Wave Height Measurements Using 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 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 incorporating the Maximum Likelihood Method (MLM) estimate technique [1]. This improves the accuracy at higher frequencies. However, for deployment depths of 10 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 following paper provides an overview of the process of (1) developing the surface track algorithms, (2) comparing with a Datawell wave buoy off the coast of Carqueiranne, France (3) and testing limiting conditions such as breaking waves and greater depths (35 meters).

I. INTRODUCTION

Nortek's AWAC (Acoustic Wave and Current, Fig. 1) has traditionally measured both the pressure and orbital velocities to estimate the wave frequency and directional spectrum. Recently, we have modified the firmware to allow us to detect the free surface using the vertical beam. The modification eliminates the constraint from the attenuation of wave properties with depth. Therefore the AWAC is now capable of measuring higher frequency waves in deeper water with a greater degree of accuracy.

This approach of measuring waves is not necessarily 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.

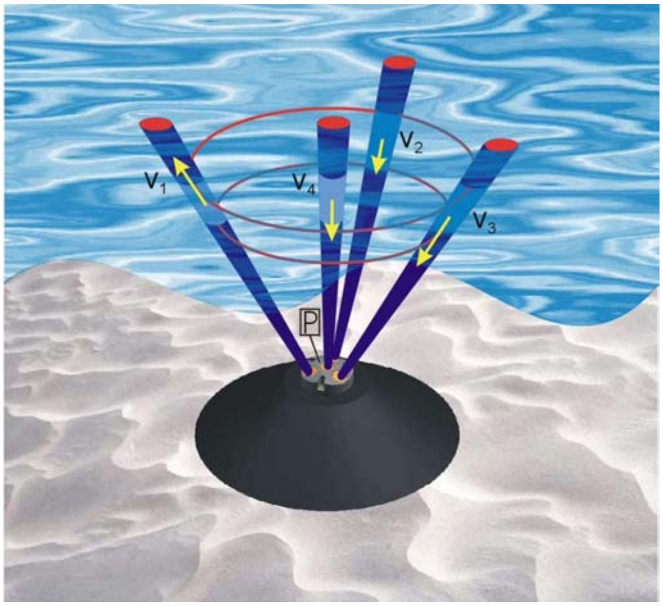

Fig. 1 Deployed AWAC with four 1 MHz beams

The development and validation of the surface tracking was performed over the course of three separate experiments. The first was performed at Drøbak, a site located in the fjord just south of Oslo. The second experiment was performed in Carqueiranne, France. Here we were able to directly compare to a DataWell WaveRider buoy. Once we established that the surface track measurements were in good agreement with the wave buoy, we implemented the surface track firmware in an AWAC online in Hwa Lien, Taiwan. This last site demonstrated that the AWAC is capable of measuring waves in depths of 35 meters, with little compromise in data quality.

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 and online mode. The target application is long term coastal monitoring of waves and currents along the coast. The wave measurement process employs a single cell per beam to minimize data volume and extend deployment duration. Furthermore the cells are adaptively located to ensure maximum signal strength.

The AWAC 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 instrument employs a fixed point DSP. Normal memory size is 20-80 MB of flash, which provides several months of current and wave data.

Other specifications:

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

III. 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 (~5 cm); (4) Apply a match filter over series of cells to locate surface; (5) Use quadratic interpolation to precisely estimate surface location. An example of the amplitude time series for the discretised signal is provided in Fig. 2.

Clearly we had to consider the prospect of false detects and no detects. No detects were easily noted since they did not exceed a specified threshold level for detection. False detects on the other hand required special determination. This began by identifying samples that exceeded a specified bound relative to the mean of the ensemble. This boundary was defined as some multiple of the standard deviation of the ensemble. This clean up step was iteratively performed with increasingly tighter bounds to ensure all false detects were removed. Finally, if the cumulative number of false and no detects exceeded 10% of the total number of samples in the ensemble, the ensemble was considered corrupt and discarded.

Once the time series for the surface has been established, we carry on with the traditional zero-upcrossing method of estimating wave statistic.

