Ocean Ambient Sound Instrument System: Acoustic Estimation of Wind Speed and Direction from a Sub-surface Package

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Abstract - **The Ocean Ambient Sound Instrument System (OASIS) consists of a conventional RD Instruments, Acoustic Doppler Current Profilers (ADCP) modified to allow the recording of high quality ambient sound in the frequency range from 1 to 75 kHz. In addition to the usual capabilities of an ADCP, this combination of acoustic instrumentation allows wind direction and speed to be inferred from a subsurface platform. The method of wind speed determination from ambient sound levels is explained identifying some of the techniques and limitations. Wind direction is inferred from surface drift velocities using the ADCP data. The design of both the hardware and software required to make combined ADCP and ambient sound recordings is discussed. The capabilities of the system are demonstrated using observations made in the Norwegian Sea at Ocean Weather Station Mike. Using previously published algorithms (and calibration constants) we find ambient sound based wind speeds that closely match direct wind observations. The typical standard deviations for hourly wind speed estimates is 1.5** ms^{-1} **when using acoustic frequencies less than 10 kHz. Higher acoustic frequencies show greater variance in wind speed estimates. OASIS estimates of the 12 hour average wind directions have an error standard deviation of 25 degrees with no mean bias.**

1. INTRODUCTION AND OVERVIEW

Wind measurements in an ocean environment are a critical component to any study of near surface processes. Direct measurement of local winds are normally made from ships or surface buoys. There are however situations when surface wind observations are compromised: conditions of high winds and sea states can damage surface anemometers. In addition, buoy motions can act to contaminate the wind speed estimates. At higher latitudes, ice can build up on sensors and surface buoys can be damaged by drifting ice. These conditions contrive to make good, long term surface wind measurements difficult to acquire. In this paper, we describe an instrument that allows local wind observations from a sub-surface platform through the use of ocean ambient sound combined with acoustic Doppler techniques. This system is not intended as a way of replacing existing wind measurement techniques, but rather as a complimentary method that is most suitable in severe, high latitude climates.

OASIS is an instrument designed to record absolute ambient sound levels in the frequency band 1-75 kHz in a system that offers Acoustic Doppler Current Profiler (ADCP) functionality. The primary goal of OASIS is to enable measurement of wind speed (or stress) using the ambient sound levels, and simultaneously, to determine wind direction from near-surface Doppler velocities. An additional objective of the OASIS system is to encourage the regular acquisition of high quality ambient sound measurements. Many aspects of ocean ambient sound are not fully understood and access to a large body of ambient sound data is required to make progress in this area.

1.1 Wind-generated ambient sound

It has long been known that ambient sound levels in the ocean can be related to surface wind speeds (Knudsen et al. 1948). The ambient sound spectrum is dominated by low frequencies with sound levels decreasing at a rate of 20 dB/decade with increasing frequency. Sound power levels at 8 kHz range from 35 to 60 dB (re 1 μPa at 1 m depth); Figure 1 displays ambient sound levels (measured with OASIS) at several different wind speeds. Ambient sound associated with wind is caused by oscillations of bubbles injected into the ocean surface as waves break (Medwin and Beaky 1989). In fact, Melville et al. (1988) demonstrated that the sound generated by a single breaking wave is proportional to the energy lost by that wave. This last point is noteworthy because it ties wind generated ambient sound to energy dissipated by wind stress rather than to the wind itself. This aspect of ambient sound generation was explored by Vagle et al. (1990) who (in addition to considering wind speeds), correlated wind stress to ambient sound levels. Their results suggest that ambient sound estimates of wind stress are comparable in quality to estimates of wind speed. For the purposes of this study, we consider only wind speed estimates because we have no direct measurements of stress.

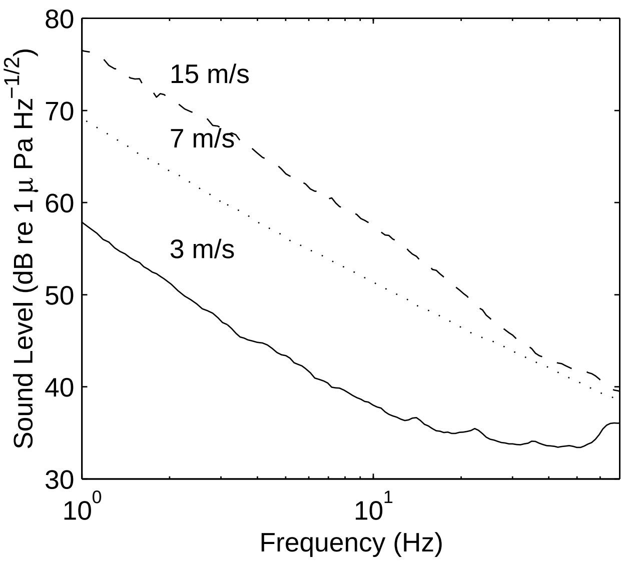

Figure 1: Ambient sound spectra observed at OWS Mike at wind speeds of 3, 7, and 15 ms^{-1} . Each spectrum is the deployment average for observations at the respective wind speed and includes no less than 8 hours of data. Sound spectra are calibrated and corrected to an equivalent receiver depth of 1 m.

