Testing and Evaluation of a Dual-Frequency Six-Beam Acoustic Doppler Current Profiler

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***Abstract* - Observations of current velocity in near-surface and near-bottom boundary layers are critically important for many scientific, operational, and engineering applications. NOAA's National Data Buoy Center (NDBC) presently maintains approximately 110 weather and oceanographic buoys, some tasked to measure full current profiles, including near-surface currents, in an operational real-time system. Nortek developed a dual-frequency, six-beam acoustic Doppler current profiler to meet the needs of observing the complete water column velocity profile, including near-surface or near-bottom currents (dependent on mounting orientation). Three acoustic beams point upward or downward in the traditional current profiler mode. Three other acoustic beams are directed horizontally and spaced equally around the circumference of the profiler with 120 deg spacing. These beams measure the two-component horizontal currents at the level of the instrument. Near-surface and water column current velocity profile observations from a 6-beam Nortek profiler mounted on an NDBC 3 m discus buoy are compared with current velocity profile measurements from a bottom mounted 600 kHz Nortek AWAC acoustic Doppler wave and current profiler located within 50 m of the buoy location. A tidal analysis suggests that velocity data from the horizontal beams (Cell 0) are of good quality and consistent in direction and magnitude with the velocity measurements in deeper cells, as well as with the AWAC velocity and with barotropic theory. Cross-spectral analysis indicates that synoptic band velocity measured at Cell 0 is highly correlated (90%) with velocity at Cell 2 and may be up to 25% higher than velocity measured 2.5 m lower in the water column. Current speed and direction differences between Cell 0 and lower cells project a spatial separation of water parcels as much as 20 km/day, with a mean separation of 8.5 km/day.**

I. INTRODUCTION

Observations of current velocity in near-surface and near-bottom boundary layers are critically important for many scientific, operational, and engineering applications. Accurate measurements of near-surface currents are required for studying the dynamics of surface features, such as freshwater plumes, harmful algal blooms, and surface contaminants; as well as useful for search and rescue operations and to corroborate HF radar maps of current velocity. Similarly, near-bottom current measurements are required by many engineering projects to be made within 1.0 m of the bottom. Processes, such as Ekman turning in the thin bottom boundary layer that tends to cause across-isobath flow, can represent a major mode of material flux, particularly of suspended sediments and nutrients, from on-shore to off-shore. . However, near-surface and near-bottom current velocity has always been intrinsically difficult to measure with acoustic Doppler current profilers due to blanking distance and/or side-lobe inference.

Acoustic Doppler current profilers have been used for more than two decades to measure profiles of current velocity. Typically, Doppler profilers are deployed in either bottom frames on the ocean floor pointed upwards or deployed on surface buoys pointed downwards. Both methods work well to measure the current profile in the middle portion of the water column, but have limitations of how close to the surface and bottom they can observe.

Upward looking profilers mounted on bottom frames cannot measure accurate velocities in the top ~10% of the water column because of side-lobe errors. Further, due to the size of most bottom frames, the acoustic transducers are typically about 1.0 m above the bottom and the necessary blanking distance (typically greater than 1.0 m, depending on acoustic frequency) positions the first measurement cell at least 2.0 m above the bottom. Therefore, a profiler mounted on the 20 m isobath will not be able to accurately observe the top 2.0 m and the bottom 2.0 m of the water column.

Similarly, downward looking buoy mounted profilers cannot observe the near-surface or near-bottom currents accurately. Buoy mounted downward looking profilers miss the top portion of the water column because of the required mounting depth and blanking distance. Most coastal and offshore buoys purposely mount the downward looking profiler at least 1.0 m below the surface to keep the transducer head below any bubbles formed by breaking waves, as bubbles attenuate the acoustic energy and can greatly reduce the total profiling range of the Doppler instrument. With a mounting depth of about 1.0 m and necessary blanking distance of typically at least 1.0 m, the first sampling location is often greater than 2.0 m below the surface. Side-lobe errors near the bottom interfere with observing the bottom ~10% of the water column.

II. EQUIPMENT

Nortek developed a dual-frequency, six-beam acoustic Doppler current profiler to meet the needs of observing more of the water column velocity profile, particularly the near-surface or near-bottom currents depending on the mounting orientation. Three acoustic beams point upward or downward in the traditional current profiler mode (25 deg head angle), and are available in a range of acoustic frequencies to meet the required profiling range (up to 60 m range). The other three acoustic beams are directed horizontally and spaced equally around the circumference of the profiler with 120 deg spacing between the beams. These beams measure the two-component horizontal currents at the level of the instrument. This geometry allows the observation of current velocity near the surface for buoy-mounted profilers and near the bottom for bottom-mounted profilers. The horizontal beams use a 2 MHz acoustic frequency for high accuracy and narrow beam width. Operationally, the system functions as a single acoustic Doppler current profiler. The near-boundary velocity is located as "Cell 0" and the rest of the water column profile begins with "Cell 1". This novel instrument is referred to herein as the Z-Cell.

