Development and Test of Subsurface ADCP Mooring for Near Surface Current Profiles in 200-300m Waters

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***Abstract*—The National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services (CO-OPS) and the East Carolina University Coastal Studies Institute (CSI) have collaborated to complete two successful, long-term field demonstrations of a new ADCP mooring, developed to address current survey needs. Recent NOAA National Current Observation Program (NCOP) field applications have required current measurements in the top 30m of a 200-300 m water column, for a 60-90 day duration. Maximum near surface current speeds at sites of interest range from 2-2.5 m/s. Historical current observations at these CO-OPS sites only measure currents beneath 50m due to limitations of the sampling methods and platforms, so derived navigational support products are not representative of conditions near the surface.**

CO-OPS developed and field tested a subsurface, moored buoy system consisting of commercial-off-the shelf (COTS) components. As its top- most component, the mooring employs an ellipsoid shaped, syntactic foam buoy, with an upward looking 300 kHz acoustic Doppler current profiler (ADCP). A relatively long line is required to position the buoy with ADCP in the upper 100m of the 250-300m water column. A strong, light weight, low- drag wire rope with fairings along the top 60m was selected for this purpose. The two field demonstrations of the new ADCP mooring were conducted during May 2017- June 2018 and October 2020 - August 2021. Both field deployments took place offshore of Cape Hatteras, NC near the edge of the Gulf Stream, where 200-500m water depths are on the shelf slope in an area frequented by Gulf Stream incursions. Results from the first field deployment are reported in two conference proceedings papers (MTS/IEEE OCEANS18, Charleston and CWTMC19, San Diego). The focus of this paper is on the latest mooring design, deployment method enhancements and results from the second field demonstration.

***Index Terms*—ellipsoid buoy, ADCP, near surface currents, subsurface buoy**

I. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) 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. Routine current surveys are conducted annually. 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 recent NCOP current survey applications have required short term collection (60-90 days) of current profile measurements in the top 30m of the water column at sites with water depths ranging from 200-300m and maximum near surface current speeds of 2-2.5 m/s. Sites of interest include North Inian Pass, Alaska as well as several locations across the Puget Sound and Straits of Juan de Fuca, Washington. Due to limitations in the present NCOP measurement system inventory, previous surveys at sites with the above conditions only capture current profiles at depths from 50 m below the sea surface and deeper. Thus, 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.

To address these critical shortcomings, CO-OPS has developed and field tested a subsurface, moored buoy system consisting of commercial-off-the shelf (COTS) components. As its top- most component, the mooring employs an ellipsoid shaped, syntactic foam buoy, with an upward looking 300 kHz acoustic Doppler current profiler (ADCP). The ellipsoid buoy offers lower drag than a spherical shaped buoy and higher buoyancy than some other available streamlined buoys. A relatively long line is required to position the buoy with ADCP in the upper 100m of the 250-300m water column. A strong, light weight, low- drag wire rope with fairings along the top 60m was selected for this purpose.

NOAA and the East Carolina University Coastal Studies Institute (CSI) have collaborated to complete two successful, long-term field demonstrations of the new ADCP mooring, during May 2017- June 2018 and October 2020 - August 2021. Both field deployments took place offshore of Cape Hatteras, NC near the edge of the Gulf Stream, where 200-500m water depths are on the shelf slope in an area frequented by Gulf Stream incursions. The region provides an ideal test environment for NOAA's new mooring system and also includes a region of interest for CSI for physical oceanography and renewable energy research. Previous CSI current observations in this area provided critical baseline information that informs the energy, oceanography, biogeochemistry and climate change communities.

