Velocity Measurements from a Moored Profiling Instrument

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Abstract—Velocity profile measurements from a recently-developed moored profiling instrument are discussed. The WHOI Moored Profiler uses a traction drive system to propel itself along a standard subsurface mooring cable at a nominal speed of 0.3 m s^{-1}. The instrument's onboard controller supports complex sampling scenarios, limited chiefly by the configuration of the mooring and the capacity of the battery. The vehicle has thus far been equipped with a CTD and an acoustic travel-time current meter; data from the latter are examined here. As part of this assessment, comparisons are made between velocity profile data obtained with Moored Profilers and those obtained from an Expendable Current Profiler, the High Resolution Profiler, and a Lowered Acoustic Doppler Profiler. We conclude with a summary of possible applications for the new instrument.

I. Introduction

The WHOI Moored Profiler [1] is designed to repeatedly sample vertical variations in the oceans' velocity field and water property distributions. The instrument, Fig 1, utilizes a traction drive to propel itself along a standard mooring wire at a speed of ~0.3 m s^{-1}. Instrument operations are managed by an onboard controller that supports complex sampling scenarios. Limitations on sampling depth are set largely by the mooring configuration, and endurance by battery capacity. (Approximately one - million meters of profiling is possible.) The measurement suite thus far deployed on Moored Profilers includes a CTD for deriving ocean temperature and salinity profiles, and an acoustic current meter that returns ocean velocity profile data.

Velocity data from the system are discussed here. The Moored Profiler utilizes the Falmouth Scientific, Inc. (FSI) 3D-ACM™ acoustic phase-shift current meter with a customized, remotely-mounted, sensor head, Fig 1b. Electrical connection to the acoustic transducers is accomplished with a 1-m multi-conductor oil-filled cable. Remote mounting allows for the electronics pressure case to be housed fully inside the Profiler cowling; the horizontal arrangement of the case required a special mount for the standard tilt sensors but no change was required to the three-axis compass. The standard four-path ACM "sting" was modified to the 45° - pyramid arrangement seen in Fig 1b to minimize measurement errors caused by wakes off the struts supporting the acoustic transducers. As the Profiler is free to align with the incident horizontal flow, the modified arrangement presents two orthogonal horizontal acoustic paths and one vertically-angled path to the incident flow that are upstream of any wake-generating support struts.

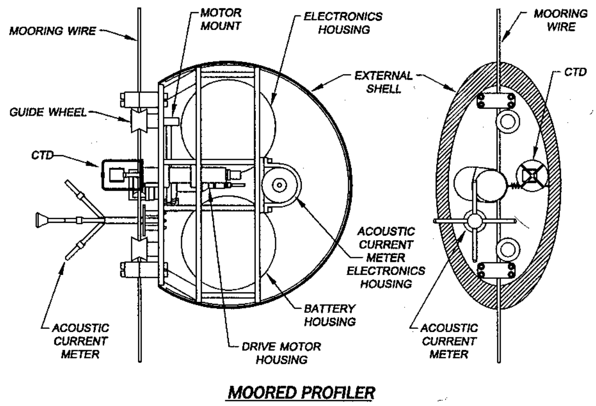

Fig 1a. Schematic drawing of the WHOI Moored Profiler. The instrument is 0.8 m tall and 0.4 m wide. Its mass is approximately 49 kg; in operation the device is ballasted to be neutrally buoyant at mid-depth.

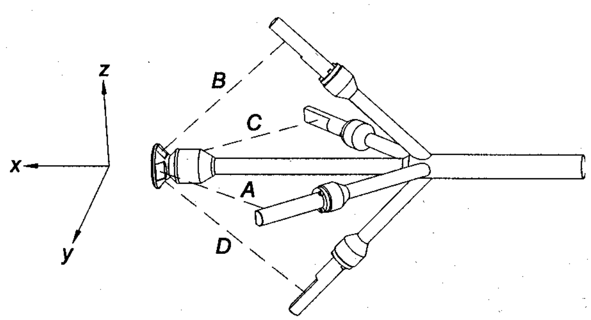

Figure 1b. Perspective view of the modified ACM sensor head employed on the Moored Profiler. The acoustic path lengths are 20 cm. When mounted on the Profiler, the sensing volume is approximately 40 cm forward of the body.