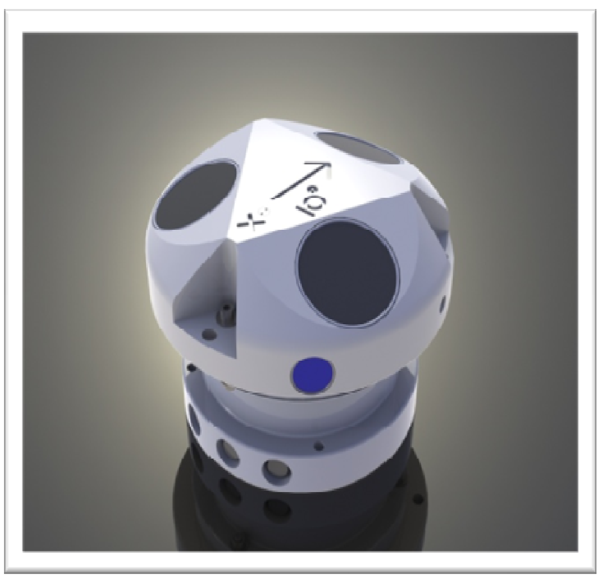

Fig. 1 Prototype design of six-beam acoustic Doppler current profiler used to measure water column profiles and near-boundary currents. Small transducers (blue), used to measure near-boundary currents, are oriented horizontally and operate at 2 MHz. Large transducers (black), used to measure the water column profile of currents, operate at either 1 MHz or 600 kHz.

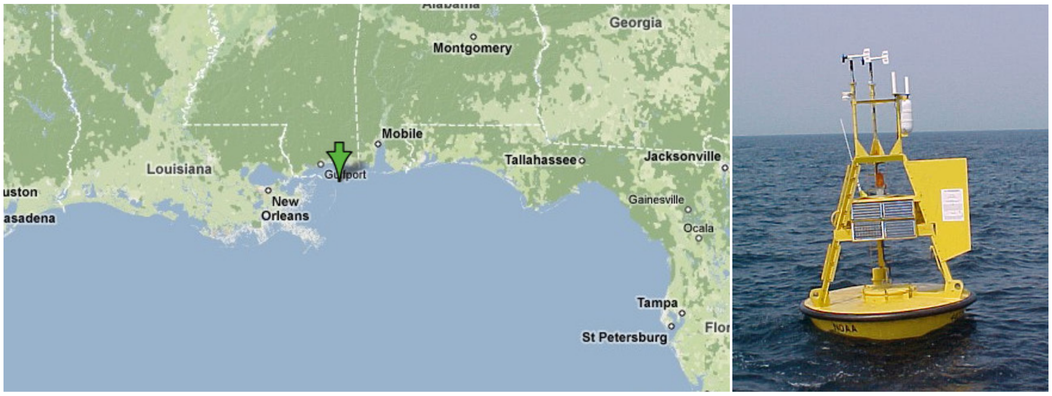

Fig. 2 Map of NDBC Station 42007 buoy location (green arrow) in Gulf of Mexico and photo of 3 m discus buoy.

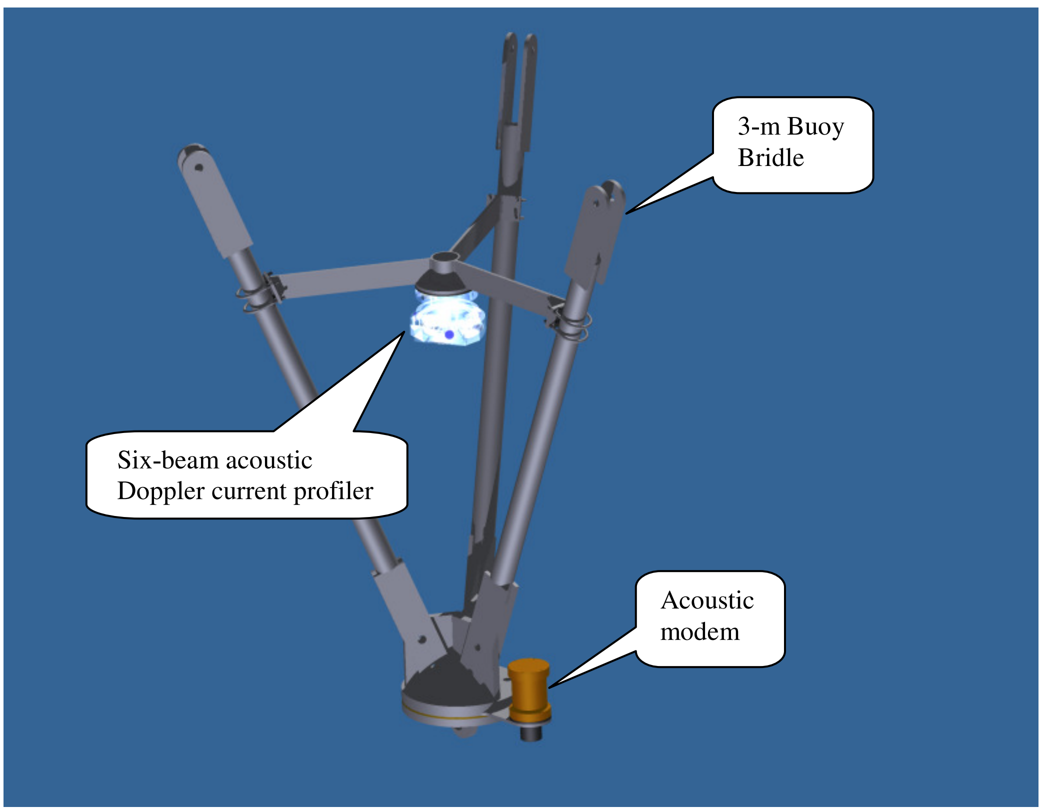

Fig. 3 3-m buoy bridle configuration showing six-beam acoustic Doppler current profiler and acoustic modem.