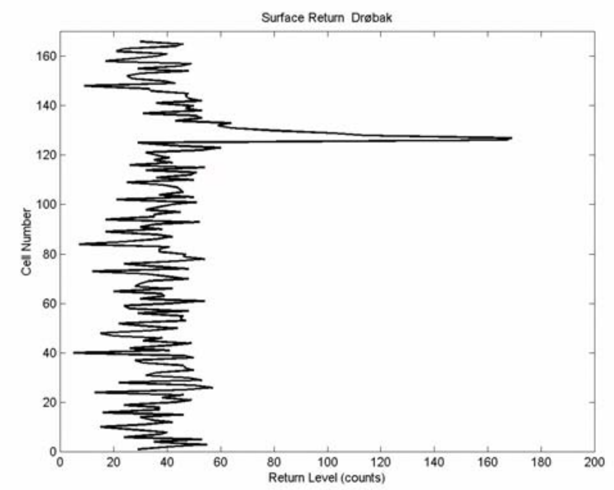

Fig. 2 Example of a echo return from the surface.

The frequency limitation for the measurable waves does not just lie with the Nyquist limit, but also with the “footprint” created by vertical beam intersecting the surface. Naturally, as the deployment depth 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.

IV. RESULTS

The organization of the results is presented in terms of the objective of each experiment. Therefore the data collected in Norway, France, and Taiwan is organized in relation to the development of the surface tracking algorithms and the subsequent validation.

A. Algorithm/Firmware Development

The first test was performed at Drøbak, a site local to Nortek in Norway. The site offers the luxury of having an AWAC online. This affords us the opportunity to quickly test out new algorithms since we can both install new firmware and upload collected data online. The site was interesting in the sense that it is virtually unexposed to the open ocean as it is still in the Oslo Fjord (Fig. 3). This means that there are three possible mechanisms for wave generation. These are (1) locally wind generated waves, (2) transient waves from local shipping traffic on way to Oslo, and perhaps if the direction was right, (3) waves from open sea.

The AWAC is located on the sill of the fjord in 21 meters of water. Data was sampled at 4 Hz and collected for over 17 minutes (1024 seconds). The receive window was set at 8 meters in length and subdivided into smaller bins so that there were 170 cells, each of which 4.7 cm long. We did not expect to ever see any waves requiring such a large receive window, however it provided ample opportunity for false detects.

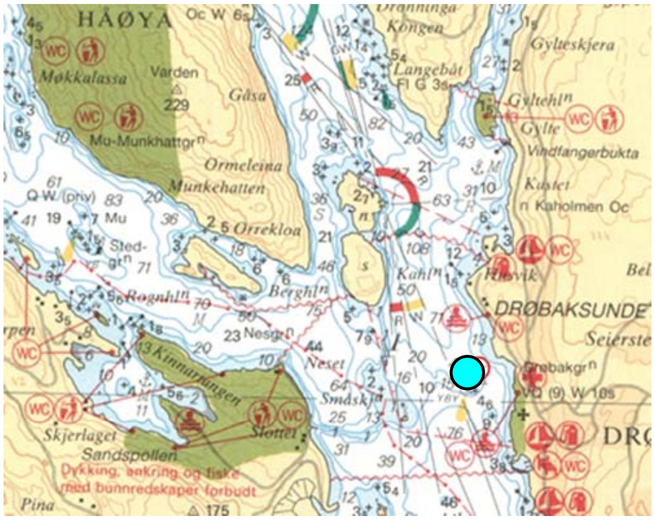

Fig. 3 AWAC test location noted by large circle, Drøbak Norway.

Initial testing was quite encouraging since we immediately noted higher frequency waves in the time series and that transient events were regularly detected since the location is exposed to considerable shipping traffic. An example of this is presented in Fig. 4. Here one can see that a passing ship's wake. The attenuated pressure signal is plotted as well. Additionally, the locally generated wind waves are clearly evident in the surface track but not in the pressure signal. The spectrum of the surface track is presented in the subsequent plot, demonstrating that energy is detectable up to 1 Hz for the given setup.

The beam casts a footprint with a diameter of 0.62 meters on the surface. Therefore the limit associated with the footprint is 1.1 Hz.