Considerable effort has been given to relating ambient sound levels to wind speed (e.g. Bourassa 1984, Evans et al. 1984, Lemon et al. 1984, Wille and Geyer, 1984, and Vagle et al. 1990). Visbeck and Fischer (1995) found that the 150 kHz receivers in ADCPs can be used to infer wind speeds. Indeed, there is some correlation between the surface target strength and the wind speed (Schott 1989). Our understanding of the relationship of wind and ambient sound is far from mature, but the domain over which accurate velocity estimates can be expected is reasonably well defined. One consistent result of previous research has been the existence of a logarithmic relationship between wind speed and sound levels;

$$log(V) = A \times ssl + B, \tag{1}$$

where V is the wind speed, ssl is the sound level in dB (re $1\mu Pa/\sqrt{Hz}$), and A and B are empirical constants. This equation forms the basis for most estimates of wind speed from ambient sound but there is considerable variability in the values required for the various constants. Vagle et al. (1990) generalized the calibration by accounting for different deployment geometries and locations. Vagle et al. (1990) also presented a slightly different relationship given by,

$$V = s^{-1}(10^{ssl8/20} - b), \tag{2}$$

Where s and b are empirical constants and $ssl8$ is the sound level observed at a frequency of 8 kHz.

1.2 Rain-generated ambient sound

Rain can represent a contaminant to the wind speed from ambient sound conversion, but it also represents a meaningful signal in itself. Medwin et al., (1992) give an overall description of the mechanisms that contribute to rain noise. Prior to Medwin et al.'s paper, these mechanisms were poorly understood. Figure 2 uses OASIS data to show how rain noise changes the wind-generated ambient sound spectra. This figure was generated by grouping sound spectra observations according to wind speed and weather conditions. Spectral differences were formed by subtracting averages from rain-free times from averages of data collected during periods of rain. We see that with 5-9 ms^{-1} winds, rain increases sound levels at frequencies greater than around 10 kHz, (this is the characteristic light rainfall signature) whereas with 15 ms^{-1} winds, rain increases sound spectra at frequencies less than 10 kHz.

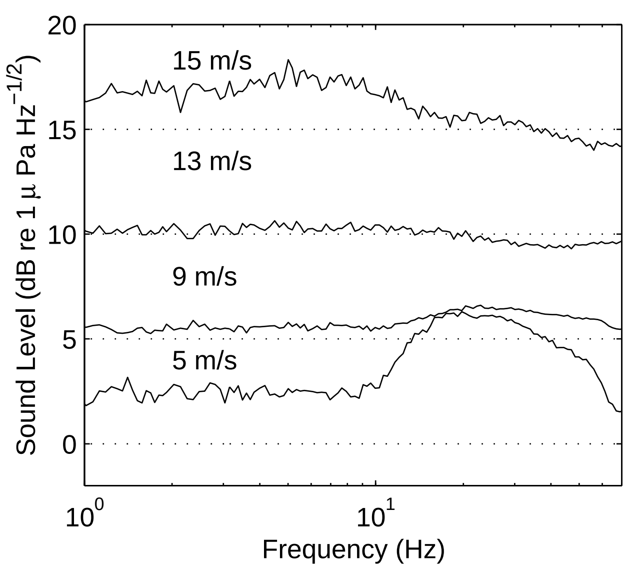

Figure 2: Spectral difference between ambient sound levels with and without rain at wind speeds of 5, 9, 13, and 15 ms^{-1} . Spectra are offset successively by 5 dB with straight lines indicating the zero reference. This figure is derived from spectra averaged over 3 or more hours of data.

1.3 Wind direction measured by ADCPs

The concept of inferring wind direction from Doppler surface returns was first suggested by Schott

(1989). Using data collected in the Gulf of Lions, Schott showed that ADCP determined surface velocity was aligned with the wind direction. Brown et al. (1992) also reported on the use of this technique but found limited success.

In Zedel et al. (1996) Schott's algorithm was modified to remove background currents and wind direction was computed using the relation;

$$\vec{V}_d(0) \approx \vec{V}(0) - \vec{V}_m(z_m), \tag{3}$$

where $\vec{V}_d(0)$ is the surface wind drift velocity, $\vec{V}(0)$ is the observed surface drift velocity, and $\vec{V}_m(z_m)$ is the current velocity at some depth great enough that local wind forcing is no longer important. The resulting direction indicated by the estimate of $\vec{V}_d(0)$ is used to indicate wind direction. Zedel et al. (1996) consider several years of data from three different sites (including the data used by Brown, et al. 1992) and found that the ADCP and buoy wind directions compared favorably for time scales of 12 hours or longer. At shorter time scales inertial oscillations will very likely corrupt the data and, at time scales in the order of minutes wave orbital velocities become important. In order to avoid aliasing from the high frequency surface waves, individual velocity profiles must be averaged over several minutes.

