WHITE PAPER
SEAGUARDII DCP WAVE WP003-APR2019

SeaGuardII DCP Wave

A 600 KHZ CURRENT AND WAVE PROFILER

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Contents

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Introduction

In this white paper we introduce the SeaGuardII DCP Wave, a 600kHz Doppler Current Profiler that has been expanded to measure directional waves from a bottom mounted installation down to 40m water depth. For the wave measurement, it utilizes an innovative solution implemented for the first time in such instruments. This solution consist of a wave height dependent adaptive transmission pulse combined with robust ambiguity resolution methods to reduce the measurement noise and improve the directional wave measurement.

The SeaGuardII DCP Wave is available as a self-recording instrument and/or can easily be incorporated into real-time systems offering two-way communication, extended real time capabilities and can measure additional parameters based on the use of sensors like temperature, conductivity/salinity/density, pressure, oxygen, turbidity, pH, algae, oil etc.

The new acoustic wave feature has been extensively tested and validated against surface buoys, Datawell Waverider and Motus/EMM 2.0 wave buoy, and pressure based wave measurements. Results demonstrate a good agreement between the three independent methods in rough winter conditions off the west coast of Norway.

1. Waves: formation and propagation

Ocean waves are generated at the air/sea interface. When air blows over the water surface, small capillary waves are created. Once capillary waves are formed, the friction from the turbulent air on the water surface increases and the energy transport from wind to waves increases. When a wave has accumulated enough energy and grows to a certain size it will “bump into” the wave in front of it which will cause them to gain height. By gaining height a wave exposes its surface to more wind and accumulates more energy. This cycle continues to produce larger waves as long as the wind blows in the same direction and there are no obstacles to stop the waves.

The transferred energy from wind to waves depends on the wind field which is characterized by the wind speed, wind duration and the fetch, the distance of free water over which the wind has blown.

If the wind field is stable over some duration of time, the wave height will reach a steady state condition (fully developed sea) and will propagate outside of the fetch area. Furthermore longer wavelengths are characterized by less propagation loss and can therefore propagate over long distances; referred to as swell. The swell is associated with larger wavelengths and can have a different direction compared to the more local wind driven waves.

In other words, waves are energy in motion. Ocean waves are gravity waves and transmit energy by interactions between potential energy and kinetic energy. The waves crest and through represent the potential energy and the orbital water current represents the kinetic energy (Figure 1).

While depth increases, the orbital movements are attenuated and become so small that the movement is negligible. This depth is called the wave base. It is equal to approximately half the wavelength (λ /2). Only wavelength controls the depth of the wave base, so the longer the wave, the deeper the wave base and hardly any wave induced motion exists below the wave base.