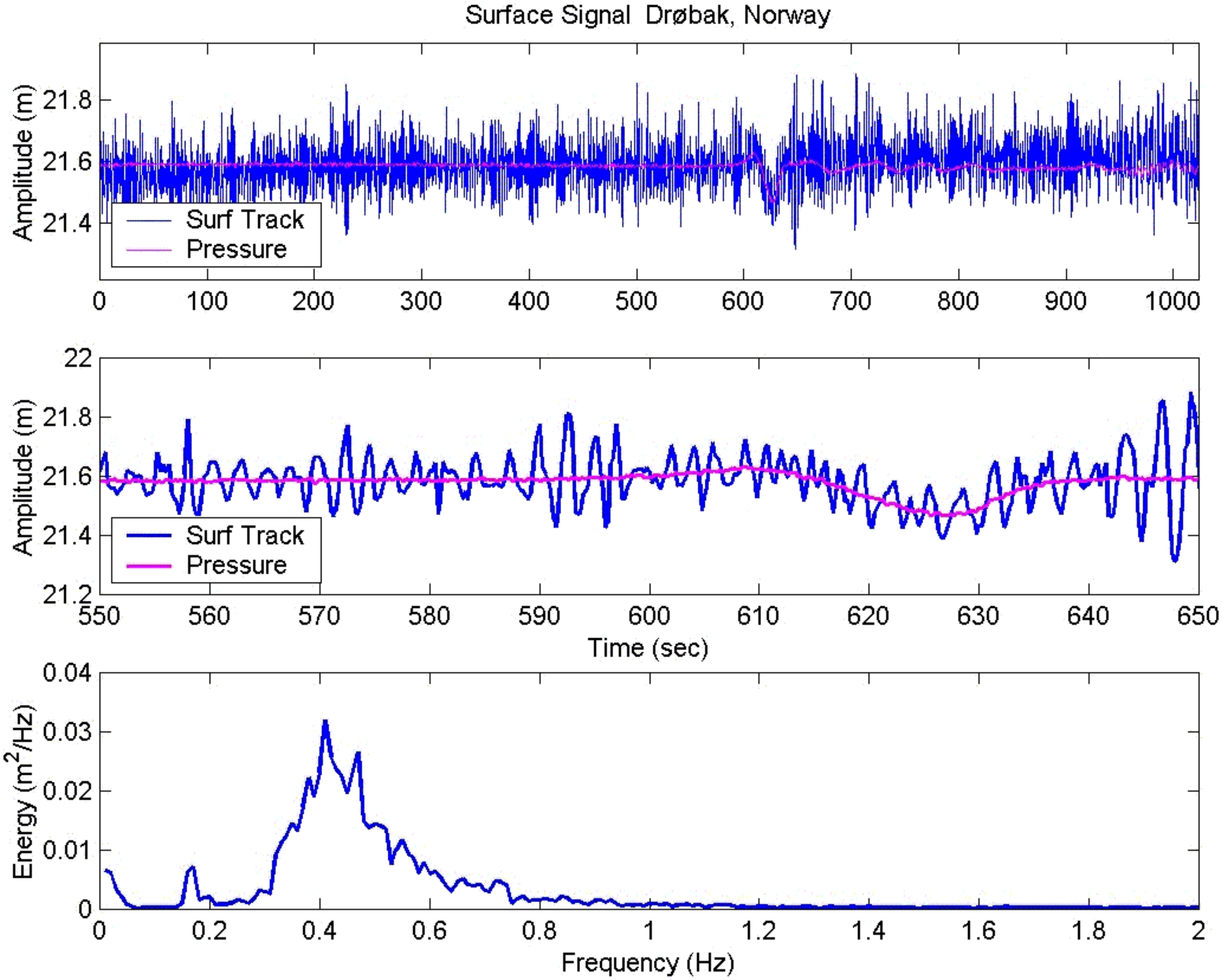

Fig. 4 Surface Track (blue) and Pressue (Purple) time series indicating a passing ship. Bottom pane shows energy spectrum for the surface track, note detectable energy up towards 1 Hz.

Surprisingly, there were very few false or no detects for the surface tracking. We attributed this to the fact that the wave environment here is only exposed to small waves and which are rarely breaking. Breaking waves seem to be the most threatening to accurate surface detection since there is greater possibility to falsely detect the entrained bubbles below the waves. The value of the tests in Drøbak was the realization of a match filter and threshold level for which we had confidence. We concluded that the next logical step was to verify the accuracy of the measurements and expose the method to both larger and breaking waves.

B. Validation

Once the algorithms and firmware were in place, we set out to compare to a reference. Nortek teamed with Thetis in the south of France off of Carqueiranne for this next phase. The wave environment was characterized by a calm period of approximately a day before a strong, persistent wind blew for two days out of the southwest. At times the wave field was rather complex, since the local wind waves and swell arrived from different directions. The days during the high winds provided breaking waves.

