Performance of the Nortek Aquadopp Z-Cell Profiler on a NOAA Surface Buoy

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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. Nortek developed the Aquadopp Z-Cell Profiler, a dual-frequency, six-beam acoustic Doppler current profiler, to meet the needs of observing the complete water column velocity profile, including the near-surface or near-bottom currents. The Aquadopp Z-Cell Profiler employs three acoustic beams 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 (cell zero), thereby eliminating the common blanking distance associated with standard ADCP's. Near-surface and water column current velocity profile observations from a Z-Cell Profiler mounted on a NOAA NDBC 3 m discus buoy (located in the northern Gulf of Mexico) are compared with current velocity profile measurements from a bottom mounted 600 kHz Nortek AWAC and 600 kHz Teledyne RD Instruments Workhorse acoustic Doppler current profiler. A tidal analysis suggests that velocity data from the horizontal beams (cell zero) are of good quality and consistent in direction and magnitude with the velocity measurements in cells below, with the AWAC and Workhorse velocity, and with theory. Several cases are presented that indicate the measurements in cell zero are important to make independent of velocity lower in the water column in order to correctly characterize the flow regime. Current speed and direction differences between cell zero and lower cells project a horizontal 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. Ekman turning in the thin bottom boundary layer tends to cause across-isobath flow and represent a major mode of material flux, particularly of suspended sediments and nutrients, from on-shore to off-shore. Many engineering projects require a current velocity measurement to be made within 1.0 m of the bottom. 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 over 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 the necessary blanking distance of approximately at least 1.0 m, the center of 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 the Aquadopp Z-Cell Profiler, 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.. Three acoustic beams point upward or downward in the traditional current profiler mode (25 deg head angle) and are available in two acoustic frequencies (1 MHz and 600 kHz) to meet various profiling range requirements (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 (Fig. 1). 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 at "Cell 0" and the rest of the water column profile begins with "Cell 1".
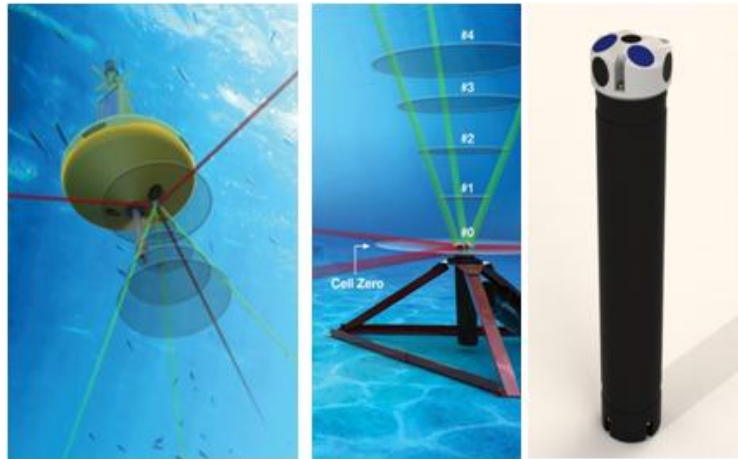

Fig. 1 Photo of a Nortek Aquadopp Z-Cell Profiler (right). Vertical transducers (blue, 1 MHz) are used to profile the water column. Horizontal transducers (black, 2 MHz) measure near-boundary currents. Buoy and bottom mount images indicate the water column profile (green acoustic beam pattern) and Cell Zero measurement (red acoustic beam pattern).

NOAA's National Data Buoy Center (NDBC) presently maintains approximately 110 weather and oceanographic buoys. Of these, some are tasked to measure full current profiles, including near-surface currents, in an operational real-time system. Under a NOAA Cooperative Research & Development Agreement (CRADA) NortekUSA and NDBC deployed the Aquadopp Z-Cell Profiler on an NDBC 3 m discus buoy at station 42007. This buoy was located approximately 35 km south-southeast of Biloxi, Mississippi in a nominal water depth of 15 m. The acoustic frequency of 1 MHz was selected to provide the optimum profiling range and resolution for the water depth. The profiler was mounted within the triangular shaped, three leg bridal below the buoy hull as shown is Fig. 2 The profiler transducer head was located 1.5 m below the water surface. This location can be considered the depth of the near-surface current observation (referred to as Cell 0). The next cell of the depth profile (Cell 1) was centered 1.5 m below the near-surface velocity observation. Data were recorded every 1 hour with a 5 min average interval. Compass and tilt data were logged every 1 sec over the 5 min average interval and were used to vector average the velocity measurements.

