WHITE PAPER 2017
MOTUS WAVE BUOYS

Oceanographic Wave Measurements on Hydrography & Navigation Buoys: Introduction, Technology and MOTUS

AANDERAA
a xylem brand

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Summary

In this white paper we introduced the Aanderaa/Xylem directional wave sensor MOTUS (movement in latin). MOTUS is a compact, low power accelerometer based sensor that is designed to accurately measure multi-spectrum directional waves from standard hydrography and navigation buoys. An inbuilt feature is its flexibility since it can be adapted to different types of buoys and that it does not need to be placed in the center of gravity of the buoy to work correctly. So far two Xylem buoys, YSI EMM 2.0 and Tideland SB-138P, have been used. In case of magnetic disturbances, normally higher at the lower part of a Hydrographic/ Navigation buoy, an external compass that give correct directional readings can be fitted higher up and be connected to the sensor. Here we present field data that have demonstrated excellent agreements between data from a dedicated circular wave measurement buoy (Datawell Waverider) and different MOTUS sensors deployed nearby and placed on different buoys. The hydrography/navigation buoys used for field trial of the MOTUS sensor was equipped with standard Aanderaa Doppler Current sensors which gave high quality current measurements at all wave condition, the maximum recorded significant wave heights were above 7 m. Since the Doppler Current Profiling Sensor (DCPS) can run both narrow and broad-band we could also demonstrate that using broadband from a platform that is rocking and moving in the sea is not suitable and give noisy/unusable current information.

Surface Waves: formation and measurement technologies

Waves in lakes and oceans can be formed by different sources like boats/ships, earthquakes, landslides, moon gravitation but the main origin is from the friction of winds blowing across the water surface.

Offshore in deep water there are mainly four parameter that decides how large wind driven waves become: how strong the wind is, how long time the wind lasts, over how large area it blows in the same direction (the fetch) and if the waves break.

In oceanography you differentiate between shorter-period waves = seas that are formed by winds in the vicinity and longer-period waves = swells that can be formed further away. In lakes and limited size inland seas no significant Swells are formed. Here all the waves can be regarded as wind generated Seas.

Because waves can travel far and contain high energy it is essential to study their characteristics to judge the impact that they can have on navigation, offshore constructions, beaches, ports/harbors etc. Waves might also have less obvious secondary effects on the environment like surface water mixing, enhanced air-sea gas exchange, generation of coastal currents and re-suspension of sediments that can affect the water quality and transport particles.

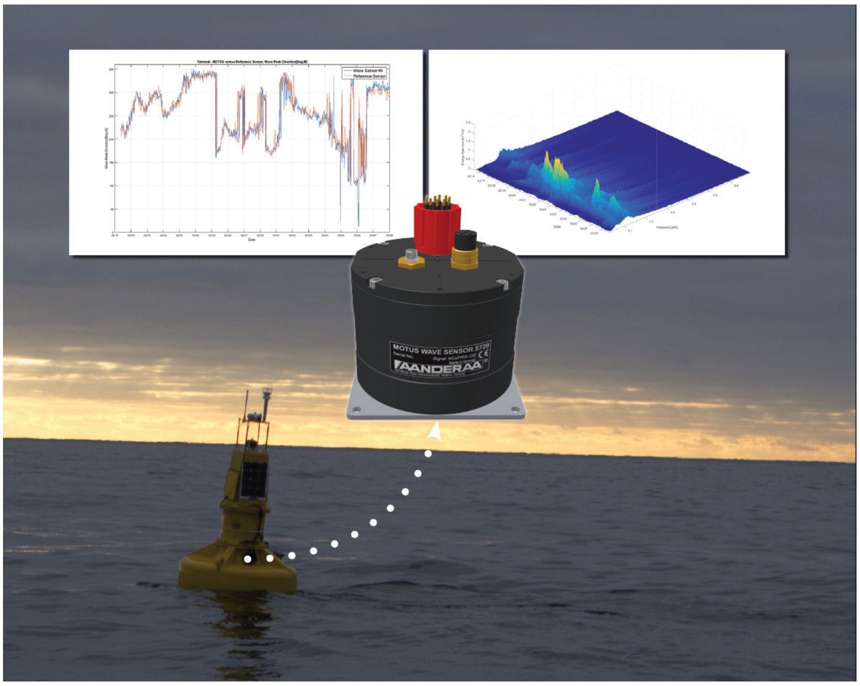


Figure 1: In this white paper we introduced the accelerometer based MOTUS sensor that is designed to accurately measure waves from standard hydrography and navigation buoys.

When large surface coverage is needed radars have been used for wave and surface current measurements. There is a wide spectrum of technologies including microwave, synthetic aperture radar from planes and satellites, high frequency radar arrays on the shore and navigational radars. The radars give an overview but cannot provide the same level of detailed information that spot measurements are capable of. In addition spot measurements with instruments are normally well suited to measure other parameters as well e.g. currents, wind, temperature, salinity, particles, oxygen, pCO_2, algae etc.