III. RESULTS

Near-surface and water column current velocity profile observations from the 6-beam profiler mounted on the NDBC buoy are compared with current velocity profile measurements from a bottom mounted 600 kHz Nortek AWAC acoustic Doppler wave and current profiler located within 50 m of the buoy location. The bottom mounted Nortek AWAC provides processed, real-time current profile and directional wave data wirelessly to the NDBC buoy through a pair of underwater acoustic modems. The 600 kHz AWAC was configured with a 0.5 m blanking distance and to profile the water column with 1 m cells with a 2 min average interval. The AWAC was deployed in a MSI trawl resistant bottom frame and the transducer head was nominally 1 m off the sea floor. This positions the center of the first cell 2.5 m above the sea floor. The surface-most velocity cell of good quality (unaffected by side-lobes) is Cell 11 of the AWAC. AWAC Cell 11 is most equivalent to Cell 1 of the Z-Cell on the buoy.

Figure 4 presents contour plots of North and East components of current velocity from the Z-Cell. The velocity structure shows currents primarily forced by diurnal tides with maximum amplitude of about 0.7 m/s. A visual inspection of the velocity contours suggest that Cell 1 may be biased towards zero at times. The exact reason for this is unknown at this time, but is likely due to side-lobe interference with the buoy bridal and/or real flow disturbance (reduction) around the buoy bridal. Due to the uncertainty of Cell 1 on the Z-Cell, some subsequent analyses will compare Cell 0 with Cell 2. The bottom 1-2 cells may also have some bias towards zero due to side-lobe contamination with the bottom. The acoustic signal strength data that can be used to corroborate these results was not available at the time of this study.

Figure 5 offers contour plots of North and East components of current velocity observed by the bottom mounted AWAC. The scales are the same as Figure 4. As apparent, the bottom mounted AWAC cannot observe currents as close to the surface as Cell 0 on the Z-Cell. Further, due to the necessary mounting height and blanking distance, the first velocity observation is equal to or higher in the water column compared to the buoy-mounted Z-Cell. Overall, the velocity structures appear similar between the AWAC and Z-Cell.

A time series of North and East components of velocity from the Z-Cell Cell 0 and Cell 1, and the AWAC velocity closest to the surface is given in Figure 6. A simple inspection indicates that all sensors are operating similarly. However, a more detailed analysis in the frequency domain is required to determine the robustness of the newly acquired Cell 0.

Siegel et al. (2008) used tidal and cross-spectra analyses to compare velocity data (velocity gain and veering angle at different frequencies as a function of water depth) collected with an Aquadopp single point current meter (with horizontal acoustic beams) mounted 1.1 m below the surface on a buoy with velocity measurements observed by a downward-looking ADCP on the same buoy. The results of Siegel et al. (2008) suggested robust near-surface measurements could be obtained by using horizontally oriented acoustic beams in the near surface zone. The velocity from Cell 0 of the Z-Cell will be treated in a similar analysis.

