Evaluating performance of acoustic current profiler sensor on small, dynamic surface buoy

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Abstract— **A sea surface following buoy equipped with a wave sensor and acoustic Doppler current profiler (ADCP) may be a useful system design option for many different coastal ocean measurement applications. However, previous work has shown that surface buoy-mounted ADCP current profile data can be negatively impacted by buoy motion in dynamic coastal environments. Between 2014 and 2018, a series of three field experiments were conducted at a site in the south Chesapeake Bay to evaluate the performance of acoustic Doppler current profilers installed on small, dynamic surface buoy platforms (< 2 m). The focus of this paper is on results from the third, most recent field experiment conducted during December 2017 – January 2018. This third experiment evaluates potential improvements offered by a new Acoustic Doppler Current Profiler (ADCP) with an integrated Attitude and Heading Reference Sensor (AHRS) and a real-time motion compensation capability. The improved ADCP with ARHS was installed on a small surface buoy in a downward looking configuration. The test buoy system was deployed at the Chesapeake Bay field site alongside a second, nearby ADCP system in a bottom mount serving as a stable reference. Results comparing current profile measurements from buoy and bottom mount sensors indicate significant improvement in the buoy mounted ADCPs performance as compared to the previous two field tests. A summary of the new ADCP instrument employed, measurement methods, field observations, and initial performance evaluation will be presented, along with plans for continuing system development and testing.**

Keywords*— *ADCP, surface buoy, currents, AHRS, bin mapping

I. INTRODUCTION

For nearshore ocean observing applications that require real-time current and wave measurements, a surface buoy platform with a wave sensor and acoustic Doppler current profiler (ADCP) may be the ideal system design option. However, previous work has shown that surface buoy-mounted ADCP current profile data can be negatively impacted by buoy motion in some dynamic, coastal environments. Between 2014 and 2018, a series of three field experiments were conducted to evaluate the performance of acoustic Doppler current profilers installed on small, dynamic surface buoy platforms (< 2 m diameter) at nearshore sites [1-5]. Results and conclusions from each experiment have led to successive modifications to the sensors employed, in an attempt to improve data quality for the system. All three experiments were conducted in the south Chesapeake Bay, eastern USA, in approximately 15 m water depth. Buoy-based current profiles were compared to reference current profiles from one or more bottom-mounted ADCPs. Results from the first two experiments (November – December 2014 and December 2015 – February 2016) have been reported previously (select references 1-3 are provided here). The focus of this paper is on the most recent field experiment results collected during December 2017 – January 2018.

In the first two experiments, the system tested consisted of a Nortek Aquadopp Profiler mounted on an AXYS Technologies TriAXYS wave buoy. Current profiles from multiple bottom mounted platforms with both Nortek and Teledyne RDI ADCPs were used as reference systems for comparison. NOAA applications of interest require reporting current profiles accurately representing 6 minute sampling periods. Previously reported results from these first two tests suggest that the of lack adequate buoy motion measurement and its compensation in real-time current profile measurements lead to inaccuracies in the current profiles from the buoy-mounted ADCP. This is in agreement with previous comparisons by other authors [6-11]. Additionally, it has been shown that these inaccuracies are accentuated during times of strong vertical shear and large buoy angular velocity due to inadequate sensor motion compensation and lack of real-time depth bin mapping of the ADCP data applied at the individual ping level.

The most recent field experiment reported here builds upon previous results. For this test, the buoy-mounted system includes a Nortek Signature Series profiler which is based on the AD2CP technology (US Patent 7.911.880). The system is capable of 16 Hz maximum ping rate with integrated internal Attitude and Heading Reference Sensor (AHRS), expanded memory capacity for single ping data storage, and full real-time vertical bin mapping based on the AHRS data.

Preliminary results from this most recent field experiment have been presented at recent conferences [4, 5]. This paper includes following analysis and further detail of results which indicate use of the ADCP with integrated AHRS and real-time bin mapping significantly improves the accuracy of current profile data measured from a small surface buoy platform.

II. METHODS

An ADCP uses its transducer geometry, the water's speed of sound, and the time between the transmit and received echo to time-gate each depth bin's distance along each beam. The vertical distance to each bin is then the projection of all beams onto the instrument's vertical axis.