Classical Ekman theory predicts surface drift currents to be directed at 45° to the wind velocity in contradiction to the results realized using (3). In classical Ekman theory, the eddy viscosity is assumed to be depth independent and this is not a realistic model near a boundary. If the eddy viscosity is considered to vary with depth, and in particular if it should tend toward zero near the surface boundary (as expected in law-of-the-wall scaling), then surface velocities parallel to the wind velocity can be expected.

2. SYSTEM IMPLEMENTATION

2.1 Accuracy Considerations

The relationships between ambient sound and wind speed presented by Vagle (1990) and Evans et al. (1984) can be used as the basis for the design of a practical ambient sound recording system. Even if the calibrations provided by these publications suffer some inherent error, they can serve to establish bounds on the accuracy of ambient sound measurement that is needed to achieve a given accuracy in wind speed estimation. Fig. 3 shows how uncertainty in wind speed estimate varies with actual wind speed given a 0.7, 1, and 1.5 dB error in ambient sound level (based on (2)). For an accuracy of 10% in wind speeds up to a maximum of 20 ms^{-1} , sound level estimates must be made to within ± 1 dB.

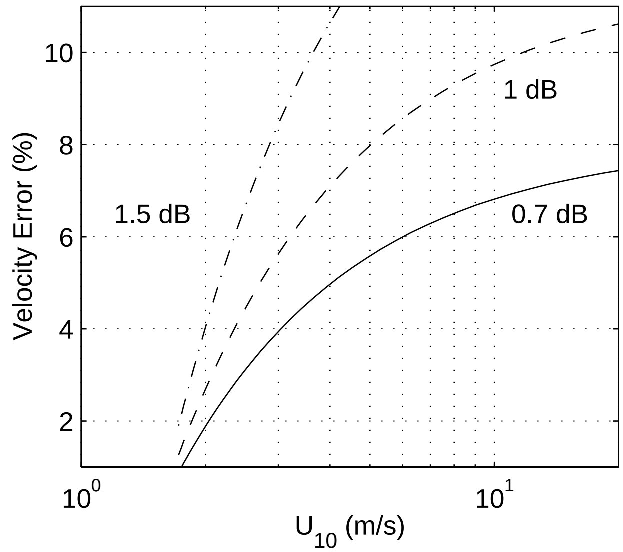

Figure 3: Percentage error in wind speed estimate resulting from 0.7, 1, and 1.5 dB sound level uncertainty (solid, dashed, and dash-dot line respectively) when using (2).

The figure of 1 dB uncertainty in ambient sound level provides a design point that must be met by all components of an ambient sound recording system. Aside from the obvious need for accuracy in electronic processing, any mechanism that can act to alter the recorded sound level by 1 dB must be accounted for in order to achieve a 10% system accuracy. Sound attenuation in water, bottom reflections, attenuation at the surface by bubble clouds, and interference by the measurement package can all contribute to degrade the quality of ambient sound measurements.

Bubble clouds created by breaking waves are likely to attenuate sound at the higher frequency ranges of the OASIS system (Lemon et al., 1984). Compare the sound spectra at 7 and 15 m/s wind speeds in Fig. 1. The apparent attenuation at 30-70 kHz frequency range for 15 m/s winds is likely caused by bubble clouds occurring at higher sea states.

The effect of near surface bubbles is at present not understood well enough to allow an adequate correction, the other sources of interference can (approximately) be accounted for. Figure 4 illustrates how acoustic absorption and bottom reflection effect the frequency response at 250 m depth in total ocean depths of 500, 2000, and 4000 m. The values presented in Fig. 4 were computed assuming bottom reflection losses of 5 dB, uniform in frequency and accounting for multiple bottom and surface reflections. At low frequencies, enhancements of about 2 dB are realized due to the multiple reflections from the bottom and the surface. At higher frequencies, the enhancement effect is overcome by acoustic absorption leading to a frequency dependent variation in response.

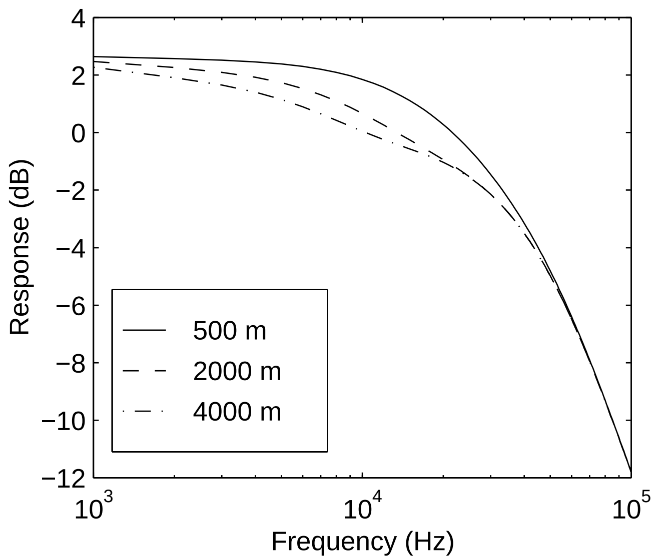

Figure 4: Predicted response at 250 m depth to a uniformly distributed white noise sources at the surface. The effective spectral response of an omnidirectional receiver for total water depths of 500, 2000, and 4000 m are shown. Refraction effects are ignored, but absorption and spherical spreading are considered.