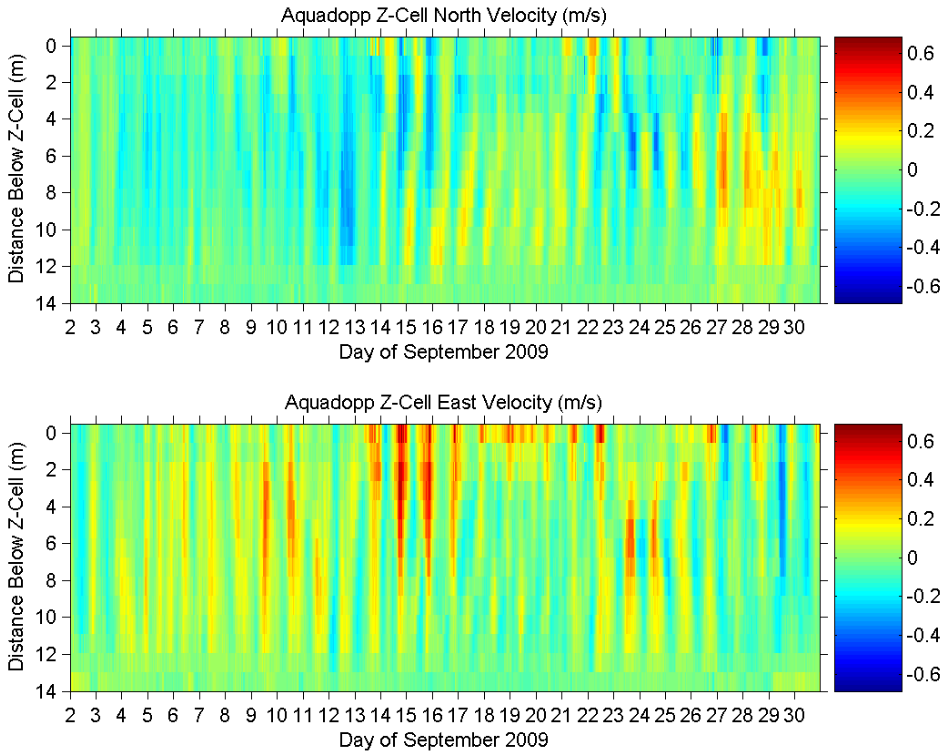

Fig.4 Buoy-mounted Z-Cell current velocity contour plots.

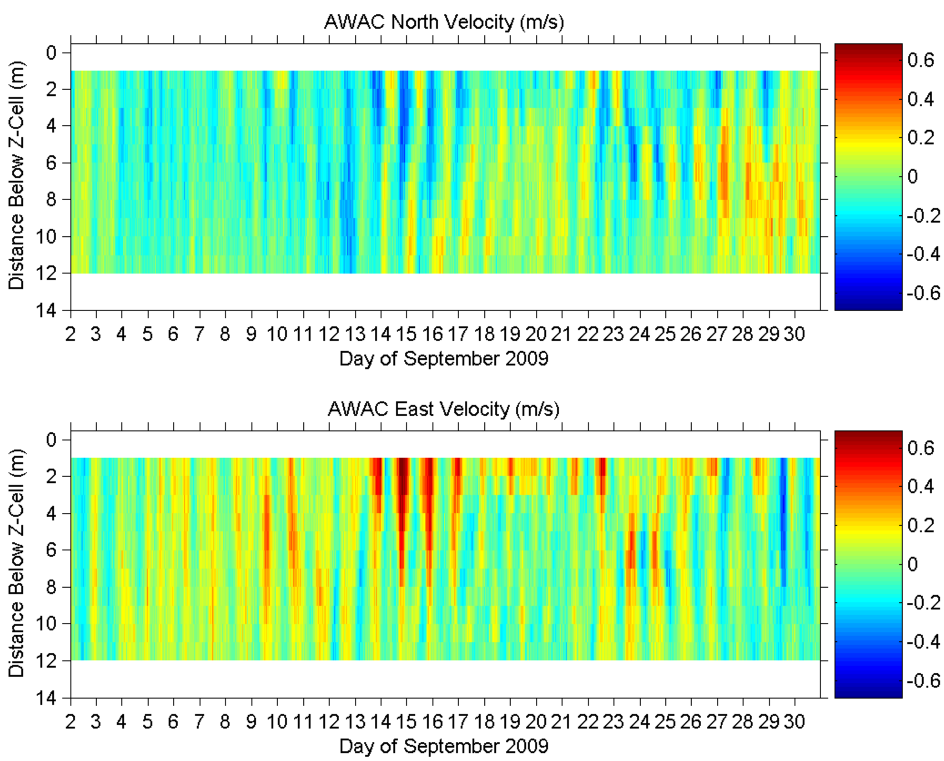

Fig. 5 Bottom-mounted AWAC current velocity contour plots (same scales as Fig. 4).

