Fine-Scale Velocity Measurement on the Wirewalker Wave-Powered Profiler

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ABSTRACT: The Wirewalker (WW) ocean-wave-powered vertical profiling system allows the collection of high-resolution oceanographic data due to its rapid profiling, hydrodynamically quiet operation, and long endurance. We have assessed the potential for measuring fine-scale ocean velocities from the Wirewalker platform using commercially available acoustic velocimeters. Although the vertical profiling speed is relatively steady, platform motion affects the velocity measurements and requires correction. We present an algorithm to correct our velocity estimates using platform motion calculated from the inertial sensors—accelerometer, gyroscope, and magnetometer—on a Nortek Signature1000 acoustic Doppler current profiler (ADCP). This correction, carried out ping by ping, was effective in removing the vehicle motion from the measured velocities. The motion-corrected velocities contain contributions from surface wave orbital velocities, especially near the surface, and the background currents. To proceed, we use an averaging approach that leverages both the vertical platform profiling of the system and the ~15–20 m vertical profiling range resolution of the down-looking ADCP to separate the surface wave orbital velocities and the background flow. The former can provide information on the wave conditions. From the latter, we are able to estimate fine-scale velocity and shear with spectral wavenumber rolloff at vertical scales around 3 m, a vertical resolution several times finer than that possible from modern shipboard or fixed ADCPs with similar profiling range, and similar to recent glider measurements. When combined with a continuous time series of buoy drift calculated from the onboard GPS, a highly resolved total velocity field is obtained, with a unique combination of space and time resolution.

KEYWORDS: Ocean; Indian Ocean; Atmosphere-ocean interaction; Internal waves; Ocean circulation; Shear structure/flows; Small scale processes; Monsoons; In situ oceanic observations; Instrumentation/sensors; Measurements; Profilers, oceanic

1. Introduction

In the ocean, processes on vertical scales of several meters or less—the so-called fine scale—play an important role in the general circulation by linking internal waves and turbulence. The advent of accurate, high precision conductivity–temperature–depth measurements allows the fine-scale density structure of the ocean to be assessed in a relatively straightforward manner. Obtaining similarly precise measurements of fine-scale oceanic velocity, on the other hand, remains an elusive goal, especially over large depth ranges in the open ocean. Acquiring these velocity measurements is a critical requirement for understanding and predicting physical problems like boundary layer dynamics (e.g., Shcherbina et al. 2018), internal wave-driven mixing (e.g., Alford 2010), and biophysical interactions (e.g., Garwood et al. 2020, 2021).

The most widely used instrument for measuring ocean velocities—the acoustic Doppler current profiler (ADCP)—utilizes the Doppler frequency shift between transmitted and

received acoustic signals scattered by drifting particles to determine the current speed at a set of ranges from the transducer (Pinkel 1980). This approach to measuring ocean velocity by a fixed or ship-installed ADCP is characterized by a fundamental trade-off between sensing range and spatial resolution. Commercially available ADCPs can use low-frequency transmissions to gather velocity observations over long ranges with coarse range resolution, or use higher frequencies—which attenuate quickly—for shorter ranges with finer range resolution. For example, a 50 kHz ADCP can cover ~1000 m at 20 m resolution, while a ~1000 kHz ADCP may only reach 20 m, but can do so at <1 m resolution.

Thus, primarily due to the range limitation of acoustic instruments for collecting velocity with high spatial resolution, measurements of fine-scale velocity in the open ocean are relatively uncommon. Recently, autonomous vertical profiling platforms like buoyancy-driven gliders and Lagrangian floats have shown great promise in overcoming this limitation by vertically cycling short-range, high-frequency ADCPs (e.g., Todd et al. 2017; Shcherbina et al. 2018). These approaches provide vertically well-resolved velocities relative to the vehicle, but must surface to acquire the GPS fixes necessary to calculate absolute ocean velocity.

Measuring ocean velocities acoustically from any moving platform is inherently more difficult than measuring them from a fixed location since the platform motion must be removed from the Doppler measurements of velocities to obtain flow speed and direction. Tracking rapid changes in platform motion can be done by the use of an attitude and

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heading reference system (AHRS) to measure acceleration, angular rate of rotation, and heading relative to Earth's magnetic field using a three-axis accelerometer, a three-axis angular rate sensor, and a three-axis magnetometer, respectively. The extraction of platform motion from velocity measurements via accelerometers, inertial measurement units, and AHRS approaches has been used successfully to improve the precision of velocity and turbulence measurements (e.g., Bluteau et al. 2016; Harding et al. 2017; Kilcher et al. 2017; Zippel et al. 2018). Similar platform motion corrections are also applied to shipboard ADCP systems in use in the global research fleet.

Here, we add to those efforts by providing a methodology to estimate the total and fine-scale velocity from the Wirewalker wave-powered profiling system (Rainville and Pinkel 2001; Pinkel et al. 2011; Lucas et al. 2017) utilizing an AHRS-based ping-by-ping motion correction and a range-and-time averaging approach. These vehicle-relative velocities are then combined with GPS-derived buoy position to determine the total current. Our approach is inspired by techniques used to estimate velocity from shipboard rosette-mounted "lowered" ADCP (LADCP; e.g., Firing and Gordon 1990) and from buoyancy-driven gliders (e.g., Todd et al. 2017).

