Measurement and Evaluation of the Wave Climate near the Wave Hub using a 5-Beam ADCP

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Abstract

The paper details the capabilities of the newly developed TRDI 5-beam ADCP system deployed near the Wave Hub in the Bristol Channel, UK at nominal water depths of ~ 40 m. The ADCP’s wave and current data are being accumulated to support resource assessment and future design of wave energy devices at the Wave Hub site off the North Cornwall coast, UK. Multidirectional waves, current modified wave steepness, and wave height, are all accurately captured in this deployment. Real-time measurement of these parameters may be relevant for adaptation of energy generation devices to complex wave climate. We show the effects of strong tidal currents on the wave climate and wave length. A Doppler shifted dispersion relationship is used to correctly determine wave number under these conditions. Data shows waves from different sources (directions) simultaneously propagating into a region of mean current. These wave spectra overlap in frequency substantially. The ADCP resolves the two separate directions and wave-number for each wave system. Time series and spectra from the 5th beam direct surface measurement independently validate the results.

Keywords: 5-beam ADCP, directional buoy, wave climate, wave-current interactions.

1. Introduction

Wave measurements using ADCPs are now a well established technique. In this study, a new TRDI 5-beam ADCP system, consisting of a traditional 4-beam Janus configuration in addition to a 5th vertical beam, was deployed in the Bristol Channel, UK, about 4 miles off the Wave Hub site. The ADCP was located in the same area where four Fugro’s SeaWatch Mini II directional wave buoys (A, B, C, D) already reside. The deployment period was from 12-23 October 2010 at a mean deployment depth of about 40 m. The long term aim is to compare the two measurement systems in terms of the accuracy of collected wave and current data, reliability, and cost-effectiveness. This study is an addition to the ongoing international research work on comparing the performance of wave instruments like buoys and ADCPs, e.g. [1-2].

2. Deployment Location and Sensors

The fixed, bottom mounted, and upward-facing ADCP was co-located with four directional, identical surface following wave buoys. The positions of the sensors at a particular time are shown in Table 1.

<table>
<thead>
<tr>
<th>Device</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buoy A</td>
<td>50°18'28&quot;N, 5°39'47&quot;W</td>
</tr>
<tr>
<td>Buoy B</td>
<td>50°18'35&quot;N, 5°40'21&quot;W</td>
</tr>
<tr>
<td>Buoy C</td>
<td>50°18'18&quot;N, 5°40'13&quot;W</td>
</tr>
<tr>
<td>Buoy D</td>
<td>50°18'40&quot;N, 5°39'58&quot;W</td>
</tr>
<tr>
<td>ADCP</td>
<td>50°18'38&quot;N, 5°40'32&quot;W</td>
</tr>
</tbody>
</table>

Table 1: Position of Sensors.
using echo-surface location technique. The ADCP was powered by two external alkaline batteries.

**Figure 1.** A side scan sonar of the deployment site showing the position of the ADCP relative to the buoys. The profile of the site bathymetry at the bottom is also shown.

Fig. 2 shows the measurement sensors. In Fig. 2(a) the 4 slanted beams (each at 20° off the vertical) form the ‘master’ unit while the separate vertical 5th beam forms the ‘slave’ unit. Fig. 2(c) shows the ADCP inside the deployment frame, with a pop-up buoy, as assembled by the University of Exeter. One wave buoy is shown in Fig. 2(b) as deployed on site.

**Figure 2.** The wave sensors: (a) 5-beam ADCP Workhorse, (b) directional wave buoy on site (c) ADCP inside its deployment frame.

Compared with a directional wave buoy, the bottom-mounted ADCP is not a hindrance to navigation, is physically away from effects of stormy sea conditions, is less likely to be stolen or vandalized, and is less susceptible to physical damage due to floating ice [2] (Hoitink et al). The 5 beam ADCP is capable of measuring both waves and currents simultaneously, from a significant deployment depth. The simultaneous measurement is important for accurately representing the environment when there is wave-current interaction. This feature is relevant to its applicability to renewable energy generation. Waves create large scale velocity structures that affect turbine design and operation. Mean currents modify wavelength and wavenumber from the standard dispersion relationship. Wave-current interaction is clearly more than a simple superposition. The four buoys incur a costly maintenance: over a period of 12 months, there were three failures that needed repair, and the required maintenance visit is every three months. The ADCP was set up to measure waves and currents continuously at 2 Hz while the buoys were each set up to record waves in bursts of 17.06 minutes at 2 Hz (i.e. 2048 samples) at the start and middle of every hour.

