SWLB measurements - Danish Offshore Wind 2030

Project Measurement Plan, All Lots

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Abbreviations

Abbreviation	Definition
ADCP	Acoustic Doppler Current Profiler
DD	Day of month 2 digits
DGPS	Differential GPS
EEZ	Exclusive economic zone
FNAS	Fugro Norway AS
GENI	GENeral Interface (FNAS data logger)
GPS	Global positioning system
GW	Giga Watts
LMCU	Lidar Motion Compensation Unit
MM	Month 2 digits
Month	Month as text
MWL	Mean water level
NaN (Not a Number)	Label indicating data as invalid/missing
PEP	Project Execution Plan
PMU	Power Management Unit
PPE	Personal Protective Equipment
QHSSE	Quality, Health, Safety, Security and Environment
SWLB	Seawatch Lidar Buoy
WMO	World Meteorological Organization
WS	Seawatch Wavescan buoy (used also in numbering SWLB before a separate number series was made for SWLB)
YYYY	Year 4 digits

Conventions

Convention	Description
Current direction	Given by where the water is flowing to
Geographical coordinates	Given in decimal degrees according to World Geodetic System (WGS84)
Time	All times given as coordinated Universal Time (UTC)
Wave directions	Given by where the waves are coming from
Wind directions	Given by where the wind is blowing from

1. INTRODUCTION

The Danish Parliament has tasked Energinet with undertaking metocean surveys for the development of five (5) offshore wind project areas within the Danish EEZ [1]. The measurements from the metocean surveys will be used as input to various environmental, metocean, and other studies and analyses to support the project development and design process, including energy yield calculations, site assessment, selection and design of foundation, grid connections, cable corridors, etc. The project areas for investigation are named below:

- Kattegat
- Hesselø South
- Kriegers Flak II (North and South)
- North Sea I

The project areas are divided in to three (3) lots in the Kattegat Sea, Baltic Sea and North Sea as shown in Figure 1-1. The metocean surveys include deployment of several floating LiDAR buoys (LB) and near the seabed current profilers (CP) as outlined in Table 1-1.

Table 1-1 LiDAR buoys and current profilers by project area and lot

Project area	Lot	Number of LB and CP	Number of spare LB	Number of spare CP
Hesselø South	1	1	1	1
Kattegat		1		
Kriegers Flak II	2	2	1	
North Sea I	3	3	1	

Fugro Norway AS entered into an agreement with ENERGINET, Denmark for the project "Danish Offshore Wind 2030 – Floating Lidar Measurements – Lot 1, Lot 2 and Lot 3". The aim of the measurement campaign is to provide a set of continuous meteorological and oceanographic (metocean) data with excellent quality and high availability through real time measurements. The measurement campaign will last 12 months, with option for extension. The results of the meteorological and oceanographic measurements should be used for verification of the wind energy potential, as basis for derivation of metocean design parameters and as a supplement to the environmental baseline description.

The project areas are briefly described in Section 1.1 to 1.3 and stations for deployment of LiDAR buoys (LB) and current profilers (CP) are defined. Distances given are approximate and to the center of the project areas, while water depths are based on the depth model by the Danish Cadaste Agency having a spatial resolution of 50 m × 50 m.

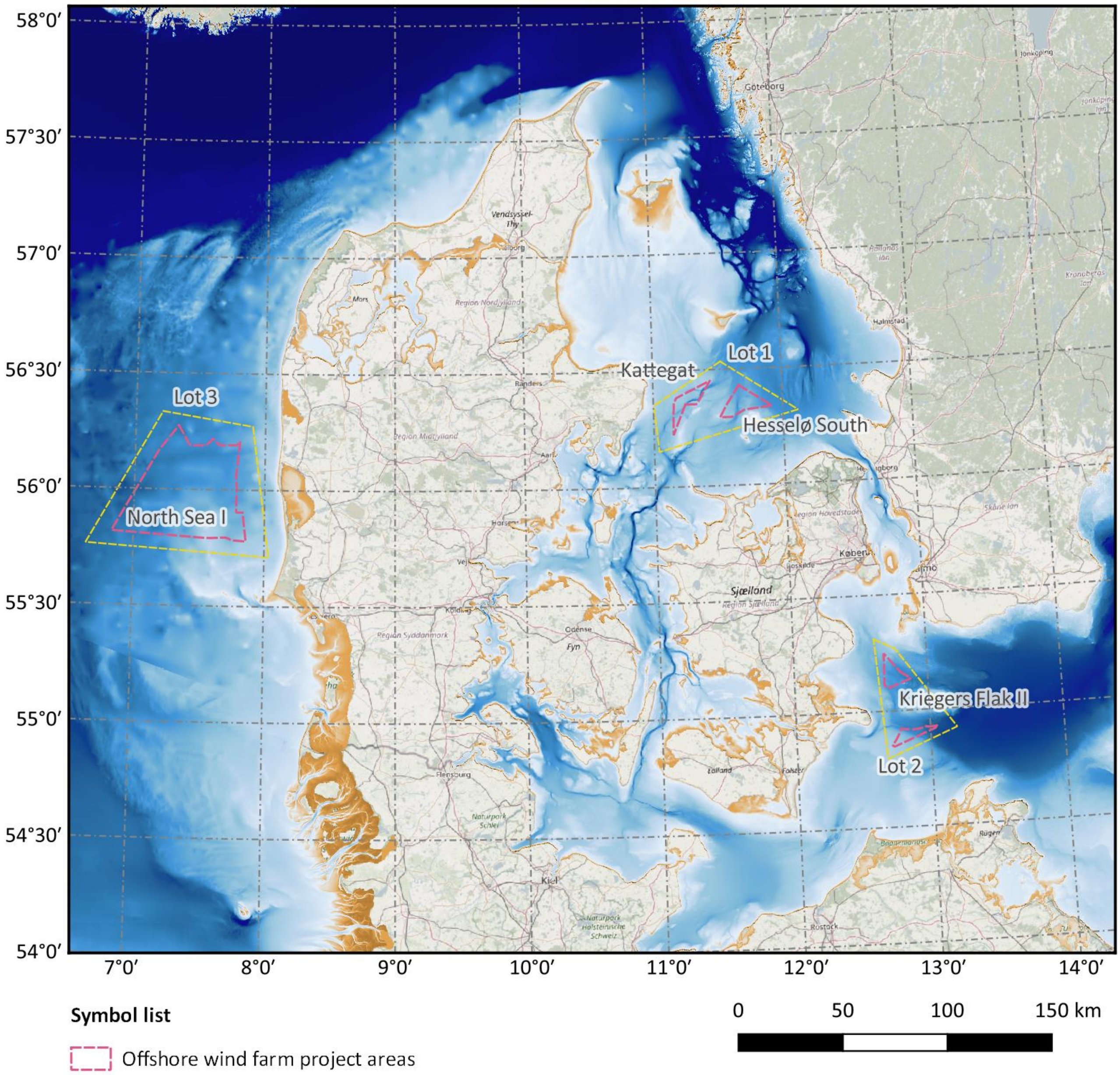

Figure 1-1 Project areas and definition of lots for Danish Offshore Wind 2030

1.1 Kattegat and Hesselø South project areas

The Kattegat project area is located 20 km east of the Djursland peninsular, protruding into Kattegat Sea. The water depth in the more than 120 km^2 area is between 17 and 38 m, see Table 1-2. The approximate distance to Grenå Port is 20 km.

The Hesselø Syd project area is located 40 km northwest off the north coast of Zealand and nearly 50 km east of the Djursland peninsular. The water depth in the 160 km^2 area is between 14 m and 32 m. The approximate distance to Hundested Port is 45 km.

The stations for deployment of LiDAR buoys (LB) and near-seabed current profilers (CP) for Lot 1 are shown in Figure 1-2. Table 1-2 lists the deployment locations with station names and water depths.

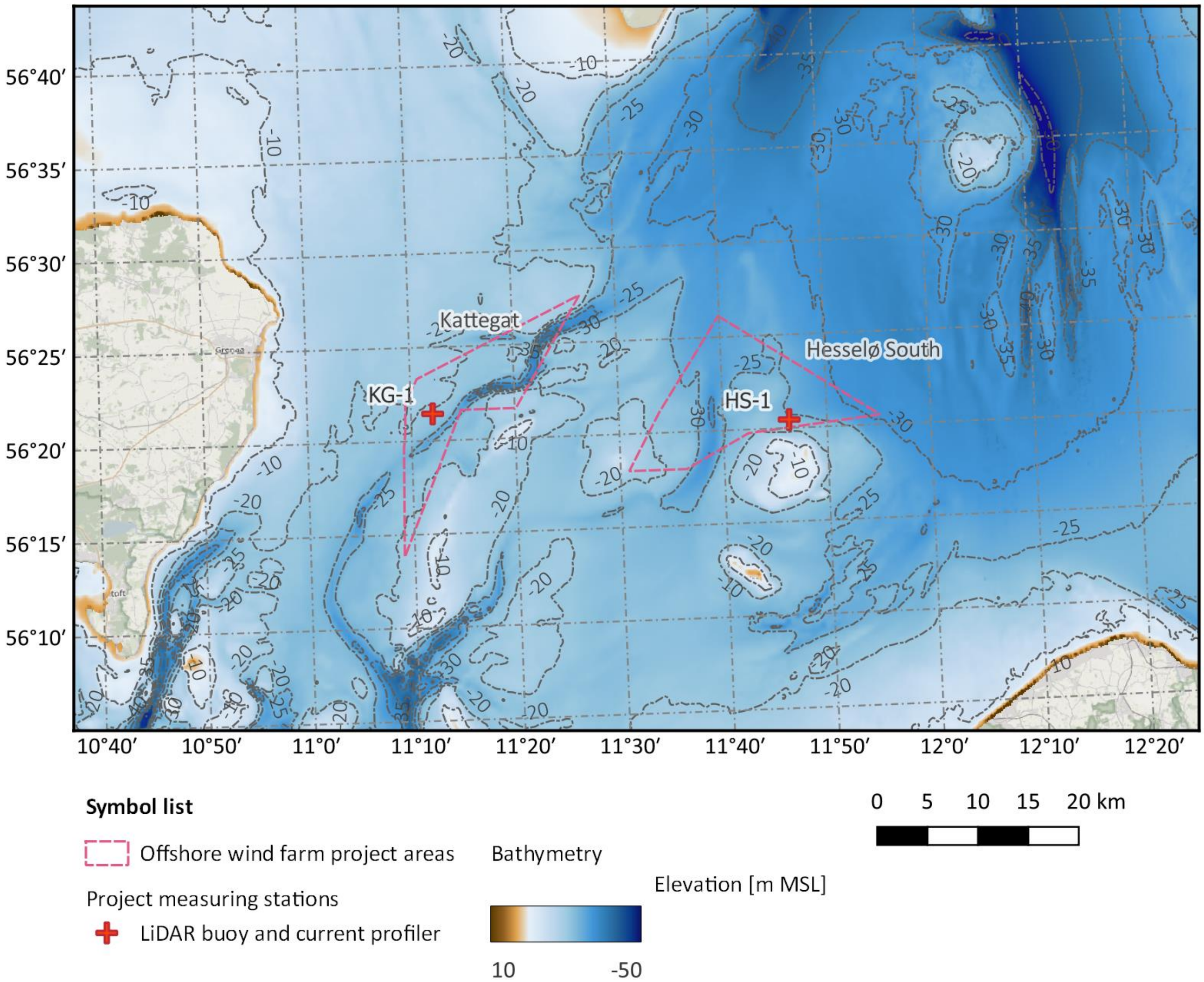

Figure 1-2 Stations Lot 1 (Kattegat and Hesselø South)

Table 1-2 Stations and water depts at Lot 1 (Kattegat and Hesselø South)

Station	Area	Instrument	Latitude [°N]	Longitude [°E]	Depth [m MSL]
HS-1-LB	Hesselø South	Lidar buoy	56,3340	11,7723	22,6
HS-1-CP	Hesselø South	Current profiler	56.3342	11.7722	22.8
KG-1-LB	Kattegat	Lidar buoy	56,3506	11,2010	20.8
KG-1-CP	Kattegat	Current profiler	56.3503	11.2011	20.7

1.2 Kriegers Flak II

The Kriegers Flak II project areas consist of a northern and southern part. The northern area is close to 100 km^2, is located nearly 25 km from Rødvig, and has water depths between 20 m and 35 m. The southern area is 75 km^2, is located about 20 km off Møns Cliff, and has water depths between 18 and 42 m. The approximate distance to Rødvig Port 55 km.