For ADCPs mounted in a moving surface platform one cannot assume the flow to be homogenous across each depth bin over each measurement interval due to orientations changes within the measurement interval. This causes inaccurate velocity data when the along-beam depth bin moves up and down, referred to as the "smearing effect" (depicted in fig. 1). In addition, vertical shear can bias the resulting velocity because the depth bins move in and out of regions with variable velocity.

Two methods can be used, either together or independently, to address this breakdown in flow homogeneity across beams: 1) increase the averaging in space and/or time, either at the ADCP level or via low-pass filters in post-processing, and 2) mapping each bin to its proper vertical location by compensating for the instrument's orientation.

As demand increases for finer spatial and temporal resolution, particularly in the upper ocean, it is less desirable to use averaging routines to compensate for the impact of motion. While bin mapping of ADCP data has been available in most systems for over 20 years, it has usually been applied at the ensemble level because they lacked gyro-compensated embedded orientation sensors required for real-time bin mapping on a ping-by-ping basis. And, although bottom tracking can be used as a proxy for general orientation, it is also performed at the ensemble level and lacks the spatial resolution to determine accurate orientation.

The objective of the field test presented here is to demonstrate performance of an ADCP that employs a full bin mapping routine with orientation change compensation from an AHRS applied to each individual ping within the measurement interval.

III. FIELD TEST

A field test was conducted in the South Chesapeake Bay, from December 2017 - February 2018, to assess improvements resulting from use of an ADCP with a fully integrated, high accuracy AHRS sensor and a real-time bin mapping routine.

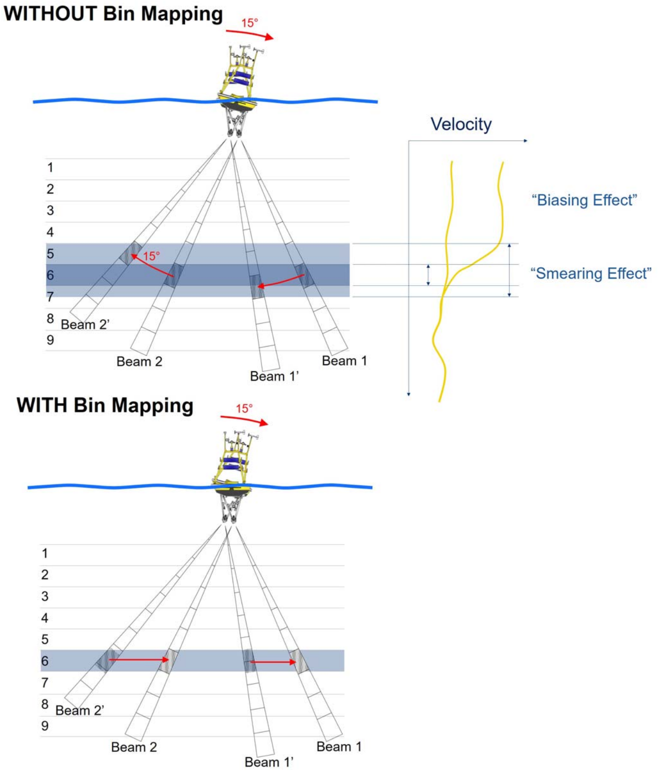

Fig. 1. Illustration showing of the impacts the "smearing effect" (top) and how bin mapping can mitigate the effect.

The sensor tested was a Nortek Signature1000 ADCP (1 MHz) with firmware modified to sample the AHRS output at the same rate as the acoustic ping rate, with precise synchronization. Based on previous test results [1-3], it was decided that initial testing of the new ADCP with AHRS would be with a basic, foam hull buoy. Test results are used to assess value of pursuing a following effort to integrate the enhanced ADCP with an actual wave measurement buoy (resulting in the same type of system used in previously reported tests).

The Signature1000 and external battery canister were installed in a 1.2 m ionomer foam buoy surface buoy. The sensor was mounted in a downward looking orientation, using the buoys built-in well and a PVC extension (figure 2). The same compliant mooring design as used for an AXYS TriAXYS wave buoy was used to allow freedom of motion so the test buoy would undergo surface following motions similar to the type of wave buoy used in previous tests.

The field test site location was at 37º 14.6745' N, 76º 05.0683' W, approximately 3.14 nmi (5.82 km) west of Cape Charles, VA (fig. 3). The site is very close to the same site of previous field tests and representative of a range of different nearshore observing sites of interest. The site has 15 m water depth and offers strong tidal currents, significant vertical current shear, and periods of energetic wind and waves during storm events.