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

III. RESULTS

Near-surface and current velocity profile observations from the Aquadopp Z-Cell Profiler are compared with current velocity profile measurements from a bottom mounted 600 kHz Nortek AWAC and 600 kHz Teledyne RD Instruments Workhorse acoustic Doppler current profiler; each located within 50 m of the buoy location. Each ADCP 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 TRDI ADCP was mounted on a Sea Spider mount. The AWAC was mounted on a MSI trawl resistant bottom frame. The transducer heads of both instruments were approximately 1 m off the sea floor. This positioned the center of the first velocity cell 2.5 m above the sea floor. The velocity cell closest to the surface of good quality (unaffected by side-lobes) is Cell 11 of the AWAC and Cell 10 for the Workhorse. AWAC Cell 11 is most equivalent to Cell 1 of the Z-Cell
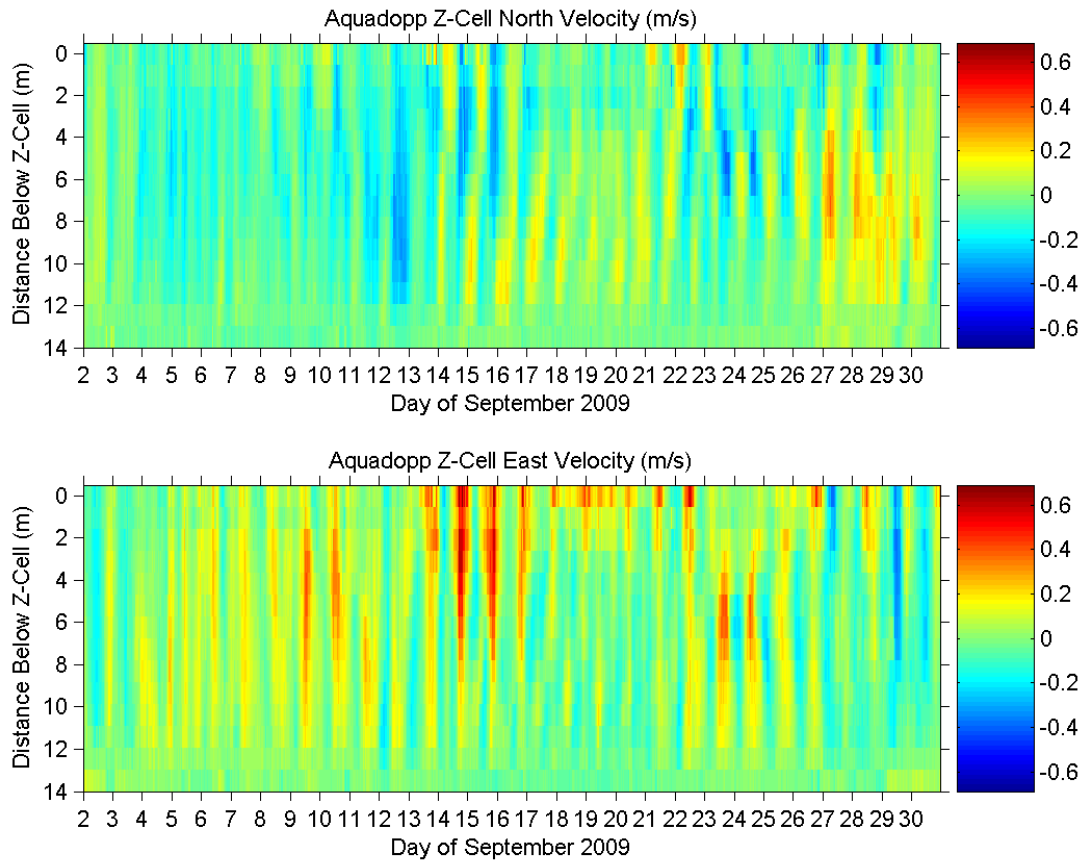

Fig. 3 Buoy-mounted Aquadopp Z-Cell Profiler current velocity contour plots for the month of September 2009.