The stations for deployment of LiDAR buoys (LB) and near-seabed current profilers (CP) for Lot 2 are shown in **Table 1-3**. Table 1-3 lists the deployment locations with station names and water depths.

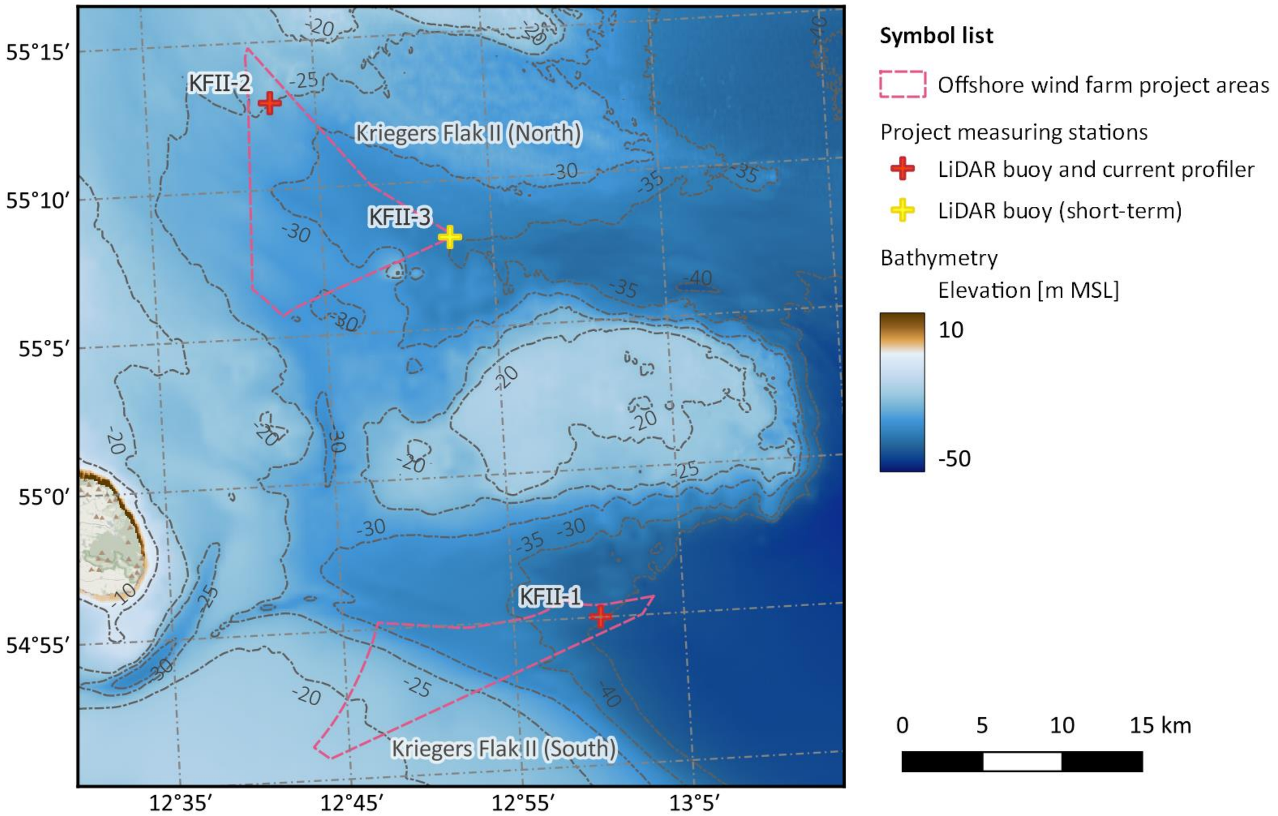

Figure 1-3 Stations Lot 2 (Kriegers Flak II)

Table 1-3 Stations and water depths at Lot 2 (Kriegers Flak II)

Station	Project area	Instrument	Latitude [°N]	Longitude [°E]	Depth [m MSL]
KFII-1-LB	Kriegers Flak II S	Lidar buoy	54.9168	12.9945	39.7
KFII-1-CP	Kriegers Flak II S	Current profiler	54.9167	12.9939	39.5
KFII-2-LB	Kriegers Flak II N	Lidar buoy	55.2156	12.6986	27.2
KFII-2-CP	Kriegers Flak II N	Current profiler	55.2153	12.6992	27.2
KFII-3-LB	Kriegers Flak II N	Lidar buoy	55.1348	12.8681	34.6

1.3 North Sea I project area

The North Sea I project area is located approximately 27 km off the west coast of Jutland. The water depth in the 2,200 km^2 large area varies from 10 m to 42 m. The approximate distances to the ports of Hvide Sande, Thyborøn and Esbjerg are 45 km, 60 km and 95 km, respectively.

The stations for deployment of LiDAR buoys (LB) and near-seabed current profilers (CP) for Lot 3 are shown in **Table 1-4**. Table 1-4 lists the deployment locations with station names and water depths.

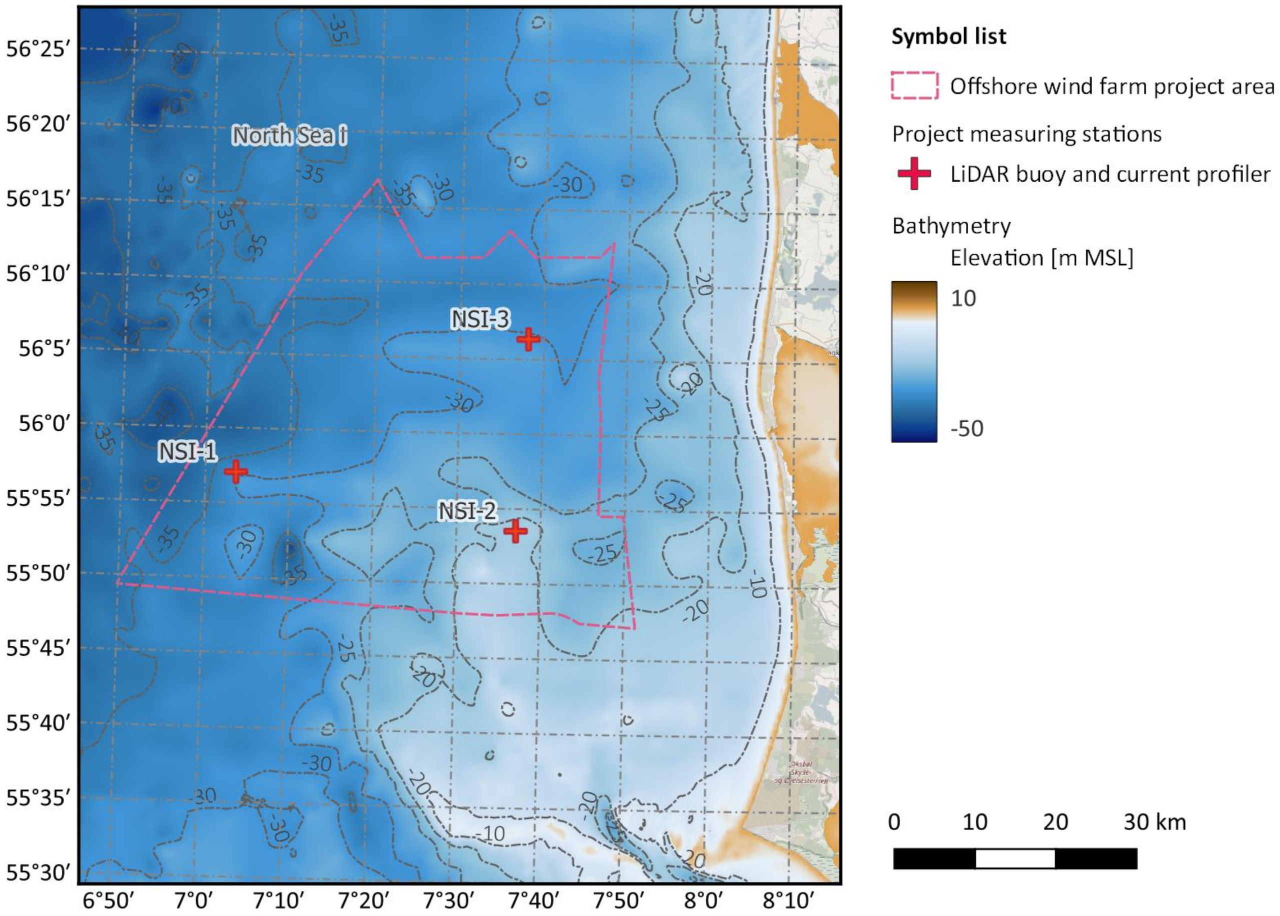

Figure 1-4 Stations Lot 3 (North Sea I)

Table 1-4 Stations and water depths at Lot 3 (North Sea I)

Station	Area	Instrument	Latitude [°N]	Longitude [°E]	Depth [m MSL]
NSI-1-LB	North Sea I	LiDAR buoy	55.9444	7.0604	30.2
NSI-1-CP	North Sea I	Current profiler	55.9441	7.0596	30.2
NSI-2-LB	North Sea I	LiDAR buoy	55.8856	7.6167	19.4
NSI-2-CP	North Sea I	Current profiler	55.8855	7.6159	19.4
NSI-3-LB	North Sea I	LiDAR buoy	56.0694	7.6356	28.4
NSI-3-CP	North Sea I	Current profiler	56.0694	7.6347	28.4

2. Instrumentation and Configuration

2.1 Overview

The Wind Lidar buoys measure:

- Wind speed, direction and turbulence intensity at 11 fixed levels up to a height of 300 m (LiDAR)
- Buoy motions (Lidar Motion Compensation Unit (LMCU) for turbulence measurements)
- Wind speed and direction (acoustic sensor)
- Air pressure
- Air temperature
- Humidity
- Rainfall
- Visibility
- Wave height, period and direction
- Current velocity and direction profile, measured at 1 m intervals
- Water temperature
- Water level

The measurement of buoy motions allows for later correction of measured turbulence intensity.

In addition to the Wind LiDAR buoys, separate upward looking current profilers (on/tethered near the seabed) measure current speed and direction, seawater temperature and water level.

2.2 Sensors on the Seawatch Wind Lidar Buoys

The 10 buoys used for this campaign are Seawatch Wind Lidar Buoys. The buoys are approved and validated according to Carbon Trust [2,3, and 4] and has reached Stage 3 maturity [5].

Two versions will be used: 2.x and 3.0. The main difference is that version 3.0 has larger fuel cell compartments, which extends the possible period of operation from 8 months to 12 months. The 2.x versions will be used at Lot 1 and 2 (Kattegat, Hesselø South, Kriegers Flak II), while the 3.0 version will be used at Lot 3 (the North Sea, I).

Another difference between version 2.x and 3.0 is that version 3.0 has larger “wells” for placing water sensors. Only version 3.0 has large enough “wells” for Signature 500. It was thus agreed with Energinet to use the slimmer Aquadopp 400 kHz for the version 2.x buoys.

The buoys will be equipped with the following sensors:

- Wavesense 3 3-directional wave sensor
- ZephIR ZX300M CW LiDAR (wind profile)
- Septentrio Differential GPS buoy direction sensor (heading) and GNSS water level
- Gill Windsonic M acoustic wind sensor (single point)

- LMCU (Lidar motion compensation unit)
- ADCP current profilers with water temperature sensor
  - Nortek Aquadopp 400kHz current profiler - In 2.x buoys
  - Signature 500 current profiler – In 3.0 buoys
- Vaisala PTB330A air pressure sensor
- Vaisala HMP155 air temperature and humidity sensor
- Young precipitation sensor
- MiniPWS fog/visibility sensor

In addition, there are Thelma water level sensors with acoustic communication with the buoy placed on the seafloor at each buoy location.

The lidars used in this project are marinized versions of the ZX300 lidar type.

The lidar units are equipped with their own met. stations that also measure air temperature and pressure in addition to the main buoy sensors. These lidar met station measurements are given in the dataset as supporting data only.

A GPS receiver is included in the Iridium modem giving the buoy position in addition to the Septentrio DGPS. In addition, the buoys are equipped with a stand-alone, independent tracker.

