Field Test Results from Ellipsoid ADCP Buoy Moored at the Edge of the Gulf Stream

Laura A. Fiorentino
Center for Operational Oceanographic Products & Services
National Oceanic and Atmospheric Administration
Chesapeake, VA, USA
laura.fiorentino@noaa.gov

Robert Heitsenrether
Center for Operational Oceanographic Products & Services
National Oceanic and Atmospheric Administration
Chesapeake, VA, USA
robert.heitsenrether@noaa.gov

Chung-Chu Teng
Center for Operational Oceanographic Products & Services
National Oceanic and Atmospheric Administration
Silver Spring, MD, USA
chung-chu.teng@noaa.gov

Michael Muglia
Coastal Studies Institute
Wanchese, NC, USA
mugliam@ecu.edu

***Abstract*—The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) and the Coastal Studies Institute (CSI) recently partnered to complete a successful 401 day field trial of a new subsurface ADCP buoy. The mooring system tested was new to CO-OPS, developed in response to several emerging current survey applications that require 6 to 12 months of current profile measurements in the topmost 30-50 m of a water column with depths ranging from 200-300m. Near surface current speeds at sites of interest reach 2-3 m/s. CSI has similar interest in measuring current profiles in the topmost, 50 m of the water column within the Gulf Stream, an area where currents may not be captured by bottom mounted ADCPs nor HF radar measurements.**

The mooring developed consists of commercial-off-the shelf (COTS) components. The topmost component is an ellipsoid, syntactic foam buoy, which houses an upward looking 300 kHz acoustic Doppler current profiler (ADCP). The ellipsoid buoy has lower drag than a spherical shaped buoy and significantly higher buoyancy than many COTS available streamlined buoys, allowing the ADCP to be positioned within the top 50 m of the water column when moored with adequate line length. CO-OPS and CSI completed a long-term field demonstration of the system off the coast of North Carolina near the Gulf Stream in approximately 325 m of water, from May 2017 - June 2018. The system was successfully recovered following a 401 day deployment. An overview of the mooring system and preliminary field results were presented in a 2018 conference proceedings paper, shorty after the field test conclusion (MTS/IEEE OCEANS18, Charleston). This second conference paper presents additional data and further analysis, including model results to help interpret observed buoy depth excursions. Plans for continuing work guided by initial field test results will also be discussed.

***Index Terms*—ellipsoid buoy, adcp,**

I. Introduction

The National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) manages the National Current Observation Program (NCOP) to collect, analyze, and distribute observations and predictions of tidal currents in major ports and harbors across the United States. Data analysis products are developed and disseminated to ensure safe, efficient and environmentally sound maritime commerce and to support physical oceanographic research and coastal engineering applications. Several 2018 sites of interest including North Inian Pass, Alaska and locations across the Puget Sound and Straits of Juan de Fuca, Washington, have water depths ranging from 200-300m and maximum near surface current speeds of 2-2.5 m/s. Due to present NCOP current measuring techniques, available historical current observations for these sites only cover depths 50 m below the sea surface and deeper. Derived navigational support products are not representative of conditions in the top most portion of the water column, where currents will most significantly impact vessel operation. NCOP current survey applications require the addition of methods of short term collection (60-90 days) of current profile measurements in the top 30m of the water column.

To address these emerging NCOP needs, CO-OPS developed and tested a subsurface, moored buoy system consisting of commercial-off-the-shelf available (COTS) components from Mooring Systems, Inc (MSI). The topmost component, an ellipsoid shaped, syntactic foam buoy, houses an upward looking 300 kHz acoustic Doppler current profiler (ADCP). The ellipsoid buoy combines low drag and high buoyancy to position the upward looking ADCP as close as possible to the near surface area of interest and to keep the ADCP within desired tilt thresholds.

Members from CO-OPS Engineering Division's facility in Chesapeake, Virginia, with support from the University of North Carolina Coastal Studies Institute (CSI), Wanchese, NC, conducted an initial test deployment of the moored ADCP system at field site at the edge of the Gulf Stream approximately 40.75 km (22 nmi) East of Cape Hatteras, North Carolina, starting May 2017. The system was recovered after

401 days. Details of the mooring design, field deployment and recovery operations are presented along with a discussion of the field test results.