Measurement principles for spot measurements of waves include:

- Pressure based sensors are mounted at fixed positions below the surface. By sampling in bursts non-directional waves and water level is measured. The pressure based sensor measures the pressure induced perturbation generated at the surface. The attenuation of these pressure pertubations depends on depth and wavelength. Because of attenuation with depth the further away from the surface the sensor is located the more difficult it is to pick up smaller waves (limit 10-50m depth, depending on the quality of the sensor technology). Pressure based sensors have been placed in time-synchronized arrays or combined with high frequency acoustic current measurements (PUV) to obtain directional waves.
- Acoustic wave measurements are normally obtained by a so-called ADCPs (Acoustical Doppler Profiler) fixed below the surface. The wave parameters are calculated by measuring the orbital velocities at a certain distance from the surface. Dependent on installation depth this method has limitations with respect to short waves. With this technology it is also possible to obtain current information (water flow).
- Accelerometer and GPS based wave buoys: The first dedicated

accelerometer based directional wave buoys were introduced about 30 years ago by the Dutch company Datawell. Later, lower cost GPS based technology has also been used but this requires more power and there is a risk of losing GPS signal at higher sea states.

Accelerometer based wave measurements have remained the “golden standard” and other manufacturers have adapted similar solutions.

In this white paper we introduce the Aanderaa MOTUS (movement in Latin) sensor. It is intended to fill a need to accurately and with low power demand measure directional waves from hydrographic and navigational buoys that are not specially designed for wave measurements.

Figure 2: Picture of the MOTUS wave sensor.

MOTUS: Unique features, output and integration

The MOTUS sensor is a compact field friendly low power multi-parameter directional wave sensor. It has so far been integrated into two different standard Xylem buoys, one that was designed for navigational aid (Tideland SB-138P) the other (YSI EMM 2.0) which is mainly used for hydrography measurements (see Figure 3).

The reason that such measurements are possible from buoys that were not optimized to measure waves is that MOTUS integrates the necessary hardware (dampening, 3-axis accelerometers, magnetometers, gyros and input from an external compass, if needed) and software for signal treatment and compensation. This also makes it possible to place the sensor off-center on the buoy and automatically compensate for the extra movement the sensor will experience in that position, see example below.

Based on the collected raw data the sensor will calculate an extensive set of wave parameters. When connected to a SmartGuard logger a customer selectable set of these parameters are stored in the logger while a subset can be transmitted ashore as real-time data at a configurable interval.

Just like other Aanderaa smart sensors, MOTUS can be logged by other data loggers using its serial interface. A selected set of wave parameters can be read (polled) at an interval determined by the logger, or the sensor can be configured to send these data at a pre-configured interval.

Figure 3: Picture of an YSI EMM 2.0 buoy (left) and a Tideland SB-138P navigational buoy (right) before being deployed at sea together with a Waverider buoy.

Unique features:

- Compact stand-alone smart sensor with serial and AiCaP output
- Long-term stable and maintenance free
- Easy configurable off-center compensation: Enter the distance between sensor and buoy rotation center (X/Y) and height above waterline (Z).
- MOTUS has its own compass but for installation where the earth's magnetic field is disturbed by the buoy's structure or payload an external compass can be utilized. By installing the compass out of the disturbed field, for instance in the mast, accurate wave direction can be obtained. When used with the SmartGuard datalogger the compass data may also be distributed to other sensors that need magnetically undisturbed heading measurements, for instance a Doppler Current Profiling Sensor. Directional compensation from the external compass is automatically done inside the sensors.
- Low power requirements: In continuous mode with accelerometerdata sampled at 100Hz and waves calculated at 4Hz the power consumption is 110mW.
- Wave periods covered are 1.4-33s.
- Optional calculation and output of wave height, peek direction and period for Swell and wind waves (sea) with configurable separation frequency (default 0.1Hz = 10s).
- Configurable trough Real Time Collector (one software handles all Aanderaa smart sensors and instruments) or a standard Terminal software (e.g. Tera Terminal, Hyperterminal)
- Part of Aanderaa SmartGuard hydrography buoy solution, easy expandable with a large number of additional sensors e.g. currents in multiple layers, various water quality and meteorological sensors.

Figure 4: One of the MOTUS sensor was mounted about 50cm off-center on an EMM 2.0 buoy and another in the center.

Output parameters:

Wave Height H_{m0}	Wave Height Swell H_{m0}	Fourier Coeff. Spectrum
Wave Peak Direction	Wave Height Wind H_{m0}	Heading & Ext Heading
Wave Peak Direction Swell	Mean Spreading Angle	Pitch & Roll
Wave Mean Direction	Directional Width	StDev Heading
Wave Peak Direction Wind	Long Crestedness	StDev Pitch & Roll
Wave Mean Period T_{m02}	Directional Spectra	Input Voltage & Current
Wave Peak Period	Wave Orbital Spectrum	Used Memory
Wave Peak Period Swell	Energy Spectrum	FE Message and State
Wave Peak Period Wind		

Wave Height H_{m0} is equivalent to the significant wave height and is calculated from the entire wave spectrum limited by default from 1.4 to 30s. The long period limit might be increased to 33 seconds by the end user.

Wave Peak Direction and Wave Peak Period are the wave direction and period of the waves that contains the highest energy.

The Wave Mean Period T_{m02} is also called Zero Crossing. It is calculated from frequency spectrum and is a measure of the average time between periods when the water level is at 0.

The Mean Spreading Angle is a measure of how wide the directional cone is over which the wave direction is distributed (Kumar and Anoop, 2013) and so is the Directional Width.

A low value of Long Crestedness Parameter indicates that the waves have long crests, and thereby low spreading. Higher number indicates that they have shorter crests, and thereby more spreading. The values are in the range of [0 to 1]. This parameter is theoretically calculated.

For more information about the formulas used to calculate the different parameters and spectrums please see appendix.