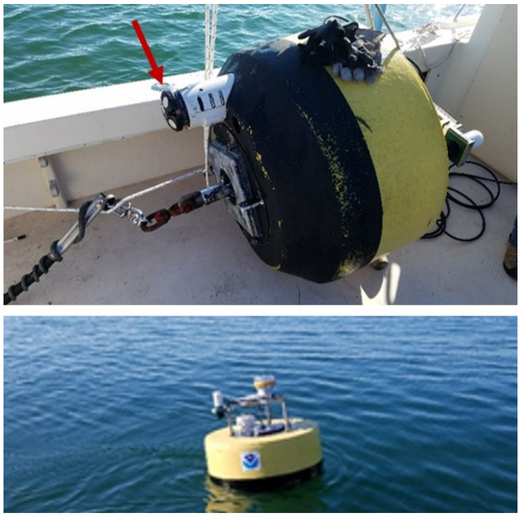

Fig. 2. Signature1000 mounted on small, surface buoy for initial test.

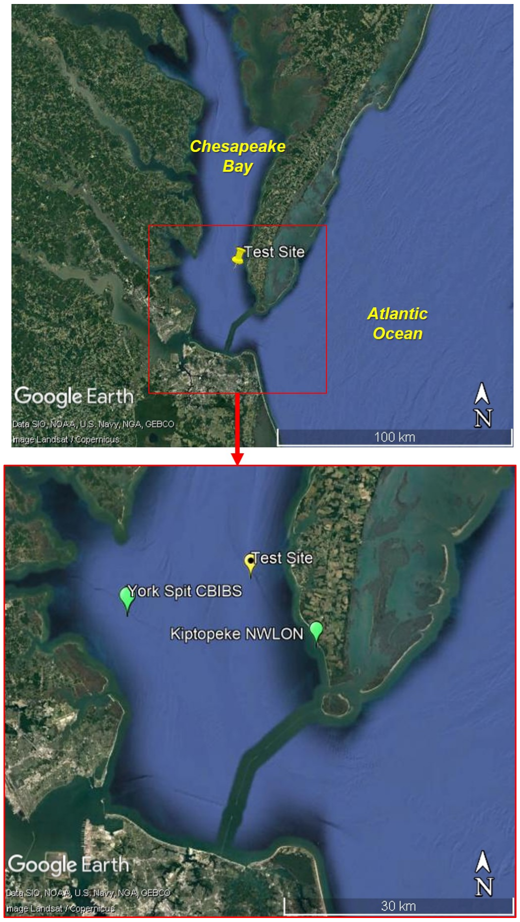

Fig. 3. Field test site.

A Nortek 1 MHz Acoustic Wave and Current Sensor (AWAC) was installed in a Mooring Systems, Inc Trawl Resistant Bottom Mount (TRBM) and deployed approximately 190 m north of the buoy as a source of reference measurements. The AWAC was configured to measure currents for 120 s every 180 s and had a wave burst interweaved with currents for 2048 points at 1 Hz every hour. The Signature1000 had two concurrently operating configurations: 1) 1200 pings at 8 Hz for 150 s every 360 s, with real-time bin mapping done on every ping, and 2) 150 pings at 1 Hz for 150 s every 360 s, with no bin mapping done (i.e. traditional ADCP configuration).

IV. RESULTS

A range of environmental conditions were experienced at the test site during the short test period. Figure 4 shows wind speed and air temperature from the two closest available NOAA stations: Kiptopeke, Virginia National Water Level Observation Network (NWLON) station (winds) and the York Spit Chesapeake Bay Interpretive Buoy System (CBIBS) station (air temperatures) along with significant and maximum wave heights measured by the reference AWAC sensor. During the test, the site experienced several storm events with winds exceeding 15 m/s and significant wave heights exceeding 2 meters; and one major winter storm event occurred, starting on January 3, when winds exceeded 20 m/s and significant wave height reached 4 m. Winds remained over 15 m/s for several days and temperatures also remained well below freezing during the event, ranging from -5 to - 10 degrees Celsius.

Time series of the Signature1000 tilt, pressure and heading shown in figure 5 indicate the buoy experienced a relatively high range of motion in response to varying wind and wave conditions, resulting in an excellent data set for initial assessment of the Signature1000 real-time bin mapping capability. During the major storm event starting on January 3, the Signature1000 data indicates the buoy fully tilted over at least once, undoubtedly due to the strong waves, winds and ice weight on the superstructure. The buoy was able to right itself back to the proper orientation within about 10 minutes however, as confirmed by acoustic signal strength data shown in figure 6. Each panel in fig. 6 corresponds to a 1200 sample bursts collected at 8 Hz. The left panel shows a normal SNR data pattern, the two middle panels shows the time when the instrument flipped, and then the rightmost panel again shows a normal SNR pattern, indicating the sensor returned to its proper, downward looking orientation.