II. Mooring System Design

The following top-level requirements guided the system design:

- water depth at the measurement site: 200–300 m
- primary measurement region of interest: within 5–30 m below the sea surface
- max expected current speed at the surface: 2-2.5 m/s (4-5 knots)
- max expected current speeds within 50–100 m below the surface: 1.5 m/s (3 knots)
- minimum deployment duration: 60–90 days
- vertical spatial resolution: 1 m
- data sampling: 6-min average, with sensor internal recording

Based on the top-level system requirements listed above and characteristics of NCOP field sites of interest, a subsurface, taut line mooring with an upward-looking ADCP was selected as the optimal basis for the system design. The option of a surface buoy with a downward-looking ADCP was ruled out, as the size and buoyancy required for a surface buoy and mooring for 300 m water depth with 2 m/s surface currents would result in a system that is very impractical for the short-term deployment/recovery cycle typical of an NCOP tidal current survey (60–90 days). In addition, all NCOP sites of interest experience high shipping traffic, so a system with no surface presence offers a significant advantage. Because real-time data telemetry is not a requirement, there would be no advantage to having a surface buoy platform.

An ADCP is expected to lose profile measurements over approximately 10% of its vertical field of view at the sea surface due to acoustic side lobe interference. As such, one main challenge of resolving near-surface currents in 300 m water depth is positioning the upward-looking ADCP as close as possible to the top section of the water column to reduce the total size of the 10% region of loss. Also, the ADCP tilt must remain less than the $\pm 15^{\circ}$ tolerance required for quality current profile measurements.

The new mooring was designed with support from Mooring Systems, Inc (MSI). A 58 in diameter (1.47 m) ellipsoid-shaped, syntactic foam buoy, which houses the upward-looking ADCP (Fig. 1) along with a GPS locator beacon, is the topmost component. The ellipsoid buoy offers significantly lower drag than a spherical shaped buoy (drag coefficient of 0.07 compared to 0.5) and significantly higher buoyancy (1,155 lb) than streamlined buoys that are currently available in CO-OPS' NCOP existing inventory [1].

A relatively long line is required to position the buoy with ADCP in the topmost section of a 250–300 m water column. Wire rope was selected for this purpose, which combines strength, low weight, and low drag. The topmost section of the wire rope includes a fairing to eliminate potential strumming of the taut line. The particular fairing used was

Fig. 1. Ellipsoid buoy with ADCP from Mooring Systems Inc.

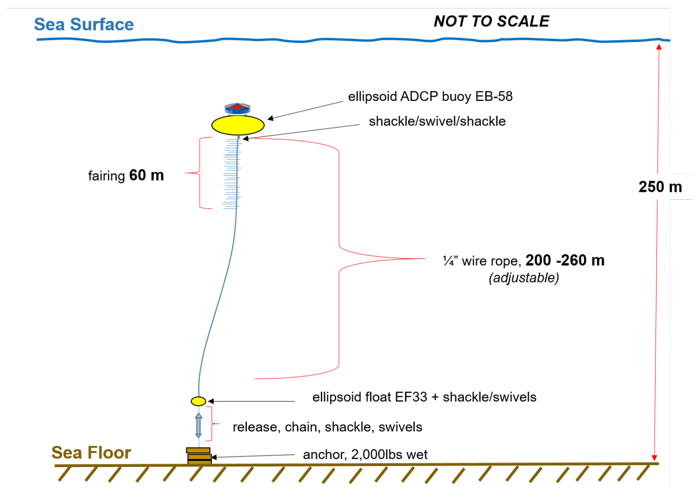

Fig. 2. Design diagram for ellipsoid buoy ADCP mooring

from Zippertubing and consists of 0.01 in thick PVC coated polyester and 3.5 inch long fingers.

The bottom of the mooring includes an acoustic release mechanism with a smaller, 33 in diameter (0.84 m) ellipsoid buoy, with 200 lb buoyancy, to keep the release upright and off the seafloor. The recommended anchor weight for the system is 2000 lb (wet).

In support of CO-OPS' design effort MSI produced results with mooring performance model and prediction software, SMOOR, designed by Henri Berteaux [2], [3], to predict mooring trajectory and loading of the subsurface ADCP buoy for a variety of different mooring configurations. Site conditions listed in requirements were used as model input. Results were used to optimize mooring parameters, focused on positioning a 300 kHz ADCP close enough to the sea surface to resolve the topmost 5–30 m of the water column. Fig. 2 shows a diagram of the mooring and Table 1 provides a top down listing of the mooring's components.