Heading is the compass heading from the MOTUS compass. External heading is the heading given by an external compass, if there is one in use. Pitch and Roll gives the leaning of the buoy. Input Voltage, Input Current and Used Memory are all quality control parameters that should be checked mainly if the sensor is malfunctioning. FE Message Counter, FE State and FE Notification are system parameters used for debugging purpose by company experts if the sensor is not giving correct readings.

Integration to an existing buoy

Upon delivery the sensor has been calibrated, temperature compensated and verified at the factory.

The ideal point of installation for a wave sensor is close to the waterline at the vertical centerline. In many cases however it might be difficult or unpractical to install a sensor in the center. The MOTUS Wave Sensor is therefore equipped with an algorithm that compensates for the extra motion caused by an off-center installation and thus enables the sensor to provide high quality wave measurements also in such cases (Figure 5). For correct compensation the three dimensional distance from the center, as shown below, must be set in the “Off-center XYZ” sensor property.

Performance tests show that the algorithm corrects wave height measurements down to an error level of a few centimeters with off-center distances of up to 0.6m on a 2m diameter buoy. To ensure optimal data quality larger distances from the rotational center both in vertical and horizontal should be avoided.

An important input parameter for wave direction is the heading information. The sensor can obtain heading either from its own internal compass or an external compass connected to the auxiliary compass input connector. If the magnetic distortion at the location where the sensor is to be installed is unacceptably large the heading should be provided input from an external compass placed at a location with lower magnetic influence, for instance in the mast. Checking the magnetic distortion at a potential location can be done before deploying (for details see manual).

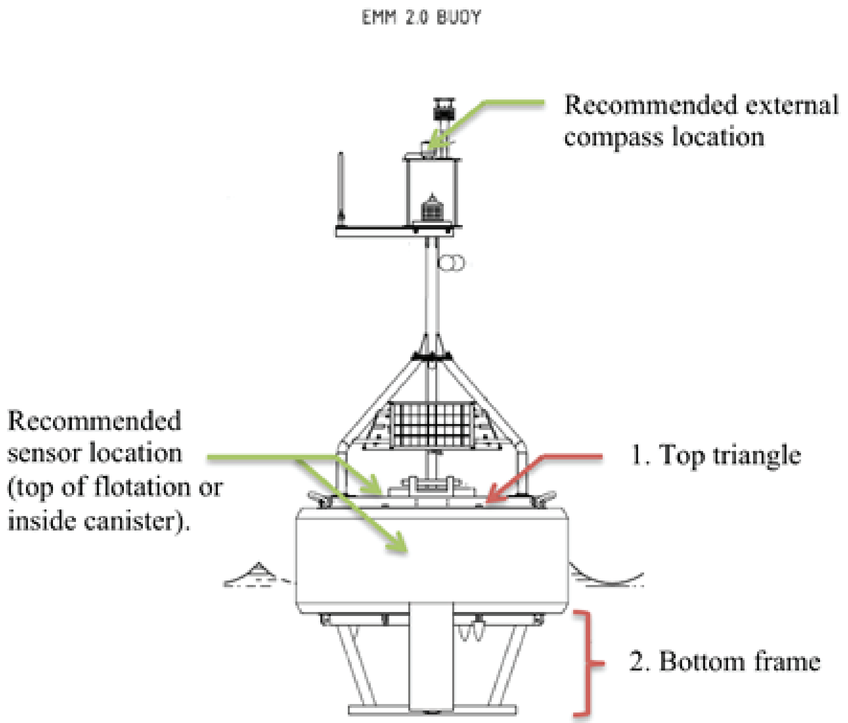


Figure 5: Recommended locations of MOTUS sensor and external compass on an EMM 2.0 buoy.

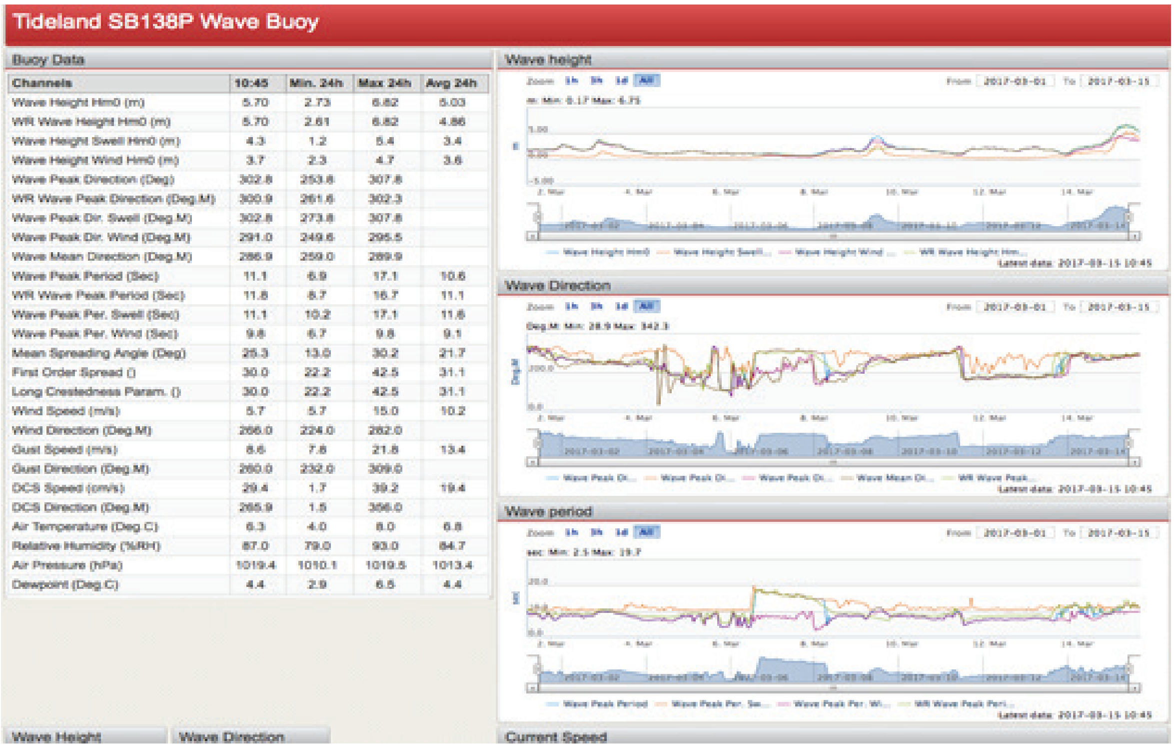
Field data: performance and inter-comparisons

