High Resolution Doppler Profiler Measurements of Turbulence from a Profiling Body

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***Abstract*—A Nortek Aquadopp High Resolution (HR) Profiler was mounted on a moored vertical crawling oceanic profiler to determine if measurements made from a moving platform could be utilized to measure turbulence. Initial results are promising for this application but have highlighted potential challenges which must be addressed in the post-processing stage, in particular removal of the profiler motion from the measured velocities. Despite the potential complexity of this process, measurements from a moving body yield correct order of magnitude estimates of turbulence intensity at a study site in the Puget Sound region.**

Keywords-moored profiler; turbulence; pulse coherent profiler;

I. INTRODUCTION

Moored profilers are used to autonomously profile the water column, measuring physical properties such as temperature and salinity. Two models currently in use are the McLane Moored Profiler (MMP) manufactured by McLane Research Laboratories, Inc. of East Falmouth, Massachusetts (www.mclanelabs.com) and the SeaCycler, developed by Bedford Institute of Oceanography and the Department of Fisheries and Oceans Canada and licensed by ODIM Brooke Ocean (www.brooke-ocean.com).

Moored profilers feature a profiling body (hereafter referred to as the profiler) carrying instruments and a control system. The profiler either crawls up and down a mooring line or is buoyant and ascends/descends under the control of a winch. Vertical profiling speeds are on the order of 0.3 – 0.5 m/s.

Acoustic travel time current sensors are often fitted to the profiler body to measure velocities at a single point. Single point velocity measurements from a vertical profiler present some problems for turbulence measurements. Because they are moving vertically through the water column, sampling a homogeneous region of turbulence is not guaranteed due to stratification, and vertical segments identified for analysis may contain very few measurements, leading to high uncertainty in statistics.

An acoustic Doppler profiler like the Nortek Aquadopp HR Profiler has significant advantages over a single point velocity measurement. Acoustic backscatter is a valuable additional parameter capable of observing zooplankton populations, turbidity, and other scatterers in the water column. For turbulence measurements, the along beam velocity profiles produced by the HR Profiler provide measurements in horizontal layers, measuring across the stratification gradient and matching the expected structure of the water column.

The HR Profiler belongs to a class of instruments which use a pair of coherent acoustic pulses to measure a relative phase shift of reflected sound due to the speed of particles in the water. Pulse coherent processing results in very low noise data compared to more traditional Doppler instruments and travel time sensors.

Researchers have used pulse coherent profilers to measure turbulence in lakes and the surface mixed layer [1, 2, 3]. Agreement with acoustic Doppler velocimeter and particle image velocimetry measurements is quite good. Reference [2] includes estimates of dissipation from temporal spectra which compare well to estimates from a co-located acoustic velocimeter.

Pulse coherent Doppler instruments have additional advantages compared to acoustic travel time current meters for long term deployments. In addition to their low noise, there is zero drift in measurements and no calibration is required. Physically, the instrument has a higher tolerance for bio-fouling, and measures a remote, undisturbed, volume of water away from the profiler.

II. METHODS

A Nortek Aquadopp High Resolution (HR) Profiler was mounted on an MMP deployed in the Hood Canal of Puget Sound, Washington. Local water depth was approximately 150 m, with the MMP profiling between 30 m and 140 m.

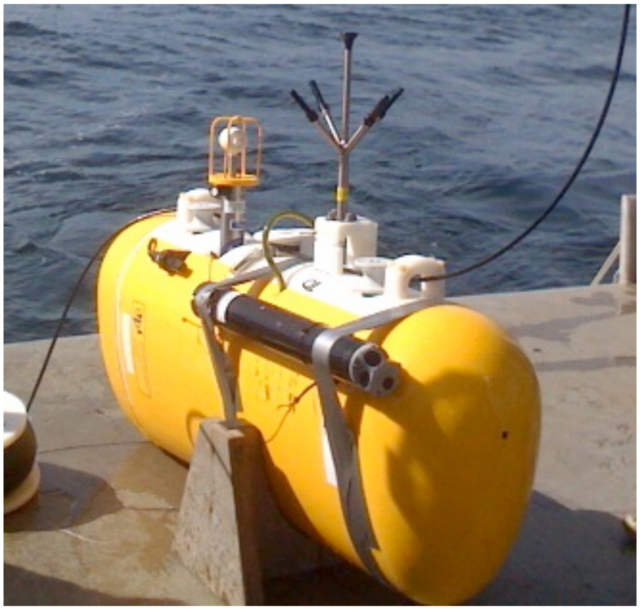

Figure 1. The Aquadopp HR Profiler temporarily attached to the side of the MMP just prior to deployment. The top of the profiler is at right in the photo.