Pressure readings from the bottom mounted AWAC indicate the water column depth above the sensor averaged approximately 15 m with depths varying over a 1.5 m range throughout the test. Profile measurements from the buoy mounted Signature1000 were depth interpolated to the vertical bins of the AWAC sensor, which remained fixed relative to the sea floor. Each Signature1000 six minute vertical current profile was interpolated individually. For each, the known Signature1000 transducer depth below the sea surface and the most recent AWAC water depth reading were used to estimate the vertical separation between the two sensors' range bins. Next, the Signature1000 profile measurements were interpolated to the AWAC bin depths using a basic linear interpolation function in Matlab.

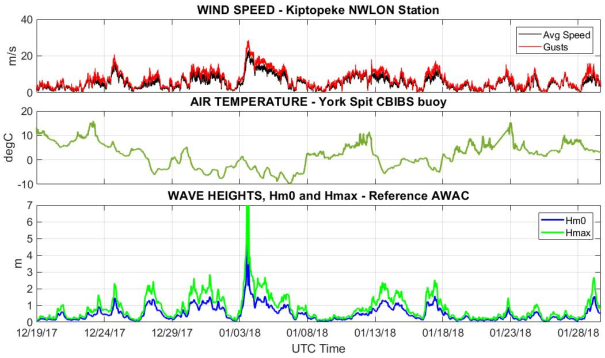

Fig. 4. Winds and air temperatures during the field test, measured at nearby NOAA systems.

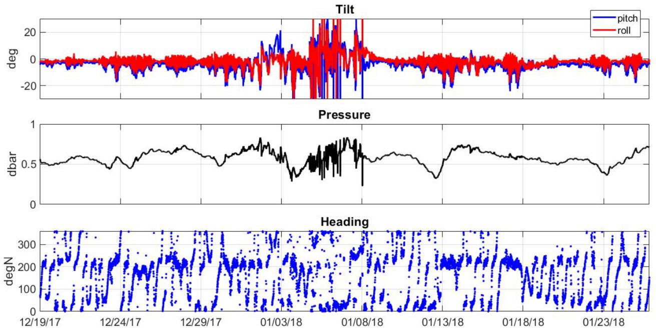

Fig. 5. Six minute average motion data from the buoy mounted Signature1000 sensor.

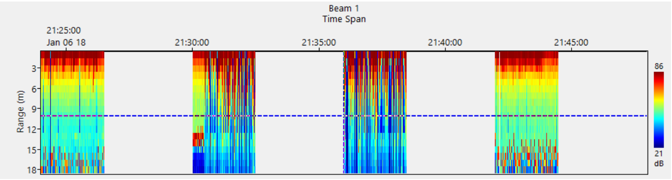

Fig. 6. Four 1200 sample bursts of acoustic SNR showing time of buoy capsize event during the winder storm.

Initial comparisons of Signature1000 vs AWAC current magnitude indicate significant improvement in the buoy mounted sensor's performance as compared to previous tests. Figure 7 (a) shows Signature1000 vs AWAC depth averaged (2 - 14 m above the seafloor) current magnitude. Data points during the onset of the January 3 winter storm, when it is known the buoy underwent extreme motions, are marked in red. Figure 7 (b) shows a similar plot, but from the 2014 field test: the Aquadopp (buoy mounted) versus AWAC (bottom mounted) depth averaged currents. Figure 8 shows the distribution of differences between the two sensors current magnitudes (Signature1000 - AWAC magnitudes, shown in blue), along with similar results from the 2014 field test (Aquadopp – AWAC, shown in red). Comparison of 2014 and 2018 buoy versus bottom ADCP differences in fig. 7 and 8 indicate significantly improved performance of the buoy mounted sensor during the 2018 field test. The difference in buoy Signature1000 versus bottom AWAC measured current magnitude root mean squared difference is 3.1 cm/s and differences remained less than 5 cm/s for more than 95% of the test period.