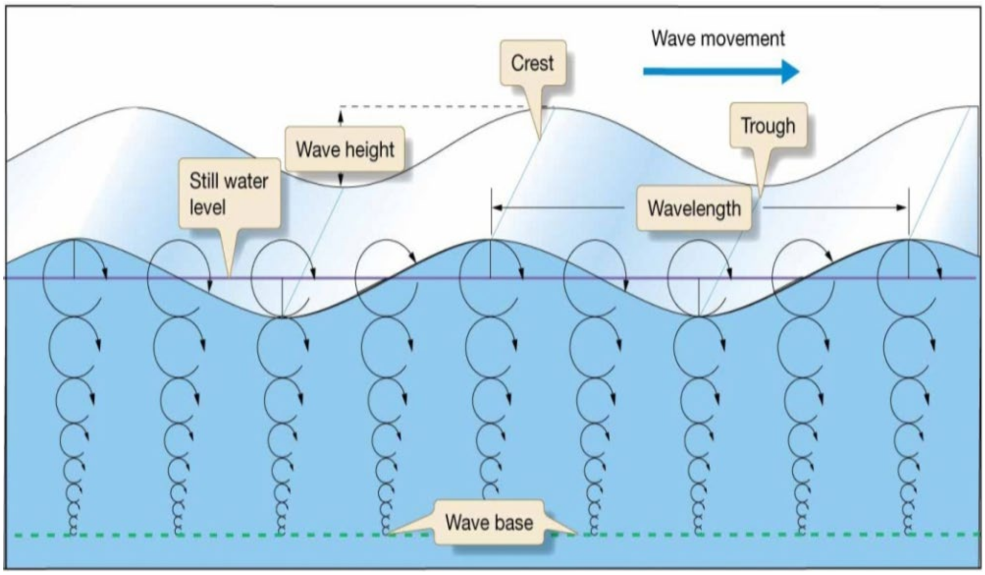

Figure 1: Illustration of orbital motion generated by gravity waves

2. Methods to measure waves

There is a wide spectrum of methods to detect waves and wave fields ranging from satellites, different types of coastal/ship/platform mounted radars to buoy measurements at the surface and to pressure and acoustic based methods from below the surface (see Figure 2). Surface buoys are considered to be the preferred method to obtain the most accurate wave measurement.

Figure 2: Different methods to measure waves. Aanderaa can offer three different methods, circled with red frames. MOTUS based navigational/environmental wave/current buoys. Acoustic profiler, discussed in this white paper and a pressure based method based on a well-proven wave/tide/pressure sensor.

3. Challenges to measure directional waves with acoustic Doppler profilers

As written above in chapter 1, waves with shorter wavelengths will decay, attenuate, more rapidly with water depth compared to longer wavelengths. The attenuation of the orbital movement for a given water depth is a function of the wavelength, the depth of interest, where the orbital movement is measured, and the total water depth. This decay can be described as the transfer function from surface elevation to the horizontal v_h and vertical v_z speed components of the orbital motion. When measuring the waves with a slanted beam, like with the Aanderaa SeaGuardII DCP Wave, the measured orbital motion will be a combination of vertical and horizontal orbital motion. Input parameters to the horizontal and the vertical transfer functions are wavenumber (k, a function of the wavelength), total water depth (z), and distance from seabed to observation cell where the orbital current is measured (d).

$$v_h = \omega \cdot \frac{\cosh[k(d+z)]}{\sinh(kd)}$$

$$v_z = \omega \cdot \frac{\sinh[k(d+z)]}{\sinh(kd)}$$

Horizontal and vertical transfer functions k-wavenumber, d distance from seabed to cell depth, z-total water depth

k is the wave number (which is 2π/λ where λ is the wavelength)

To illustrate the behavior of the transfer functions, refer to the plots below Fig 3 a-d.

