Enhancing the accuracy of current profiles from surface buoy-mounted systems

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***Abstract*— The present work focuses on improving motion compensation in current profile data from surface buoys by integration of an Attitude and Heading Reference Sensor (AHRS) to a state-of-the-art Acoustic Doppler Current Profiler (ADCP), thus expanding its use into applications where fine spatial and temporal resolutions are desired. Presently, the applicability of surface buoy-mounted ADCPs is generally limited to those applications where spatial and temporal averaging are acceptable methods to address motion concerns. However, the increasing demand from both the research and operational communities for ever finer resolution in space and time is rendering averaging as an unacceptable method for these type of deployments. But recent technological advances in miniature motion sensors (improved accuracy and resolution, and reduction in physical size, power consumption, and cost) promises to address some of the earlier concerns with surface buoy-mounted ADCPs by enabling real-time bin mapping at the individual ping level. Additionally, these advances allow for more precise validation of surface buoy-mounted ADCP data against static-mounted reference systems.**

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

I. Introduction

Starting in the mid-1980s researchers successfully deployed self-contained ADCPs on mooring lines [1] as well as on the top float of subsurface moorings [2-3]. Following on these experiences, ADCPs were subsequently deployed from surface moorings, either on the surface buoy itself, or in cages immediately below the buoy [4-6].

The benefits of mounting ADCPs in surface buoys were readily recognized, including: easier access for maintenance, simpler infrastructure required to send real-time data to telemetry systems on the buoy, and ability to measure long time-series of near surface currents and current profiling from a single instrument. However, it was also recognized that surface buoy-mounted ADCPs also suffered from issues not generally faced when deployed on bottom frames or more stable subsurface buoys [7-9], including: wave-induced vertical velocities, rapid instrument rotation rates, dynamic attitude variations, interference from near surface bubbles, velocity bias due to plankton migration and pelagic fish interference.

Throughout the 1990s and into the 2000s, several studies were carried out to validate current profile data collected from surface buoys through comparisons with reference systems (such as Vector-Measuring Current Meters or bottom-mounted ADCPs) as well as against theoretical values [10-17]. In general these studies report agreeable comparisons. However, due mostly to lack of surface buoy motion measurement and compensation, they almost exclusively focused on large spatial and temporal scales (e.g. horizontal scales of hundreds of m to few km; vertical scales of several meters; temporal scales of few to several hours or even days). So while some of the previously mentioned issues were dealt with by averaging in space and time, the technology available has been insufficient to address all concerns, especially for studies requiring finer spatial and temporal resolutions.

More recently, work done in two separate deployments within the Chesapeake Bay, USA [18-20], suggested that the lack of buoy motion measurement and compensation, coupled with inadequate bin mapping, leads to inaccuracies between surface buoy-mounted ADCPs and collocated reference systems, in particular when the ADCP is to be mounted on smaller (under 2 m diameter) wave riding buoy platforms. This is especially the case during times of strong vertical shear and large buoy angular velocity. The present work builds upon these previous experiences to test and validate this conclusion, especially as it pertains to deployments on smaller buoys, as most previous works have focused on large (> 3 m diameter) buoys.

II. Method Description

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. Standard ADCP processing assumes the flow to be homogenous across each depth bin over each measurement interval, conceptually illustrated in Fig. 1.

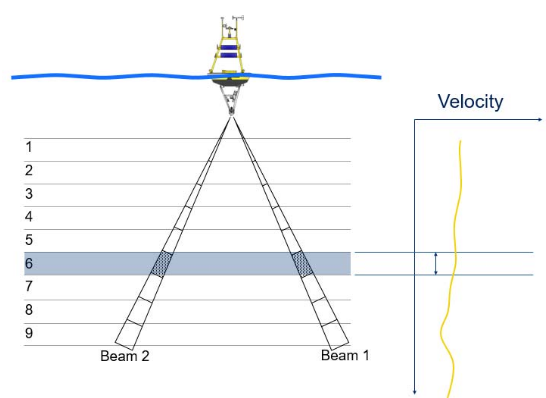

Fig. 1. General concept for how a standard ADCP operates. The assumption is that, on average, flow is homogenous across all beams for a given depth.