Figure 9 shows the Signature1000 - AWAC difference in depth average current direction. Results compare reasonably well, however there is a mean directional offset between the two sensors of approximately 8.1 degrees. This offset is also reflected in tidal current harmonic analysis results shown below. Continuing analysis will involve closer investigation into this direction difference.

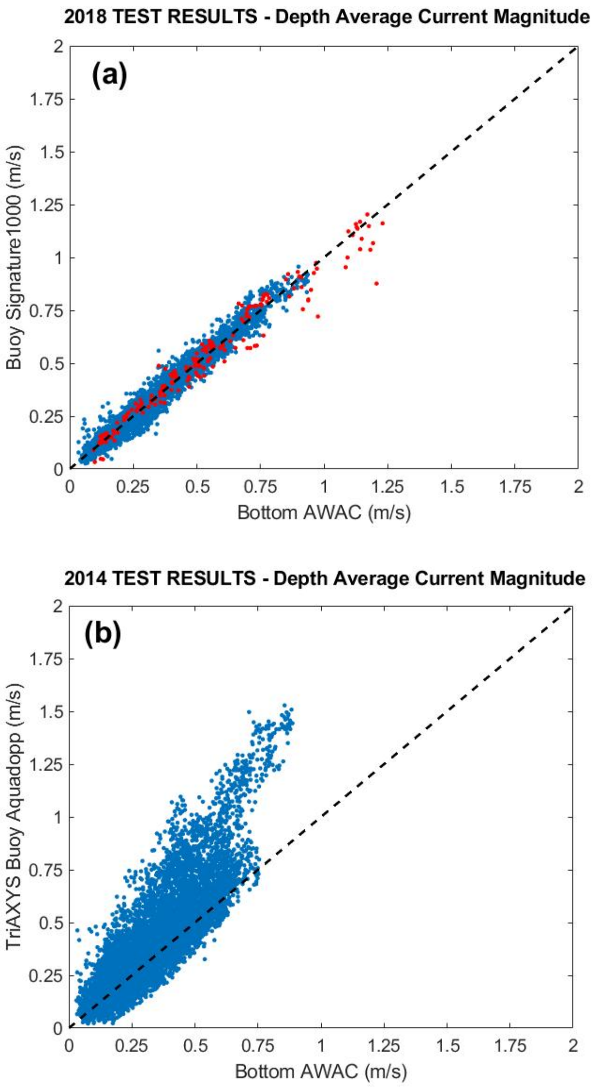

Fig. 7 Buoy mounted ADCP – bottom ADCP difference in depth average current magnitude, (a) 2018 field test results and (b) 2014 field test results. Red points in (a) are data taken during the January winter storm.

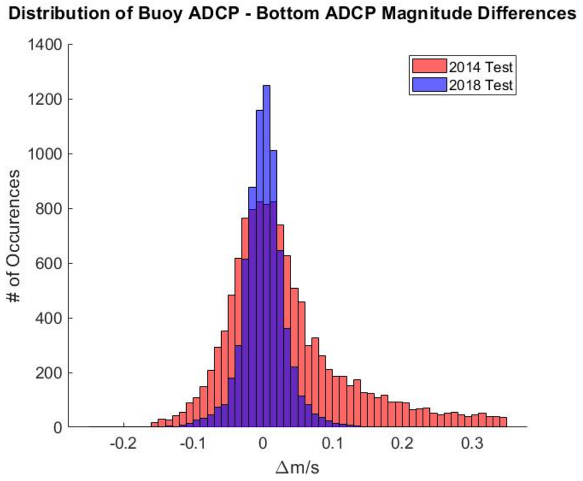

Fig. 8. Distribution of buoy mounted ADCP – bottom ADCP difference in depth average current magnitude, 2018 field test results (blue) and (b) red.

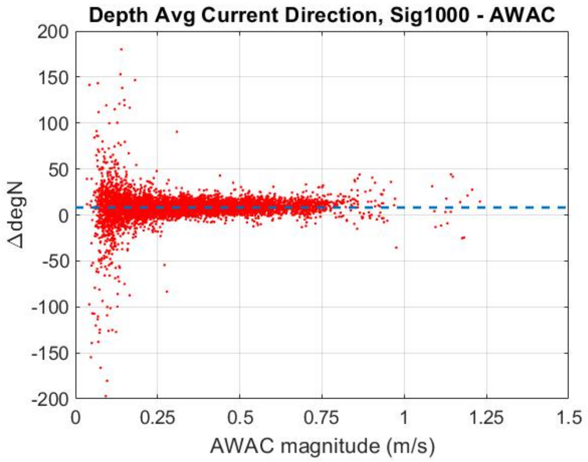

Fig. 9. Signature1000 – AWAC difference in current direction versus current magnitude.