Results from the first field deployment are reported in two conference proceedings papers [1], [2]. The focus of this paper is on the latest mooring design and deployment method enhancements and results from the second field demonstration. The referenced proceedings papers (2018, 2019) summarize results from the May 2017 - June 2018 field test, including comparisons of measured currents to those from a nearby bottom mounted 75 kHz ADCP and HF radar, and mooring model results to interpret observed buoy motion. The deployment and recovery procedures were successful and the system performed well. With the exception of the fairing, all mooring components were recovered in excellent condition. A broad range of current conditions were captured, with currents near the buoy ranging from 2-3 m/s. Data indicated the ADCP remained within the desired sensor tilt threshold (±15 degrees) more than 99% of the time, and observed buoy depth excursions compared well with model results.

While the initial deployment was for the most part successful, there were two major shortcomings that needed to be addressed, which led to the second test deployment in 202-2021. The first shortcoming was the depth at which the buoy was deployed. The ultimate goal of the deployment was to capture currents in the upper 50m of the water column. Due to variability in the site bathymetry and difficulty deploying, the buoy was anchored in deeper water than intended. The other major shortcoming that needed to be addressed was the fairings used to reduce drag on the mooring line. The Zippertubing fairings, which consist of 0.01 in thick PVC coated polyester and 3.5in long fingers, did not work as intended. It is likely that they initially increased the drag on the mooring, and then eventually broke apart. Because of the breakdown of the fairings, drag increased and, at times the buoy was more than 100m below the surface. The improvements made to the system in order to address these and other issues are described below.

Based on results and lessons learned from the initial test, several design enhancements and improvements on deployment and recovery were made. These include new fairings, the use of an improved ADCP cable, the change from a single to a dual acoustic release system, improved deployment methods, and better site selection. Additionally, two conductivity-temperature-depth (CTD),sensors and one acoustic monitoring and logging device were included along the mooring line. The CTD sensors were intended to support detection of different large scale water masses entering the region and the acoustic device was in support of Florida Atlantic Coast Telemetry Network (FACT) fish tracking efforts. The second field test was conducted near the first, approximately 22 nmi (40.75 km) East of Cape Hatteras, North Carolina, starting on 15 October 2020. The site is at the edge of the Gulf Stream and the depth is approximately 235 m. The system was successfully recovered on 18 August 2021, resulting in a 306 day field test.

Details of the mooring design and enhancement, field deployment and recovery operations are presented along with field test results.

II. SYSTEM DESIGN AND ENHANCEMENTS

The following top-level requirements guided the initial 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)
- deployment duration: 60–90 days
- vertical spatial resolution: 1 m
- data sampling: 6-min average, with internal sensor recording

Based on the top-level system requirements listed above, along with other 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 system consists of a 58 inch diameter (1.47 m) ellipsoid-shaped, syntactic foam buoy, which houses the upward-looking ADCP along with a GPS locator beacon, wire rope with fairings on the top portion, a 33 in diameter ellipsoid float, and an acoustic release (Fig. 1). Table 1 provides a top down listing of the mooring's components.

Sensors on the mooring include:

- Teledyne RD Instruments (TRDI) 300 kHz Workhorse ADCP, with external battery pack (upward looking, at top of mooring in EB-58 buoy)
- Two SeaBird SBE37 SMP Conductivity-Temperature-Depth Sensors (both on the wire rope, one just below the EB-58 buoy, one approximately 70 m down)
- Vemco acoustic monitoring receiver and logger
- XEOS Technologies Xmi GPS locator beacon
- Two Edgetech 8242 acoustic releases

Several design enhancements were made for the second field test based on results from the first. As noted in the

