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Evaluation of AUV-based ADCP measurements

Derek A. Fong and Nicole L. Jones
Environmental Fluid Mechanics Laboratory, Stanford University, Stanford, CA, USA

Abstract

Recent development and commercialization of relatively portable and inexpensive autonomous underwater vehicles (AUVs) have led to new methods for making hydrodynamic, chemical, and biological measurements in near-coastal, lake, and estuarine systems. Equipped with Doppler velocity log (DVL) technology to allow for dead-reckoning navigation, this new class of AUVs has the potential to log not only vehicle motions, but water velocities as well. In this article, we assess the performance of the DVL acoustic Doppler current profiler (ADCP) equipped on the REMUS AUV (Hydroid) in three different environments: a tidally forced lake; a wave-forced, near-shore fringing coral reef; and a gently sloping continental shelf. In all three data sets, the water velocities measured by the AUV DVL compare favorably with measurements from nearby stationary acoustic Doppler current profilers. Nevertheless, the water velocity component measured parallel to the vehicle's tracks exhibited a bias in the direction of AUV motion, consistent with a previously reported bias found for the ship-mounted ADCP application in low-scattering environments. The fringing reef data suggest that DVLs are capable of partially resolving wave motions.

Introduction

The development of relatively low-cost, portable autonomous underwater vehicles (AUVs) in the past few years has made a new class of ocean measurements possible. For example, the REMUS (Remote Environmental Monitoring UnitS) AUV built by Hydroid has been used to make a variety of biological, chemical, and physical measurements in the near-shore environment. REMUS has been used to measure properties including scale-dependent dispersion on the continental shelf (Fong and Stacey 2003), bioluminescence (Moline et al. 2005), and turbulence microstructure (Hayes and Morison 2002; Levine et al. 2002, Goodman et al. 2006), and also to successfully track chemical plumes using an adaptive mission planner (Farrell et al. 2003, 2005). More recently, investigators have used the vehicle to deduce bottom roughness characteristics (G. Pawlak, personal communication), quantify sand ripple structure (P. Traykovski, personal communication), and measure chlorophyll *a* concentrations (N. Jones, unpublished data). In each of these example applications, the REMUS AUV has provided a platform much more stable than typical ship-deployed/-mounted instrumentation as well as greater maneuverability and more accurate positioning. In several instances, instrumentation installed on the REMUS AUV has been used as a substitute for traditional ship measurement techniques and, in some cases, has allowed for the collection of data unattainable by traditional ship-based techniques (e.g., Hayes and Morison 2002).

To navigate accurately, modern AUVs (REMUS, Bluefin Robotics Bluefin AUV, and Lockheed's Cetus AUV, for example) use a combination of acoustic (both long baseline [LBL] and ultra-short baseline [USBL]) or inertial navigation systems (INS), with a dead-reckoning navigation system based on a Doppler velocity log (DVL) (Purcell et al. 2000; Whitcomb et al. 1998). The most commonly used DVL is manufactured by RD Instruments (RDI). RDI DVLs are similar to RDI Workhorse broadband acoustic Doppler current profilers (ADCPs) and can be used to measure both vehicle speed over the bottom and water velocity profiles. Very little published work has discussed or exploited the latter capability, however. One exception is the recent work of Farrell et al. (2005), who used the measured water velocities by the upward and downward DVL ADCPs on a REMUS AUV to infer upstream and downstream plume advection and track a chemical plume. Nevertheless, Farrell et al. (2005) did not rigorously compare the reported DVL velocities with any other reference measurements. It

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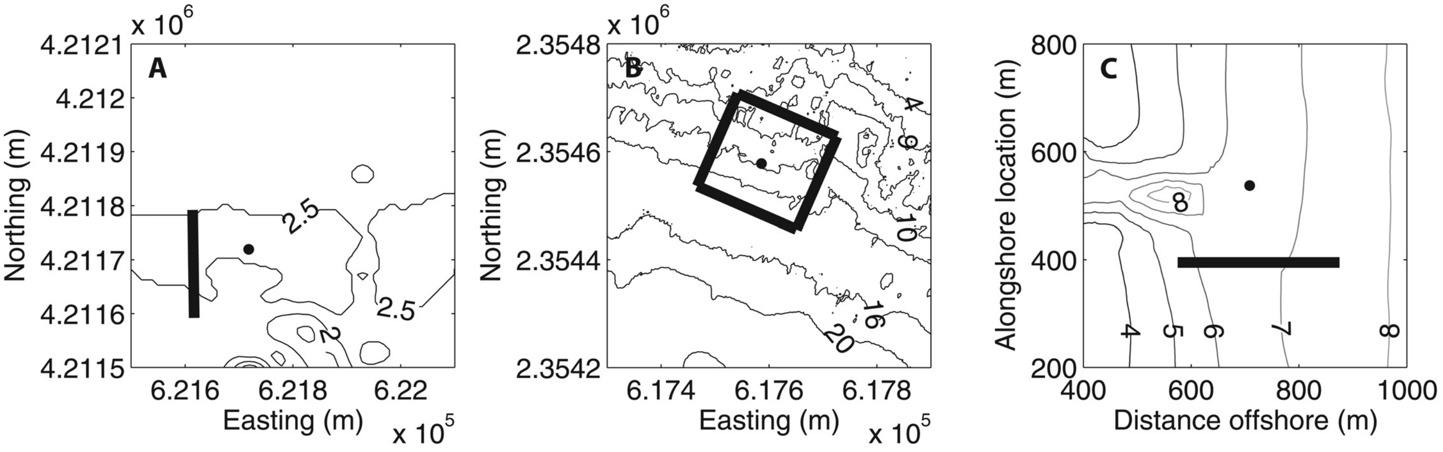

Fig. 1. Field sites for this investigation. (A) Franks Tract, CA (note: region of study is relatively flat: variation is less than 0.5 m over area plotted). (B) Kewalo Basin, HI. (C) Duck, NC. Solid lines indicate REMUS AUV transect paths, and filled circles indicate location of stationary ADCPs. Isobath labels are in units of meters.

seems plausible that AUV-mounted DVLs may perform better than ship-mounted ADCPs owing to the reduction of surface influences such as wave-induced chop and bubble entrainment near the air-water interface. In addition, for smaller AUVs such as the one discussed in this study, the small hull should result in much smaller flow disturbance than from shipboard measurements (Cutchin 1985; Cutchin et al. 1986).