Figure 2-1 shows the basic shape of the buoy illustrating the principle for wind and current profile measurements for the buoys with air cooling. **Figure 2-2** shows the buoys with water cooling. Wind Lidar buoys with serial number lower than WS182 has air cooling, while buoys with serial number higher than WS182 has water cooling.

Figure 2-3 shows the 3.0 buoys.

The mooring assembly for Lot 1 and 2 is shown in **Figure 2-4** using Kattegat as an example. All moorings for Lot 1 and 2 are the same, except for the length of the Dyneema rope.

The mooring for North Sea is shown in **Figure 2-5.** Compared to the Energy Island project in the North Sea, the moorings for North Sea I has been reinforced by using triple rubber cord.

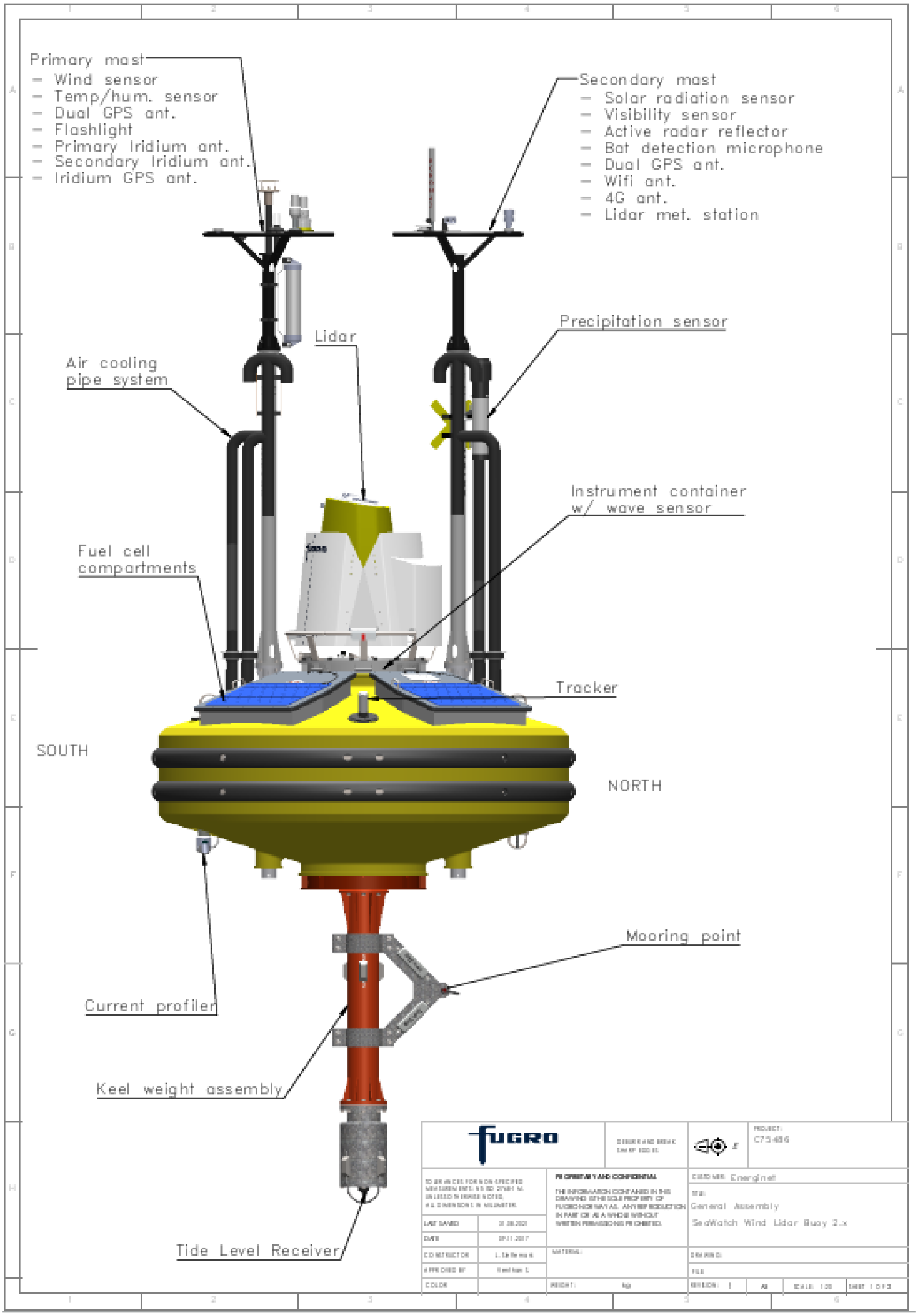

Figure 2-1 SWLB 2.x Mounting arrangement (air cooling)

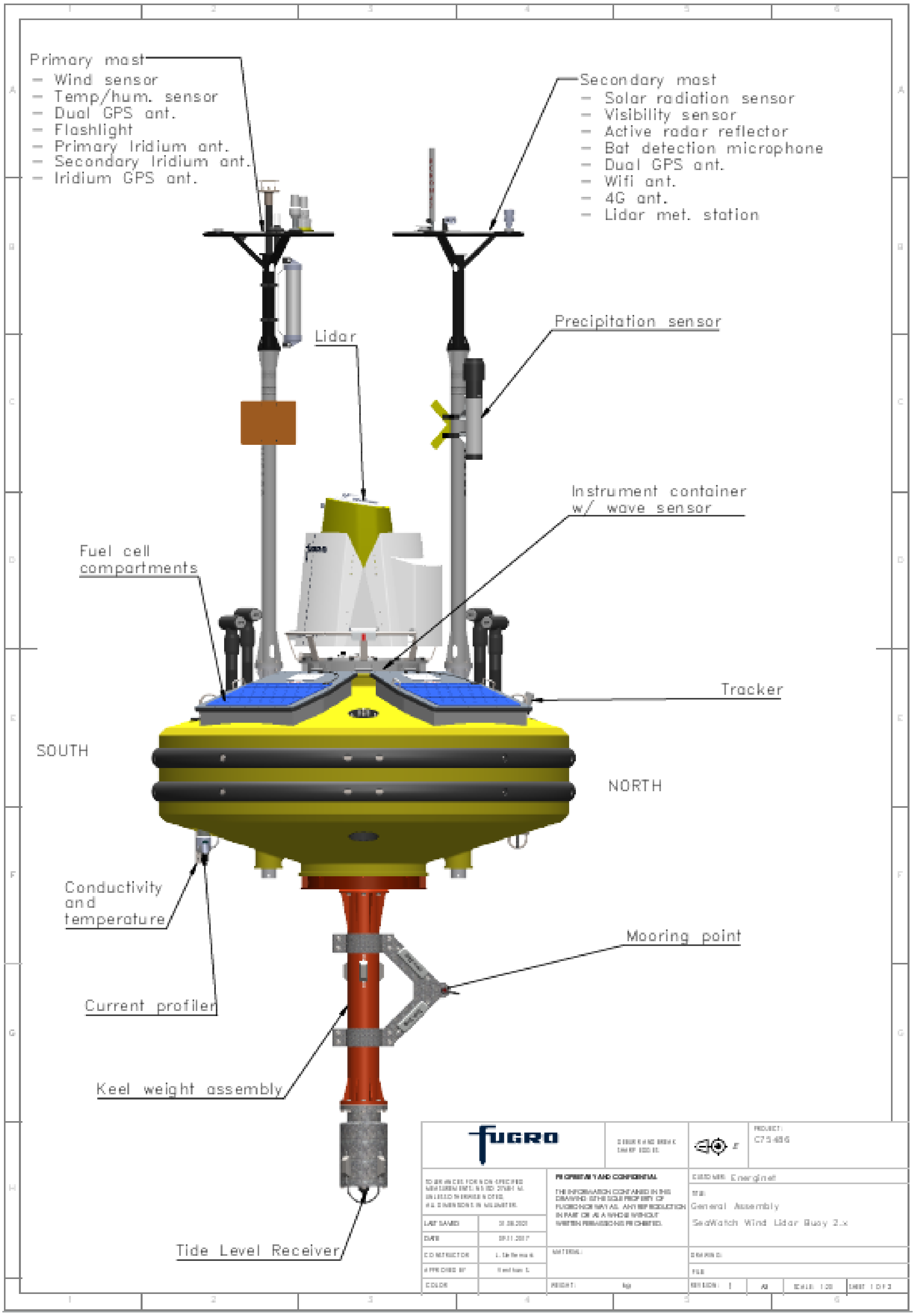

Figure 2-2 SWLB 2.x Mounting arrangement (water cooling)