Waves

A Tideland SB-138P and an YSI EMM2.0 buoy were deployed about 0.5 nautical mile apart in the exposed North Sea off the coast of Karmøy (Figure 6). Halfway between these buoys a circular 0.7m diameter Directional Waverider MkIII from Datawell was deployed. The Tideland SB-138P was equipped with one MOTUS sensor while the EMM 2.0 buoy was fitted with two MOTUS sensors one installed close to the rotational center of the buoy the other close to the edge of the upper buoy deck (Figure 4).

Figure 6: Deployment location of the three buoys (Tideland SB-138P, EMM 2.0 and a Waverider) offshore in the North Sea. Deployment was done in mid-February, 2017.

The systems are reporting data in real time using the Aanderaa GeoView software for presentation (see Figure 7 for an example) and can be fully accessed by two-way communication for changing/testing of different settings.



Channels	10:45	Min. 24h	Max 24h	Avg 24h
Wave Height Hm0 (m)	5.70	2.73	6.82	5.03
WR Wave Height Hm0 (m)	5.70	2.61	6.82	4.86
Wave Height Swell Hm0 (m)	4.3	1.2	5.4	3.4
Wave Height Wind Hm0 (m)	3.7	2.3	4.7	3.6
Wave Peak Direction (Deg)	302.8	253.8	307.8	
WR Wave Peak Direction (Deg.M)	300.9	261.6	302.3	
Wave Peak Dir. Swell (Deg.M)	302.8	273.8	307.8	
Wave Peak Dir. Wind (Deg.M)	291.0	249.6	295.5	
Wave Mean Direction (Deg.M)	286.9	259.0	289.9	
Wave Peak Period (Sec)	11.1	6.9	17.1	10.6
WR Wave Peak Period (Sec)	11.8	8.7	16.7	11.1
Wave Peak Per. Swell (Sec)	11.1	10.2	17.1	11.6
Wave Peak Per. Wind (Sec)	9.8	6.7	9.8	9.1
Mean Spreading Angle (Deg)	25.3	13.0	30.2	21.7
First Order Spread ()	30.0	22.2	42.5	31.1
Long Crestedness Param. ()	30.0	22.2	42.5	31.1
Wind Speed (m/s)	5.7	5.7	15.0	10.2
Wind Direction (Deg.M)	266.0	224.0	282.0	
Gust Speed (m/s)	8.6	7.8	21.8	13.4
Gust Direction (Deg.M)	260.0	232.0	309.0	
DCS Speed (cm/s)	29.4	1.7	39.2	19.4
DCS Direction (Deg.M)	265.9	1.5	356.0	
Air Temperature (Deg.C)	6.3	4.0	8.0	6.8
Relative Humidity (%RH)	87.0	79.0	93.0	84.7
Air Pressure (hPa)	1019.4	1010.1	1019.5	1013.4
Dewpoint (Deg.C)	4.4	2.9	6.5	4.4

Figure 7: Screen shot of real time data from Tideland and Wave Rider (WR) buoys.

The highest reported significant wave height since the deployment started is 7.2m. The wave parameters from the three MOTUS sensors compare well with the Waverider data (Figures 8, 9 and 10). Figure 11 compares the two MOTUS sensors that were mounted on the same buoy with the off-set compensation switched on and off.

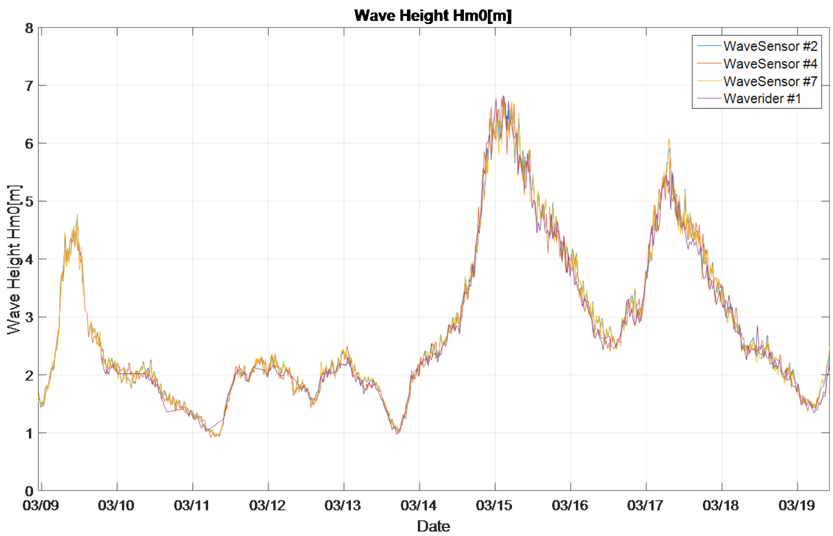


Figure 8: Significant wave height (Hm0) from Waverider (purple) and three MOTUS sensors on the Navigational buoy (#4 orange, mounted in center) and on the Hydmet buoy (#7 yellow, 50cm off-center and #2 blue, in center).