It should be emphasized that a DVL is simply a "custom-fit" ADCP designed for installation onboard an AUV or remotely operated vehicle (ROV). Theoretically, a DVL ADCP has the same capabilities as a standard broadband ADCP with bottom-tracking enabled. For clarity, we here use "DVL" to denote a vehicle-installed ADCP and "ADCP" to specify a typical ship-mounted or stationary deployed Doppler profiler.

ADCP Background—For over two decades, ship-mounted ADCPs have been the primary tool for inferring spatial distributions of ocean currents in a vertical plane (e.g., King et al. 2001; Hummon and Firing 2003; Valle-Levinson et al. 1998). To measure the water currents relative to the Earth, the motion of the ship must be measured and subtracted from the ADCP estimate of the ship's velocity relative to the different layers (depths) of water. The ship's motions can be deduced from either the ship's gyrocompass (pitch, roll, and heading) coupled with a global positioning system (GPS) or Loran-C satellite tracking (Trump 1986) or, more recently, using a bottom-tracking system built into the ADCP (e.g., RDI's bottom tracking Mode 1).

In spite of their wide use, velocity transects measured from ship-mounted ADCPs are not without their problems. For example, in the absence of bottom-tracking, the ship's gyrocompass can contaminate ADCP speed estimates (Bowditch 1977; Trump 1986; Joyce 1989; Pollard and Read 1989). Even modern gyrocompasses that attempt to account for these errors require in situ and site-specific calibration (Trump and Marmorino 1997). Many of these problems can be overcome if the ADCP has bottom-tracking and a self-contained gyrocompass. Fong and Monismith (2004) (hereafter, FM04) have recently shown that the accuracy of RDI's bottom-tracking system is comparable to the precision of a kinematic GPS system.

Nevertheless, in spite of the accuracy of measurements of vessel speed via bottom-tracking, FM04 also report that in many coastal or near-coastal applications another problem may exist when using an ADCP to measure water velocity profiles via a moving platform. For several low-scattering environments, such as oligotrophic waters near coral reefs, they find a water velocity error that is unexplainable by either compass or bottom-tracking errors. Repeated transects in opposing directions show a bias in measured water velocities in the direction of ship motion that is up to ± 5 cm s^{-1}. FM04 note that this bias also tends to exhibit depth variations; errors are largest near the ADCP transducers.

Present study—In this short paper, we investigate the efficacy of using a DVL to infer water velocity profiles. Our primary goal is to determine the usefulness of velocities derived from DVLs. We compare velocities logged by a pair of upward- and downward-facing RDI DVLs installed on a REMUS AUV and compare them with measurements made using stationary Doppler profilers at three different sites under a variety of hydrodynamic conditions. We compare both the along- and cross-vehicle components of velocity with the stationary measurements and assess whether the previously reported bias issue (FM04) is pertinent to the AUV application. We also examine the influence of wave activity on the velocity measurements.

Materials and procedures

In this study, we evaluated DVL-derived water velocities for three different sites (Figure 1). A REMUS AUV owned and operated by Stanford University was employed for the first two experiments, and a different REMUS vehicle was used in the third experiment (Duck, NC). The latter vehicle and data set were used primarily to determine the generality of the results obtained from the first two data sets.

REMUS autonomous underwater vehicle—The AUV-based measurements presented were conducted using a REMUS AUV built by Hydroid. REMUS is a 1.6 m long vehicle that weighs approximately 38 kg in air. The vehicle is equipped with a variety of instrumentation. It comes standard with a downward DVL and a conductivity, temperature, and depth (CTD) probe to measure sound speed and density. It can also be equipped with several optional instruments such as sidescan sonar, chlorophyll *a* and rhodamine WT fluorometers, fast-response CTD, bioluminescence and optical backscatter, and turbulence microstructure sensors. For the data sets presented below, the vehicles used were equipped with upward- and downward-facing 1200 kHz RDI DVLs. The pair of DVLs allowed for water velocity profiling both above and below the vehicle. Both DVLs have a blanking distance of approximately 0.6 m; coupled with the vehicle diameter of approximately 0.2 m, there is a 1.4 m region surrounding the vehicle where velocities cannot be measured. The vertical bin size for all REMUS-based velocity measurements shown below was 0.5 m.

The REMUS AUV navigates by both acoustic (LBL and USBL) navigation and dead reckoning using the downward DVL, as noted previously. With accurate transponder placement, horizontal navigation is accurate to within 2 m. In the vertical direction, the vehicle is programmed to hold a fixed altitude above the bottom. REMUS can maintain its programmed altitude to within 0.1 m.

REMUS can also measure water velocities using its pair of upward and downward DVLs. The upward and downward DVLs ping the water column sequentially to avoid interference between the DVLs. Bottom-track pings (using the downward DVL) measure vehicle speed for both upward and downward velocity profiles to reference water velocities with respect to the Earth. The resulting water velocity time series logged by the vehicle is recorded at approximately 0.5 Hz for profiles both above and below the vehicle. Velocity measurements near the bottom and water surface are not attainable due to reflections that contaminate the water pings. In all experiments, the vehicle's DVLs were configured to record ensemble-averaged velocities using four water pings and four bottom pings to maintain reliable dead-reckoning capabilities. For all three data sets presented, the REMUS vehicle was programmed to repeatedly measure transects in opposing directions to both ascertain the presence of any measurement bias and compare with measurements from a nearby stationary ADCP.