2.2 Instrument Design

The OASIS system is built around a conventional RD Instruments, 150 kHz BB-ADCP and the system uses the BB-ADCP computing and data storage capabilities. The only significant hardware change is the addition of an International Transducer Corporation (ITC) 6050C hydrophone used to measure sound levels and an interface capability to digitise the ambient sound signal. The hydrophone is placed on a 3 m long cable so that it can be positioned away from any acoustic scattering that might occur due to the BB-ADCP instrument housing. Interference from the ADCP active sonar is avoided by appropriate timing of the data acquisition.

Ambient sound over the frequency range recorded by OASIS can span 70 dB in sound level. This dynamic range requirement presents a data processing and recording challenge if the required accuracy levels (± 1 dB) are to be preserved. Our approach has been to pre-whiten the spectrum to remove the 20 dB/decade spectral roll off, firmware is then used to adjust gain levels allowing data to be digitized using a 12-bit analog to digital converter. The choice of a 12-bit digitizer in this case was largely motivated by the favourable power requirements of this unit.

Firmware controls the OASIS gain level by monitoring the root-mean-square (rms) value of the digitized signals. When the rms value exceeds 2^{10}, the gain is reduced and if the rms value is below 2^8, the gain is increased. Ideally, the gain control should maintain the digitized data with an rms value of $2^9 = 512$. The digitized time domain signal is transformed to a frequency representation using a 16 bit integer Fast Fourier Transform (FFT) algorithm to allow rapid computation. In this case, computational speed is not required for data throughput, but rather to reduce power consumption. Overflow and underflow conditions are regulated through the FFT by scaling spectra at each pass through the FFT butterfly. The product is a 16 bit spectrum with a scaling value which also includes the hardware gain setting. For the OWS Mike observations, we used the full bandwidth of the hydrophone (75 kHz) combined with the maximum frequency resolution available to the OASIS system (i.e., a full 8192-point ambient sound time series sampled at 300 kHz). Ambient sound was sampled every minute and averaged into 3-minute ensemble intervals. Data storage requirements were limited by averaging the 4096-bands of power spectra into 129 logarithmic frequency bins so that the relative bandwidth, (ΔF/F), of each bin is held constant.

2.3 Calibration

The 6050C hydrophone comes from ITC with a factory calibration but we repeated the calibration using OASIS hardware. A series of calibration tests using ITC's facilities was undertaken by transmitting pure tone pulses toward the hydrophone in a calibration tank. Plots of observed signal level versus the source level at each calibration frequency were produced. Figure 5a provides an example taken from the 8 kHz calibration: to highlight the accuracy of the results, the difference between the measured and known source level is indicated on an expanded scale in Fig. 5b. In all cases the calibrations came out linear with some offset from the (mean) hydrophone sensitivity of -162 dB (generally less than 2 dB). The tests confirmed the ITC calibration and verified that the OASIS calibration tracked properly through changes in the gain settings. Results for both the factory and OASIS calibrations are shown in Figure 6.

An additional calibration can be achieved by assuming that the natural ambient sound spectrum averaged over an entire deployment has little frequency structure. In that case, by applying an offset to the pre-whitened spectrum, the deployment average spectrum can be treated as a calibration relative to a flat frequency response. The observed mean spectrum (also shown in Fig. 6) shows a structure similar to the laboratory calibrations but with 129 data points made possible by the OASIS sampling scheme. Notable differences include a well defined minimum at about 20 kHz in the field data which is not seen in either tank calibration. In addition, the resonance peak seen in all data at about 50 kHz is much higher in the field data. These differences can be accounted for by the narrow spectral resolution of the OASIS system. In the calibration facility, frequency resolution is limited by the need to use short tone pulses with a finite bandwidth. Both the ITC and subsequent OASIS calibration are restricted to a bandwidth of 1000 Hz. The OASIS system however resolves spectral structure with a resolution of 55 Hz.

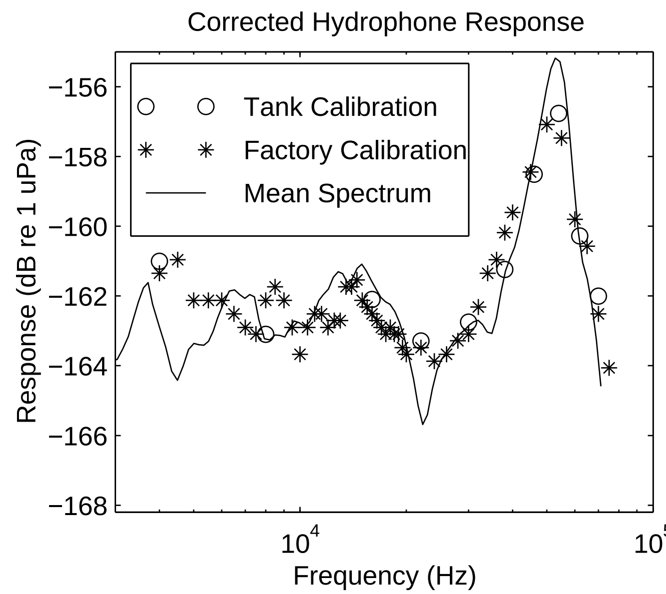

Figure 6: Calibration results including the ITC factory calibration (Factory Calibration) a laboratory calibration performed on the OASIS system (Tank Calibration) and a field calibration (Mean Spectrum). The Mean Spectrum is an average of all of the data from the 1996 OWS Mike deployment with no correction for the applied prewhitening and it is adjusted to match the mean calibration level. The Mean Spectrum does not provide an absolute calibration but does indicate the relative system sensitivity to different frequencies.

