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WHITE PAPER
MOTUS WAVE BUOYS WP002-OCT2018

Data Validation for the MOTUS Directional Wave Buoys

ONE YEAR OF DATA COLLECTION

AANDERAA
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Contents

Summary

The development of the Aanderaa MOTUS Wave Buoys was motivated by the need to provide a cost-effective solution for real-time environmental monitoring from the sea surface. Navigational buoys designed for environmental monitoring are usually not optimized for wave measurement. To solve this, Aanderaa Data Instruments has developed the MOTUS Wave Sensor, a compact, highly accurate, low power accelerometer-based sensor.

This document is a complement of the 2017 MOTUS white paper and describes the exceptional ability of two standard navigational and environmental buoys equipped with MOTUS Wave Sensors to provide accurate directional wave and currents data in all kinds of weather and sea conditions.

1. The MOTUS Directional Wave Sensor

The MOTUS Wave Sensor is designed to accurately measure multi-spectrum directional waves, solving the challenges of measuring waves from non-ideal buoys (buoys that are not optimized to follow the wave movement). The wave sensor processes wave data and is configurable to produce a comprehensive set of wave parameters and spectrums directly. Wave calculations are performed both in the time and frequency domain. Each of these processing chains delivers data at a rate defined by the recording interval, but the integration time for these two processing chains can be set up independently. For the frequency domain based parameters, the wave integration time sets the duration for the samples used in the frequency domain calculations. For the time domain based data, the time series record length gives the duration for the samples used in the time domain calculations and also the duration of the time series output (Figure 1).

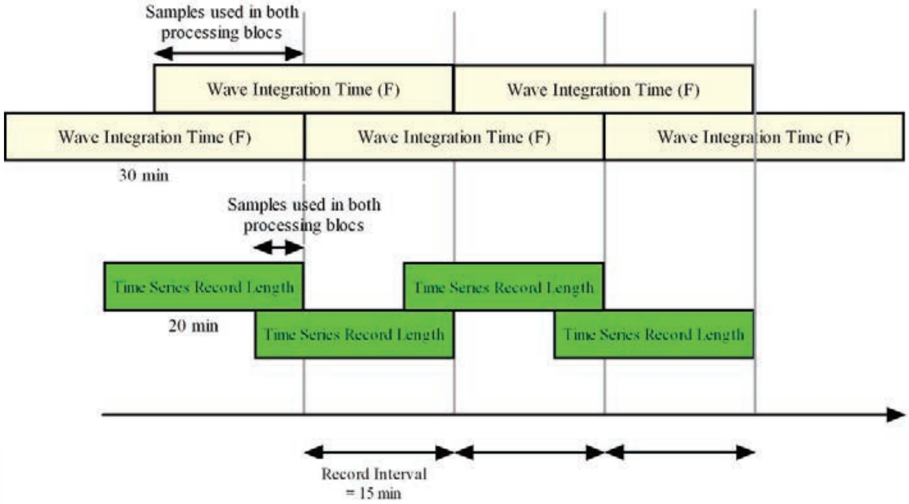

Figure 1: In this example, data are given out every 15 minutes as defined by the recording interval. The wave integration time sets the duration for the frequency domain based calculation, 30 minutes in this example. So every 15 minutes the parameters for the frequency domain will be calculated using the data samples from the 30 previous minutes.
The time series record length defines the duration for the time domain calculation, 20 minutes in this example. So every 15 minutes the parameters for the time domain will be calculated using the data samples from the 20 previous minutes.

1.1 Operating Principle

The sensor's core consists of a temperature fully compensated and calibrated AHRS (Attitude Heading Reference Sensor) delivering 3D accelerometer and orientation data at 100Hz. The sensor referred 3D accelerometer is converted into an earth referred 3D accelerometer using the 3D AHRS output. The 3D accelerometer data is processed in the front end PCB through a 256-pole low pass FIR filter before it is decimated to 4Hz giving a flat response in the wave processing band. The double integration is performed in the frequency domain, even for the time series output, giving a 3D displacement output used for the wave calculations.

1.2 Innovative and Unique Features

A significant amount of development has been invested in optimizing the sensor performances to provide reliable and accurate data when used on any kind of buoy.