It is worth noting that any differences observed between the DVL and stationary ADCP measurements can be attributable to several sources including instrument measurement uncertainty/error for either the fixed ADCP or DVL, error in instantaneous position measured by bottom tracking (or LBL navigation, for the Franks Tract data set discussed below), and spatial variability in the currents. Whereas the first of these is well known from RDI specifications, the latter two are not easy to determine or separate. For example, FM04 demonstrate that in the mean (over the length of a several-hundred-meter transect), bottom tracking measures ship motion to an accuracy comparable to kinematic GPS; nevertheless, on an instantaneous basis, bottom tracking may itself introduce some uncertainty to an individual velocity measurement. Without an absolute reference such as kinematic GPS to estimate bottom tracking error on an ensemble basis, we cannot distinguish between real spatial variability and measurement error from bottom tracking.

RDI Workhorse monitor ADCP—For all three data sets presented below, a stationary, upward-facing RDI Workhorse ADCP was deployed to collect velocity profiles concurrent with the REMUS measurements. Each ADCP was deployed near the bottom on a rigid frame, level with respect to the local bathymetry. In each case, ensemble-averaged (120 s) velocities were used for comparison with the REMUS-derived water velocities. A 1200 kHz model was used for the tidal lake and fringing reef data sets with 0.07 m and 0.25 m spaced bins, respectively, and a 600 kHz model with 0.50-m bins was deployed for the gently sloping continental shelf data set (see below). It should be reiterated that the stationary ADCP data plotted in the figures below are only useful as a rough comparison to the transect-averaged velocities from REMUS measurements. Small differences between the stationary ADCP- and DVL-reported velocities are expected due to spatial variability in water velocities as well as uncertainty in both sets of measurements.

Assessment

Franks Tract, CA—REMUS DVL velocity data were collected as part of a benthic grazing experiment at Franks Tract in the Delta region of San Francisco Bay on 6 May 2004. Franks Tract is a shallow lake that is tidally forced at its boundaries. Currents in the study region are predominantly east-to-west and vary semidiurnally. The REMUS vehicle was programmed to perform repeat 200 m long transects at an altitude of 2 m. The transects were conducted in a north-to-south direction for a nearly 7 h period (see Figure 1A). Because the water column was so shallow, only one water velocity bin from the downward DVL provided consistently reliable data.

Using the navigation data recorded by the AUV, the time series of velocities collected by the DVL was converted into velocity as a function of horizontal position (latitude and longitude) and subdivided into 94 individual north-south transects, 47 transects in each of the northward and southward transect directions. Bottom-tracking for this data set was unreliable, consistent with difficulties in previous measurements at Franks Tract using a ship-mounted ADCP (A. Blake, personal communication). Because of these problems, vehicle velocities from the LBL navigation system were used in place of bottom-track velocities to determine water velocities with respect to the fixed bottom.

For each transect, the transect-averaged water velocity was calculated and separated into its eastward and northward