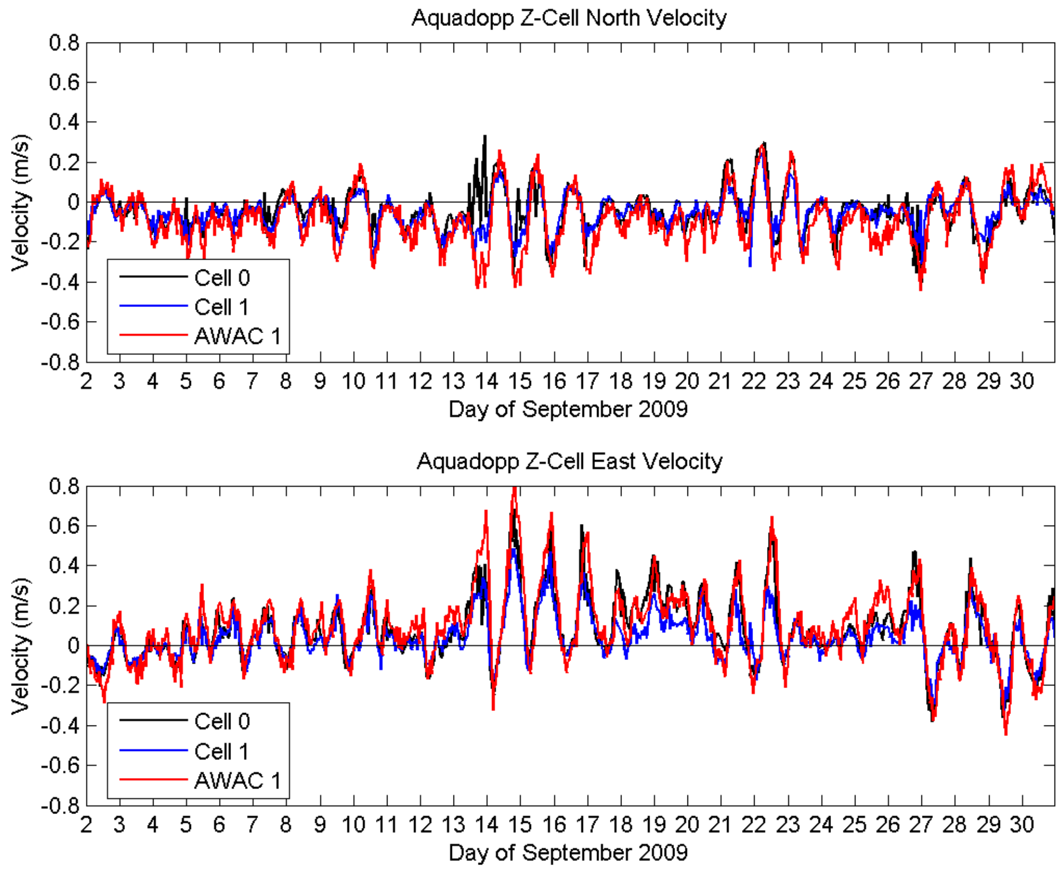

Fig. 6 Time series of velocity from Z-Cell Cell 0, Cell 1, and AWAC Cell 11 (most similar position to Z-Cell Cell 1).

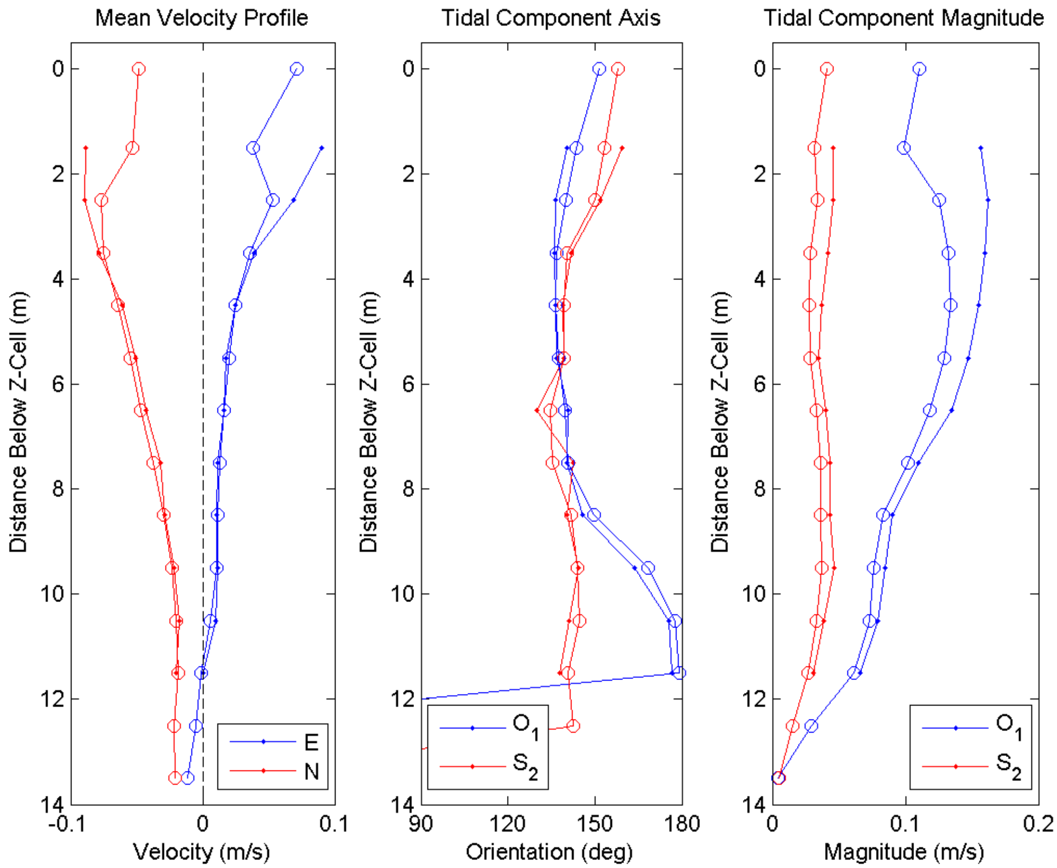

Fig. 7 Record length mean velocity profile from Z-Cell (circle) and AWAC (dots) [left]. Orientation of semi-major tidal ellipse [middle]. Magnitude of semi-major tidal ellipse [right].

Record length mean velocity profiles for both the Z-Cell and AWAC are presented in the first plot of Figure 7. The profiles of mean velocity look similar for both instruments in the middle and lower portion of the water column. The top several meters of the water column show some dissimilarity with the upward looking AWAC showing larger mean velocities near the surface. This is supported by the analysis of Mayer et al. (2007) that observed that downward looking ADCP's on buoys may have a low bias compared to upward looking ADCP's. Some low bias in Z-Cell Cell 1 is also observed in the mean profiles. As discussed earlier, this is likely due to either side-lobe effects from the buoy bridal and/or real flow disturbance around the buoy bridal.