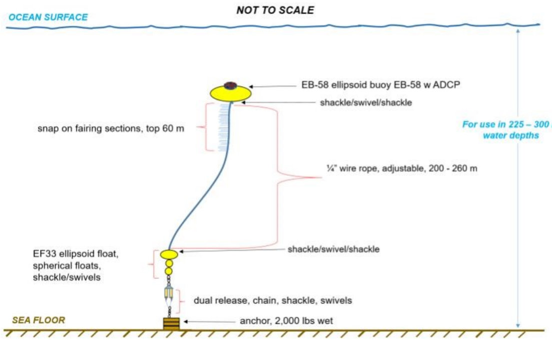

Fig. 1. Mooring diagram

TABLE I
MOORING COMPONENTS

Component	**Size/Length**	**Weight (in air)**	**Buoyancy**
ellipsoid buoy	58” x 30”	850lb	1,155lb
shackle	1/2”		
swivel	1/2”		
shackle	1/2”		
wire rope with fairing	1/4” rope, 200m, fairing on topmost 60m	85lb	
shackle	1/2”		
ellipsoid float	33” x 18”	129lb	200lb
dual sphere float	14” diameter (2)	30lb total	75lb
shackle	1/2”		
chain	3/8”, 2m		
shackle	1/2”		
dual acoustic release and mounting system		190lb	
shackle	1/2”		
swivel	1/2”		
shackle	1/2”		
chain	1/2”, 3m		
shackle	1/2”		
railroad wheel anchor	3 standard	2500lb	

introduction above, these consisted of replacement fairings, and deployment technique enhancements. One notable result from the first deployment was the failure of the fairings on the top portion of the mooring line. The fairings were very damaged upon recovery, and it is unclear how long they may have lasted (Fig. 2a,b). Additionally, the movement of the buoy from the onset of the test indicates that the fairings did not reduce drag, and may have even increased it. For the second deployment, snap-on plastic fairings from Deep Water Buoyancy were used instead (Fig. 2c). A second change made to the mooring was the replacement of the single acoustic release with one with dual release capabilities to reduce the risk associated with recovery operations.

III. FIELD TEST

A. *Test Site*

The test site for both deployments, approximately 22 nmi (40.75 km) East of Cape Hatteras, was selected for the following reasons:

Fig. 2. A) Field test one fairings before deployment, B) Field test one fairings after deployment, C) Field test two, snap on fairing example

- A mid-Atlantic field test 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
- Opportunity for collaboration and technical exchange with East Carolina University Coastal Studies Institute (ECU\CSI)
- Nearby reference measurements are available for data evaluation including, the IOOS supported HF radar and CSI’s bottom mounted 150 kHz ADCP

The coordinates of the second test was 35°08.306’ N, 75 °06.344’ W and the water depth was approximately 235m (Fig. 3).

B. *Deployment and Recovery*

The vessel selected for the field test deployment and recovery was the ECU\CSI 42-foot Miss Caroline offshore research vessel (Fig. 4). The vessel has an A-frame, winch and davit suitable for the lift and deployment of the mooring

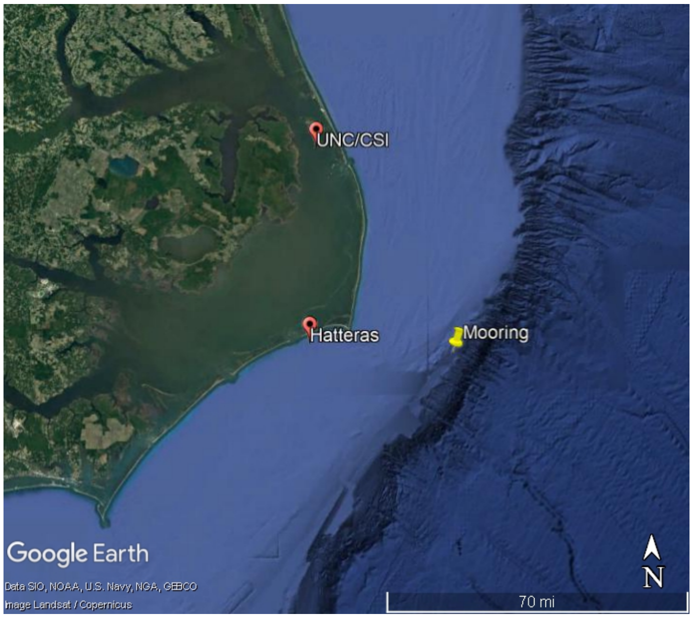

Fig. 3. Map with test site location

Fig. 4. RV Miss Caroline used to deploy and recover the mooring with the mooring visible on the deck