An AWAC and a non-directional DataWell Waverider buoy were deployed in 14 meters of water off the coast of Carqueiranne. Fig. 5 shows both the AWAC (center of the triangular frame) and the wave buoy before deployment. The instruments were located approximately 20 meters laterally from one another. Again the AWAC used 4 Hz sampling for 1024 seconds. Wave data was collected once an hour for nearly four days. The wave buoy was setup to collect wave data every half hour, with a 2.56 Hz sampling rate, and a duration of 20 minutes. The startup time for both instruments was synchronized, however since the wave buoy measured for slightly longer, only the identical sampling time was used for the subsequent analysis and comparison.

Estimates for significant wave height are presented in Fig. 6. Note that the difference is rarely more than a few centimeters. Spectra for the two instruments are also presented for the pressure, surface track and wave buoy (Fig. 7), again indicating strong agreement. The spectra associated with the pressure show near perfect agreement with the surface track, however it is only valid for the lower frequency range before the signal falls into the noise floor and the transformation to surface spectra is no longer applicable. The wave buoy shows a slight difference, but in general has favorable agreement.

It appears that the surface track detected a little more energy at the higher frequencies than the wave buoy. This difference is illustrated with estimate for the mean period (Fig. 6). Here the surface track nearly always has a lower mean period than the wave buoy. This is also noted in the spectra; the energy for surface track always exceeds that of the wave buoy above 0.75 Hz. This is probably due to the fact that buoy has an unwanted response near 1 Hz and the signal is most likely low passed filtered just below this point to handle this unwanted effect. Therefore we expect the buoy to measure waves out to some frequency just below 1 Hz.

The limitation for the frequency response of the surface track is the footprint of the vertical beam. Clearly for the shallow depths in Carqueiranne, we will be capable of measuring waves of shorter period. The footprint has a diameter of 0.42 meters and therefore the upper frequency limit is 1.4 Hz.

The concern of falsely detecting a breaking wave's bubble plume instead of the surface did not seem to be realized. A strong south westerly wind induced continuous breaking of the waves. This did not seem to negatively influence estimates, as the wave heights between the two instruments seem to be in close agreement throughout the experiment. The waves never exceeded much more than 1 meter in significant wave height since the waves were limited by the relatively short fetch along the French coast. Therefore the surface track remains to be tested for extreme wave events.

Fig. 5 Waverider and AWAC (center of triangular frame) prior to deployment, Carqueiranne, France.

