Current and Wave Measurements in Support of the Chesapeake Bay Interpretive Buoy System

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***Abstract*— The Chesapeake Bay Interpretive Buoys System (CBIBS, www.buoybay.org) is - at present - a 9-buoy system of observational buoy platforms located around the Chesapeake Bay, operated bythe NOAA Chesapeake Bay Office. The buoys themselves are AXYS Watchkeeper buoys based on the Tideland Signal SB 138 P hull, moored with all chain rode with a 2.5:1 scope. All of the buoys have downward looking NORTEK AquaDopp 1 mHz profilers mounted in the hulls; six of the buoys are equipped with AXYS TriAXYS OEM wave measurement modules. To evaluate the performance of these buoy mounted sensors, concurrent wave and current profile data were collected at one site (34 days of data at the SN 'Six Foot Knoll' buoy, 21 foot depth) using an adjacent bottom-mounted 1 mHz NORTEK Acoustic Wave and Current (AWAC) instrument. Using one Hz overlapping single ping current profile data, the following conclusions were reached:**

- ***Ten minute averages calculated and transmitted by the AXYS Watchman controller accurately represent internally recorded current profiler data (however the comparison revealed a correctable Watchman firmware error);***
- ***Over four 1-meter bins, absolute differences in magnitude among 10 minute means of AquaDopp and AWAC currents are less than 0.005 meters/second, with standard deviations of 0.02 - 0.03 meters/second;***
- ***Absolute differences in direction over the same bins were 7-10 degrees. By only including velocities in excess of 0.1 meters/second, direction errors were reduced by nearly one half;***
- ***AWAC and buoy currents were subjected to harmonic tidal analysis at each level. Differences in the orientation of the major axis of the tidal ellipses were 0.3 to 1.6 degrees;***
- ***Current measurement accuracy was not affected by sea state / buoy motion, at least up to the 1.5 meter waves heights experienced during this comparison;***
- ***An analysis of the 'errors' (assuming AWAC data as the standard) shows that accuracy does not improve after 120 pings (2 minutes) of averaging. In a power-limited environment such as a buoy, this is a significant result.***

Typical Chesapeake Bay wind waves - one to three feet height, two to three second period - are difficult to measure with a 1300-pound 1.75 meter diameter buoy. But accurately distinguishing between 1 and 2 foot waves is important to many of the small craft boaters using the CBIBS system. In comparing the TriAXYS (20 minute sample) and AWAC (2 Hz, 2048 samples) wave measurements, we found that for simple wave parameters of interest to us – maximum wave height and mean direction – the instruments were in good agreement. A linear fit to maximum wave heights had a slope / intercept of 1.05 / .02 (meters) . Similarly, comparison of mean wave direction from both instruments agreed well, with slope/intercept of 1.01 / -5.1 (degrees).

I. OVERVIEW OF THE CHESAPEAKE BAY INTERPRETIVE BUOY SYSTEM

The Chesapeake Bay Interpretive Buoy System (CBIBS) was conceived as a multipurpose observing system, serving a broad range of users in the Chesapeake Bay region. The system was initially funded to provide interactive, interpretive support for the National Parks Service's Captain John Smith Chesapeake National Historic Trail, specifically referencing Captain Smith's historic small boat exploration of the Chesapeake Bay in 1607 and 1608. The scope of the system grew to deliver information along three different lines.

- Education and Outreach: This included the original historical, cultural, geographic, and environmental information associated with the buoy locations, as well as an educational curriculum based on the real-time data available from the buoys.
- On-the-water-users: The buoys collected and disseminate data that are of use to "John Smith Water Trail" followers, sailors, recreational and commercial fisherman, and commercial maritime interests. Data improve the recreational experience, enhance marine safety, and further commercial interests.
- Management and Science: Long –term, quality-controlled measurement of the appropriate parameters contribute to scientific studies, monitoring water quality and environmental change, and accurate models and forecasts by operational agencies and management decision makers.

Beginning in May 2007, in collaboration with users of all types, buoys have been placed at locations on the Chesapeake Bay and tributaries. The present system consists of nine buoys, with a tenth scheduled to be deployed in May 2011. A map and location details are shown in Fig. 1 and Table 1, respectively.