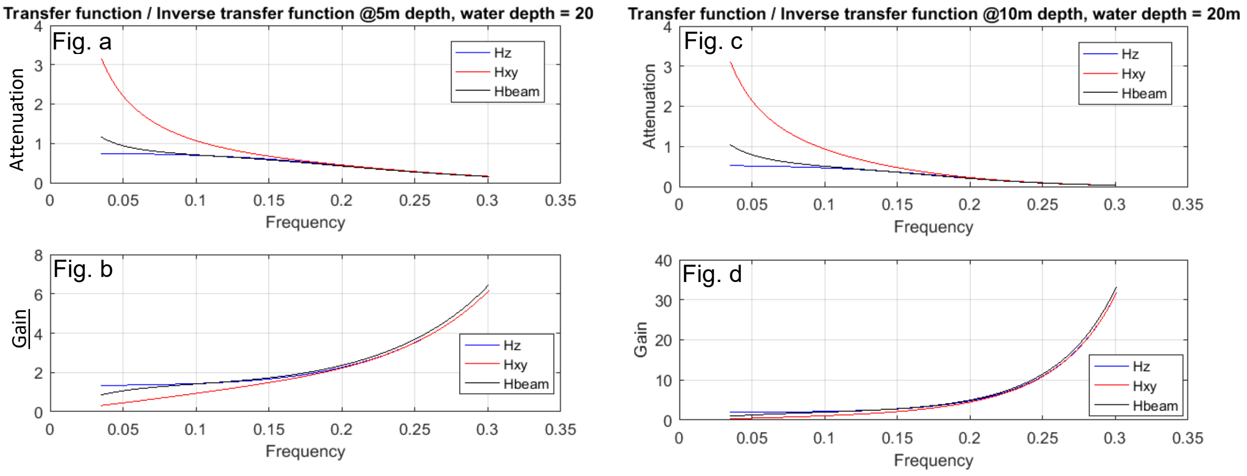

Figure 3

a) Transfer function as function of frequency for observation depth of 5 meter. Total water depth is 20 meter.
b) Inverse transfer function used to find equivalent orbital motion at water surface for observation depth of 5 meter.
c) Transfer function as function of frequency for observation depth of 10 meter. Total water depth is 20 meter.
d) Inverse transfer function used to find equivalent orbital motion at water surface for observation depth of 10 meter.

If we select a single observation depth we can plot the attenuation as a function of frequency. In the figure 3a above both horizontal, H_{xy} and vertical transfer function, H_z are plotted as well as the transfer function observed by the beam tilted 25 degree of the vertical plane, H_{beam}. Figure 3b is a plot of the inverse transfer function given in 3a. It represents the gain factor, or gain vector needed to convert the orbital movements at 5m and 10m depth into equivalent orbital movement at the surface. The measured Beam Speeds will then be multiplied by this vector.

By comparing the inverse transfer function for 10 meters toward the transfer function for 5 meters we can conclude that the orbital wave motion measured at 10 meters needs to be multiplied by larger factors, especially at high frequency (short wavelength).

The acoustic profiler calculates the wave energy spectrum and the directional spectrum based on acoustic measurement of the orbital speed. The SeaGuardII DCP Wave has a four beam Janus configuration with beams separated by 90 degree in the horizontal plane and tilted 25 degree off the vertical plane. The instrument should be located at the bottom looking upwards.

In order to cover most of the shorter wavelengths of the wave energy spectrum, the measurement of the orbital motion should be located as close to the surface as possible, but still be outside the zone contaminated by the direct reflections from the side-lobes. If the bandwidth is too extended in the short wavelength end (high frequency), or the cell is too far away from the surface, the Doppler detected speed of the orbital motion risk to be so low that it is dominated by the self-noise of the instrument.

For this reason it is important that the self-noise of the acoustic measurement system is kept at a minimum. The next chapter describes features that have been implemented in the SeaGuardII DCP Wave system to keep the sensor self-noise at a minimum.

4. SeaGuardII DCP Wave: innovative methods to maximize data quality

4.1 Adaptive pulse technology

To be able to calculate the full wave field with energy distribution and directions the induced orbital speed along the beams are measured. Typically the orbital water speed measured along the beams will vary from a few centimeters to several meters per second. A major challenge is to cover this wide range of beam speeds with one single mode. Narrowband mode can be used for practically any wave height and corresponding beam speed, but has a self-noise that would limit the useful bandwidth in a low wave height situation. On the other hand a low noise broadband would be excellent for measuring waves in a low sea state situation, but would fail in case of increasing wave heights. To overcome these contradictions the Tx mode and properties adapts itself to the wave situation. Not only does it switch between broadband and narrowband mode, but it also adapts the lag between the sub pulses in broadband mode in order to select the optimum tradeoff between noise and measurement range for the given wave situation. This method was for the first time implemented in the SeaGuardII DCP Wave.

In broadband the four transducers send out two frequency modulated (HFM/Chirp) pulses at 4 Hz with a short pause/lag in-between each measurement. The double pulse is reflected back against particles that move with the water. Depending on the movement of the water the returning pulse will have a positive/negative Doppler shift that is analyzed to obtain the orbital current speed for each of the four acoustic beams.