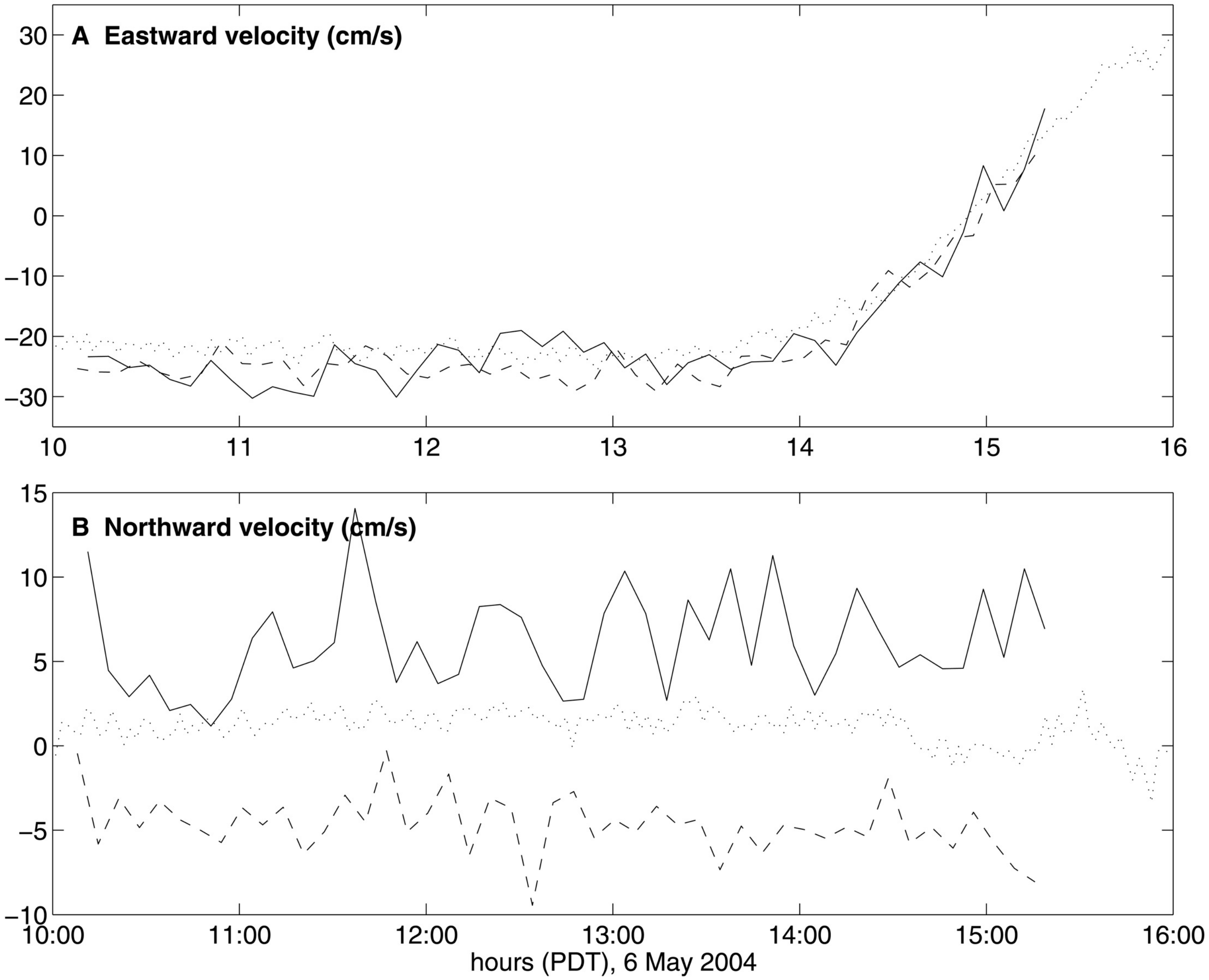

Fig. 2. Transect-averaged velocity for Franks Tract, CA, experiment. (A) Eastward velocity for first downward bin (z = 1.05 mab). (B) Northward velocity for first downward bin (z = 1.05 mab). Northward directed transects indicated by solid line, and southward directed transects by dashed lines. The dotted line indicates velocities measured at a nearby stationary ADCP (see Figure 1A). Note: vertical axis scale is different for each subpanel.

components. Time series of the transect-averaged velocities for northward and southward AUV transects are shown in Figure 2 along with velocities measured at a nearby stationary ADCP for the same height above the bottom (see Figure 1A). The eastward components of velocity compare favorably with those measured from the stationary ADCP. The transition from ebb to flood is evident in both the AUV and fixed velocity measurements, with slack water occurring at approximately 15:00. The amplitude of the dominant east-west velocities measured by the AUV are slightly larger than those by the stationary ADCP. This discrepancy is likely due to the spatial variability in the flow field and the 100 m distance between the REMUS transect and the location of the stationary ADCP.

There is a more noteworthy difference in the northward component of velocity. The northward velocities reported by the stationary ADCP are nearly zero, but the AUV reports water velocities of O(5) cm s^{-1}. The sign of the reported DVL northward velocity component depends on the direction of vehicle motion: when REMUS is traveling northward, a northward velocity is reported, when it travels southward, a southward velocity is measured. This behavior is consistent with the bias error studied by FM04 and discussed above.

