Possibilities and limitations of Acoustic Surface Tracking

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abstract - **Nortek has improved upon its AWAC, a current and wave measurement sensor package, by introducing a vertical, acoustic beam that detects the surface. This added functionality allows for directly measuring waves as opposed to inferring wave estimates from a truncated wave energy spectra.**

Traditionally, wave measurements from bottom-mounted instruments, such as the combined pressure-velocity (*PUV*) approach, are limited in their frequency response. This is due to attenuation of the surface signal with increasing depth. Recent advances employ the alternative solution of measuring orbital velocities close to the surface and employ the Maximum Likelihood Method (MLM) estimate technique [1]. This improves the accuracy at higher frequencies. However, for deployment depths of 20 meters or deeper, these methods cannot resolve waves periods that are 3 seconds or shorter. Moreover, these bottom-mounted systems do not measure the real surface time series, which makes it difficult to calculate extreme value statistics.

The introduction of Acoustic Surface Tracking (AST) with the vertical acoustic beam has permitted the AWAC to measure waves in deeper waters with greater accuracy and extended frequency response. This paper provides a closer look at the frequency response of the AST and when it is permissible to use it to determine water level.

I. INTRODUCTION

Nortek's AWAC (Acoustic Wave And Current, Fig. 1) approach to using a vertical beam to measuring surface waves is not a new concept [2]. However it represents a considerable step forward from existing bottom mounted sensors now available, which generally rely just on the pressure and velocity measurements.

The development and validation of the surface tracking has been documented before [3]. However for reference, we present in Section IV the comparison with a Directional WaveRider buoy. This test was carried out in a water depth of 32 meters and clearly demonstrates the value of the AST.

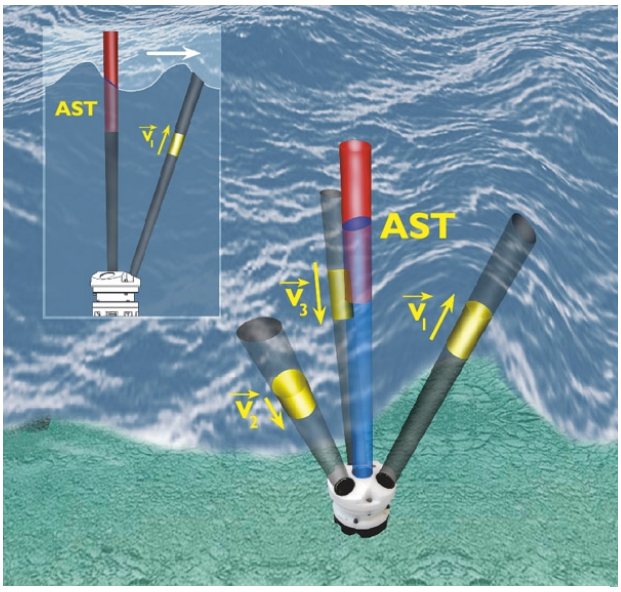

Fig. 1 Deployed AWAC with four beams

It has become increasingly clear that the AST represents the cornerstone for accurate wave estimates which are nearly depth independent. Our attention has been drawn to gaining a greater understanding of the depth limitations for the AST. In order to achieve this, two AWACs have been deployed at depths of 12 and 24 meters and configured to measure simultaneously. A comparison is presented herein.

Apart from understanding the depth response of the AST, we look at what other possibilities the AST affords us. This includes the AWAC's AST use as a water level gauge and short wave measurements in water depths of 60 meters.

II. SYSTEM OVERVIEW

The AWAC is designed to measure both the current profile and the wave directional spectrum using acoustic Doppler technology. It can be used in stand-alone or online mode. The target application is long term coastal monitoring of waves and currents. The wave measurement process employs a single velocity cell per beam to minimize data volume and extend deployment duration. Furthermore the cells are adaptively located for each wave burst measurement to ensure maximum signal strength.

The AWAC that was tested has four, 1 MHz transducers. One center and the other three are equally spaced around it, angled 25° off the vertical axis. Beam width is 1.7° (3 dB point). The 600 kHz AWAC differs only in that it has a larger center transducer to maintain a narrow beam width for the AST.

The instrument employs a fixed point DSP. Normal memory size is 20-152 MB of flash, which provides several months of current and wave data.