The lag between the broadband sub pulses is an important configurable parameter for the overall measurement noise. The longer the lag the lower the noise but if the current speed exceeds a limit value, typically between 80-120 cm/s depending on the lag, ambiguity/interference problems will occur. In the case that the current speed exceeds the limit an error corresponding to the ambiguity interval will bias the measurement. As written above a longer lag will give lower noise with the tradeback that ambiguity issues occur at a lower speed. A shorter lag will give higher noise but extend the unambiguous speed intervall. Depending on dominant wave size/orbital speed the SeaGuardII DCP Wave automatically selects the most suitable method which is either broadband with longer lag, mode 0, for the lowest waves heights (Hs≈2m) or broadband with overlap, mode 1, for intermediate waves (~ 2m<Hs< 3-4m) or narrowband, which have no ambiguity issues, for the highest waves (typically above 3-4 m).

4.2 Measuring directional waves and currents simultaneously: resolving ambiguity issues

New methods have also been developped to correct for potential ambiguities. The advantage of this feature is that a low noise highly accurate broadband mode can be used even in a higher wave situation. The ambiguity resolution method compensates to some extent the drawback of a broadband solution and extends the useful range for a given broadband mode.

Depending on the conditions different methods are used to avoid ambiguity contamination. When one of the two broadband modes is used to detect the waves it will frequently occur that the prevailing irregular orbital speed will pass above the ambiguity limit creating a spike in the measured speed from one measurement to the next. By subtracting the newest measured value from the previous these spikes can be detected and the contaminated measurements removed (Fig. 4). At 4Hz this method has been validated on offshore wave deployment to work flawlessly at Doppler speeds which are 50% above the ambiguity interval.

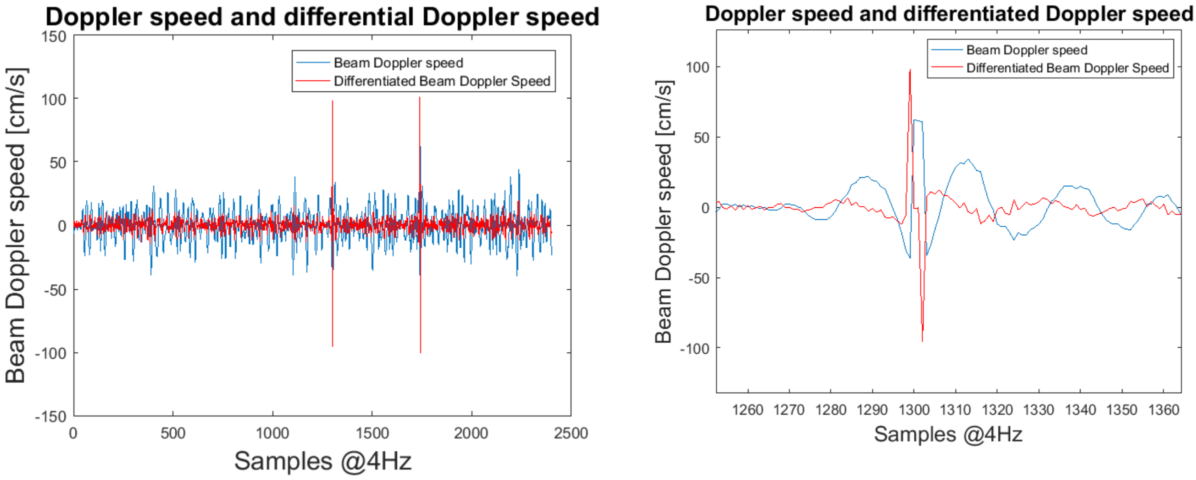

Figure 4 Left: Blue curve; ambiguity in the beam speed. Red curve; differentiated beam speed. The ambiguities become large spikes compared to the normal variations in the beam speed. Right: Zoom of beam speed and differentiated beam speed ambiguity.

In more extreme wave situations, the sensor will automatically switch to a Narrowband mode, typically around 3 – 4 m significant wave height. No user interaction is needed for the sensor to select the optimum transmission mode. The switching between the different modes is executed automatically. The wave solution in the SeaGuardII DCP uses the maximum beam speed during a wave recording interval in order to decide which of the broadbands or narrowband mode should be used for the next interval.