TABLE I
MOORING COMPONENTS

Component	Size/Length	Weight (in air)
ellipsoid buoy	58” x 30”	850lb
shackle	1/2”	NA
swivel	1/2”	NA
shackle	1/2”	NA
wire rope with fairing	1/4” rope, 200m, fairing on topmost 60m	85lb
shackle	1/2”	NA
ellipsoid float	33” x 18”	129lb
shackle	1/2”	NA
chain	3/8”, 2m length	NA
shackle	1/2”	NA
acoustic release	NA	79lb
shackle	1/2”	NA
swivel	1/2”	NA
shackle	1/2”	NA
chain	1/2”, 3m length	NA
shackle	1/2”	NA
railroad wheel anchor	3 standard	2400lb

The make and model of mooring instrumentation components are as follows:

- ADCP - Teledyne RDI, 300 kHz Workhorse, with external battery canister
- Acoustic Release - Edgetech, 8242XS
- Locator Beacon - XEOS Technologies, XMi

The ADCP was configured with a typical CO-OPS NCOP sampling scheme of 6 minute ensembles and 1 meter vertical bins. Considering the mooring line length, planned water column depth, and the ADCP power and memory requirements for a 12 month deployment, the ADCP was configured to measure over 70 bins. Three battery packs (18VDC, 36 D-Cell) were used with the ADCP, one installed in the ADCP unit and the two other in an external battery case. Fig. 3 shows the ADCP and external battery case installed inside the MSI mounting cage for the 58 in ellipsoid buoy.

III. FIELD TEST

A. Test Site

The field site selected for the initial test of the mooring system was 35.1374 N, 75.0940 W, approximately 40.75 km (22 nmi) east of Cape Hatteras, at the continental shelf break (Fig. 4). The depth at this location is approximately 250 m. This region was selected for the following reasons: The location is close to the CO-OPS engineering facilities in Chesapeake, Va; the coast of NC offers the shortest east coast transit to 200–300 m deep water (at the continental shelf break); the edge of the Gulf Stream offers near surface currents 2 m/s and higher; it presented an opportunity for collaboration and technical exchange with University of North Carolina’s Coastal Studies Institute; nearby reference measurements are available for data evaluation including, the IOOS supported HF radar and CSI’s bottom mounted 150 kHz ADCP.

B. Deployment

The vessel selected for the field test deployment and recovery was the CSI 42-foot Duffy offshore research vessel. The vessel has an A-frame, winch and davit suitable for the lift and deployment of the mooring components. It is berthed at the CSI waterfront facility in Wanchese, N.C. (location shown in Fig. 5). Fig. 5 show the vessel before and after the test mooring components were loaded.

Fig. 3. ADCP, extra battery canister, and locator beacon installed in mounting cage of ellipsoid buoy

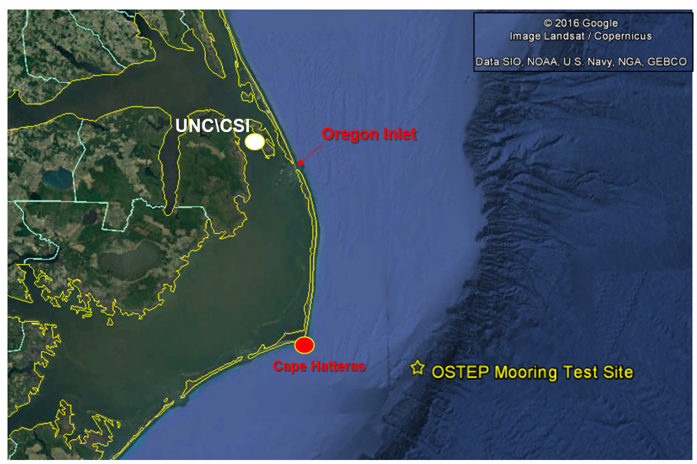

Fig. 4. Field test site, North Carolina, US, coast

The vessel departed the dock on the morning of 17 May 2017. Transit time from CSI to the test site took approximately 4 hours, with arrival on site near 1130 EST. Once on site, the deployment procedure followed a top-down approach (relative to mooring components). First, the topmost buoy with ADCP was lifted and deployed using the vessel’s A-frame and winch. Next, the buoy was allowed to drift out while the moorings wire rope was paid out. Once the rope’s end was near,

