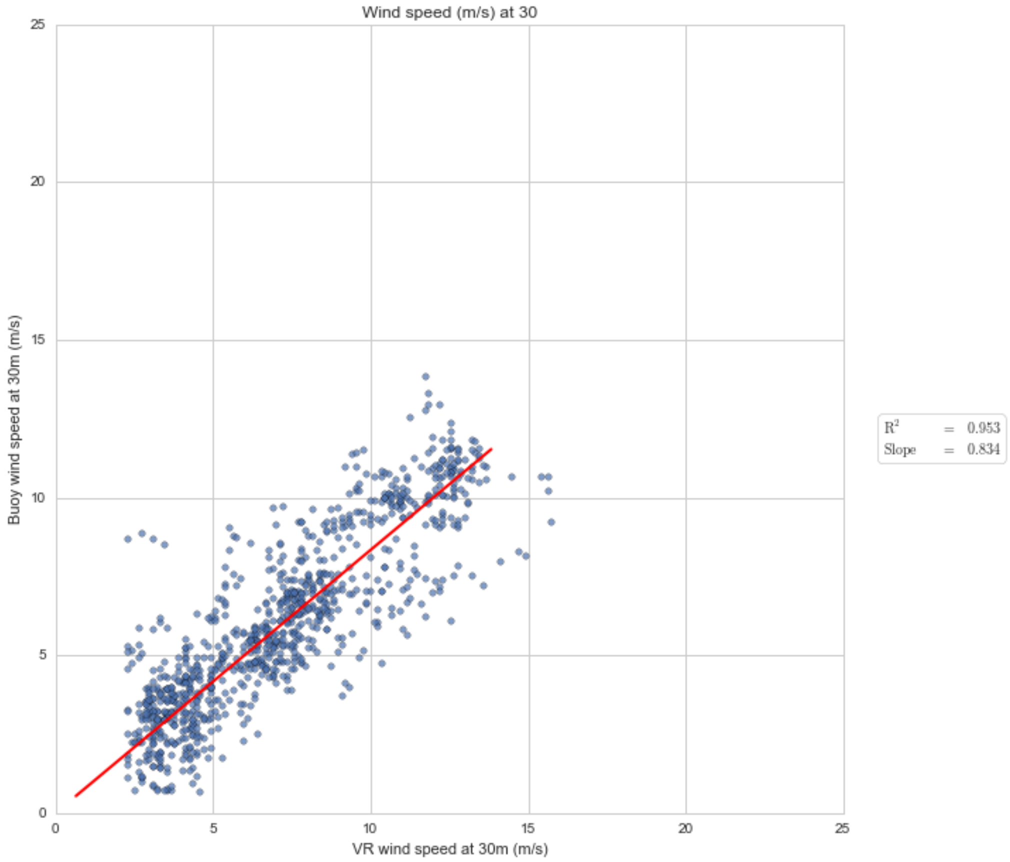

Figure 3.8 Scatter plot comparing the wind speed at 30 m above sea level measured by the Lidar buoy compared to the wind speed at Vlakte van de Raan adjusted to 30 m a.s.l. (Regression formula: y = Slope * x)

The time series of wind direction are compared in Figure 3.9, which also shows the wind speed at Vlakte van de Raan. Samples with speed less than 2 m/s are excluded. Again we see that the variations in directions are correlated between the two sites, and there seems to be a more or less constant deviation. This is also reflected in the scatter plot in Figure 3.10, which shows an average offset of 18° between the wind directions at the two sites. The offset is calculated as the average of the difference between the wind directions. The offset appears to be the same for SW and NW wind in this period, which is quite short. The spreading in the wind direction scatter plot is not unexpected due to the distance between the locations. The offset is not thought to indicate a fault in the buoy, but rather seen as a result of real differences connected to the situation of the buoy and reference stations relative to land and the weather patterns. The Lot 1 and Lot 2 buoys show approximately the same directional offset versus the VR directions.