As reported in previous, 2014-2016 test results, measurement error from the buoy mounted ADCP without real-time bin mapping is most pronounced during times of high vertical shear, as a result of the "smearing effect" illustrated in figure 1. During the 2018 test, once again, periods of shear were experienced at the test site, when northward velocity increases with depth. There were no large increases in the buoy mounted versus bottom mounted ADCP measurement deviations during periods of higher shear, as was seen in 2014 and 2015 field tests [2, 3].

Figure 10 shows vertical shear during the 2018 field test estimated as the difference between AWAC measured currents speeds at 13 m and 3 m above the sea floor. Figure 11 shows examples of the north component current profile plots from both the bottom AWAC (top) and buoy Signature1000 during one period of high shear (marked red arrow in fig. 10). The profiles compare very well and show improvements over results from the 2014 field test as a result of the AHRS and bin mapping capability (similar buoy versus bottom ADCP results during period of high shear shown in fig 12).

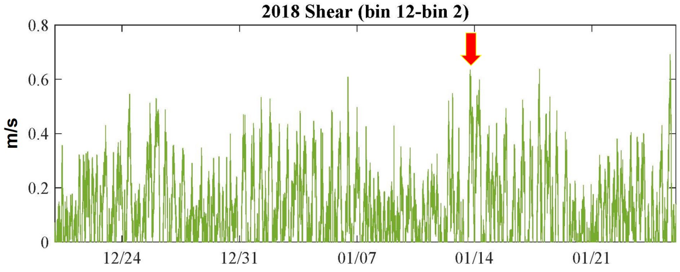

Fig. 10. Vertical current shear estimated by subtracting AWAC measured currents at 13 m and 3 m above the sea floor.

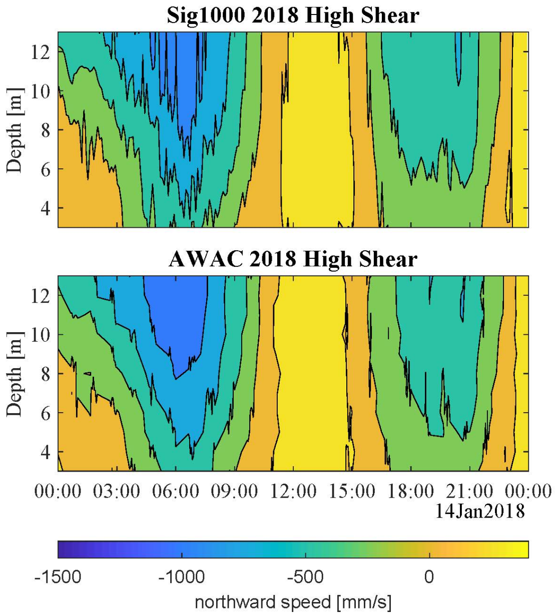

Fig. 11. North component current profile from bottom AWAC (top) and buoy mounted Signature1000 during corresponding to time of high shear marked by red arrow in figure 10.

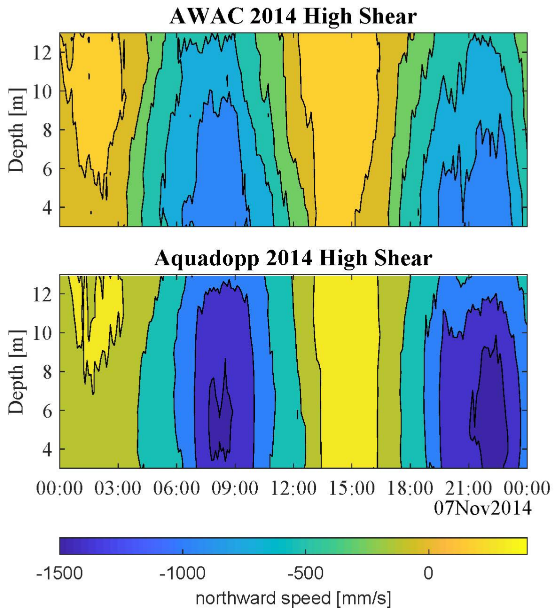

Fig. 12. Similar result as fig. 10, but from the 2014 field test. North component current profile from bottom AWAC and buoy mounted Aquadopp