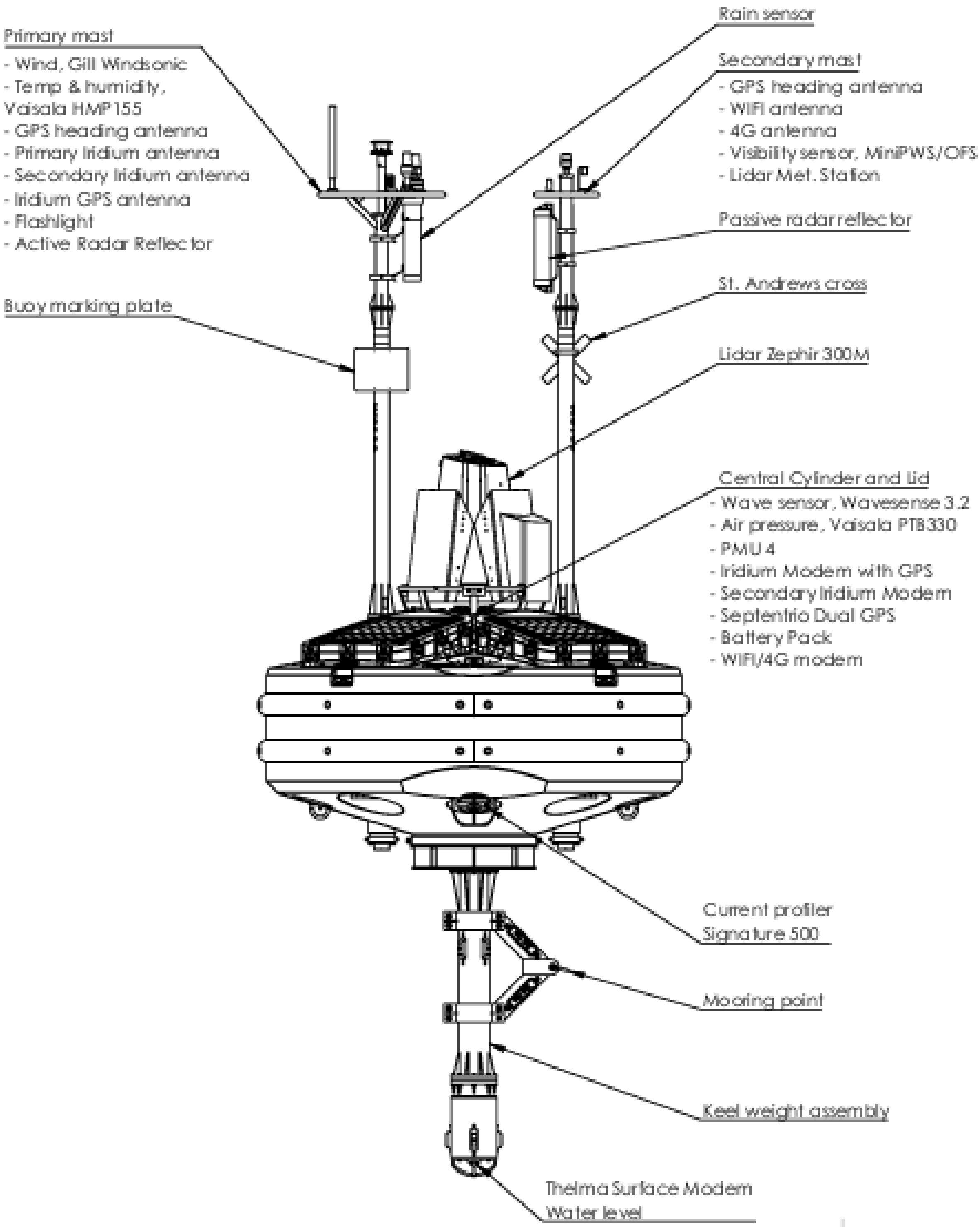

Figure 2-3 SWLB 3.0 Mounting arrangement

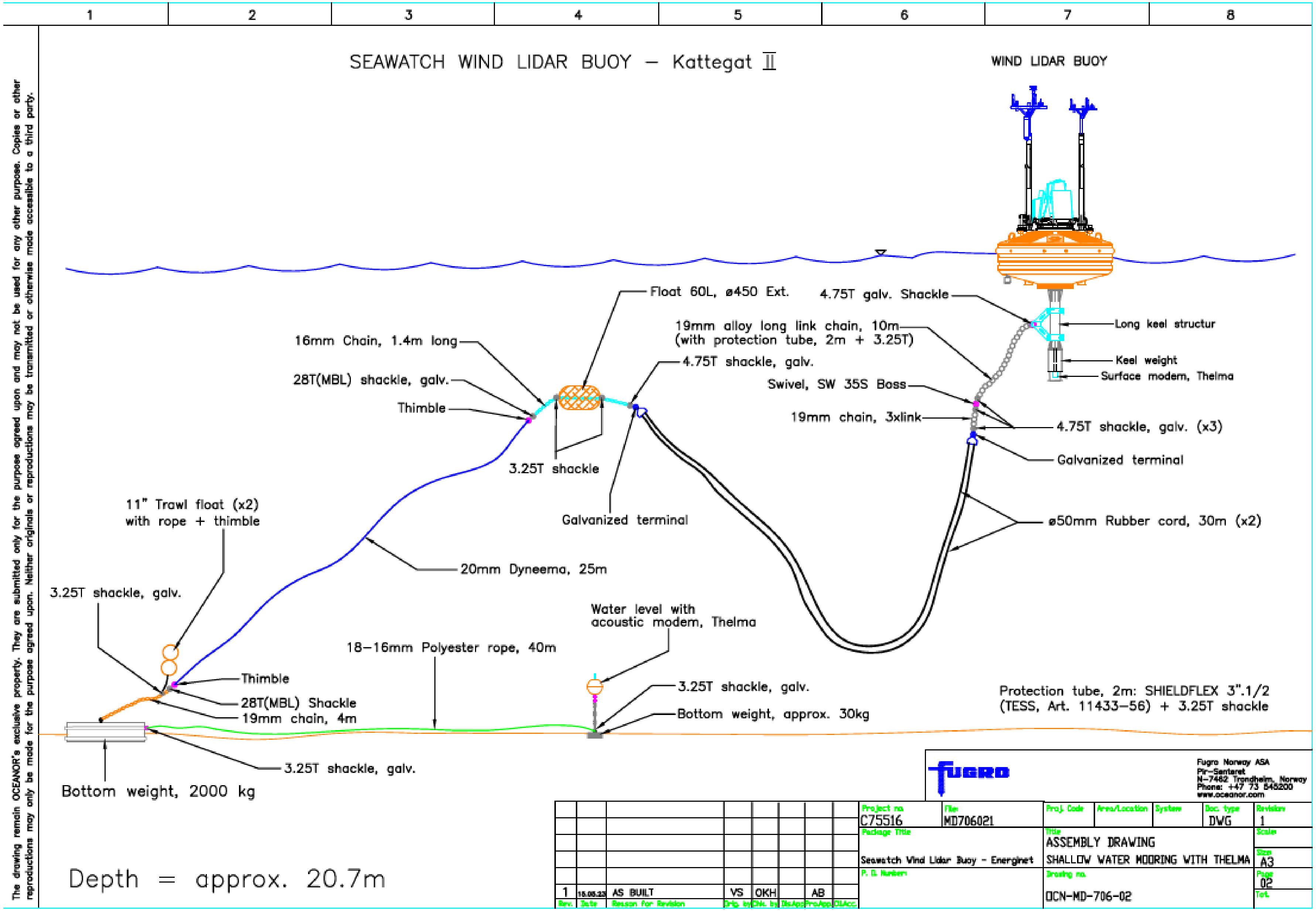

Figure 2-4 SWLB mooring at Kattegat

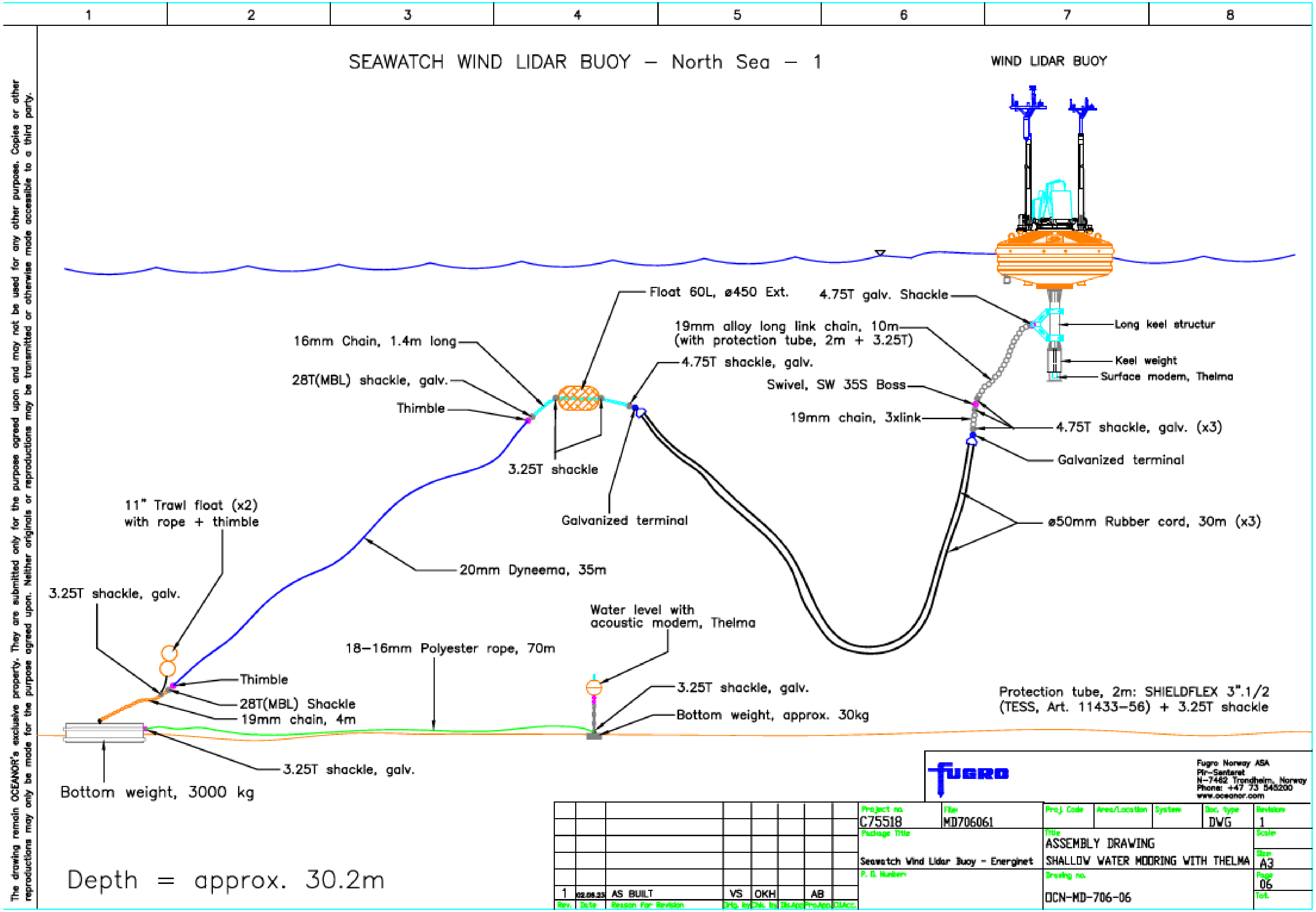

Figure 2-5 SWLB mooring North Sea

The measurement setup is detailed in Table 2-1.

Table 2-1 Configuration of measurements of the Seawatch Wind Lidar buoys

Instrument Type	Sensor Height [m]	Parameter Measured	Sample Height[1] [m]	Samp-ling Interval [s]	Averaging Period [s]	Burst Inter-val [s] [2]	Measure-ment Resolution	Trans-mitted ?
Wavesense 3	0	Heave, pitch, roll, heading	0	0.5	Time series duration: 1024 s	1024	0.1m, 0.2°, 0.2° 0.5°	No
		Sea state parameters[3]	0	600	1024	1024	0.1m, 0.2°, 0.1s	Yes
ZephIR ZX300 Lidar	2	Wind speed and direction at 10 heights and the reference level at 40 m	40[4], 12, 80, 100, 130, 150, 170, 190, 220, 260, 300	17.4[5]	600	600	0.1m/s 1°	Yes
Lidar Motion Compensation Unit (LMCU)	0	Roll, pitch, yaw Surge, sway, heave (velocities)	0	0.2	-	24h	-	No
	2	Line-of-sight data (copied from ZX300 Lidar)	Same as ZX300 Lidar heights	0.02	-	24h	-	No
Gill Windsonic M	4.1	Wind speed and direction	4.1	1	600	600	0.01m/s 1°	Yes
Nortek Aquadopp 400 kHz	-1	Current speed and direction profile, water temperature (at 1m depth)	-2 … -bottom[6]	1	600	600	2 cm/s 1° 0.1°C	Yes
Nortek Signature 500	-1	Current speed and direction profile, water temperature (at 1m depth)	-2 … -bottom[6]	1	180	600	2 cm/s 1° 0.1°C	Yes
Vaisala PTB330A	0.0	Air pressure	0.0	30	60	600	0.05 hPa	Yes
Vaisala HMP155	4.1	Air temperature Air humidity	4.1	5	60	600	0.1°C 1%	Yes
MiniPWS (fog)	4.1	Visibility	4.1	600	600	1	0.6 m	Yes
Young Precipitation sensor	4.0	Precipitation	4.0	600	600	60	0.001 mm	Yes
Septentrio DGPS	4.1	Buoy orientation	4.1	5	10	1	0.35°	No

Instrument Type	Sensor Height [m]	Parameter Measured	Sample Height[1] [m]	Samp-ling Interval [s]	Averaging Period [s]	Burst Inter-val [s] [2]	Measure-ment Resolution	Trans-mitted ?
Thelma Biotel TBR700	See table 1-1 and 1-2	Bottom water pressure and bottom temperature	See Table 1-1 and 1-2	1	600	600	0.01m 0.01°C	Yes

Notes

[1] = Height relative to actual sea surface.

[2] = A burst of measurements is the raw data time series used to calculate the average parameters. The burst interval is the time from the beginning of one burst to the beginning of the next burst, and equal to the interval between writing of raw data to disk and transmissions. Note that wave bursts overlap by 424 s.

[3] = Wave parameters as defined in **Table 2-2**.

[4] = The reference level, which is not configurable and referred to as 40.0 Ref.

[5] = 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. 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. A minimum of 9 samples per height must be measured in the 10-minute interval in order to produce wind speed and direction, and derived parameters thereof. This applies after signal-noise filtering internally in the lidar is carried out.

[6] = Bottom depths are found in Tables 1-1 and 1-2, see also **section 5.2.5**

Table 2-2 Definition wave parameters

Parameter	Unit	Description
hm0	m	Estimate of Hs (significant wave height). Hs is the average of the one third highest waves. $hm0 = 4\sqrt{m0}$ where m0 is the zeroth order moment of the spectrum.
hm0a	m	Estimate of Hs (significant wave height) in the **a** frequency band.*
hm0b	m	Estimate of Hs (significant wave height) in the **b** frequency band.*
hmean**	m	Average height of individual waves. Calculated from zero-upcrossing analysis.
hmax**	m	Height of the highest individual wave in the sample. Calculated from zero-upcrossing analysis.
hs**	m	Significant wave height, average of the one third highest waves. Calculated from zero-upcrossing analysis.
mdir	°	Mean spectral wave direction. Computed from spectral analysis.
mdira	°	Mean spectral wave direction in the **a** frequency band.*
mdirb	°	Mean spectral wave direction in the **b** frequency band.*
sprtp	°	Wave spreading at the spectral peak period. Computed from spectral analysis.
thhf	°	Mean wave direction at the spectral peak period. Computed from spectral analysis.
thtp	°	High frequency mean wave direction. This is the mean wave direction over the frequency band 0.40 – 0.45 Hz, corresponding to wave periods between 2.2 – 2.5 sec.
tm01	s	Estimate of mean wave period Tz or the average period of the individual waves. Calculated from the spectral moments. tm01 = m0/m1 where mn are the nth order spectral moments.