Figure 3 presents contour plots of North and East components of current velocity from the Aquadopp Z-Cell Profiler. 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. This low bias is due to side-lobe interference with the buoy bridal as evidenced by higher-than-expected acoustic signal echo return. Due to the uncertainty of Cell 1 on the Z-Cell, some subsequent analyses will compare Cell 0 with Cell 2. In addition the bottom two cells may also have some bias towards zero due to side-lobe contamination with the bottom.

Figure 4 offers contour plots of North and East components of current velocity observed by the bottom mounted Nortek AWAC. The scales are the same as Figure 3. 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. Figure 5 shows the contour plots of the TRDI Workhorse North and East components of the current velocity. The bottom mounted TRDI has good data from bin 1 (near bottom) to bin 11, approximately 3 meters below the surface. In general, the velocity structures of the AWAC and the TRDI appear similar to the Z Cell.
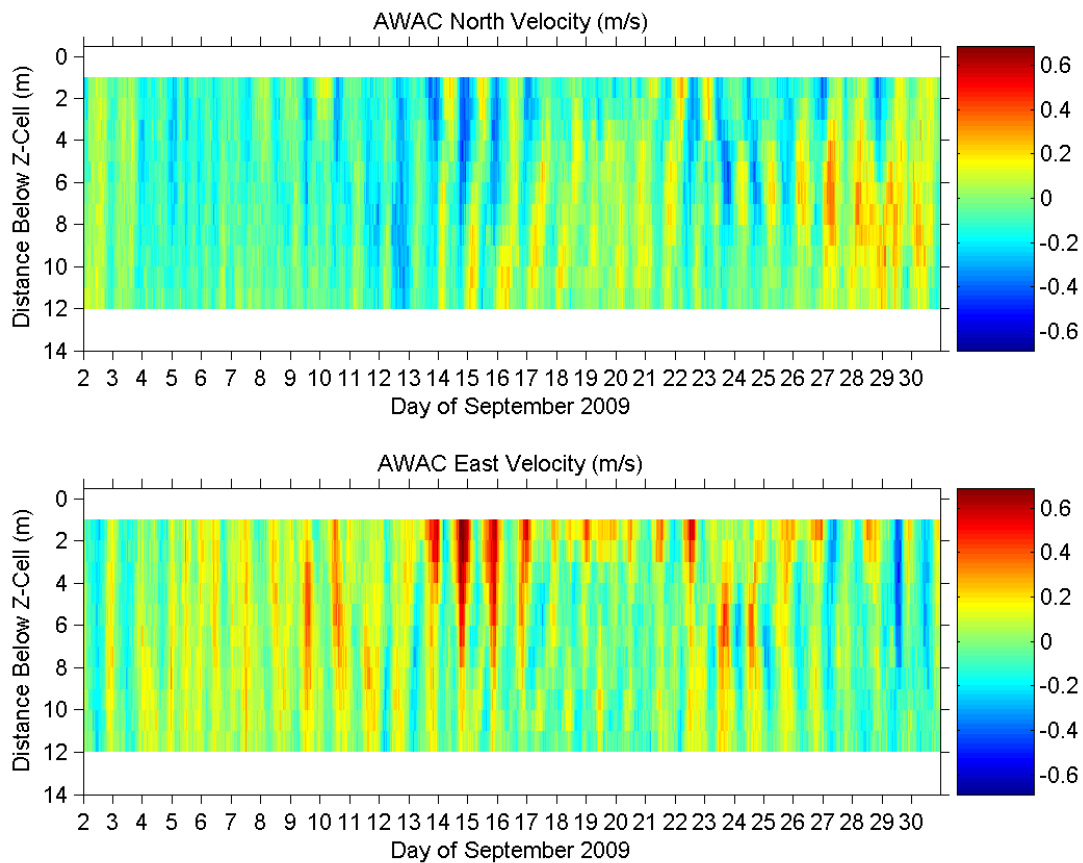

