Wave Measurements from Subsurface Buoys

Torstein Pedersen
Nortek AS
Vangkroken 2
1351, Rud Norway

Eric Siegel
NortekUSA
222 Severn Ave.
Annapolis, MD 21403

Abstract- **Directional wave measurements in deep water locations are intrinsically difficult to measure without the use of a surface wave buoy. Traditional acoustic Doppler current profilers do not have the appropriate data collection and processing technique to be mounted on a subsurface buoy. Nortek developed the SUV wave data collection and processing technique for measuring ocean waves from a subsurface buoy using a Nortek acoustic wave and current profiler (AWAC). In 2006 Nortek initiated a collaborative experiment to validate the SUV method and explore mooring performance by deploying two Nortek AWACs on different shape subsurface buoys offshore of Lunenburg Bay, Nova Scotia, Canada. A surface wave buoy was located nearby as an independent reference. The AWACs were deployed from September to November 2006 and measured waves over 4 m in significant wave height during three storms. The results indicate that the acoustic surface tracking (AST), used to measure non-directional wave properties, was a robust technique and worked very well with the AWACs deployed on a subsurface buoy. Greater than 99% of all AST measurements passed the quality control checks (comparable to results from a bottom mounted AWAC) and measurements of wave height and period were in excellent agreement with the surface wave buoy. The wave directional estimates were in good agreement with the surface wave buoy, but indicated clear frequency bands with increased directional uncertainty. An analysis of buoy motion suggests that the frequencies of poor directional estimates are coincident with the natural frequency of the mooring system. Guidance is offered to design a subsurface buoy which has a natural frequency outside of the wave band such that this technique may be used widely for offshore directional wave measurements.**

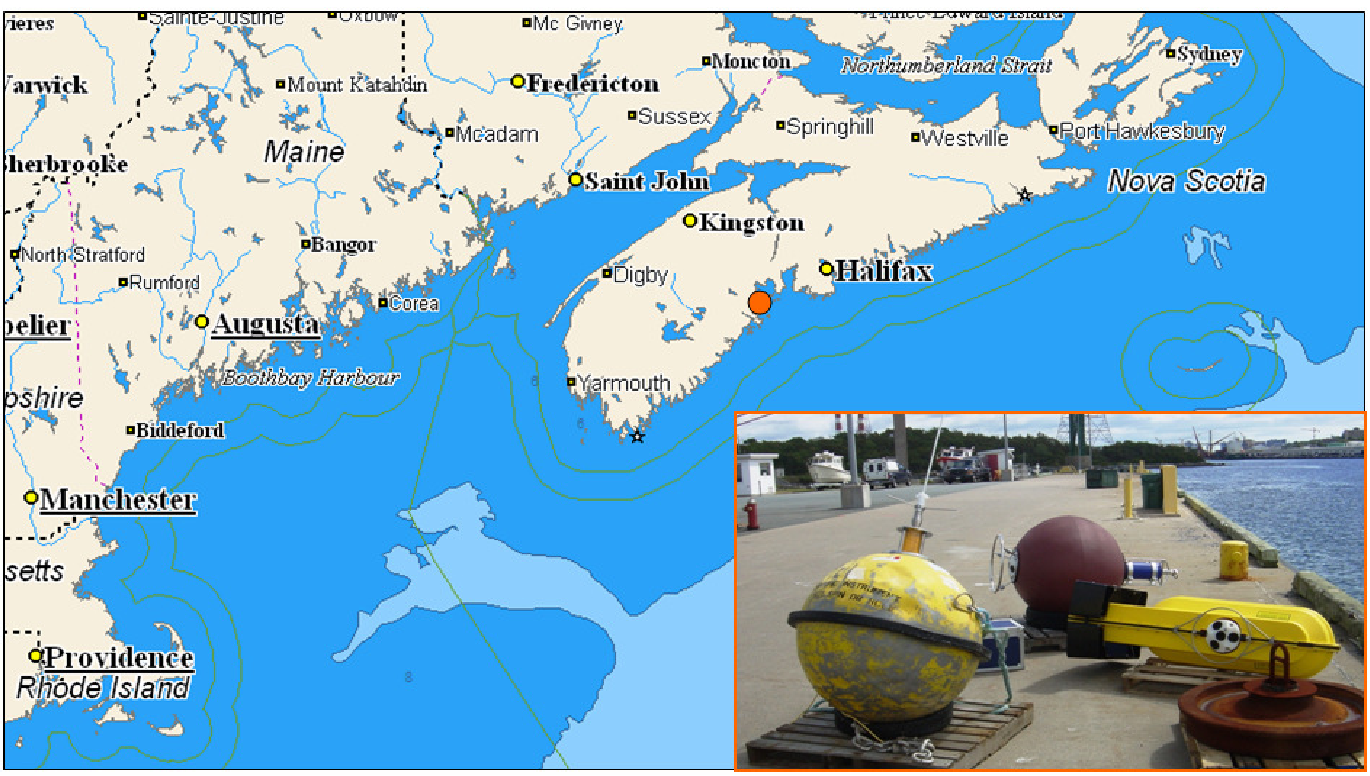

Figure 1. Test Location: Entrance of Lunenburg Bay, Nova Scotia. The inset photo shows the test equipment (left to right): Datawell Waverider (DWR), AWAC in Sphere buoy with battery canister below, AWAC in SUBS buoy

I. INTRODUCTION

Long term directional wave measurements in deep water environments (> 50 m depth) are intrinsically difficult to achieve. Surface wave buoys may be damaged by storms, ships, ice, debris and vandalism. Bottom mounted gauges are typically too deep to provide the directional resolution necessary for research and commercial requirements. The ability to mount an acoustic Doppler current profiler and wave gauge on a subsurface buoy would permit the instrument to be close enough to the surface for high quality wave measurements yet be removed from the dangers of exposure at the surface. Unfortunately, there has been no clear commercial off-the-shelf solution to date.