- **Mechanical anti-vibration filter**

Wind, waves and current may induce vibrations on the buoy structure. Those vibrations may cause an increased noise being folded back into the wave processing band due to a violation of the Nyquist criteria. To avoid this, a mechanical low pass filter is implemented and has been tuned and tested in the laboratory using a shaker plate (Figure 2).

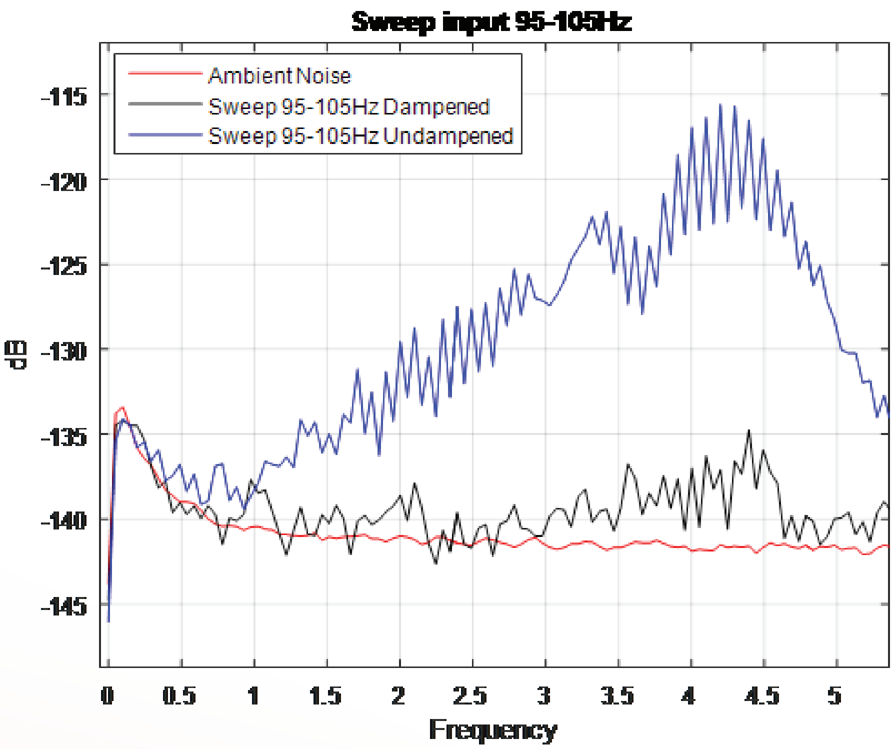

Figure 2: Effect of the mechanical filter. The blue curve represents the noise induced by the shaker plate. The black curve represents the noise while using the mechanical filter and the red curve represents the ambient noise without any shaker plate excitation.

- Off-center correction

It is often impossible or unpractical to install the wave sensor in the buoy's center of gravity. When the sensor is not positioned in the buoy center, this will result in a displacement error. The MOTUS Wave Buoys use the sensor's orientation combined with the installation position (x, y, z) relative to the rotational origin and is able to offset compensate by subtracting the added displacement. As a result, the sensor can be installed in a convenient place without sacrificing on the accuracy (Figure 3).

- Transfer function compensation

The size of the buoy and the mooring design may modify the buoy wave response and the data quality. A user configurable transfer function can be defined to compensate for the buoy behavior and provide maximum system flexibility without sacrificing wave measurement accuracy.

- Frequency leakage compensation

It is important to reduce frequency leakage coming from the Fast Fourier Transform when implementing an accelerometer-based wave sensor. Even though the frequency leakage is equal in the high and low end, the effect of the leakage will be biased due to the frequency dependent factor 1/(f2) used in the conversion from the acceleration to displacement. In order to keep this leakage minimal, a window function is implemented and reduces this effect. The remaining frequency dependent error is estimated and compensated for by the sensor (Figure 4).