3. Results

3.1 ADCP Surface Track

The new ADCP configuration allows echolocation of the surface in high resolution using the vertical beam while freeing the Janus beams to profile water velocity. The 300 kHz ADCP system used here was configured to surface track with 20 cm range cells while using 4 m range cells for measuring orbital velocity. The surface track algorithm actually improves upon the resolution of the bin size by a factor of \( \sqrt{12} \) assuming Gaussian shape. The single ping resolution for surface track is about 6 cm and the long term accuracy is better yet. This means that in a wavy environment, typical error sources for surface track (such as quantization error) are zero mean processes that do not create bias and reduce with averaging.

**Figure 3.** ADCP’s 5th beam spectrum up to 1 Hz.

A value of the 5th beam ADCP to this deployment is that even very small waves were measured all the way out to 1 Hz, from 40 m water depth, see Fig. 3. Because the surface tracking beam uses echolocation, the resolution of the vertical beam dictates its performance. The resolution does not vary with water depth and the expected performance should be identical for deployments at 20 m depth or 80 m depth. By contrast, traditional 4-beam ADCPs simultaneously ping four beams and this result is used for both echolocation and velocity profiling. Echolocation benefits from small high resolution range cells but orbital velocity profiling benefits from larger range cells with lower velocity variance. This bin size tradeoff is an inherent limitation to having a single ping performing both kinds of measurement. The 5th beam system was not limited by this tradeoff.

The ADCP offers three means of estimating non-directional wave spectra: surface track (5th beam), orbital velocity (4 inclined beams) and pressure signal. Spectra show high frequency content in relatively deep water. The wave height spectra shown in Fig. 3 illustrate tight agreement between all three sources of wave measurements provided by the ADCP in a narrow frequency range up to 0.12 Hz bound for the pressure and 0.23 Hz for orbital velocity. One can see that the surface track provides clean measurement of wave energy up to 1 Hz. The high resolution of the surface
track allows the measurement of even small high frequency waves in deep water.

Another value of the surface track is the ability to calculate zero crossing parameters and maximum wave height from the time series of direct surface measurement. The time-series in Fig. 4 shows the detail to which the surface track and vertical orbital velocity measurements can resolve individual waves and correlate well in general, over few seconds, as shown by the fact that peaks in surface track align with the peaks of vertical velocity.

![Figure 4. Correlation between surface track and vertical orbital velocity. The horizontal axis is time in seconds.](image)

**3.2 ADCP Orbital Velocity**

This deployment was configured with 4 m range cells and a correspondingly low variance of 14 mm/s. Because the vertical beam is providing a high quality non-directional wave spectrum the primary value of the orbital velocity measurement is wave direction. The ADCP estimates wave direction by measuring the along beam, orbital velocities in a virtual array above the instrument, then applying array processing. The process is phase coherent and benefits from having a larger array aperture. Because the deployment depth was 40 m, the placement of the bins and beams in the water volume was further from the instrument and has greater spread. In phase coherent techniques the larger aperture improves directional acuity and helps resolve multiple wave directions at one frequency.

**3.3 Multi Directional Waves**

**Buoy:** Buoy data and PUV gauges by contrast, make three measurements (triplet) at a single point, and derive wave direction from the cross spectra of these three measurements [3].

The theoretical expectation based on the mathematics of these two approaches, is that array processing can resolve multiple wave directions at the same frequency, and that triplet processing cannot unless the peaks are widely spaced. With this in mind the ADCP data set was reviewed, looking for times when the peak period was constant (single mode in period) but the wave direction shifted discretely between two values (bi-modal in direction).