This assumption often holds true for bottom-mounted, up-looking systems as the ADCP typically observes minimal to no orientation change within the averaging interval. For ADCPs mounted in dynamically moving surface platforms, this assumption can break down due to orientation changes within the measurement interval. This results in a "smearing effect" on the velocity data caused by the along-beam depth bin moving up and down the water column proportionally to the buoy's orientation. Furthermore, if there is strong vertical shear in the water column, the resulting velocity can also be biased as the depth bins are constantly moving in and out of regions with variable velocity (Fig. 2).

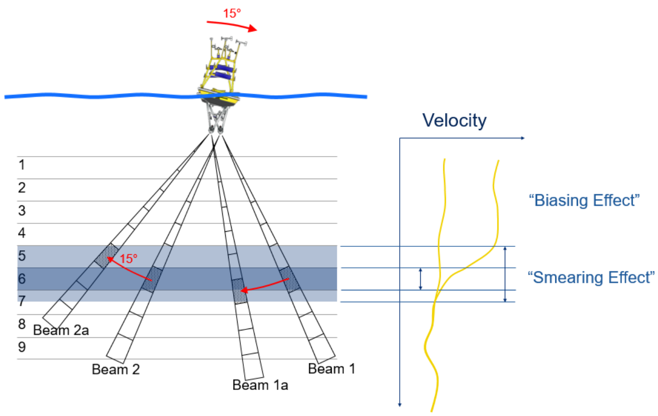

Fig. 2. Illustration of "smearing effect" and velocity bias caused by the ADCP's orientation change during the measurement interval. In this example, an orientation change causes the bins along some of the beams to be moved lower in the water column than they should be, while others to be moved higher than they should be, thus resulting in a "smearing effect" on the data. And, in the presence of vertical shear, this also introduces a bias on the data.

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 (Fig. 3). With the increasing demand from the research and operational communities for ever finer spatial and temporal resolution, especially in the upper ocean, averaging routines often used to compensate for the impact of motion in the velocity data are becoming less and less desirable. Additionally, although the bin mapping of ADCP data has been available in most systems for over 20 years, this process has so far been applied at the ensemble level, mostly because ADCPs have up to now lacked embedded orientation sensors capable of the time response, accuracy and resolution required for real-time bin mapping on a ping-by-ping basis as required for proper compensation. Although conceptually Bottom Tracking can be used as a proxy for the instrument's general orientation (in place of or in combination with the embedded tilt sensor), it is also performed at the ensemble level and lacks the spatial resolution to determine accurate orientation given its designed purpose is the measurement of horizontal displacement and not orientation.

III. FIELD VALIDATION

We propose that a proper bin mapping routine to compensate for orientation changes must be applied to each ping within the measurement interval, as the motion frequency negates compensation at the ensemble level. To test this hypothesis, a Nortek Signature1000 ADCP (Fig. 4) was fully integrated with an internal high accuracy, full 3D Attitude and Heading Reference Sensor (AHRS), capable of internal sampling rates in excess of 100 Hz, and deployed on a single point mooring surface buoy. The Signature1000's firmware was modified to sample the AHRS's rotation matrix output at the same ping rate the velocity is sampled. The details of this modifications are beyond the scope of this paper, but suffice to say that over a profiling range of 30 m, the difference between when the acoustic ping is in the water and the orientation is sampled is less than 30 ms. Precise synchronization is required because the lag between velocity and orientation measurements translates into discrepancies between where the ADCP computes the location of each bin, and their true location in the water column. This in turn drives the "smearing effect" and bias stated earlier.

