Analysis of Band-Passed Directional Wave Data

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Abstract **The last 10 years have seen the development of a new class of acoustic Doppler systems that can measure the wave directional spectrum in addition to their classical current profiler capability. Among these systems is the Nortek AWAC (Acoustic Waves and Current), which uses three acoustic beams angled at 25 degrees from vertical for wave direction estimation and profiling current velocities. A fourth beam pointed towards the sea surface is dedicated to measuring surface displacement. This particular system has been the subject of extensive studies worldwide. As a result, we have been able to quantify the AWAC's performance characteristics compared to conventional wave buoys and other forms of wave measurements.**

Historically, wave data have typically been represented in the form of a series of parameters that characterize the spectral and directional nature of the sea state (e.g. significant wave height, peak period, mean period, peak direction and mean direction). In many applications, such as structural response models or in studies of coastal sediment or pollutant transport in areas with variable bottom topography, this single-parameter representation is not sufficient. Instead, a more comprehensive parameterization is required where the wave data are separated into frequency bands and the wave energy and direction is provided as a function of each band. In turn, this puts more stringent requirements on the accuracy of the wave sensing system itself, which not only has to work in a bulk sense, but also has to be able to provide a true description of the sea state even if the energy content in a given frequency band is quite low.

During a recent study near the Diablo Canyon, California, a Datawell Waverider buoy was located only 20 m away from an AWAC deployed in 25 m of water. In this paper, we will describe the results of the comparison between the two instruments and discuss the implications for the possibility of using the AWAC small scale wave array to characterize long waves.

I. INTRODUCTION

The AWAC (Acoustic Waves And Current profiler) is Nortek's solution for both wave and current measurements. The instrument is a Doppler type of instrument that measures the traditional current profiles as well as directional waves. The AWAC first appeared in 1999. Since this time the capabilities have improved considerably. This is largely attributed to the introduction of the AST feature (Acoustic Surface Tracking), which is a method of directly measuring sea surface position. This allows the AWAC to circumvent the traditional shortcomings of the inferred estimates from either the pressure or the velocity measurements.

The AWAC's performance as a wave measurement instrument has been well demonstrated; comparative studies have been performed with the Directional Waverider and have shown very good agreement [10][11]. These studies focused on deployment locations generally considered challenging for bottom mounted instruments (North Sea and Mediterranean Sea). These locations are typically exposed to short waves, which are not easily sensed at the bottom.

Evaluating the AWAC's performance for long waves (T>15 seconds) remained unqualified prior to the Diablo Canyon test. Measuring long waves from the bottom are not as challenging as the short waves with similar amplitude. However we do note that directional estimates for long waves becomes increasingly challenging if the energy level is low at these lower frequencies.

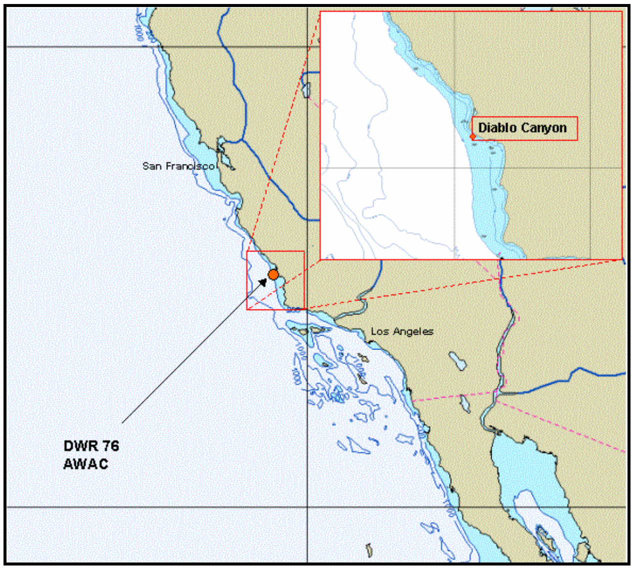

Fig. 1. Location of the AWAC and Datawell buoy offshore of Diablo Canyon, California.

Accurately estimating long wave energy from the ocean bottom generally is not a problem since pressure sensors can easily measure this signal from the bottom (lower attenuation). The real challenge for long waves is the ability to measure wave direction accurately in the presence of noise. Clearly, this is most evident when the magnitude of the orbital velocities are small for long waves with low amplitudes. Long waves tend to be more challenging because of a spatial resolution issue. The phase difference between array measurement locations becomes small when the wavelength relative array spacing increases. This leads to a solution that is more sensitive to noise.