Previous efforts to measure velocity on board the Wirewalker

The Wirewalker was developed at Scripps Institution of Oceanography (SIO) and uses mechanical rectification of ocean-surface-wave-induced buoy motion to drive a profiling body vertically downward along a wire (Rainville and Pinkel 2001). Upon reaching the bottom of the desired profiling range, the profiling cam is released, and the vehicle ascends to the surface due to its positive buoyancy. Equipped with a conductivity–temperature–depth (CTD) sensor, a fluorescence sensor, a nutrient sensor, and an ADCP, the Wirewalker measures physical properties of the upper ocean, including density, chlorophyll, nitrate concentration, and velocity (Lucas et al. 2017). The energy for vertical profiling in the Wirewalker system is provided by the ocean waves which allows for prolonged measurements of the internal wave continuum. Typical Wirewalker vertical velocity averages 0.5 m s^{-1} , permitting several hundred meter profiles to be covered on time scales of tens of minutes continuously over the course of a deployment (Pinkel et al. 2011).

We have made several attempts to measure velocity from the Wirewalker using commercially available velocity sensors. Most of our early efforts focused on single-point Doppler velocimeters, e.g., the Nortek Aquadopp and Aquadopp high-resolution (HR) systems. These single-point velocimeters produce a velocity estimate at a single range (generally $<1 \text{ m}$ from the transducer) or over a very short range interval (HR) several times per second. When mounted on a vertically profiling Wirewalker, time averages in the vertical can be assembled within bin sizes of several meters containing dozens of velocity observations. In this way, estimates of horizontal velocity are produced on vertical profiles (Lucas et al. 2016; Hamann 2019).

We found that this technique—while yielding acceptable subsurface velocities below depths of $\sim 100 \text{ m}$ —contains a mix of low-frequency and surface wave orbital velocities at shallower depths. These are combined with wave-induced motion of the Wirewalker to produce a signal that is challenging to interpret.

To address the contamination of the measured velocities by vehicle motion, we gathered information on the translational and rotational motion of the Wirewalker during the free-ascent profile. To do so, we fitted the Wirewalker with a Nortek 1000 kHz Signature ADCP with onboard AHRS sensors, sampling at 16 Hz (Nortek 2011). The Signature has four slanting beams at 25° from vertical and one-fifth vertical beam (not used in our experiment). The ADCPs were attached to the Wirewalker in two different orientations and tested to assess the degree to which measurement noise could be reduced by removing the Wirewalker motion on a ping-by-ping basis (Fig. 1).

First, the ADCP was mounted in a "horizontal-looking" (90° to the vertical) orientation (Fig. 1a). We tested this side-looking configuration in both standard and HR mode of Signature1000 on short test deployments in the waters offshore of Southern California. The results of those experiments are not shown here, but they indicated that a motion-compensation side-looking configuration had improved velocity precision relative to a single point current meter at depth, but suffered from the same inability to separate surface wave orbital velocities from background currents.

We next tested a vertically down-looking orientation (Fig. 1b) during an Office of Naval Research sponsored cruise in the northern Indian Ocean [the Monsoon Intraseasonal Oscillation–Bay of Bengal (MISO-BOB) 2019]. With those data, we show that motion correction and a combination of range/depth/time averaging—which we refer to here as "box" averaging—is capable of producing velocity measurements with high vertical resolution even in the surface mixed layer.

In the following, we analyze the Wirewalker motion using the onboard AHRS sensor and present an algorithm to calculate vehicle motion integrated forward from the acceleration measurements to east, north, up (ENU) velocities (section 2). After providing the down-looking ADCP configuration and relative deployment information in section 3, we then show fine-scale velocity observations estimated after motion correction and a novel depth–range–time average from the down-looking configuration (section 4), and provide a discussion and conclusions (sections 5 and 6).

2. Wirewalker motion

We gain intuition regarding the Wirewalker motion by examining the accelerometer and gyroscope measurements. As shown in Fig. 2, the amplitude of the measured motion is small at depth and increases as the Wirewalker approaches the surface. This increase in acceleration and rotational motion toward the surface matches the theoretical shape of the surface gravity wave orbital velocities in the deep-water

FIG. 1. Schematic drawing of (a) side-looking ADCP and (b) down-looking ADCP. Here, down-looking orientation is $\sim 20^\circ$ offset from vertical. The axes notation used throughout this paper is as follows: uppercase (X , Y , and Z) refer to ADCP's coordinate system and lowercase (x , y , and z) refer to Wirewalker's coordinate system. Here, we define the Wirewalker x - y - z coordinate system with x positive pointing forward, nominally upstream, y positive pointing nominally cross stream, to the right of x , and z positive pointing up.

approximation, which decays exponentially with depth, indicating a tight relationship between Wirewalker horizontal motion and the surface wave field (cf. to the exponential curve shown as dashed lines in Fig. 2c). Furthermore, the power spectra in Fig. 2 have peaks in the surface wave band (2–25 s), which is consistent with the interpretation that the cause of the observed motion is primarily due to surface-wave-induced displacements of the surface buoy and the orbital velocity induced motion of the Wirewalker package.