In 2005, a new wave processing technique, called the SUV method, was introduced for measuring ocean waves from a Nortek acoustic wave and current profiler (AWAC) mounted on a subsurface buoy [1]. The SUV method differs from the traditional maximum likelihood method (MLM) array approach of measuring waves from a Doppler profiler because it permits the instrument to rotate during the wave burst. This is a requirement for mounting the instrument on a subsurface buoy.

In 2006, Nortek initiated a collaborative experiment with Bedford Institute of Oceanography (BIO), Dalhousie University, Open Seas Instrumentation (OSI), and Mooring Systems, Inc (MSI) to validate directional wave measurements made from subsurface buoys. Two Nortek AWACs were deployed on two subsurface buoys (spherical and asymmetric shapes) next to a Datawell Directional Waverider (DWR) wave buoy for independent reference. The deployment location was offshore Lunenburg Bay, on the eastern side of Nova Scotia, Canada, with open exposure to Atlantic Ocean waves coming from the South and East (Fig. 1). The total depth of the site was 32 meters and both buoys had a 12 meter mooring so they were at a nominal depth of 20 meters.

II. METHODOLOGY

The approach discussed herein to solving this problem is to apply a technique similar to the PUV technique, where we replace the pressure data with the AST data and compute interpolated horizontal velocities *U* and *V*, vertically aligned with the AST. This is depicted in Fig. 2. We shall refer to the method as "SUV". Estimates of *U* and *V* are possible since the AWAC is equipped with a compass and tilt sensor which is sampled at the same frequency as the beam velocities. Since the interpolation is carried out instantaneously, *U* and *V* estimates may be obtained even in the presence of buoy motion.

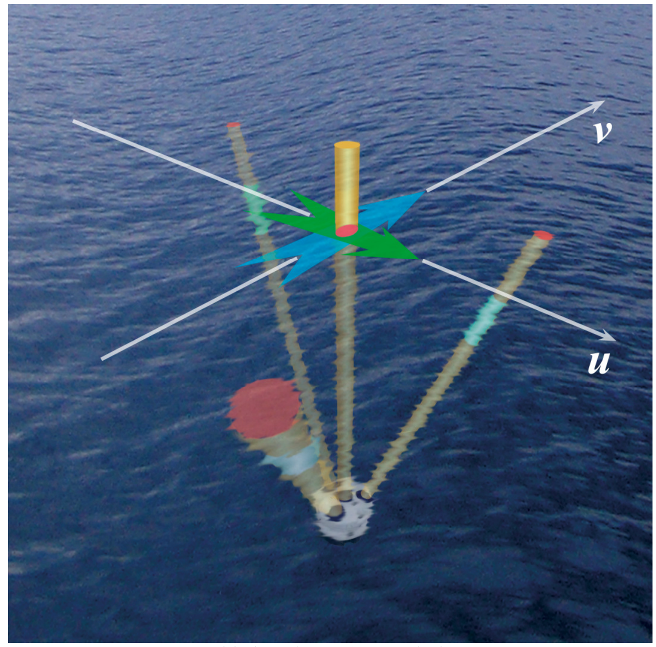

Figure 2 AWAC pictured below the surface with three current measurement cells and one AST measurement. Beam measurements are transformed to U and V for the SUV.

The transformation from the along beam measurements to (*U,V*) applies the standard formula for current profiling instruments. The transformation assumes that currents are uniform within the plane created by the three cells. This assumption is clearly not valid when measuring waves, since the beam cells are spatially separated and therefore the orbital velocities will not be the same at different cells. However, the directional analysis does not need the exact magnitudes of *U* and *V*. From the definition of the directional Fourier coefficients, it is easily seen that factors multiplying *U* and *V* will drop out from the definitions of the Fourier coefficients relations as long as the factors are functions only of frequency and equal both for *U* and *V*. In the present case, the factors have this property to leading order.

The analyses of wave direction can thus be done using simple PUV techniques, where P is replaced with AST and *U-V* are measured close to the surface to accommodate for the attenuation of orbital velocity of short waves.

A. SUV Estimation Technique

The SUV directional estimation procedure is a version of the standard triplet analysis utilizing surface elevation and horizontal velocity in a fixed point. We refer to Kahma et al. [5] for the derivation of the method, which assumes a directional spectrum of the form

$$E(f,\theta) = S(f) D(\theta, f) \qquad (1)$$

The directional distribution is written as a Fourier series

$$D(\theta, f) = \frac{1}{\pi}\left[\frac{1}{2} + \sum_n \{a_n \cos n\theta + b_n \sin n\theta\}\right], \qquad (2)$$

and the triplet analysis produces estimates of the first two pairs of Fourier coefficients,

$$a_1(f) = \frac{C_{SU}}{\sqrt{C_{SS}(C_{UU} + C_{VV})}}, \tag{3}$$

$$b_1(f) = \frac{C_{SV}}{\sqrt{C_{SS}(C_{UU} + C_{VV})}}, \tag{4}$$

$$a_2(f) = \frac{C_{UU} - C_{VV}}{C_{UU} + C_{VV}}, \tag{5}$$

$$b_2(f) = \frac{2\,\mathrm{Re}[C_{UV}]}{C_{UU} + C_{VV}}. \tag{6}$$

Where C_{**} are the cross spectra indicated by the indices; and the *S* index corresponds to the AST and the *U* and *V* correspond to the *X* and *Y* respectively.

Standard directional parameters are the frequency dependent mean wave direction and directional spreading, repectively:

$$\theta_1(f) = \arctan 2(b_1(f), a_1(f)), \tag{7}$$

$$\sigma(f) = [2(1 - r_1(f))]^{1/2}, \tag{8}$$

where $r_1 = \sqrt{a_1^2 + b_1^2}$. The parameters may be averaged over various frequency bands, or calculated at the peak frequency (f_p) of the energy spectrum, as given by the AST power spectrum. Hence, the peak wave direction is

$$\theta_{peak}(f) = \arctan 2\left(b_1(f_p), a_1(f_p)\right). \tag{9}$$

III. EXPERIMENTAL DESIGN

A. Mooring Description

Two subsurface buoy shapes were evaluated during the experiment. The first system (now referred to as "Sphere") was an MSI 0.89 m (35 inch) symmetrical spherical buoy. The Sphere buoy was made from syntactic foam with a stainless steel internal frame to support the AWAC. The second system was an OSI asymmetrical submarine-shaped buoy (now referred to as "SUBS"). The SUBS buoy was made from a plastic fairing which covered an internal Delrin support for the AWAC and two (2) 17" glass floatation spheres. Both moorings were deployed with a 12 m cable and anchored to the bottom with an acoustic release attached to a single railroad wheel anchor. The total water depth was 32 m, which positioned the subsurface buoy nominally 20 m below the surface.