Other specifications:

- Pressure sensor, 50/100 m range
- Compass
- Tilt sensor
- Temperature sensor
- 1 Watt typical power consumption
- 9-16 Volts DC
- 1, 2, or 4 Hz Wave burst sampling
- 512, 1024, or 2048 samples per burst

III. AST PROCESSING

The approach used to detect the surface is relatively simple. It can be broken down into the following sequence of steps. (1) Transmit a pulse of a given length; (2) Specify a receive window covering the range of all possible wave heights; (3) Discretise the receive window into multiple cells (~2.5 cm); (4) Apply a match filter over a series of cells to locate surface; (5) Use quadratic interpolation to precisely estimate surface location. An example of the amplitude time series return signal is provided in Fig. 2.

The resulting time series of AST range measurements is naturally subjected to false detects. These false detects arise from competing peaks in the echo return from the surface. This may occur if there are targets other than the surface in the acoustic beam's path. False detects require special determination and are identified by analyzing the time series of the free surface. This process begins by identifying range estimates that exceed a specified outlier boundary relative to the mean of the ensemble. This boundary is defined as some multiple of the standard deviation of the ensemble. The clean up step is iteratively performed with increasingly tighter bounds to ensure all false detects are removed. Handling of the false detects involves a simple interpolation of the neighbor values. Finally, if the cumulative number of false detects exceeds 10% of the total number of samples in the ensemble, the ensemble is considered corrupt and discarded. The occurrence of this has proven to be relative low (1-2%), and wave estimation process can be replaced with one of the backup estimation methods using either the velocity or pressure measurements.

Once the time series for the surface has been established, we carry on with the traditional zero-upcrossing method. This is done for determining extreme wave estimates (H_{10}, H_{max}), whereas spectral methods is used for all other wave estimates.

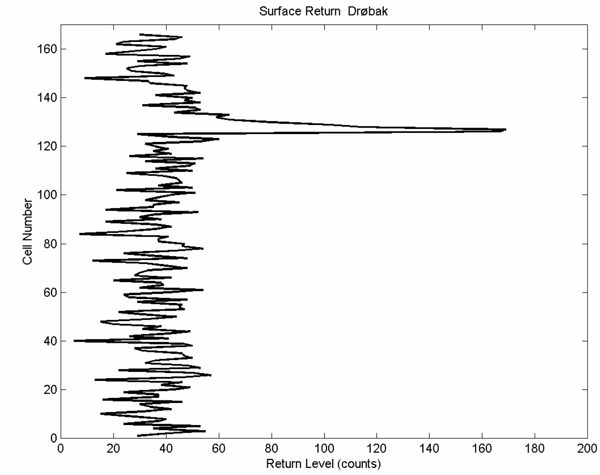

Fig. 2 Example of a echo return from the surface.

The frequency limitation for the measurable waves does not just lie with the Nyquist, sampling limit, but also with the "footprint" created by vertical beam ensonifying the surface. Naturally, as the range increases, the footprint increases. As a general rule, we follow a Nyquist like reasoning; the frequency limit associated with the footprint is when half the wavelength is on the order of the diameter of the footprint. This clearly is the absolute shortest measurable wave. We can expect that the frequency response begins to roll off just prior to this point.

IV. RESULTS

The organization of the results is presented in terms of each AST objective. The subsections present an overview of the possibilities and discuss the limitations one can expect for the specific application. This includes (A) performance comparison with a directional Waverider buoy, (B) depth dependent limitation for short wave measurements, (C) water level (tide) measurements with the AST, (D) short wave measurements in deep water with a 600 kHz AWAC.

A. Gabbard

A first long term comparison was conducted with a directional wave buoy off the southeast coast of the UK, near Gabbard. This comparison was carried out in cooperation with the Centre for Environment, Fisheries and Aquaculture Science (CEFAS). Data was collected over a period of six weeks where the AWAC was configured to record one wave burst per hour. The AWAC was located in 32 meters of water. This test used sample rate of 2 Hz.

