WAVE MEASUREMENTS AT WETS: COMPARISON OF WAVERIDER AND ADCP IN-SITU RECORDS

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INTRODUCTION

The US Navy Wave Energy Test Site (WETS) consists of three grid-connected berths at 30m, 60m and 80 m depths offshore the Kaneohe Marine Corps Base Hawaii (MCBH). Prototype wave energy conversion (WEC) devices are currently being tested at the 30 m and 60 m berths. The WETS location within the state of Hawaii is shown in Figure 1. The site provided by the US Navy is 1600 to 2000 m wide and extends approximately 2600 m offshore from the 30 m depth contour to the approximate 100 m depth contour.

The Hawaii National Marine Renewable Energy Center (HINMREC) of the Hawaii Natural Energy Institute (HNEI) at the University of Hawaii, under contract with the Department of Energy and the U.S. Navy is charged with the independent evaluation of WEC device performance. Device power output (kW) must be measured as function of wave parameters to follow the International Electrotechnical Commission (IEC) specification for the power performance assessment of WEC devices [1]. For this purpose, HINMREC-HNEI maintains wave measurement devices. These consist of the industry standard as represented by Datawell Directional Waverider buoys as well as latest generation Acoustic Doppler Current Profilers (ADCPs). It was the primary objective of this effort to provide statistically significant comparisons between a Waverider and the latest generation ADCP device collocated seaward of the WETS berths along the 80 m depth contour.

The latest generation ADCPs, like the RDI Sentinel V100 installed at WETS, use five beams instead of the traditional four and software that has been updated to resolve some of the issues identified during previous field tests.

Comparison between Waverider buoys and earlier version of ADCPs have been performed [2] based on field data obtained at shallower depths. It must be emphasized that previous work was performed with ADCP devices installed at depths not exceeding 45 m and separated by as much as 30 km from the Waverider such that data had to be transformed to different depths using linear theory correction for shoaling and refraction effects. It was learned that estimates of wave parameters obtained with those ADCPs correlated favorably with those obtained with Waveriders in waters shallower than about 20 m. In general significant wave height, peak frequency and mean direction parameters were in agreement but directional spreading was not. The directional information is not an issue for some type of WEC devices (e.g., heave only point absorbers) but is important and required for the control of others that need to also tune additional degrees-of-freedom (e.g., their roll, pitch, surge and sway) to the wave environment.

We installed the latest generation (5-beam) ADCP and a Waverider along the 80 depth contour and only separated by 400 m. To the best of our knowledge, this had not been performed before.

AT-SEA TEST

HINMREC-HNEI with Sea Engineering Inc. deployed a Teledyne RDI Sentinel V100 ADCP over six months in close proximity to a WETS Datawell Waverider buoy (CDIP#198). The purpose of this study was to compare the measurements from the ADCP to the measurements of the Waverider buoy over the range of wave environments encountered at WETS. Figure 2 shows the locations of the Waverider buoy and the ADCP in a Google Earth™ image. The wave measurement devices are approximately 400 meters apart along the ~ 80 meter bathymetric contour.

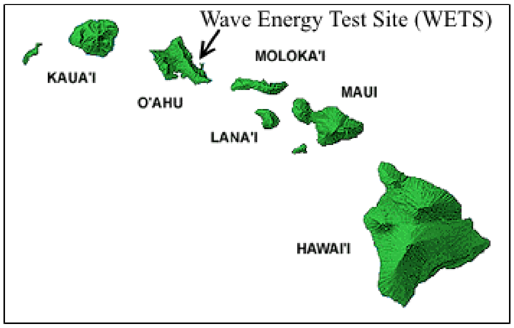

FIGURE 1. WETS LOCATION.

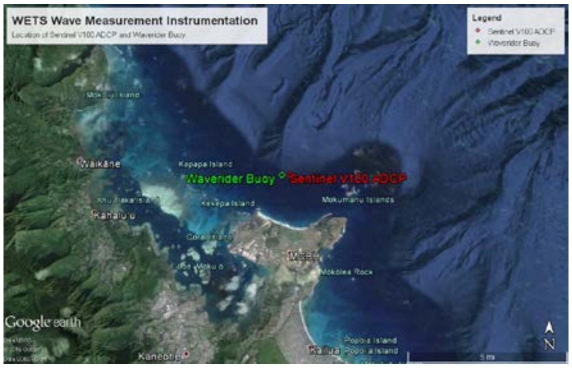

FIGURE 2. WETS WAVE MEASUREMENT INSTRUMENTATION.