Resolving ambiguities for current measurement application with no or little wave and turbulence interaction is also possible, but other methods have to be used. In this case the measurement does not require high fixed sampling rate and the pings can either be evenly spread out or transmitted with maximum ping rate in a burst transmission. For the SeaGuardII DCP a multiple stage ambiguity resolution/current measuring scheme is implemented based on the transmission of two double broadband pulses with slightly different lag. This extends the limits for which broadband can be used to measure currents by the instrument.

More detailed information on the theory and the methods implemented in this instrument are given in “SeaGuardII DCP Wave: Adaptive Tx pulse for wave measurements” Tholo et al. (2019 in press).

The SeaGuardII DCP Wave — 600 kHz current and wave profiler

The SeaGuardII DCP Wave instrument measures and calculates a number of wave parameters. An overview can be found in table 1, below.

Significant Wave Height H_{mo}	Wave Mean Period T_{m02}	First Order Spread σ	Orbital Ratio Spectrum K(f)
Peak Wave direction θ	Wave Energy Period T_{m-10}	Energy Spectrum E(f)	Fourier Coefficients Spectrum A1(f), A2(f), B1(f), B2(f)
Wave Peak Period T_p	Mean Spreading Angle θ_K	Directional Spectrum $DWS_m(f)$	

Table 1: Wave parameters provided by the SeaGuardII DCP Wave instrument

5. Field data validation and inter-comparison

5.1 The site

In order to validate the directional wave solution, a SeaGuardII DCP Wave was deployed in the winter 2018-2019 in a bottom frame at 20m depth off the coast of Karmøy, South West of Norway in the North Sea and connected to shore by a 300 meters long ruggedized cable. The instrument was also equipped with a standard Aanderaa Wave and Tide pressure sensor for non-directional wave measurement. The deployment position is showed in Figure 5 below. The test site also included one Datawell Waverider MkIII buoy and one EMM2.0 MOTUS directional wave buoy equipped with a single point current sensor DCS and a Doppler Current Profiler Sensor DCPS600.

Figure 5: Location of test site off the west coast of Norway and bathymetry; 0.5 meters contour lines used (right).

Data from the three different systems were available in real time and stored in a web based database that allows retrieval of historical data. In addition there was two-way communication with the SeaGuardII DCP Wave so that different settings and calculations options could be changed and tested.

5.2 Results

Due to the proximity to the shoreline and the bathymetry at the test site, the data correlation between the different systems will depend on the full 3D wave field, i.e. the total wave energy distribution and the frequency dependent wave direction. In wave situation where the wave energy is mainly from west the wave field should be fairly homogenous across the different platform locations. At the sea bed station located in the Eastern most position the pressure based wave sensor and the SeaGuardII DCP Wave will of course be exposed to the same wave field independent of the wave situation.

Figure 6 gives a comparison of significant wave height from the SeaGuardII DCP Wave, the Waverider buoy and the MOTUS buoy. In the same figure the automatically selected Tx mode is plotted. The criterion for the automatic mode switching is based on the maximum beam speed compared to a predefined threshold level.

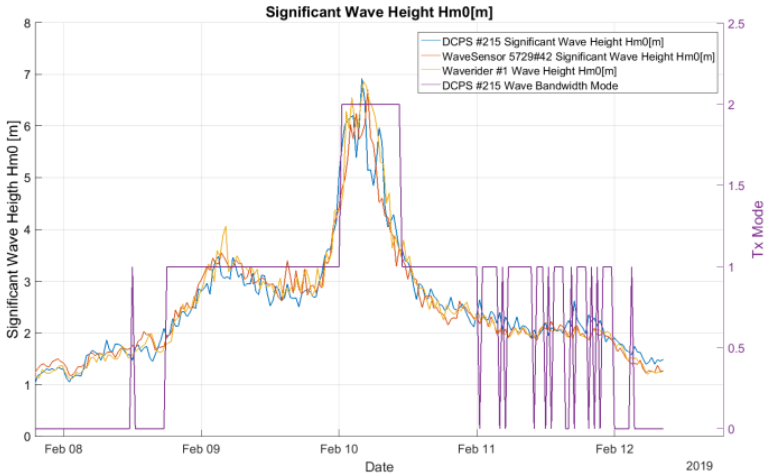

Figure 6: Comparison of significant wave height between SeaGuardII DCP Wave(blue), Waverider (yellow) and Motus /WaveSensor 5729#42 (red). The Mode is also plotted in violet. 0-Broadband short lag. When H_{m0} reaches approximately 2m, the mode switches to 1-Broadband long lag, and when H_{m0} reaches about 4m, the instrument will switch to a robust 2-Narrowband mode with no practical speed limitations.