Fig. 5. CSI vessel before and after loaded mooring system

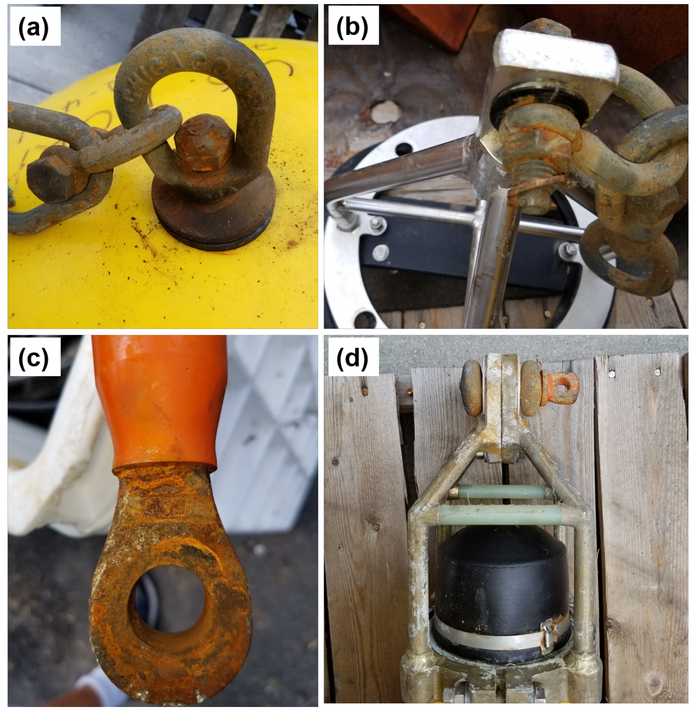

Fig. 6. System components after 401 day deployment: a) swivel, shackle, ring on lower buoy b) shackle and swivel on ADCP cage, c) termination on wire rope, d) top of acoustic release

it was tied off, while the lower buoy and acoustic release were attached and prepared for deployment. Following the deployment of the lower buoy and release, the anchor was carefully dropped off the aft deck using the winch lift and A-frame.

C. Recovery and System Condition

The recovery took place on 22 June 2018, 401 days following the deployment. Upon arrival to the site, communications were successfully established with the Edgetech acoustic release using a Benthos universal deck box. Once within range, a release command was issued and received, and the release successfully detached the mooring from the anchor. Once the top buoy reached the surface the XEOS XMi beacon successfully transmitted latitude-longitude positions (via Iridium satellite system).

After the surfaced buoy was located, the recovery of all components was successfully completed in less than 30 minutes. First, the large topmost buoy was recovered and brought on deck using the vessel's A-frame and winch. The wire rope was brought in by hand, and then the smaller buoy and acoustic release were lifted with the A-frame and winch.

The system's two buoys, wire rope, acoustic release, beacon, shackles, swivels and rings were all in good condition. All swivels maintained rotary mobility. Pictures of the moorings key components following recovery are shown in Fig. 6 and 7.

The system's 60 m section of PVC coated polyester fairing along the top most section of wire rope did not hold up well. As shown in Fig. 7(b)-(d), several sections had torn fingers, some were twisted and deformed sections, and others were torn off and detached from the wire rope. CO-OPS is working closely with MSI to assess what may have occurred and how to improve use of fairing in future deployments.

The power pin on the ADCP bulkhead connector was discovered corroded following recovery. The ADCP used was from CO-OPS existing inventory, had more than 10 years in service and passed a series of pre-deployment checks and tests prior to deployment. Further post-recovery investigation found