Fig. 4   Bottom-mounted AWAC current velocity contour plots for the month of September 2009 (same scales as Fig. 3).
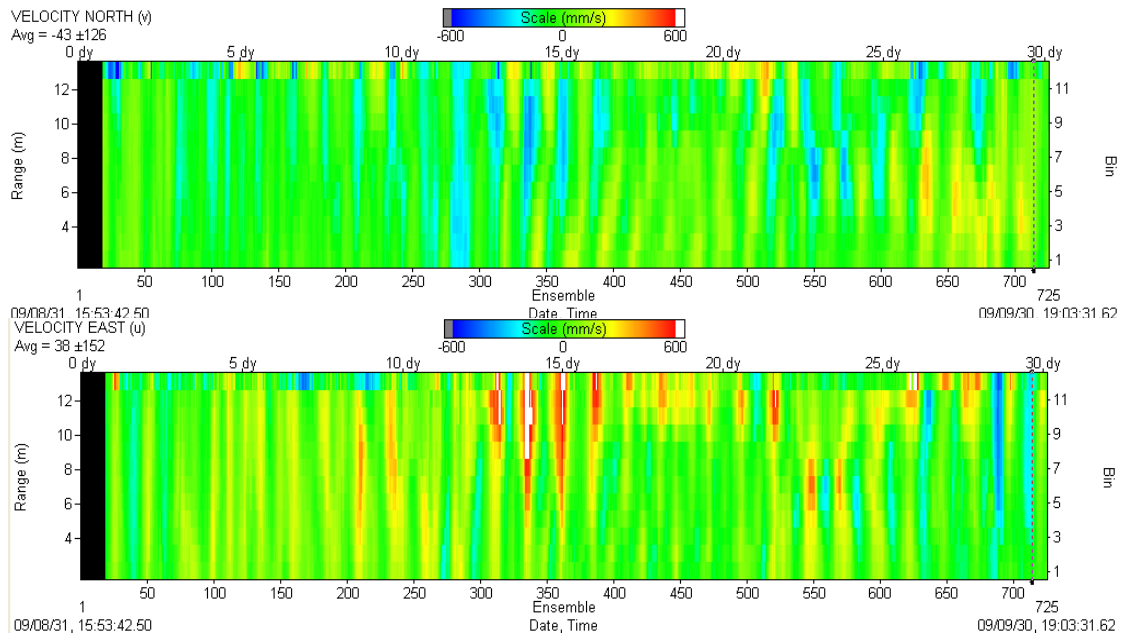
Fig. 5 Bottom-mounted TRDI Workhorse current profile contour plots for the month of September 2009.
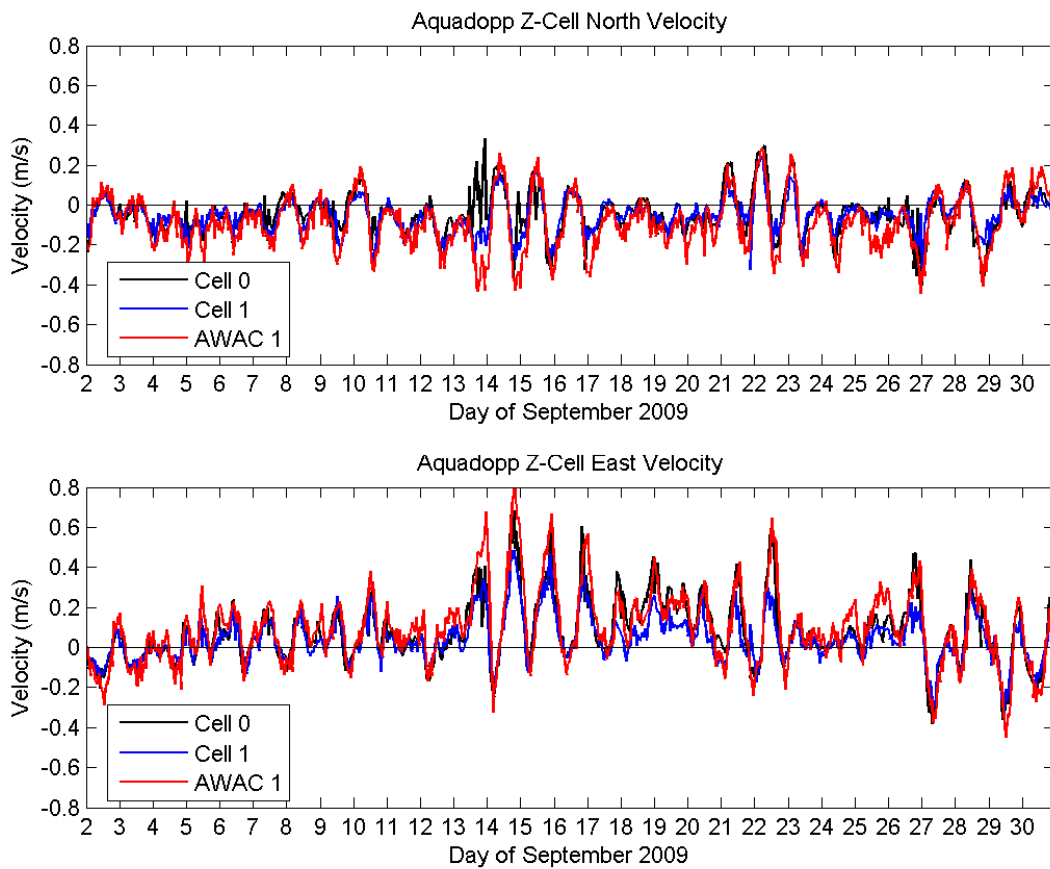