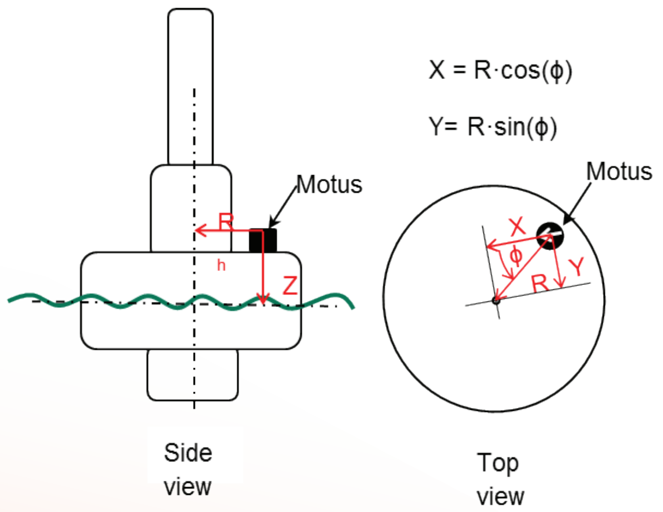

Figure 3: Illustration of off-center installation of MOTUS Sensor

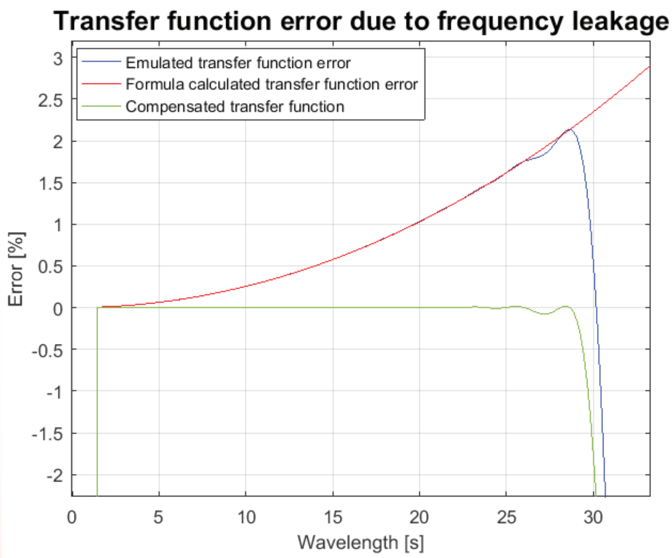

Figure 4: Transfer function error due to frequency leakage

2. The MAROFF Project

In order to further validate the MOTUS Wave Sensor concept and performances in the laboratory and in the field, a collaborative project with three major research institutions in Bergen, Norway started in 2016:
Christian Michelsen Research (CMR); in charge of the validation of technology through simulation and downscaled tank tests, uncertainty analysis.
The Norwegian Meteorological Institute (MET); in charge of data validation and comparison towards SWAN modeling.
Uni Research Polytec; in charge of data validation and field testing.

Figure 5: Tank test facility. Validation of the IMU in tank reference system and optical reference system

For the data validation, two MOTUS Wave Buoys were deployed off the south-west coast of Norway together with one Datawell Waverider MKIII used as the reference. The system consisted of one navigational buoy Tideland® SB138P (a Xylem company) measuring waves with the MOTUS Wave Sensor, surface currents with an Aanderaa single point Doppler Current Sensor (DCS) and meteorological parameters with Airmar and GILL weather stations. The second buoy was a YSI® EMM 2.0 (a Xylem company) environmental platform equipped with two MOTUS Wave Sensors; one installed close to the buoy's center of gravity and the other installed on the outer buoy rim in order to evaluate the off-center correction. In addition, this buoy was equipped with a downward facing Doppler Current Profiler Sensor DCPS-600 (able to measure in broadband or narrowband) and a DCS to measure the surface currents. Those two sensors combined provide a full current profile coverage.