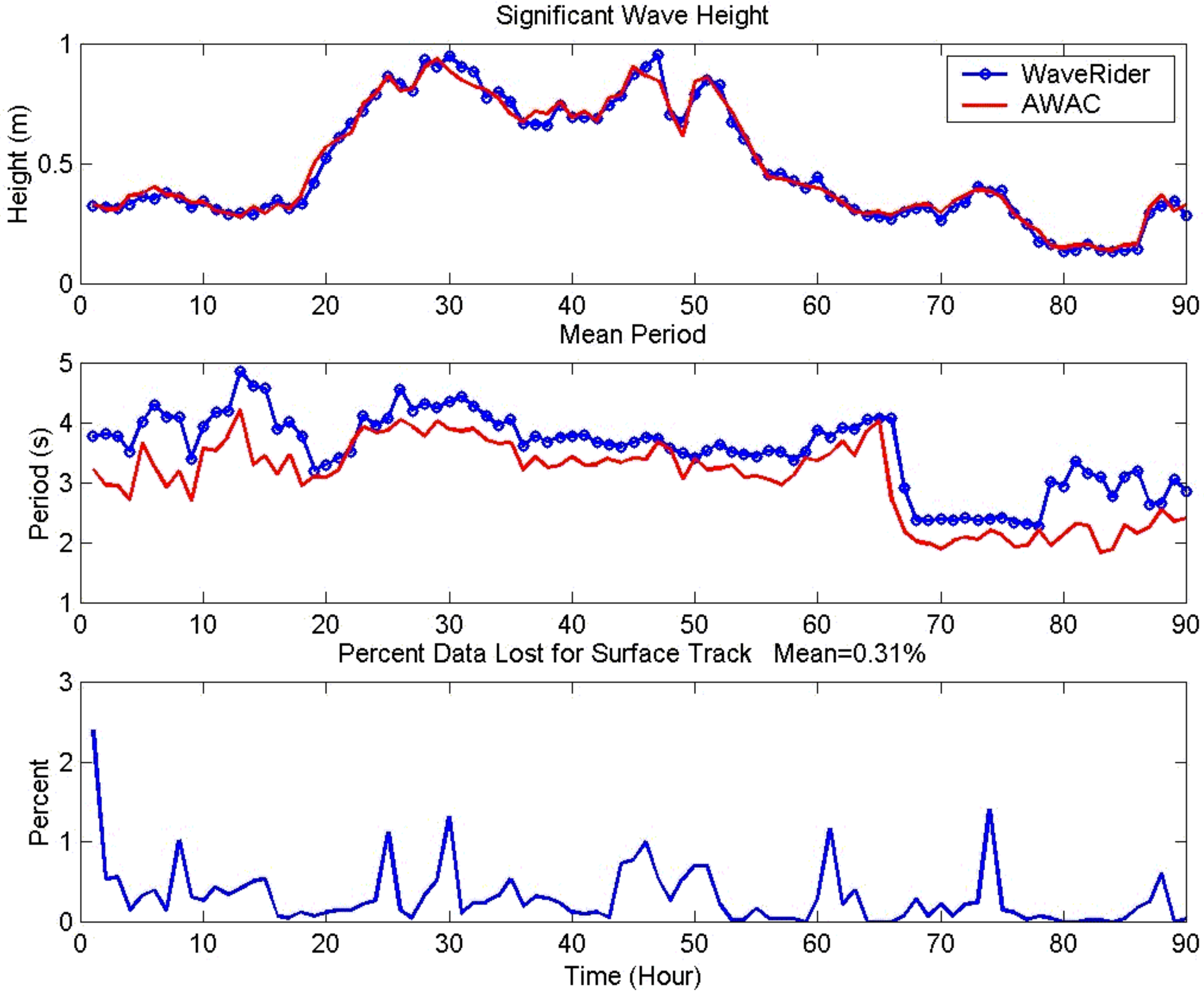

Fig. 6 Estimates of significant wave height, mean period for both surface track (red) and Waverider (blue). The bottom pane show percentage of data loss for surface track.

C. Testing Limitations

Once the AWAC's surface tracking accuracy was verified to be comparable to the wave buoy, we decided to expose the surface detection to a more rigorous environment that would indicate some limits of performance. This was carried out in cooperation with the Taiwan Institute of Harbor and Marine Technology (IHMT), who has a national network of AWACs for wave measurement. These instruments are all online. Therefore it was once again relatively easy to upload the surface track firmware and monitor the results.

The AWAC at Hwa Lien was used for this test and is located in 34 meters of water. This test however used a smaller sample rate of 2 Hz. At this depth, waves above 0.9 Hz are limited by the footprint of the vertical beam, so it does not appreciably improve estimates to sample at a higher rate.

The estimates for the significant wave height indicate how the pressure and velocity estimates will underestimate the wave heights (Fig. 8). This is particularly true when there is wave energy above 0.2 Hz.

The results presented in Fig. 9 show that there is favorable agreement once again between the pressure, velocity, and surface track spectra. The pressure and velocity spectra are limited by the depth attenuated response. Recall this result in Fig. 7, when the pressure based surface spectra was grossly overestimated as the frequency increased. This is generally handled by finding some local minimum below where the spectra dramatically increases and extrapolating downwards according to the Pierson-Moskowitz Spectrum.