II. DIABLO CANYON COMPARITIVE STUDY

A 1 MHz AWAC was deployed in very close proximity to a Directional Waverider buoy (DWR) located at the Diablo Canyon site (Figure 1). Diablo Canyon is located approximately 150 nautical miles northwest of Los Angeles, California. The buoy is part of CDIP (Coastal Data Information Program), who have several buoys along the California coast. CDIP makes available all of the data from these buoys at their web site (http://cdip.ucsd.edu). The fact that the DWR data is regularly posted on the website meant that we had an easy means of retrieving and evaluating this DWR data for this study.

The comparison test was conducted for a period of 23 days. Unfortunately, only the first 7 days we useable for a rigorous comparison. This was due to the loss of the Waverider, which apparently broke free from its mooring. A replacement was in place 8 days later, but as the comparison shows, this second DWR has a noticeable performance difference relative to the AWAC unlike the initial DWR. It is understood that a calibration was not performed on the second DWR prior to deployment. For this reason, much of the following discussion focuses primarily on the first 7 days of the data collection.

The sea conditions during the relatively short evaluation was characterized by both long wave energy as well as energetic short waves attributed to local storm activity.

A. Deployment Setup

The water depth for the deployment site was 25 meters and the horizontal separation between the AWAC and DWR was approximately 20 meters. The replacement DWR was positioned similarly close (100 meters).

The AWAC was anchored to the sea floor using the Aquaquad pictured in Fig. 2. The frame was deployed with a diver which ensured survivability and that the instrument was oriented correctly (pointing normal to the surface). The apparatus remained stationary throughout the test according to the AWAC's heading and tilt sensors.

Fig. 1. The AWAC was mounted on the top of the Nortek Aquaquad Deployment Frame and fixed to the bottom utilizing fence anchors.

The CDIP's DWRs are configured to collect approximately 27 minutes of data at 1.28 Hz. This is performed twice an hour. The AWAC was set up to profile current velocities in 1 m cells every 20 minutes with a 3 minute average interval. Waves were measured every 60 minutes at 1 Hz (2 Hz for AST) with 2048 samples (34 minutes). The 23 days of data resulted in 546 wave ensembles.

The DWR and AWAC had slightly different measurement configurations, where the AWAC's was slightly longer but only performed once an hour. Furthermore, the two instruments were slightly out of sync, where the AWAC began 1 minute after the DWR, meaning that 25.5 minutes of respective ensembles overlapped.

B . Processing

The AWAC has three independent methods of measuring and estimating the non-directional wave spectra. These are based on the pressure signal, the near surface velocity measurements, and the Acoustic Surface Tracking (AST).

The pressure-based estimates follow the standard linear wave theory transformations to arrive at the surface spectra. It therefore is capable of only measuring the longer waves (approximately 6 seconds and longer for a 25 meter deployment depth).

The velocity-based estimates utilize the 3 measurement cells from each of the three slanted beams. The velocity measurements are closer to the surface, and therefore suffer from less attenuation and have better frequency response. In order to transform the velocity to surface spectra, the direction must first be determined at each frequency. This is performed using the Maximum Likelihood Method (MLM). Once the direction distribution is determined, then the non-direction spectra can be determined according to linear wave theory transformations.

The key to the AWAC's success is the AST. This measurement does not suffer from the depth limitation like the other two methods. Furthermore, it provides a direct measurement of the free surface as opposed to inferred estimates from the velocity and pressure. The AST is also included in the MLM solution, which provides better directional estimates than just the purely velocity based solution.

The advantage of having three independent estimates for the non-directional spectra is that we are able to use this as an internal check to verify that the system, as a whole, is functioning properly. As we will see, this was helpful for identifying the second DWR as the "odd one out" when comparing all the estimators.

The post processing of the AWAC data was done in such a way that most closely matched the processing of the DWR. The DWR performs an FFT on 256 samples (200 seconds) which is sampled at 1.28 Hz. The average of 8 of these spectra is reported once every half hour to provide 16 degrees of freedom on 1600 seconds of data.

The difference in the sampling scheme for the AWAC (2048 samples at 1 Hz) and spectral smoothing approach (averaging in frequency domain) meant that the same exact smoothing could not be employed. However, a similar band resolution was achieved by using 20 degrees of freedom in the frequency domain. This is fewer than is suggested for MLM directional processing.

The non-directional estimates are typically based just on the AST measurements since this has a higher frequency resolution. The definitions of the standard estimates are as follows:

$$H_s = 4\sqrt{M_0}\,, \tag{1.1}$$

$$T_{mean} = \sqrt{M_0/M_2}\,, \tag{1.2}$$

where the moments M_n are defined as,

$$M_n = \int C_{SS} f^n df\,, \tag{1.3}$$

C_{ss} is the auto-spectra based of the AST.