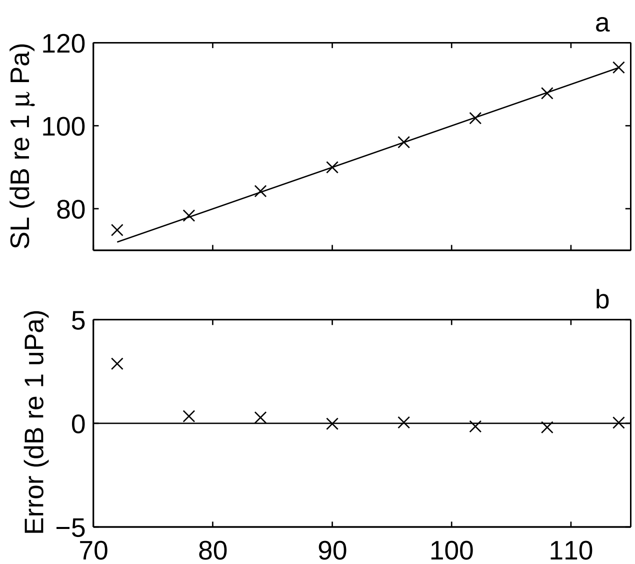

Figure 5: a) Measured versus source sound level at 8 kHz. b) difference between the measured and source sound level. The units for measured and source levels are dB relative to 1 $\mu Pa/\sqrt{Hz}$ at 1 m range.

3. OBSERVATIONS

3.1 Deployment

The OASIS system was deployed at Ocean Weather Station Mike, located 210 km west of Bergen at 66° N, 2° E (Gammelsroed et al. 1992). The water depth at the site is about 2000 m and the ADCP was deployed at a nominal depth of 250 m in 1996, and 100 m in 1997. Figure 7 indicates the deployment location relative to the Norwegian coastline. A weather ship is maintained at this location (within 10 km of the OASIS mooring) providing accurate and consistent reference meteorological observations.

Our first data set was collected over a 40 day period starting on May 17, 1996. For this first deployment, we were concerned about the ability of the gain control algorithm to keep track of sound level changes from sample to sample. The gain level for a given sample is initialized to the gain value used for the last ensemble of the previous sample. If significant changes in sound levels occur between sample times, inappropriate gain values would be used and data faults would occur. Our approach to avoid this difficulty was to select a sampling rate that was rapid compared to short term fluctuations in wind speed. The sampling rate we arrived at was one sample every 3.5 minutes. As it turned out, the gain control system worked well with 90 % of the computed FFT's having no saturation events. our experience with the algorithm indicates that this level of data rejection results in no detectable change in resolved spectral levels.

An unexpected problem did complicate the data analysis from the first deployment. The instrument

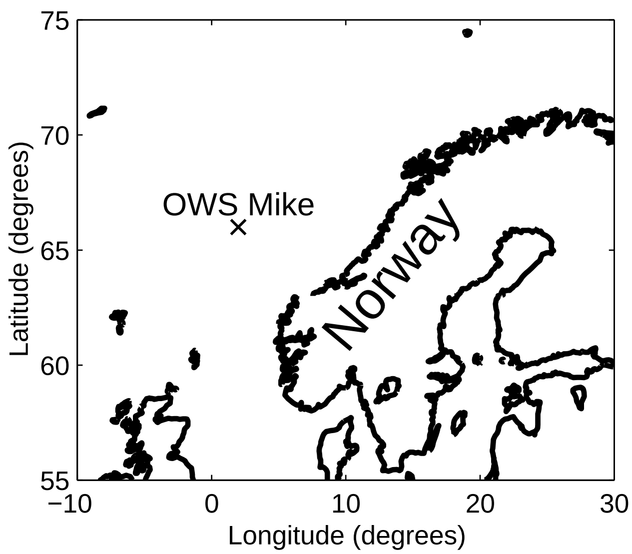

Figure 7: Location of Ocean Weather Station Mike in relation to the Norwegian coastline.

did not measure the surface drift velocity because the surface was located beyond the current profiling range. (The ADCP depth was 250 m and the profiling range was typically less than 200 m). We had selected BBADCP mode 4 (see RD Instruments 1997) which requires a minimum contiguous range of good data or it rejects the resulting velocities. The relatively small range of good data received from the surface echo was insufficient to satisfy the data quality check. We avoided the problem in our second deployment by positioning the instrument closer to the ocean surface, thereby ensuring that the surface echo was within the current profiling range. We would likely have obtained good surface data from the first deployment had we used BBADCP mode 1. Future firmware modifications in these instruments should enable reliable measurement of the surface drift velocity, even if the surface is beyond the profiling range.