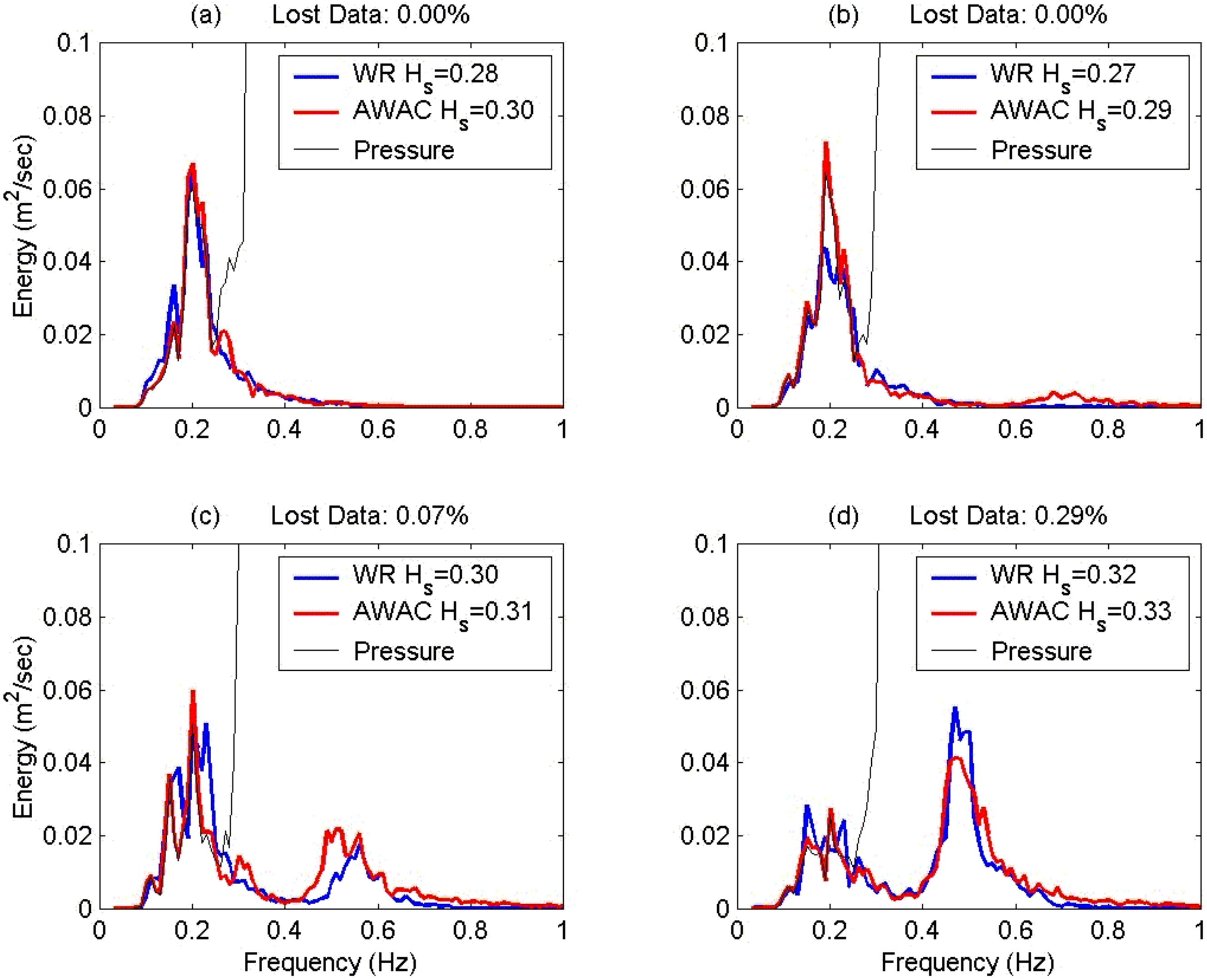

Fig. 7 Spectra for four consecutive wave ensembles from the surface track, pressure, and Waverider

The amount of lost data for a depth of 35 meters is noticeably greater than that of the tests in France. In Taiwan it was on average 1.25%, and peaked near 10% for two of 46 ensemble measurements; whereas in France, for a depth of 14 meters, we noted less than 0.5% data loss on average.

V. CONCLUSIONS

Surface tracking for coastal wave measurements has been developed and added to Nortek's AWAC sensor. This added feature provides a useful compliment to the pressure and velocity wave measurements; so that there are three independent estimators. More importantly it does not suffer from the attenuation effects associated with increasing depth and therefore estimates waves directly using the time series, opposed to spectral inferred estimates. This fact means we are now able to offer time series wave statistics such as top 10% (H_{10}) and max wave heights (H_{max}).

The surface track's ability to measure energy at higher frequencies (shorter period waves) suggests that we will be less likely to underestimate wave heights in general.

This series of tests first began with the algorithm development in Drøbak. Testing confirmed the ability to measure energy at higher frequencies and the ability to detect transient events as local shipping traffic was continuously noted.