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While profiling, raw current meter data (four path-velocity values, three components of magnetic compass and two of tilt, all logged at 2 Hz) are temporarily recorded on the ACM's internal RAM; these data are downloaded to the Profiler's controller and archived to hard disk at the end of each profile. Communications between the instrument controller and external oceanographic sensors follow the RS-485 standard.

Four successful deployments have thus far been made of Moored Profilers equipped with an ACM. In Oct.-Nov. 1997, an instrument was moored on the continental slope south of New England at the 1500-m isobath. This system cycled continuously, acquiring 501 profiles between 100 and 1400 m prior to its recovery. Subsequently, three Profilers were deployed in a triangular array about the 1200-m isobath off the Virginia coast in May-June 1998. These instruments were synchronized to initiate a round-trip between ~1200 m and ~90 m and back every three hours. Data from these ocean deployments are used here to assess the performance of the system.

II. THEORETICAL ANALYSIS

Post-processing of Moored Profiler ACM data yields estimates of the ocean's east, north and vertical velocity as a function of depth. Conversion from path- to Cartesian-coordinates fixed to the Profiler body involves straightforward linear combination of the two "horizontal" paths (V_A, V_C) and the "up-stream" vertically angled path (V_B or V_D), Fig 1b.

Theoretically, the velocity measured by the ACM at a given time is the vector difference between the ocean's velocity and that of the Profiler as it translates along the possibly-tilted mooring wire:

$$\overline{\mathbf{U}}_{\mathbf{rel}} = \overline{\mathbf{U}}_{\mathbf{O}} - \overline{\mathbf{U}}_{\mathbf{MP}} = [S_O, \Phi_O, \Theta_O] - [S_M, \Phi_W, \Theta_W] .$$

On the right hand side above, we have converted to spherical coordinates and ignored any motion of the mooring wire relative to the ground. S_O is the 3-dimensional speed of the ocean current with its direction given by the angle from vertical, Φ_O, and azimuth angle Θ_O. Similarly, S_M is the speed of the Profiler along the mooring wire whose angle from vertical is defined by Φ_W and Θ_W. An expression for the relative velocity measured by the ACM is obtained by rotating the coordinate system to align with that of the ACM sensor sting:

$$\Phi' = \Phi - \Phi_W - \phi_s \; ; \; \Theta' = \Theta - \Theta_{MP} - \theta_s.$$

Here the azimuth angle (compass heading) of the Profiler is given by Θ_{MP} with ϕ_s and θ_s accounting for possible misalignment of the ACM sensor sting relative to the axis of the Profiler (which is taken to be along the mooring wire). Converting back to Cartesian coordinates yields expressions for the three velocity components measured by the ACM (V_X, V_Y, V_Z):

$$V_X = \{ |U_H| \cos(\Phi_W + \phi_s) - W_O \sin(\Phi_W + \phi_s) \} \bullet \cos(\Theta_O - \Theta_{MP} - \theta_s) - S_M \sin(\phi_s) \cos(\Theta_O - \Theta_{MP} - \theta_s)$$

$$V_Y = \{ |U_H| \cos(\Phi_W + \phi_s) - W_O \sin(\Phi_W + \phi_s) \} \bullet \sin(\Theta_O - \Theta_{MP} - \theta_s) - S_M \sin(\phi_s) \sin(\Theta_O - \Theta_{MP} - \theta_s)$$

$$V_Z = W_O \cos(\Phi_W + \phi_s) + |U_H| \sin(\Phi_W + \phi_s) - S_M \cos(\phi_s).$$

Here $|U_H|$ is the magnitude of the ocean's horizontal velocity and W_O is the magnitude of its vertical component.

In the usual case of small mooring wire tilt from vertical and small ACM sensor sting misalignment ($\Phi_W \approx \phi_s \approx 0$), the Moored Profiler measures the ocean's horizontal velocity directly. Assuming the ocean's pressure is dominantly hydrostatic, the time rate of change of measured pressure provides an estimate of the Profiler's vertical velocity S_M that, together with measured V_Z, facilitates estimating the ocean's vertical velocity. If the mooring wire angle is large, the above expressions may be used to derive the ocean velocity profile from the measured relative velocity and tilt data. Note that because the Profiler measures Cartesian component velocities in a coordinate system that tilts with the mooring wire, apart from the misalignment error, the Profiler's motion appears only in the "vertical" component equation. Also from above, we see that ACM sting misalignment causes a projection of the vertical profiling speed into the sensed horizontal ocean currents that goes as the sine of the misalignment error. Thus a 1° mounting error at 0.3 m s^{-1} profile speed introduces a velocity error of 0.5 cm s^{-1} (that changes sign with the direction of profiling).