Parameter	Unit	Description
tm02	s	Estimate of mean wave period Tz or the average period of the individual waves. Calculated from the spectral moments. $tm02 = \sqrt{(m0/m2)}$ where mn are the nth order spectral moments.
tm02a	s	Estimate of mean wave period Tz or the average period of the individual waves in the **a** frequency band.*
tm02b	s	Estimate of mean wave period Tz or the average period of the individual waves in the **b** frequency band.*
tp	s	Period of the spectral peak
thmax**	s	Period of the highest wave. Calculated from the zero-upcrossing analysis.
tz**	s	Average period of individual waves. Calculated from the zero-upcrossing analysis.
ts**	s	Average period of the one third highest waves. Calculated from the zero-upcrossing analysis.
ui	-	Unidirectivity index, an indicator for the unidirectionality of the spectral wave components. If all mean wave directions are propagating in the same direction, ui=1

* Swell and wind sea frequency ranges:

Band "a" (Swell): 0.04 – 0.10 Hz (corresponding to wave periods between 10-25 sec, i. e. long waves)

Band "b" (Wind sea): 0.10 – 0.50 Hz (corresponding to wave periods between 2-10 sec, i. e. short waves)

** zero-upcrossing requires a certain number of "high" wave in the data series to be calculated e.g. 25. Both hmax and thmax thus are usually not calculated if significant wave height is lower than approximately 0.3 m.

2.3 Upward Looking Current Profiler

In addition to the Wind LiDAR buoys, separate upward looking current profilers (on/tethered near the seabed) measure current speed and direction, seawater temperature and water level (see also section 3.11.3). This sensor is offline, and data is downloaded at services and at the end of the campaign. The measurement setup is detailed in **Table 2-3**.

Table 2-3 Configuration of measurements of Upward Looking Current Profiler

Instrument Type	Sensor Height [m]	Parameter Measured	Sample Height[1] [m]	Sampling Interval [s]	Averaging Period [s]	Burst Interval [s] [2]	Measurement Resolution	Transmitted?
Nortek Signature 500	-1	Current speed and direction profile, water temperature (at 1m depth)	-2 … -bottom[6]	1	180	600	2 cm/s 1° 0.1°C	Yes

Notes

[1] = Height relative to actual sea surface.

[2] = A burst of measurements is the raw data time series used to calculate the average parameters. The burst interval is the time from the beginning of one burst to the beginning of the next burst, and equal to the interval between writing of raw data to disk and transmissions. Note that wave bursts overlap by 424 s.

[6] = Bottom depths are found in Tables 1-1 and 1-2, see also **section 5.2.5**

3. Measurement Principles

3.1 Heading sources

There are two main heading sources on each SWLB: the magnetic compass and the DGPS system. The compass gives direction relative to magnetic north, while the DGPS system gives direction relative to true north. For wind direction, the Gill sensor uses the compass as heading source, while for the LiDAR wind directions the DGPS system is the main heading source. However, wind directions from the LiDAR can also be given using the magnetic compass as heading source if the DGPS system is unavailable. Raw 1 Hz heading data are stored on disk as backup/fallback. Each mast and instrument is mounted such that all instruments are correctly aligned to the buoy reference and that no directional bias due to mounting is present.

In addition, the Wavesense and Aquadopp/Signature each have a built-in compass that is used as heading source to align the wave and current directions respectively (both relative to magnetic north).

The upward looking current profiler also have built-in compass used as heading source.

3.2 Buoy Position

Coordinate positions with latitudes and longitudes are measured by two systems: the Iridium GPS and the Septentrio GPS. The latitudes and longitudes recorded from these two systems are compared to verify the positioning of the buoy.

The position measurements from the LiDAR met station are not used in this campaign as the sensor is showing slow response.

3.3 Directional Wave Sensor Wavesense 3

The wave measurements are based on the fact that the discus shaped buoy will respond to the waves by following the height and slope of the waves, so that the wave motion can be interpreted as the motion of the sea surface. The Wavesense 3 wave sensor employs accelerometers, rotation sensors and a compass to calculate the position, velocities and rotations of the buoy in all directions in space. From these data the spectra of wave height and direction are calculated, and the wave parameters listed in **Table 2-2** are derived.

Before further analysis, means are removed from buoy acceleration and slope time series. Wave elevation data (heave, east and north) are transformed to the frequency domain using FFT algorithms. After band filtering between 0.04 Hz and 0.5 Hz, an inverse transform is applied to the heave spectrum to generate the corrected time series on which the "zero up-crossing" analysis is applied and maximum wave height, hmax, the period of the highest individual wave, thmax, etc. are calculated. This routine contains a “small wave discrimination” criterion, which requires 25 valid zero-crossings in 17 minutes. As a result, the zero-upcrossing parameters will not be calculated when significant wave height, hm0, is less than approximately 0.3 m.

Raw and smoothed directional spectra are calculated from the distribution of wave elevation as a function of both wave frequency and wave direction using the Burg Maximum Entropy Method. Fourier coefficients are determined from cross and quad spectra and directional wave parameters are calculated.

The wave parameters are based on a time series of 2048 2 Hz values, i.e. 17 minutes (1024 s ≈ 17 min). When the acquisition is complete, the analysis phase starts using FFT (Fast Fourier Transform) algorithms. Wave bursts overlap by 424 s, i.e. data is collected for 1024 s, but data is analyzed and written to file every 600 s. Approximately 25 minutes in total are needed for a full measurement cycle, including "heat-up", 17 min sampling and time to run FFT analysis. The measurements are taken continuously and the processing windows overlap.

The wave sensor is integrated with the Fugro control and data acquisition unit GENI 3 and the processing of the wave data (height, period and direction) is done on board. The raw 2 Hz wave sensor data (heave, pitch, roll and compass from SWLB, are saved for later recalculation and detailed analyses).

3.4 Wind sensor Gill WindSonic

The Gill WindSonic is an ultrasonic wind sensor measuring the wind along the two horizontal axes defined by the sensor transmitting and receiving elements. The travel time difference of ultrasound emitted in opposite directions along the two perpendicular axes is used to calculate the wind speed components along those axes. From the components the wind speed and direction relative to the instruments x-axis is computed. The average wind speed, gust and wind direction are calculated and included in the buoy data acquisition system.

3.5 The ZX 300M LiDAR

The ZephIR LiDAR is a Continuous Wave (CW) LiDAR system. The continuous beam emitted from the window at the top of the LiDAR is slanted at an angle from the vertical and rotates with a period of 1 s around the central axis to continually scan a cone in the air. The return is focused to a particular elevation using an optical focus stage and samples individual line of sight points around the circle. The magnitude of the Doppler shift of the backscattered individual line of sight samples is used to reconstruct the 1 s wind field at a particular elevation.

The LiDAR focuses at each of the 10 pre-selected heights sampling the wind profile in sequence. Before going back to another profile, the LiDAR spends some time doing other tasks, such as looking for precipitation, fog and cloud base, and measuring at the reference height of 38 m above the laser. The effective interval between each profile is about 17 s.

The profiles collected at 17 s intervals are averaged to give a time series of 10-minute average horizontal and vertical wind which are stored on the LiDAR unit but not used by the SWLB system. The SWLB Wavesense 3 processing unit, takes the raw 1 Hz LiDAR data and uses data from the DPGS system to produce the 10-minute averages relative to north. From the components, the wind speed and direction relative to the instrument's x-axis are computed. Then the wind direction is calculated using the measurement of buoy heading from Septentrio DGPS. Wind directions are also checked in real-time against the data from the Gill wind sensor to resolve the 180 ambiguity in the results due to the ambiguity in the magnitude of the Doppler shift. In addition to being stored on the LiDAR unit itself, the 1 Hz data from the LiDAR are also stored on the GENI 3 data logger independently of the LiDAR unit as second backup.

Up to a total of 36-37 wind data packages are collected in 10 minutes. A minimum of 9 packages (25 %) are required to qualify as a valid measurement.

Averaging over 10 minutes also serves as motion correction for average speed and direction.

The LiDAR is equipped with a met station that includes a compass. However, this instrument suite shows slow responses compared to the main independent sensors. Data acquired by the lidar met station is considered supporting data fallback/backup. Any errors in the met station do not impact the LiDAR wind measurements except for instances where the LiDAR unit is restarted.

3.6 Motion Compensation for Lidar Turbulence Measurements

Fugro has implemented a process to compensate lidar data for the influence of motion on estimates of turbulence intensity and can now offer fully motion-compensated TI estimates from the SWLB as an optional and additional task. In the work published by Kelberlau et al. (2020) [6] we show that it is possible to measure TI as accurately as with a fixed lidar when all effects of motion are compensated for in the lidar data processing. This proven motion-induced turbulence compensation requires the availability of line-of-sight (LoS) velocities (50Hz data). A collaborative effort between ZX Lidar and Fugro led to the release of modified firmware of the ZX300 lidar that allows automated recording of LoS data. The process of motion compensation is based on high resolution measurement data and can only be performed after data has been downloaded. Provision of real-time data is only possible for uncompensated TI data.

The Lidar Motion Compensation Unit (LMCU) is an auxiliary motion sensor and data logger specifically designed to capture data needed for turbulence intensity (TI) calculations. It contains an inertial navigation system, that calculates attitude and translational motion using triaxial accelerometers and gyroscopes aided by a dual-antenna GNSS with heading measurements. In addition, the LMCU copies the quality-controlled line-of-sight data made available by the wind lidar to ensure data for a whole campaign is backed up and stored. The TI calculations themselves are performed at a later stage.

3.7 Air Pressure

The Vaisala pressure sensor PTB330A inside the buoy includes Vaisala's top class BAROCAP® pressure sensing technology. The sensor is exposed to the pressure of the open air through a diffusor head on the mast which removes the pressure reducing effect of the wind from the air pressure measurement. The sensor is located inside the buoy hull with free access to the atmosphere through the battery venting system.

3.8 Air Temperature and Humidity

The Vaisala HMP155 measures air temperature and humidity using a state-of-the-art HUMICAP® 180R humidity sensor element and a fast temperature probe. The mounting of the sensor in a protective housing on the mast top sensor carrier ensures that the sensor is exposed to the free air and yet shielded from cooling and heating due to solar and diffuse radiation.

3.9 Visibility

Visibility is measured by a MiniPWS optical sensor for visibility and precipitation. The sensor uses an IR VCSEL laser. The sensor is heated to a few degrees above ambient temperature in order to keep moisture away from the lenses. In order to keep the electronics dry, a membrane ventilator keeps the pressure inside at the same level as outside. Output recorded are the measured visibility in meters and WMO codes for precipitation.

3.10 Precipitation

Precipitation is measured by a Young Precipitation Gauge that measures rain or snow precipitation without moving parts. Designed with a centrally located capacitive sensor, it is unaffected by unsteady conditions. Rain or snow collected in the catchment funnel is directed into the measuring chamber. Column level is sensed by a capacitive probe and converted to a linear voltage signal.

3.11 Sea water temperature

Sea surface water temperature (at approximately 1 m depth) is measured by both the Aquadopp and Signature current profiler. Both are on-line and are regarded as accurate sensors.

In addition, the Thelma acoustic receiver in the end of the keel weight is equipped with a temperature sensor. This is placed at approximately 2 m depth. This temperature sensor is also on-line.

Bottom water temperature near seafloor is measured by the Thelma water pressure sensor.

3.12 Current velocity profile

3.12.1 Downward looking Aquadopp (on SWLB 2.x)

The Nortek Aquadopp 400 kHz current profiler is mounted in the buoy hull with the acoustic head immediately below the hull facing vertically downward. The three slanted transducers emit sound pulses forming 3 acoustic beams at an angle from the vertical. The Doppler shift of sound echoed from particles such as plankton in the water is used to calculate the current velocity component along the beam. The vertical and horizontal velocity components are then calculated, and a large number of pulses are used to calculate the 10-minute average current velocity.

Signal-to-noise (here "amplitude") information is stored internally in the current profiler and also stored in the data logger. A high-pass filter on amplitude is applied to the current data using the beam with the lowest signal strength.