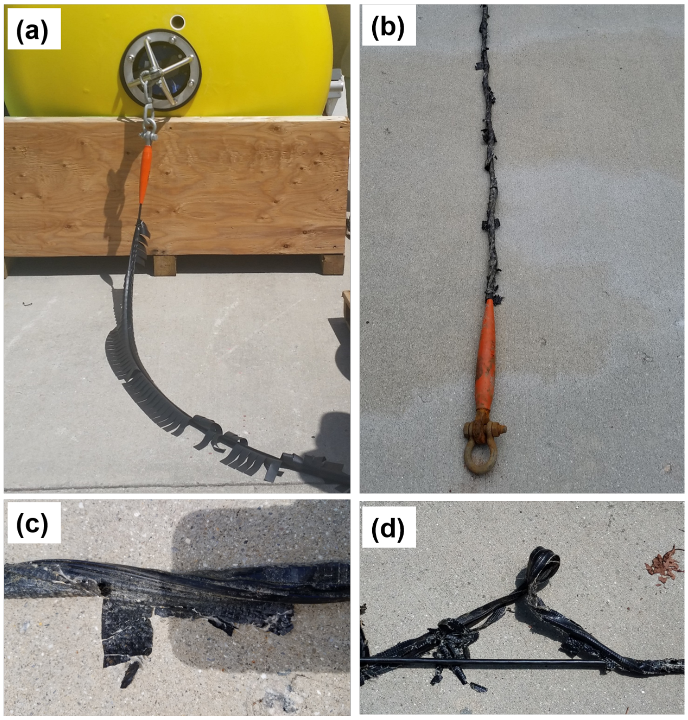

Fig. 7. Wire rope fairing before (a) and after (b-d) field deployment

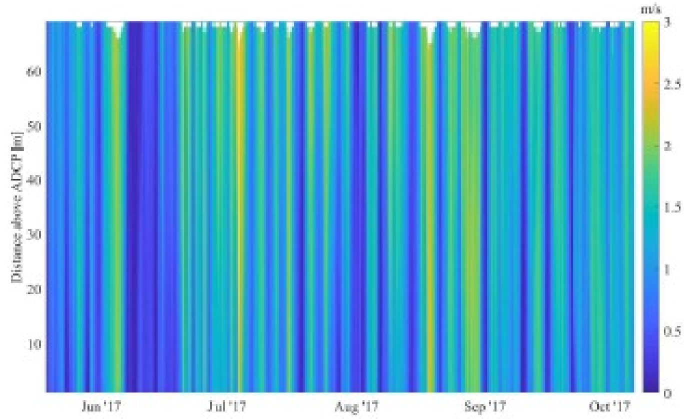

Fig. 8. ADCP profile of current magnitude

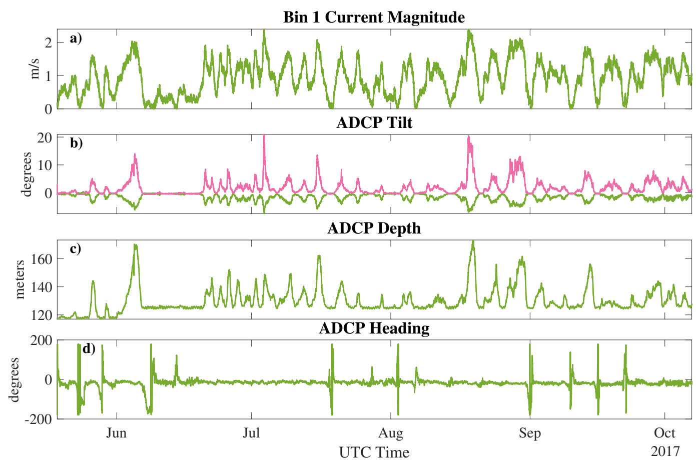

Fig. 9. ADCP measurements: a) bin 1 current magnitude, b) tilt, c) depth, d) heading

that Teledyne RDI (TRDI) had previously noted a similar, commonly reported issue with external connector failures of some WorkHorse ADCPs manufactured prior to March 2012. TRDI summarized findings and recommended corrective actions in a field service bulletin that was published in August 2012 (FSB-208). Reported cases of connector pin corrosion involved system configurations where the ADCP was cabled to an external battery case, as it was in the system reported here. CO-OPS missed addressing the issue with the particular ADCP unit used during the field test reported here, in part due to CO-OPS's limited use of external battery canisters for ADCPs in NCOP current survey applications. For most NCOP applications, ADCP deployment duration ranges from 45-90 days, and a single battery pack installed inside the ADCP unit itself provides adequate power supply.

The recovered ADCP data indicate the sensor operated and recorded successfully for approximately six months of the 13 month deployment. Data missing for the last seven months of the test are most likely a result of the ADCP failing after the power pin corroded. The resulting available data are adequate for assessment of the mooring systems performance.

IV. Results

Fig. 8 shows profiles of the horizontal current magnitude from May - October 2017. Data shows that a broad range of currents occurred at the site throughout the field test, resulting in an excellent data set to evaluate system performance. During the six months of data collection, currents were in the range from 1.5-2 m/s. On a few occasions, currents in the entire vertical measurement range remained below 0.5 m/s for several days; and currents reached as high as 3 m/s in the upper portion of the ADCPs vertical aperture. It is important to note that the intended location depth was 250 m, which would place the buoy and ADCP at 50 m depth. Due to current speed, wave conditions, and vessel size, it was difficult to deploy in a precise location. Based on pressure readings, the system was deployed in water approximately 325 m deep, and the buoy was at 125 m depth.

Fig. 9(a) shows a time series of currents at the ADCP's first range bin, representative of currents closest to the buoy, and corresponding motion data available from the ADCP sensor: (a) tilt from the liquid tilt sensor (b) depth from the pressure sensor, and (c) degree heading from the compass.

An initial look at a scatter plot of sensor tilt versus current speed (Fig. 10) shows that the ADCP remained within the recommended tilt threshold of ±15 degrees for the majority of the test. The threshold was slightly exceeded on a small number of occasions, when current speeds near the ADCP buoy exceeded 2 m/s.