The subsurface buoys also differed considerably in terms of buoyancy. The Sphere had 215 kg buoyancy while the SUBS had 45 kg of buoyancy. The buoyancy has considerable influence on the different response of the two mooring systems. The inset to Fig. 1 shows the subsurface moorings on land prior to deployment.

B. Deployment Description

The equipment was deployed offshore Lunenburg Bay (Fig. 1) on 7 September 2006 and recovered on 11 November 2006. This two month deployment was scheduled to coincide with the deployment of the BIO wave buoy and represents a typically active season for large waves from tropical storms.

The two 1 MHz AWACs were configured to measure current profiles every 30 minutes (25 cells at 1 m each) and measure waves every 1 hour (1024 sample wave burst measured at 1 Hz, providing a ~17 minute burst duration). This 2 month deployment used about 675 Wh of power and 40 MB of memory on the AWAC recorder.

III. RESULTS

A. Buoy Motion

The Sphere had a tendency to rotate around more freely than the SUBS. However, the rotation was at a slow enough rate that the compass was able to keep up with the rotation and provide accurate measurements. There are no data to suggest that the extra rotation of the Sphere causes any problems with the directional wave measurements.

The Sphere had similar tilt for both the roll and pitch. Conversely, the SUBS was relatively stable for the roll (side to side), but the pitch was larger during time of increased wave energy.

The estimates of tilt are complicated by the fact that liquid tilt sensors (as used by the AWAC) actually measure a combination of the instrument's tilt and horizontal acceleration. This means that the measured tilt is likely to be overestimated as compared to the real tilt. Separating these quantities requires an additional multi-axis accelerometer or another manner to track the position. Wood et al [4], who have demonstrated in similar mooring configurations that the tilt is mild and the measurement thereof can be attributed to acceleration.

B. Band Analysis

The AWAC data were compared to an existing DWR wave buoy. During the two month test there was a three week interruption of the data telemetry with the DWR. The raw DWR data were lost, but some processed spectral data were logged in the DWR internal recorder. These data are not presented in this analysis. The coincident data span a little over 6 weeks for the comparison, which for the purpose of the present study is sufficient (Fig. 3).

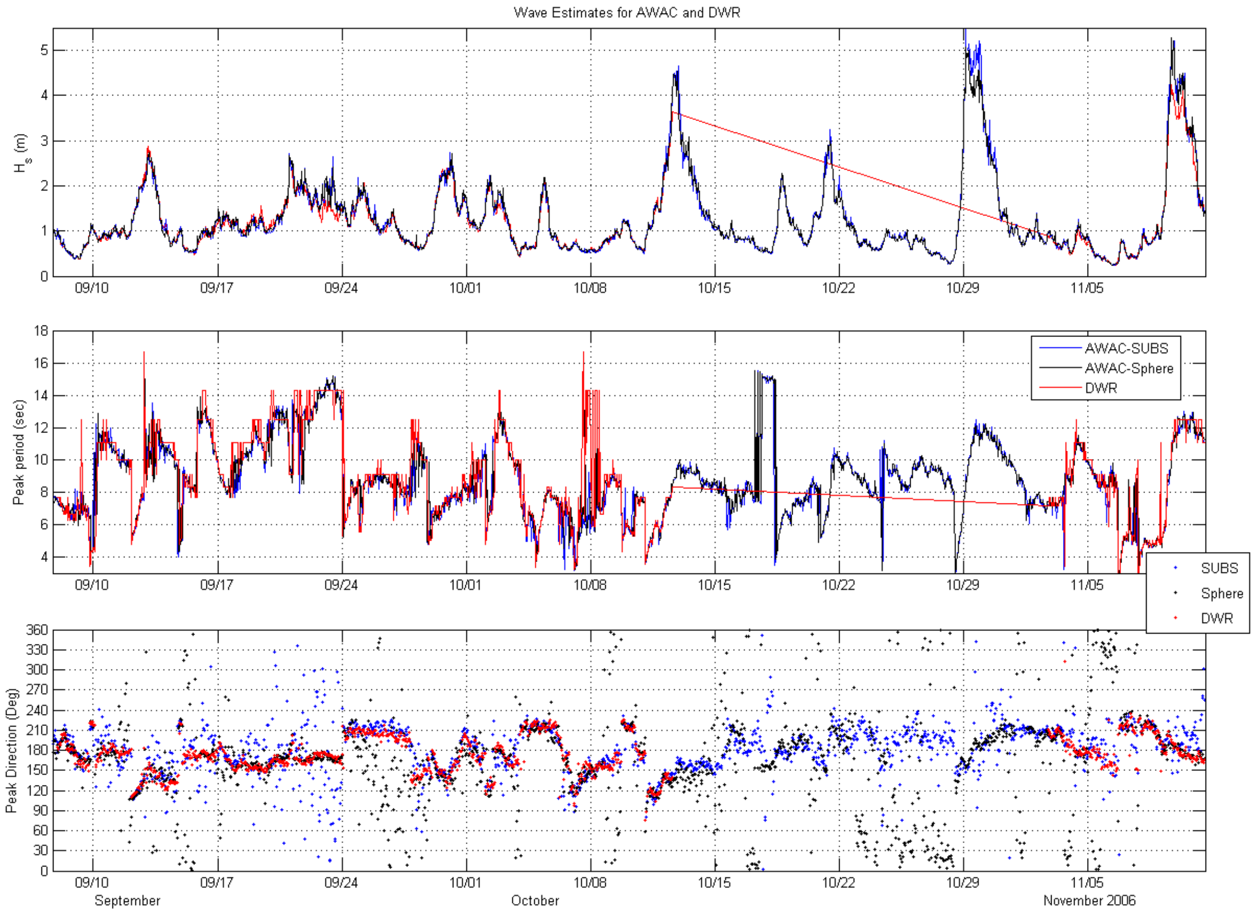

Figure 3 Standard wave estimates of significant wave height (H_s), peak period, and peak direction from the SUBS (blue), Sphere (black) and wave buoy (red).