Fig. 5. Deployment photos - clockwise from top left: large elliptical buoy deployed, view of the deployment from drone footage, anchor being moved into place, tabletop for fairing installation, preparation of smaller elliptical buoy

components. Dr. Muglia's team of highly trained and qualified vessel operators and marine technicians have two decades of expertise deploying oceanographic equipment across the NC continental shelf and Gulf Stream region. The vessel is berthed at the ECU\CSI waterfront facility in Wanchese, N.C. (location shown in Fig. 3).

Deployment methods were improved for the second test based on previous experience. Based on maximum observed and modeled depth excursions, the length of the wire rope was optimized for the planned deployment depth, and the ADCP was configured to optimize the vertical sampling range. CO-OPS and CSI collaborated to develop an improved cable reel and spool system for controlled payout of the 200m wire rope section. An improved anchor deployment method and mechanism was also developed. During the second deployment, careful planning and execution ensured that the mooring system's final anchoring location was in optimal water depth to ensure measurement of the topmost region of the water column.

The buoy was deployed on 15 October 2020. 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. The topmost CTD sensor and several fairings were already attached. Next, a fitted section of plywood was placed atop the buoy's holding crate to serve as a tabletop for fairing installation. The buoy was allowed to drift out while the mooring's wire rope was paid out , controlled by the wire rope reel and spool system. During the controlled cable payout, 12 inch fairing sections were snapped on one at a time using the tabletop work area. The fairing installation process took less than 20 minutes. The second CTD sensor was clamped to the wire rope after the last (200th) faring was attached (approximately 65 m down from the ADCP buoy). Once the 200 m wire rope's end was near, it was tied off to a vessel stop point, while the lower buoy and dual acoustic release were prepared for deployment. Following the attachment and deployment of the lower buoy, release, and chain, the anchor was deployed using an improved anchor lever arm and lift technique. The lever arm was extended into a two section railway. This allows the anchor to be positioned further forward during transit, and then once on site, the vessel winch and pulley system can be used to slide the anchor to the vessel stern for the same type of lever arm drop off that was used during the 2017 deployment [1], [2]. Photographs of deployment procedures are shown in Fig. 5.

The system was recovered on 18 August 2021, 306 days following the deployment. Upon arrival at the site, communications were successfully established with the Edgetech acoustic release using a Benthos universal deck box. 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 beacon transmitted latitude-longitude positions (Fig. 6). The buoy was located and all components were recovered using the vessel's A-frame and winch.

IV. RESULTS

A. Mooring Durability

The system's two buoys, wire rope, acoustic release, beacon, shackles, swivels and rings were all in good condition. All swivels maintained rotary mobility. Some example pictures of the moorings key components following recovery are shown in the series of pictures in Fig. 7. Some biofouling occurred (Fig. 8), but was not serious enough to have impeded either the ADCP measurements or the mooring system functionality. No evidence of an increase in biofouling during the deployment was evident in the ADCP acoustic returns, pitch and roll, or other metrics.

The fairings held up well during the deployment. About 75% of them were still attached and in good condition when the wire was recovered. Similarly to the first field test, there was a problem with one of the pins on a connector for the ADCP. Previously, a power pin on the ADCP bulkhead connector was corroded, so the ADCP stopped recording about sux months into the deployment. This time, a pin on the power cable was corroded and the ADCP stopped recording 8 months into the deployment.

The CTD sensor that was attached to the wire rope just below the topmost ellipsoid buoy was successfully recovered, however, the second, lower CTD was lost. The CTD sensors were attached to the wire rope only with SeaBird's standard plastic compression clamps. It is speculated that tightened bolts may have sheared threading in the plastic clamps. Future deployments should include a secondary, backup method of CTD attachment.