The HR Profiler provides measurements of along beam velocity and acoustic backscatter from three monostatic transducers. Transformed beam velocities result in three orthogonal components of velocity. Either in an instrument coordinate system or East, North and Up (ENU) using the onboard compass and attitude sensors (pitch, roll) in the transform. High temporal or spatial resolutions are possible, up to 8 Hz and 7 mm, respectively. Sampling at a fast rate requires larger range cells, while smaller range cells require a slower sample rate.

The instrument used in these experiments operates at 2 MHz and is equipped with a “mooring head.” Two beams are in a plane oriented perpendicular to one another with the third beam oriented 45º from this plane and aligned with the angle bisector of the other two beams. When deployed, the two co-planar beams measure horizontal velocities. The third beam will measure a combination of the vertical and horizontal velocity. Fig. 1 shows the orientation relative to the MMP body just prior to deployment.

The HR Profiler recorded profiles at 2 Hz with 0.01 m range cells, 34 total range cells for a profile length of 0.34 m. The first range cell was located 0.10 m from the instrument. Data were collected almost continuously for the duration of the deployment, approximately one day, in bursts of 600 seconds with a 2.5 second break between bursts. Velocity was recorded in beam coordinates, with attitude sensors (heading, pitch, roll) and environmental (temperature, pressure) also sampled at 2 Hz. All data were recorded to internal memory.

The HR Profiler collected over 150,000 velocity profiles (approximately 90 water column profiles) for analysis. Subsequent deployments have been made with an HR Profiler mounted on a SeaCycler near Halifax, Nova Scotia during October to December 2010.

III. ANALYSIS

A. *Estimation of Profiler Motion*

The velocities measured by the HR Profiler can be thought of as the sum of three components, the mean velocity of the water, U, the motion of the profiler through the water, $\hat{U}(t)$, and a fluctuating component of velocity attributable to turbulence $u'(t)$.

$$u(t) = U + \hat{U}(t) + u'(t) \tag{1}$$

Where $u(t)$ is the beam velocity measured by the HR Profiler.

When the instrument is stationary, the middle term $\hat{U}(t)$ vanishes and (1) reduces to a standard Reynolds decomposition [4]. In the case where $\hat{U}(t)$ is not zero, it must be estimated to accurately measure the mean flow and turbulence.

Ideally, the profiler is moving only vertically through the water column. But, forces such as drag on the profiler, interaction with the profiler wake, and drag on the mooring line cause horizontal motion which must also be estimated and removed from the measured velocity data.

Fig. 2 shows ENU velocities averaged across all range cells corrected for vertical motion. Two different length moving average filters, at one second and 37.5 seconds, have been applied to the data. In the one second moving average data (thin line), a strong oscillation in the velocities is evident, especially in the East component. The amplitude of this oscillation decreases slightly with depth. The instrument heading shows a similar structure. Examining the heading frequency spectrum (Fig. 3) periods of 17 and 8 seconds are detected. A temporal beam velocity spectrum from one range cell is also plotted in Fig. 3, showing the lower frequency period of 17 seconds but less energy at the higher frequency.

An analysis of a subsurface mooring line of 150 m length

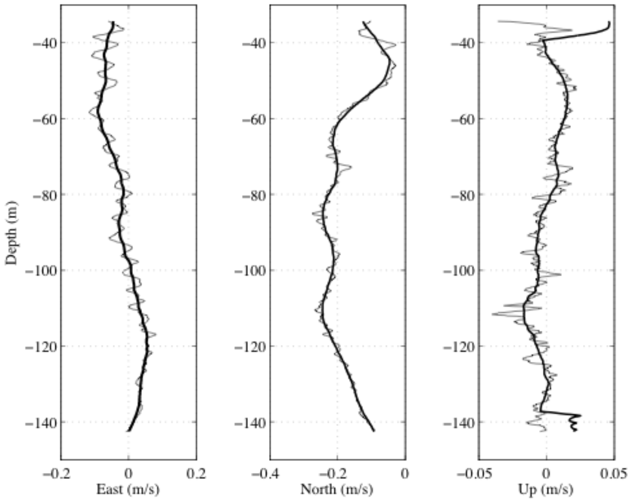

Figure 2. Mean East, North and Up velocities corrected for vertical motion from one water column profile. Thin line is the mean across all range cells, heavy line is a 37.5 second moving average of velocity.