The directional estimates for both instruments uses the first two pairs of the Fourier coefficients. These are commonly used to describe the full directional spectra. The AWAC's determination of the full directional spectra is done according to the Maximum Entropy Method[3].

The directional estimates can be described in terms of the mean direction at each frequency or an average direction, which is an energy weighted estimate over a frequency band. These estimates are respectively, $\theta_{mean} = \arctan(a_1, b_1)$, $\theta_a = \arctan(a_a, b_a)$. The mean direction is based on the first pair of Fourier coefficients at each frequency, whereas the average direction is defined by energy weighted estimates;

$$a_a = \int C_{SS}(f)\cos(\theta_{mean}(f))df \Big/ \int C_{SS}(f)df \tag{1.4}$$

$$b_a = \int C_{SS}(f)\sin(\theta_{mean}(f))df \Big/ \int C_{SS}(f)df \tag{1.5}$$

C. Directional Wave Estimates: SUV and MLM Processing

The directional estimates of are calculated using two different types of processing approaches; although based upon the same measurements of velocity and AST. The first is the MLM. As mentioned earlier, this is a general method for estimating directional wave spectra from spatial arrays of wave measurements (Kahma et al., 2005)[3].

The SUV solution is a relatively new approach and is most similar to the PUV solution (pressure P, and horizontal velocity components U and V). In the SUV solution we replace the pressure with the AST measurement, whereas and the U and V velocities are attenuated versions interpolated by the measurements of the array. The SUV method is a type of triplet formulation that allows for a directional analysis presented by Longhuet-Higgens [7]. A more formal description is presented in [12].

III. DATA ANALYSIS

A. Bulk Analysis

The term "bulk estimates" is a means of distinguishing the standard estimates many are familiar (H_s, mean period, and mean direction) from those in the a subsequent band analysis. These bulk estimates are based on the full wave spectra and provide a broad picture of the entire wave field for a given ensemble period.

These estimates are an efficient manner to provide a general picture into the way we understand the full wave distribution. The most familiar estimate, significant wave height, indicates the total energy by means of a meaningful value (height). The mean period provides an indication of energy distribution in frequency space. The mean direction provides and indication of the primary wave direction and it is an energy weighted direction estimate. Errors with the distribution of energy will clearly have a negative influence on these estimates.