Both the AWAC and DWR used 64 degrees of freedom for spectral smoothing. The processed data were in the form of the energy density spectra and first four Fourier coefficient spectra. This format of data allowed for a band comparison of both the energy and directional estimates.

The bands contain estimates of energy, mean direction, and spread. The directional estimates in each band are based on the energy weighted Fourier coefficients. A complete description of the band analysis procedure is described in Ref. [2].

This type of analysis was limited to three period bands in an effort to keep this report concise (Figs. 4-6). The bands used in this analysis are from 30-10 s, 10-7 s, and 7-4 s. These three bands represent the majority of the wave energy and were chosen based on issues with buoy response, which become clear in the directional analysis.

C. Acoustic Surface Tracking Performance

The AWAC uses the vertical center acoustic beam for acoustic surface tracking (AST). The AST is used to rapidly and accurately measure the distance from the AWAC to the water surface as the primary method for the non-directional wave estimates (e.g. wave height and period). More information about the use of AST for wave measurements can be found in Ref. [3].

It was expected that potentially excessive subsurface buoy motion or large tilt could lead to some AST errors. The AWAC wave processing software labels an AST measurement as a “bad detect” if the estimate does not pass certain quality control parameters. When more than 10% of the AST samples in a single wave burst are consider “bad detects”, then the AST data are deemed of poor quality and they are not used for the non-directional estimates (in this case, independent measurements of pressure and near-surface orbital velocity are used for the non-directional estimates of wave energy).

The results suggest that the AST performed well. This is true for the entire two month test period, which saw significant wave height (H_s) estimates of greater than 4 m during 3 different storms. Both buoys had only 10 bursts out of more than 1,500 bursts that were deemed not useable because the AST had too many bad detects. For the Sphere buoy, 96% of the wave bursts had less than 1% AST bad detects. For the SUBS buoy, 94% of the bursts had less than 1% AST bad detects. Not only was the AST robust for both systems, but it was also quite similar. In fact, the AST data quality was similar to traditional bottom mounted systems, confirming that the AST functions well even on a moving platform.

D. Wave Energy Estimates

A review of the gross estimates of H_s, suggest that there is very good agreement between the subsurface AWACs and the surface DWR wave buoy (Fig.3). This means that the total measured energy is accurate. A more detailed method of comparison would be to look at the estimates in individual bands. A band analysis is often helpful when trying to identify issues associated in narrow bands and as we will later see, it will help identify the characteristic response of the subsurface buoys. Figs. 4-6 show that the energy estimates from the DWR and both the AWACs in subsurface buoys had very good agreement.

E. Mean Direction Estimates

The mean wave direction from the Sphere and SUBS buoy are given in Fig. 3. This figure indicates that while the bulk wave direction estimated by the SUV method was similar to the reference direction from the DWR wave buoy, there was also a lot of noise in the data with many outlying points. A closer look at Fig. 3 suggests that poor estimates of wave direction are associated with particular wave periods.

The directional spectrograms (Figs. 7-8), as well as the three band estimates of mean direction (Figs. 4-6), clearly shows that both buoys have well defined bands which have poor performance and bands which have good performance. Figures 7 and 8 present spectrograms of the mean direction, which shows the distribution of the directional estimates over frequency for the length of the test. The colors indicate direction, and for the most part show waves coming from south and south west. It is clear where the directional estimates are noisy – where the color is not consistent. Each instrument shows two distinct bands where the directions are noisy, a broad high frequency band and a narrow low frequency band.

The directional spectrograms in Figs. 7-8 show that both buoys had a band of directional noise which extends from 0.35 Hz and higher. This is the “cut-off” frequency limit established by the geometric positions of the near surface array used to measure current velocity for the directional estimates. This cut-off limit necessarily occurs for all subsurface, upward looking Doppler profilers, and is a function of distance below the surface. The high-frequency cut-off limit improves by moving into higher frequencies as the distance between the instrument and the surface decreases.

The directional spectrogram for the Sphere buoy (Fig. 8) indicates that there was a band of poor directional performance centered at about 0.11 Hz (9 sec). The directional spectrogram for the SUBS buoy (Fig. 7) indicates that there was a band poor directional performance centered at about 0.05 Hz (20 sec). These findings are corroborated in the plots of wave direction in the band analyses (Figs 4-6).

The different, yet well defined bands of poor directional estimates lead to a natural question about the source of the error on the directional estimates. Directional estimates are made using the AST and velocity estimates. The accurate estimates of wave energy (via the AST) make it clear that the AST is working well despite the buoy motion. Therefore, the velocity measurements are the suspect for error introduced by the buoy motion.

It is important to notice that most of the difficulties with the directional wave estimates arise when the wave energy is relatively low. During these periods the associated wave orbital velocities have decreased amplitude and therefore are more vulnerable to sources of noise. A buoy that is in motion can potentially “create” a perceived velocity if the instrument is moving relative to the fluid in the overlying measurement cells. This is particularly true when the real velocity in the frequency band is low. This may be in contrast to the expected result. Figs. 7-8 show that when the waves are large, the wave direction estimates were less noisy, even across the bands of typically poor performance. Only when the waves are small (low energy) are there bands of poor directional performance. The band of directional noise for the SUBS may be wider than the Sphere because the wave orbital velocities tend to be weaker in the 0.05 Hz frequency band and therefore more sensitive to effects of externally introduced noise from buoy motion.