An additional measured velocity signal arises from "wagging" of the Profiler about the mooring wire. As the ACM sensing volume is displaced a distance L from the pivot axis defined by the mooring wire, wagging physically moves the sensor sting at a speed of L $d\Theta_{MP} / dt$. Though not desirable, instrumental velocity signals from wagging should be correctable knowing L and the time series of Profiler heading.

III. System Performance

The accuracy and noise level of the velocity data obtained by the Moored Profiler are a function of both the ACM and the characteristics of the platform supporting it. Tow-tank tests were performed in the WHOI facility to investigate the response of the modified FSI 3D-ACM. Experiments were run where just the sensor sting was in the tank, and also with the full Moored Profiler body and sensor suite immersed. Noise levels, bias values and scale factors were examined. We note that the WHOI tank is far too small for a careful study of flow distortion about the Profiler body, and is marginal for measurements with acoustic current meters given the pulse length such instruments use and the possibility of sound reflection from the tank walls.

A representative example of an isolated-sting tow-tank run is given in Fig 2 for the case where the sensor sting was aligned with the tow direction. Bias in an individual component is indicated by its initial values being non-zero. As the instrument records raw data, these biases, once determined, may be corrected during post-deployment processing. Variation in bias values for individual channels of 1-2 cm s^{-1} have been observed in individual current meters over several days. If real (and not a tank artifact) we suspect bias drift associated with changing electrical characteristics of the connecting cable (that in our tank tests was not well secured and so flexed in response to drag forces produced by the relative currents). The cable is well secured when mounted on the Moored Profiler body.

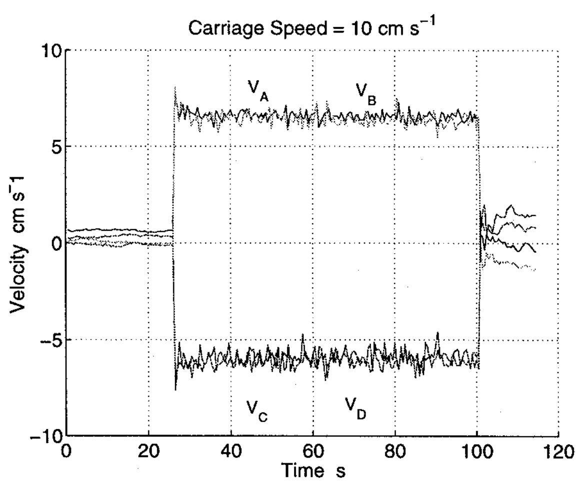

Fig 2. Raw path-velocity data from the modified FSI ACM derived on one tow-tank run. The ACM sensor sting was aligned in the tow direction and the carriage speed was 10 cm s^{-1}. The sense of the transducer wiring causes two of the channels to read positive and two negative for incident flow parallel to the sensor sting.

Estimated noise levels based on standard deviations of the instrument readings at rest are very small: ~0.05 cm s^{-1}. Much larger variability was observed during tows (0.2 - 0.4 cm s^{-1}), in large part caused by irregular motion of the tow carriage and vibration of the sensor sting. (The mounting arrangement of the sting to the tow carriage was not particularly stiff.) Somewhat larger noise was observed in acoustic paths that were normal to the incident flow, possibly the result of wake effects near the forward transducer. We are currently considering modified designs for the sensor sting to reduce flow noise. Significantly greater noise and clear under-estimation of the incident current was observed in paths obviously downstream of sensor support struts.