Based on the favorable sound level statistics from the first deployment, we relaxed the sampling rate to once every 72 minutes. Also, the instrument was deployed at depth of 100 m to ensure velocity measurements of the surface were realized. The second deployment commenced on April 16, 1997 and collected data for 80 days.

The critical difference between the two deployments is that for the first deployment, no wind direction estimates can be made from the OASIS data. The range of wind speeds that were observed during the first deployment is a little greater than those observed during the second deployment. For this reason, where comparisons of wind speed measurement performance are of interest, we use data from the first deployment.

The change in depth between the two deployments does not significantly effect the ambient sound observations. The ocean surface acts as an infinite plane acoustic source and there is no change in intensity with distance from such a source (see Evans et al. 1984). Slight changes in intensity do occur at higher frequencies due to acoustic absorption but corrections are applied for these effects.

3.2 Computed wind speed

We computed wind speed using both the Vagle et al. (1990) algorithm (2) and the model given by (1). Constants for (1) were determined by correcting Evans et al. (1984) data for depth effects and using a 19 dB/decade spectral slope to determine coefficients at various frequencies. At 8 kHz, the values used were;

$$\begin{aligned} A &= 4.19 \times 10^{-2} \quad \sqrt{Hz}/\mu Pa \\ B &= 1.33. \end{aligned} \tag{4}$$

Rain noise (see Fig. 2) and shipping noise (Vagle, 1990) have the potential to degrade wind speed estimates, we however have made no attempt to identify periods of such data contamination and all data are included in the analysis. Wind speed estimates are made by averaging over one hour of OASIS ambient sound data.

The overall performance of the algorithms is determined by considering errors in OASIS velocity estimates as determined relative to the direct OWS Mike observations. Two aspects are important; the mean errors and the variance or standard deviation of the errors. Mean errors as a function of acoustic frequency are shown in Fig. 8a for the 1996 deployment. Results for wind speed estimates made using (1) are indicated as a dashed line, and those made using (2) are indicated using a solid line. For the OWS Mike data, mean errors are about the same for both methods and are generally less than 1 ms^{-1} increasing somewhat at higher frequencies. Figure 8b shows how the estimate standard deviations vary with frequency. The algorithm based on (1) provides wind speed estimates with lower variance than those of (2). Considering Figures 8a and b, the optimal frequency range for estimating wind speeds is from 2 kHz to 10 kHz.

An alternative view of the data can be presented through scatter-plots between OASIS estimates and direct wind speed observations. Figure 9 presents scatter-plots for hourly OASIS wind speed estimates (as based on (1)) at 2, 4, 8, and 16 kHz for the

1996 deployment. The 16 kHz data stand out in that they fail to accurately record wind speeds above 15 ms^{-1} . This limit to the range of the high frequency response is most likely due to high concentrations of subsurface bubbles that would occur at higher wind speeds. It is also noteworthy that there is no indication of a speed threshold as was seen by Wille and Geyer (1984).

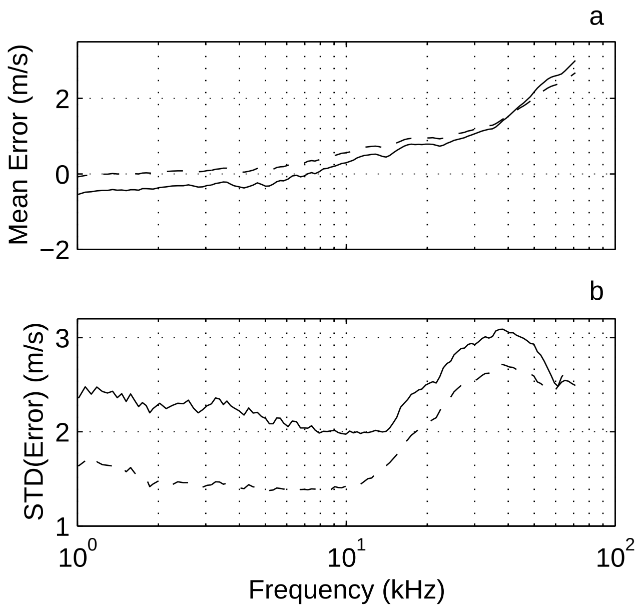

Figure 8: a) Mean error and b) standard deviation of errors in hourly OASIS wind speed estimates at OWS Mike for the 40 day period starting May 17, 1996. Errors are estimated as the differences between direct wind speed observations and OASIS wind speed estimates generated using relations (1) (dashed line), and (2) (solid line).

3.3 Wind Direction

Wind directions for the 1997 OASIS deployment were computed using (3) with velocities for $\vec{V}_m(z_m)$ taken from a depth of 64 m. Each wind speed estimate is based on an average over 12 hours of data. Figure 10 compares OASIS estimated wind directions with weather ship observations as a scatterplot. Notice that while some points might be considered as outliers, a few of these are simply values near 0° or 360° that have been wrapped around the axes.