Next, we calculate the motion of the Wirewalker using a rigid body assumption, allowing the motion to be decomposed into translational and rotational components, represented as $\mathbf{V}_{\text{motion}} = \mathbf{V}_{\text{translation}} + \mathbf{V}_{\text{rotation}}$. The rotational velocity ($\mathbf{V}_{\text{rotation}}$) is calculated as $\mathbf{V}_{\text{rotation}} = \boldsymbol{\omega} \times \mathbf{H}$, where $\boldsymbol{\omega}$ is the angular rate of rotation measured by the gyroscope and $\mathbf{H}$ is the distance between the rotation center and ADCP ($\sim 1, 1, 0.4$ m for ω_x , ω_y , and ω_z , respectively, set by the geometry of the Wirewalker). The translational velocity can be calculated as $\mathbf{V}_{\text{translation}} = \int \mathbf{a}_{\text{dynamic}} dt$, where $\mathbf{a}_{\text{dynamic}}$ is the dynamic acceleration. As raw acceleration from the accelerometer is measured relative to its own inertial frame at each time, dynamic acceleration relative to Earth can only be obtained by extracting the acceleration of the inertial frame relative to Earth, which is called static acceleration here,

from the raw data. This static acceleration can be calculated as

$$\begin{aligned} a_{\text{static},X} &= \sin(\phi)g, \\ a_{\text{static},Y} &= \sin(\theta)\cos(\phi)g, \\ a_{\text{static},Z} &= \cos(\theta)\cos(\phi)g, \end{aligned} \quad (1)$$

where g is gravitational acceleration, θ is roll angle and ϕ is pitch angle. Thus, the translational motion of the Wirewalker can be calculated from the AHRS system on the Signature1000 using the following steps:

- 1) Obtain dynamic acceleration.

Dynamic acceleration can be obtained by removing static acceleration [Eq. (1)] from raw acceleration which is given below:

$$a_{\text{dynamic},i} = a_i - a_{\text{static},i}, \quad (2)$$

where a_i is measured acceleration and i denotes three different directions, namely, X , Y , and Z .

- 2) Determine the frequency band of acceleration.

As measured acceleration has a relatively broad frequency band, a coherence analysis between the AHRS-measured

FIG. 2. AHRS measurements during one Wirewalker profile (the same profile used throughout the paper, collected during the ONR MISO-BOB 2019 cruise). A gyroscope records the rotation of the Wirewalker around its (a) x , (c) y , and (e) z axes and the three-axis accelerometer measures linear acceleration along (g) x , (i) y , and (k) z axes. Note that all signals presented here have already been transformed from the ADCP coordinate system to Wirewalker coordinate system (Fig. 1). (left) time is shown by the lower x axis and the corresponding Wirewalker's vertical location is shown by the upper x axis. Note that the positive rotating direction is defined by the right-hand rule. Dashed lines in (c) show the envelope of the signal as a function of depth via least squares-fitting peaks of the measurement signal with an exponential function. (right) Spectrum results of the corresponding signal at the surface and bottom region, respectively, with thin black lines as error bars.

FIG. 3. Coherence between $\partial V_X/\partial t$ and $acce_X$ from the AHRS. Velocity and acceleration data used in this example plot are from the same profile used throughout the rest of the paper from the MISO-BOB 2019 cruise. V_X is the raw range-averaged X -ward velocity and the partial derivative is simply calculated by a first-order differentiation. (a) The spectrum, along with (b) estimated coherence and (c) phase. Note that phase is shown only where coherence is above the uncertainty level. Here, the velocity is quality controlled by extracting data that have less than 50% correlation between the transmitted acoustic signal and received acoustic signal, and then range averaged to obtain a time series for one Wirewalker profile. Spectra of velocity and acceleration are calculated by dividing the data into 646 points per group (about 12.5 m in depth) with 50% overlap and then applying a Hanning window. Dashed lines in (b) and (c) denote the uncertainty level.

platform acceleration and the time derivative of ADCP-estimated water velocity (ADCP-derived acceleration) is applied to identify the frequency band where acceleration and velocity are in phase (Fig. 3). From Fig. 3b, the ADCP-derived acceleration and AHRS-measured acceleration have significant coherence from 0.1 to nearly 1.2 Hz, which means that ADCP velocity estimate is strongly influenced by the instrument's motion in this frequency band. It is also important to mention that the decreasing of coherence between ADCP-derived velocity and AHRS-measured acceleration beyond 1.2 Hz does not necessarily indicate that measured velocity is no longer contaminated by the platform motion at the high-frequency region, since the decreased coherence primarily arises from the ADCP-derived acceleration reaching its noise

floor due to the uncertainty per ping characteristics of the ADCP (as shown in Fig. 3a).

3) Transfer acceleration to a fixed coordinate system.