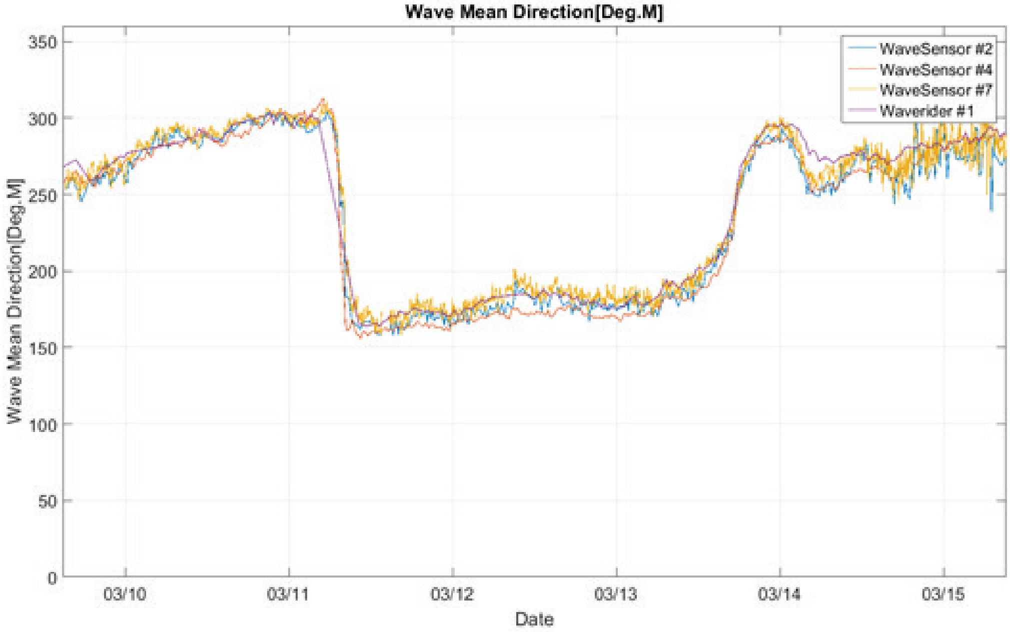


Figure 9: Wave mean direction from Waverider (purple) and three MOTUS sensors mounted on the Navigational buoy (#4 orange, in center) and on the Hydmet buoy (#7 yellow, 50cm off-center and #2 blue, in center). All the MOTUS sensors received input from an external compass.

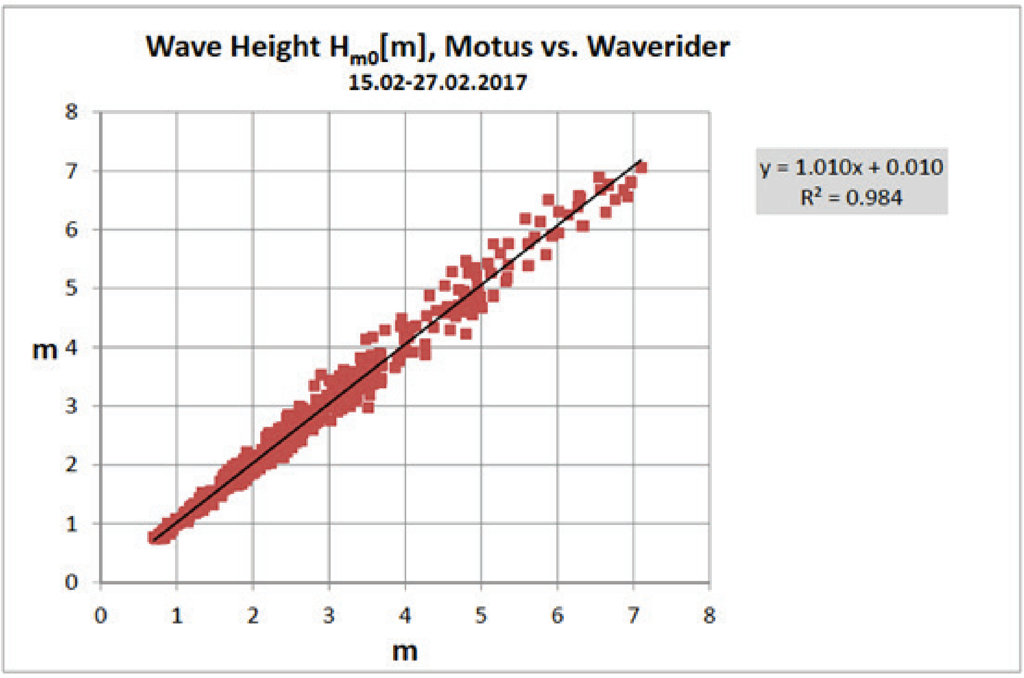


Figure 10: Hm0 wave height of MOTUS sensor on Tideland SB-138P, navigational buoy, versus wave height measured by Waverider (n = 583 measurements)

Current measurements from Xylem buoys in different sea states

The two Xylem buoys in these trials were also fitted with standard Aanderaa Doppler Current Sensors. The EMM 2.0 buoy carried a Single Point Doppler Current Sensor (DCS) for surface current measurements combined with a Doppler Current Profiling Sensor (DCPS) pointing downward. This is a frequently used combination on the EMM buoys in navigational and monitoring applications. The Tideland SB-138P, navigational buoy, was fitted with a single point DCS.