The other plots in Figure 7 are tidal analyses using the T_Tide routine (Pawlowicz et al., 2002). The semi-major ellipse orientation and magnitude of the two primary tidal constituents at this location (O_1 and S_2) are shown for both the Z-Cell and AWAC. The direction of the semi-major ellipses from Cell 0 match the ellipse orientations in the velocity measurements made lower in the water column for both the Z-Cell and AWAC. This is consistent with tidal theory that suggests little rotation in the water column from the barotropic forcing. While there is some discrepancy in the tidal velocity magnitude between the Z-Cell and AWAC (as discussed above), the amplitude of the Z-Cell Cell 0 tidal velocity is reasonable compared to the other amplitudes observed by the Z-Cell for both tidal constituents.

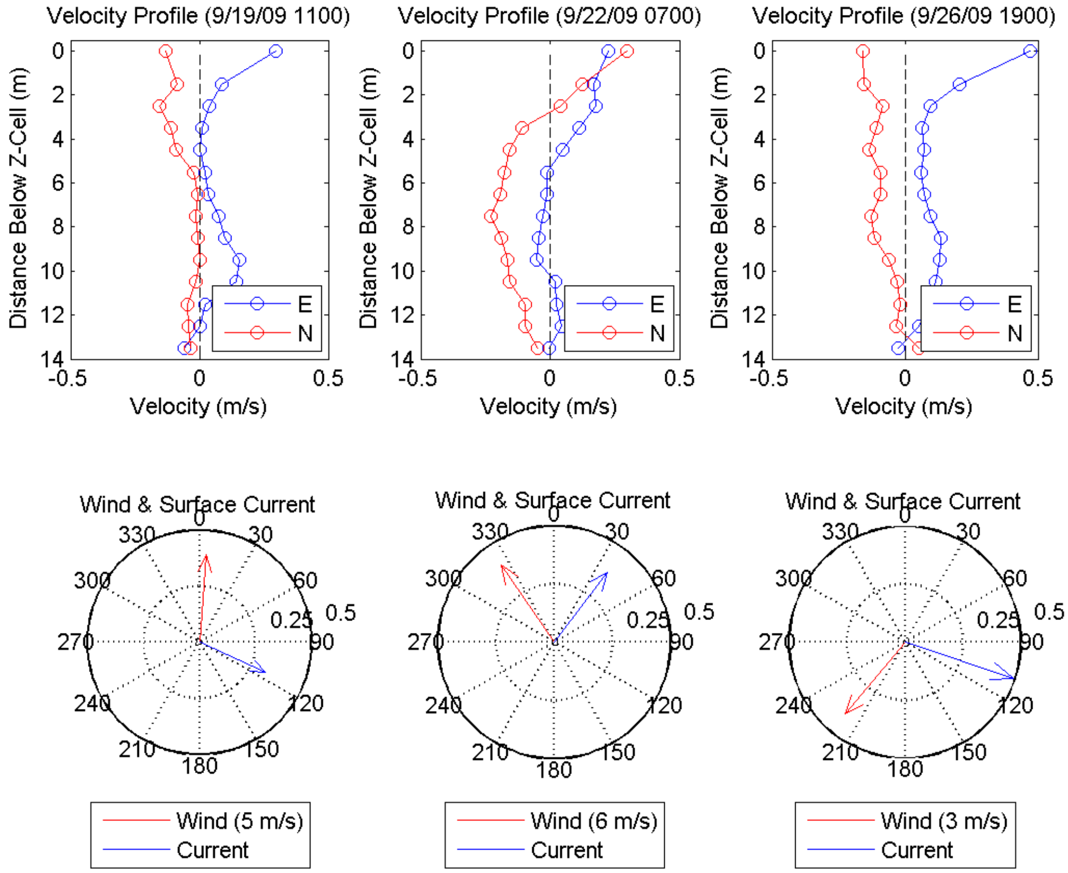

Fig. 8 Three Z-Cell velocity profiles showing high velocity shear near the surface [top]. Compass plots of wind direction and current direction for each current profile [bottom]. Wind speed in given in the lower legend. Wind vector has arbitrary but constant magnitude (only plotted to indicate wind direction). Current vector has correct magnitude and direction.

The currents in this study region (northern Gulf of Mexico) are complex and controlled by several factors including tidal forcing, bathymetry, wind, and thermocline depth. On several occasions the near-surface currents observed in Cell 0 exhibit strong shear compared to the velocities observed in Cell 1 and deeper, just 1.5 m below. Figure 8 provides three representative examples of high shear in the upper 1.5 m of the water column.

Ekman theory indicates that near-surface currents should be 45 deg to the right of the wind direction in the Northern Hemisphere, and the currents should continue to rotate to the right with increased depth. On many occasions, the large rotation in the upper portion of the water column (perhaps related to a shallow thermocline) provides a situation where the near-surface currents observed in Cell 0 have a sign reversal (other direction) compared to the velocity measured in Cell 1 and below. Figure 9 provides three examples of times when the near-surface current velocity vectors have a different sign compared to observations lower in the water column. In 5 of 6 examples (Figures 8 & 9), the near-surface currents are oriented to the right of the wind direction, typically about 90-120 degrees. In the one case where the currents were not to the right of the wind, the winds at the time were light and variable (less than 3 m/s).