IV. BUOY RESPONSE

Based on the results presented above, it is important to get a better understanding of the expected motion of the subsurface buoys. The idealized motion of subsurface buoys most closely resembles an inverted pendulum. In this experiment, this is perhaps most applicable to the Sphere buoy since it had considerably more buoyancy than the SUBS.

Each buoy has its own characteristic response based on several design parameters, such as mass, buoyancy, drag, and mooring line length. Balancing the forces on the buoy given a nominal displacement from equilibrium results in a simple, linearized differential equation of motion which can be used to estimate the natural frequency of a subsurface buoy to first order as follows:

$$\omega_n = \sqrt{\frac{R}{ML}} \tag{10}$$

$$T = \frac{2\pi}{\omega_n} \tag{11}$$

$$R = F_B g \tag{12}$$

$$M = M_{buoy} + M_{added} \tag{13}$$

Here ω_n is the natural frequency of the mooring system, T is the corresponding period of oscillation, L is mooring line length, R is the cable tension of the mooring (restoring force), F_B is the buoyancy in mass units (kg), and M is the total mass of the buoy plus the added mass (estimated as the mass of displaced water).

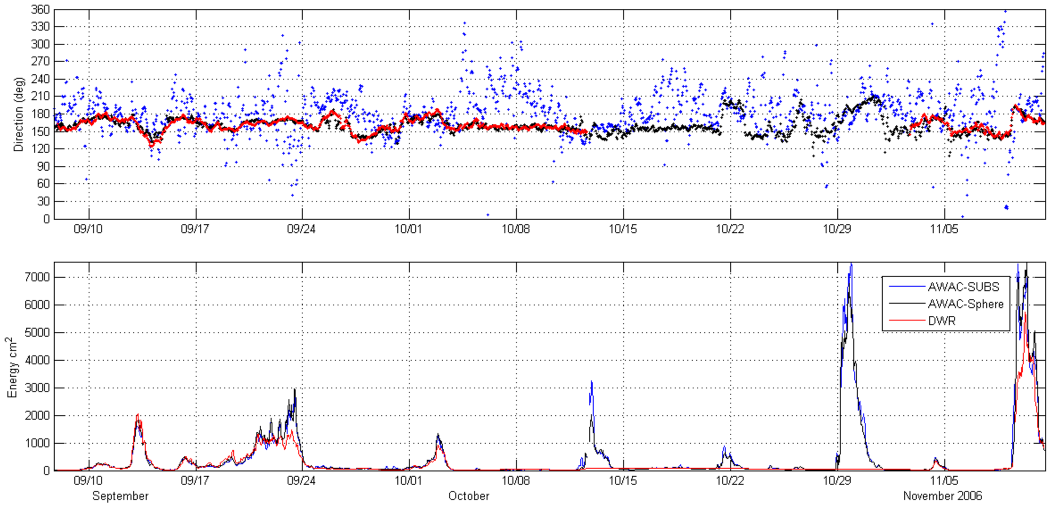

Figure 4 Band 1: 10-33 seconds. (A) Mean Direction, (B) Energy.