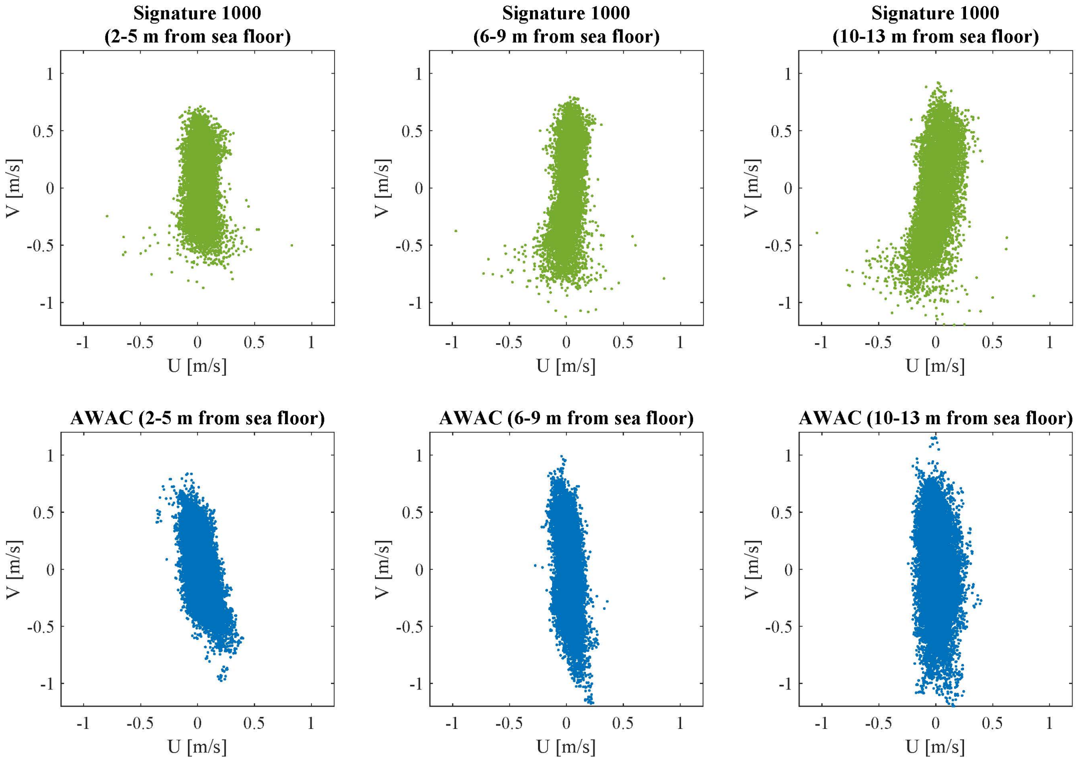

Fig. 13. U-V Scatter plots for buoy mounted Signature 1000 (top) and bottom AWAC (bottom) averaged over near bottom (left), mid depth (middle) and near surface (right) bins.

TABLE I. TIDAL HARMONIC ANALYS RESULTS OBTAINED WITH T_TIDES

	Signature 1000					**AWAC**			
Constituent	**Major axis (m/s)**	**Minor axis (m/s)**	**Ellipse orientation (degN)**	**Constituent phase**		**Major axis (m/s)**	**Minor axis (m/s)**	**Ellipse orientation (degN)**	**Constituent phase**
M2	0.429	-0.023	355.14	63.82		0.441	-0.020	4.688	63.09
N2	0.112	-0.003	354.69	31.72		0.110	-0.001	5.670	29.37
S2	0.066	-0.004	355.21	88.79		0.074	-0.002	4.033	90.76
K1	0.066	-0.003	350.54	223.21		0.066	0.000	2.515	222.51
O1	0.055	-0.006	352.90	219.63		0.057	-0.003	1.211	217.78
	% of Variance from Tidal Constituents	**82.1%**				**% of Variance from Tidal Constituents**	**84.10%**		

One common NOAA application for nearshore current profiles measurements is tidal current analysis and predictions derived from harmonic analysis. The publically available Matlab implementation of the T_TIDES software tool [12] was used to conduct harmonic analysis on data collected from both buoy and bottom ADCPs to generate example tidal analysis products for comparison.