Preliminary analyses of depth excursions estimated from

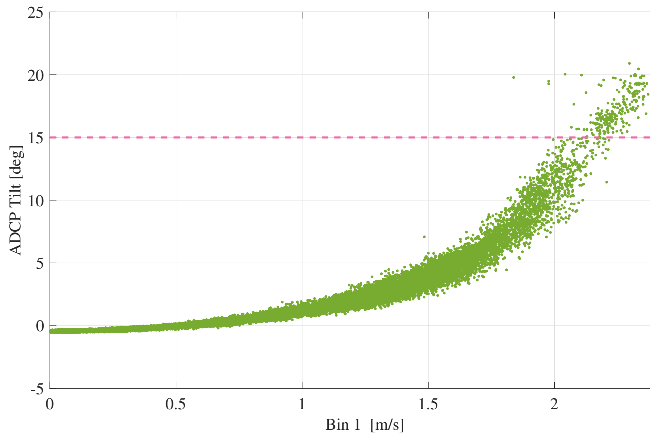

Fig. 10. ADCP tilt versus bin 1 current magnitude

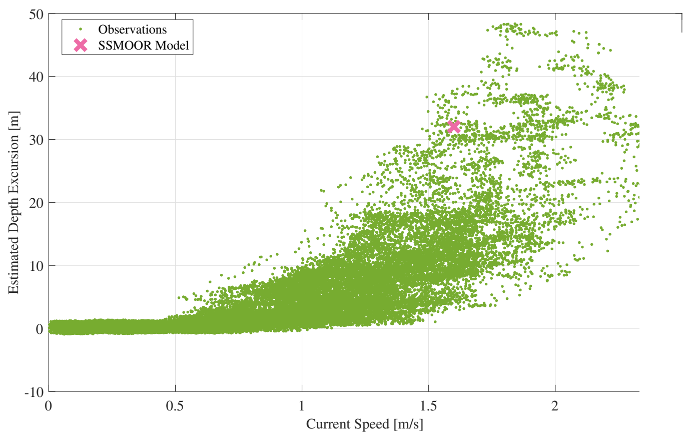

Fig. 11. Measured depth excursion versus bin 1 current magnitude (dots). Pink x is modeled depth excursion from SMOOR

the ADCP pressure sensor readings show excursions remained within a reasonable range when considering system configuration options and measurement requirements. Fig. 11 shows observed depth excursions versus bin 1 current speeds (green dots). The pink x shows the estimated maximum expected depth excursion provided by MSI from SMOOR model outputs. The maximum excursion experienced by the buoy in currents speeds around 1.5 m/s, about 30 m, matches the output from the model. As the current speeds reach 2 m/s and greater, the maximum observed buoy depth excursions are approximately 50 m. One feature seen in Fig. 11 that warrants further evaluation is the broad range of depth excursions experienced at a given current speed. For instance, at 1.5 m/s, we see excursions that range from approximately 0 m to 30 m. At times, current speed peaks correspond to deeper excursions, and on other occasions, they do not (Fig. 12).

First we compared depth excursion to ADCP tilt (Fig. 13). We see a general correlation between tilt and excursion, but this is expected due to the link between current speed with tilt and current speed with excursion. Overall, we could not use tilt to explain the range of excursions seen at individual current speeds.

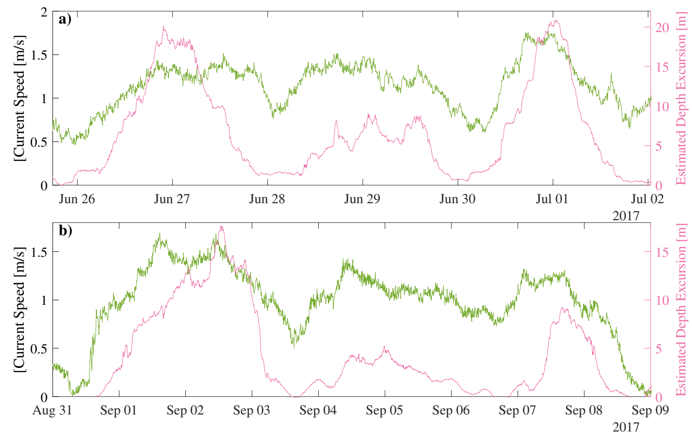

Fig. 12. Examples of varying mooring depth excursion (pink, right axis) during current peaks (green, left axis)