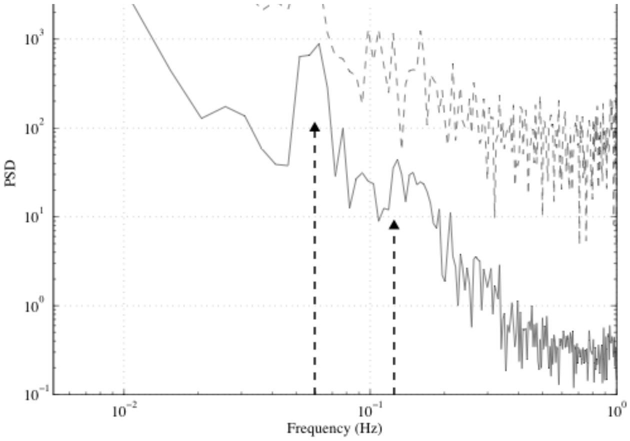

Figure 3. Heading (–) and velocity spectra showing the two oscillation periods of 17 and 8.5 seconds.

with 400 kg of buoyancy yields a oscillation period of 18 seconds. This oscillation is suspected to be a horizontal 'sailing' of the profiler at the natural period of the mooring line. The HR Profiler's pitch and roll data show energy at the 17 s period, but at relatively small angles of 0.5º on average. This 'sailing' motion can be considered a left-to-right wandering (East-West) of the profiler as it points into the mean north–south flow.

The vertical motion of the profiler can be estimated from multiple sources. The HR Profiler on board pressure sensor provides estimates of the profiler's vertical motion via numerical differentiation (i.e. *dp/dt*) yielding both an average value and a slope from a linear least squares fit. The third beam of the HR Profiler measures a portion of the vertical velocity, typically dominated by the profiler's vertical motion. The measured velocities can be used to estimate the profiler's vertical motion if the water velocity is small in comparison. The specified travel rate of the profiler is 0.25 m/s, while the estimates from the pressure sensor differentiation and least squares fit are both 0.292 m/s. The HR Profiler measured vertical velocity is 0.302 m/s. Because pressure is measured relative to a known zero reference (the surface) it is preferred for estimating the vertical profiler velocity.

Estimating the horizontal motion of the profiler is more difficult. Typical moving platform applications of Doppler instruments utilize a variety of techniques to estimate and remove platform motion. None of these, such as differential GPS, bottom tracking or assumption of a zero movement layer, are applicable to this data set. In the absence of an independent measurement of $\hat{U}(t)$, it must be estimated in some other manner from the measured velocity data.

By differencing the two smoothed profiles shown in Fig. 2, a rough estimate of the velocity attributable to the horizontal profiler motion was developed accounting for a portion of the east-west sailing.

B. *Correcting the Measured Velocity*

Each vertical profile of the water column was identified by examination of pressure data. Data outside the profile range was removed from analysis. A synthetic velocity profile in ENU coordinates representing the estimated profiler motion was created. The synthetic velocity profile is simply an appropriately sized array, in this case with dimensions of 34 x number of measurements x 3, filled with zeros initially. Each slice (the third dimension) represents a velocity component and each column of the slice a range cell.

The East and Up components were filled with the profiler velocity estimates developed in the previous section, assuming each range cell saw the motion. The synthetic profiler velocity data was transformed to beam coordinates utilizing recorded heading, pitch, and roll and subtracted from the measured beam velocities. The corrected beam velocities were then transformed to ENU coordinates for averaging and presentation.

By estimating the profiler motion in ENU velocities, aliasing due to heading, pitch and roll is accounted for in the correction. While this method is successful at removing the profiler's vertical motion, the horizontal motion of the profiler is not completely removed with a small amount of energy persisting at the identified 17 sec period.