The upward looking bottom mounted ADCP uses four angled acoustic beams to measure the water particle velocities induced by the passing waves. These velocities are used to calculate the ocean surface displacements to yield estimates of wave height, period and direction. The acoustic reflection of a beam that is up current from the ACDP will arrive before the reflection of a down current beam. With the reflection return timing of multiple beams, the direction of waves and currents can be calculated [3]. A fifth vertical acoustic beam, included in the new generation ADCPs, provides an additional estimate of wave height by tracking the time it takes for the beam to reflect back from the ocean surface to the ACDP. In addition a pressure sensor provides an independent estimate of surface elevation.

The heave-pitch-roll Waverider uses three accelerometers, compass and tilt sensor to determine the motions of a 0.9 m diameter moored buoy. The buoy is designed such that the mooring line and anchor have minimal impact on the motion of the buoy. The motion of the buoy is representative of wave motion, and is used to calculate wave parameters from the time series of horizontal and vertical displacement from which directional wave spectra can be estimated.

ADCP SETUP

The Sentinel V100 ADCP was programmed to measure both waves and current using the settings listed in Table 1.

TABLE 1. ADCP PARAMETERS.

	Waves	Current
Ping Interval (s)	0.5	1
Number of Pings	2300	300
Range (m)	84	84
Cell Size (m)	1.0	1.0
Duration(minutes)	19.17	5

The wave measurement occurs once per hour over a 19 minute and 10 second period. Current measurements occur over a 5 minute period 30 minutes after the start of the wave measurements. This setup was chosen to accommodate two separate deployments each three months long. Useful data was collected from November 13th, 2014 to April 24th, 2015.

For the purpose of this report, data obtained with the ADCP was used to calculate the following wave statistics: significant wave height (H_s); peak period (T_p), and peak direction (D_p).

WAVERIDER DATA

The WETS Waverider buoy (#198) data is displayed at http://cdip.ucsd.edu/. Time series of surface elevation derived from the three accelerometers are available online. The wave statistics considered herein are tabulated every half hour. Waverider accuracy had been previously established around Hawaii and is, therefore, considered the standard [4].

COMPARISON OF WAVE STATISTICS

Figure 3 shows the November 2014 to April 2015 time series of the significant wave height (H_s), peak period (T_p), and the peak direction (D_p) from the two devices (Waverider in red). These time series show overall H_s and T_p agreement throughout the six month deployment but in the case of D_p there is agreement only when the wave field is dominated by winter swells generated in the Northern Pacific (e.g., Nov-Feb).

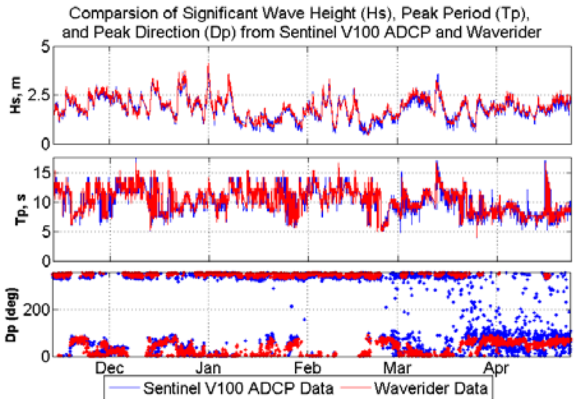

FIGURE 3. TIME SERIES OF SENTINEL V100 ADCP AND WAVERIDER CDIP #198 (11/14 – 04/15).

The following error metrics can be used to compare the peak period (T_p) and significant wave height (H_s) parameters estimated from the Sentinel V100 ADCP with those estimated from the Waverider records: Mean Error (ME), Normalized Mean Error (NME), Root Mean Square Error (RMSE), Normalized Root Mean Square Error (NRMS), and Correlation (COR). Mean error, also known as bias, is an average difference between Sentinel V100 ADCP and Waverider data. ME is helpful in determining whether one instrument is consistently measuring higher or lower than the other. RMSE is a measure of how close, on average, the instrument measurements are to each other. Small RMSE and NRMS estimates indicate a small difference between compared measurements.