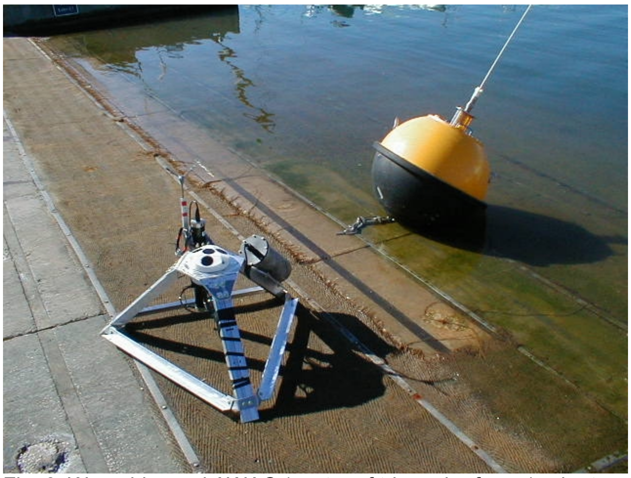

Fig. 3 Waverider and AWAC (center of triangular frame) prior to deployment.

Figure 4 shows a comparison of the results from the AWAC (red) and the Datawell Directional WaveRider (blue). The three plots show H_s, peak period, and direction at the peak period, respectively. There is very good agreement between the two instruments aside from a few exceptions. The exceptions include spikes in the wave buoy estimates as well as scattering for the directional estimates. The scattering for the directional estimates appears to occur when the waves are both short (less than 4 seconds) and small (less than 0.5 meters). However this appears to be the case for both instruments.

The comparison test demonstrates that the AWAC is capable of measuring waves during rather large storms. Breaking waves represented an initial concern since there is greater potential for false detects created by bubbles entrained in the water column. However this does not appear to be a problem. In the end, less than 1% of the AST based estimates were discarded due false detects. There was no apparent correlation between false detects and wave height.

In the event that the AST was not available, there are two alternative solutions for estimating wave parameters. The first is based on the pressure signal and the second is the estimates derived from the measurements of the waves orbital velocity. Since the AWAC has several measurement options the data tends to be spike free.