Figure 11: Significant wave height Hm0 from a field test conducted at Bjørnafjorden December 2016. The red trace is from an offset installed MOTUS wave sensor on a Tideland SB-138P and the blue trace is from a Datawell Waverider. The red arrow marks the moment when the off-center compensation is switched on.

For mechanical and bio-fouling protection and easy cleaning the Doppler current and the other hydrological sensors are mounted inside PVC tubes that penetrate the buoy hull (Figure 12). The sensors are installed on retractable fixtures for easy access during maintenance.

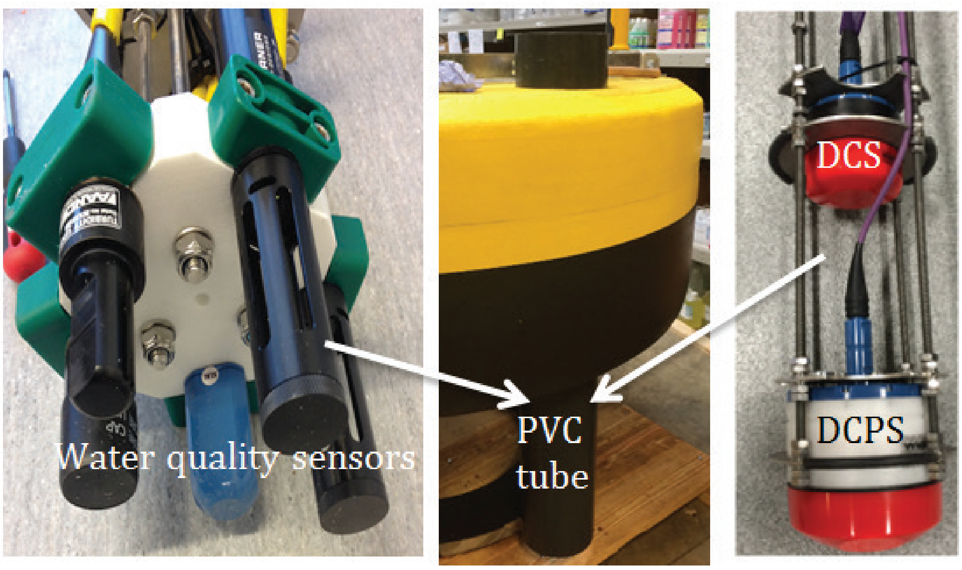


Figure 12: Doppler current and water quality sensors are mounted inside PVC tubes. The DCS measures through the wall of the PVC tube.

Measurements from the three sensors were compared for periods with more or less waves. Although placed on two different buoys that were approximately 0.5 nautical miles apart, the current measurements from the three sensors agree well (Figure 13) and there are no signs of noise introduction in heavier sea states (7m Significant wave Height).

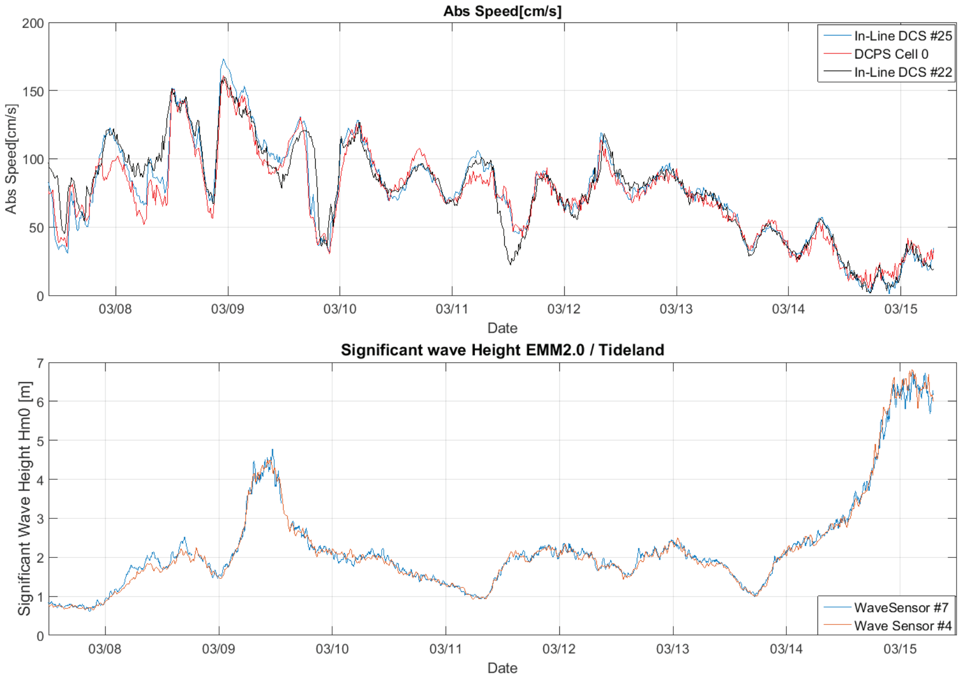


Figure 13: Current speed from DCS #25 (blue) on navigational buoy and #22 (black) and DCPS first cell (red) on Hydrographic buoy. The DCPS first cell is located about 2.5m below the two DCS sensors.