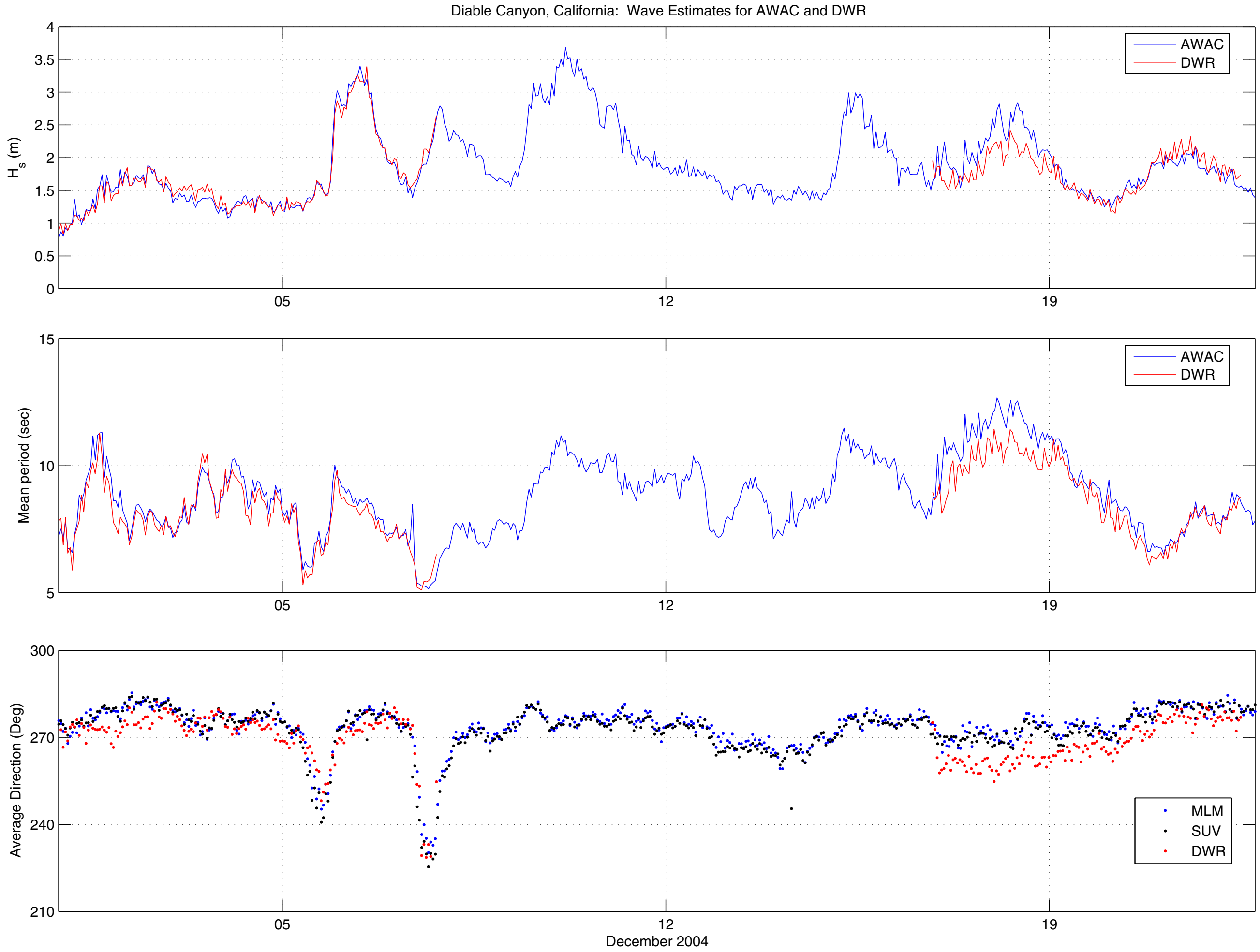

Fig. 3. (a) H_s, (b) Mean Period, (c) $\Theta_{ave.}$ AWAC-blue, DWR-red, SUV-black.

Fig. 3 shows the time history plot of these estimates. The plots show the full three weeks of data collection of the AWAC with both the original DWR during the first week and the second DWR during the last week. The most meaningful comparison focuses on the first 7 days with the original DWR. As we can see the estimates for H_s have very good agreement. The mean period estimates again indicate good agreement, but the DWR tends to estimate lower mean period. The mean direction estimates of both instruments are similar, however there appears to be mean difference between the two; the DWR tends to estimate lower direction. The overall trends for all estimates agree well.

The regression plots presented in Fig. 4 provide a direct quantitative means of comparing the two results. It is interesting to note that a Datawell intra-buoy comparisons separated by a few hundred meters has shown similar correlation for estimates of H_s (R=0.986) and T_{mean} (R=0.953) [1]. Differences in the intra-buoy comparisons performed by Datawell were attributed to the spatial separation. The results are therefore encouraging if we consider the measurements were made at different locations and times. We should also bear in mind that the generalized measurement approach differs where one is wave following and the other a point measurement.

B. Band Analysis

The bulk estimates that we presented in Figures 3-4 show very good agreement, however the finer complexities or differences are not clearly apparent. A relatively simple example of these complexities is noted with a sea state that is composed of both swell and local wind waves (sea). Contribution from each of these could be unique for frequency, amplitude, and direction. One obvious way to isolate these two wave events would be to perform a band analysis over a defined band.

CDIP commonly provides energy and directional estimates for nine separate bands. For brevity, we perform a similar analysis over three bands (somewhat arbitrary): 14-25, 8-14, and 4-8 seconds. The hope is to separate waves that have long, intermediate, and short wavelengths, and characterize performance differences between the directional estimation methods.