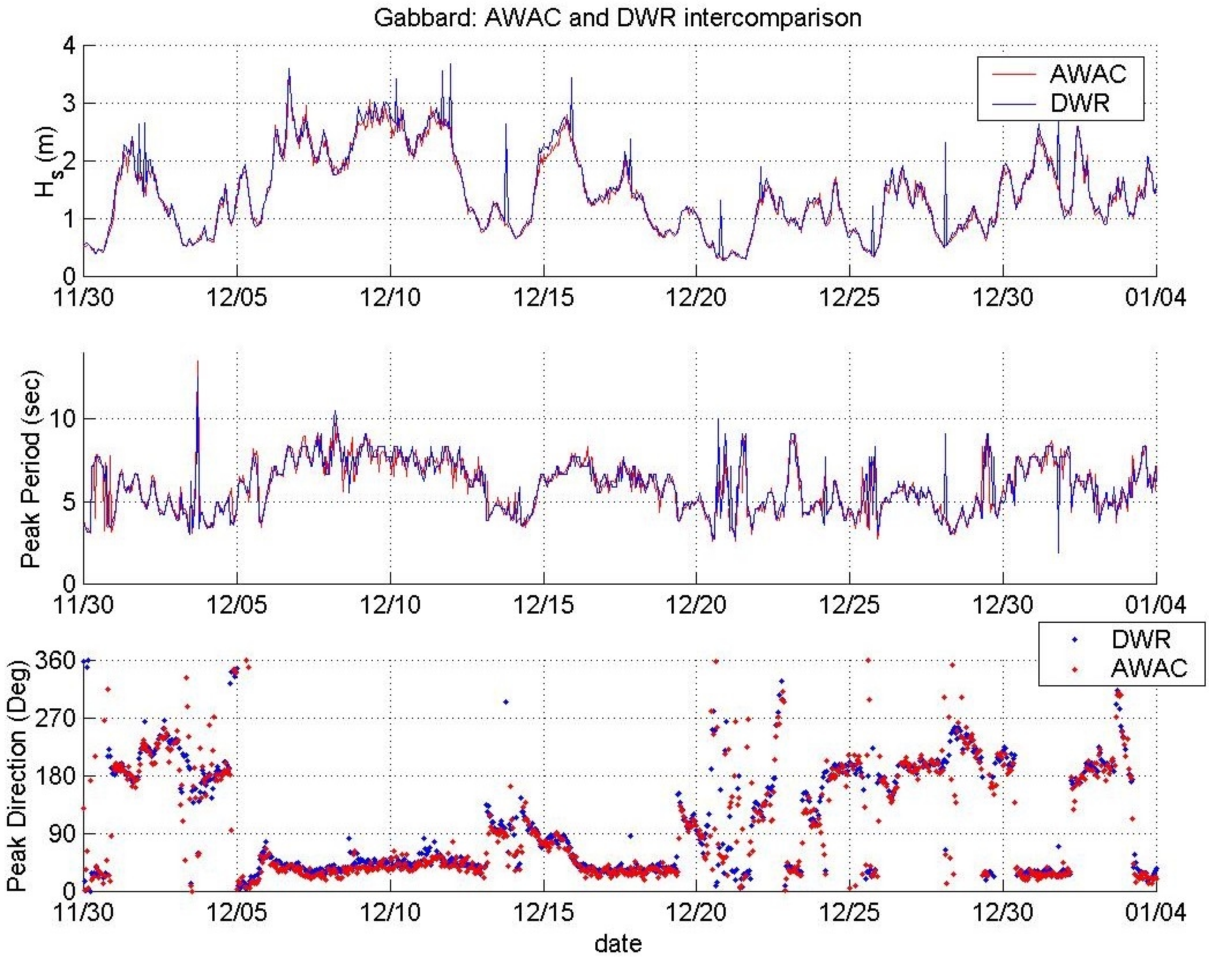

Fig. 4 Comparison results for the AWAC (red) and the Directional WaveRider (blue). Estimates provided in the three plots are significant wave height, peak period, and peak wave direction.

B. AST Intercomparison

After confirming that the AWAC provides comparable wave estimates with a directional Waverider, we decided to investigate the performance of the AST more closely. The AST has demonstrated accurate wave measurements but the exact frequency limit for short waves at different depths was unclear.

The AST can sample as high as 4 Hz which means the shortest wave that can be resolved is a 2 Hz wave. However we know that there exists a limit presented by the ensonified footprint on the free surface. When the footprint begins to equal half the wavelength we can no longer accurately measure these high frequency waves. The footprint can be calculated from the transducer's beamwidth (1.7°) and the range to the surface using simple geometry.

$$\theta = Beamwidth$$

$$D = Depth$$

$$F = Footprint\ Diameter$$

$$F = D\sin(\theta)$$

$$2F < Wavelength$$

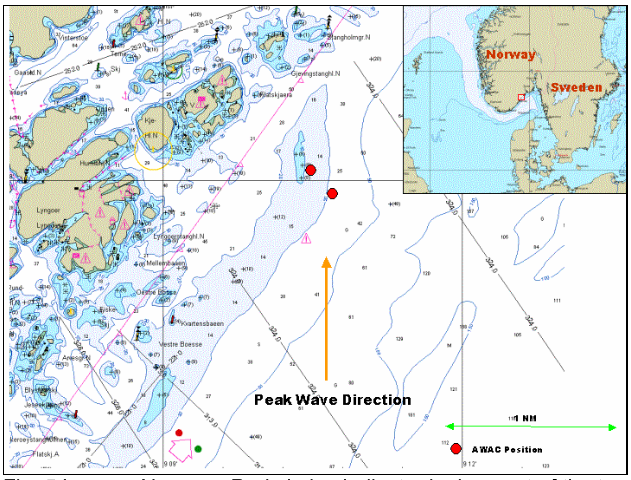

Fig. 5 Lyngør, Norway. Red circles indicate deployment of the two AWACs. Waves are dominantly from the south.

The footprint contributes just partially to the AST response, and other factors play a roll in the overall estimate of the range to the surface (match filter, surface roughness, etc.). In fact, even the estimated footprint can not be accurately defined by the 3 dB beam width which we use as a starting point for this estimate