Representative 2-Hz raw current meter data acquired during an ocean profile are given in Fig 3a. Noise levels of the three unobstructed velocity paths range between 0.6 and 1.5 cm s^{-1} (standard deviation of observations high-pass filtered at 33-s period, the larger noise figure characterizes incident horizontal currents greater than 20 cm s^{-1}). The noise is largely a consequence of the Profiler vehicle motion along the irregular mooring wire; the high frequency variability of velocity data acquired after the Profiler was halted at the mooring stop (placed to prevent the Profiler from impacting the wire termination) fell to values comparable to what were observed in the tow-tank.

Data from the three unobstructed velocity-paths are used to derive the relative velocity vector in body coordinates, Fig 3b. For incident horizontal flows of about 10 cm s^{-1} or less, the Profiler body appears to align well with the incident current. In stronger currents, the instrument adopts a persistent angle to the incident flow of about 20°, independent of profile direction, possibly due to asymmetries in the cowling and/or sensor arrangement, Fig 3c. This attitude presents greater surface area to the horizontal flow and likely increases drag somewhat. The incident angle of the relative flow at these times does remain within the valid measurement sector of the ACM, however. Unlike an earlier prototype we studied, the present Moored Profiler does not appear to wag while profiling. The derived compass heading of the Profiler varies slowly with time (depth) depending on the structure of the horizontal flow, Fig 3c. Wagging has been observed when incident currents are greater than about 20 cm s^{-1} after the vehicle comes to rest at the mooring stops. We may be seeing the effects of vortex shedding off the instrument cowling, though it is unclear why this happens only when the instrument is at rest. A tail fin to improve the Profiler's alignment with the flow and reduce its wagging has been considered but not yet implemented.

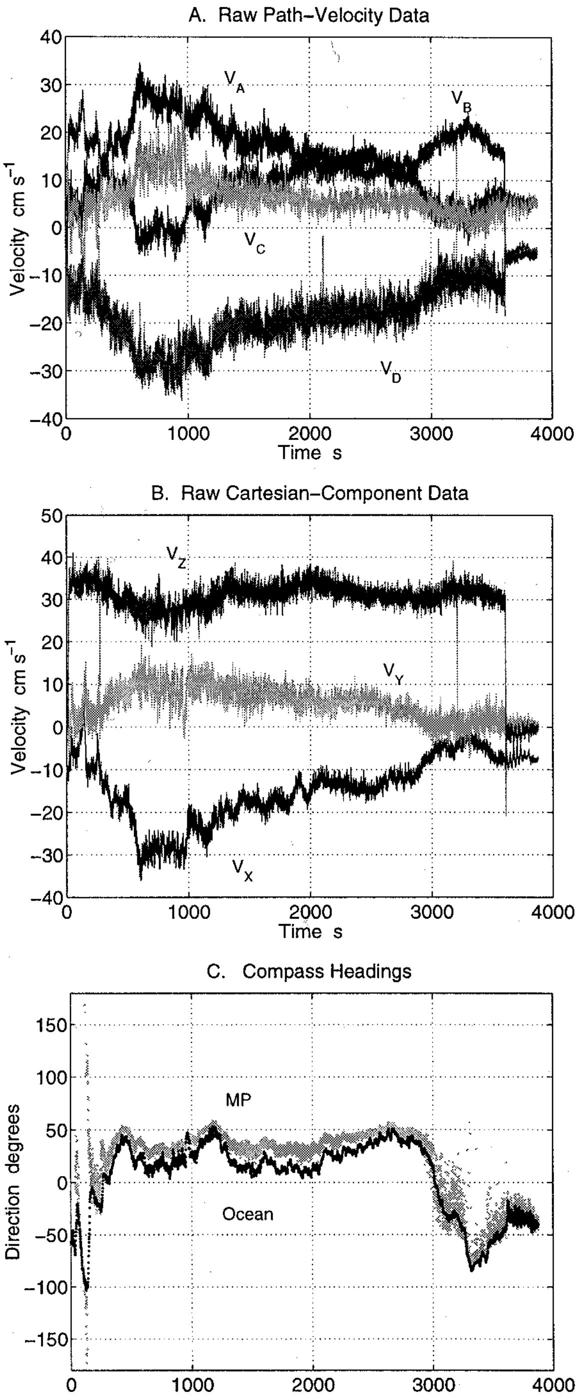

Fig 3. Raw velocity data from the Moored Profiler derived on a down-going profile between 98 and 1193 m. Panel A shows the four path velocities at their sample rate of 2 Hz. Path D is in the wake of the sensor strut in this profiling direction and not used. The instrument impacted the bottom stop about time=3600 s. Panel B shows the relative velocities in Cartesian coordinates. The compass heading of the Moored Profiler and the direction of the derived horizontal ocean current are in Panel C. Data for this plot were low-pass filtered at 0.03 Hz.