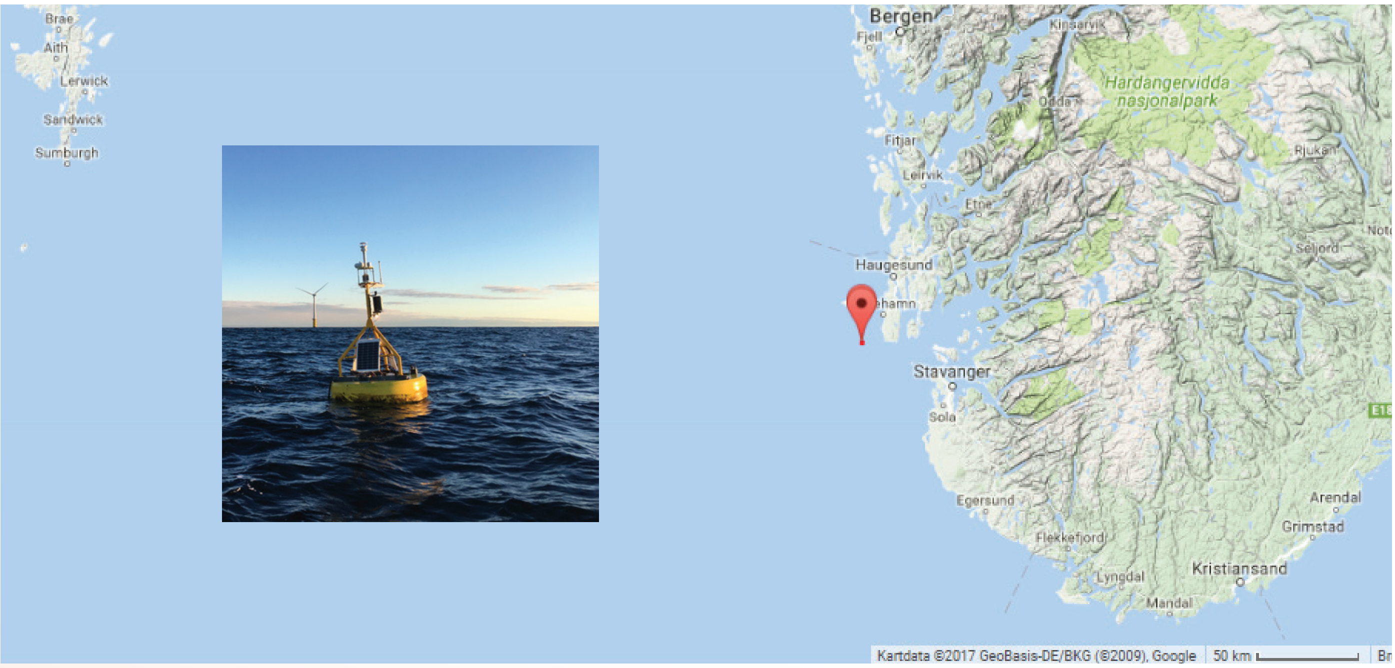

Figure 6: Location of the field tests, off Karmøy, Norway. Photo of EMM 2.0 buoy.

The three buoys have been collecting data since February 2017 providing accurate and reliable wave and currents measurements. On certain occasions with high sea state and strong currents, the smaller 0.7m Datawell buoy can lose data transmission because it is submerged (ref. figure 10 for example). For high currents/deep moorings, Datawell recommends using their 0.9m version Waverider. Deployment depth at the site is 200 meters.

Data are transmitted in real-time to shore and are available through a web-based database for easy extraction. Data is updated every 30min.

You may view historical data via our website: https://hydweb.xyleminc.com (Figure 7).