Contour plots of North and East velocities are shown in

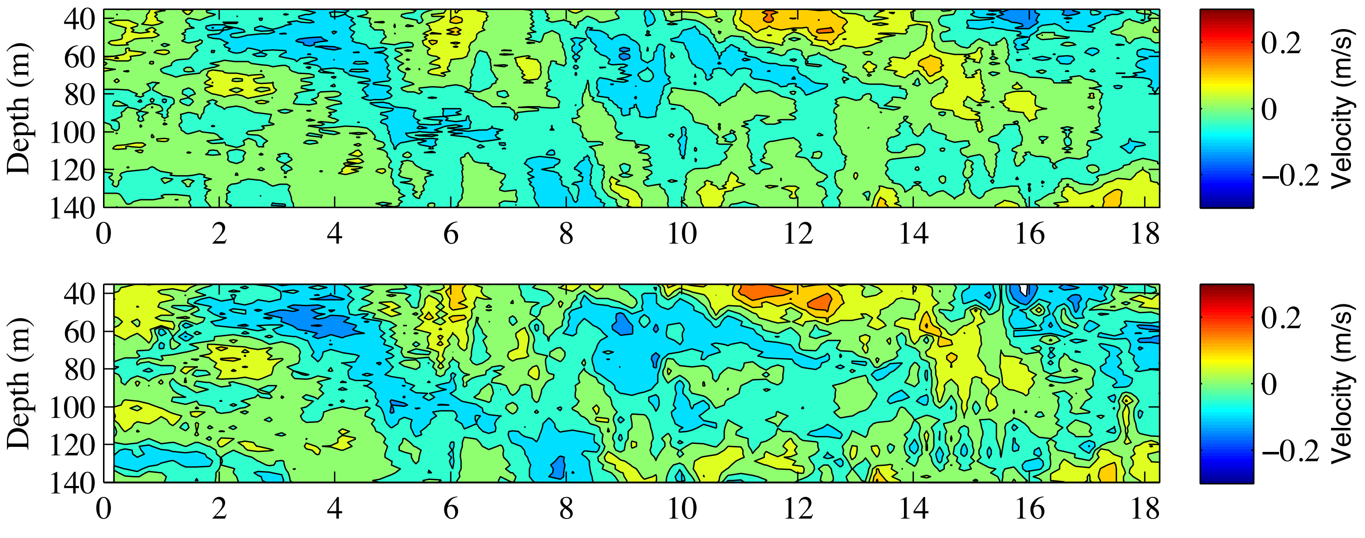

Figure 4. Mean East velocities during the deployment period. HR Profiler (top), FSI Travel Time sensor (bottom). Contour levels are every 0.05 m/s.

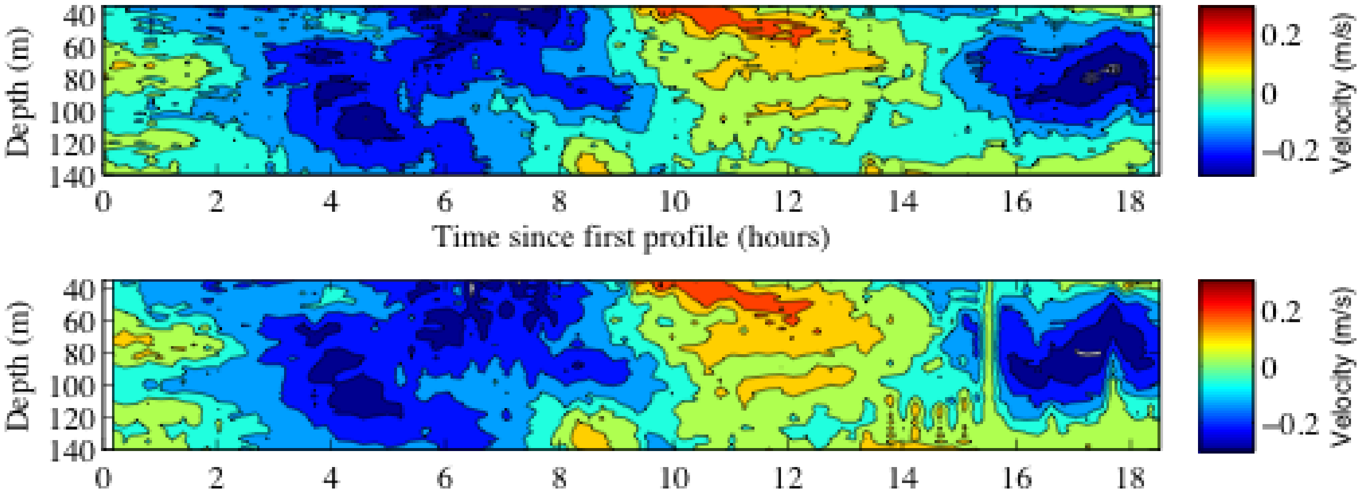

Figure 5. Mean North velocities during the deployment period. HR Profiler (top), FSI Travel Time sensor (bottom). Contour levels are every 0.08 m/s.