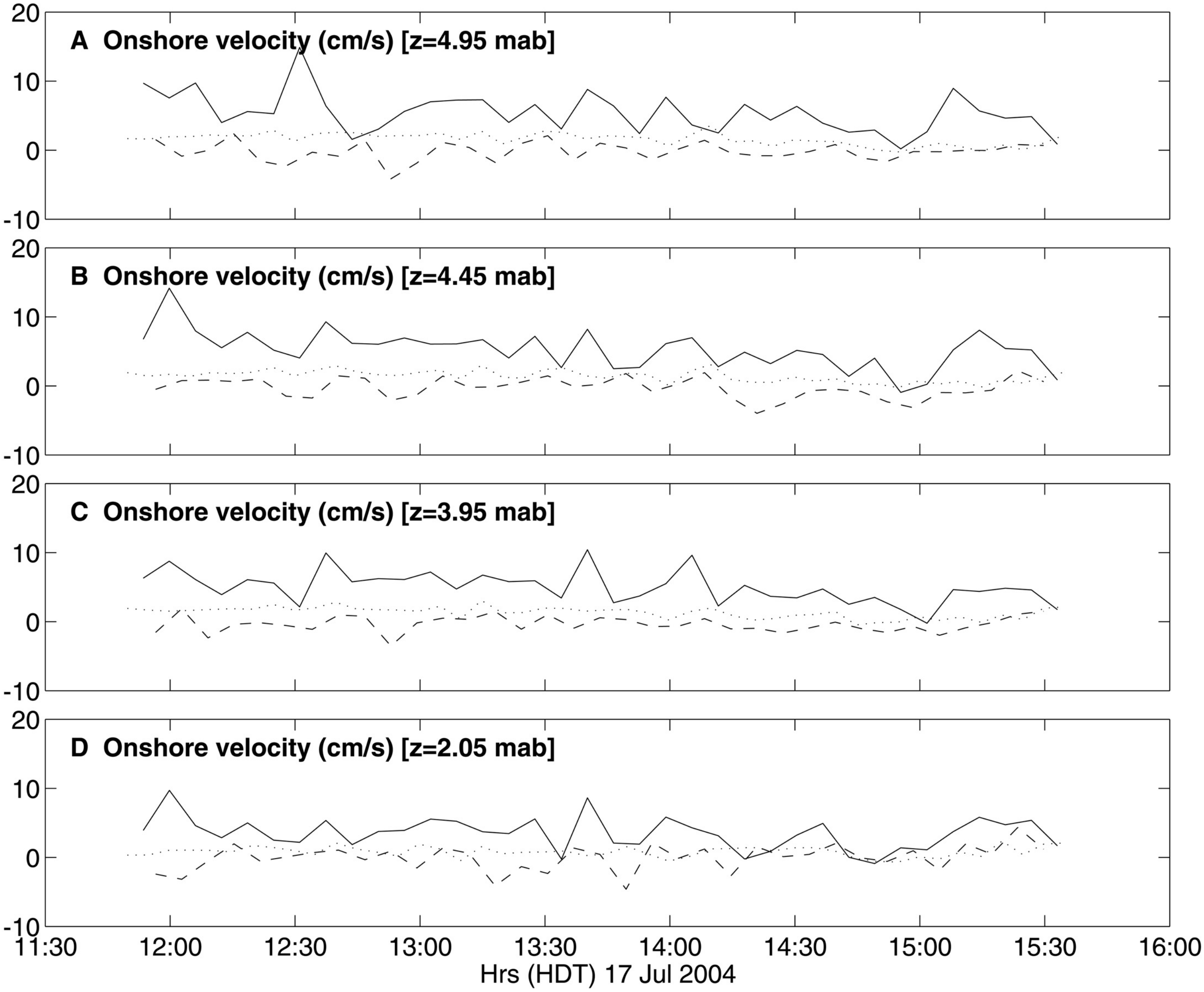

Fig. 3. Transect-averaged onshore velocities for Kewalo Basin, HI, experiment. (A) Onshore velocity for third bin of upward DVL (z = 4.95 mab). (B) Onshore velocity for second bin of upward DVL (z = 4.45 mab). (C) Onshore velocity for first bin of upward DVL (z = 3.95 mab). (D) Onshore velocity for first bin of downward DVL (z = 2.05 mab). Onshore transects are shown with solid lines, and offshore transects with dashed lines. The dotted lines indicate velocities measured at a nearby stationary ADCP (see Figure 1B).

Kewalo Basin, HI—REMUS DVL data were collected on 17 July 2004 during a dye dispersion study over a wave-forced, fringing coral reef in Kewalo Basin located on the south shore of Oahu. Currents are predominantly alongshore on this reef system, with strong waves on this day with significant wave heights of 1 to 2 m (R. Lowe, unpublished data). REMUS was programmed to repeat a 200 m side square box pattern for 3.5 h at an altitude of 3 m (see Figure 1B).

Similar to the tidal lake data set, navigation data were used to decompose the time series into 140 transects, 35 each in the onshore, offshore, upcoast, and downcoast directions. For this data set, reliable velocity data (see below) were collected for four depth bins, three above the vehicle with its upward DVL and one below the vehicle using its downward DVL. The transect-averaged velocities were calculated and decomposed into the upcoast and offshore components.

A comparison of the onshore component of velocity for the on- and offshore transects is shown in Figure 3 for the four reliable velocity bins. The bias error seen by FM04 and present in the tidal lake data set is readily apparent for the upward facing DVL measurements. Velocities are biased toward the direction of vehicle motion: onshore transects measure an onshore

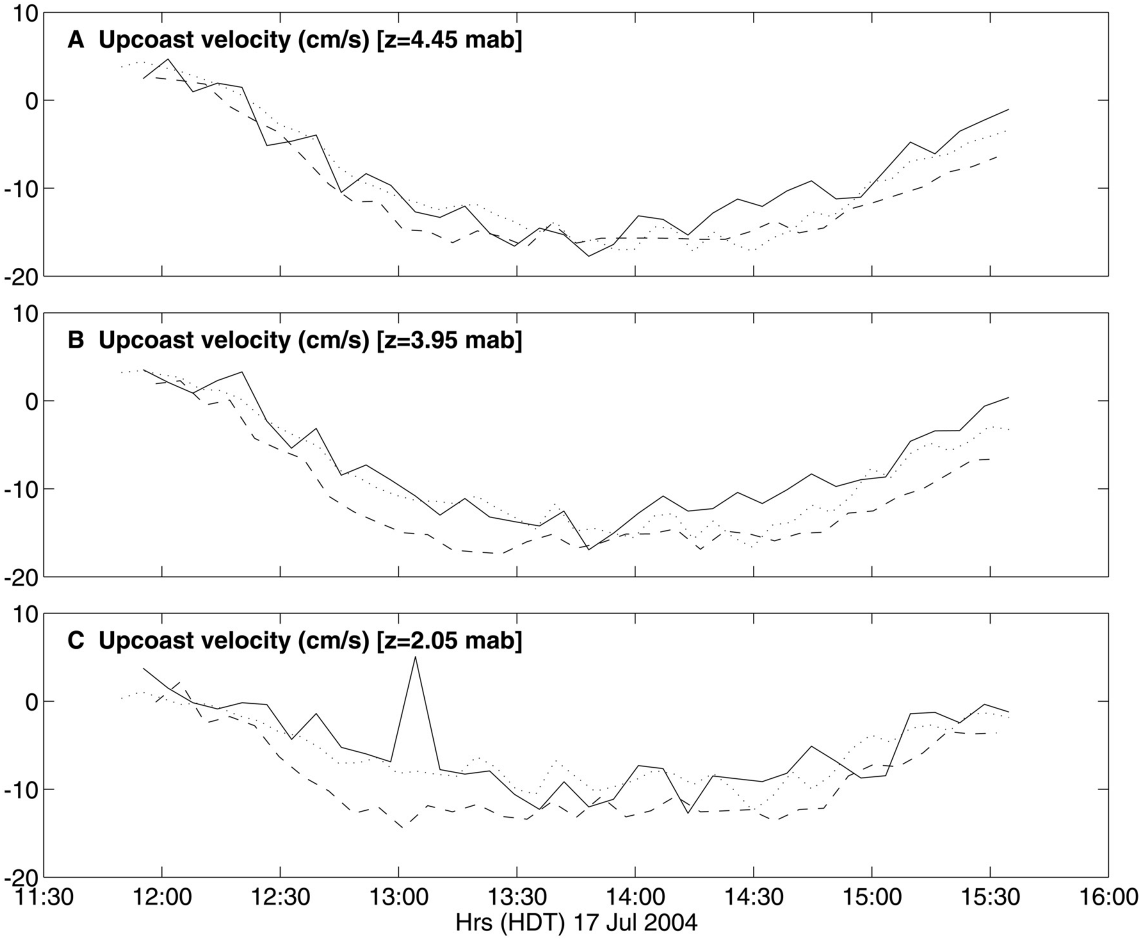

Fig. 4. Transect-averaged upcoast velocities for Kewalo Basin, HI, experiment. (A) Upcoast velocity for second bin of upward DVL (z = 4.45 mab). (B) Upcoast velocity for first bin of upward DVL (z = 3.95 mab). (C) Upcoast velocity for first bin of downward DVL (z = 2.05 mab). Upcoast transects are shown with solid lines, and downcoast transects with dashed lines. The dotted lines indicate velocities measured at a nearby stationary ADCP (see Figure 1B).