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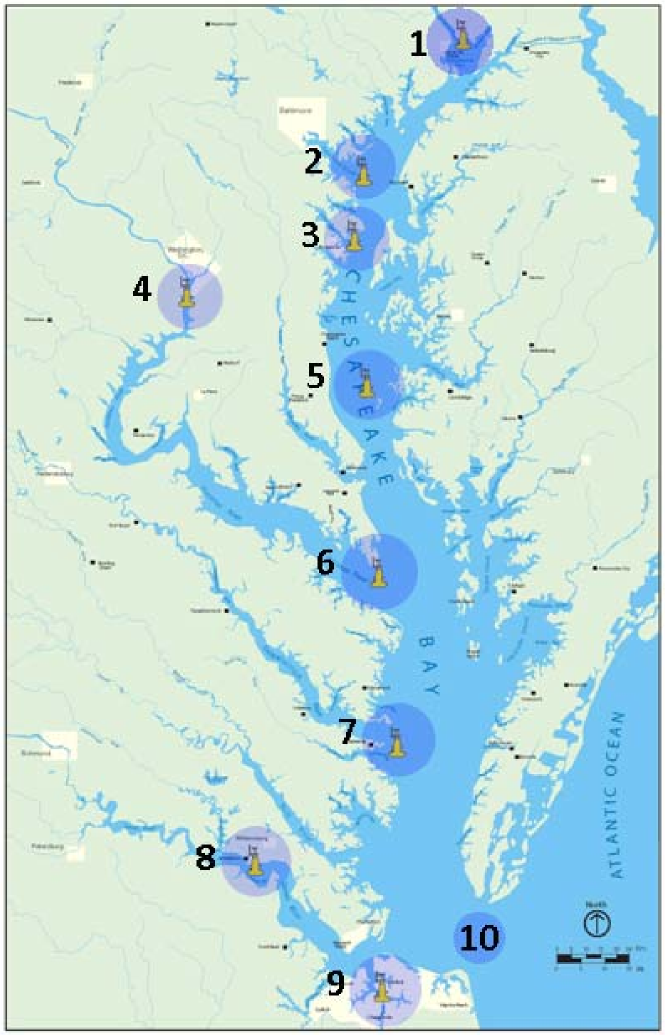

Figure 1. Location of the CBIBS buoys. See Table 1 for more information on individual buoys.

The CBIBS buoys are a standard AXYS Technologies Watchkeeper buoy, based on the Tideland Signal SB138P hull. The hull is made of three sections of 12 mm rotomolded polyethylene plastic, with aluminum frames for solar panels and instrumentation; the bottom hull section is ballasted with concrete and filled with expanded polyurethane closed cell foam. Buoys have a maximum diameter of 1.75 meters at the waterline and approximately 1 m draft and 3 m height above the water. A two point, 1.125" chain bridle with 2 m legs connects the buoy to a swivel above a 1" all chain anchor rode with 2.5:1 scope. Anchors are typically 3 steel railroad wheels, weighing approximately 1000 kg. Dry weight of a buoy less mooring hardware is approximately 600 kilograms.

Standard buoy instrumentation can be divided into packages, as referenced in Table 1.

- The Meteorology instrument package consists of an R.M. Young 5103 Wind Speed and Direction sensor; a Rotronics MP101A Air Temperature and Relative Humidity sensor; a Vaisala PTB101 barometric pressure sensor; and a KVH C100 compass.
- The Water Quality instrument is a WETLabs WQM water quality meter with integrated Seabird pumped Temperature, Conductivity, and Dissolved Oxygen sensors, and WETLabs FLNTU Turbidity and Chlorophyll-A sensors.
- The Current Profile instrument is a NORTEK AquaDopp 1 mHz acoustic current profiler. Both the WQM and the AquaDopp are mounted below the waterline in 250mm diameter PVC through-hull "moon pools" for easy access from the surface.
- The Waves measurement instrument is an AXYS Technologies TriAXS OEM wave module mounted over the buoy centerline approximately 500 mm above the waterline. The Gooses Reef buoy uniquely uses a YSI 6600 water quality instrument for both buoy- and bottom-mounted measurements; bottom data are transmitted to the buoy using a pair of WFS Technologies radio modems.