Figs. 4 and 5 alongside velocities measured by the travel time sensor on the MMP. Data from the HR Profiler was interpolated onto a one meter pressure grid using linear interpolation within a profile. The travel time sensor data was binned and averaged into 2 m bins. Maximum mean current speeds are 0.30 m/s and are primarily tidally driven at this site. The predominant flow direction is north–south with a smaller contribution from the east–west component.

Individual velocity profiles for a downwards and upwards water column profile are shown in Fig. 6 for both instruments. The two profiles are taken from the data in Figs. 4 and 5 at hour 9.2 and separated in time by approximately 12.5 minutes. The velocity correction for the HR Profiler data removes a majority of the profiler motion, but oscillations are still evident in both components.

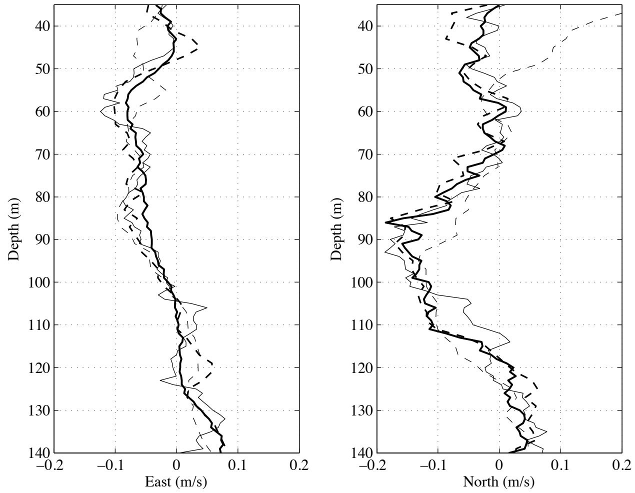

Figure 6. Mean East and North velocities from two adjacent in time profiles. Heavy lines are downward profiles, thin lines are upwards. The solid lines are data from the HR Profiler, dashed lines are from the acoustic travel time sensor.

C. *Duty Cycle*

Power on autonomous profilers is heavily constrained and long deployments require minimal power use by on board instrumentation. There are many ways to reduce power consumption by the HR Profiler.

Resampling the continuous dataset approximates different duty cycles, such as sampling at a fast rate for 25 cm over every 100 cm of vertical travel (a 25% duty cycle). The main features of the flow are still resolved with significantly less power usage. Additional power saving considerations, such as disabling one of the acoustic beams (measurement of vertical velocity) and reducing internal ping rate can also be utilized to bring power consumption down to typical travel time sensor levels of 0.1–0.2 W.

D. *Turbulent Decomposition and Analysis*

After successfully estimating the mean currents and profiler velocity, a turbulence analysis can be performed. One of the most significant advantage of the HR Profiler over a point sensor in this application is the along beam profiles of velocity it produces. The along beam velocity fluctuations have been shown to yield valid turbulent velocity data in numerous environments [1, 2, 3]

For most turbulence statistics, point velocity measurements necessitate the use of Taylor's Frozen Turbulence Hypothesis [4] to transform a temporal measurement into a spatial measurement. When mounted on a vertical profiler, the velocity sample rate of a point measurement needs to be high enough and the profiler's velocity needs to be slow enough to allow sampling in a homogeneous region of the water column, while collecting a large number of samples to provide reliable statistics. For example, if the profiler was moving vertically at a rate of 0.30 m/s and sampling at 10 Hz, then 33 samples would be collected each meter at approximately 0.03 m resolution. It should be noted specialized profilers used for this type of measurement often sample at hundreds of Hz and provide millimeter resolution. This also assumes homogeneous segments of the water column are one meter thick, not necessarily a valid assumption in strongly stratified conditions.

This limits the measurement capabilities of point sensors compared to the HR Profiler. Despite the limited number of samples in a beam velocity profile, the HR Profiler data's low noise measurements can be used to directly calculate two point correlations underlying the statistical description of turbulence without any appeal to vertical homogeneity.

For the analysis presented here, the two horizontal beams are used to estimate the turbulent intensity, calculate velocity spectra and the variance due to Doppler noise.

The fluctuating turbulent velocity is estimated using (1) and the mean and profiler velocities discussed in Section II.A and II.B. The fluctuating velocity data is used to estimate the turbulence intensity in each range cell, defined as

$$\sqrt{\langle u'(r)^2 \rangle} \tag{2}$$

The angle brackets represent a spatial average along the beam, r is the distance to the range cell, and u' is the instantaneous fluctuating velocity obtained from (1) at some time t. Pseudo color plots of the turbulence intensities are shown in Fig. 7. The banding in turbulence intensity is due to the incomplete removal of profiler motion. Upward profile intensities are always higher than downward profiles, pointing to problems with the profiler velocity estimation and correction.