velocity and offshore transects measure an offshore velocity. In contrast, cross-shore velocities measured by a stationary ADCP, in the center of the box, are very close to zero. The downward DVL measurement shown in Figure 3D (z = 2.05 mab) does not show as large a bias. Data from the downward DVL for this experiment were extremely noisy, with several missed water pings (more so for bins < 2 mab). It is likely that the variability in coral density and formations (and hence bottom topography) and lack of scatterers affected these near-bed measurements. The alongshore components of velocity for these transects did not exhibit any significant bias and compare favorably with the fixed measurements (not shown).

Along-transect bias is less apparent when comparing the upcoast velocity component for the up- and downcoast transects (Figure 4). Velocities are not shown for the third bin from the upward DVL because it was contaminated by surface reflections during the upcoast transect. As previously observed, the cross-transect velocities do not exhibit any bias.

For the alongcoast transects, there was a tendency for alongcoast velocities to be slightly larger (upcoast) for the upcoast transects; the difference in velocities measured for the up- and downcoast transects are small, however. The lack of identifiable bias for the alongshore transects is likely explained by spatial variabilities of the alongshore flow in the cross-shore direction. It is expected that the flow will be significantly different over the 6 and 12 m isobaths (nominally the water depths where the upcoast and downcoast transects were conducted), and the abrupt change in bathymetry near the offshore transect leg (see Figure 1B) is likely to further complicate the spatial current patterns. The box transect path used in this study to investigate dye dispersion and measure mass fluxes in a control volume is not optimal for assessing bias errors. A more ideal data set for evaluating the bias error would have been a repeated transect similar to the one conducted at Franks Tract, CA, and Duck, NC (see below). Nevertheless, there is a striking difference in offshore velocities for