The mean difference between OASIS and ship determined wind directions is $0° \pm 25°$. The uncertainty here is the standard deviation of the difference when wrapped data points are not included. If surface drift direction alone is used as a measure of wind direction the mean difference between OASIS and direct observations is $-3° \pm 30°$. At this location, only a

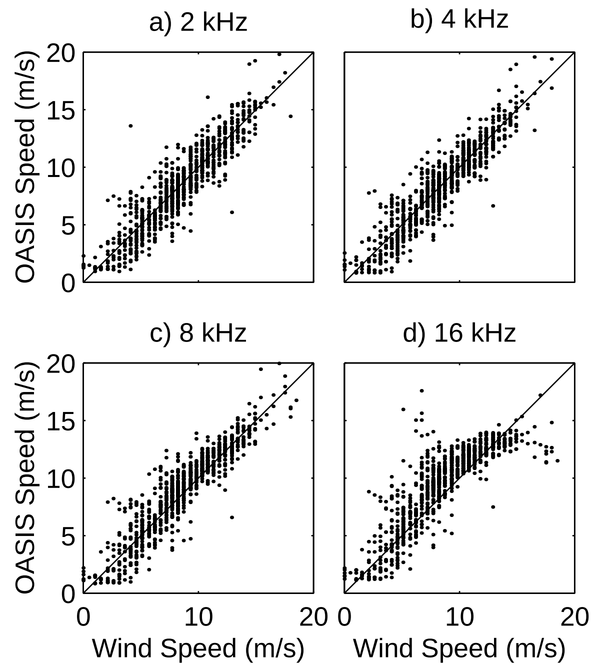

Figure 9: Scatter plots between observed wind speeds and OASIS wind speed estimates based on (1) using ambient sound at a) 2 kHz, b) 4 kHz, c) 8 kHz, and d) 16 kHz: the standard deviation (wind speed - oasis speed) for these estimates are 1.5, 1.4, 1.4, and 1.9 ms^{-1} respectively. Data are hourly samples from the OWS Mike deployment starting May 17, 1996 and lasting for 40 days.

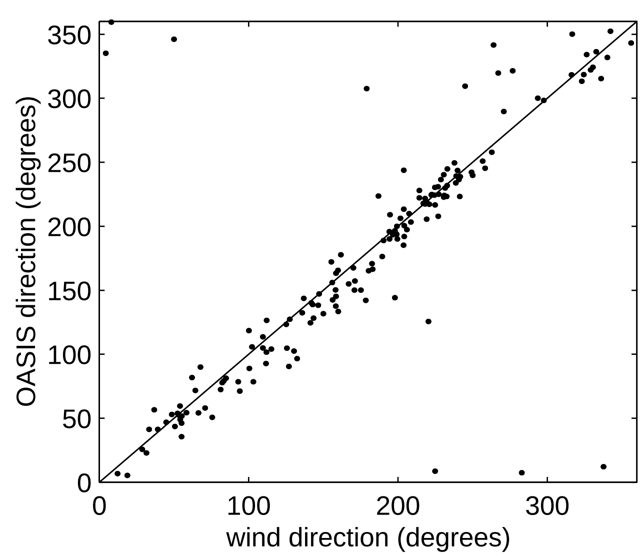

Figure 10: Scatter plot between OASIS wind direction estimates and direct wind measurements. Data points represent 12 hour averaged and are for the 80 day period starting April 16, 1997.