B. System Performance

While the system was deployed for 306 days, due to the corroded ADCP battery pin, the ADCP stopped working on 20 June 2021, 248 days into the deployment. All data was recovered from the operational period. The topmost Seabird recorded data for the entire deployment period, while the lower one was not recovered. To perform quality control on an ADCP, one of the first tests performed is to find peaks in echo amplitude, which indicates a boundary like the sea surface. Bins beyond this boundary are flagged as bad and removed for the time series. As the ellipsoid buoy in this case moves up to 30m vertically in the water column, choosing one cutoff bin for the entire deployment would result in the loss of a lot of potentially good data. We developed an algorithm to remove the "bad" bins for each sample independently. We stepped through each one second sample to find the largest peak of the echo amplitude, and remove anything above. Additionally, once the surface bin is identified, several bins below the surface are removed due to side lobe interference caused by the angled ADCP beams reflecting off the relatively hard surface return. This is done for each of the four beams to ensure that any bad data is removed. Fig. 9 illustrates this process. Fig. 9a shows the echo amplitude of beam 1. One can see the peak that varies between bins 10 and 35. An example of a one second time sample of echo amplitude is shown in Fig. 9b. The red dot indicates the last bin (8 in this case) before the first large peak. Finally, Fig. 99c shows the echo amplitude after each "bad" bin is removed. The black line indicates the buoy position.

Fig. 10 shows the horizontal current magnitude profile measured from October to June during the field test. 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 eight months of data collection, currents generally ranged from 0-2.5 m/s, but did reach as high as 3 m/s on a few occasions. For this portion of the water column, the speeds were mostly uniform vertically. Depth adjusted currents in figure 10 show that for the majority of the test, the upward ADCP successfully sampled current profile in the desired vertical aperture of the water column 10-25 m below the sea surface.

Fig. 11a 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 (b) depth, and (c) degree heading. The recommended tilt threshold to ensure accurate results for the RDI Workhorse is 15 degrees. The buoy exceeded this threshold in less than 5% of the samples, primarily when current speeds at the buoy were over 2.1 m/s.

The first field test was unsuccessful in capturing the full upper portion of the water column, because the knockdown of the buoy was much larger than expected. In addition to

Fig. 6. Both of the mooring systems ellipsoid buoys surfaced following acoustic release from sea floor upon recovery

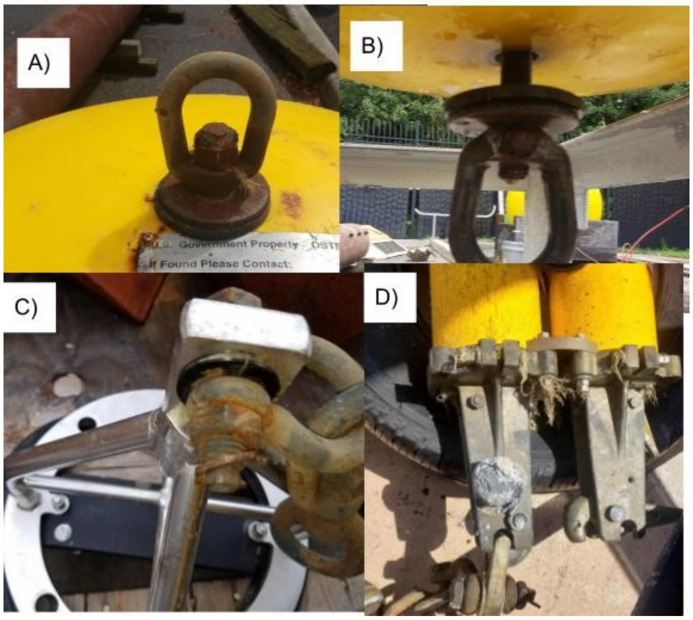

Fig. 7. System components upon recovery. A-C) Shackles & swivels, D) Acoustic releases

Fig. 8. Evidence of some biofouling on the buoy and cage

being placed in deeper water than intended, the buoy ended up moving as much as 50m vertically (Fig. 12). For the second field test, the final anchor location was in the targeted depth (235m) and the knockdown was significantly reduced by the use of the snap-on fairings. The maximum vertical excursion experienced by the buoy was 30m.