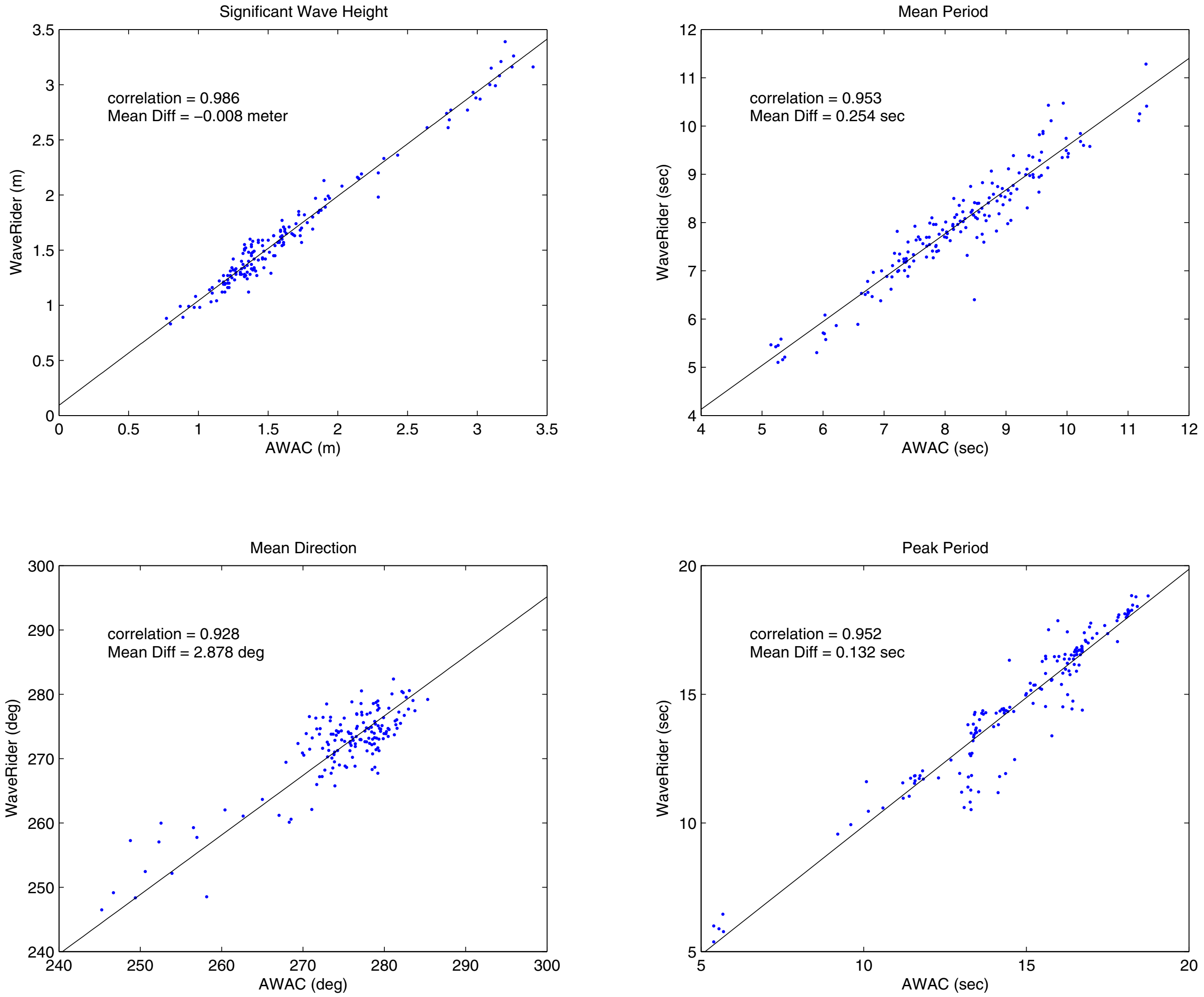

Fig. 2 Regression analysis for AWAC (horizontal axis) and DWR (vertical axis). Clockwise starting at upper left is (a) Hs, (b) Mean Period, (c) Peak Period, (d) Mean Direction.

As indicated previously, the second DWR was possibly deployed without proper calibration. Therefore, energy and directional estimates from the period of December 17 – 22, should be evaluated with caution. The initial indication of the comparison is that all estimators of the energy and direction are very similar. We note that the energy estimates have better agreement between the AWAC's AST and pressure measurements, than either has with the DWR. This may be attributed to the time difference for sampling.

1) Long Wave Band 14-25 seconds

It is apparent in the lower bands that the AWAC's AST and the DWR's estimates of energy are different for certain periods of time. It is encouraging to see that the AWAC's energy estimates for the AST and pressure are very agreeable.

The mean direction estimates for this long wave band tends to show a greater variability for all three estimators. This is not of great surprise since energy levels for the band could be quite low at times. The effects of array spacing relative to wave length are more apparent for the spreading estimate. The MLM based spreading estimate seems to be higher than either the SUV or DWR estimates during low wave energy events. Overall the longest wave band, which tends to be the most challenging, indicated good agreement for estimators.

2) Intermediate Wave Band 8-14 seconds

This band tended to have much more energy and we noticed a much closer agreement with all three estimates (AST, pressure, DWR), however there still appeared to be closer agreement between the AST and pressure estimate. Of course, the like sampling periods of these two estimates again aided in better agreement.