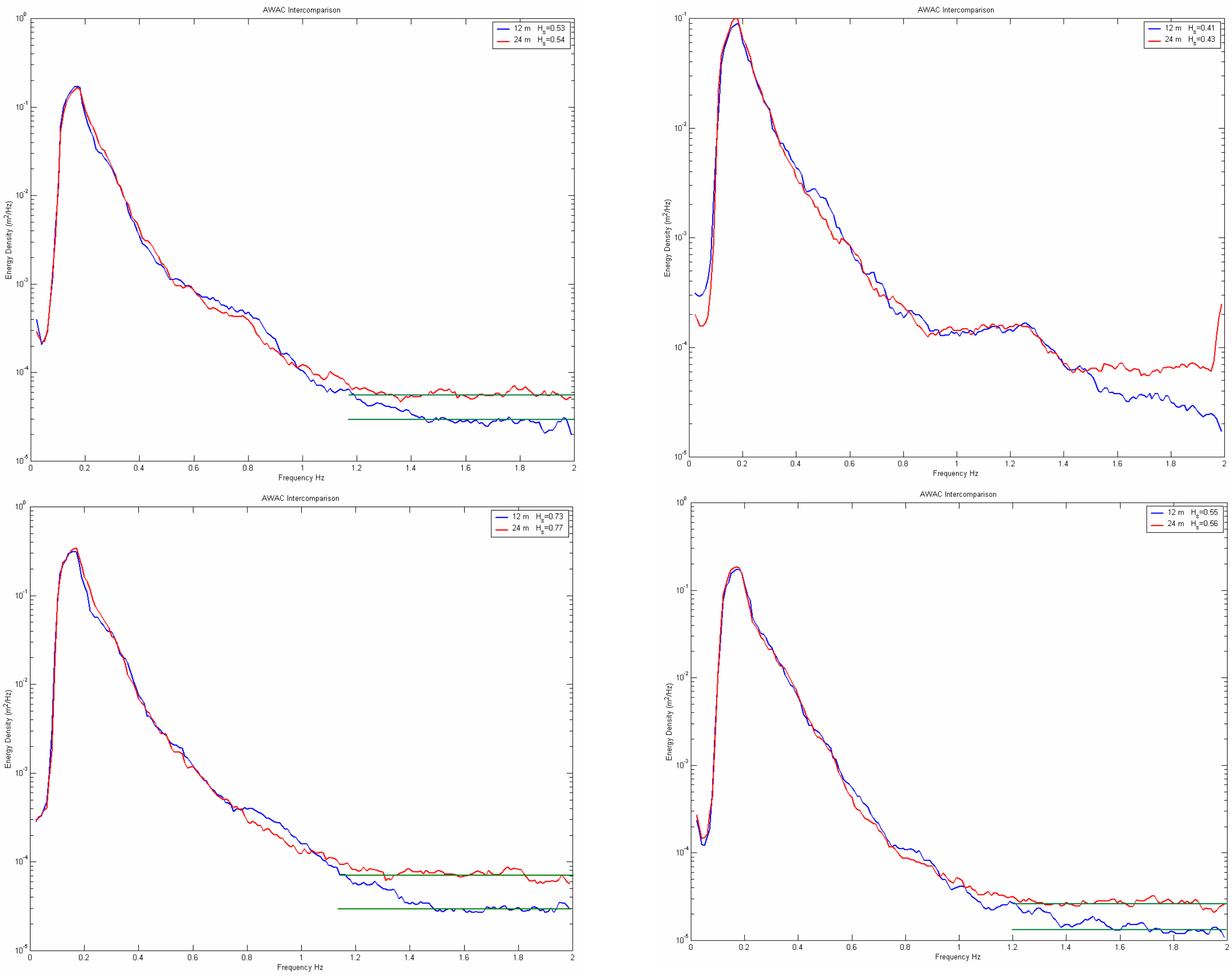

Fig. 6-9 Spectra of four individual wave bursts. 12 meter (blue), 24 meter (Red), Noise floor (Green)

Table 1 Depth dependent AST limits			
Depth (m)	Footprint Diameter (m)	Wavelength (m)	Freq (Hz)
6	0.20	0.40	2.0
12	0.38	0.75	1.4
24	0.74	1.47	1.0
36	1.08	2.16	0.9
48	1.42	2.85	0.7
60	1.79	3.58	0.7

In order to find the effect of the footprint we performed a side by side test with two AWACs in different depth waters. This test was conducted along the southeast coast of Norway in water depths of 12 and 24 meters (Fig. 5). Both AWACs were deployed with less than 1° of tilt and therefore the footprint may be approximated as a circle. The AWACs were positioned as near to one another as possible and configured to sample simultaneously such that they measured the same waves. Of course slight differences are expected due to spatial separation.