Since we aim to integrate the acceleration measurements forward to estimate the time-dependent platform motion, we first must establish a fixed coordinate system. The most convenient is Earth coordinates, east/north/up. Otherwise, as the Wirewalker rotates in the water, the direction of x - y - z axes is constantly changing and integration of acceleration will be meaningless. For this transformation, Euler angles (pitch, roll, and heading), provided by the ADCP AHRS are required. In matrix form, the transformation is (Nortek 2020; Guerra and Thomson 2017; Guerra 2021)

$$\begin{bmatrix} a_{\text{ENU},E} \\ a_{\text{ENU},N} \\ a_{\text{ENU},U} \end{bmatrix} = \begin{bmatrix} \cos\psi\cos\phi & -\cos\psi\sin\phi\sin\theta + \sin\psi\cos\theta \\ -\sin\psi\cos\phi & \sin\psi\sin\phi\sin\theta + \cos\psi\cos\theta \\ \sin\phi & \cos\phi\sin\theta \end{bmatrix} \begin{bmatrix} a_{\text{dynamic},X} \\ a_{\text{dynamic},Y} \\ a_{\text{dynamic},Z} \end{bmatrix}, \quad (3)$$

where θ is roll angle, ϕ is pitch angle, ψ is heading angle, $a_{\text{dynamic},i}$ are dynamic accelerations in ADCP's XYZ axes, and $a_{\text{ENU},j}$ are transferred accelerations, where j indicates three different components, namely, east-west, north-south, and up-down.

4) Bandpass acceleration.

To perform the integration, it is advantageous to narrow the bandwidth of the acceleration estimates. Based on the coherence analysis (Fig. 3), the frequency band of “Wirewalker

motion-related" acceleration is estimated. Then a_{ENU} are bandpassed using a first-order Butterworth filter with cutoff frequencies of 0.1 and 1.2 Hz. After filtering, the mean of the acceleration data is removed.

5) Integrate acceleration in time.

The Wirewalker translational velocities ($\mathbf{V}_{\text{translation}}$) are obtained by integrating filtered acceleration in time in the Earth coordinate system. The Wirewalker platform motion at each time can then be removed from each ADCP velocity estimate to yield a motion-corrected ADCP velocity product.

3. Down-looking ADCP configuration

When mounted on a surface buoy, ADCPs are often configured to collect bursts of time-continuous data at each sampled range, allowing for averages to be computed over minutes. In such an average, the surface wave orbital velocity contribution is expected to be small, leaving the low-frequency current. A vertically moving vehicle, on the other hand, only dwells at any specific depth for a short time. A profiling Wirewalker might only spend 2–3 s within one 1 m vertical bin. Thus, a single-point measurement of velocity will only provide a few seconds of observations at any depth, precluding the ability to make an average where the contribution of the surface waves is zero.

When fitted with an up- or down-looking ADCP, the "dwell time" within any 1 m vertical bin becomes a function of both the Wirewalker's vertical speed and acoustic profiling range of the instrument. Since the Signature1000 has a ~ 20 m range, and the Wirewalker profiles at a vertical speed of $\sim 0.5 \text{ m s}^{-1}$, we are able to collect time series of many tens of seconds within 1 m depth bins over an arbitrary depth range. These time series, containing dozens to hundreds of pings in each box, allow us to both lower measurement uncertainty through averaging, and to separate the surface wave orbital velocities and the background flow.

Below we present observations collected over the course of an Office of Naval Research funded campaign to the Bay of Bengal (the MISO-BOB Departmental Research Initiative). There, we fielded three drifting buoy systems. Developed in collaboration the Woods Hole Oceanographic Institution (WHOI), the Drogued Buoy Air-Sea Interaction System (D-BASIS) combines a WHOI air-sea flux buoy, a SIO Wirewalker profiler equipped with CTD, bio-optical and irradiance sensors, and a down-looking Nortek Signature1000 with AHRS. The D-BASIS is drogued at depth, where the flow is sluggish, and can be deployed on long-term drifts at a fraction of the cost of a traditional deep-sea mooring. The combination of research-quality air/sea fluxes and rapid profiles of the upper ocean with high vertical resolution allows for the physics of ocean boundary layer response to atmospheric forcing to be elucidated in detail. Such observations are critical to improved forecasting of the ocean and atmosphere.

We show observations from a single D-BASIS system, MISO-3. The Nortek Signature1000 was configured to sample with four slanted beams at a 16 Hz rate, with a 0.25 m cell

size, a 0.1 m blanking distance from the transducer, and at maximum transmit power. This combination yielded 87 cells (0.1–21.6 m range), sampled continuously over the course of the deployment. MISO-3 was deployed in the vicinity of $16^{\circ}30'N$, $84^{\circ}45'E$ on 11 July 2019 and recovered on 28 July 2019. The sea state and winds were generally moderate over the course of the first half of the deployment. After mid-deployment, several calm, clear days were followed by a series of passing fronts and wind speeds increasing to $>10 \text{ m s}^{-1}$. The increase in winds during the second half of the deployment led to an elevated sea state, with waves exceeding 2 m in amplitude.