Post-processing involves combining relative velocity data, compass heading and tilt observations from the ACM and pressure data from the CTD to estimate the ocean's vertical profile of velocity. Our procedure involves low-pass filtering the ACM data at 0.08 Hz and averaging the derived ocean data in 2-dbar pressure bins. As observed mooring tilts have been small (maximum of 8° and typically less than 2°), we have thus far ignored tilt and ACM sting misalignment effects in deriving ocean velocities. Misalignment error was explored in an analysis of 226 down-up profile pairs from the fall 1997 deployment. For each available profile, the estimated speed of the horizontal ocean current (with no tilt corrections) between 1300 and 1400 m depth were averaged. The speeds sampled on down-profiles were different from those sampled on the subsequent up-profiles by only 0.5 cm s^{-1} on average (up profiles larger) with a standard deviation of 0.9 cm s^{-1}. This small defference between up- and down-going velocity estimates could be explained by a one-half degree misalignment of the current meter sensor sting relative to the vertical axis of the Profiler body/guide wheels.

IV. Velocity Comparisons

An experiment conducted in May-June 1998 on the continental slope east of Virginia provided an opportunity to compare velocity profile data from the Moored Profiler with velocity profiles derived from three independent measurement systems. Three Profilers were deployed on subsurface moorings in a small triangular array about the 1200 m isobath in this experiment. The Profilers were synchronized to initiate a cycle from the bottom mooring stop (1100-1200 m) to the top stop (~100 m) and back every three hours. In addition to the Moored Profilers, velocity profile data were collected with the High Resolution Profiler (HRP) [2], Expendable Current Profilers (XCP) [3] and a wire-Lowered acoustic Doppler Current Profiler (LADCP) [4]. For inter-comparison purposes during the cruise, an XCP and the HRP were launched simultaneously within 1 km of these moorings when the Profilers were midway between their top and bottom stops. The LADCP was deployed about 1 hour prior to this, also about 1 km from the Profiler moorings.

Good correspondence is seen between the various independent measurements of ocean velocity, Fig 4a. Depth offsets between individual velocity features seen in the XCP and Moored Profiler data may be due to error in the XCP fall-rate prescription. Similar offsets may be in the LADCP profile, caused by error in estimating depth from the time integration of the relative LADCP vertical velocity. (We have not as yet merged the LADCP data with the CTD pressure observations obtained on the cast.) Though good on vertical scales greater than 50 m, it is clear that the LADCP does not resolve ocean currents on as small a vertical scale as the other instruments [5]. Comparison of simultaneous velocity data from the three Moored Profiler instruments, Fig 4b, suggests that much of the remaining velocity differences apparent in panel A may be real spatial differences.