The criteria used to specify the frequency limit for the AST is defined as where the noise floor first begins to present itself as we move up in frequency. Fig.6-9 show the energy density spectra plotted in log space (12 meter Blue, 24 meter Red). The noise floor is noted by the green line. The frequency at which the spectra begin to fall into the noise floor represents the frequency limit for the particular range of the AST. It is clear that there is some variation from spectrum to spectrum but it appears the limit for the 12 meter range is 1.5 Hz, and for the 24 meter it is 1.2 Hz. The two sided beamwidth footprint has a corresponding limit that is 1.4 Hz for 12 meters and 1.0 Hz for 24 meters. This suggests that our 3 dB beam width limit may be a little conservative, particularly for the greater ranges of the AST.

Table 1 shows the geometric depth dependent footprint and associated frequency limit for a 3 dB beam width of 1.7°. The wavelength presented in Table 1 is equal to twice the footprint diameter and the frequency corresponds to this wavelength.

C. AST level detector

We primarily use the perturbations of the range estimates for wave analysis. However under certain conditions it is entirely feasible to use the AST as a range detector. This is particularly interesting because the AST as a level detector is not subject to atmospheric pressure variations like a subsurface pressure sensor.

Range estimates are calculated using the travel time of the surface return and an estimate of the speed of sound. The potential source of error with the range estimate comes primarily from the speed of sound estimate. The range estimate for two way travel is as follows,

$$Range = CT/2 \, ,$$

C is the speed of sound,
T is the two way travel time.

A comparison of water level estimates is provided in Fig. 10. The AWAC is located in 18 meters of water and is at the entrance of Geraldton Harbor, Australia. The Handar Tide recorder is located at the inner harbor, 3 km away. The AST water level estimate has been shifted down to the same level as the Handar sensor. Despite the different locations, it is clear that there is favorable agreement between the two estimates. The Handar estimates tend to be less variable since it is in a protected harbor whereas the AST is exposed to the open sea.

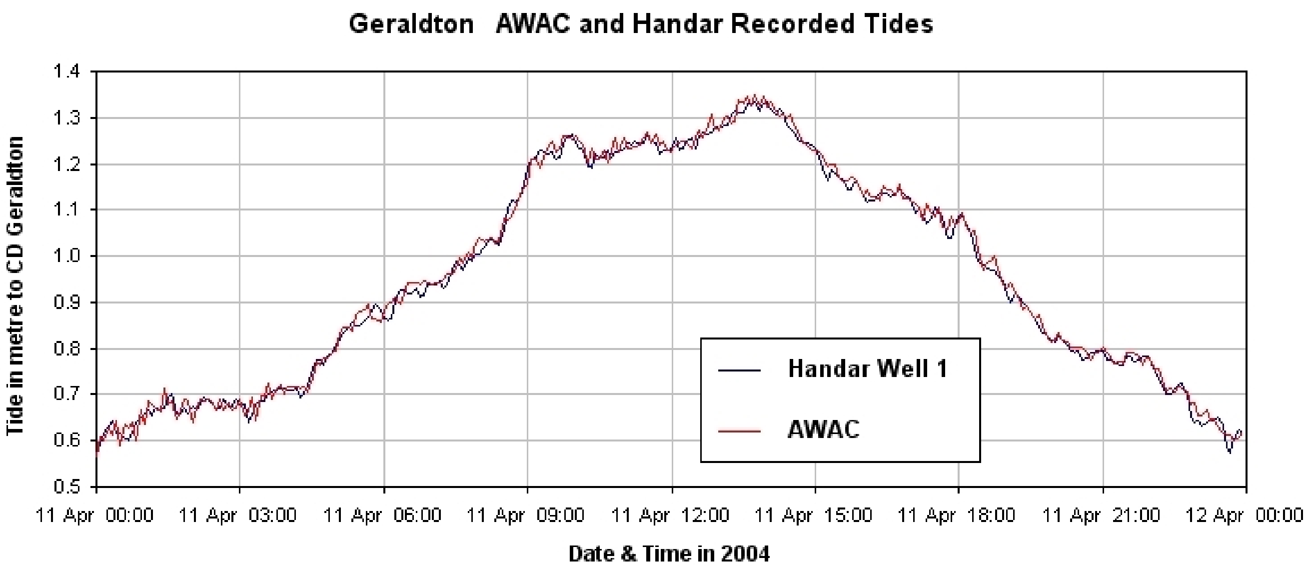

Fig.10 Comparison of water level estimates from the AWAC-AST and Handar tide recorder Geraldton, Australia. The analysis is compliments of MetOcean Engineering and Tremarfon