C. Model Comparison

In order to better understand the forcing mechanisms that drive mooring dynamics and to support continued design enhancements, a marine dynamic analysis software, Proteus DS [3], was used to interpret observed mooring motions. DSA Ocean's Proteus DS is a time-domain, finite element, dynamics analysis software package that can be used to test offshore and subsea marine systems, including buoy moorings. Before the first test, we had model results from both SMOOR and WHOI Cable. We initially concluded that the model and test results compared well. However, after addressing issues with mooring configuration in the model setup, corrected knockdown results from the model software did not correspond well to the ADCP measurements, and the knockdown of the buoy was much larger than expected at higher current speeds. We worked with DSA Ocean to construct a better model representation of the mooring system. With the improved model setup, we determined that the fairings were most likely increasing the drag instead of lowering it. After adjusting the drag coefficient for the section of wire containing the fairings,the model results matched well with the test results.

For the second field test, the model was updated with the parameters for the new snap on fairings, wire length, and water depth. The model results, including tilt and knockdown, matched well with those from the test (Fig. 13). The model was run several times, using different current profiles. We cannot know the exact current profile below the mooring's topmost buoy where the upward looking ADCP measurements start, but have included a range to cover most likely velocity profile scenarios, including linear drop to 0 m/s from top to bottom, uniform to the bottom, and uniform in the top 50m with a linear drop from 50m to bottom. Observed tilt compared best with the linear current profile. At greater than 1 m/s surface current speeds, the other modeled profile options lead to a very large tilt in the model results that was not observed in the field data. Model outputs can vary significantly for different vertical current profile types. The linear current profile knockdown results align with the center of field test results. The other two profiles match well with the upper envelope of the knockdown results. The two current