Data collection is controlled by an AXYS technologies Watchman 500 controller, and transmitted to shore at 10 minute intervals using fixed-IP Sierra Airlink Pinpoint X modems on the Verizon wireless CDMA network. Data are collected using the AXYS DMS running on a commercial 'virtual' server system and downloaded to an MS SQL data base. XML-based Web Services connect this data 'back end' to data management 'middleware'. A Data Archive Handler performs transformations and preliminary QA/QC checks and stores the data. A Data Retrieval Handler interfaces with Storage and provides external and internal access to the data. The middleware contains an OpenDAP server, access to external data sources, and a Client Data Request Handler. Typical requests include browser based or designated users (e.g., the Verizon voice IVR, NWS, CBOS, applications including Android and Iphone, and kiosks) via an API key. For internal management, applications provide notification for off-line buoys, erroneous sensors, or deviations from a geographic location ('anchor watch'). The system also supports applications for data delivery through RSS feeds and widgets, or any XML requests. Several free-standing kiosks – one actually duplicating the look of the buoy - featuring an audio and touch screen interface have been implemented at museums and parks near the buoy locations.

Web access to the buoy system is through the site http://www.buoybay.org . From this location users can access the data in graphical or tabular form and discover other applications, including CBIBS educational resources, interpretive information, "dial-a-buoy" access to data via 1-877-BUOYBAY, and social media (e.g., Facebook) sites related to CBIBS.

TABLE 1. INFORMATION ON INDIVIDUAL BUOYS IN THE CBIB SYSTEM .

Figure 1 Reference	USCG Designation	Name	Date Established	Latitude North	Longitude West	Water Depth Feet	Instrument Packages
1	S	Susquehanna	2008	39° 32.541'	76° 04.495'	25	B
2	SN	Six Foot Knoll	2007	39° 09.114'	76° 23.466'	21	A
3	AN	Annapolis	2009	38° 57.762'	76° 26.820'	22	A
4	UP	Upper Potomac	2010	38° 47.256'	77° 02.136'	20	B
5	GR	Gooses Reef	2010	38° 33.378'	76° 24.876'	37	C
6	PL	Point Lookout	2007	38° 01.980'	76° 20.124'	45	A
7	SR	Stingray Point	2008	37° 34.032'	76° 15.444'	23	A
8	J	Jamestown	2007	37° 12.246'	76° 46.626'	45	A
9	N	Norfolk	2008	36° 50.682'	76° 18.024'	12	D
10		*TBD*	*2011*	*In the vicinity of the Chesapeake Bay entrance*			

Instrumentation Code Key
A Meteorology, Water Quality, Waves, Current Profile
B Meteorology, Water Quality, Current Profile
C Meteorology, Water Quality, Waves, Current Profile, Bottom Water Quality
D Meteorology, Water Quality

II. WAVES AND CURRENTS INTERCOMPARISON EXPERIMENT

There was little information available about the performance of the TRIAXYS OEM wave module mounted on the relatively large and heavy Watchkeeper buoy in measuring the short (2-4 sec period) and small amplitude (0 – 2 m) wind waves typically seen in the Chesapeake Bay. Yet with a large proportion of our users using the real-time wave information to make decisions on the safety of small boat activities, the ability to discriminate wave characteristics in this range was important. Similarly, there was also little information on the quality of current profiles collected from a surface buoy. n order to evaluate the performance of the TRIAXYS OEM wave module and the NORTEK AquaDopp current profiler, we conducted a comparison with wave and current data collected at the same location using a stationary bottom-mounted instrument.

A 1mHz NORTEK AWAC AST (with Nortek Internal Processor disabled) was deployed looking upward in a gimbaled MSI trawl-resistant frame within 20 m of the SN CBIBS buoy near the mouth of the Patapsco River off Baltimore, MD. Current measurement setup was 0.45 blanking, 100 cm bin size, with ensembles of 55-ping 1 Hz sample recorded every 60 seconds. Wave measurement setup used 2048 samples at 2Hz starting top of each hour.