Fig. 6 Time series of velocity from Z-Cell Cell 0, Cell 1, and AWAC Cell 11 (most similar position to Z-Cell Cell 1).

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 Fig. 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.

Reference [1] 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 a Nortek 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 Ref. [1] suggested that quality near-surface measurements could be obtained by using horizontally oriented acoustic beams in the near surface zone. Reference [1] was an important foundation for the development of the Z-Cell and the velocity from Cell 0 of the Z-Cell will be treated in a similar analysis.
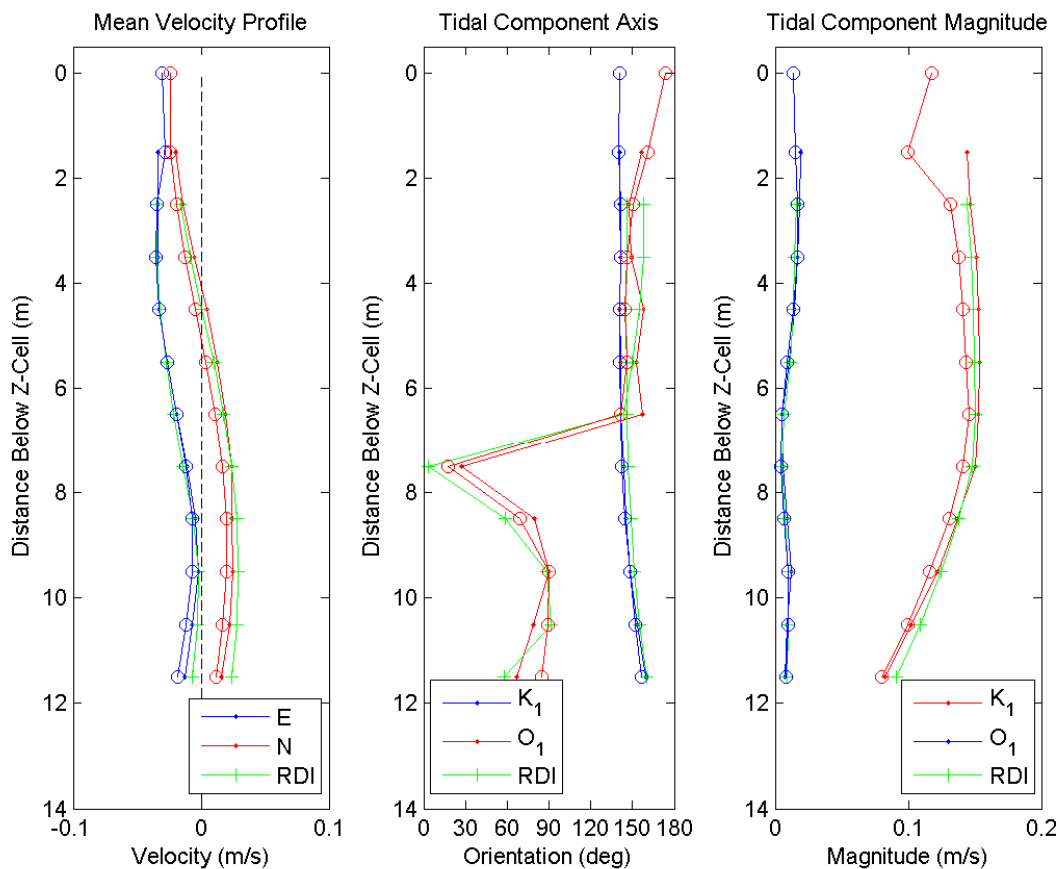