3.12.2 Downward looking Signature (on SWLB 3.0)

The Nortek Signature 500 current profiler is mounted in the buoy hull with the acoustic head immediately below the hull facing vertically downward. The Signature 500 has four slanted beams and a fifth vertical beam. The four slanted beams are used for measuring the Doppler shift. Each pair of beams (beams number 1and 3 and 2 and 4) measures one horizontal and one vertical velocity component. The 3D velocity is the resultant of the horizontal velocity from beam 1 and 3, horizontal velocity from beam 2 and 4 and one of the vertical velocities. The vertical (5^{th}) beam ensures a well-resolved vertical motion.

Signal-to-noise (here echoIntxx) information is stored internally in the current profiler and also stored in the data logger. A high-pass filter on amplitude is applied to the current data using the beam with the lowest signal strength.

3.12.3 Upward looking Signature (moored separately)

A Nortek Signature 500 current profiler is placed on the bottom near the buoy on its own mooring. This upward looking sensor is measuring current profile from bottom to surface. This sensor is offline, and data are downloaded at service.

The Signature 500 has four slanted beams and a fifth vertical beam. The four slanted beams are used for measuring the Doppler shift. Each pair of beams (beams number 1 and 3 and 2and4) measures one horizontal and one vertical velocity component. The 3D velocity is the resultant of the horizontal velocity from beam 1 and 3, horizontal velocity from beam 2 and 4 and one of the vertical velocities. The vertical (5^{th}) beam ensures a well-resolved vertical motion.

3.13 Water level

The main method for determining water level is the use of the Thelma pressure sensor.

Water level is not measured directly but inferred from measurements of water pressure at the seabed. The Thelma water level sensor is mounted on its own mooring connected to the buoy mooring. The pressure sensor head is free floating and located at nominally 1 m above the seabed.

To get the proper height of the water column above the sensor, the air pressure measurement from the buoy must be subtracted from the total measured water pressure as follows:

$$h_w = \frac{P_w - P_a}{\rho g}$$

where h_w is the height of the water column, P_w is the measured total water pressure, P_a is the measured total air pressure, ρ is the average density of the water, and g is the normal acceleration of gravity.

In addition, the bottom-mounted Nortek Signature 500 also records water pressure and contains an upward-looking echo sounder. These independent data can also be used as backup water level measurements.

4. Redundant parameters

The total system has several fully and partially redundant sensors:

- Air pressure
- Air temperature
- Surface water temperature
- Bottom temperature
- Water level
- Current profile

The results from these measurements are made available for the data acquisition unit and are transmitted to shore. These redundancy measurements can serve two functions; to be backup sensors for the mentioned parameters that can easily be switched in in case of failure of the main sensors and to be used for verification on the main sensor results.

4.1 Air temperature and air pressure

In addition to the main independent sensors (Vaisala), the Lidar on the buoy is equipped with a meteorological station that also measures air pressure and air temperature.

In general, the main sensors for air pressure and air temperature are regarded to give higher data quality/accuracy than the same parameters measured by the Lidar met. station. The sensors are tested against each other during pre-deployment validation and the results from the met station can thus be corrected for eventual offset.

4.2 Sea Surface Water Temperature

Surface water temperature (at approximately 1 m depth) is measured by both the Aquadopp and Signature current profiler. Both are on-line and are regarded as accurate sensors.

In addition, the Thelma acoustic receiver in the end of the keel weight is equipped with a temperature sensor. This is placed at approximately 2 m depth. This temperature sensor is on-line.

4.3 Bottom Temperature

Water temperature close to bottom is measured by both the Thelma water pressure sensor and the Signature 500 current profiler. The Thelma bottom temperature is on-line and is used for monthly reporting. The Signature 500 data is offline and will be downloaded at service. They can be used to replace or supplement the Thelma bottom temperature data at a later stage.

4.4 Water Level

Water level is measured by four different systems:

- Thelma water pressure sensor (on-line)
- Signature 500 water pressure sensor (offline)
- Signature 500 echo-sound sensor (offline)
- Septentrio GNSS based water level measurements (backup, data store internally in Septentrio, must go through comprehensive processing if it needs to be used)

The Thelma water pressure data will be used in monthly reporting. The Signature water level data will be downloaded at service and can replace or supplement the Thelma data at a later stage. Both the Thelma and the Signature water level data has good accuracy; resolution 1 cm. The Septentrio GNSS water level measurements have accuracy 6-10 cm, and raw data are recorded as backup. Due to comprehensive need for post-processing, it will not be used unless the Thelma and the Signature 500 fail.

4.5 Current Profile

The Wind Lidar buoy is equipped with either an Aquadopp 400 kHz or a Signature 500. This downward looking sensor is measuring current profile from surface to bottom. Data from this sensor is on-line and will be used in the monthly reporting. In addition, there is a Signature 500 current profiler placed on the bottom near the buoy. This upward looking sensor is measuring current profile from bottom to surface. This sensor is offline, and data are downloaded at service.

The downward looking sensor will not give good data close to bottom due to reflections from the bottom. The upward looking sensor will not give good data close to surface due to reflections from the surface. The sensor in the buoy will move around with the buoy and will tilt with the buoy, while the bottom mounted sensor is in a fixed position all the time, but will tilt if the bottom current is strong. The current profilers, especially the one in the buoy, is subject to biofouling in the summer period.

The final data set will be the best combination of the two profilers.

5. Data flow, post-processing, and quality control

5.1 Data Flow

For each instrument on a SWLB, the measurement processes are set-up individually according to the resolution needed. The measurements are stored in the onboard in-memory database and, every 10 minutes, packed into encrypted messages and stored. Selected measurements are averaged over 10 minutes and/or used in internal processes together with other measurements from other sensors:

- GPS position and current data (i. e. Aquadopp or Signature-produced 10-minute-averages including sea surface temperature) are delivered by these instruments every 10 minutes for storage. No further treatment of either data is done on board.
- Air pressure, air temperature, air humidity, precipitation, and visibility as well as data from the bottom mounted Thelma pressure sensor are stored in the internal memory database at their respective measurement rates. 10-minute-averages are calculated for storage every 10 minutes.
- Wave parameters are calculated onboard from raw data and stored every 10 minutes.
- Heading information (compass and DGPS) and data from the Gill sensor are continuously stored at 1 Hz and averaged for each 10-minute interval. In addition, these measurements are also made available in real time for the LiDAR processes.
- The LiDAR unit measures at 1 Hz. The LiDAR data are combined with buoy heading information to reference buoy direction to north before calculating the 10-minute-averages. Averaging over 10 minutes also serves as motion correction.

The buoy converts all measurements to physical quantities in SI units. Every 10 minutes the data are timestamped and packed for simultaneous transmission and storage in binary integer numbers using a proprietary compression algorithm (pff), giving sufficient digital resolution while using minimal storage space. The digitization resolution is higher than the actual measurement resolution ensuring lossless compression. The high resolution also ensures that there is no biasing effect due to the digitization of the data. The data are stored in several pff messages to further minimize file size.

Each SWLB is set up with unique telemetry message identifiers. Together with deployment records, timestamps and position data, the datasets for each of the buoys/stations in this campaign will be kept separate and will be unique.

Data measured at each buoy is simultaneously both stored locally and transmitted via satellite to allow for near real-time operations checks, maintenance scheduling and monthly reporting. At the receiving end the data are unpacked to physical values in real numbers using the reverse conversion method. The application of the compression algorithm also means that the data in transmission are encrypted.

When a buoy is serviced, the following stored data are downloaded:

- stored pff messages
- raw data stored in the GENI 3 data logger (raw wave data, raw Thelma data)
- raw data stored on the major instruments (LiDAR, DGPS, Aquadopp, Signature as well as LMCU) as they have their own independent storage capacity

10-minute averages transmitted via satellite form the basis of the monthly reports. Any gaps in the transmitted data or data deemed suspicious after the monthly quality checks are performed, are flagged. These gaps and issues are investigated once stored data are available.

10-minute averages stored in the pff messages on the GENI 3 datalogger form the basis of the final campaign dataset. This eliminates gaps due to transmission problems. In addition, any data downloaded during a service or at the end of the campaign (pff and raw) are used to investigate gaps in the data set that occurred during the deployment. When necessary and if available (no other instrument issues), the data can be re-processed using raw data and used to fill gaps.

5.2 Post-processing

5.2.1 General Steps and Filtering

No tampering or modifications are applied to increase the post-processed availability or enhance the data quality. In post-processing the system integrity is maintained. Post-processing is limited to use of data from the system itself, not depending on use of data from any external sources.

Post-processed data are those values following the steps below. Post-processing is therefore limited to qualifying those quantities by:

a. Deployment period, i.e. removing values outside of those times where the system is deployed at the target position (e.g. in transit to/from shore or onshore)

b. Check that data was saved for all 10-min intervals. If not, substitutions of NaN values when all data for a 10-min time step is missing

c. Removing duplicated measurements (if all measurements/parameters by one sensor are repeated over several time step, the duplicated values are removed)

d. Removing out of range values (e.g degrees above 360) and replacement by NaN (**Table 5-1**)

e. Applying parameter group / instrument specific quality control measures for specific groups outlined below

f. Inspection and assessment (QA/QC) by senior meteorologist/oceanographer

Unless otherwise agreed, post-processing is done as a part of the monthly reporting.

The QA/QC filter ranges used for each parameter (group) are listed in **Table 5-1**.

Table 5-1 QA/QC filter ranges for each parameter

Parameter	Minimum Value	Maximum Value	Unit
Wind speed lidar	0.001	58	m/s
Wind speed Gill	0.001	35	m/s
Direction (**all**)	0	360	°
Current speed	0	135	cm/s
Current signal strength criteria - Aquadopp	2 x noise floor (given in sensor certificate)	-	counts
hm0	0	18	m
hmax	0	24	m
tp	0.1	23	s
thmax	0.1	23	s
Air humidity	0.01	100	%
Air pressure	905	1100	hPa
Air temperature	-10	35	°C
Water temperature	0.1	30	°C
Water pressure	5 dbar below Maximum Value	Equivalent to water depths, Tables 1-1 and 1-2	dbar
Visibility	10	5000	m
Precipitation	0	10	mm/10min

5.2.2 Duplicate Data (“Flatliner”) Filtering

Repeated values in the processed dataset can be due to measurement resolution, digital binning and/or slow changing physical processes. The challenge is to remove duplicate values, but not real measurements that is being constant during stable conditions. Some natural processes are fast, like wind, while others are slow (e.g. water temperature).

The following duplicate data filtering is applied:

- If any parameters measured by the same sensor is changed from one time step to another, the measurement are regarded as good. Example; air temperature and humidity is measured by the same sensor; if one of them change from one time step to the next, then the measurement for both is good.

- Any single duplicate is flagged to respective wind, ancillary wind, wave and current parameter groups. i.e. all parameters in respective group should be identical in the next timestamp to be regarded as “duplicate” and “invalid”. Otherwise, they are regarded as good measurement.
- If any one of the components of the wind vector (horizontal, vertical or direction) has changed, then all of them must have been updated since they are stored simultaneously (atomically) by the same process and are compressed into the same pff-telegram. If for example the horizontal component is then repeated twice, it must be because it fell in the same digital step. This can happen during stable conditions.
- For air temp and humidity (Vaisala HMP155), 5 duplicates (<1 hour constant value) are allowed.
- For air pressure (Vaisala PTB330) 10 duplicates (~1½ hour constant value) is allowed.
- For near surface water temperature measured by current meter 23 duplicate values (<4 hours constant value) is allowed.
- For bottom temperature measured by Thelma 72 duplicate values (12 hours constant value) is allowed

5.2.3 Wind Data Post Processing

The following steps are applied to the wind data:

1. Check for duplicated measurements (Duplicate to NaN (all))
2. Filter Gill speed and direction (Gill only) for min and max values
3. Filter LiDAR speed (horizontal and vertical speed only) for min and max values
4. Filter LiDAR direction for min and max values
5. Apply 180° ambiguity fix on LiDAR wind directions using Gill directions
6. Calculate wind signal availability for all heights and system availability for 4-200 m (see **section 5.4**)

5.2.4 Wave Data Post Processing

The following steps are applied to the wave data:

1. Check for duplicated measurements (Duplicate to NaN (all))
2. Filter wave height, wave period and wave direction for min and max values
3. Check for hmax < hm0 and remove if found

4. Calculate wave signal availability for all parameters and system availability, excluding parameters derived from zero up-crossing (hmax, hmean, hs, thmax, ts, tz, see **section 5.4**)

5.2.5 Current Data Post Processing (online, top-down)

The following steps are applied to the current data:

1. Check for duplicated measurements (Duplicate to NaN (all))
2. Filter current velocity and direction for min and max values
3. For Aquadopp: Filter current velocity and direction for all depths based on signal strength (Amp). Current velocity and direction where signal strength is below the minimum threshold is removed. Note that there is a different minimum Amp cut-off for each sensor as a result of the different noise floors of each instrument.
4. Check and eventually remove data due to reflections near the bottom based on sharp increase in signal strength near the seafloor. The valid depth range is 1-2 dbar less than corresponding to the depth, see Tables 1-1 and 1-2
5. Calculate currents signal and system availability (see **section 5.4**)

5.2.6 Meteorological parameters (visibility, precipitation), sea surface temperature

The following steps are applied to this data:

1. Check for duplicated measurements (Duplicate to NaN (all))
2. Filter for min and max values
3. Calculate signal and system availability (see **section 5.4**)

5.3 Quality Control

Fugro follows the international standard recommendations ISO-19901-1:2015 for the collection and supply of oceanographic data, in general:

1. To verify the proper functioning of the measuring and recording systems.
2. Qualified personnel conduct the observations, selection, installation, checking and maintenance of the equipment.
3. For data quality control procedures.