The standard CBIBS buoy setup was used for waves: 20 minutes of 4Hz sampling with the TRIAXYS module, starting at 35 minutes after the hour. Wave information was evaluated by the TRIAXYS processing system, and the following results are transmitted hourly: Mean, Maximum, and Significant Wave Height; Mean Wave Direction; Mean Wave Period; and Wave Direction Spread. For this experiment, the NORTEK AquaDopp reported 10 minute averages if 1Hz data collected between :45 and :55 minutes after the hour. The profiler head is located at 0.5 m below the buoy waterline, the blanking distance is 0.55 m, and 100 cm bins are used. In standard operating mode, the Watchman controller collects single ping data and performs ensemble averaging, reporting means for each bin. In this experiment, 80 mb of extra memory was added to the Aquadopp so that all pings could be recorded for post-processing as well.

The AWAC platform was deployed on 27 March, 2008 and recovered on 30 April, 2008. All instruments performed well. Fig. 2 shows how the bin locations of the AquaDopp and the AWAC were aligned. In this water depth the AWAC should measure even the smallest waves with little attenuation; the only introduced difference was in the mismatch of wave sampling times of approximately 30 minutes, which might have an effect on comparisons of the smaller or rapidly changing wave fields.

III. ANALYSIS AND RESULTS

A primary question was: Is the Platform / Controller / Sensor configuration capable of measuring currents and waves accurately? Is that accuracy enough for our purposes? Our first test was to see how the averaging performed by the Watchman on the single-ping AquaDopp data compared to similar post-processing averaging performed on the recovered data.

A. Currents

Fig. 3 shows the comparison between Bin 2 Watchman calculated and post-processed 10-minute mean values of the northward (principal) component of velocity. Fig. 3A shows the entire record; Fig. 3B is an expanded section around 6 April, when several small deviations occurred. The RMS

Figure 2. Relative locations in the vertical of AWAC and buoy AquaDopp velocity bins.

difference of 815 Bin 2 values is 0.003 m/s, which includes 10 interpolated Transmitted values. Bins 3-5 showed similar agreement. The Bin 1 comparison revealed a problem, as seen in Fig. 3C. The transmitted value was half the post-processed value. Further investigation found a coding error in the AquaDopp device handler in the Watchman – the mean was being calculated using 2N in Bin 1 only – which was

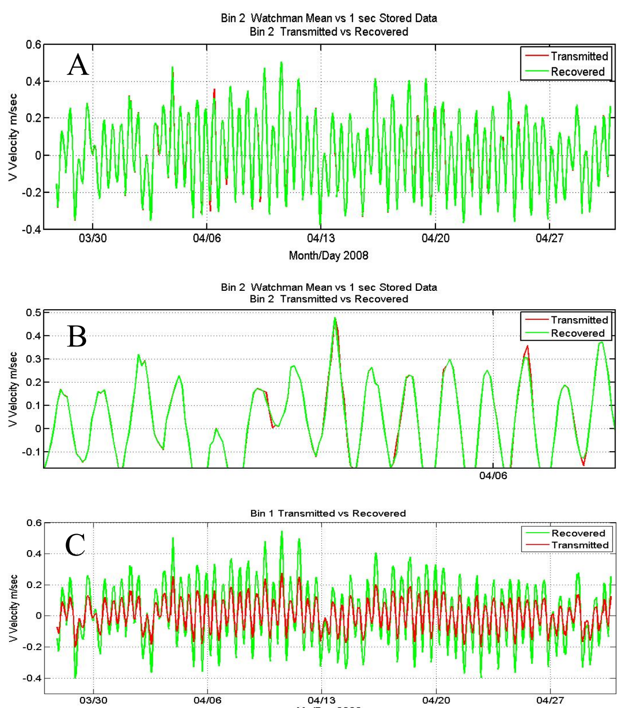

Figure 3. Bin 2 Watchman-calculated and post-processed 10-minute mean values of the northward (principal) component of velocity. A) Entire record; B) expanded section around 6 April; C) Bin 1 amplitudes.

subsequently corrected in all buoys and reported to AXYS. Our first analysis proved that the current data transmitted accurately reflects the data being collected, and the corrected bins 1-5 buoy data can be used in further comparisons with AWAC data.