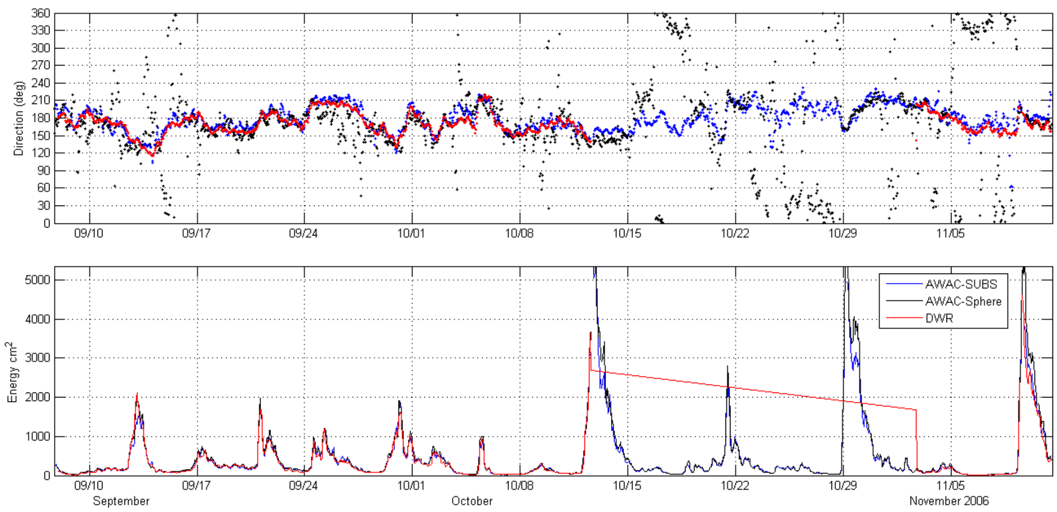

Figure 5 Band 2: 7-10 seconds. (A) Mean Direction, (B) Energy

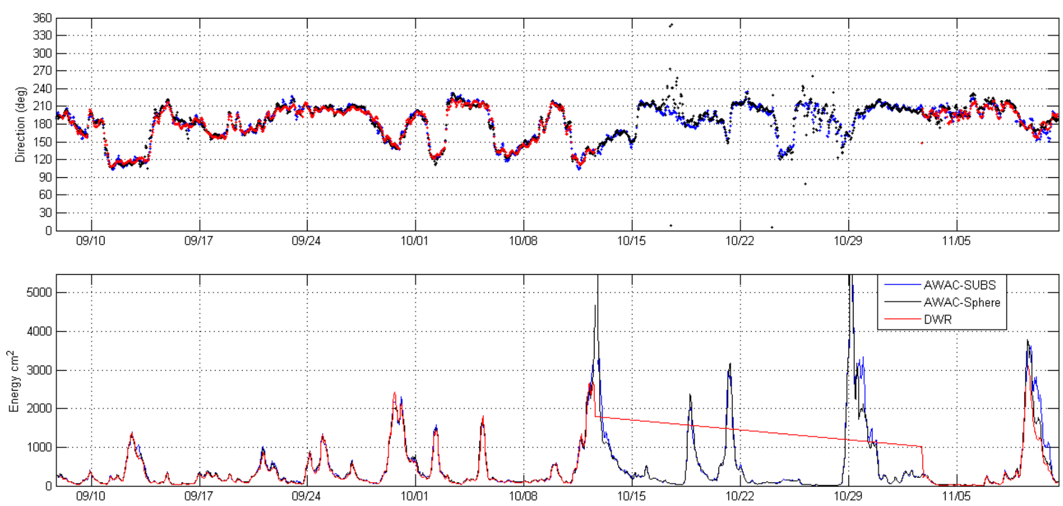

Figure 6 Band 3: 4-7 seconds. (A) Mean Direction, (B) Energy

The damping factor ξ can also be calculated to indicate the potential for resonant behavior at the system natural frequency (equation 14). An overdamped system is defined as $\xi>1$ and returns to its equilibrium position without overshoot; no free oscillations are possible, even at the system's natural frequency. An underdamped system has a $\xi<1$, and suggests a system capable of overshoot oscillations (e.g. when disturbed can sway back and forth through multiple cycles before returning to rest). Underdamped systems experience resonant motions if the external forcing, in this case waves, occurs at the system natural frequency. While both over- and underdamped systems respond to wave forcing across the spectrum, the underdamped system is the most troublesome since it can create persistent artificial velocities at the natural frequency of motion. The damping factor ξ is defined as:

$$\xi = \frac{D}{2M}\sqrt{\frac{ML}{R}} \tag{14}$$

where D is a coefficient defined by the buoy drag coefficient, cross sectional area and water density, M is the mass term, R is the reserve buoyancy, and L is the mooring length.

The two subsurface buoys in this experiment have the following characteristics:

<u>Sphere buoy</u>
R = 215 kg x 9.81 m/sec^2
M = 167 kg + 191 kg
L = 12 m
D = 159 kg/sec
T = 8.97 seconds (0.11 Hz)
ξ = 0.317 (underdamped)

<u>SUBS buoy</u>
R = 45 kg x 9.81 m/sec^2
M = 75 kg + 315 kg
L = 12 m
D = 113 kg/sec
T = 20.4 seconds (0.05 Hz)
ξ = 0.47 (underdamped)

To these first order estimates, both systems are underdamped, with the Sphere buoy having a natural frequency of motion centered at about 9 seconds (0.11 Hz) and the SUBS buoy a natural frequency of about 20 seconds (0.05 Hz).

V. Discussion

The most likely explanation for the false velocities, and thus the poor directional performance at certain periods, is that the buoys were being displaced from their equilibrium position with wave energy at other frequencies. Once displaced, the mooring systems return to their equilibrium position, swinging back and forth at their unique natural frequency, and thus creating an apparent velocity in the velocity measurement cells. This is more troubling for mooring systems that are under-damped since they will sway back and forth through several cycles and this will add to the error. This was the case for both of the moorings used for this test.

In order to understand the buoy motion a little better we compared the normalized energy spectra (Frequency Diagram) calculated independently from both the AST and the velocity measurements. Because the wave energy estimates made with the AST agreed quite well with the reference buoy energy estimates, it is assumed for the following analysis that the AST is the "true" or "correct" estimate. The normalized spectra are used in this analysis because it is most important to determine the frequency where the energy lies and not the absolute magnitude of the energy. The frequency diagrams for the Sphere displaying the normalized energy spectra (as a function of time) from the independent AST and velocity measurements are presented in Figs. 7-8, respectively.

Assuming that the AST spectra (Fig. 9) are "correct" and the velocity spectra (Fig. 10) have errors due to the relative velocity associated with the moving buoy, then the difference between the normalized AST and velocity spectra should indicate the frequency bands where there was motion induced velocity. The difference between the AST and velocity spectra is presented in Fig. 11. As predicted, the greatest difference appears to lie in the same band (centered near 0.11 Hz) which the Sphere had trouble estimating wave direction. The buoy motion analysis (Section IV) suggests that this is also the natural frequency for the Sphere. Again, this affect from motion is most pronounced when the wave energy is low. This presents a rather strong case that the frequency band with poor directional estimates is caused by apparent velocities induced by the subsurface buoy moving at its natural frequency. The same analysis was not performed for the SUBS buoy.