4. Data analysis procedures for fine-scale velocity measurements

The approach to the data analysis procedure is shown schematically in the flowchart in Fig. 4 (box I), with an equivalent velocity decomposition in Eq. (4). In Eq. (4), the observed velocity ($\mathbf{V}_{\text{OBS}}$) is composed of the ocean background velocity independent of surface wave orbital velocities ($\mathbf{V}_{\text{INT}}$), Wirewalker motion ($\mathbf{V}_{\text{Wirewalker}}$), residual surface wave orbital velocity ($\mathbf{V}_{\text{SW}}$), the drift velocity of the Wirewalker system ($\mathbf{V}_{\text{Buoy}}$), and noise ($\mathbf{V}_{\text{Noise}}$):

$$\mathbf{V}_{\text{OBS}} = \mathbf{V}_{\text{INT}} + \mathbf{V}_{\text{Wirewalker}} + \mathbf{V}_{\text{SW}} + \mathbf{V}_{\text{Buoy}} + \mathbf{V}_{\text{Noise}}. \quad (4)$$

The step-by-step description of Fig. 4 is as follows.

a. Transform beam velocity to XYZ velocity, step 1 in Fig. 4 (box I)

The ADCP is configured to sample in beam coordinates, which requires transformation to a Cartesian (X - Y - Z) coordinate system relative to the ADCP (and thus the Wirewalker). A convenient choice is a right-hand frame of reference with the positive X axis in the direction of the projection of beam 1 on the transducer plane, positive Y axis in the direction of the projection of beam 4 on the transducer plane, and positive Z axis in the direction normal to the transducer plane.

The transfer matrix is (Nortek 2020; Guerra and Thomson 2017; Guerra 2021)

$$\begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} = \begin{bmatrix} \frac{1}{2\sin\alpha} & 0 & -\frac{1}{2\sin\alpha} & 0 \\ 0 & -\frac{1}{2\sin\alpha} & 0 & \frac{1}{2\sin\alpha} \\ \frac{1}{4\cos\alpha} & \frac{1}{4\cos\alpha} & \frac{1}{4\cos\alpha} & \frac{1}{4\cos\alpha} \end{bmatrix} \begin{bmatrix} V_{B1} \\ V_{B2} \\ V_{B3} \\ V_{B4} \end{bmatrix}, \quad (5)$$

where V_X , V_Y , and V_Z are X , Y , and Z velocities, V_{B1} , V_{B2} , V_{B3} , and V_{B4} are beam velocities, and α is the beam angle (25° for Signature1000). Sample X , Y , and Z velocity fields are shown in Figs. 5a–c.

b. Transform XYZ velocity to ENU velocity, step 2 in Fig. 4 (box I)

The X - Y - Z coordinate system is relative to the ADCP, which is a moving object. To study velocity data free from

FIG. 4. Schematic demonstrating the sequence of data processing using velocity data collected by a down-looking ADCP to obtain fine-scale low-frequency flows (box I) and pseudosurface wave velocity spectrum (box II). The velocity product at each step is indicated by a letter while the associated data processing step is given by the number.

platform's movement, we require a fixed coordinate system (e.g., "Earth" coordinates). Therefore, XYZ velocities are further transformed into ENU velocities following Eq. (3). Sample ENU velocity plots are shown in Figs. 5d–f.

c. Extract Wirewalker motion from velocity measurement, steps 3/4 in Fig. 4 (box I)

To show the relationship between the strong, oscillating velocity signal and platform motion, we compare the range-averaged raw ENU velocity at each time and the Wirewalker translational motion, $\mathbf{V}_{\text{translation}}$, calculated above (step 5 in section 2) in Fig. 6. During a typical upcast, the angular rate of rotation ranges from 1° s^{-1} at the bottom of these profiles (100 m), where the influence of the surface wave field is small, to 10° s^{-1} at the surface (Fig. 2c). The rotational velocity ranges from 0.0175 to 0.1745 m s^{-1} , while the translational velocity can reach up to 1.8 m s^{-1} (blue lines in Fig. 6). Since the rotational velocity is relatively small, we have neglected this component. In what follows, $\mathbf{V}_{\text{Wirewalker}} = \mathbf{V}_{\text{translation}}$. The implications of this assumption are revisited in the discussion.

From Fig. 6, we see that the raw XYZ and ENU velocity are significantly correlated with the Wirewalker motion. The averaged coherence for the east–west velocity is 0.97 between 0.1 and 1.2 Hz at a phase around 0° ; similarly, the averaged coherence for north–south velocity is 0.96 at a phase around 0° . This coherence occurs at each measurement range, as would be expected if it arose from translation of the measurement platform.

For each velocity component, the motion of the Wirewalker agrees well, but not perfectly, with the range-averaged raw ENU velocity. This shows that the Wirewalker motion estimation from the AHRS is effective and that the "vertical stripes" in the raw velocity data are correlated with platform motion. Motion-corrected velocity profiles are shown in Figs. 5g–i.

d. Box averaging technique, step 5 in Fig. 4 (box I)

Due to the vertical profiling of the Wirewalker, the z position of each velocity measurement in time changes, producing a sliding window with a length determined by the profiling

FIG. 5. Velocity plots showing different processing stages for one Wirewalker profile. (a)–(c) XYZ velocities for the X , Y , and Z directions, respectively. (d)–(f) ENU velocities for east–west, north–south, and up–down directions, respectively. (g)–(i) Motion-corrected velocities for east–west, north–south, and up–down directions, respectively. (j)–(l) Box-averaged velocities for east–west, north–south, and up–down directions, respectively. The second axis in each panel is the zoomed-in view of the data in the same dashed box shown in (a). Also, the black box in the second axis of (g)–(i) represents the “1 m box” for box averaging.