Figure 7, left gives a comparison between the SeaGuardII DCP Wave and the Aanderaa Wave and Tide sensor. Both sensors are colocated and should give approximately equal wave height results. It should be noted that there are minor differences in the integration time which is 17 minutes for the Aanderaa Wave and Tide versus 20 minutes for the SeaGuardII DCP Wave. The agrement between the three independent methods has been excellent at this test site with significant wave heights ranging from 0.8-7m.

To the right in Figure 7 the wave peak direction is compared bewteen the Datawell Waverider buoy and the acoustic system of the SeaGuardII. Also here the agrement is good between the two buoys at the surface and the bottom mounted acoustic instrument. Due to bandwidth limitation of the SeaGuardII DCP Wave, an option of separate output for wind driven waves and swell is not implemented. The Motus sensor for buoy will report both swell and wind driven waves.

The SeaGuardII DCP Wave — 600 kHz current and wave profiler

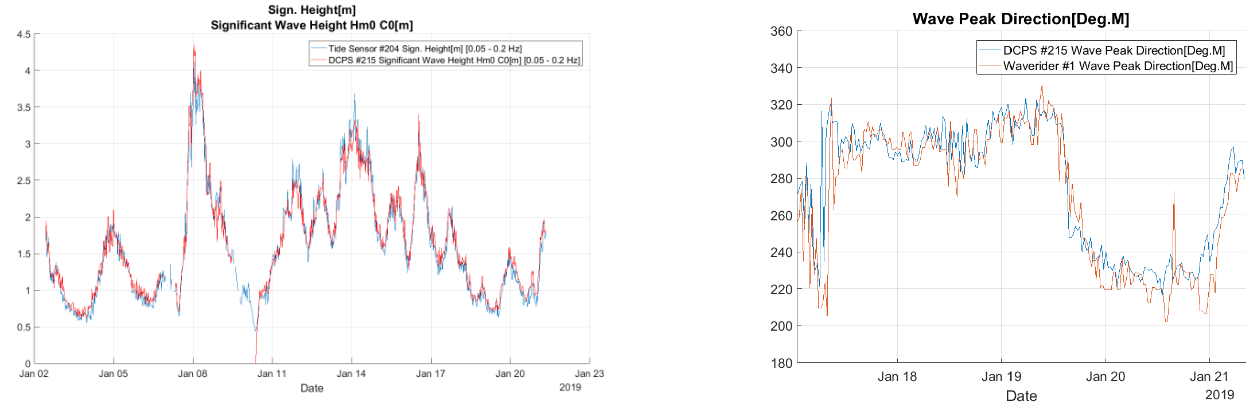

Figure 7, left: Comparison of significant wave height between pressure based wave and tide sensor and SeaGuardII DCP Wave. Equal bandwidth is used. Right: Wave direction from Dastawell Waverider and SeaGuard II.

Figure 8, left shows the Energy Spectrum given by the Waverider for a duration of one week compared with the same Energy Spectrum given by the SeaGuardII DCP Wave, Figure 8 right. The bandwidth provided by the Waverider has an upper frequency limit of 0.6 Hz, but is limited for comparison purpose in the figure to match the bandwidth of the SeaGuardII DCP Wave