A preliminary gross comparison between 10-minute averages of AWAC and buoy data was estimated by performing a basic tidal analysis on the relatively short (33 day) tidal harmonic analysis of both records. Using 5 basic constituents(O1, K1, N2, M2, S2) we compared percent of variance explained and the orientation of the principal axis of the tidal ellipse, the latter being the more robust measurement. Results are shown in Table 2; note that comparisons go as AWAC Bin 1 to Buoy Bin 4, A2-B, A3-B2, and A4-B1. The result is a good overall evaluation of the accuracy of the 10-minute average direction estimates, at least for the strongest tidally forced currents.

Statistical comparisons of individual 10-minute bin-by-bin current magnitude and direction values measured by the AWAC and the buoy were also compared. A comparison of velocity magnitude from AWAC Bin 4 and Buoy Bin 1 is shown in Fig. 4a. The mean difference for this pair was 0.001 m/s with a standard deviation of 0.022 m/sec. Mean and standard deviations for all bins are shown in Table3. it is fair to say that absolute differences in magnitude among 10 minute means of AquaDopp and AWAC currents are less than 0.005 meters/second, with standard deviations of 0.02 - 0.03 meters/second.

The comparison of velocity direction (in magnetic degrees) for the same A4-B1 pair are shown in Figure 4b, plotted against current velocity magnitude. Agreement improves dramatically above about 0.10 m/s; Fig. 4c shows an expanded scale for velocity magnitudes greater than 0.10 m/s, showing that they continue to increase with increasing speed.

TABLE2. CHARACTERISTICS OF TIDAL ANALYSES OF CORRESPONDING BINS OF AWAC AND AQUADOPP CURRENT VELOCITIES

Source	%Tidal Var	Axis °M	Source	%Tidal Var	Axis °M	Axis Diff.
			AWAC Bin 5	68.4	12.6°	
Buoy Bin 1	76.7	11.3 °	AWAC Bin 4	80.7	10.3°	1.0°
Buoy Bin 2	79.7	11.8 °	AWAC Bin 3	84.7	11.5°	0.3°
Buoy Bin 3	81.8	14.7 °	AWAC Bin 2	80.1	13.9°	0.8°
Buoy Bin 4	75.4	17.5 °	AWAC Bin 1	73.6	15.9°	1.6°
Buoy Bin 5	76.8	19.2 °				

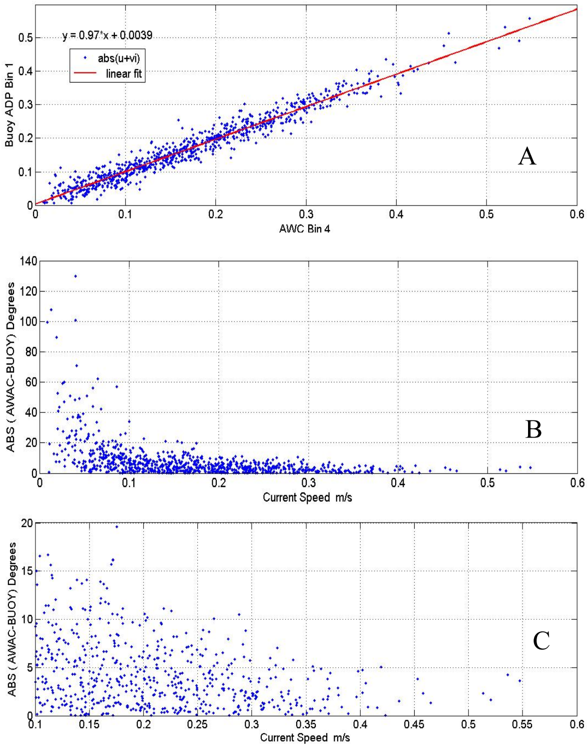

Figure 4. Comparison of velocity magnitude (4a) and direction (4b) from AWAC Bin 4 and Buoy Bin 1. Fig. 4c includes only speeds > 0.1 m/s.

Table 4 summarizes the absolute differences in direction by bin pairs. The first mean value is of all the absolute differences for speeds exceeding 0.10 m/s; and the third is the arithmetic mean (not absolute values) of the differences where speed exceeds 0.10 m/s. By only including velocities in excess of 0.1 meters/second, direction errors were reduced by nearly one half.