Data are first checked for gaps, instrument and buoy operation issues and timestamp and compass alignment as well as duplicated values indicating potential instrument or data logger issues. Data plots are prepared during post-processing showing the original data set and the effect of the post-processing filters applied. In general, all the measured parameters are expected to vary over time depending on the parameter. In addition, the sensors represent parameters that are dynamic and variations in one parameter are typically coupled to variations in one or several other parameters.

The quality control steps are divided into the following categories:

A. Buoy operation:

- "Household" parameters, i.e. power supply (fuel cells, batteries, power consumption by instrument), error logs, and position data are used to assess the function of the buoy.
- Any reboots and power supply issues leading to loss of data are identified here.
- Buoy position is checked to verify the buoy stayed in position during the deployment.
- Info and status flags from the ZephIR LiDAR unit are stored as part of the household parameters and are used to track the functionality of the LiDAR unit.

B. Variation of single parameters:

- Some degree of variation is expected. Duplicated values and missing data are indications for instrument operation issues.
- The measured data are checked against ongoing weather conditions. Reasonable agreement with the nearest weather observations is expected.
- For currents the diurnal and semidiurnal variations due to the tides should be observed.

C. Variation of related parameters:

- Humidity and air temperature are expected to increase in rain and fog.
- The wave period will generally increase with increasing wave heights.
- Max wave height is at the average 1.9 x significant wave height
- Correlation between speed and direction at adjacent levels for both wind and currents is expected.
- Reasonable agreement between Gill and LiDAR measurements is expected.
- The gust (from Gill sensor) should be 10-40 % higher than the wind speed.
- Wind against waves (e.g. high waves during high winds, low winds with long swells, wind from offshore expect correlation between increasing wind speed and wave height).

D. Variation between buoys:

- Taking variations between the buoys due to location/distance/water depth into account.
- Air pressure should be very similar.
- Temperature (both in air and water) should not differ by more than 2-3 °C.
- Wind speed and direction should be correlated.

5.4 Availability calculations

5.4.1 Monthly System Availability: One-Month Average

The Floating 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. by NaNs or 9999s) for the given month.

Note that for the system to be considered “ready”, at least one valid data point must be recorded (at any height).

The Monthly Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10-minute) data entries including periods of maintenance within the respective calendar month.

5.4.2 Monthly Post-processed Data Availability: One-Month Average

The Monthly Post-processed Data Availability is the number of those data entries remaining after subtraction of all non-valid entries caused by including but not limited to:

- downtime (due to equipment failure, maintenance, weather, damage, malfunction, theft, or any other events)
- Lidar internal (unseen) filtering (as set by the Lidar manufacturer)
- application of quality filters based on system own parameters

These are divided by the maximum possible number of 10-minute data entries within the respective month based on the given time interval of 10-minutes.

5.4.3 Post-processed parameter group availability

The monthly post-processed parameter group availability is determined as follows:

a. Wind:

   Average of the 10-minute averaged monthly post processed data availabilities per measured elevation, speed and direction up to and including 200 m from the LiDAR but excluding measurements at height > 200 m, and also including near surface wind speed and direction, i. e. wind measured in mast top (4 m height) by the Gill Windsonic sensor:

b. Atmospheric pressure:

c. Air temperature:

d. Air humidity:

e. Sea surface temperature:

WaterTemp001 degC (Aquadopp) or ADCP_temperature degC (Signature)

f. Wave:

Average of wave parameters excluding any zero-upcrossing parameters (10-min frequency)

g. Current:

Average of valid current speed and direction over the water column, except the bin nearest to bottom.

h. Water level:

Water pressure for monthly report

In the case of multiple (redundant) measurement instruments determining one parameter value, the availability of at least one parameter value is the determining base for the data availability. For more details see Chapter 4.

Table 5-2 Parameter group availability (monthly)

Parameter group	Parameters	
Wind	WindSpeed004m m/s, WindSpeed012m m/s, WindSpeed040m m/s, WindSpeed080m m/s, WindSpeed100m m/s, WindSpeed130m m/s, WindSpeed150m m/s, WindSpeed170m m/s, WindSpeed190m m/s, WindDir004m deg, WindDir012m deg, WindDir040m deg, WindDir080m deg, WindDir100m deg, WindDir130m deg, WindDir150m deg, WindDir170m deg, WindDir190m deg,	
Atmospheric pressure	AirPressure hPa	
Air temperature	AirTemperature C	
Air humidity	AirHumidity %	
Sea surface temperature	Aquadopp	WaterTemp001 degC
	Signature	ADCP_temperature deg C
Wave	hm0 m, hm0a m, hm0b m, mdir deg, mdira deg, mdirb deg, sprtp deg, thhf deg, thtp deg, tm01 s, tm02 s, tm02a s, tm02b s, tp s	
Current *	Aquadopp	AqSp002 cm/s, AqSpd003 cm/s, ..., AqSpd(bottom) cm/s, AqDir002 deg, AqDir003 deg, ..., AqDir(bottom) deg

	Signature	currSp002 cm/s, ..., currSp(bottom) cm/s, currDir002 deg, ..., currDir(bottom) deg
Water level *	WaterPressure dbar	

*Data from the Signature on the bottom can be used to fill in and improve availability when such data becomes available after service

5.5 Post processed data in each delivered data file

Table 5-3 summarize the contents of each delivered datafile following the post-processing steps outlined in **Chapter 5**.

Table 5-3 Post-processed SWLB data by files

File	Signals
CurrentData	The file contains 10-minute average data calculated on the buoy from the current profiler. All timestamps are set at the end of the averaging period. For all current speed and direction signals AqSpd(d) and AqDir(d), where d = 2,3,4,5, ..., (water depth – 2 m) m, the data are checked for out-of-bounds values and signal strength. For timestamps and depths where the speed is outside the accepted range, the speed and direction are set to NaN.
MetOceanData	The file contains 10-minute average data calculated on the buoy from the meteorological and oceanographic sensors. All timestamps are set at the end of the averaging period. Parameters: Air and Water Temperatures, Air Pressure, Humidity from all available sensors, precipitation, visibility, water pressure,. All data with values outside the accepted range are replaced by NaNs.
PosData	The file contains 10-minute average position data from all available sources. All timestamps are set at the end of the averaging period.
Status	The file contains hourly buoy status data. Parameters: fuel, voltage, battery, error codes.
WaveData	The file contains the wave data at 10-min frequency based on 17 min sampling. Parameters: hm0, hm0a, hm0b, hmax, hmean, hs, mdir, mdira, mdirb, sprtp, thhf, thmax. thtp, tm01, tm02, tm02a, tm02b, tp, tz, ts. All data with values outside the accepted range are replaced by NaNs.
WindSpeedDirectionTI	The file contains 10-minute averaged wind speed and direction measurements as well as turbulence intensity calculated on the buoy. The signals are all timestamped with the end of the averaging period. All wind measurements must have wind speed and direction values. For timestamps where either the wind speed or direction is outside this range, the speed and direction are set to NaN. To correct for 180 degrees ambiguities in the lidar wind directions, an additional correction with 10-minute average directions from the Gill wind sensor as ground truth is used. The correction is done automatically using an algorithm checking each height for ambiguous wind directions and flipping it 180 degrees if necessary.

File	Signals
WindStatus	This file contains status information from the lidar unit. Parameters: Packet count, mirror temperature, rain count, battery voltage, POD humidity, status flags, info flags

5.6 Offline Data Delivery

High frequency data and other offline data will be delivered after downloading data after services and at the end of the measurement campaign. This includes:

- Raw wave data (2 Hz)
- Raw buoy motion data
- Raw Lidar data (10 min and 1 Hz)
- Raw current profile data from sensor on the buoy
- Raw current profile, water temperature, water pressure and distance to surface data from the bottom mounted Signature

All raw data will be delivered as they are. Only processing will be to cut off data from periods when the unit was out of position.

Data from the upward looking Signature on the bottom will be processed as described earlier. Data about water level will be used to make water level data as complete as possible.

The 1 Hz Lidar data together with the collected buoy motion data will be used to make motion compensated turbulence intensity (TI) data if/when this is agreed.

The raw wave data can be used to make wave spectra.

5.7 Final campaign dataset

10-minute averages transmitted via satellite form the basis of the monthly reports. Any gaps in the transmitted data or data deemed suspicious after the monthly quality checks are performed, are flagged.

The final campaign dataset is based on the 10-minute averages stored in the pff messages onboard the buoys. This eliminates gaps due to transmission problems. The same quality control procedure is applied to this data as for each monthly report. In addition, any data downloaded during a service or at the end of the campaign (pff and raw) is used to investigate gaps and issues in the data set that were flagged during the monthly reporting. When necessary and if raw data is available (i.e. no other instrument issues), data gaps can be filled with in-house re-processed data using the available raw data. Re-processed data are calculated using the same algorithms as onboard the buoys. Otherwise, gaps and remaining issues are explained to the point that that is possible with the information stored.

Therefore, the data provided monthly are quality checked and fit for preliminary further investigations. However, there may be gaps.

The final campaign dataset covers the whole campaign period, is further quality checked and is as complete as possible.

5.8 Signal tables

The following tables contain a description of each parameter delivered in each data file including digital resolution and maximum valid range encoded in the pff algorithm.