Broadband versus Narrowband from a moving buoy

The DCPS sensor can be set to use either broadband or narrow band. Broadband has the advantage of about 3-5 times lower power consumption to obtain similar data quality as narrowband. In autonomous applications, running on internal batteries, it is recommended to use broadband especially on bottom-mounted platforms or moorings that are not moving/vibrating much.
When the DCPS is installed on a surface buoy that is rocking and moving in the waves, broadband is not recommended.

Because there is two-way communication with the buoys, settings can be changed remotely to test in real time how different acoustic modes affect the data quality. Figure 14 shows a contour plot collected with the DCPS first running in broadband and then in narrowband. As can be seen the noise level and data quality is poorer/ unusable in broadband. The reason for this is that the buoy movements cause the broadband algorithm to fail. Figure 15 demonstrates the same thing for the first cell, which is placed about 2.5m below the buoy.

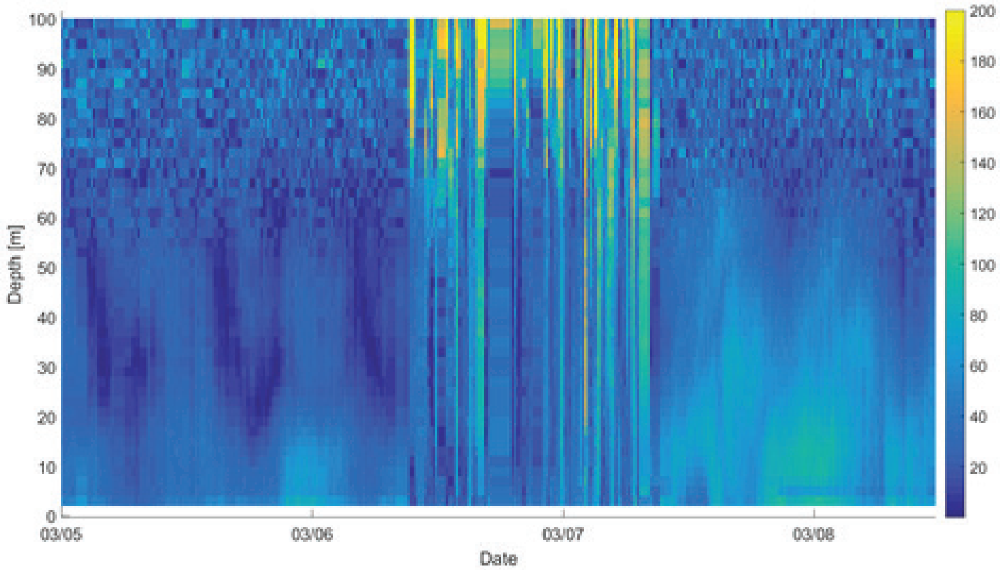


Figure 14: Broad and narrow-band measurements with a Doppler Current Profiling Sensors (DCPS) on an EMM 2.0 buoy that is moving in the waves. In the middle the DCPS is set to broadband. In the beginning and at the end the DCPS is set to operate in narrowband. In Narrowband noise levels are low and tidal variations can be distinguished. In broadband two sub pulses are transmitted. In order for broadband to work correctly there cannot be too much movement in between these two pulses as this will modify the phase measurement. For this reason broadband will not be suitable for measurement on an offshore buoy.