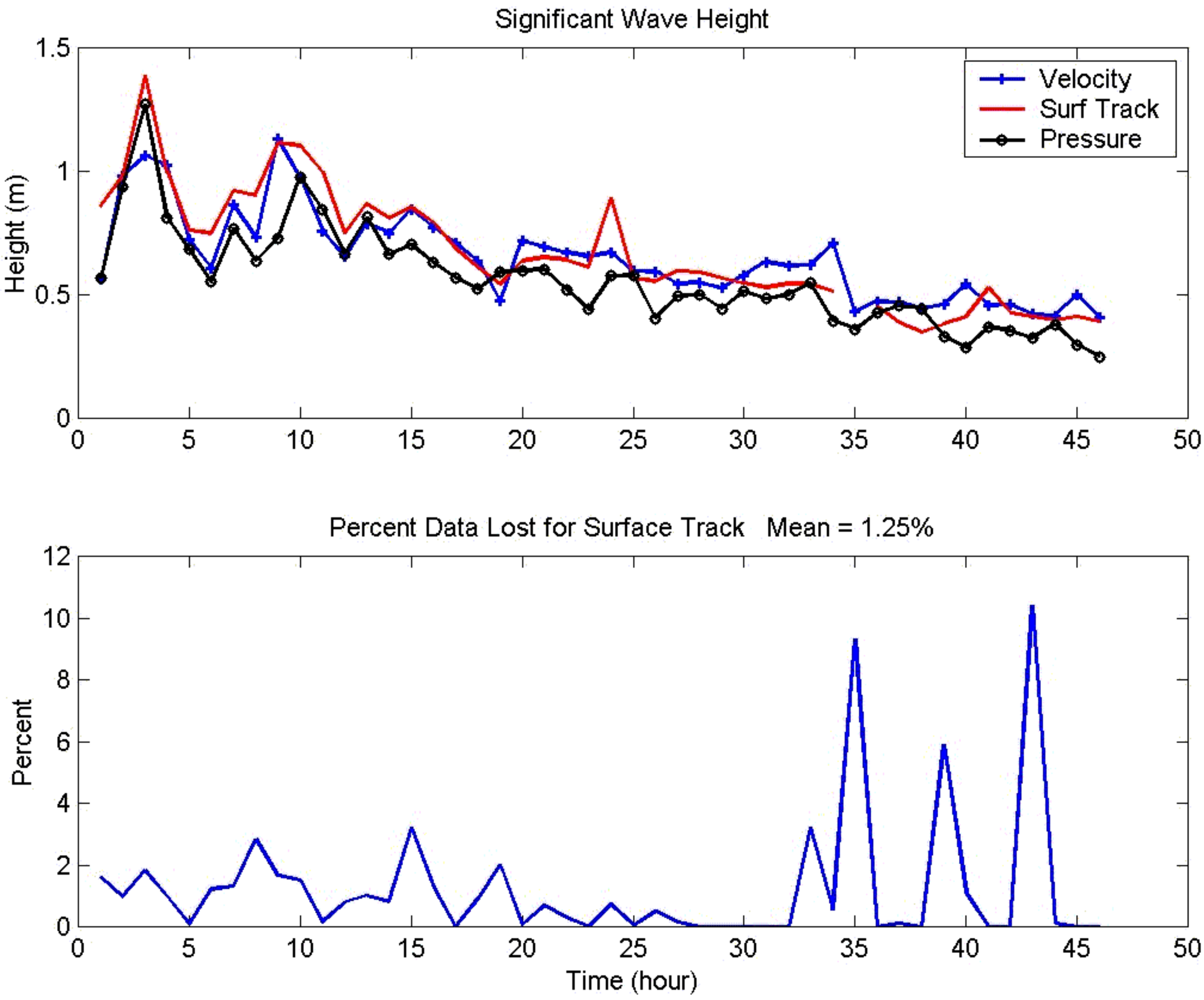

Fig. 8 Significant wave height estimates for surface track (red), pressure (black), and velocity (blue). Lower pane shows data loss for the surface track for each ensemble.

The development stage was followed up with tests in the south of France to compare to wave buoy measurements. The test validated that the surface track achieves nearly identical height estimates to that of a wave buoy. It was also noted during this test that breaking waves (H_s = 1m) did not negatively influence estimates.

Lastly, the surface track was tested at 35 m in Taiwan. This test was initiated to consider the effects of increased depth on data loss. Data loss was greater than prior tests, however the level did not exceed a loss rate that would have required us to discard the time series.