Figs. 5a and 5c show multiple directions overlapping in frequency. For comparison, the ADCP data was processed using the triplet approach. One can see that the triplet approach will tend to estimate the wave direction in between the two actual peaks (5b, 5d). This in between direction corresponds to the buoys estimate of peak direction at times when there were two peaks.

This outcome is exactly what is predicted from theory. The triplet approach used to produce direction from buoy data is limited to the first three terms in a Fourier series. If one could exactly reproduce the infinite Fourier series, it would be possible to reproduce any directional distribution including the exact directional shape and width.

Unfortunately, at a single point in space the buoy has only 3 measures of wave direction; heave, pitch, and roll. One can only derive the first familiar Fourier coefficients ($A_0, A_1, B_1, A_2, B_2$) from the measured cross-spectra. There are clear limitations to the kind of directional distributions and shapes that can be produced with only these first Fourier coefficients.

![Figure 5a. ADCP array, example 1.](image)

![Figure 5b. ADCP-based triplet processing, example 1.](image)

![Figure 5c. ADCP array, example 2.](image)
Generally the peak direction is good. More than one peak is not possible unless very widely separated. The $A_2$ and $B_2$ terms contain some partial information about directional width but they are not adequate to constrain the result. In other words there are too many unknowns and not enough equations. This leaves us with the problem that more than one possible directional distribution can be consistent with the derived coefficients. Directional width and multiple peaks are not resolved by the triplet approach. This limitation is not simply a constraint of the particular mathematics used for triplets, it is fundamentally limited by the type of physical measurement being made and the degree to which directional waves can or cannot be uniquely identified by it.

**ADCP:** The ADCP array measurement and processing is an improvement because we have the means to estimate direction with more than the traditional three measures. The estimate is improved by having an array with some aperture that capitalizes on both orientation (measuring orbital velocity direction at a single location in the array) and location (measuring the relative spatial phase differences from one sensor to the next.). The ability of the ADCP to exactly reproduce the directional distribution is dependent upon the array aperture and signal to noise ratio. Since we seldom have infinite signal to noise ratio and the array aperture is generally small compared to ocean wave wavelengths, the ADCP estimate of wave direction is still under constrained. The ADCP uses the Iterative Maximum Likelihood Method to further constrain the number of possible solutions for directional distribution. With the IMLM algorithm, directional spreading is the consequence of uncertainty. This is a benign failure mechanism but it means that the first coefficients are not preserved. As signal to noise ratio increases, the estimate of directional distribution begins to converge to the true distribution. While the ADCP estimate is better constrained, can resolve more information about directional width, and multidirectional waves, than the buoy, its coefficients are not comparable. Only the end directional distributions can be compared. So the conclusions are:

- The peak direction between buoy and ADCP should be comparable as both should produce it correctly.
- Directional width is not adequately measured by either.

- The ADCP can estimate the directional distribution adequately enough to resolve multidirectional waves.

### 3.4 Wave-Current Interaction

It has been shown that waves propagating into a mean current are Doppler shifted by the component of the current that aligns with the waves [5]. The Doppler shifted dispersion relationship governs the relationship between wave number and frequency for the case of small currents:

$$\omega - kU \cos \alpha = gk \tanh(kH)$$

In the usual notation, $\omega$ is the radial frequency, $k$ the wave number ($= 2\pi/\lambda$, $\lambda$ is the wavelength), $g$ is acceleration due to gravity, $U$ is the mean current velocity, $H$ the water depth, and $\alpha$ is the angle between the wave and the current vector. This data set had moderate (1.3 m/s) tidally driven currents and demonstrated the phenomenon well. Fig.6a shows spectra measured when there was a following current. In this case the waves are propagating on a mean current that is moving with the waves and the ADCP (fixed in the Earth reference frame) is observing wave crests at a faster (Doppler shifted) rate. So waves will be observed at a higher frequency in the Earth reference frame than they have in the water reference frame. Waves propagate in the water reference frame, so for any given observed frequency, the true frequency is actually lower. If one used the standard dispersion relationship to determine the wavelength at each observed frequency, then the observed higher frequency would give an incorrect shorter wavelength. Shorter wavelengths attenuate below the surface at a faster rate and a greater gain would be applied to translate subsurface measurements to surface displacement. So one would observe an over estimate.