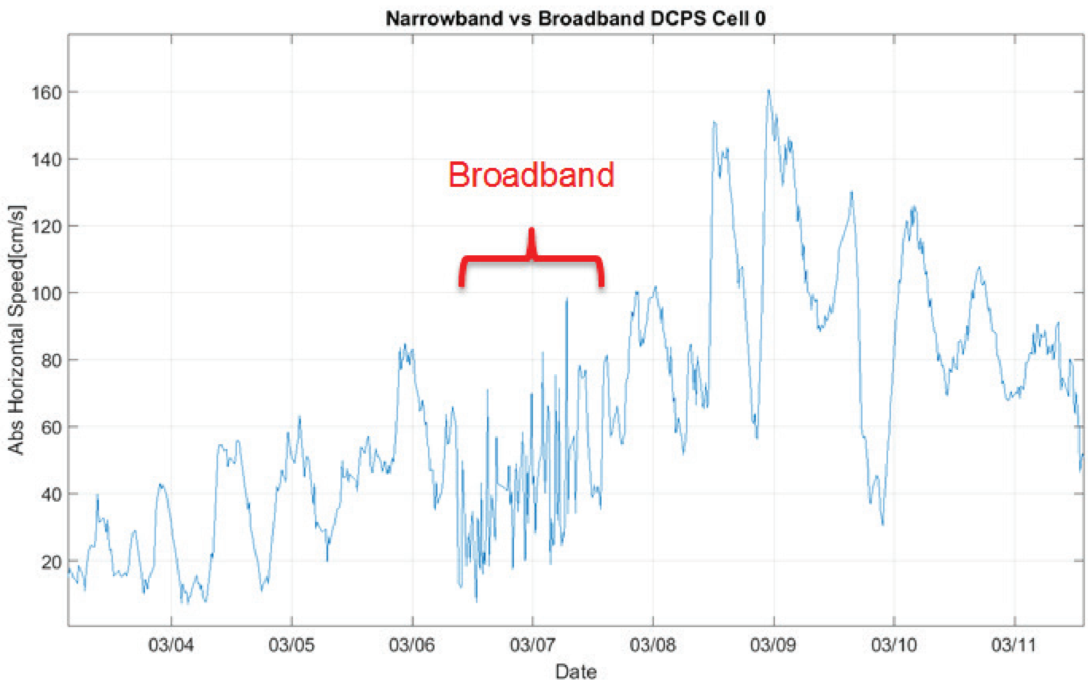


Figure 15: Broad and Narrow-band measurements for the first cell with a DCPS on an EMM 2.0 buoy that is moving in the waves. In the middle period the DCPS is set to broadband. In the beginning and at the end it is set to operate in narrowband. In narrowband noise levels are low and tidal variations can be distinguished. In broadband the sensor is giving very noisy/unusable results.

Future aspects

As all Aanderaa sensors the MOTUS wave sensor is designed to be accurate, precise, long-term stable and to have modest power consumption. Another inbuilt feature is its flexibility in the sense that it can easily be adapted to different types of buoys and that it does not need to be placed in the center of gravity of the buoy to work correctly. In case of high magnetic disturbances, normally at the lower part of a buoy, an external compass that give more correct directional readings can be fitted higher up and be connected to the sensor. There is also an optional build-in frequency response compensation algorithm that can be used for adapting the sensor to buoys that have a non-ideal response to the wave motion, for instance dampening of short high frequency waves.

So far MOTUS sensors have been evaluated on two Xylem buoys. In the future we are expecting trials and integration to other type of buoys as well.

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Appendix:Used mathematical formulas

The **Energy Spectrum E(f)** gives the vertical wave energy density for each frequency bin, accumulated from all directions.

Two different directional Spectrums are calculated

1. **Mean Wave Direction Spectrum** is calculated as mean wave direction for each frequency bin in the spectrum based on the first order Fourier Coefficients.

$$\theta_1(f) = atan(b_1(f_i)/a_1(f_i))$$

2. **Principal Wave Direction Spectrum** is calculated based on the second order Fourier coefficients. The principal wave direction has an ambiguity direction of 180 degrees, but is forced to be in the same interval as the mean wave direction.

$$\theta_2(f) = 0.5 \cdot atan(b_2(f_i)/a_2(f_i))$$

The **Wave Orbital Spectrum** gives the ratio of vertical to horizontal motions corrected for the wavenumber and water depth.

$$\mathrm{R(f)} = \left\{\frac{1}{\tanh(\mathrm{k(f)} \cdot \mathrm{h})}\right\} \cdot \sqrt{\frac{\mathrm{C_{11}(f)}}{\mathrm{C_{22}(f)} + \mathrm{C_{33}(f)}}}$$

where:
C11(f), C22(f), and C33(f), are the cross-spectra of displacement in Vertical, East and North direction. k(f), is the wave number and h is the water depth.

Wave Mean Direction is the energy weighted mean direction over all frequency bins.

$$\theta_0 = atan\left(\sum_i E(f_i) \cdot b_1(f_i)/a_1(f_i)\right)$$

The spreading angle is a measure of how wide the directional cone is over which the wave direction is distributed (Kumar and Anoop, 2013).

Three different spreading parameters are calculated.

1. The **Directional width** (σ) (First order Spread) is a measure of directional spreading based on the first order Fourier coefficients, calculated for the frequency corresponding to the peak in the directional energy spectrum Kuik et al. (1988).

$$\sigma = \sqrt{2(1 - \mathrm{r}_1)},\ \mathrm{r}_1 = \sqrt{a_1^2 + b_1^2}$$

2. The **Mean spreading angle** is the spreading function based on the first and second order Fourier coefficients, calculated for the frequency corresponding to the peak in the directional energy spectrum.

$$\theta_k = atan\left[\frac{0.5b_1^2(1 + a_2) - a_1 b_1 b_2 + 0.5a_1^2(1 - a_2)}{a_1^2 + b_1^2}\right]$$

3. The **long crestedness parameter** gives the normalized spreading function, calculated for the frequency corresponding to the peak in the directional energy spectrum.

$$\tau = \sqrt{\frac{1 - \sqrt{a_1^2 + b_1^2}}{1 + \sqrt{a_1^2 + b_1^2}}}$$

For long-crested waves the direction of all wavefronts are the same and the spreading function reaches 0. When the wave fronts no longer are uniform and the become more spread, the length of the wave crests will be shorter and the Long Crestedness parameter will increase.

Xylem |ˈzīləm|

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

We're a global team unified in a common purpose: creating advanced technology solutions to the world's water challenges. Developing new technologies that will improve the way water is used, conserved, and re-used in the future is central to our work. Our products and services move, treat, analyze, monitor and return water to the environment, in public utility, industrial, residential and commercial building services, and agricultural settings. With its October 2016 acquisition of Sensus, Xylem added smart metering, network technologies and advanced data analytics for water, gas and electric utilities to its portfolio of solutions. In more than 150 countries, we have strong, long-standing relationships with customers who know us for our powerful combination of leading product brands and applications expertise with a strong focus on developing comprehensive, sustainable solutions.
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