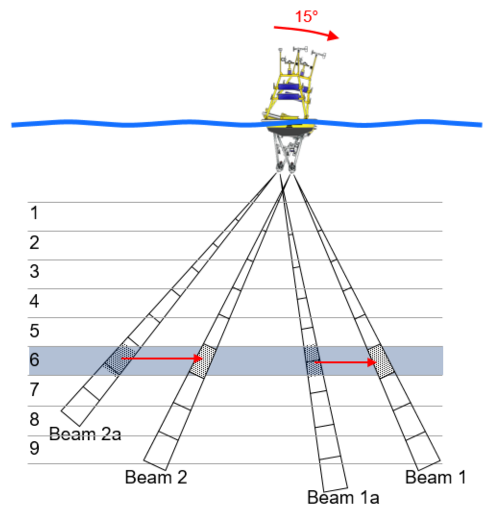

Fig. 3. When bin mapping is enabled, the location of each bin (depth cell) is shifted either up or down along each beam such that the resulting data comes from the proper depth.

Fig. 4. The Signature1000 is a 5-beam ADCP with optional embedded AHRS, 1000 kHz frequency and maximum sampling rate of 16 Hz.

The test deployment was conducted between December 2017 and February 2018 in the SE Chesapeake Bay, USA, in about 15 m of water, west of Cape Charles, Virginia (Fig. 5). This is the same location used in previous tests [18-20] and is an area known for strong tidal currents and pronounced vertical shear, as well as being subjected to large waves (> 3 m Hs) during winter months. The Signature1000 was mounted on a small ionomer foam surface buoy (1.2 m diameter; chine cut shape) on a well towards the edge of the buoy in a downward looking configuration (Fig. 6) and powered by an external battery canister in the buoy. As a reference, a Nortek AWAC 1 MHz ADCP was deployed on the seafloor in an upward looking configuration using a trawl resistant bottom mount, and installed around 190 m due north of the Signature1000 buoy. Both instruments set for 1 m depth bin sizes. For accurate comparison between the two systems, the dynamic Signature1000's bins were interpolated to the static AWAC bins by factoring in the tidal range (as measured by the AWAC's pressure sensor), assigning weights to each range, and also removing near bottom and near surface bins affected by sidelobe interference. This still allowed for no less than 11 bins of overlap between the two systems at all times (Fig. 7).

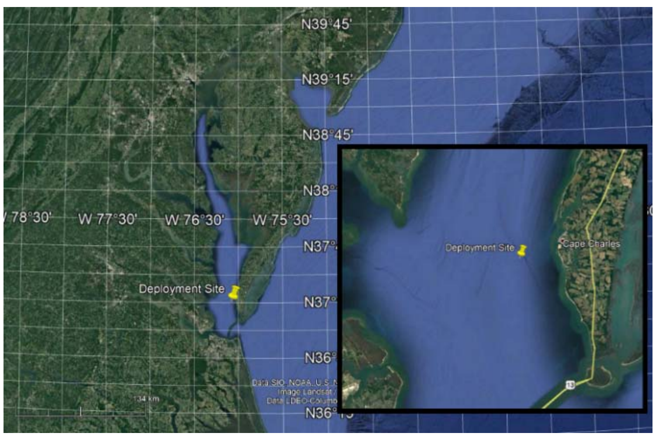

Fig. 5. Deployment location in the SE Chesapeake Bay, USA. Mean water depth at the site is about 15 m.