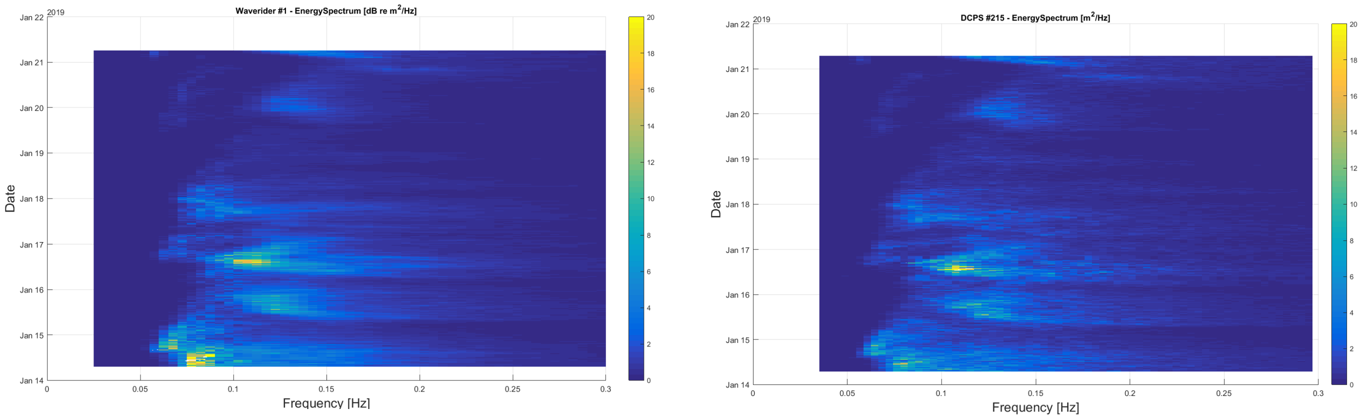

Figure 8, left: Energy spectrum from Waverider. January 14 – January 22. Right: Energy spectrum from Waverider. January 14 – January 22

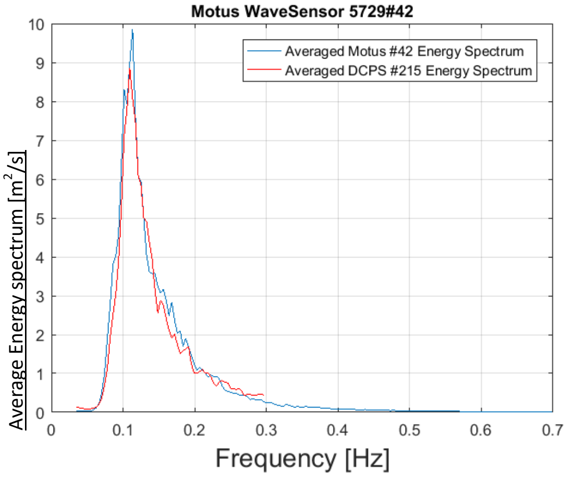

Figure 9: Comparison of averaged Energy Spectrum covering 60 records of 30 minutes from MOTUS fitted EMM2.0 buoy and the SeaGuardII DCP Wave.

To do a better estimate of the frequency response of the different sensors, a time average of the Energy Spectrum is calculated and presented in figure 9. The figure gives an example of Energy Spectrum average over a duration of 30 hours for MOTUS #42 and SeaGuardII DCP Wave.

Conclusions

The SeaGuardII DCP has been extended with an acoustic wave solution based on a four beam Janus configuration. An adaptive Tx pulse has been implemented in order to optimize the Broadband lag and thereby the maximum unambiguous Doppler speed that can be measured to match the requirement given by the wave induced orbital water speed. To extend the ambiguity interval for a wave application, methods for ambiguity correction have been evaluated and validated. By combining adaptive Tx pulse with ambiguity resolving methods, the measurement noise has been reduced and the available bandwidth for wave height measurement has been extended. This innovative technology has been compared with surface placed wave buoys and pressure based wave measurements at the bottom off the west coast of Norway through the rough winter months 2018-2019 and found to produce very similar results. In conclusion, the data quality of the acoustic directional wave measurements from 20m water depth and from the wave pressure sensors at the same location are excellent and compared with wave measurements from the two surface buoys, MOTUS and Waverider.

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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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