The speed of sound in salt water is influenced by the salinity and temperature. The AWAC has a temperature sensor and a user defined salinity level for inputs into the internal speed of sound calculation [7]. Given that the salinity is input correctly and the water column is well mixed, then a very good estimate of the water level is available.

The variation of speed of sound in coastal waters tends to be not as substantial as deep water gradients, however they are occasionally large enough to be taken into consideration. An example where the gradient would be substantial is 1480 m/sec to 1530 m/sec. This would lead to an error for the range estimate of approximately 1.5 %.

The favorable performance of the AST for water level estimates at the Geraldton location is possible because the water is well mixed and there are no substantial gradients with the speed of sound (temperature primarily). Therefore using the AST as a water level estimate is fine for locations that are well mixed, but it should be noted that locations with large and variable gradients in the water column are susceptible to greater errors.

D. Deeper coastal waters performance

Once the 1 MHz AWAC proved its capability to measure waves accurately to depths of 35 meters we decided to transfer the technology to the 600 kHz AWAC (Fig 11). Transmitting at 600 kHz frequency permits wave measurements in depths which are approximately twice as deep. This means the 600 kHz AWAC can profile currents out to 50 meters and use the surface tracking to depths of 60 meters. The one obvious difference is the center transducer's larger diameter. The larger center transducer allows the AST to maintain a narrow center beam (1.7°).

Testing the performance of the 600 kHz was kept relatively simple since the AST has been adequately studied with the 1 MHz. The most interesting capability for the 600 kHz to explore is the ability to measure both small and short waves at a depth of 60 meters. To accomplish this, we deployed two AWACs in the protected Oslo Fjord. One AWAC, a 1 MHz, was deployed in 12 meters of water to serve as a reference. The 600 kHz was deployed in 57 meters of water approximately 500 meters away. Waves were generated by driving a 12 meter fishing boat between the two AWACs.

Understandably, the wave environment at each instrument was different for several reasons, but on a base level the test proved to serve well for comparison of short and small waves.

Results are presented in Figure 12. Here one can see that the time series have good agreement in terms of picking up the maximum wave height of 28 cm and that both instruments measure the initial wave which is less than 5 cm. Furthermore, both instruments indicate a similar peak period below 2 seconds in the spectra plot

V. CONCLUSIONS

Surface tracking for coastal wave measurements has been developed and added to Nortek's AWAC sensor. The AST does not suffer from the attenuation effects associated with increasing depth. Furthermore the AST estimates waves directly using the time series, opposed to spectral inferred estimates. This fact means we are not just able to view profiles of nonlinear and transient waves but also able to estimate time series wave statistics such as top 10% (H_{10}) and max wave heights (H_{max}). The AST's demonstrated capabilities suggest that it is better used as the primary means for wave measurements whereas the pressure and velocity serves as useful compliments. This means there are three independent estimators.

A Comparison test near Gabbard demonstrated that the AWAC compared very well with a directional Waverider. The test occurred in 32 meters of water. The test period was exposed to a widely varying wave environment of storms and calm periods.

Lastly, the AST technology was transferred to the 600 kHz AWAC and successfully tested at a depth of 57 meters. This last test shows that AWAC is capable of measuring waves which are shorter than 2 seconds and smaller than 5 cm for deployment depths as great as 60 meters

Acknowledgments

Thanks is in order to those who contributed to the variety of studies: The buoy comparison was conducted by Jon Rees at CEFAS (U.K.). The surface level analysis was conducted by MetOcean and Tremarfon (Australia). The two AWAC deployments for the inter-comparison was performed by Morten Person (Norway).