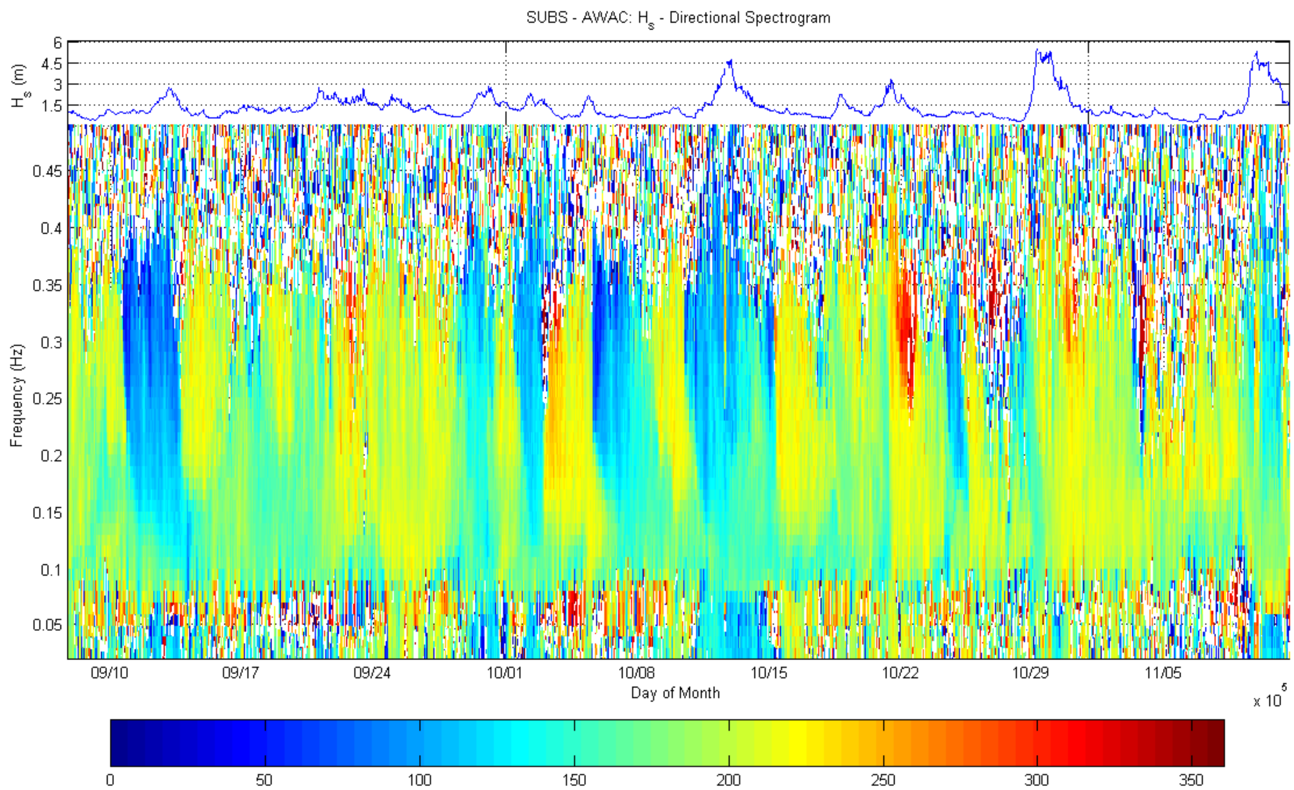

Figure 7 Directional Spectrogram for SUBS with H_s provided on top for reference.

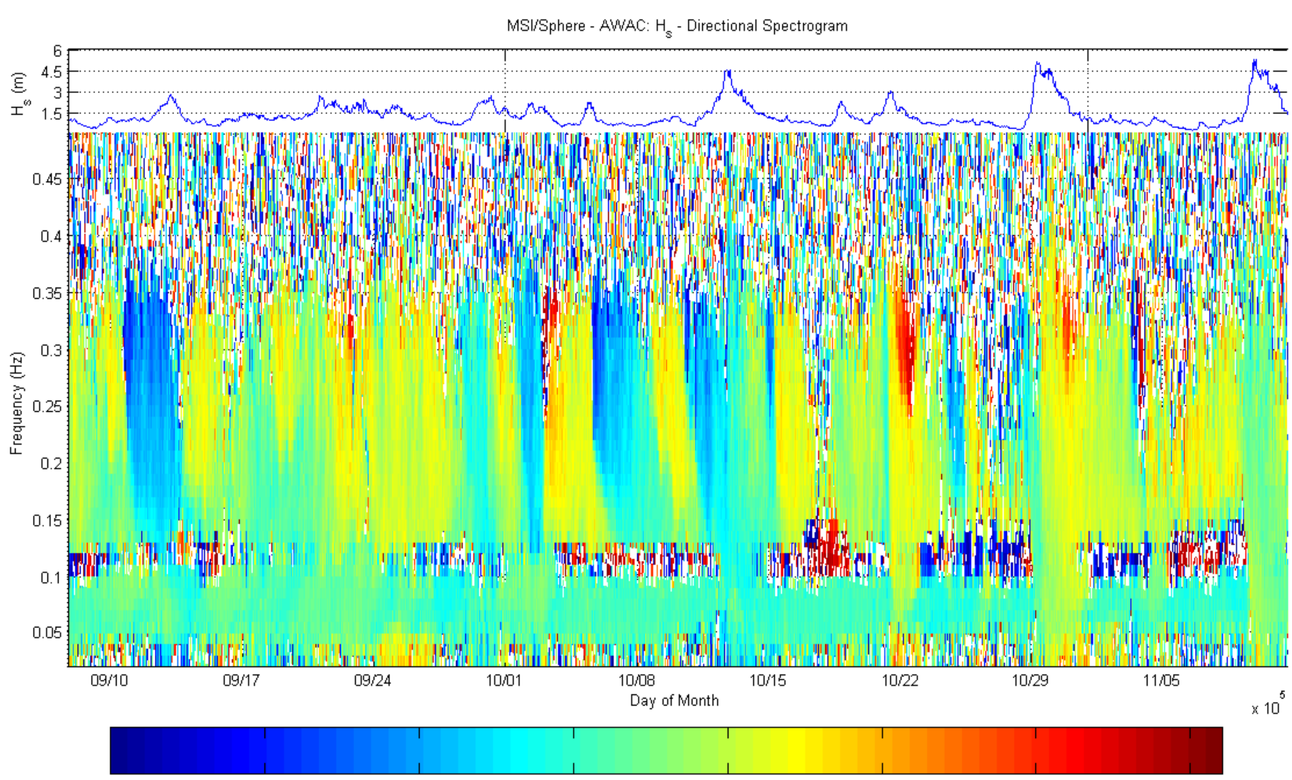

Figure 8 Directional Spectrogram for Sphere with H_s provided on top for reference.

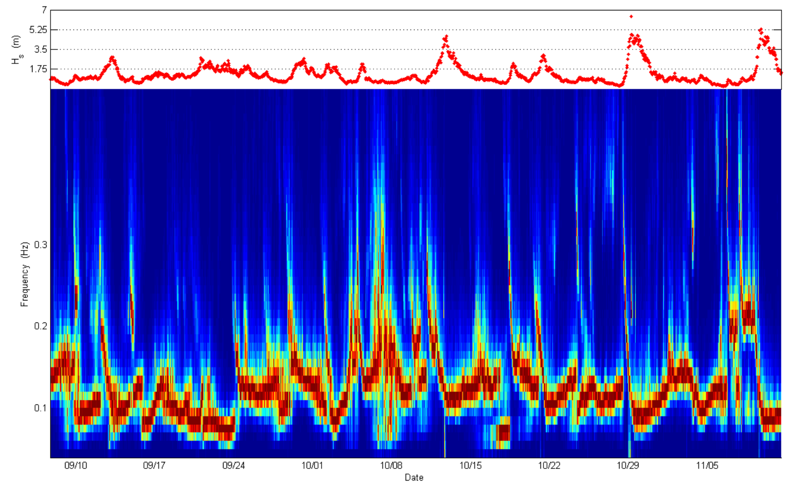

Figure 9 Normalized energy spectrogram for the AST measurements from the Sphere with H_s provided on top for reference.