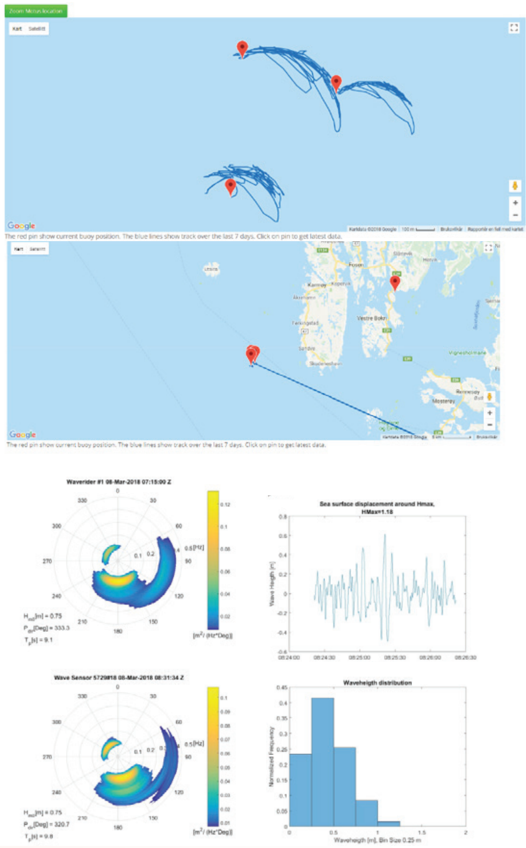

Figure 7: Data received in real-time

2.1 Project Results

For evaluation purpose, a Matlab based data import/ export and analysis tool was developed. With this tool, we are able to export data into the renowned CDIP Wave EvaluationTool. The CDIP (Coastal Data Information Program) developed this tool in order to assist the wave measurement community to compare and validate the quality of various wave sensors. CDIP is operated by the Ocean Engineering Research Group (OERG), part of the Integrative Oceanography Division (IOD) at Scripps Institution of Oceanography (SIO). In the MAROFF project, this tool has been used to compare data from the Datawell Waverider and the MOTUS sensors on the two buoys. The comparison is based on the “first five” Fourier coefficients and does the frequency-based analysis of sensors used in the test. Some examples of the comparison are presented in Figure 8 and 9.

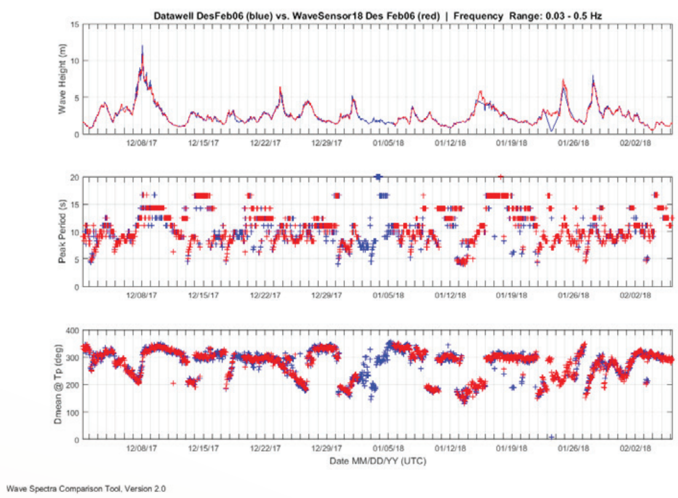

Figure 8: CDIP WaveEvalTool time domain comparison. Comparison of wave height (upper graph), peak period (graph in the middle) and peak direction (lower graph) shows excellent agreement between the Waverider and the three MOTUS Sensors on two buoys (Navigational and Environmental). This example represents the comparison between Datawell and the MOTUS Sensor number 18 in the Tideland Buoy.

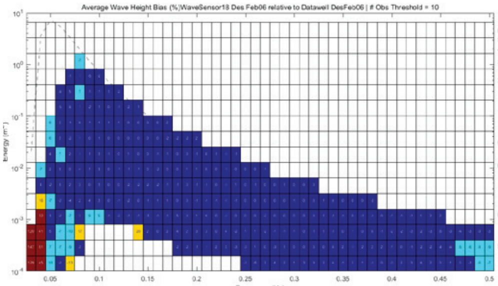

Figure 9: Each wave component is defined by a frequency-energy bin. The numbers in the wave component bins are the % bias. The color coding of the bias is simply to aid the eye (blue = lower biases, red = higher biases). For further details about this figure interpretation, refer to the [CDIP wave intercomparison manual](). Data from the navigational buoy Tideland MOTUS compared to Waverider MKIII generated by CDIP waveEVALTOOL showing excellent agreement. Some deviations can be found at the lower end of the frequency band. These deviations can partly be explained by Datawell's cut-off frequency (-3dB) at 30sec compared to the more flat response of the MOTUS Sensor, and partly due to some remaining noise combined with the low valued energy in this part of the wave frequency band.

The results from this CDIP comparison confirm that wave data obtained from the MOTUS Buoys provide excellent correlation to the reference. A minor deviation can be found in the low energy low-frequency end of the wave frequency band as indicated by figure 9.