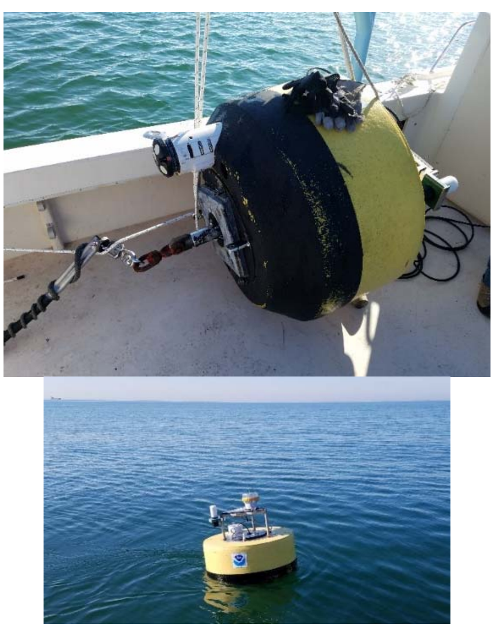

Fig. 6. The Signature1000 mounted on the 1.2 m diameter ionomer foam buoy, as seen during recovery (top) and during a calm day (bottom). Note the buoy was listing about 5°, which was "desirable" to stress the limits of the test.

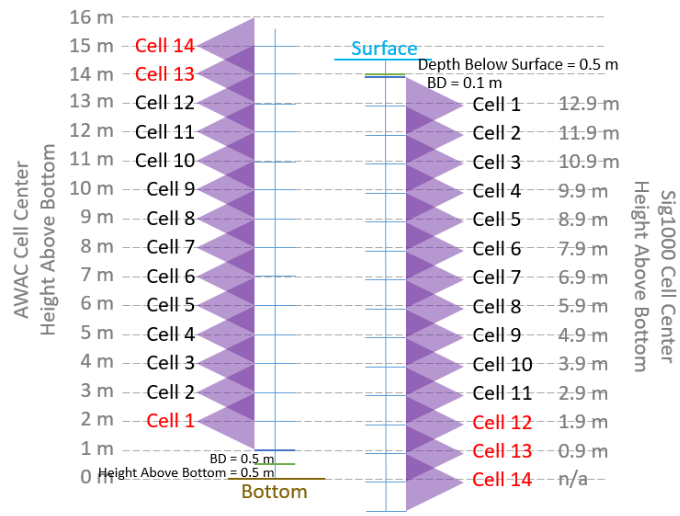

Fig. 7. Sample bin match assignment for low tide. Depths are the center of each depth cell (bin). A triangular weighting is used for each bin as the transmit pulses and the receive windows are matched to each bin size. Red cells were removed due to sidelobe interference from bottom/surface.

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 concurrent 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). These configurations allowed for four 150 s sample averages to be compared between the two instruments every hour. All single ping data were recorded for the Signature1000, making up over 8 GB of data for the entire deployment.

IV. Results and Discussion

As expected of winter conditions in this region, the site observed a range of weather, from almost no winds and waves, to stormy conditions, including one large storm that brought snow, ice, winds gusts exceeding 20 m/s (Fig. 8; all times in UTC) and maximum wave heights reaching 6 m, during January 3-8 (Fig. 10). Velocity magnitude during the deployment ranged from ~0 m/s during slack water to greater than 1.2 m/s driven by semidiurnal tides, with pronounced vertical shear at times.

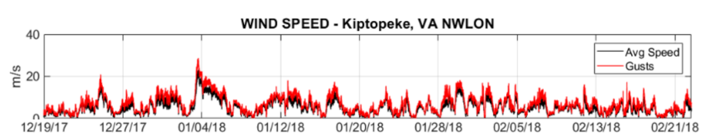

Fig. 8. Wind speed and gust during deployment duration at the site. During the storm on 04/Jan/2018, near surface water temperature was less than 1 °C, as measured by the Signature1000's temperature sensor. It is believed the buoy was iced over during this time.

The buoy was subjected to high degrees of tilt, in excess of 20°, in response to the wind and wave conditions. This was actually welcomed as it afforded several occasions during the deployment to test the proper real-time bin mapping algorithms. Additionally, the fact that the Signature1000 ADCP was mounted off-center on the buoy meant that at times of strong currents it acted as a rudder, minimizing rotation even though the higher frequency 8 Hz data from the AHRS (not shown) still indicates noticeable rotational rates during these times.