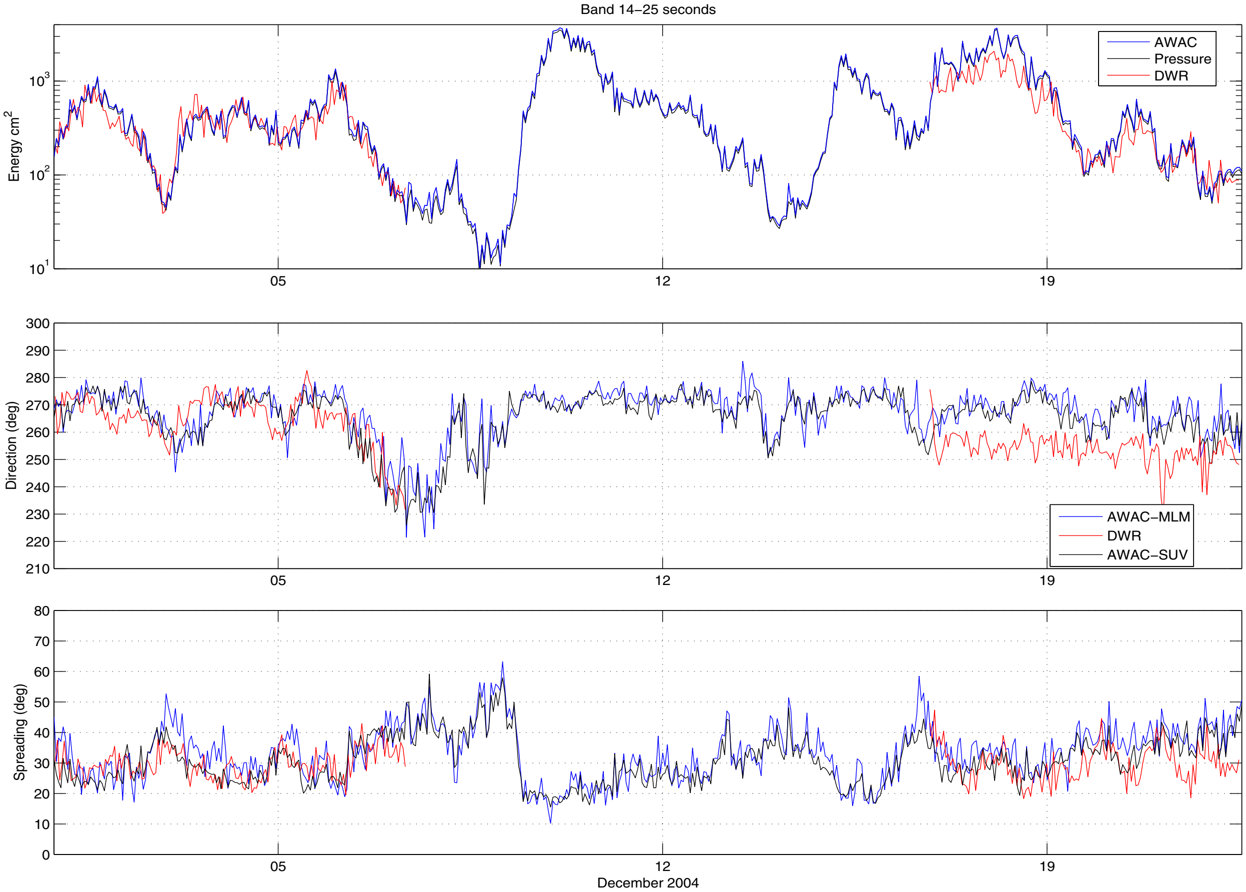

Fig. 5. Low frequency band: 14-25 seconds, (a) Energy, (b) Average direction, (c) Spread. Red is DWR, blue is AWAC-MLM, black is AWAC-SUV.

The good news is that there is improved agreement of the directional estimates for these bands; where it is important to keep in mind that the wavelengths for these bands are still quite long. The general trends of the direction are present with both estimates. The AWAC estimates a more northerly direction with a bias of 5-10 degrees. A finer band resolution could provide more information since this band shows a greater bias than the other two.

Spreading estimates tend to be lower for this more energetic band and all estimators show improved agreement.

3) Short Wave Band 4-8 seconds

The short wave bands show good agreement for the energy estimates from the AST and DWR. The poor agreement of the energy estimates from the pressure in this band is attributed to information loss of the highly attenuated short waves (below 6 seconds).

The directional estimates for this band tends to be more interesting as the direction changes widely. This good agreement for the estimates indicates that there is not a direction sensitivity for the estimation procedures.

Perhaps more interesting is that the DWR provides lower spreading estimates for the short waves when the energy is lower than 200 cm^2. The MLM and SUV provide closer agreement despite the different processing approach.