2.2 Withstanding Hard Conditions

During more than one year of deployment, the buoys withstood all kinds of weather including the storm Aina on the 7th of December 2017 when winds were more than 30 m/s with the significant wave height reaching 11 meters and the maximum wave height 18 meters.

Events with high currents (surface currents higher than 150 cm/s) have also been observed. Figure 10 shows some examples.
Figure 11 illustrates the ability of the MOTUS Wave Buoys to accurately measure low currents in high waves. Figure 12 revealed the observation of an eddy passing by the buoy from South to North.

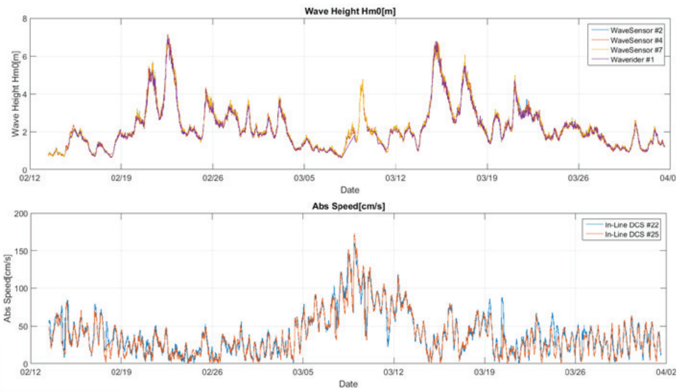

Figure 10: Wave height from four sensors (upper graph) and surface currents from the two Xylem buoys from the 12th of February to the 2nd of April. Around the 8th of March, an event with currents over 150 cm/s and 4m significant wave height was registered. During this event, the data transmission from the Waverider buoy is lost during a period of time due to the buoy submersion while the MOTUS Buoys provide good and reliable data.

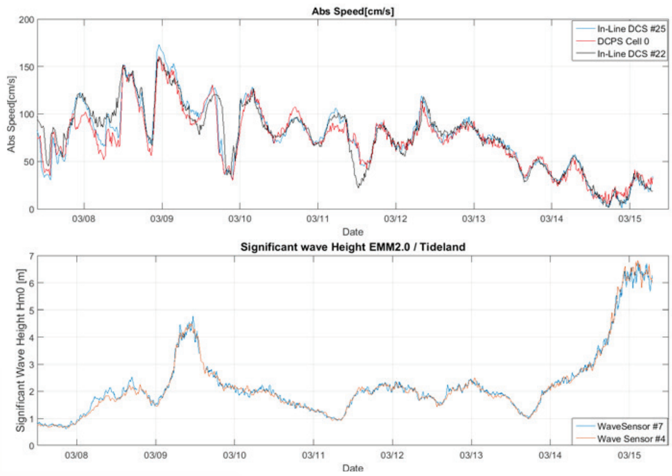

Figure 11: The two DCS, on separate buoys, about 250 m from each other, always agree well in speed and direction even in wave heights up top 18 m. Surface current data also frequently agree with the first cell measured with the Doppler Current Profiler sensor (DCPS). See [Helsingborg harbour application note]().

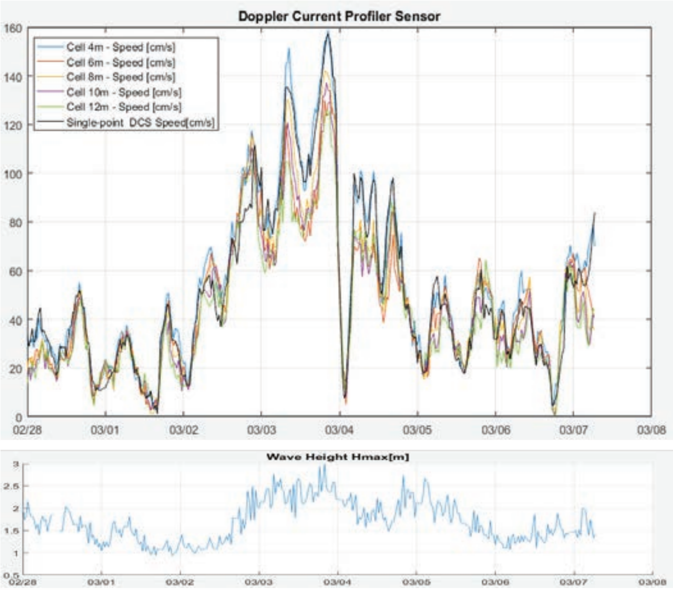

Figure 12: Eddy observation: The first graph represents the current values from the surface down to 12m. The second graph represents the wave height during the same period. Before the 4th of March 2018, currents have increased gradually and then decreased rapidly down to few centimeters.