Scatter plots of North (V) and East (U) current components for bottom, mid, and surface water column from both sensors (fig. 13) provide a first indication of the tidal flow pattern. Scatter plots for both sensors were generated using the depth interpolated version of the Signature1000 data (described above) so all data are aligned with the bottom AWAC sensor depth bins. Table 1 shows harmonic analysis results from both sensors for the first 5 tidal constituents, including magnitude of major and minor ellipse axes, axes orientation, phase and total percentage of the measured variance that is associated with the tidal constituents. Most tidal analysis results between the two sensors compare very well: total tidal variance is within 2 %, constituent magnitudes are all within 1.5 cm/s, constituent phases are within 4 degrees However, direction of major ellipsoid axes range from approximately 8-11 degrees, which is not surprising considering the mean difference between the two sensors current directions noted above.

Ongoing data analysis includes closely evaluating the impact of full AHRS bin mapping on measured current profiles. Raw recorded data from the AHRS were used to reprocess velocities three ways. This reprocess was possible because the AHRS is comprised of not only accelerometers and magnetometers (used in standard compass and tilt sensors in most ADCPs), but also a gyro sensor, which thus allows the AHRS to differentiate between the acceleration due to gravity from the acceleration due to normal motion. With all three sensor's 3D data available for every ping, reprocessing can simulate how the 2018 field test data would result if a standard ADCP configuration were used (non-gyro compensated compass and tilt sensor). The three different reprocessing methods applied to raw data:

1. Bin mapped, using the full AHRS Heading/Pitch/Roll values (equivalent method of all processed 2018 data shown above).

2. Bin mapped, using simulated "standard" Heading/Pitch/Roll values (equivalent to having a "standard" compass and tilt sensor in the Signature1000, instead of an AHRS).

3. Not bin mapped, using only known bin range from sensor transducer (equivalent to method used with Aquadopp on TriAXYS buoy in previous tests).

Full evaluation of reprocessed raw data remains a work in progress at the time this paper was submitted. More details will be presented at the associated October 2018 conference. Here, we show one particular example of north component currents reprocessed from a single ensemble burst (Fig. 14). The period selected is from 12/25/2017 when significant wave heights exceeded 1.5 m. An initial look at results indicates a significant difference in velocities resulting from full AHRS bin mapping. Continuing analysis will further summarize and quantify the impact of improved full AHRS processing over a range of different test site conditions.

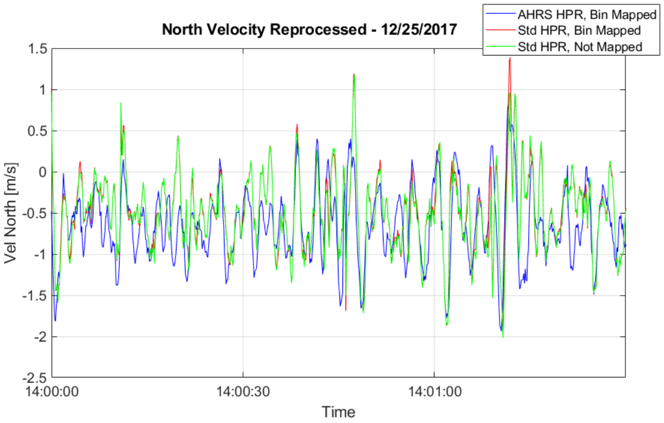

Fig. 14. Example of 90 s sample of data for period with high sea station reprocessed using the 3 difference ways described above

V. SUMMARY AND FUTURE WORK

Many different nearshore ocean observing applications require real-time measurements of waves and near surface current profiles. The system consisting of a small surface following wave buoy and integrated downward looking ADCP sensor offers a convenient and practical field observing option. However, previous test results indicate that inadequate motion compensation of the ADCP sensor will result in significant error in current profile measurements, in particular when a relatively short sampling interval is used (6 minutes) and the buoy undergoes significant orientation changes.

Latest field test results collected with a new and improved ADCP with AHRS and real-time bin mapping capability indicate significant improvement of the buoy mounted ADCPs performance as compared to previously reported test. Many of the measurement issues associated with the buoy mounted ADCPs reported in 2014 and 2015 field tests have been addressed by the improved, high frequency orientation compensation.

Continuing work will include further analysis of reprocessed raw data to better quantify the impact of additional motion compensation employed by the buoy mounted sensor in the most recent, 2018 field test. Also, improved results presented here will likely lead to integration of the Signarure1000 with an actual wave measuring buoy. The latest status of this system integration and testing will be reported at the associated October 2018 conference.

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