Because the turbulent fluctuations are simply the variance of a signal, it is important to verify the fluctuations have some structure associated with canonical turbulence and are not simply noise. A first order check on this condition is to examine the turbulent velocity spectrum (either from temporal or spatial data). The turbulent velocity spectrum at intermediate scales, called the inertial subrange, is expected to show a -5/3 slope. This slope is predicted by Kolmogorov's theory of isotropic turbulence, specifically his second similarity hypothesis [4].

Using the fluctuating velocity profiles, wavenumber velocity spectra are calculated for each beam, and then averaged over 1.5 s (3 profiles) to reduce noise. Example velocity spectra are shown in Fig. 8. The -5/3 slope is also plotted. At low wavenumbers, the spectra follow the expected slope before noise begins to dominate at wavenumbers greater than 60 rad/m. As a simple first order test, velocity spectra support the HR Profiler is measuring turbulence.

To obtain a better estimate of the variance due to noise of the HR Profiler, a frequency spectrum was calculated for each range cell (not shown). Noise is expected to increase approximately linearly with range from the transducer [5]. The noise was estimated from these spectra by assuming the spectral value at frequencies above 0.6 Hz was representative of the noise at all frequencies. The variance due to noise is then estimated as [5]

$$(n\,\Delta f)^{1/2} \tag{3}$$

Variance in all beams and range cells was found to be approximately 1.0 mm/s, with a slight linear dependence. This value is well below the variance due to turbulence. A similar procedure for spatial spectra provides a variance estimate of slightly less than 1.0 mm/s.

IV. DISCUSSION

The HR Profiler provides an impressive amount of data for a single instrument, demonstrating the power of including a Doppler profiler on a moored profiler.

The simple corrections for profiler motion are sufficient to yield reasonable estimates of the mean velocity and turbulence intensities. Correcting for profiler motion is still the most

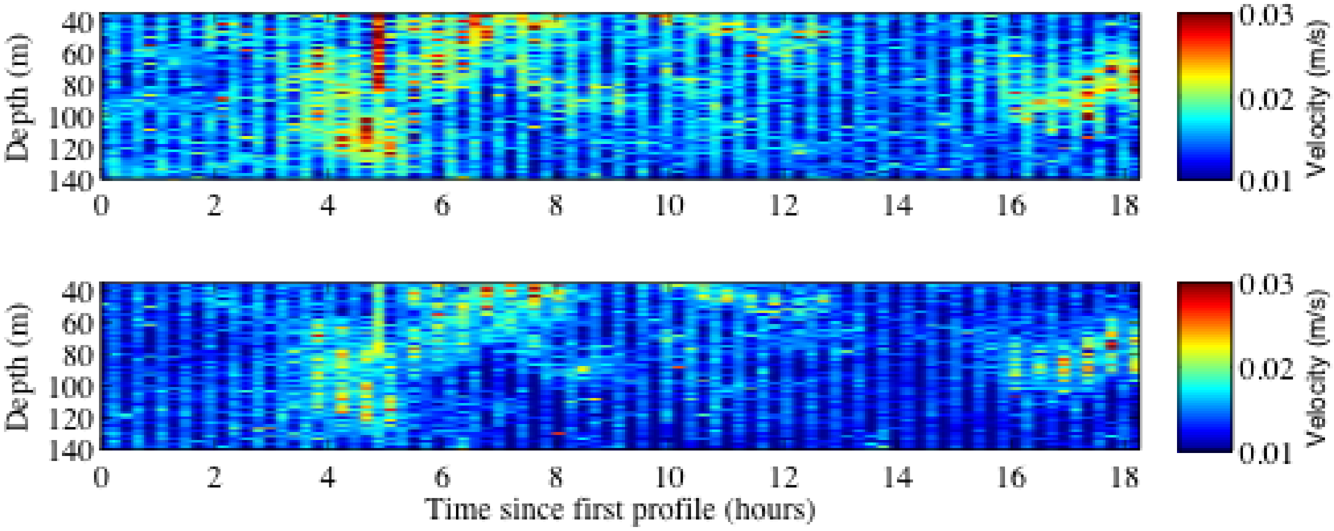

Figure 7. Turbulence intensities from the two horizontal beams. Beam 1 (top) and Beam 2 (bottom).