FIG. 6. Range-averaged raw ENU velocity and Wirewalker motion velocity for one Wirewalker profile. Here, Wirewalker motion velocity has been multiplied by -1 for a clear comparison. Note that for the vertical component, Wirewalker motion is simply calculated by time differentiation of measured pressure (dp/dt), as this is a more direct measurement of vertical motion instead of integration of z -component acceleration. The second axis on the top represents the vertical location of the Wirewalker at the corresponding time.

range of the ADCP, and where the dwell time at any depth is a function of the ADCP's range and the vertical speed of the platform. This “dwell” duration can be approximated by $T = R/V_{\text{Wirewalker},z}$, where R is the profiling range of the ADCP and $V_{\text{Wirewalker},z}$ is the Wirewalker vertical speed.

To produce a profile of ocean velocities over the length of each Wirewalker profile, we utilize a “box-averaging” approach, where time series of velocity are produced for a particular depth bin width from the motion-corrected velocities. These “time series” within each depth bin can be produced with duration of several to many surface wave periods (tens of seconds to minutes), and can be averaged in time to reduce the contribution for the residual surface wave field to the velocity estimate within each depth bin:

$$\mathbf{V}_{\text{box-averaged}}(z_i) = \frac{1}{N_i} \sum_{n=1}^{N_i} \mathbf{V}_{\text{mc}}(\hat{z}_n, t_n), \quad (6)$$

where $\mathbf{V}_{\text{mc}}$ is motion-corrected velocity, i represents each depth bin, N_i is the total number of velocity measurements in each depth bin, and subscript n denotes each velocity measurement in each bin. The bin width in the vertical is inversely related to the precision of the resulting velocity estimate since a larger bin includes more individual measurements.

The effect of each processing step outlined above can be seen in comparison of the time series for selected depth bins (Figs. 7b–e). Spikes in the raw data associated with vehicle's motion are effectively reduced by the motion correction. The number of measurement samples within a 1 m vertical bin is

depth dependent, increasing from 1000 to 6000 from 100 to 20 m depth, where the maximum acoustic scattering is found for this particular profile. Thereafter, the number of samples gradually decreases as the Wirewalker approaches the surface. At a minimum of 1000 samples, time series of about 20 s are produced in each depth “box.”

Figure 8 shows the frequency spectrum of the time series inside each box for raw and motion-corrected eastward velocity and motion-corrected velocity using a 1 m vertical bin. Besides the noticeable energy decrease induced by the motion correction until 1–2 Hz where noise starts to dominate, these spectra show that the surface wave time scales are still energetic even after motion correction, as indicated by the energy peaks in the 0.1–0.2 Hz frequency band (thick black lines in Figs. 8a–d).

To provide a quantitative assessment of the trade-off between the vertical spacing of the resulting velocity estimate and the precision of the estimate within each bin, we compute the vertical wavenumber spectrum using the vertical profiles of the horizontal velocity obtained for various box sizes. Results (not shown here) show that spectrum with varying box sizes have almost the same shape and noise starts to dominate beyond 0.33 cpm (an example is shown in Fig. 10). Therefore, we use a vertical bin width of 1 m in what follows.

e. Total velocity field, steps 6/7 in Fig. 4 (box 1)

The total reconstructed velocity field comes from the sum of the reconstructed box-averaged velocity, which is depth dependent, and the buoy drift velocity, which is depth-uniform.

FIG. 7. (a) Dwell duration (bottom x axis) and the number of independent velocity measurements (top x axis) sampled for each 1 m box. The solid black line corresponds to the same profile used throughout the paper characterized by weak acoustic scattering strength and the dash-dotted black line is obtained from another profile with strong acoustic scattering strength. (b)–(e) The depth-averaged eastward velocities in the 1 m box at four different depths [marked by dotted horizontal lines in (a)] of two velocity products, corresponding to the solid black line in (a).

The total velocity field is shown in Figs. 9a and 9c for the MISO-3 deployment.

We estimate the precision of the total velocity field by calculating the standard error of the mean (SEM; the standard deviation of the mean of multiple sample means). It is expressed as

$$\text{SEM}(i) = \frac{\sigma_i}{\sqrt{N_i}}, \quad (7)$$

where i represents boxes at different depths, σ is the standard deviation of the time series of depth-averaged motion corrected velocity in each box, and N is the number of the independent ADCP pings in each box. The SEM value ranges between 0.006 m s^{-1} , where N is large, to 0.01 m s^{-1} , where N is small, such as the bottom and surface region of the Wirewalker profile.

5. Discussion

a. Fine-scale velocity measurements from the Wirewalker profiler

The motion correction implemented here would provide an improved knowledge of buoy or mooring motion relative to

previous systems that did not carry AHRS measurements, and so could be used to improve velocity precision from ADCPs fixed on buoys or moorings. However, velocity measurements made from a fixed depth come with the implicit trade-off between the range of depths that can be covered and the resolution in the vertical that can be achieved. Many applications require knowledge of finer vertical scales than can be achieved from a fixed ADCP over ranges where that variability must be known. For example, the wind can trigger a near-inertial response in the ocean that transports energy from the atmosphere into the ocean interior. Because of the physics of this response, the near-inertial internal wave that affects this transport has a small vertical wavelength, typically with a maximum energy at a vertical wavenumber cutoff of 0.1 cpm or higher (Pinkel 1983; Pinkel and Anderson 1997a,b). Fixed or commercial shipboard ADCPs with vertical ranges of $>100 \text{ m}$ struggle to achieve the necessary vertical resolution. Those with ranges of several hundred meters or more are typically lower frequency and have less vertical resolution, often missing this important signal entirely.