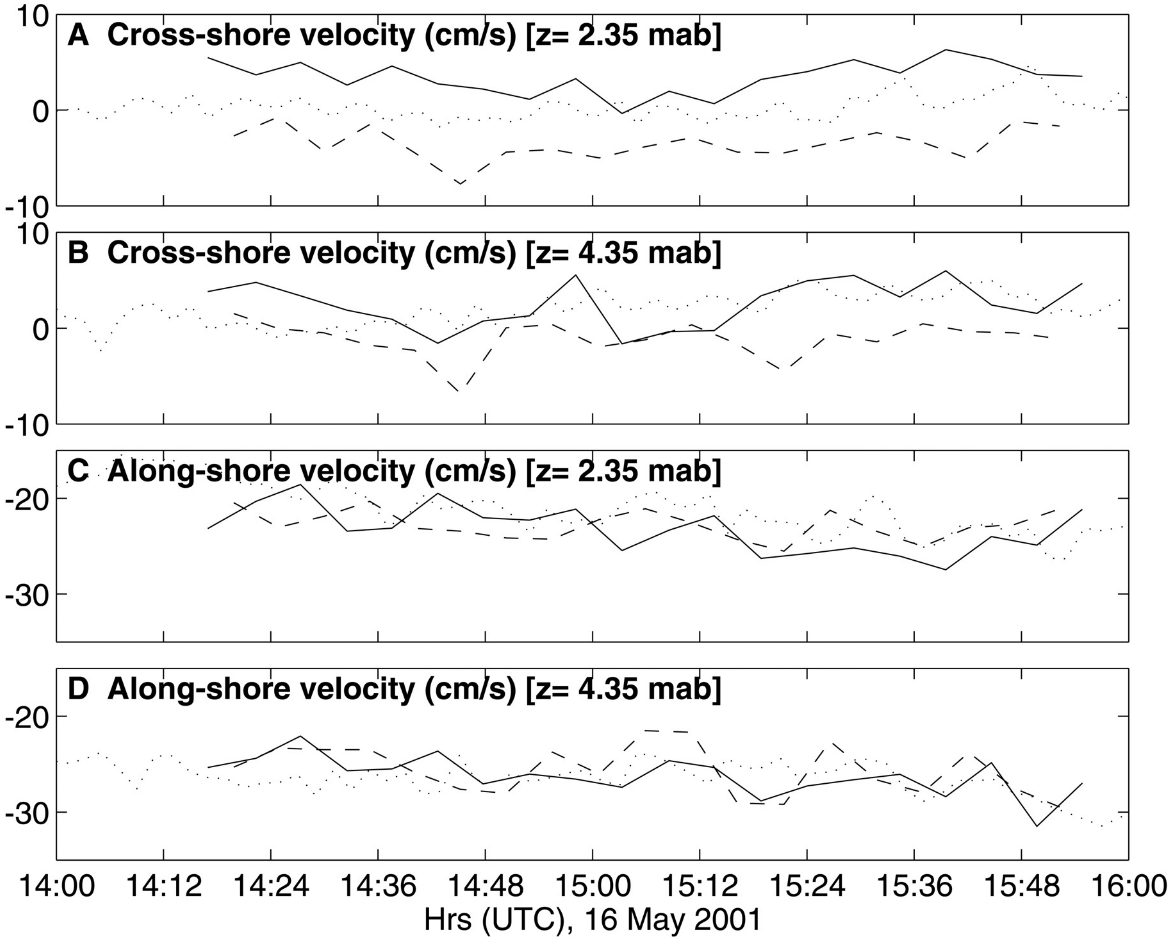

Fig. 5. Transect-averaged velocity for Duck, NC, experiment. (A) Cross-shore velocity for first bin of upward DVL (z = 2.35 mab). (B) Cross-shore velocity for fifth bin of upward DVL (z = 4.35 mab). (C) Along-shore velocity for first bin of upward DVL (z = 2.35 mab). (D) Along-shore velocity for fifth bin of upward DVL (z = 4.35 mab). Offshore directed transects are indicated by solid lines, onshore directed transects by dashed lines. Dotted lines indicate velocities measured at a nearby stationary ADCP (see Figure 1C).

the on- and offshore transects that depends on the direction of vehicle travel, consistent with FM04.

Duck, NC—As a final evaluation of the DVL performance, we examined data collected using a different REMUS vehicle during a hydrodynamics experiment conducted for ONR's Chemical Sensing in the Marine Environment Program at Duck, NC, on 16 May 2001. For this study, REMUS was programmed to repeat a 300 m long transect in the cross-shore direction to measure turbulent dispersion and wave-induced transport (see Fong and Stacey 2003; Monismith and Fong 2004) on the gently sloping shelf offshore of the Army Corps of Engineers Field Research Facility. The AUV flew at an altitude of 1.5 m; therefore, only the upward DVL could be used reliably to measure water velocities (there were roughly five useful bins of water velocity data). Currents were predominantly alongshore and wind forced.

Similar to the previous experiments, subdivision and averaging of the velocity data were performed to arrive at the 40 transect-averaged velocities shown in Figure 5. Once again, the bias reported by FM04 is evident. The bias in the direction of vehicle motion is most evident closest to the bottom (i.e., near the DVL transducer faces and 2.35 m above the bottom) and is not as large for the fifth bin situated 4.35 m above the bottom. This vertical variability is also consistent with the findings of FM04, who found the largest bias nearest the ADCP transducers. As before, the alongshore velocities perpendicular to the vehicle's transect exhibit no regular bias and compare favorably with the stationary ADCP measurements (Figure 5C and 5D).

Discussion

The velocities reported by the DVLs aboard the REMUS vehicle exhibit considerable inter-ensemble variability. The four-ping ensemble data recorded from the DVLs typically exhibit significant variability (standard deviation ~10 cm/s) that can be attributed to both measurement uncertainty and real flow fluctuations in space and time. Similar short-time and -spatial scale variability is found in ship-mounted, bottom-tracked ADCP measurements (e.g., FM04, Lacy and Monismith

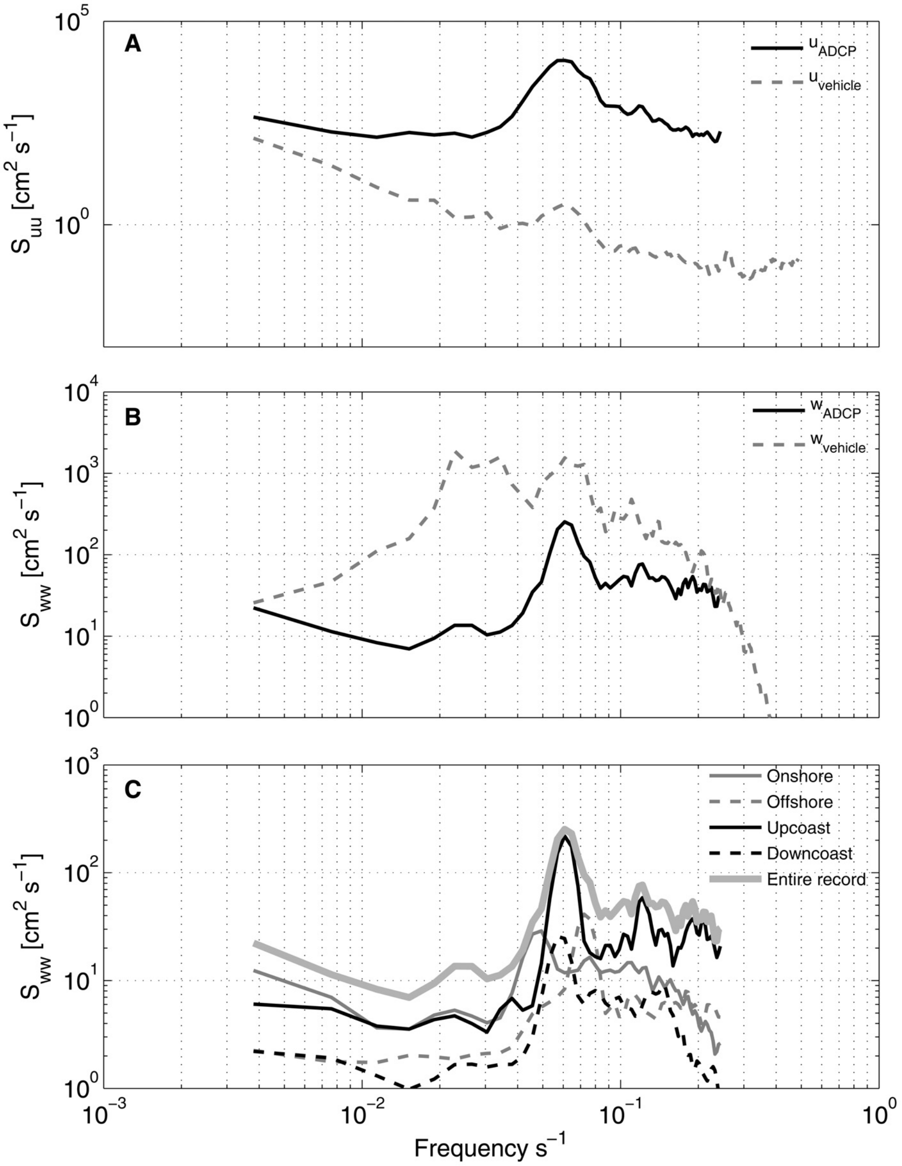

Fig. 6. Power spectral density for fringing coral reef data set. (A) Cross-shore navigation velocity and water velocity spectra. (B) Vertical vehicle and water velocity spectra. (C) Vertical water velocity spectra by transect direction.