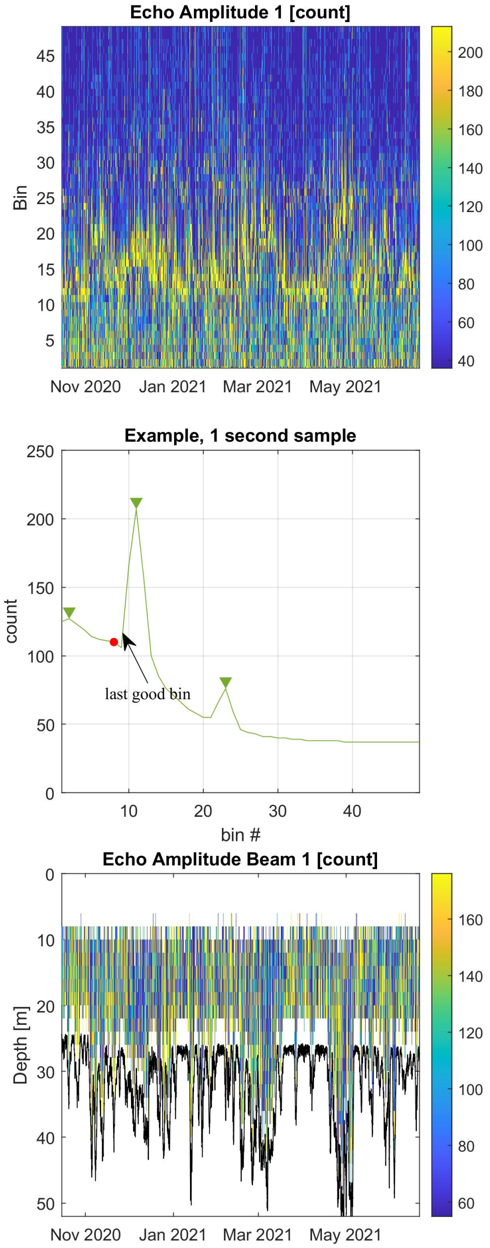

Fig. 9. Echo Amplitude Quality Control method illustrated for beam 1

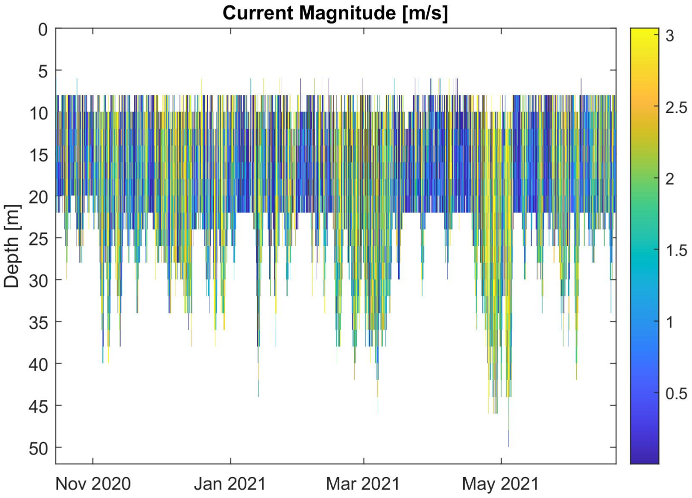

Fig. 10. Current magnitude for the duration of the ADCP dataset, showing maximum velocities of about 3 m/s (6 knots).

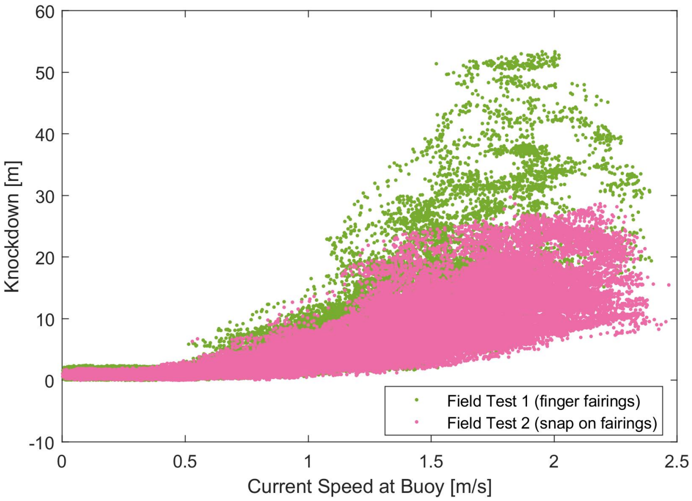

Fig. 12. Knockdown comparison between the first test (green) and the second field test (pink)

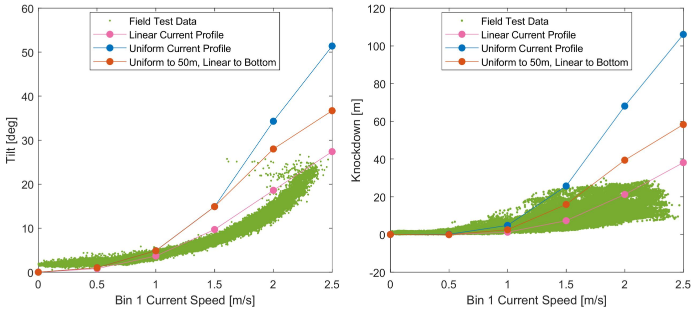

Fig. 13. Model tilt comparisons to field data (panel 1) and knockdown comparison (panel 2)

profile results with uniform currents in all or part of the profile compare less well as surface current speed increases, confirming that the current speeds below the buoy may not be as high as the surface. Future work will involve closer evaluation of different potential current profiles lower in the water column along with investigation of true/empirical drag coefficients versus theoretical drag specified by component manufacturers. Additionally, temporal variation in knock down and tilt will be investigated in order to consider the impact of marine growth on buoy drag.