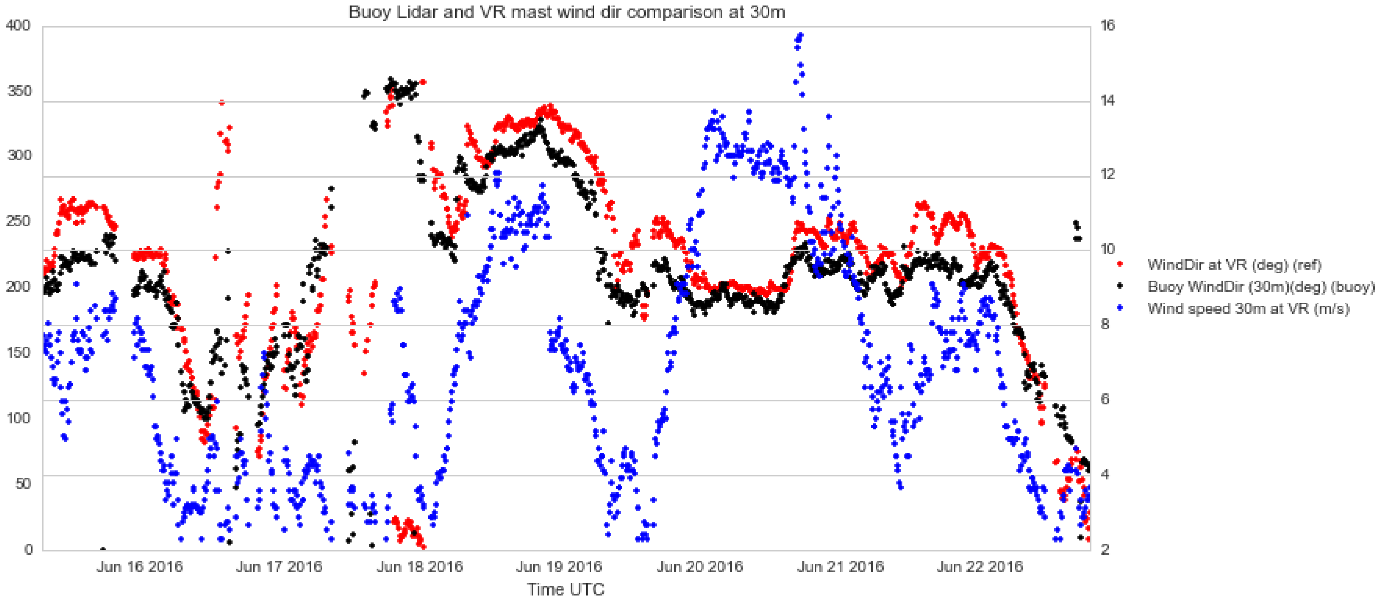

Figure 3.9 Wind direction at 30 m above sea level measured by the Lidar buoy (black dots) compared to wind direction at Vlakte van de Raan (red). The blue dots show the VR station 30m wind speeds. (Samples with VR wind speed less than 2 m/s are excluded.)