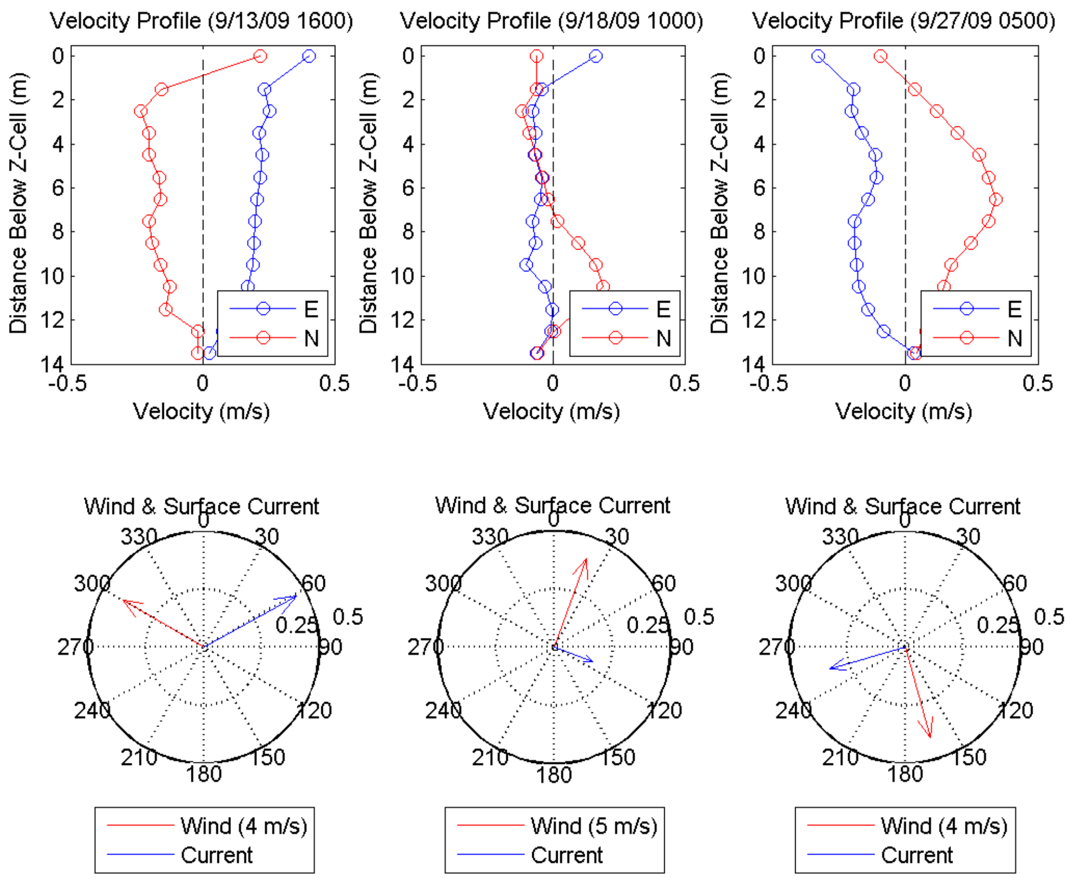

Fig. 9 Three Z-Cell velocity profiles showing high velocity shear and rotation with vector sign difference between Cell 1 and Cell 2 near the surface [top]. Compass plots of wind direction and current direction for each current profile [bottom]. Wind speed in given in the lower legend. Wind vector has arbitrary but constant magnitude (only plotted to indicate wind direction). Current vector has correct magnitude and direction.

The cases where Cell 0 has higher current magnitude and/or direction are very interesting for the perspective of search and rescue, HAZMAT control, and numerical modeling. If a program manager or researcher were trying to predict the location of a water parcel based only on information from Cell 1 velocity, the net location of the parcel, after some time, could be substantially different compared to a more accurate prediction of the location based on Cell 0 velocity. An analysis to estimate the difference in position of a water parcel after 24 hours (assumed to have constant velocity) using velocity from Cell 0 and Cell 2 of the Z-Cell is presented in Figure 10.