VI. CONCLUSIONS

We noted earlier that the study was composed of two buoys. The initial buoy broke free from its mooring 7 days into the comparison. It was replaced with another DWR 8 days after this. The second DWR is understood to be un-calibrated and therefore lacks the standard accuracy expected of the DWR.

The general characterization of the performance of the two instruments for the band analysis showed that there was good agreement for the higher frequency bands and poorer agreement at the lowest frequency. This may largely be attributed to the energy present in the respective bands; where the very lowest bands had little energy and the higher bands had considerably more.

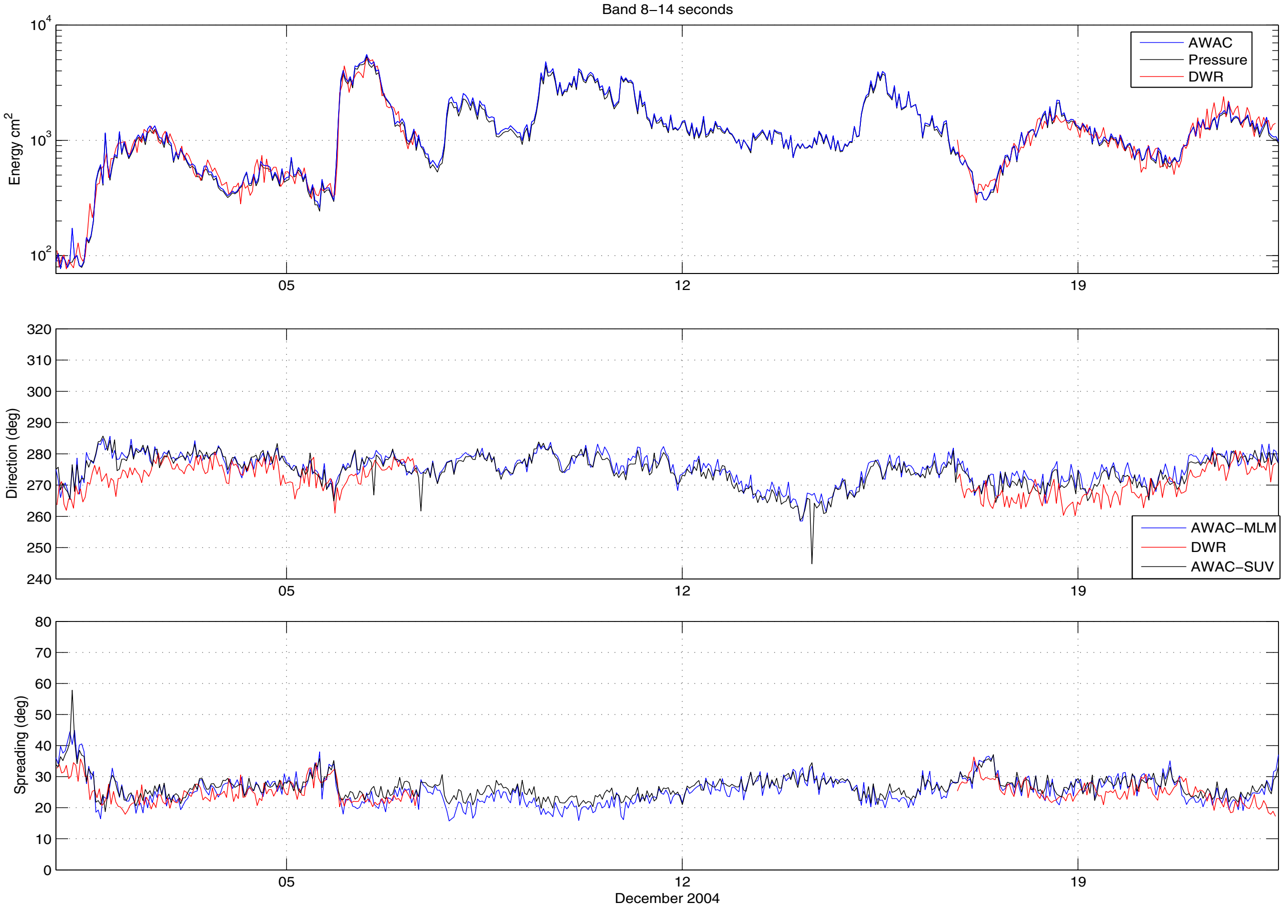

Fig. 6. Intermediate frequency band: 8-14 seconds, (a) Energy, (b) Average direction, (c) Spread. Red is DWR, blue is AWAC-MLM, black is AWAC-SUV.