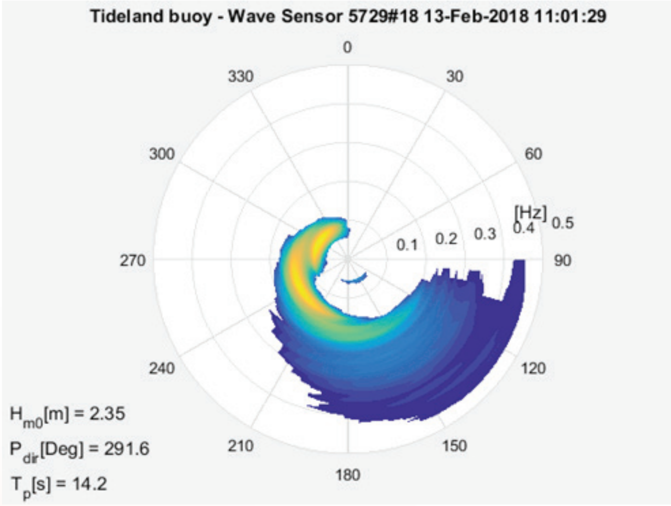

Figure 13: Example of the representation of the directional energy spectrum revealing two dominant wave fields, separated by frequency and direction.

2.3 Wind Waves Measurements

In order to test the performances of the MOTUS Buoys in small wind waves, a Datawell Waverider and a Tideland MOTUS Buoy were deployed 400 m from each other in protected waters of the Bjørnafjorden (Figure 14).