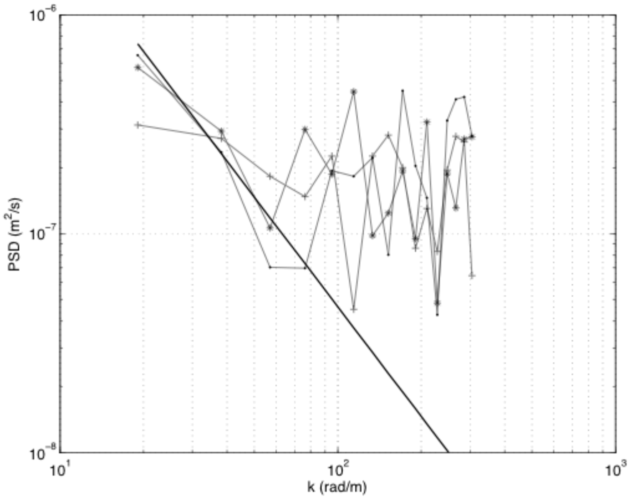

Figure 8. Example beam velocity spectra. Beam 1 (•), beam 2 (+), and beam 3 (*). The solid line is a -5/3 slope.

significant challenge in obtaining a high quality dataset, however. Ongoing experimental work utilizing high resolution accelerometers alongside Nortek instrumentation could provide a significantly better correction by providing an independent measure of the profiler velocity.

The present correction for the profiler's vertical motion is better than for the horizontal motion due to the independence of the velocity estimate obtained from pressure data. Correcting for the horizontal profiler motion reduces contamination in the measured velocities, but is not as successful as the vertical correction. After correction, mean velocities agree well with expected values for the site and data obtained during the same deployment from an acoustic travel time velocity sensor.

The mean velocity comparisons in Figs. 4 and 5 show the HR Profiler performs well measuring the mean flow. The vertical structure compared to measurements from the acoustic travel time sensor matches at the largest scales with minor differences (e.g. around 120 m between hours 14–16) at smaller scales. Magnitudes are also in agreement, with most differences attributable to the averaging and interpolation applied to the data.

The turbulence analysis performed here is basic but provides significant evidence for the potential of this type of deployment. Profiles of oceanic turbulence are typically made with specialized, ship based profilers which free fall through the water column. They provide detailed data on vertical structure, but are sporadic in both space and time as they are tethered to research vessels.

The HR Profiler mounted on a moored profiler can provide a nearly continuous data stream for days, weeks, or months provided sufficient power and memory are available. Power will typically be the biggest constraint. Cheap, high capacity flash memory and external logging options make storage less of an issue.

The spatial velocity data allows for a more detailed analysis than presented here, including estimates of turbulent dissipation and is the subject of ongoing work.

Turbulence intensities are approximately 10% of the mean velocity, a typical order of magnitude estimate for many flows. Noise levels estimated from velocity spectra are below the measured turbulence intensities at approximately 1 mm/s. For this deployment, range cells were 10 mm, almost the smallest size available for the HR Profiler. Larger range cells will reduce this noise and improve turbulence measurement quality at the expense of spatial resolution (i.e. wavenumber resolution) of the spectra.

One potential problem with pulse coherent instruments is their limited velocity range, generally relegating them to slower flows found in lakes and protected waters. A rule of thumb to assess measurement suitability is called the velocity-range product. This is simply the maximum expected velocity times the profile range.

Measured velocities including the profiler motion are at most 0.40–0.50 m/s, while the velocity profile range is on the order of 0.5 m. This velocity-range product is 0.25 m^2/s compared to a maximum recommended value of 0.5 m^2/s. An ambiguity resolution scheme employed by the HR Profiler (called Extended Velocity Range or EVR), utilized here, raises the maximum velocity-range product to 0.9 m^2/s, well above the value for this deployment.

Another constraint on the HR Profiler is the maximum unambiguous beam velocity measurable. With EVR, the ambiguity velocity for this deployment was 0.69 m/s, well above the maximum beam velocities recorded of 0.40 m/s. Reducing the velocity range will reduce noise in the measurements at the risk of phase wrapping in the velocity signal. Setting the velocity range conservatively but appropriately for a site is generally recommended given the wide range of conditions many deployments will likely experience. While phase wrapping can be corrected, it is often difficult to automate the correction scheme if more than a few phase wraps occur in a data set.

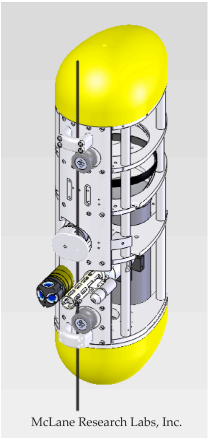

Figure 9. HR Profiler integrated into the MMP profiler. Image courtesy Mclane Research Labs, Inc.