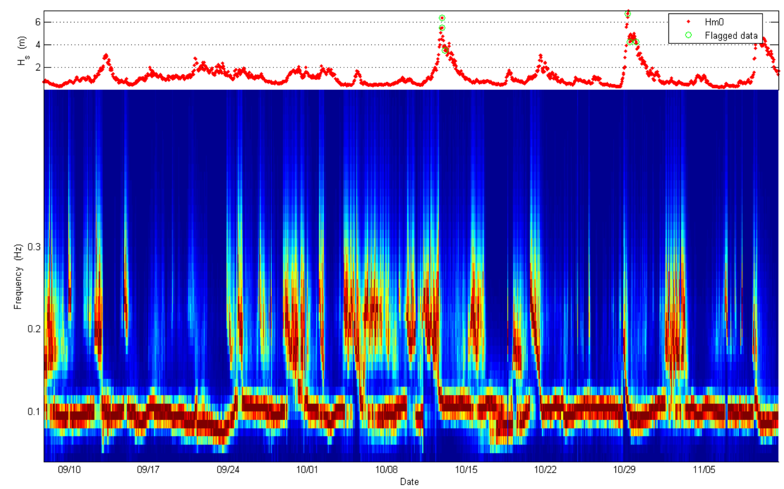

Figure 10 Normalized energy spectrogram for the velocity measurements from the Sphere with H_s provided on top for reference.

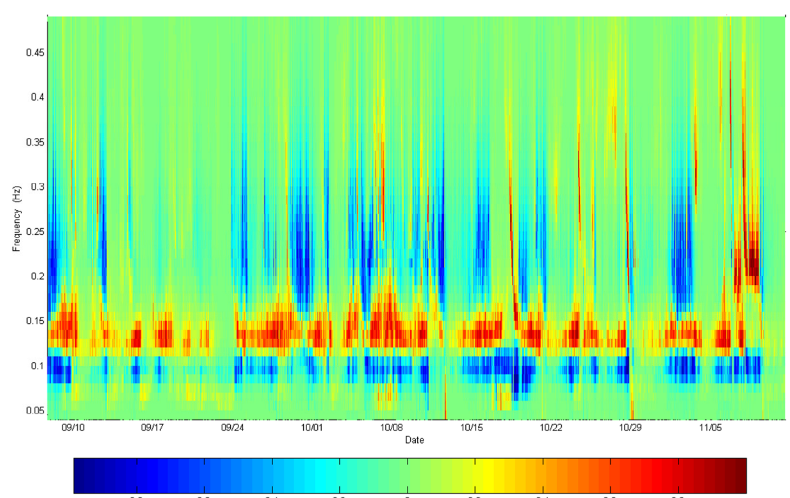

Fig. 11 Difference between normalized energy spectrogram for the AST and velocity measurements from the Sphere with H_s provided on top for reference.

VI. CONCLUSIONS AND FUTURE WORK

Analyses from the experiment demonstrate that the SUV method worked to allow directional wave measurements with an AWAC mounted on a subsurface buoy. The results suggest that a well conceived mooring system is required to ensure that the response of the subsurface buoy has a natural frequency outside of the dominate wave frequency. The test represented some of the more challenging conditions for this type of application. This includes a very energetic wave environment with three storms having H_s in excess of 4 meters. The shallow water depth at the experiment site (32 m) meant that the subsurface buoy was deployed closer to the surface than was ideal.

There were many positive conclusions from this test. The performance and robustness of the AST was demonstrated. AWAC energy estimates throughout the measurement band were in good agreement with the reference wave buoy. The number of AST "bad detects" were quite low and are consistent with those of a typical bottom mounted AWAC.

The directional estimates were agreeable with the reference wave buoy. However, there were clear frequency bands where there was poor agreement. These are attributed to the motion of the subsurface buoys at their natural frequency and the resulting effects on velocities estimates in the band surrounding this natural frequency.

The motion of the AWAC was measured with the internal liquid-style tilt sensor. Tilt measurements are a combination of the tilt and any acceleration of the platform. Earlier work by Wood et al [4] indicates that a large part of the tilt measurement can be a result of the platform's acceleration, which is likely for this energetic position in the water column. The primary concern with the erroneous tilt estimates is that they are used when estimating the horizontal components of the current velocity. Tilt measurements are used in two manners. The first is a conversion from beam coordinates to Earth coordinates that utilizes the tilt in the transformation. The second, and more subtle usage of the tilt measurements, is that they are used when estimating the AWAC's heading from the magnetometer. This second type of error is more prominent at higher latitudes where the Earth's field vector is more "vertical" and thus the magnetometer is more sensitive to tilt. The result is that wave estimates likely have a correct mean directional estimates but the measurements themselves (directional spread) are noisy.

Both subsurface buoys had their strengths and weaknesses, however neither is clearly a better choice for this type of mooring system. The SUBS had more pitch and the Sphere had more rotation. A critical aspect for deployment considerations when using the SUV system is the natural frequency of the mooring system. The important elements of a mooring system are the buoyancy, drag, and mooring length. A proper design should focus on ensuring that the subsurface buoy has a natural frequency below 0.03 Hz (outside of the dominate wave frequency) and that it is designed to be overdamped. The effects of wave motion on a subsurface buoy can be further reduced by using a 600 kHz AWAC deployed on a subsurface buoy that is nominally 40 m below the surface (compared to 20 m in this experiment).

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