V. Conclusion

Results from the two NOAA CO-OPS and ECU\CSI field deployments have demonstrated successful performance of the new ADCP mooring system. Results and experiences from the initial field demonstration led to several enhancements in the system design and deployment methods, leading to improved results during the second deployment. Aside from the loss of one CTD sensor and 25% of the snap on fairings, the mooring was successfully deployed and recovered in a relatively dynamic, high risk coastal environment. The duration of the first field demonstration was 13 months and the second 10 months, both far exceeding the 60-90 day duration to be required for future NCOP applications.

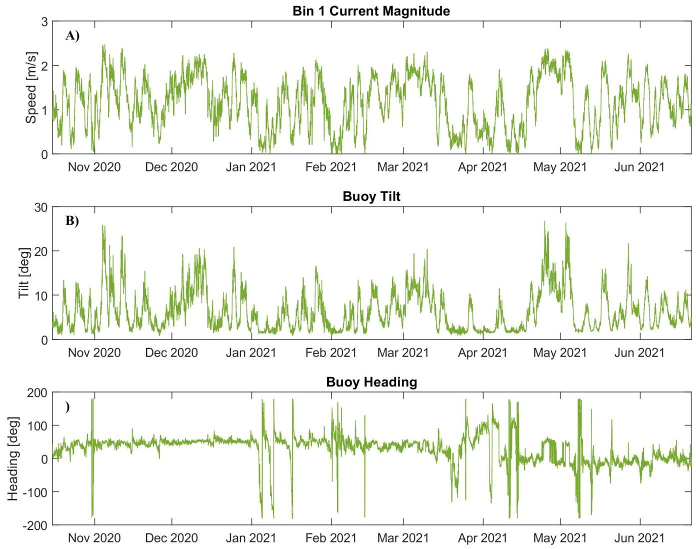

Fig. 11. ADCP motion

A major improvement in mooring design for the second field test was the replacement of the finger fairings with snap-on fairings from Deep Water Buoyancy. The second field trial was in the same region as the first, but inshore in a shallower water depth 235m. A broad range of current conditions were captured, with currents near the buoy ranging from 2-3 m/s. Observations from the instrument indicate the ADCP remained within the desired sensor tilt threshold (±15 degrees) for more than 95% of the time and the observed tilt and buoy depth excursions compared well with model results. Knockdown was significantly diminished with the use of the new fairings. As a result, the system was more successful in capturing the velocity observations at the top of the water column in the second demonstration. For the majority of the test, the upward ADCP successfully sampled the current profile in the desired vertical aperture of the water column 10-25 m below the sea surface.

The model results from the Proteus DS software, including tilt and knockdown, compared well with those from the second field test. Future efforts will involve further use of the Proteus mooring modeling software to guide mooring design details and deployment plans based on expected conditions at sites of interest.

Future plans include deploying the new mooring system in various coastal regions of the U.S. Pacific Northwest to support NCOP objectives to improve various current prediction analysis products. Locations of interest include Puget Sound, WA, North Inian Pass, AK and other tidally influenced regions with 200-300m water depths along the coasts of northern California and Alaska. Adequately resolving current profiles in the water columns top 30 meters at these locations has eluded the program until now.

CO-OPS is also discussing with ECU\CSI plans for additional collaborative deployments of the new mooring system off the coast of Cape Hatteras, North Carolina. Although initial deployments in the two test locations described above primarily served CO-OPS' objectives of system development, test, and evaluation, resulting near surface current data at the sites are valuable for a range of different CSI research applications. CSI research applications include assessment of potential marine renewable energy and the study of processes that drive the exchange of water between the deep ocean and continental shelf [4].

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