During the storm around 04/Jan/2018, the AHRS's raw 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 up within about 10 minutes, and the Signature1000 ADCP's acoustic signal strength data corroborates this event, shown on Fig. 9, where each panel corresponds to a 1200 sample burst collected at 8 Hz every 6 minutes. On the leftmost and right most panels, normal SNR data pattern is shown, while on the second panel it shows the time when the instrument flipped. It remained flipped through the third panel, eventually righting itself up sometime between 21:39 hrs. and 21:43 hrs.

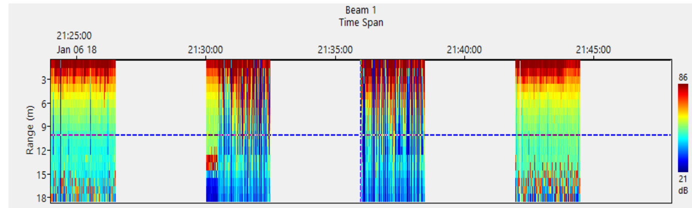

Fig. 9. Acoustic signal strength data (SNR) for beam 1 during one occasion when the buoy fully tilted over during the 04/Jan/2018 storm. See text for description.

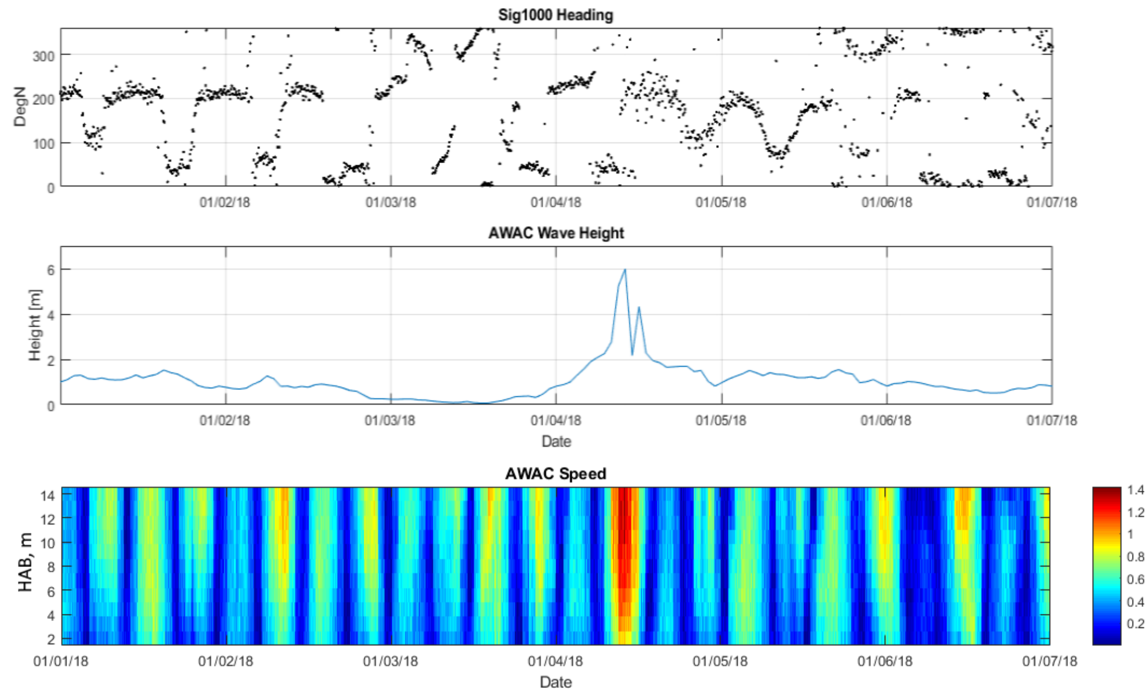

Fig. 10. Data panel centered around 04/Jan/2018 storm. Instrument heading is shown on the top panel and indicates the buoy's rotation roughly followed the tide direction, with the off-center Signature1000 acting as a rudder. Significant wave height, Hm0, as measured by the AWAC is shown on the middle panel, with the storm period clearly standing out. Bottommost panel shows speed countour plot, as measued by the AWAC, plotted versus height above bottom in meters.