Fig. 7   Record length mean velocity profile from Z-Cell (circle), AWAC (dots), and RDI Workhorse (green +) [left]. Orientation of semi-major tidal ellipse [middle]. Magnitude of semi-major tidal ellipse [right].

Record length mean velocity profiles for the Z-Cell, AWAC, and TRDI Workhorse are presented in the first plot of Fig. 7. The profiles of mean velocity look similar for all instruments over the full water column. The low- bias of Cell 1 of the Z-Cell (1.5 m below Z-Cell) is evidenced in the magnitude of the K_1 tidal ellipse (red circle, far right plot). As discussed earlier, this is likely due to side-lobe effects from the buoy bridal.

The other plots in Fig. 7 come from a tidal analysis using the T_Tide routine [2]. The semi-major ellipse orientation and magnitude of the two primary tidal constituents at this location (O_1 and K_1) are shown for the Z-Cell, AWAC and TRDI. 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 the Z-Cell, AWAC and Workhorse. This is consistent with tidal theory that suggests little rotation in the water column from the barotropic forcing.
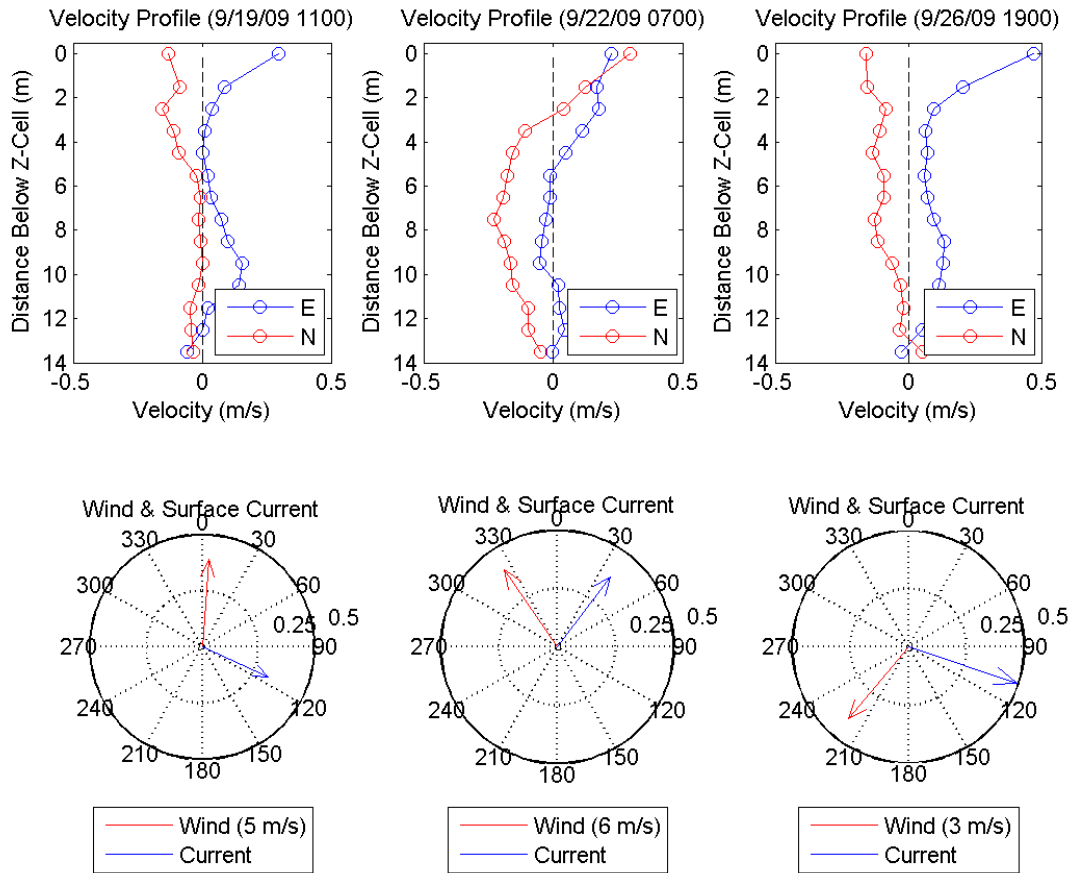
Fig. 8 Three Z-Cell velocity profiles showing high velocity shear near the surface [top].   Compass plots of wind direction and current direction for each current profile [bottom]. Wind speed is given in the lower legend. Wind vector has arbitrary but constant magnitude (only plotted to indicate wind direction). Current vector has correct magnitude and direction.