Both instruments suffer from low frequency response issues. The DWR suffers both for directional and non-directional measurements. This is due to the double integrations of the accelerometer inputs and the very low tilts associated with long waves. The AWAC and similar MLM measurement arrays see greater directional variability for these long waves. This is a result of the decreased ability to resolve phase difference between measurements in the presence of noise.

This is most apparent when the array size is small relative to the wavelength. This was particularly clear for waves in the band longer than 18 seconds (267 meters wavelength) and the array size is 9 meters between nearest measurements in the array.

The limitations imposed by the MLM solution applied to the small array did not appear to be as problematic as anticipated. This may partially be attributed to the fact that the relative wide band had sufficient energy. For lower energy levels we expect that the SUV solution will circumvent the issues of a small array relative to wavelength. In fact, the SUV method is better suited for such cases, when the *U* and *V* estimates better approximate a triplet measurement. It is at least apparent in the lowest band (14-25 seconds) that the SUV had slightly lower variability for the mean direction estimate during low energy wave events. The SUV method also indicated lower directional spread estimates during these events.

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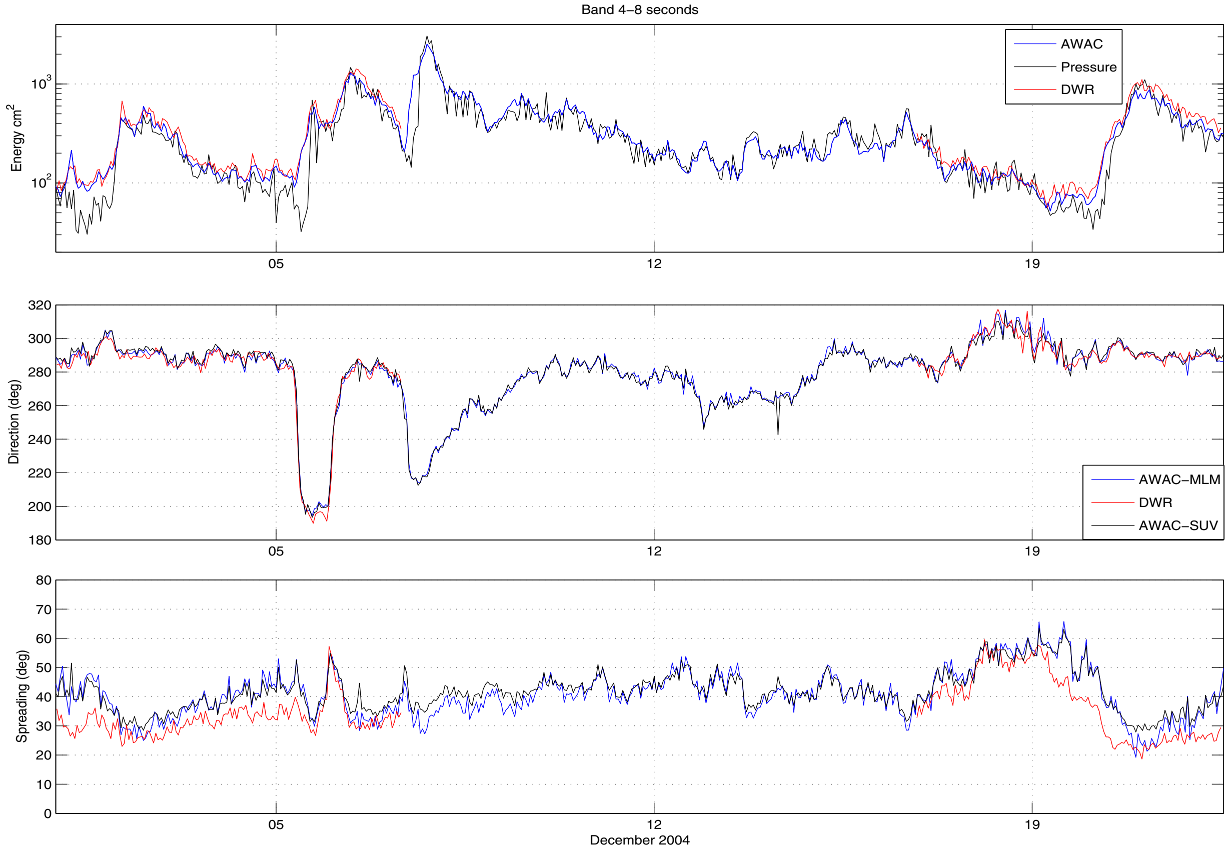

Fig. 7. High frequency band: 4-8 seconds, (a) Energy, (b) Average direction, (c) Spread. Red is DWR, blue is AWAC-MLM, black is AWAC-SUV

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