The full dataset from this deployment is still being processed and analyzed so that the performance of the real-time bin mapping algorithms can be fully assessed, with one of the objectives being guidance on performance limitations. However, this deployment already shows promising results, especially when compared to previous deployments at this site and on similar sized surface buoys. As shown on Fig. 11, a direct comparison of all speed data shows excellent agreement with the reference bottom-mounted ADCP system, which is a significant improvement from prior work at this site [18, 20] and only minor outliers. For this deployment, > 95% of the differences between the buoy-mounted ADCP and bottom-mounted reference are within ± 5 cm/s. Additionally, because all single-ping raw data was recorded, future analysis can be done on this dataset and improvements applied, if needed.

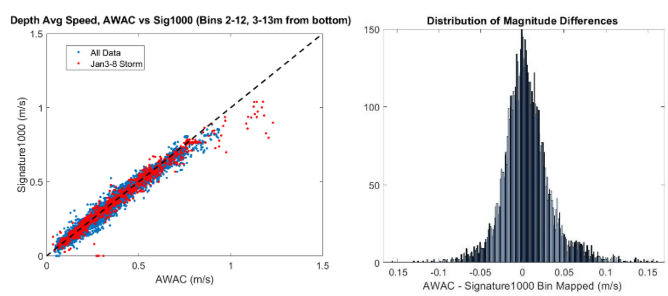

Fig. 11. Linear regression between AWAC speed and Signature1000 bin-mapped speed (left) and histogram of differences between AWAC and Signature1000. Both plots include all data points, less bins removed due to sidelobe interference. Data measured during the 04/Jan/2018 are shown in red on the regression and contain most of the outliers.

To illustrate the performance of the real-time bin mapping algorithm, Fig. 12 and Fig. 13 show plots of the velocity magnitude for the topmost, middle, and bottommost bins between the two systems, for the bin-mapped, unmapped, and reference ADCP data. Although the overall quality of all data are generally high, there are times of noticeable differences in the unmapped data, especially towards the bottom where the beam separation from the surface-mounted ADCP is greatest. During the storm period the data is affected, with at least a portion of it impacted by the extreme tilt and, of course, when the instrument was out of water when the buoy flipped. Other times, however, differences of around 20% between unmapped data and reference data can be seen even though variability in mean tilt angles was low (e.g. 12:00 on 06/Jan/2018), while at the same time the mapped data shows good agreement with the reference system. These are encouraging results and ongoing analysis hopes to provide further insights into these data and test the limits of the real-time bin mapping algorithm used to enhance the accuracy of current profiles from surface buoy-mounted systems.