The currents in study region (northern Gulf of Mexico) are complex and are 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 8 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 (Figs. 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).
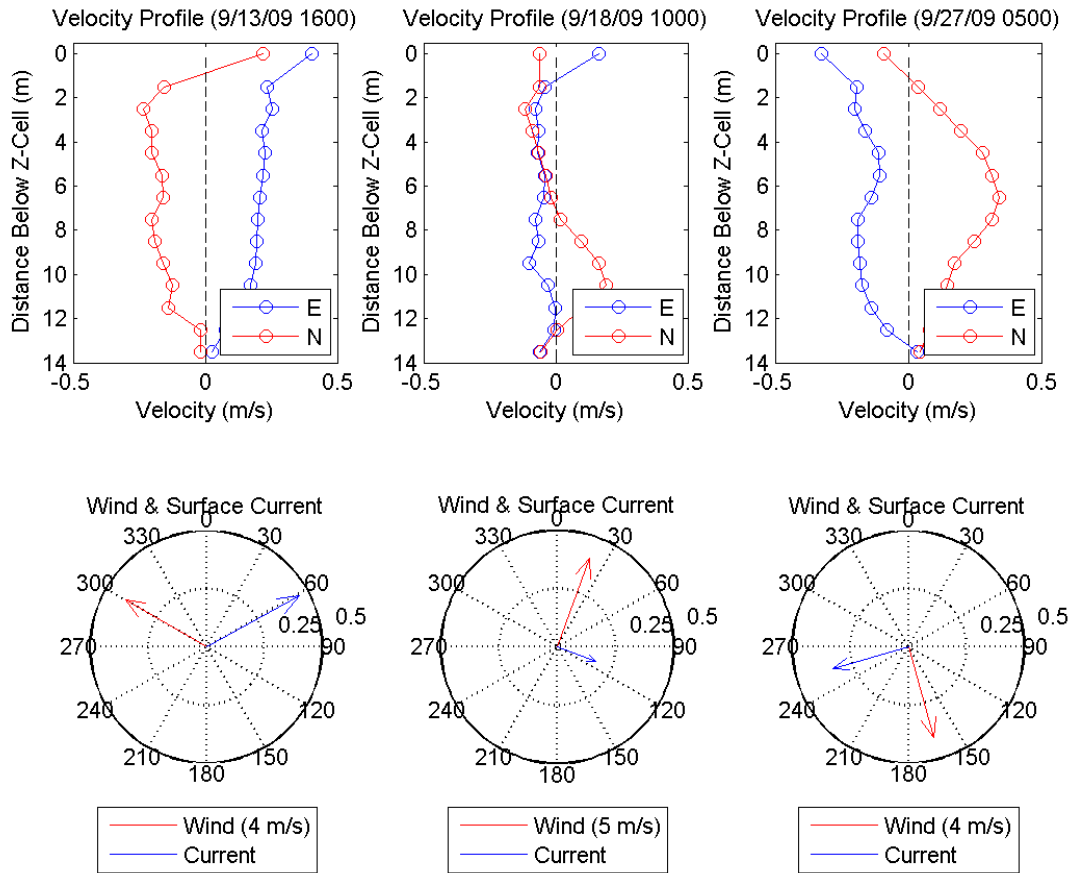
Fig. 9 Three Z-Cell velocity profiles showing high velocity shear and rotation with vector sign difference between Cell 1 and Cell 2 near the surface [top].   Compass plots of wind direction and current direction for each current profile [bottom]. Wind speed in given in the lower legend. Wind vector has arbitrary but constant magnitude (only plotted to indicate wind direction). Current vector has correct magnitude and direction.