Correlation (COR) is the statistical relationship between two or more variables such that systematic changes in the value of one variable are accompanied by systematic changes in the other. The closer COR is to 1, the closer the relationship between the Sentinel V100 ADCP measurements and the Waverider measurements.

$$ME = \frac{1}{N}\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})$$

$$NME = \frac{1}{N}\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})}{\sum_{i=1}^{N}(X_{WRi})}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})^2}{N}}$$

$$NRMSE = \frac{1}{(\max(X_{WR}) - \min(X_{WR}))}\sqrt{\frac{\sum_{i=1}^{N}(X_{ADCPi} - X_{WRi})^2}{N}}$$

$$COR = \frac{\sum_{i=1}^{N}(X_{ADCPi} - \overline{X_{ADCP}})(X_{WRi} - \overline{X_{WR}})}{\sqrt{\sum_{i=1}^{N}(X_{ADCPi} - \overline{X_{ADCP}})^2}\sqrt{\sum_{i=1}^{N}(X_{WRi} - \overline{X_{WR}})^2}}$$

In the equations listed above, ADCP and WR subscripts denote the Sentinel V100 ADCP data and Waverider data respectively, and N is the number of data pairs. The over bar denote mean of values. The statistics for both the significant wave height and peak period for the entire six-month data base are given in Table 2. The ADCP used herein yields negative biases of approximately 6 cm and 0.2 seconds in H_s and T_p over the entire data base with values ranging from about 0.5 m to 3.8 m and 7 to 15 seconds.

TABLE 2. ADCP MEASUREMENT METRICS OVER SIX-MONTHS IN RELATION TO THE STANDARD.

	RMSE	NRMSE	ME (Bias)	NME	COR
H_s	0.17m	0.046 (4.6 %)	-0.06m	-0.033 (-3.3 %)	0.96
T_p	1.69s	0.133 (13.3 %)	-0.19s	-0.018 (-1.8 %)	0.71

	ADCP Circ. Mean	Wavrdr Circ. Mean	ME (Bias)	RMSE	COR
D_p	10.5°	17.4°	-3.2°	35.5°	0.59

The statistical analysis for the peak direction (D_p) must account for the fact that directional measurements are angular and not linear. For instance, the mean direction of 359° and 1° is 0° and not 180°. The angle measurements from the ADCP and the Waverider were broken into vector components to calculate the true mean and RMSE angle differences for the entire six-month deployment as given in Table 2. The ADCP used herein yields a correlation of about 0.6, a negative bias of about 3° but a RMSE of almost 36° over the entire six-month deployment. In the case of the months of January and April, for example, the D_p RMSEs are 28° and 50° with corresponding correlations of 0.6 and 0.2 respectively. This indicates that the ADCP yields mean direction as accurate as a Waverider but its RMSE (e.g., directional spreading) might not be acceptable for certain applications.

This can be further illustrated making use of Rose Plots showing that during the entire month of January 2015, under swell dominated wave conditions, there was general agreement between the ADCP and the standard (see Figures 4 and 5). However, during April 2015, with the wave field dominated by trade-winds generated seas arriving from the northeast, there is poor correlation between the ADCP and the Waverider as shown in Figures 6 and 7.

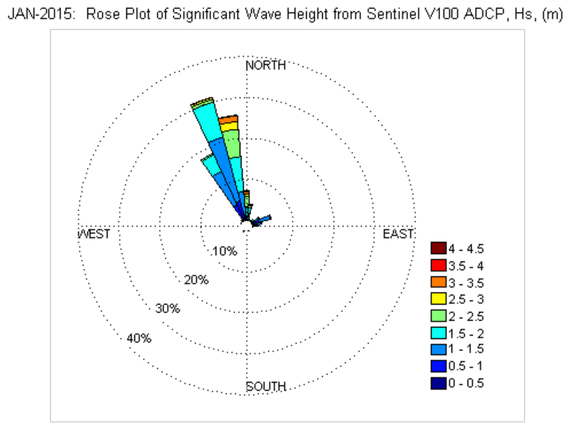

FIGURE 4. MONTH OF JANUARY 2015 ROSE PLOT OF SIGNIFICANT WAVE HEIGHT FROM SENTINAL ADCP.