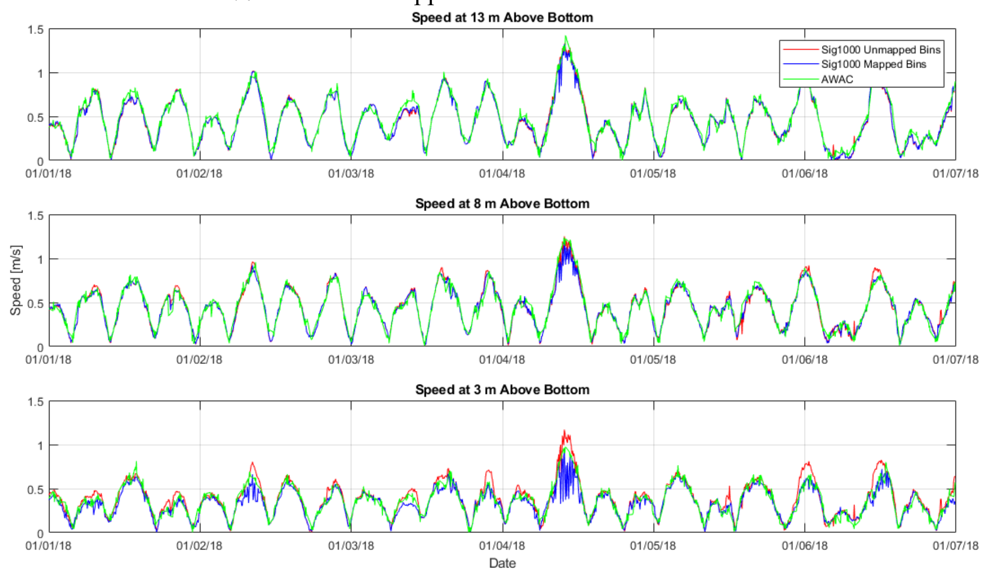

Fig. 12. Buoy-mounted ADCP speeds for unmapped and bin mapped speeds, and bottom-mounted reference ADCP for first week of 2018.

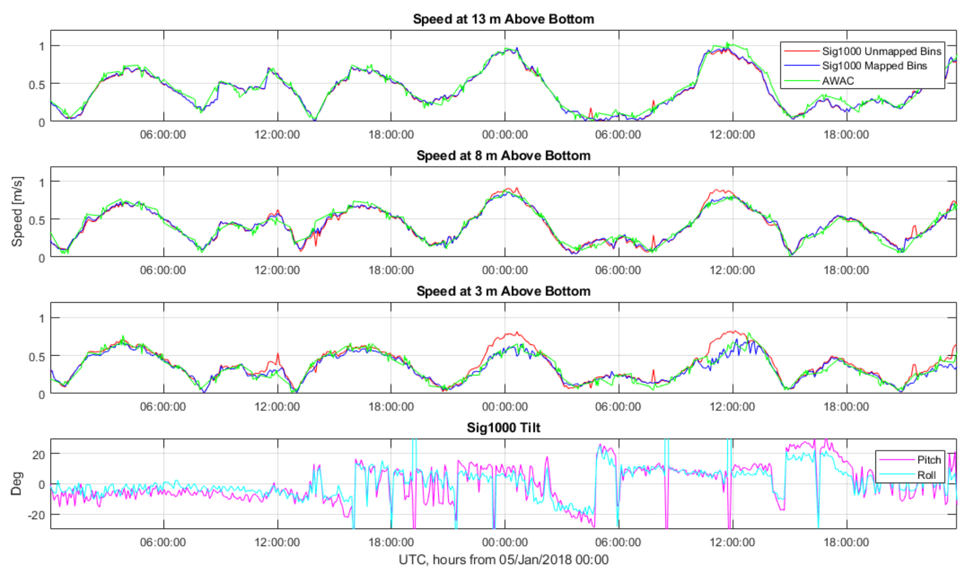

Fig. 13. Similar data as in previous figure, but zoomed into a 48 hour period from 05-06/Jan/2018, and buoy (Signature1000 ADCP) tilt added on bottommost panel.

V. Conclusions

Several previous work has shown that surface buoy-mounted ADCP current profile data can be negatively impacted by buoy motion. The mechanism for this impact can vary, but lack of real-time bin mapping of ADCP data, at both a fast-enough data rate and precisely timed with the velocity sampling ping, can lead to smearing effects and bias on the current profile data. An enhancement to this approach has been presented in this work, where a test deployment was conducted to validate improvements obtained by performing real-time bin mapping on a ping-by-ping basis to a surface buoy-mounted ADCP. Data from a collocated bottom-mounted ADCP shows strong agreement of the bin mapped data, while the unmapped data shows lesser agreement with the reference. Ongoing analysis is still being performed on the vast dataset collected and future work expanding on this paper is planned.

VI. References

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