At some trade-off in time resolution, a short-range, high-frequency ADCP can be moved vertically through the ocean to provide highly vertically resolved velocities over large depth ranges. This has been accomplished with buoyancy

FIG. 8. Spectrum results of the time series inside the 1 m box for four different depths of two velocity products [corresponding to (b)–(e) in Fig. 7].

gliders (Todd et al. 2017) and Lagrangian floats (Shcherbina et al. 2018). However, those platforms can only determine their path-mean velocity based on GPS fixes during surfacing—which, in the case of a typical glider mission, might be only once every 6 h. Here, we add to that technical capacity by demonstrating that a similar approach can also be implemented for the Wirewalker ocean wave-powered profiler. Velocity with high vertical resolution relative to the drifting profiler is combined with the drift velocity calculated from continuously tracked surface buoy to reconstruct the full velocity field over the profiling ranges on time scales of minutes.

The presence of a surface buoy comes with other trade-offs. Surface orbital wave-induced horizontal displacements of the buoy are transmitted to the profiling vehicle via the tensioned profiling wire. In general, these “buoy-motion” displacements of the vehicle are different from the in situ wave orbital velocities, which decay exponentially with depth. Removal of this motion by the onboard accelerometer and gyroscope leads to a motion corrected time series of velocity ($\mathbf{V}_{mc}$) that is composed of wave-orbital and background

velocities, ($\mathbf{V}_{mc} = \mathbf{V}_{SW} + \mathbf{V}_{INT}$). The time-average $\langle \mathbf{V}_{mc} \rangle$ is approximately equal to $\langle \mathbf{V}_{INT} \rangle$ since $\langle \mathbf{V}_{SW} \rangle \rightarrow 0$ as the time over which the average is made extends to many surface wave periods. At depths and times where surface waves induce strong orbital velocities, the dwell time must be several tens of seconds at least to effectively separate the orbital velocities from the background flow.

The dwell time at any depth is a function of the vertical speed of the Wirewalker and the realized range of the ADCP. In regions or times where the acoustic scattering strength is weak (e.g., at 80 m depth for the solid black line in Fig. 7a), the realized range of the ADCP may drop by more than half of its total average. When the ADCP’s realized range is at a minimum, the dwell time can be reduced to 30 s or less, complicating efforts to separate the orbital from the background velocities. In the data presented here, minimum scattering strength was found below 80 m, and varied in time with the migration of the deep scattering layer (comparison between the solid black line and the dash-dotted black line in Fig. 7a). The scattering conditions will vary from region to region, and from open to coastal oceans, depending on the biological

FIG. 9. (a) The buoy drifting velocity. (b) The velocity variance inside each 1 m box using raw eastward velocity. (c) The eastward velocity estimated after motion correction and box averaging. (d) The eastward velocity shear, which is calculated from vertical differentiation of velocity in (c). The vertical resolution is 1 m. The time resolution is not uniform but has an average resolution of 5 min per profile. The total duration of this measurement is 16.8 days, but about 10 days of data are shown here. Black lines in (b) and (c) are isopycnals with values from 1020.7 to 1023.9 kg m^{-3} with a 0.8 kg m^{-3} interval.

activity. In general, scattering is weakest at depths below 100 m, where orbital velocities are weak for most wave and swell conditions. Further improvement over the time averaging approach used here might also be achieved with a model based on surface wave physics and constrained by the Wirewalker velocity observations, in order to yield an improved separation of the wave orbital velocities. There are of course other reasons why a more sophisticated approach might be useful, including the characterization of the directional wave spectrum.

Our approach to obtain ocean velocity (i.e., $\mathbf{V}_{\text{INT}}$) can be assessed with a test case: What is the effective vertical resolution of the reconstructed velocity shear profiles (d/dz velocity)? Velocity shear for an open ocean, drifting Wirewalker

deployment in the Bay of Bengal is shown in Fig. 9d, along with the depth of selected isopycnals estimated from onboard CTD observations. In the figure, velocities are estimated over 1 m vertical bins (0.5 cpm vertical wavenumber Nyquist frequency) over the 100 m profiling range of the Wirewalker.

The qualitative correspondence between the time evolution of the isopycnals and the time evolution of the bands of vertical shear in Fig. 9 is consistent with our expectation that the high-mode shear of near-inertial waves is displaced vertically by passing internal waves just as density surfaces are (e.g., Alford et al. 2016; Le Boyer et al. 2020). As in Fig. 10, both the vertical wavenumber spectrum of horizontal velocity and vertical shear show slopes that are in agreement with internal wave theory, k^{-3} and k^{-1} , respectively (e.g., Duda and Cox

FIG. 10. (a) The vertical wavenumber spectrum for horizontal velocities with the dashed line showing the k^{-3} slope. (b) The vertical wavenumber spectrum for estimated horizontal velocity shear, with the dashed line showing the k^{-1} slope. Ship ADCP data were collected by a 300 kHz RDI ADCP mounted on the bottom of the ship. Wirewalker spectrum is averaged across available 2294 profiles with a depth range from 6 to 100 m. While ship ADCP spectrum is averaged across 18 339 pings with a depth range from 10 to 60 m. Texts in between these two panels show wavelength values corresponding to wavenumbers.