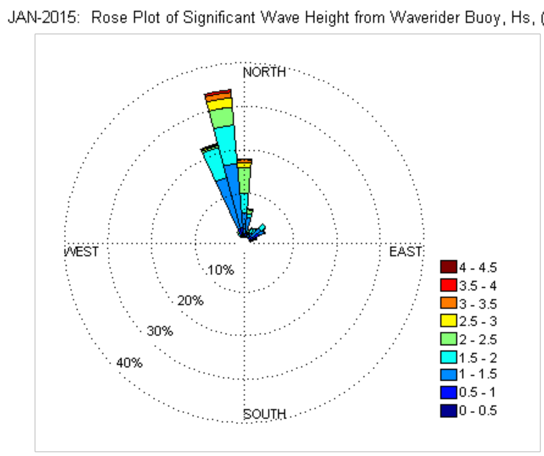

FIGURE 5. MONTH OF JANUARY 2015 ROSE PLOT OF SIGNIFICANT WAVE HEIGHT FROM WAVERIDER.

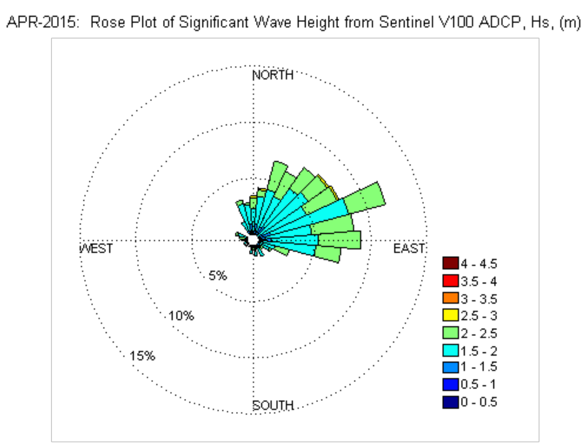

FIGURE 6. MONTH OF APRIL 2015 ROSE PLOT OF SIGNIFICANT WAVE HEIGHT FROM SENTINAL ADCP.

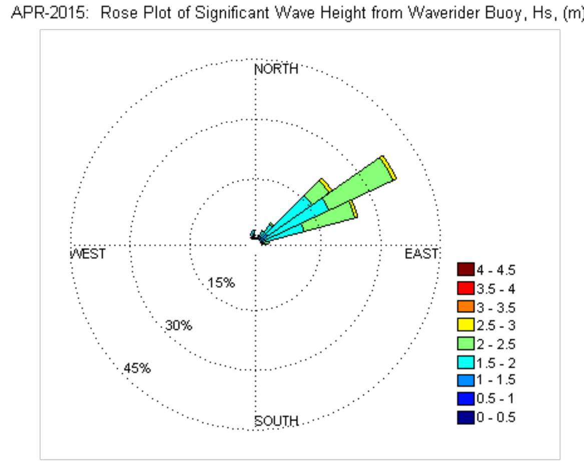

FIGURE 7. MONTH OF APRIL 2015 ROSE PLOT OF SIGNIFICANT WAVE HEIGHT FROM WAVERIDER.

The two devices can be further compared by considering 1D wave spectra estimated from ~ 30 minute long records. Figure 8 and 9 provide samples from January 2015 and April 2015 respectively. Figure 8 represent a wave field dominated by swell conditions with a Waverider spectral peak at 13.33 s (0.075 Hz) while Figure 9 is for a sample under mixed conditions with the sea spectral peak at 7.14 s (14 Hz) and a secondary swell peak at ~10 s (0.1 Hz). Spectra labeled "ADCP Velocity" are from the standard 4-beam measurement of wave induced vertical velocities. Those labeled "ADCP Surface" are from the vertical ("fifth") acoustic beam. These figures also include spectra derived from the pressure sensor with a cutoff at about 0.11 Hz (9 s). Waves of shorter period cannot be detected with the pressure sensor installed at 80 m depth. This situation is more pronounced under predominately (shorter period) sea conditions (Figure 9).

Table 3 provides parameters estimated from the sample records from which spectra in Figures 8 and 9 were derived using the software provided by the ADCP manufacturer [3] and for the Waverider the data is stored at CDIP. Independently of the process (e.g., sampling windows for spectral estimates) followed, differences between the ADCP and the standard Waverider can be discerned.

TABLE 3. WAVE PARAMETERS FROM 30-MINUTE LONG RECORDS.