### Figure 5d. ADCP-based triplet, example 2.

![Figure 5d. ADCP-based triplet, example 2.](image)

**Figure 6a.** Following Current.

![Figure 6a. Following Current.](image)

**Figure 6b.** Opposing Current.

![Figure 6b. Opposing Current.](image)

Conversely, when the current opposes the waves the observed frequency would be lower, causing an under estimate. Fig.6b shows uncorrected velocity derived...
spectra and reference (blue) for the opposing currents case.

Figure 7. Periodicity in wave height correlated with tidal currents: current direction (CD) and current magnitude (CM).

In Fig. 7 we note the vertical stripes or periodicity in the time-series of spectra and significant wave height. The periodicity in wave height is correlated with the peak tidal current on the time scale of the tidal currents. At first sight one might be inclined to conclude that there must be some kind of error. This data, however, has been corrected for the Doppler shifted dispersion relationship and the spectra match spectra derived from direct surface measurement. After more careful scrutiny we see that the mean currents can actually modify wave height, not just change the dispersion relationship. At this point a key distinction must be made between two different conditions creating wave-current interaction. There is a difference between waves propagating into a region of mean current versus waves that are developed on the mean current.

Case 1: Waves that were formed in the open ocean in the absence of significant mean current adhere to the standard dispersion relationship. If those waves then propagated into a region of mean current they would be stretched or compressed accordingly. If the wavelength is shortened the wave height increases. If the wavelength is stretched the wave height decreases. Wave action flux is conserved. This stretching or compressing of wavelength as waves move into a region of mean current amplifies or diminishes wave height and therefore wave steepness. In large opposing currents, waves may become steep enough to break, or cannot pass because the mean current has exceeded their group velocity. In large following currents waves may stretch so much that their wave height becomes insignificant.

Case 2: For the case in which waves have been created on the mean current, waves still adhere to the Doppler shifted dispersion relationship because they are propagating in the water reference frame and the measurement is made in the earth reference frame. In this case however, the waves have not transitioned from one reference frame to another so the wave height/steepness is not changed and is consistent with the normally developing wind seas.

Relevance to Renewable Energy Generation and Efficiency
Waves, mean currents and turbulence are a few of the desired measurements important to renewable energy. These influence the design of turbine and offshore structures, site location and real-time adaptation of equipment to the environment. Because these structures are in the fixed Earth reference frame there are several phenomena that are relevant, including:

(i) Waves that are developed on a mean current will impact the location at a faster or slower rate in time than the standard dispersion relationship would predict. This may influence design and efficiency.

(ii) Waves that have propagated into a mean current may have greater or lesser steepness than would normally be found in nature.

Using the Doppler shifted dispersion relationship based on mean tidal currents one could make much more realistic predictions about what a wave climate site should actually expect with each tidal cycle. In addition, local measurement of wave steepness could be used in real-time to protect equipment and adapt for greater efficiency.

4. Non-directional Comparison

Although the ADCP was co-located with the buoy array comparison of the two types of instruments is important because the measurement techniques for both are different.

In the long term, it also helps to assess where the two systems are favourably compared, and when they are not. Generally the non-directional wave parameters for the ADCP and the buoys agreed very closely, despite some occasional bias. Because there was such good agreement over the majority of the data set, it is conspicuous that there were sporadic time frames when they clearly did not agree. It was important to understand under what conditions, and exactly why the two different measurement techniques did not agree. We have chosen to focus on those differences even though they were infrequent.

The ADCP wave parameters were obtained from the velocity spectra, surface track, and pressure sensor through RDI’s WavesMon software. The spectra from these three independent measurements overlaid quite closely providing a data quality indicator and an upper bound for the error of measurement. The average spectral difference between the three different ADCP power spectra is less than 1%. The wave buoy data processing was performed on the basis of wave standard analysis by Fugro Oceanor with additional data quality control procedures (e.g. removal of outliers, interpolation of missing data, etc) as applied to this data by Ashton [4].
Figure 8a. Spectral derived $H_s$ comparison.