Future work includes looking at the possibility of using the vertical beam to measure the surface velocity (using Doppler estimates) as yet another independent estimator. However, as it stands now, the AWAC represents a complete wave measurement system for coastal waters with several internal data quality checks.

Other objects in consideration are to develop a better understanding of the limitations of the surface track with regard to depth and exposure to larger breaking waves.

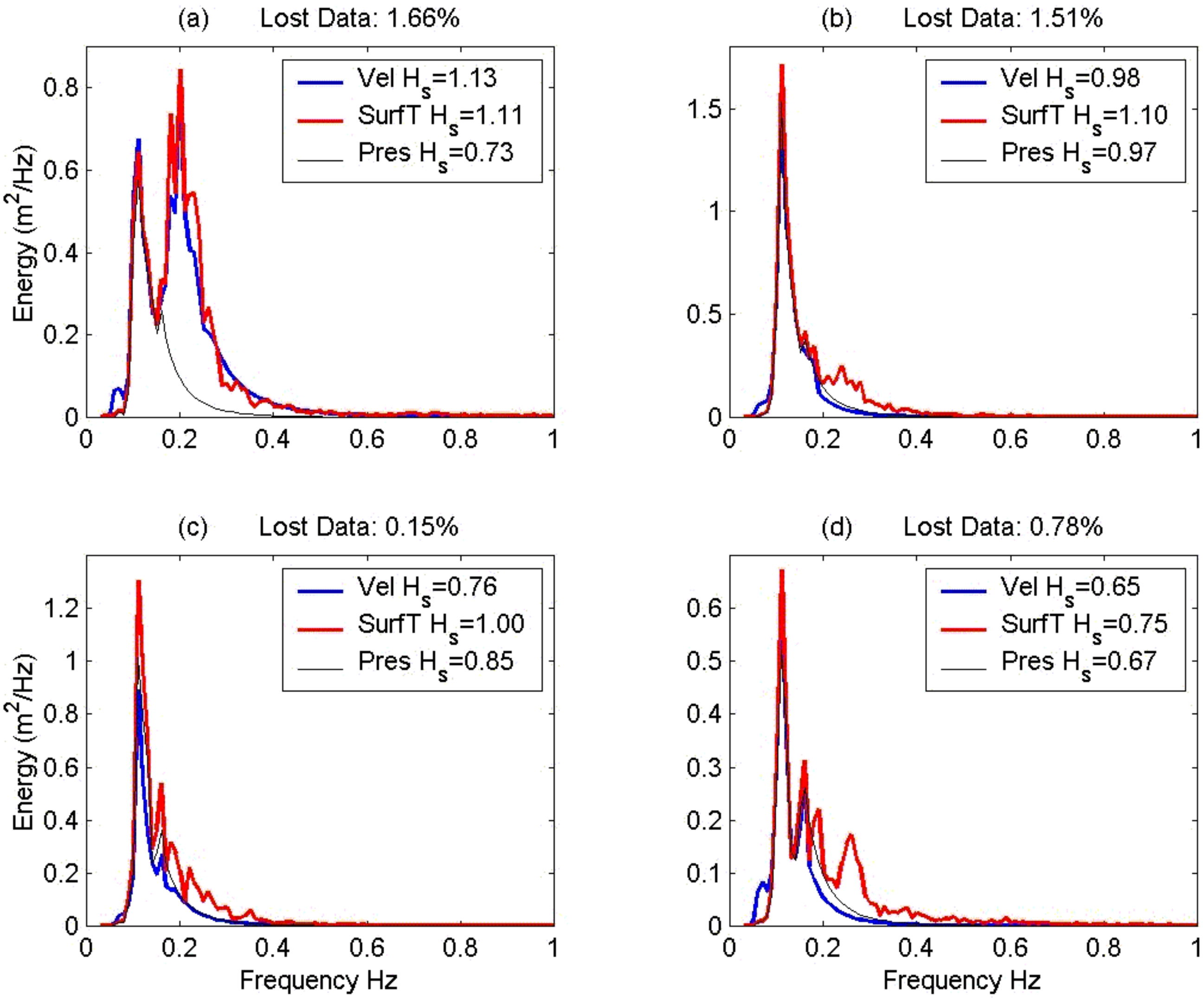

Fig. 9 Spectra for Hwa Lien, Taiwan

Acknowledgments

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