One might suspect that the poorest agreement might correspond to the highest wave states and corresponding buoy accelerations. The AquaDopp records 1-second values of roll and pitch; using the sum of the squares of the roll and pitch values over each ten minute interval as a proxy for energetic buoy motion (as corroborated by comparison with hourly wave heights, Fig. 5a), we can evaluate the effect of motion on the direction error. The plot of absolute direction difference for the B1-A4 pair (where one might expect the largest buoy errors) shows no trend with buoy motion (Fig. 5b).

TABLE 3. COMPARISON OF VELOCITY MAGNITUDES BY BINS.

Bin Pair	Mean	Standard Deviation
AWAC4 – BUOY1	0.001 m/s	0.022 m/s
AWAC3 – BUOY2	0.005 m/s	0.025 m/s
AWAC2 – BUOY3	0.005 m/s	0.026 m/s
AWAC1 – BUOY4	-0.002 m/s	0.028 m/s

TABLE 4. SUMMARY OF DIRECTION DIFFERENCES BY BIN PAIRS. VALUES ARE EXPLAINED IN TEXT.

Bin Pair	Direction (Degrees)				
	Mean	Mean*	Mean**	Stdv	Stdv*
ABS(AWAC4 – BUOY1)	7.9	4.4	1.9	12.0	3.9
ABS(AWAC3 – BUOY2)	8.8	4.7	0.5	15.2	5.0
ABS(AWAC2 – BUOY3)	9.0	5.0	-0.8	13.6	5.5
ABS(AWAC1 – BUOY4)	10.1	6.7	-3.5	15.5	9.8

On a platform like a buoy with limited power, one cannot afford run the acoustic profiler longer than necessary. Fig. 6 shows the mean absolute velocity difference, for all 10 minute averages for all bin pairs, as a function of averaging duration in minutes. Following this analysis, the standard CBIBS averaging time for all buoy current measurements was reduced from ten to five minutes.

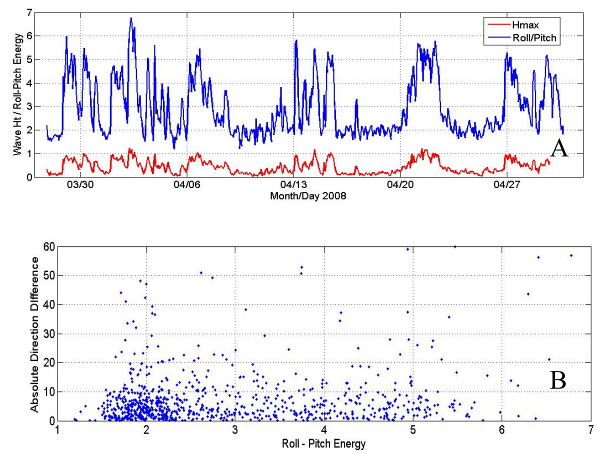

Figure 5. Effects of buoy motion on current direction measurement. A) Roll-Pitch energy as a proxy for wave height; B) AWAC-Buoy direction vs. buoy motion.

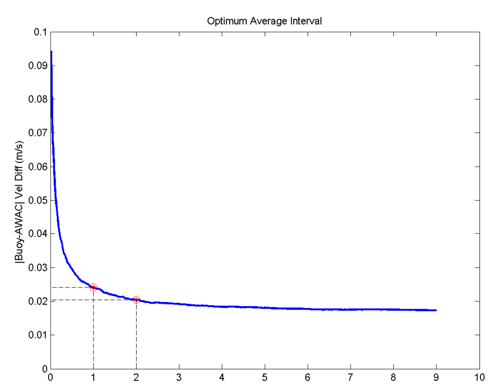

Figure 6. AWAC vs. Buoy velocity magnitude difference as a function of averaging length (one second values)

B. *Waves*

Typical Chesapeake Bay wind waves - .03 to 1.5 meters height, two to three second period - are difficult to measure with a heavy 1.75 m diameter buoy. But accurately distinguishing between 1 and 2 foot waves is important to many of the small craft boaters using the CBIB system. AWAC wave data were based on 2048 samples, 2 Hz (17 min) starting at the top of each hour. TRIAXYS wave data were based 20 min samples ending at the top of each hour. Contiguous (assigned to the top of the hour) TRIAXS-AWAC pairs are compared. Because of processing differences and the fact that only the final processed TriAXYS data were used, only a few wave measurements could be directly compared. Fig. 7a shows maximum wave heights from the two sources. Simply overplotting the heights shows excellent agreement at all values of wave height. Fig. 7b quantifies the relationship. Blue dots are all measurements; the linear fit to all data has a slope of 1.052 and an intercept of 0.02 m. To investigate possible bias due to the preponderance of low amplitudes, measurements were binned by 0.1 m bins and averaged (red dots); these values show no bias.