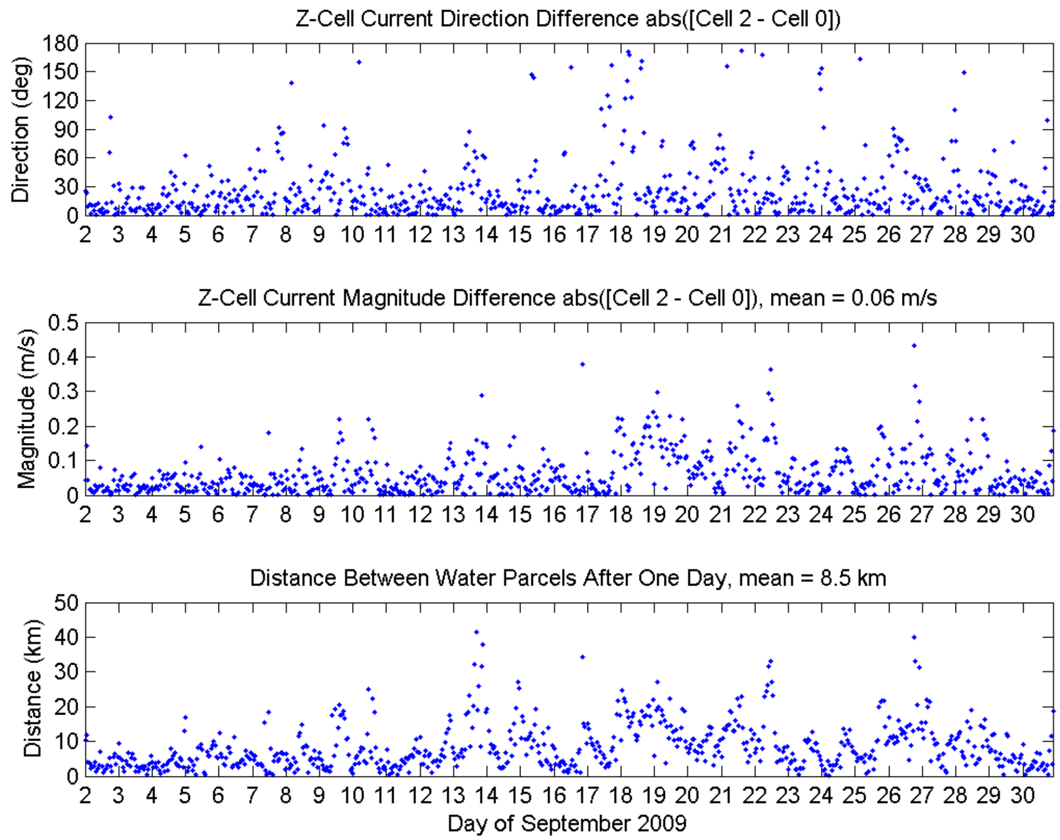

Fig. 10 Absolute value of the difference of current direction between Z-Cell Cell 0 and Cell 2 [top]. Absolute value of the difference of current magnitude [middle]. Distance between water parcels predicted after 24 hours based on velocity differences between Cell 0 and Cell 2 [bottom].

The top plate of Figure 10 gives the absolute directional difference between Cell 0 and Cell 2 of the Z-Cell. The middle plate gives the absolute magnitude difference between Cell 0 and Cell 2. The mean magnitude difference is 0.06 m/s, but can frequently range from 0.10 to 0.20 m/s. Vector calculations of the net distance between water parcels after 24 hours (bottom plate of Figure 10) is calculated as,

$$\text{magnitude}(\mathit{vector}) = ([b_u - a_u]\ [b_v - a_v])$$

where a is the vector velocity (u,v) from Cell 2 and b is the velocity vector from Cell 0. The magnitude in m/s is converted to km/day by,

$$\frac{m}{s} * \frac{86400\,s}{day} * \frac{km}{1000\,m} = \frac{km}{day}$$

The mean difference in position from this analysis is 8.5 km/day. However, frequently a horizontal separation of 20 km/day can result from the difference in velocity observations between Cells 0 & 2. To put this in some perspective, the edge of the horizon is located about 4.7 km away from the typical observer standing up in a small boat. This difference in horizontal position can make a large difference to search and rescue operations, hazardous materials response and numerical models focused on predicting storm surge level and harmful algal bloom dynamics.

IV. SUMMARY

A Nortek six-beam acoustic Doppler current profiler (Z-Cell) was developed and tested on an NDBC 3-m discus buoy in the Northern Gulf of Mexico in September 2009. The Z-Cell has three acoustic transducers (2 MHz frequency) oriented horizontally to measure near-surface currents at Cell 0. Three acoustic transducers (1 MHz frequency) are pointed downward (25 deg head angle) to profile the water column velocity, beginning at Cell 1. A 600 kHz Nortek AWAC Doppler profiler was bottom-mounted nearby the buoy to corroborate Z-Cell velocity measurements.

The Z-Cell was easy to integrate into the NDBC buoy design and telemetry system. Real-time velocity profiles were sent every 1 hour to NDBC headquarters via GOES. Tidal analysis suggests that velocity data from the horizontal beams (Cell 0) are of good quality and consistent in direction and magnitude with the velocity measurements in cells below, with the AWAC velocity, and with theory. Cross-spectral analysis indicate that synoptic band velocity measured at Cell 0 is highly correlated (90%) with velocity at Cell 2 and may be up to 25% higher than velocity measured 2.5 m lower in the water column. Current speed and direction differences between Cell 0 and lower cells project a spatial separation of water parcels as much as 20 km/day, with a mean separation of 8.5 km/day. The near-surface velocity measurements in Cell 0 may be critical to resolving the dynamics of surface features, such as freshwater plumes, harmful algal blooms, and surface contaminants, as well as useful for search and rescue operations and HAZMAT planning and response.

V. References

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[2] D. Mayer, J. Virmani, and R. Weisberg, “Velocity comparisons from upward and downward acoustic Doppler current profilers on the West Florida Shelf”, *J. Atmos. and Oceanic Tech.*, 24, pp. 1950-1960, 2007.

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