Figure 8b. $T_p$ comparison.

Figure 8c. $D_p$ comparison.

$H_s$ time series comparison

As indicated in Fig. 8a, the agreement in terms of spectral derived $H_s$ is generally good. Because the agreement was so close in most of the data set the circled time frames in Fig. 8a stood out. We took a closer look at these time frames to try to understand what might have occurred. The ADCP’s data spectra during these times were of high quality and unambiguous. On closer inspection, reviewing Figs. 8a and 8b one can see that when there is a difference, the buoy estimate of $H_s$ is always lower and that the times when this occurs the waves are long period ($>14s$). It is our understanding that directional buoys may have difficulty measuring long period waves because of the nature of the mooring. While it is simply a conjecture, it would appear from this data that whenever the wave period is particularly long, the buoys underestimate the wave height.

$T_p$ time series Comparison

The peak period also compared well over most of the deployment (Fig.8b). The times where it differed between ADCP and buoys fell into two categories. Case 1: particularly long period waves. Case 2: Bimodal systems with closely matched peak heights.

Early in the deployment there was a time frame characterized by a bi-modal system with a long period swell peak and a wind sea at slightly higher frequencies. The ADCP correctly identifies the long period swell as the largest peak in the spectrum during this time. The buoys seem to show the higher frequency peak as the largest. This is also the time frame characterized by an under estimation of significant wave height. The observation is consistent with the hypothesis that the buoys have difficulty measuring the longer period waves. By underestimating the long period swell peak, the higher frequency peak would show as the dominant peak.

Let us consider Case 2 when the spectrum was bi-modal and the two peaks are closely matched in height. When a system has two peaks in frequency that are close to the same height we would expect the choice for peak period to alternate between the two peaks from one sampling interval to the next with some sensitivity. In this scenario the differences between the ADCP and buoys are simply an artifact of the process of peak picking. When there are two very closely matched peaks in the spectrum, there is a high sensitivity to slight differences between the heights of those peaks (see Fig. 9). This case does not constitute an error on the part of either measurement technique. Both ADCP and buoys chose between the same two peaks.

Figure 9. A bi-modal system with closely matched peak heights.

$D_p$ time series Comparison

The peak direction also matched well over most of the deployment. Because there are differences in choice of peak period, we expected there to be differences in peak direction that correlate with the times when there is a bimodal system in frequency. In Fig. 10 at time frame A, the buoy under-estimated the long period waves and sometimes chose a different peak than the ADCP. This could lead to a different choice for peak direction. Sometimes the differences are uninteresting as they are simply an artifact of peak picking. The time frame marked by the letter B in Fig. 10 is an example of this.
There were however, several time periods when both ADCP and buoy agreed that the spectrum had a single dominant peak in frequency, yet the peak direction differed. In this case (see time marked by the letter C in Fig. 10) a closer look at the ADCP directional spectra (Figs. 5a-5d) show that the system is bi-modal in direction. Waves are arriving from two different directions at the same time, and they overlap in frequency. Our experience and theoretical expectation is that the array measurement technique and processing is capable of resolving these multidirectional waves and that the triplet based processing used for buoy data cannot.

Figure 11 is the scatter plot for Hs between the ADCP and the four buoys. The determination coefficient R² of linear regression of significant wave height between the ADCP and all the buoys was 0.96.

5. Conclusions
Wave and current data have successfully been measured by an improved 5-beam ADCP at the Wave Hub site in the Bristol Channel, UK. A co-located array of four directional buoys provided instantaneous wave measurements for comparison purposes. The 5-beam ADCP accurately resolved the waves up to 1Hz and currents in deep water. It was found that the ADCP and buoys compared well almost everywhere. When they did not compare the ADCP represented the environment more accurately. The few differences seen between the two instruments are exactly what one would expect from theory. The 5-beam ADCP was able to uniquely resolve multi-directional waves and current modified wave steepness. The ability to resolve current modified waves may be important to design and real-time adaptation of renewable energy generation equipment to the environment.

6. References

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