5.8.1 Signal tables SWLB

Table 5-4 CurrentData parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code *	Resolution	Valid Range
AqDir00xx† deg	deg	-2 … -depth – 2 m	Current direction	Nortek Aquadopp	B	0.176758	0, 360
AqSpd00xx† cm/s	cm/s	-2 … -depth – 2 m	Current speed	Nortek Aquadopp	B	0.293945	0, 200
AqAmpxx† int	count	-2 … -depth – 2 m	Signal strength	Nortek Aquadopp	B	1	0, 128
currDir0xx† deg	deg	-2 … -depth – 2 m	Current direction	Nortek Signature	B	0.176758	0, 360
currSp0xx† cm/s	cm/s	-2 … -depth – 2 m	Current speed	Nortek Signature	B	0.293945	0, 300
echoInt0xx† int	count	-2 … -depth – 2 m	Signal strength	Nortek Signature	B	1	0, 256

* Proc. Code: Code describing the level of processing applied to data after receipt from the buoy:

B: Data as delivered by the buoy and quality checked

D: Data are calculated during post-processing

† xx = 2, … , (water depth – 2 m) m corresponding to measurement depth

Table 5-5 MetOceanData parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code *	Resolution	Valid Range
AirHumidity %	%	4	Air humidity	Vaisala HMP155	B	0.107422	0, 100
AirPressure hPa	hPa	0	Air pressure	Vaisala PTB330	B	0.0976563	905, 1100
AirTemperature C	°C	4	Air temperature	Vaisala HMP155	B	0.0537109	-15, 40
AirPressure_lidar hPa	hPa	2	Air pressure from lidar met station	ZephIR	B	0.0976563	905, 1100
AirTemp_lidar C	°C	2	Air temperature from lidar met station	ZephIR	B	0.0537109	-15, 40
tnSNR dB	dB	1 m above bottom, see Tables 1-1 and 1-2	Bottom sensor signal strength	Thelma	B	0.703125	0, 90
thTBRtemperature degC	°C	-2	Surface water temperature	Thelma modem	B	0.0996094	2.9, 40
thTilt deg	deg	1 m above bottom, see Tables 1-1 and 1-2	Bottom sensor tilt	Thelma	B	0.703125	0, 180
BottomTemperature degC	°C	1 m above bottom, see Tables 1-1 and 1-2	water temperature at seafloor	Thelma	B	0.00976563	-5, 35
WaterPressure dbar	dbar	1 m above bottom, see Tables 1-1 and 1-2	Bottom water pressure	Thelma	B	0.0012207	0, 160
precipitation mm/10min	mm/10min	4	Precipitation sensor	Young	B	0.000762939	0, 50
pws_visibility m	m	4.1	Visibility	MiniPWS	B	0.610352	0, 5000
pws_WMOcode int	int	4.1	Visibility decoded	MiniPWS	D	-	-
WaterTemp001 degC	°C	-1	Sea surface temperature	Nortek Aquadopp	B	0.019043	-4, 35
ADCPTempxxx degC	°C	-1	Sea surface temperature	Nortek Signature	B	0.019043	-4, 35

* Proc. Code: Code describing the level of processing applied to data after receipt from the buoy:

B: Data are presented as delivered by the buoy

D: Data presented are derived from post-processing

Table 5-6 PosData parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code *	Resolution	Valid Range
irLatitude deg	°N	4.1	Latitude (position) from the Iridium modem	Iridium	B	4.77E-06	0, 80
irLongitude deg	°E	4.1	Longitude (position) from the Iridium modem	Iridium	B	5.36E-06	-180, 180
spLatitude deg	°N	4.1	Latitude (position) from Septentrio DGPS	Septentrio	B	4.77E-06	0, 80
spLongitude deg	°E	4.1	Longitude (position) from Septentrio DGPS	Septentrio	B	5.36E-06	-180, 180

* Proc. Code: Code describing the level of processing applied to data after receipt from the buoy:

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Table 5-7 Status parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code *	Resolution	Valid Range
fcCurrentz** A	A	0	Current produced by fuel cell z**	GENI 3	B	0.0390625	0, 10
fcErrorz** int	int	0	Error number from fuel cell z**	GENI 3	B	1	0, 128
fcFuelRemz** l	l	0	Remaining fuel connected to cell z**	GENI 3	B	0.0585938	0, 120
fcOpTimez** h	h	0	Operational time of fuel cell z**	GENI 3	B	1	0, 16384
fcULFz** V	V	0	Fan voltage of fuel cell z**	GENI 3	B	0.0585938	0, 15
leadAhCharged Ah	Ah	0	Net battery charging by solar panels during last hour	GENI 3	B	0.0048828	0, 5
leadAhDischarged Ah	Ah	0	Energy drawn from batteries during last hour	GENI 3	B	0.0048828	0, 5
leadBatteryVoltage V	V	0	Voltage in the lead acid batteries	PMU	B	0.0087891	6, 15
lithiumAhDischarged Ah	Ah	0	Discharge of the litium batteries during last hour	PMU	B	0.53125	0, 1088

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code *	Resolution	Valid Range
lithiumBattVoltage V	V	0	Battery voltage in the lithium batteries	PMU	B	0.0087891	6, 15
pmuCardNo no	int	0	Card no in use in the power management unit, 1 or 2	PMU	B	0.25	0, 4
sysUptime unknown	s	0	Time (in seconds) since last reboot of the buoy	GENI 3	B	3600	0, 5.90E+07
thTBRid unknown	Int	0	ID number of the water level sensor at bottom	Thelma	B	1	0, 1024

* Proc. Code: Code describing the level of processing applied to data after receipt from the buoy:

B: Data as delivered by the buoy and quality checked

D: Data are calculated during post-processing

** z= 1,2,3,4 = number of fuel cell

Table 5-8 WindSpeedDirectionTI parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code*	Resolution	Valid Range
WindDir004m	deg	4	Ultrasonic anemometer wind direction	Gill anemometer	B	0.353516	0, 360
WindSpeed004m	m/s	4	Ultrasonic anemometer wind speed	Gill anemometer	B	0.0074463	0, 35
WindGust004m	m/s	4	Ultrasonic anemometer wind gust speed	Gill anemometer	B	0.0074463	0, 35
WindDirxx†	deg	12 .. 300	Lidar wind direction 10 min average calculated on buoy	ZephIR lidar	D	0.176758	0, 360
WindSpeedxx†	m/s	12 .. 300	Horizontal lidar wind speed 10 min average calculated on buoy	ZephIR lidar	D	0.0074463	0, 58
VerticalWindSpeedxx†	m/s	12 .. 300	Vertical lidar wind speed 10 min average calculated on buoy	ZephIR lidar	D	0.0244141	-15,15
windMax_horxx†	m/s	12 .. 300	Maximum horizontal wind speed in 10 min interval	ZephIR lidar	D	0.0595703	0, 58
windMin_horxx†	m/s	12 .. 300	Minimum horizontal wind speed in 10 min interval	ZephIR lidar	D	0.0595703	0, 58

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code*	Resolution	Valid Range
Standard Deviation xx†	m/s	12 .. 300	Standard Deviation of wind speed in 10 min interval using lidar data	ZephIR lidar	D	0.0003662	0, 58
TIxx†	-	12 .. 300	Turbulence intensity#, calculated on buoy	ZephIR lidar	B	0.0003662	-1,5

* Proc. Code: Code describing the level of processing applied to data after receipt from the buoy:

B: Data are presented as delivered by the buoy

D: Data presented are derived from post-processing

† xx = 12m, ... , 300m corresponding to measurement height

\# **Turbulence Intensity** (TI) is defined as: $(\sigma/\bar{u})$ / C where σ is the standard deviation and $\bar{u}$ is the mean of the wind speed for a 10-min period. C = 0.95 is a constant needed to convert the scan-averaged lidar measurement to the point measurements of a cup anemometer. Note that this definition frequently gives relatively high values in situations with low but variable wind speed. Note also that TI is not compensated for the motion of the buoy, which is a source of increased standard deviation in the measurements, and TI is therefore over-estimated compared to what would be obtained from a lidar on a fixed platform. Methods for motion compensation are being developed and corrected data may be calculated in the future. (Z300 MODBUS interface, a user's guide, 19th Dec 2013, issue K, ZephIR Lidar)

Regarding LMCU data, see table 2.1

Table 5-9 WindStatus parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code*	Resolution	Valid Range
liBattteryVoltage**	V	2	Lidar battery voltage	ZephIR lidar	B	0.0087891	6, 15
liPODHumidity**	%	2	Lidar pod humidity	ZephIR lidar	B	0.0976563	0, 100
liRain**	int	2	Lidar rain count	ZephIR lidar	B	1	0, 64
liMirrorTemp**	°C	2	Lidar mirror temperature	ZephIR lidar	B	0.0537109	-5, 50
liStatusFlagHi**	int	2	Lidar status flag high bits	ZephIR lidar	B	1	0, 65536
liStatusFlagLow**	int	2	Lidar status flag low bits	ZephIR lidar	B	1	0, 65536
liInfoFlagHi**	int	2	Lidar info flag high bits	ZephIR lidar	B	1	0, 65536
liInfoFlagLow**	int	2	Lidar info flag low bits	ZephIR lidar	B	1	0, 65536
liStatusFlag**	Int	2	Lidar status flag combined	ZephIR lidar	D	1	0, 65536

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code*	Resolution	Valid Range
liInfoFlag**	int	2	Lidar info flag combined	ZephIR lidar	D	1	0, 65536
liStatusFlagText**	-	2	Lidar status flag translated to text	ZephIR lidar	D	-	-
liInfoFlagText**	-	2	Lidar info flag translated to text	ZephIR lidar	D	-	-
liPacketCountxx†	-	12 .. 300	Number of samples for the averaging period	ZephIR lidar	B	1	0, 37

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D: Data presented are derived from post-processing

† xx = 12m, ... , 300m corresponding to measurement height

** only transmitted 1x per hour

Table 5-10 WaveData parameters SWLB

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code*	Resolution	Valid Range
hm0	m	0	Significant wave height	Wavesense 3	B	0.0196289	0, 20
hm0a**	m	0	Significant wave height, a-band**	Wavesense 3	B	0.0196289	0, 20
hm0b**	m	0	Significant wave height, b-band**	Wavesense 3	B	0.0196289	0, 20
hmean***	m	0	Average height of individual waves***	Wavesense 3	B	0.0196289	0, 20
hmax***	m	0	Height of the highest individual wave***	Wavesense 3	B	0.0293945	0, 30
hs***	m	0	Significant wave height, average of the one third highest waves***	Wavesense 3	B	0.0196289	0, 20
mdir	°	0	Mean spectral wave direction	Wavesense 3	B	0.705078	0, 360
mdira**	°	0	Mean spectral wave direction, a-band**	Wavesense 3	B	0.705078	0, 360
Mdirb**	°	0	Mean spectral wave direction, b-band**	Wavesense 3	B	0.705078	0, 360
sprtp	°	0	Wave spreading at the spectral peak period	Wavesense 3	B	0.705078	0, 360
thhf	°	0	Mean wave direction at the spectral peak period	Wavesense 3	B	0.705078	0, 360

Signal Name	Unit	Height [m]	Description	Sensor	Proc. Code*	Resolution	Valid Range
thtp	°	0	High frequency mean wave direction	Wavesense 3	B	0.705078	0, 360
tm01	s	0	Estimate of mean wave period tz, calculated from spectral moments tm01 = m0/m1	Wavesense 3	B	0.101563	0, 24
tm02	s	0	Estimate of mean wave period tz, calculated from spectral moments $tm02 = \sqrt{(m0/m2)}$	Wavesense 3	B	0.101563	0, 24
tm02a**	s	0	Estimate of tm02 in a-band**	Wavesense 3	B	0.101563	0, 24
tm02b**	s	0	Estimate of tm02 in b-band**	Wavesense 3	B	0.101563	0, 24
tp	s	0	Period of spectral peak	Wavesense 3	B	0.101563	0, 24
thmax***	s	0	Period of the highest wave***	Wavesense 3	B	0.101563	0, 24
tz***	s	0	Average period of individual waves***	Wavesense 3	B	0.101563	0, 24
ts***	s	0	Average period of the one third highest waves***	Wavesense 3	B	0.0196289	0, 20

* Proc. Code: Code describing the level of processing applied to data after receipt from the buoy:

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D: Data presented are derived from post-processing

** Swell and wind sea frequency ranges:

Band “a” (Swell): 0.04 – 0.10 Hz (corresponding to wave periods between 10-25 sec, i. e. long waves)

Band “b” (Wind sea): 0.10 – 0.50 Hz (corresponding to wave periods between 2-10 sec, i. e. short waves)

*** zero-upcrossing requires a certain number of "high" wave in the data series to be calculated e.g. 50. Both hmax and thmax thus are usually not calculated if significant wave height is lower than approximately 0.3 m.

6. References

[1] Energinet ITT_380883 Documents, reference number 22/08580.

[2] Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology, The Carbon Trust, version 2.0, 9th October 2018.

[3] Assessment of the Fugro/ OCEANOR SEAWATCH Floating LiDAR verification at RWE Ijmuiden met mast. Report No.: GLGH-4257 13 10378-R-0003, Rev. B. DNV GL/ GL Garrad Hassan, 30 January 2015.

[4] Floating LiDAR validation analysis, SEAWATCH Wind LiDAR Buoy, Report nr.: 1124607/D. Natural Power on behalf of The Carbon Trust, 7 December 2016.

[5] DNV, Technical Letter 10299802-L-1-B, SEAWATCH Wind LiDAR Buoy Stage 3 confirmation, 2022-02-17.

[6] Kelberlau, F.; Neshaug, V.; Lønseth, L.; Bracchi, T.; Mann, J. Taking the Motion out of Floating Lidar: Turbulence Intensity Estimates with a Continuous-Wave Wind Lidar. Remote Sens. 2020, 12, 898. https://www.mdpi.com/2072-4292/12/5/898