1989). Our observations are capable of resolving the ocean shear field down to a cutoff wavenumber of 0.33 cpm, at which point the variance of the ocean signal is smaller than the precision of the velocity observations and the spectrum becomes white (Fig. 10b).

To provide a point of comparison, velocity observations collected from R/V *Sally Ride*'s RDI 300 kHz ADCP during the same time period within 100 km of the drifting Wirewalker were analyzed (black line in Fig. 10). This direct comparison shows the improvement in vertical resolution relative to the shipboard ADCP, which is barely capable of resolving the vertical wavenumber shear maximum at roughly 10 m scales. This is probably principally due to ship motion. Since most of the shear variance in the Wirewalker time series exists at roughly 0.06 cpm, and a profile was collected over the entire 100 m every 5 min, the Wirewalker observations are capable of providing a robust and well-resolved picture of the vertical structure and time evolution of near-inertial wave-induced shear from days to minutes in a way that shipboard

measurement cannot. It is thought that these high vertical wavenumber fluctuations drive much of the turbulence and mixing in the ocean interior.

There are limitations to this approach for measuring the ocean fine-scale velocity variability, and several sampling strategies can be explored. For example, ADCP frequency, cell size, sampling bandwidth, and profiler speed, as well as practical considerations like memory and power limitations, all can be optimized based on the desired resolution in the vertical and the expected surface wave state.

Furthermore, one of the major assumptions applied here is that the Wirewalker's rotational motion is neglected. However, under certain conditions, the rotational motion could become important and should be included in the motion calculation. This correction is left for future work.

b. Surface wave orbital velocities and ocean mixed layer velocities from the Wirewalker profiler

To show the potential of the WW/ADCP combination to quantify surface waves (see schematics in Fig. 4, box II), we calculate a range-averaged velocity at each time from the Wirewalker velocities before motion correction. This time series is examined over the upper 10 meters of the water column during the ascent and subsequent descent of each profile. Frequency spectra can be calculated for each profile over the entire surface wave band (Fig. 11). The time average of 3 weeks of these profiles shows the domain of spectral power in the wind-wave band (Fig. 11a). The variance over the surface-wave band can be estimated as the integral of the frequency spectra from 2 to 20 s period, and is presented as a time series in Fig. 11b. Since the average spectrum is dominated by the wind-wave band, it is not surprising to see the close correspondence of the surface wave band variance and the wind speed measured by a meteorological package on the surface buoy.

Ultimately, these data could be used with array approaches to estimate important aspects of the surface wave field, like its directional spectrum. When combined with displacement of the surface buoy, this would create a profiling system that could also work as a wave buoy. Likewise, detailed information regarding the surface wave field could be input into physics-based models to more effectively extract the orbital velocities from the ocean currents being measured. Hybrid data/model extraction of the surface wave orbital velocity signal might allow precise enough measurements to observe subtle dynamics like wave-induced Stokes drift, Langmuir circulations, and other important processes in the upper ocean and ocean mixed layer.

6. Conclusions

We present an algorithm to obtain ocean velocities from a vertical profiling vehicle below a surface buoy. The methodology requires a up- or down-looking high-frequency ADCP and a concurrent estimate of platform motion in three spatial dimensions and time. Using a test case, we show that a Nortek Signature1000 with AHRS, configured to sample at 16 Hz over a

FIG. 11. Surface wave orbital velocities measured from the Wirewalker platform. (a) Average (blue line) and individual frequency spectra (gray lines) from transducer depths < 10 m (2245 profiles). A dashed line corresponding to f^{-5} is shown for reference. (b) A comparison of the variance in the surface wave band and the collocated wind speed measured from a WHOI meteorological system installed on the surface buoy.

range of ~ 20 m, mounted on a Wirewalker profiler moving vertically at $0.3\text{--}0.5\text{ m s}^{-1}$ is capable of producing velocity estimates that can characterize the ocean fine-scale velocity field to vertical wavenumbers of $1/3$ cycles per meter, over a 100 m vertical range, every few minutes. The MATLAB code for this algorithm, along with raw velocity data collected from one Wirewalker upcast, can be found in the online supplemental material.

The primary challenge is that, unlike a Lagrangian float, the design of the Wirewalker is such that it is in a quasi-Eulerian frame of reference relative to surface waves. Due to this fact, even after motion correction, the velocity measured at a single point still has a surface wave signature.

With a vertical profiling “window,” where simultaneous measurements of velocity are collected across a range of depths from a vertically moving platform, a motion-corrected up- or down-looking ADCP alleviates this problem, giving time aperture at all depths. This allows the surface wave orbital velocities and the background flow to be separated. The technique reported here builds on previous efforts to measure velocities from autonomous platforms and by ships using “lowered ADCP” techniques. Improvement of ocean velocity estimation from autonomous platforms of all kinds is a crucial observational tool for understanding and predicting the physical state of the ocean.

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