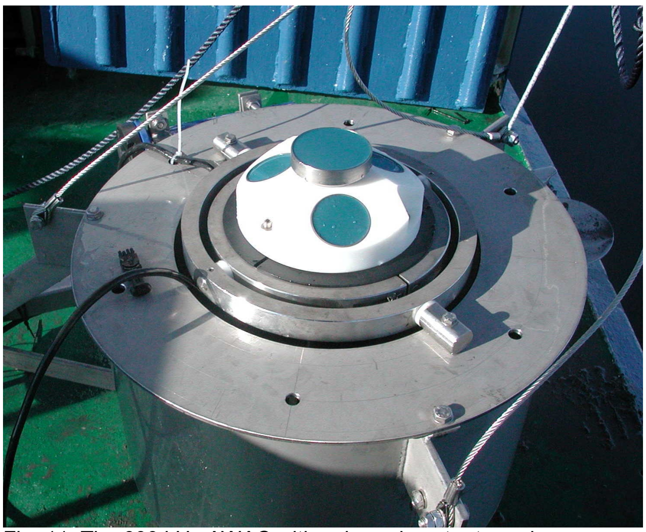

Fig. 11 The 600 kHz AWAC with enlarged center transducer.

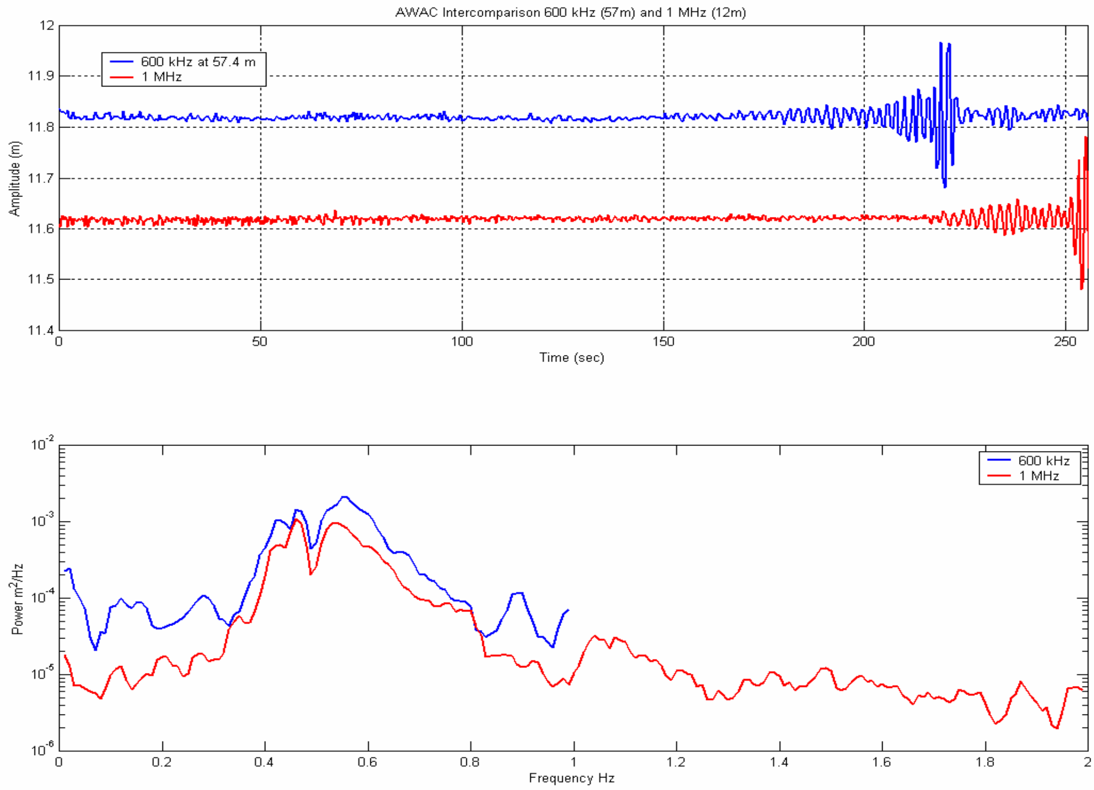

Fig. 12 Wave measurements for the 600 kHz (blue) and 1 MHz (red) AWACs. The top pane is the time series of the AST where the 600 kHz has been shifted from 57.4 meters to 11.8 meters for comparison purposes. The bottom pane shows the spectra for the two instruments, note the energy in these spectra would correspond to waves with a significant height of less than 10 cm.

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