The cases where Cell 0 observes higher current magnitude and/or direction are very interesting from search and rescue, HAZMAT control and numerical modeling perspectives. 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.
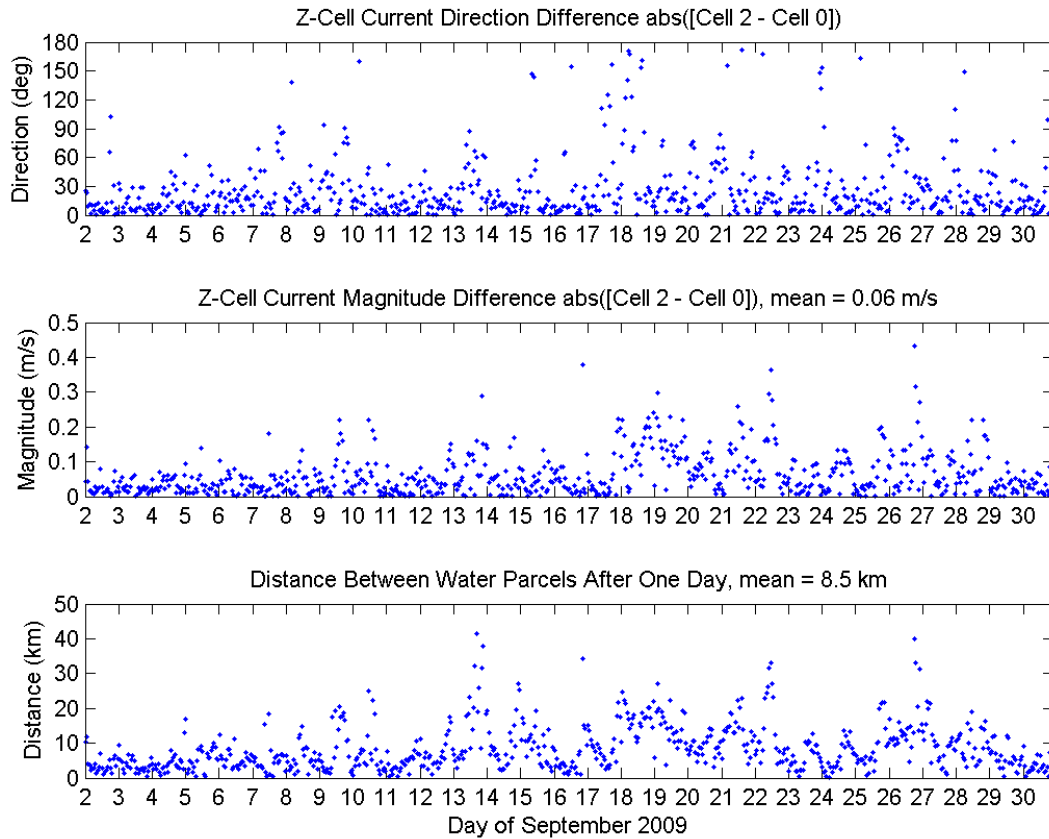
Fig. 10 Absolute value of the difference of current direction between Z-Cell Cell 0 and Cell 2 [top]. Absolute value of the difference of current magnitude [middle]. Distance between water parcels predicted after 24 hours based on velocity differences between Cell 0 and Cell 2 [bottom].

The top plate of Fig. 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 Fig. 10) is calculated as,

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

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, the Aquadopp Z-Cell Profiler, was 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 and 600 kHz Teledyne RD Instruments Workhorse acoustic Doppler current profiler were 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 and Workhorse velocity, and with theory. 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 showing that 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

[1]   E. Siegel, D. Mayer and R. Weisberg, "A comparison of near-surface current measurement methods", *IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology*, pp. 44-49, 2008.

[2]   R. Pawlowicz, B. Beardsley, and S. Lentz, "Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE", Computers and Geosciences 28, pp. 929-937, 2002.