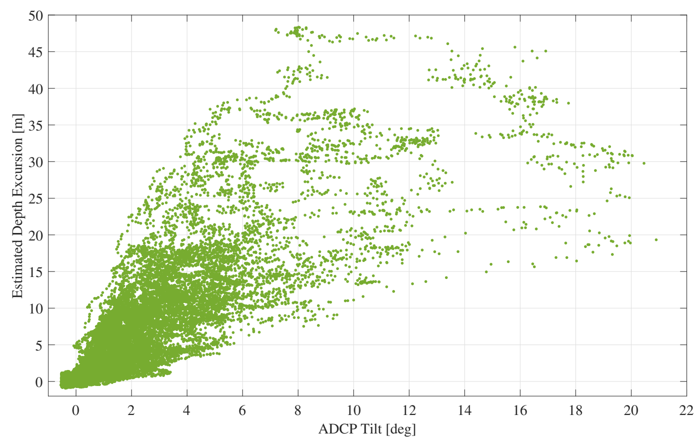

Fig. 13. Mooring depth excursion versus ADCP tilt

Since currents shown in Fig. 11 are only from the single ADCP range bin closest to the buoy, next we consider the impacts of the current profile in the lower region of the water column, below the buoy. Initial modeling efforts by CSI used a current profile with 2.05 m/s at the surface, 1.54 m/s from 5 m to 100 m , and then a linear drop to 0 at the sea floor. Unfortunately, there are no measurements of current profiles available below the mooring's buoy from the test time and location. However, CSI had deployed a bottom mounted 150 kHz ADCP about 20 mi south and closer to shore, though along the same cross shelf transect. There is only a short period of overlapping records between this CSI ADCP and the test subsurface buoy mooring, but results provide and example of the variety of current profiles near the test region.

The test mooring system was located on the edge of the continental shelf break, where the Gulf Stream edge follows. The current speeds and profiles in the region can vary greatly, depending on the location of the Gulf Stream, as shown in example measurements from the CSI bottom mounted ADCP. When the stream is against the shelf slope, the higher velocity currents are pushed against it and can be seen nearly to the

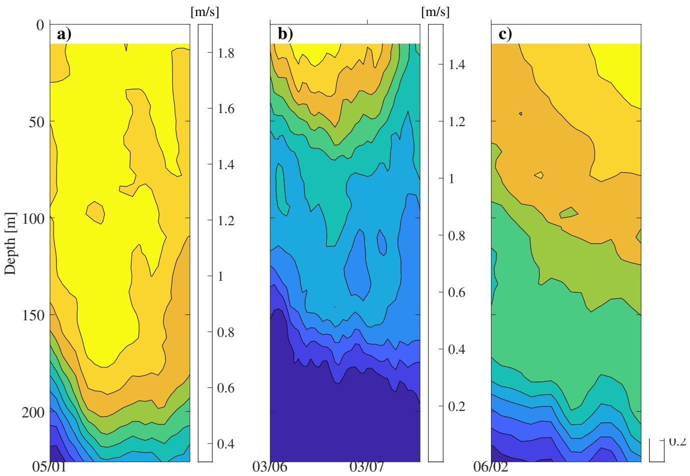

Fig. 14. Examples of current profiles seen from CSI bottom mounted ADCP

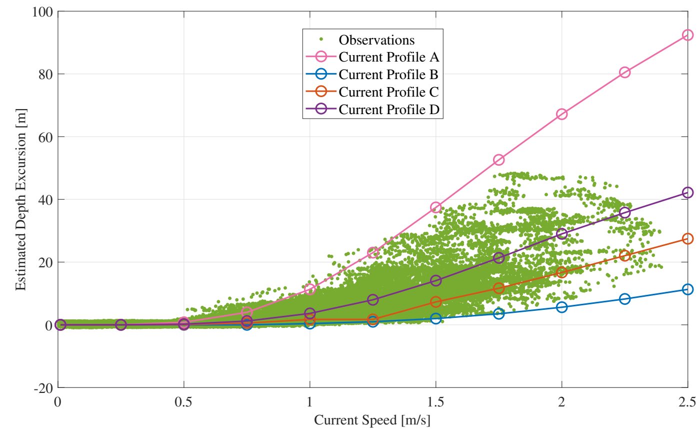

Fig. 15. Measured depth excursion versus bin 1 current magnitude (green dots). WHOI Cable model results for four different current profiles are shown in pink, purple, orange, blue

bottom. When it is offshore of the slope, higher currents are located only near the surface.

Fig 14 shows examples of current profiles measured by the CSI bottom mounted ADCP mentioned above. Select examples show uniformly high velocity currents (a), or located only near the surface (b), or there can be a linear-like drop from surface to bottom (c). Though these profiles were captured in the month before our system's deployment, and a distance away, they provide an example of current profile variability in the region resulting from meanders of the Gulf Stream along the continental shelf break.