	H_s (m)	T_p (s)	D_p (°)
0006/01/01			
Waverider	3.72	13.33	352
ADCP	3.67	11.64	339
2306/04/19			
Waverider	*2.50*	*7.14*	*64*
ADCP	*2.23*	*6.10*	*54*

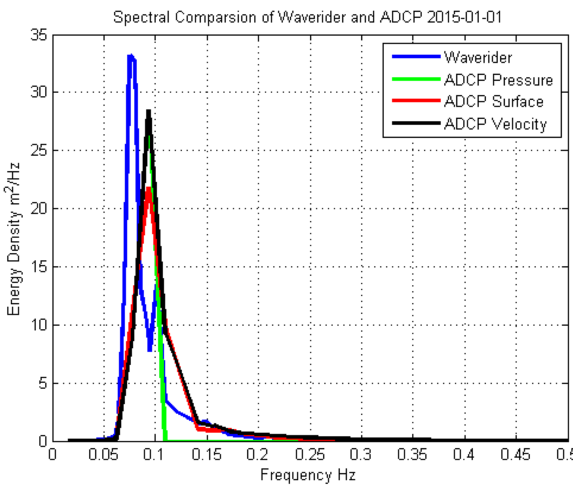

FIGURE 8. WAVE SPECTRA JANUARY 1, 2015 FROM 30 MINUTE RECORD ENDING AT 0006 HOURS (HST).

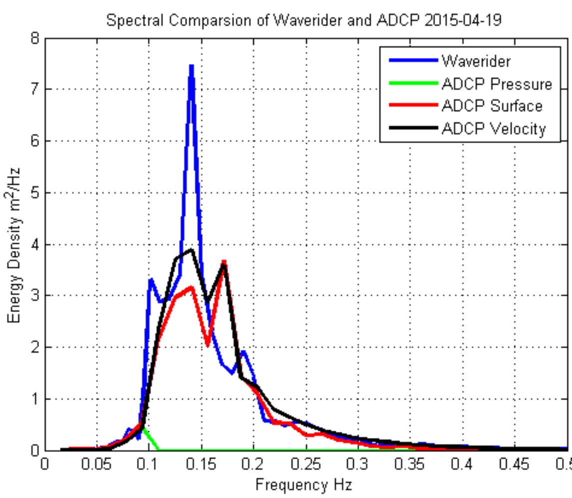

FIGURE 9. WAVE SPECTRA APRIL 19, 2015 FROM 30 MINUTE RECORD ENDING AT 2306 HOURS (HST).

CONCLUSION

HINMREC with Sea Engineering Inc. deployed a 5-beam Teledyne RDI Sentinel V100 ADCP with redundant wave measurement capabilities at WETS from November 13th, 2014 to April 24th, 2015. The ADCP was deployed 400 m from the WETS Waverider buoy (CDIP#198) along the same 80 m depth contour.

Figures 3 through 7 illustrate the relatively close correspondence between the measurements from the Sentinel V100 and the Waverider. Table 2 provides statistical metrics of the ADCP measurement error in relation to the standard provided by the Waverider. The significant wave height correlation estimated at 0.96 for the entire period (with 1 indicating 100% correlation) indicates that the ADCP is as accurate as the Waverider in the estimation of wave height. In the case of wave period and direction, as represented by the peak period and peak direction, the correlations are 0.71 and 0.59 respectively. These indicate that in relation to the Waverider the period and direction estimates derived from this ADCP are not as precise as the wave height estimates. The lower ADCP correlation of the peak direction is due to the large range of directional values, and the large jumps in direction – from 360° to 50° – that can occur quickly at WETS as a swell event subsides and trade wind seas become dominant.

For the purpose of WEC device testing at WETS, Directional Waveriders will continue to be the primary instruments with the ADCP providing a secondary measurement. However, depending on the type of WEC device under testing at WETS, the ADCP measurement bias (ME) and the root-mean-squared-error (RMSE), as given in Table 2, might be acceptable in the determination of direction and period parameters.

ACKNOWLEDGEMENTS

Work sponsored by the US Department of Energy's Wind and Water Power Program under Award DE-FG36-08GO18180 to the Hawaii National Marine Renewable Energy Center (HINMREC) of the Hawaii Natural Energy Institute (HNEI) of the University of Hawaii . The support and guidance provided by Tim Ramsey, DOE Technical Project Officer, are greatly appreciated.

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