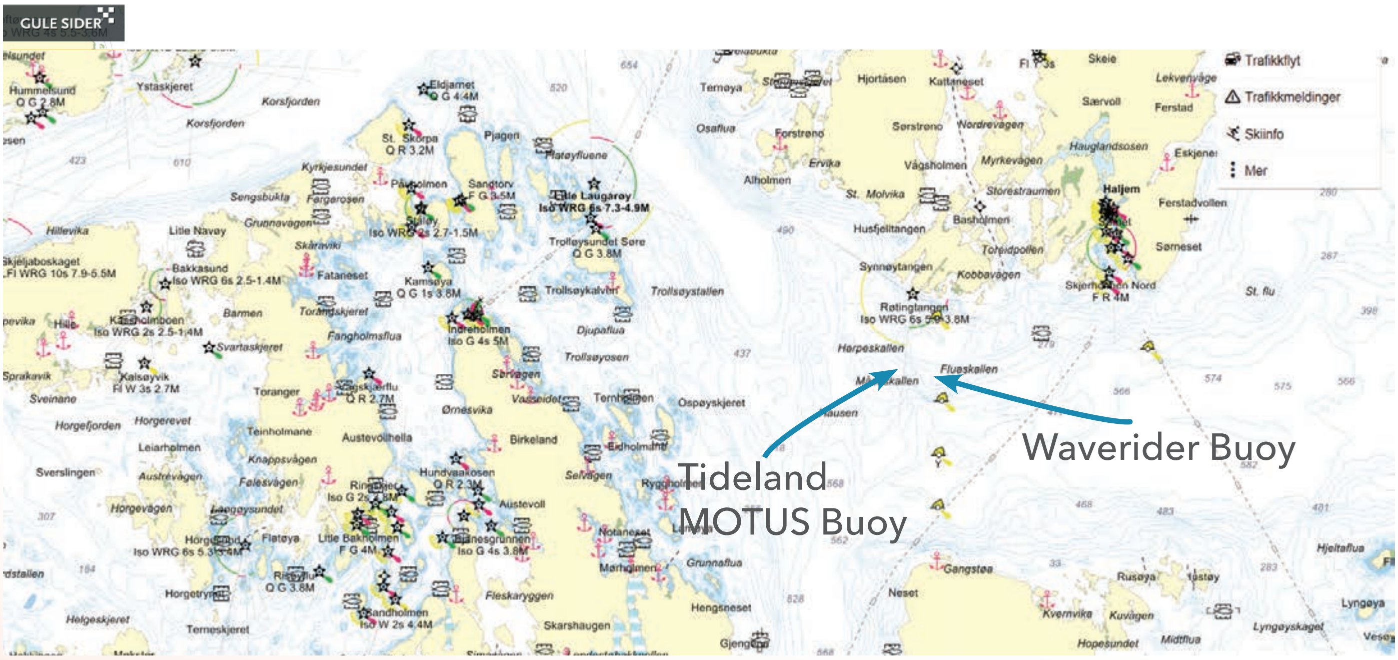

Figure 14: Deployment location for the test in wind waves conditions.

During the deployment, waves less than 20cm significant wave height were observed and the Tideland MOTUS Buoy provided equivalent measurements to the Datawell. Even though the Tideland Buoy is 1.75m in diameter, it still shows its ability to measure small wind waves with high accuracy (Figure 15).

A similar test in Bjørnafjorden (July 2016), compared an EMM 2.0 Buoy to the Datawell in wave generated by light wind during daytime and occasional ferry traffic. Despite the size of the buoy (2.0m), the MOTUS Buoy and Waverider show good correlation down to 6-7cm significant wave height (Figure 16).

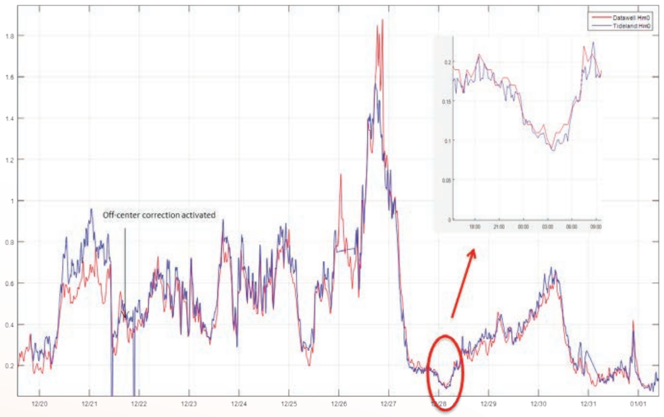

Figure 15: Significant wave height from Datawell waverider and Tideland MOTUS Buoy deployed in the Bjørnafjorden.

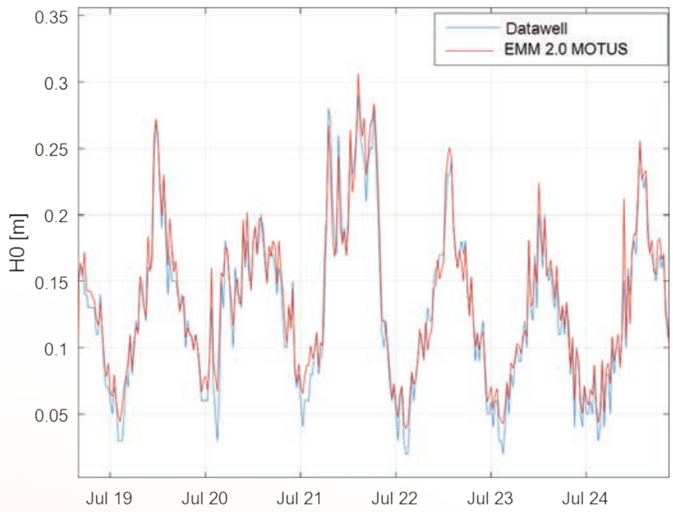

Figure 16: Significant wave height from the EMM2.0 MOTUS Buoy and the Waverider in the Bjørnafjorden.

Conclusion

During more than a year, the MOTUS Wave Buoys have been intensively tested and revealed their ability to accurately measure waves and currents from a full scalable navigational/ environmental buoy in all weather and sea states conditions.

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1) The tissue in plants that brings water upward from the roots;
2) a leading global water technology company.

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