To examine the effect of different current profiles on the mooring, we used the program WHOI Cable [4], a time domain numerical simulation of moored and towed oceanographic systems. Mooring system components were input into the software, and a static solution was found for a variety of current profile scenarios. Results are shown in Fig. 15. We tested four different current profiles: uniform current (A), linear drop to 0 m/s from 0 m to 325 m (B), uniform current from 0 m to 100 m, linear drop to 0 m/s to 325 m (C), and uniform current from 0 m to 150 m, linear drop to 0 m/s at 325 m (D). Observations from the field test are shown in green, where current speed is that from bin 1, near the buoy. In each profile, the current along the x-axis is the surface current (which is the same as the current magnitude near the buoy in scenarios C and D). The pink line is results from model using current profile A, uniform current. This result is consistent with observations with highest depth excursions. The blue line shows results using current profile B. These results align with observations with the lowest excursions. The orange and green lines are results from current profiles C and D, respectively. One can see from model results the impact of the current profile over the enture water column on the ADCP buoy depth excursion magnitude. As currents are increased across the lower section of the water column, the modeled depth excursions increase, as expected considering the forcing impacts on the more than 200 m of mooring components below the topmost buoy. It is encouraging that the range of possible current profiles input into the model results in a series of corresponding depth excursions that span the range of those observed. Additional modeling work will consider the potential for the buoy's actual drag coefficient to be higher than the theoretical value specified previously (0.07).

V. Conclusions

Emerging CO-OPS NCOP applications at U.S. west coast sites require current profile measurements in the topmost portion of a water column with 200-300m depth. To address this need, CO-OPS worked with MSI to design a subsurface moored system using an ellipsoid buoy with an upward looking ADCP. CSI and CO-OPS worked together to complete the first field test deployment of the mooring off the coast of North Carolina, on the edge of the Gulf Stream. Observing system deployment and recovery were successfully completed and the mooring system performed outstanding. With the exception of the 60 m section of fairing, all mooring components were recovered in excellent condition following the 401 day deployment. ADCP measurements cover 6 months capturing a broad range of current conditions, resulting in an excellent data set to further evaluate system performance. Initial analyses of the data show that the ADCP remained within the desired sensor tilt threshold (±15 degrees) for more than 99% of the time. Observed depth excursions remained close to or less then the model result used to guide system design analysis prior to the field test deployment (SSMOOR results generated by MSI). However, observations show a large range of buoy depth excursions for instances of each particular near surface buoy current speed. Results from previous CSI ADCP measurements and study show a wide range of vertical current profiles experienced near the test site, mainly driven in meanders of the Gulf Stream edge along the continental shelf break. Variation in current profile below the test mooring systems buoy is very likely one reason for the significant range in buoy depth excursions that we see at each near buoy current speed instance. Results generated with the WHOI

Cable modeling software, using a range of possible current profile scenarios, confirm the potential impact of lower water column currents on buoy depth excursions. The range of modeled depth excursions fit nicely over the range of observed excursions over each near buoy current speed. Continuing work will include additional modeling to guide design details and field deployment plans. An additional field deployment involving an ADCP with replaced end cap and a wire rope with new fairing, along with other minor system enhancements, is planned for 2019.

ACKNOWLEDGMENT

The authors would like to thank both Paul Devine (Teledyne RD Instruments) and James Cappellini (Mooring Systems, Inc), for system design and modeling support; and special thanks to the staff of the Coastal Studies Institute, including Nick DeSimone, and Patterson Taylor III, for system design review and many things related to the planning and execution of a successful field deployment and recovery.

REFERENCES

[1] R. W. Bourgerie, T. Garner, and H. Shih, "Coastal current measurements using an adcp in a streamlined sub-surface mooring buoy," in *OCEANS'02 MTS/IEEE*, vol. 2, pp. 736–741, IEEE, 2002.

[2] H. O. Berteaux, A. Bocconcelli, C. F. Eck, and S. M. Kery, "In situ measurements of the dynamics of a full scale bottom moored mine model," tech. rep., Woods Hole Oceanographic Institution, 1993.

[3] H. O. Berteaux, *Buoy engineering*. Wiley New York, 1976.

[4] J. I. Gobat and M. A. Grosenbaugh, "Whoi cable v2. 0: Time domain numerical simulation of moored and towed oceanographic systems," tech. rep., Woods Hole Oceeanographic Institution, MA, 2000.