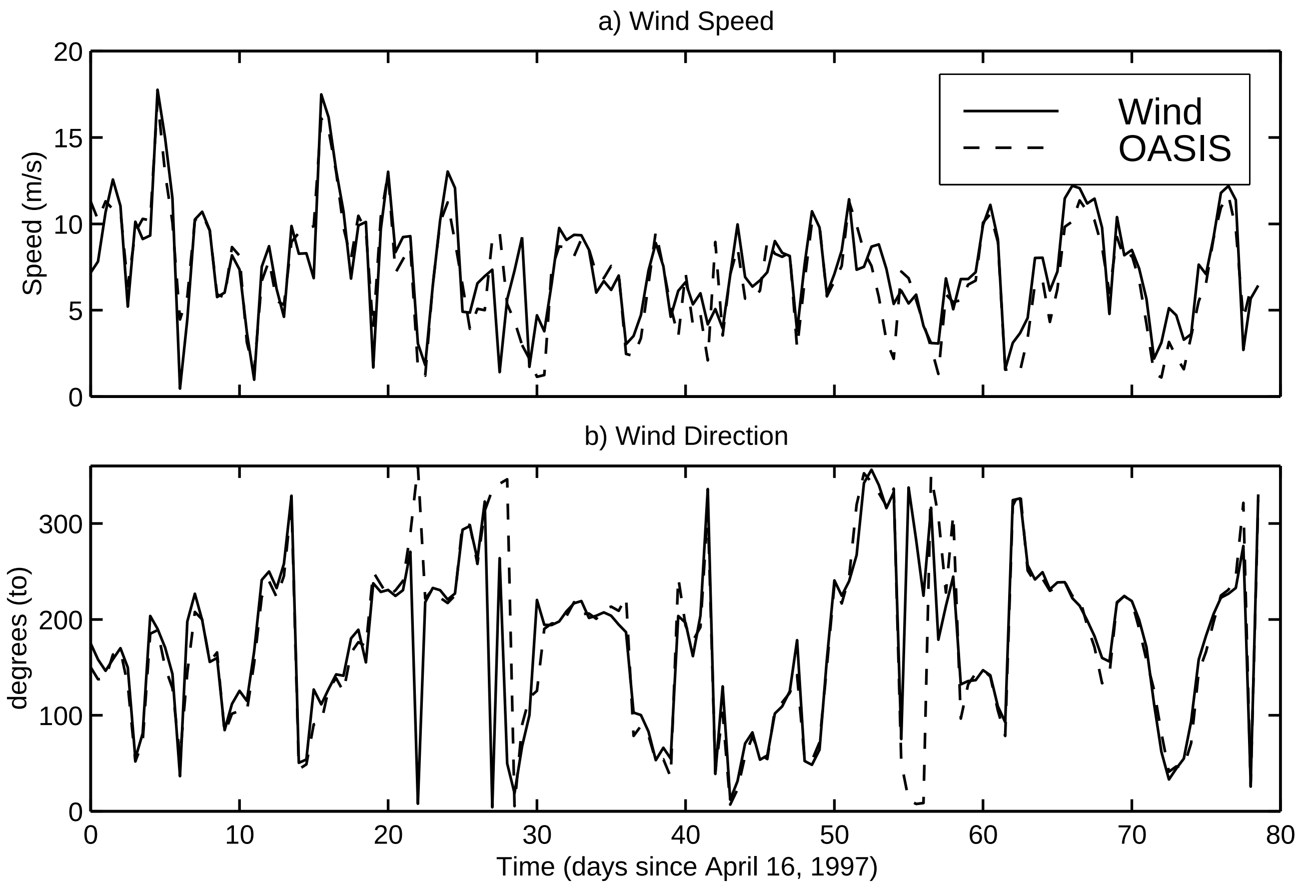

Figure 11: Comparison of OASIS derived wind speeds (a) and wind directions (b) with direct wind observations at OWS Mike. Data represent 12 hour average values for the 80 day period starting April 16, 1997.

small benefit is realized by using the correction given by (3). It is also worth noting that for this deployment, we found that the choice of reference depth ($\vec{V}_m(z_m)$ in (3)) did not greatly effect the results.

4. CONCLUSIONS

We have presented a discussion of the OASIS system which provides ambient sound recording capability in an ADCP. The primary objective of the OASIS system is to allow wind speed and direction measurement from a subsurface platform: wind speed is determined from ambient sound levels and wind direction from the surface drift direction perceived by the ADCP. We have discussed the considerations that lead to the eventual OASIS design. Of particular note is the need for careful signal conditioning to allow 70 dB of dynamic range while retaining 12 bit A/D converters and using a 16 bit integer FFT algorithm. We have presented OASIS ambient sound observations made during two deployments at OWS Mike (off the coast of Norway). A critical result of the first deployment was the demonstration that the gain control firmware could successfully track sound level fluctuations.

OASIS sound levels were converted to wind speed using (1) deriving the required empirical constants from observations reported by Evans et al. (1984) and also using (2) with the constants presented by Vagle et al. (1990). We found that good wind speed estimates could be achieved over a broad range of frequencies but the best performance was achieved in the band from 2 kHz to 10 kHz. In this frequency range, both estimates based on (1) and (2) provided mean errors of less than 0.5 ms^{-1} . However, (1) provided smaller error standard deviations with values of about 1.5 ms^{-1} compared to values of about 2 ms^{-1} for the estimates based on (2).

The final product of the OASIS system is wind speed and direction from a subsurface platform. Figure 11 provides an example of 2 kHz ambient sound, 12 hour wind speed and direction estimates for the 80 day period beginning April 16, 1997. For comparison, wind speed and direction as observed directly at OWS Mike are also indicated in Figure 11. Large differences in OASIS and OWS Mike wind directions occur only at the discontinuity between 0° and 360°.

There is some suggestion that OASIS over estimates high wind speeds (at the 2 kHz ambient sound frequency). Higher frequency estimates tend to underestimate these high frequencies but provide noisier results at intermediate wind speeds. An obvious next step will be to integrate information from various frequencies to provide an overall improved wind speed estimate.

The high quality ambient sound capability provided by OASIS is not restricted to use as a wind measurement device but is in fact intended to allow research into ocean ambient sound processes. For example, the upward looking ADCP component provides information on near surface air bubbles allowing for investigations on the relationship between ambient sound attenuation and sea state. It is our hope that the availability of OASIS systems for wind measurements will also lead to an increase in the availability of high quality, high frequency ambient sound data. Such a data base is needed to improve our understanding of rain noise, and would contribute to our understanding of ocean ambient sound in general.

5. ACKNOWLEDGEMENT

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Figures