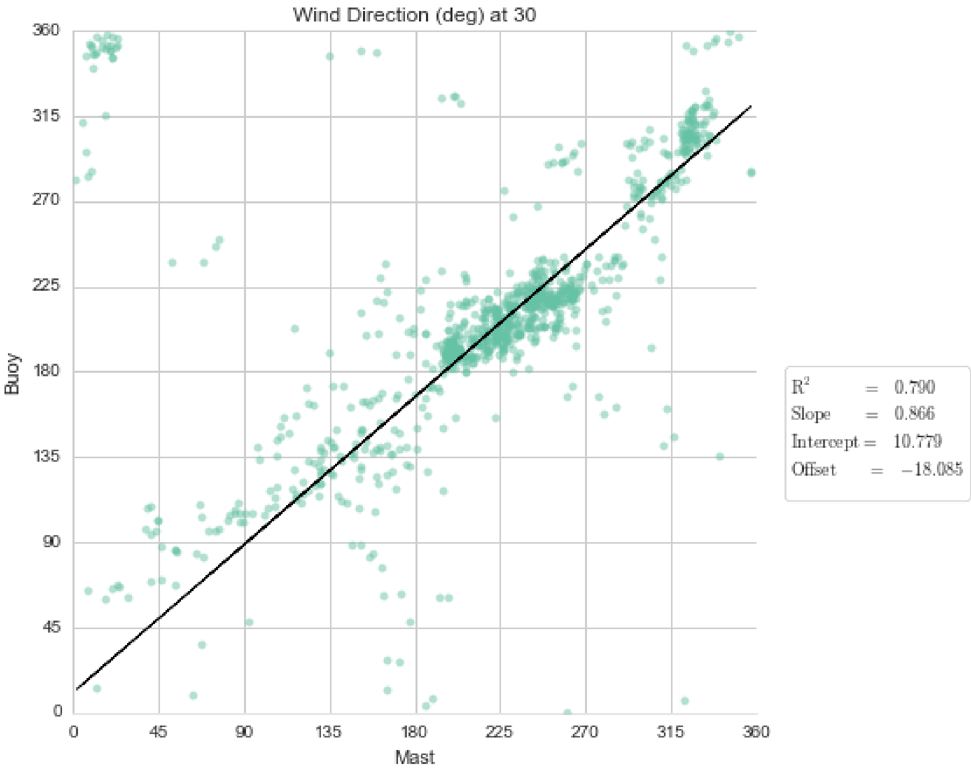

Figure 3.10 Wind direction at 30 m above sea level measured by the Lidar buoy compared to wind direction at Vlakte van de Raan. (Samples with VR wind speed less than 2 m/s are excluded.) ("Offset" is the average difference of directions.)

3.4 Conclusions

The comparisons to the reference station data presented above indicate that the buoy has collected data of good quality for winds and waves. The Lot 2 Seawatch Wind Lidar buoy has transmitted data continuously until the end of the data collection period, but there are a few short gaps in the Lidar data where the received data are replaced by the "missing data" flag at all heights. The gaps are mainly single profile dropouts in the Lidar data only. The wind profile data series is short since the LiDAR was shut down when there was no more fuel for the fuel cells, which gives little basis for comparison against the reference wind station.

Appendix A

Buoy deployment record

DEPLOYMENT/RECOVERY SHEET

Project Name:	**WS lidar buoy to Borssele-nederland**		
Project no:	C75339	Latitude:	51°38.7780'N (y=5,721,704)
Station name:	Borssele – Lot 2	Longitude:	2°57.0846'E (x=496,638)
WS buoy no:	WS156	Approx. depth:	30m
PFF numbers:	33920 – 33926	Buoy marking:	

Buoy module/sensor	**Serial number/ID**
Wavesense 3 data logger	279
XSense	0770017B
PMU	346
Vaisala PTB330	K2740014
Compass	1039696
Iridium modem	IMEI: 300125060202800 SIM: 8988169514001092381 MSISDN: 881623489332 MSISDN-C: 881692788814
UHF service radio Adeunis ARF7940BA	B142500101 Addr:11562
UHF service radio Adeunis ARF7940BA	B142500109 Addr: 11570
L3 AIS	Ser.no: ? MMSI. 992572061
Gill wind sensor	14360066
Vaisala air HMP155 temperature/humidity	L3050100
Buoytracker	ID: 730307 Name: Borssele 2 WS156
LIDAR ZephIR300	501
Flashlight	329387
Nortek Current meter	AQP6691/AQD8621
Fuel Cell 1	**efoy : 302306-1536-36837** **stack: 151010086--00092**
Fuel Cell 2	**efoy : 302306-1536-36834** **stack: 151010086--00088**
Fuel Cell 3	**efoy : 302305-1444-34726** **stack: 151010084--01192**
Fuel Cell 4	**efoy : 302305-1443-34636** **stack: 151010084--01171**

CONFIGURATION

Data transmission interval:	Continuous mode. ‘
Listening window	NA

POWER OPTIONS

Lead batteries type	**4 x 62Ah**
Lithium batteries:	**6 x 272Ah**
Fuel cells	**4 fuel cells with 10 methanol cartridges 28 litres each.**

DEPLOYMENT HISTORY

	YEAR	MONTH	DATE	GMT

First measurement	2016	February	12	14:10
First measurement in position	2016	February	12	16:20
Out of measuring position	2016	July	7	11:35
Last measurement				

Comments:

Deployment vessel: Multrasalvor 3	Recovery vessel: Dutch Power
Deployed by: Edvard M. Elgsæther	Recovered by: Ole Kristian Høiby