Both systems also measured mean wave direction; these are compared for all data in Fig. 8. In this plot, directional values of waves with a mean height greater than 0.3 m (1 foot) are shown as black dots. Linear fit to the mean directions from waves greater than 0.3 m gives an excellent fit (slope of 1.01) with an approximately 5 degree offset.

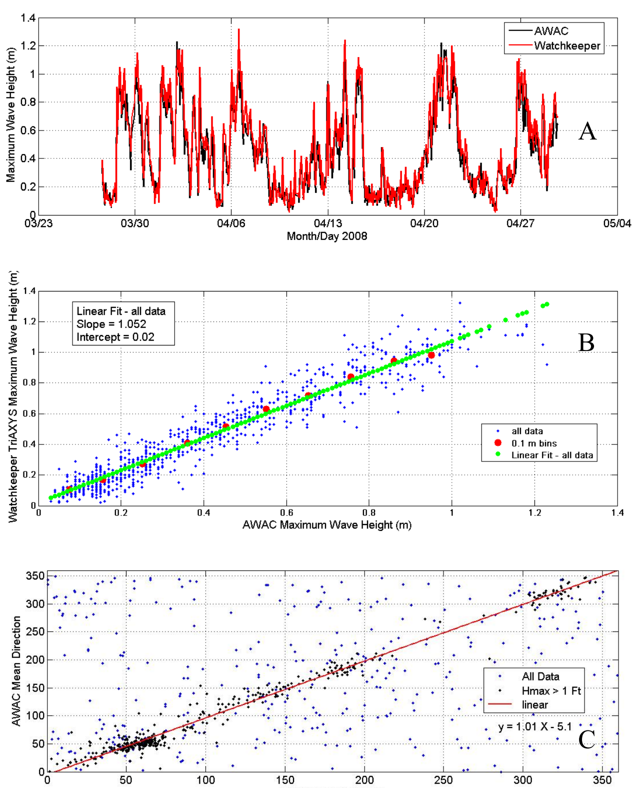

Figure 7. Comparison of AWAC and TriAXYS wave measurements. A) Maximum wave height; B) Maximimum wave height linear fit; C) Mean wave direction linear fit.

IV. SUMMARY AND CONCLUSIONS

The comparison of wave and current measurements between the fixed, bottom-mounted AWAC and sensors mounted on an adjacent buoy provided a needed verification of buoy results. We were able to deploy the two instruments in a manner that allowed direct comparison between the data sets. Comparisons showed that currents measured from an AquaDopp profiler mounted on a moving buoy were not significantly different from those measured from a fixed AWAC. Ten-minute averages from each instrument agreed to within better than 0.01m/s in each of the four tested bins. Further study of averaging length showed that close to maximum velocity magnitude accuracy was achieved in as little as 2 minutes. By several measures, directional agreement was within roughly 5 degrees. Magnitude agreement was little affected by current speed, but direction comparisons improved greatly when values with speeds less than 0.1 m/s were not included. However, buoy motion did not seem to have a significant impact on direction agreement.

The wave data comparison lacked adequate data for a rigorous study; only processed values from the two instruments were available, and processing methods differed greatly and resulted in somewhat different calculated values. However, two resultants of primary significance to us – maximum wave height and mean wave direction – could be directly compared. Both showed excellent agreement, well within our requirements. A future experiment to better compare wave results should be of longer duration – we have seen 3 m maximum waves in the CBIBS array, but only saw 1.2 m maxima during this deployment. It would also collect all high frequency sampling data in order to better compare derived parameters.

For the CBIB system, the study showed that wave and current measurements from a surface buoy more than met our requirements for accuracy. The additional difficulty and expense of maintaining a real-time bottom-mounted array is not necessary for this system.