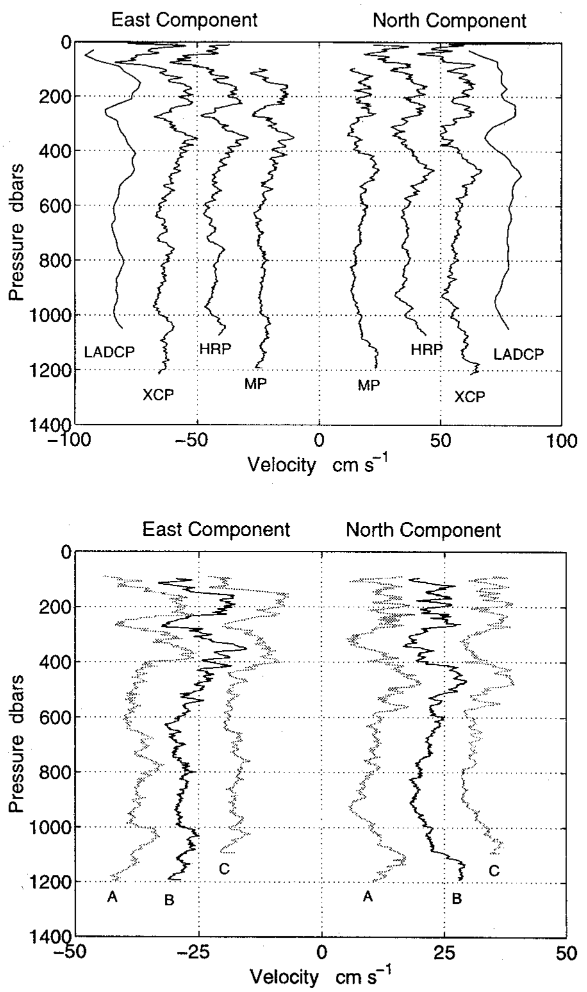

Fig 4. Comparison of velocity profile data obtained with four independent instrument systems. Panel A shows estimated East and North velocity components (successively offset by ± 20 cm s^{-1}) derived from nearly simultaneous sampling by a Moored Profiler (MP), the High Resolution Profiler (HRP), an Expendable Current Profiler (XCP) and a Lowered Acoustic Doppler Current Profiler (LADCP). Panel B shows simultaneous velocity profiles from three Mooed Profilers separated by approximately 500 m. Instrument B's velocity data have been offset by ± 25 cm s^{-1}; A and C's are shown shifted ± 10 cm s^{-1} relative to B's.

An intercomparison was also made of the shear vertical wavenumber spectra derived from 13 simultaneous HRP and Moored Profiler profiles, Fig 5. The HRP deployments were made in a grid about the Moored Profiler at a maximum distance from the mooring of 1 km. For each instrument, both velocity components between 100 and 1100 m depth were extracted, linear trends were removed, the data were transformed and average shear spectra derived. Both instruments show the "white" spectral character of the ocean internal wave shear field. Based on where the two spectra diverge, the figure suggests that shear from the Moored Profiler was resolved above the noise level to about 10 m vertical wavelength on this experiment.

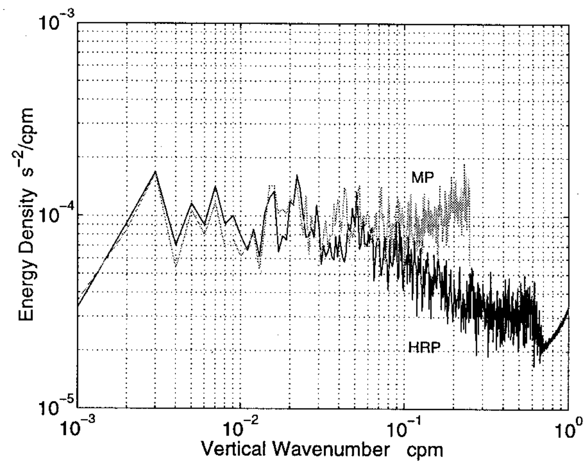

Fig 5. Average 1-component shear spectral energy density versus vertical wavenumber derived from a Moored Profiler (MP) and the High Resolution Profiler (HRP). The two spectra are derived from 13 simultaneous profiles. (No band averaging was done.)

V. CONCLUSIONS

Our Moored Profiler testing program is beginning to demonstrate the promise of this new technology for oceanographic research. The ability to collect rapidly-sampled temperature, salinity and velocity time-series at high-vertical-resolution nearly spanning the full water column is proven. The accuracy of the absolute velocity data appears to approach 1 cm s^{-1}; vertical shear is measurable above the noise down to wavelengths of about 10 m. Limited-duration process studies that exploit these capabilities, such as the experiment in May-June 1998 that investigated internal waves on the continental slope, are immediately possible. Testing of the Profiler's long-term behavior, a capability required for monitoring studies in remote regions of the world, is underway. One interesting application here is the use of Moored Profilers to monitor the transport and hydrographic properties of flow through ocean straits and channels.

In addition to our own research, we are also working to make Moored Profilers available to the community. A nascent shared-use facility has been created at the Woods Hole Oceanographic Institution to provide Profilers to individual researchers for specific experiments. Moreover, the Moored Profiler technology has been licensed to McLane Research Laboratories, Inc. of Falmouth Ma. who anticipates commercial release of the system when development is complete.

VI. Acknowledgments

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