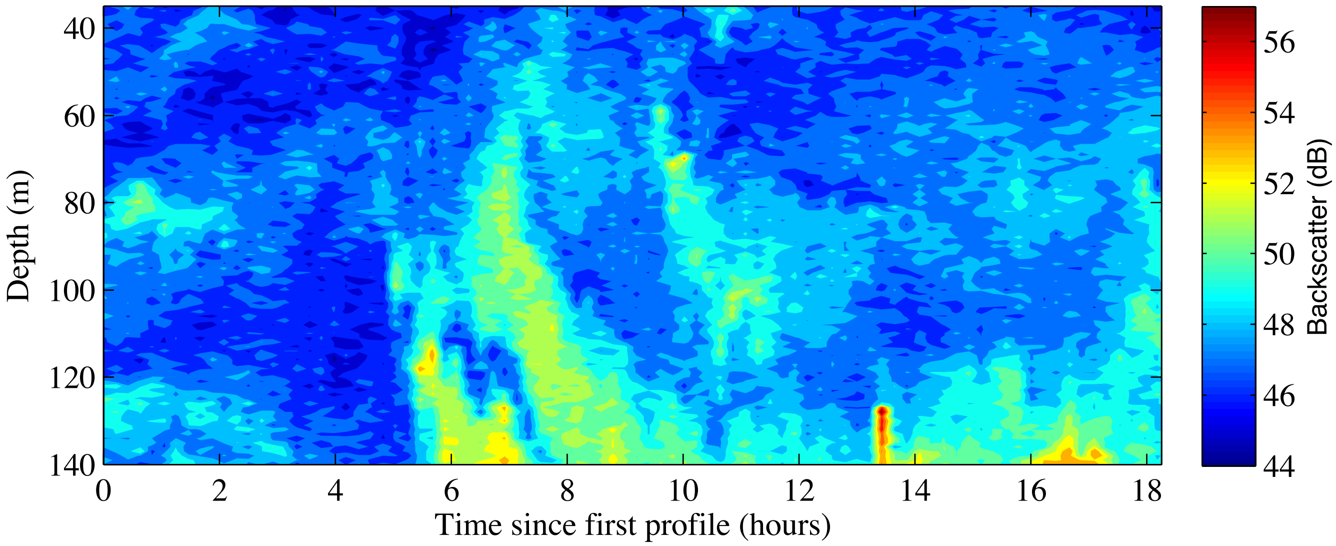

Figure 10. Average backscatter in decibels from beam 1.

The HR Profiler can be integrated into the MMP body (Fig. 9), altering the beam orientation relative to the profiler. This has two benefits, the MMP body is now more streamlined and along beam velocities are reduced by the sine of the beam angle, assuming the profiler orients with the predominant flow direction.

The main challenge in deploying any velocity sensor on a moving platform is accurately estimating the platform motion. Correcting for this motion is essential to interpreting measured velocities and maximizing the information obtained from the instrument.

As a final example of the potential power of Doppler instruments on moored profilers, a contour plot of backscatter, averaged across all range cells, is shown in Fig. 10. There is an increase in backscatter around hour 6 of the deployment, approximately 12:00 AM local time that is suspected to be a downward migration of zooplankton. Because backscatter is recorded as part of the normal diagnostic data for the instrument, it provides a free additional measurement of suspended particulates to augment other on board sensors.

V. CONCLUSIONS

A Nortek Aquadopp HR Profiler was mounted to a McLane Moored Profiler deployed in 150 m of water in the Puget Sound. The instrument operated continuously for the 24 hour deployment providing 90 vertical profiles for subsequent analysis of mean currents and turbulence.

Utilizing estimates of the profiler's vertical ascent/descent rate from pressure sensor readings, a correction for the profiler's vertical motion is applied. A similar correction based on estimating the horizontal profiler velocity via differencing two smoothed velocity profiles corrects for some of the horizontal motion of the profiler. This correction scheme is adequate for a first pass analysis, but needs refinement for improved measurement quality.

A triple decomposition of the measured velocities yields reasonable values for turbulent intensities. Structure visible in velocity spectra, namely the -5/3 slope indicative of the inertial subrange, indicates these measurements are not simply noise.

As a proof of concept, the experiment presented here shows the potential of high resolution velocity measurements made from moving platforms.

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