2001). In both ship-mounted and AUV-derived velocity transects, significant averaging [O(100) m] is often necessary to deduce a useful estimate of water velocity.

One expected benefit of using an AUV/ROV to measure velocity transects is the ability to operate away from the water surface where wave chop and bubbles can contaminate the measured velocities. Previous ship-mounted ADCP transects in wavy conditions have typically yielded very noisy velocity data (D. Fong, unpublished data). Moreover, wave motions near the surface can be significantly larger than those at depth (e.g., Dean and Dalrymple 1991).

Power spectra associated with the vehicle motion and recorded water velocities illustrate the performance and stability of the REMUS AUV in the presence of an appreciable wave field for the fringing coral reef experiment. Spectra of the vehicle's horizontal velocity and reported water velocity in the cross-shore direction for the fringing coral reef data set clearly suggest the presence of wave motions (Figure 6A); the spectral peak of 0.06 s^{-1} agrees well with the independently measured significant wave period from a Seabird Electronics SBE26 wave gauge (R. Lowe, unpublished data). The spectral peak, is, however, much larger for the reported water velocities. The lower spectral peak related to the vehicle's motions suggest that its horizontal position was known well enough to allow for the resolution of some of the wave-induced water motions.

The waves are also evident in the power spectra of the vertical velocity reported by the upward DVL (Figure 6B) with a spectral peak centered about 0.06 s^{-1}. A similar, slightly larger, spectral peak was also found in the time rate of change of vehicle altitude, suggesting that the DVL cannot distinguish wave-induced vertical velocities in the water column from wave-induced vehicle motions in the vertical. The inability to accurately measure vertical water velocities is not surprising. Unlike the horizontal vehicle position and speed, which are monitored by both bottom tracking and acoustic navigation, vertical vehicle motions are not known well enough to correct the measured vertical water velocities. The logged altitudes reflect both bathymetric changes as well as vehicle motions in the vertical. Although REMUS is programmed to maintain a fixed altitude, its response time to changes in altitude is not fast enough to compensate for wave motions. (R. Stokey, personal communication)

It should be noted that the spectral peaks shown in Figure 6A and 6B are influenced and broadened by the horizontal motion of the vehicle: the vehicle is moving with the waves for the onshore transects and against them for the offshore transects, hence creating a Doppler shifting of the actual wave motions. For the alongshore transects (upcoast and downcoast), there is no Doppler shifting. Spectra of the vertical velocity for the different transect directions are shown in Figure 6C. The spectral peak is shifted to a higher frequency for the offshore transect and lower frequency for the onshore transect. The upcoast and downcoast transects have a peak at 0.06 s^{-1}, but much narrower in width than the spectral peak seen for the entire data set.

It seems plausible that a more sophisticated sonar and/or INS system might be able to precisely track vertical vehicle motions and thereby permit usable vertical water velocity measurements in wavy environments; more instrument development will be necessary to explore this option. Nevertheless, the ability of the REMUS DVLs to delineate the wave signature is an interesting discovery that may potentially be useful to study wave motions.

Comments and recommendations

In this work we have shown that AUV-derived velocity transects offer a promising alternative to ship-mounted ADCP transects. Autonomous underwater vehicles are potentially more stable platforms for conducting velocity transects and are more immune to the artifacts introduced by surface chop and near-surface bubbles that typically contaminate ship-based measurements. To the first order, we have shown that the velocities measured by the DVL compare well with a stationary ADCP. Nevertheless, AUV velocity transects are not without their problems.

Not surprisingly, the DVL-reported velocities for the three experiments presented exhibit the previously observed bias for ship-mounted ADCPs in the direction of vessel/vehicle motion. As seen by FM04, velocities perpendicular to the vehicle track can be reliably inferred from the DVLs; the reported velocities along the vehicle track are somewhat more problematic. To measure the primary currents, it is advisable to perform transects perpendicular to the dominant flow direction. For weak or secondary current measurements (such as those shown here), the bias in the vehicle direction of motion can be comparable to or larger than the actual water velocities. One potential strategy is to take repeated transects in opposing directions, as was done for the first and third experiments presented here, and average them to compute an “unbiased velocity.” This less than perfect compromise assumes a steady-state flow field over the time-scales of the repeated transects and that the bias is direction invariant (i.e., independent of vessel direction with respect to compass heading).

An explanation and solution for reducing or eliminating the bias error has proven difficult to come by. The lack of bias seen for boat-mounted ADCP measurements collected in high-scattering environments suggests that ringing may be partially responsible for the biased measurements in low-scattering cases (S. Monismith, personal communication). Nevertheless, Franks Tract, CA, is a fairly high-scattering environment. The bias issue continues to be one of active research.

We have also identified that AUV-derived velocities are known well enough to identify horizontal motions induced by waves; vertical motions, however, are not sufficiently resolved to isolate wave motions. It is advisable that one carefully consider the influence of the wave climate before deducing any meaningful conclusions about the vertical water velocities reported by AUV DVL technology. In nonwavy environments, vertical velocity data should be usable, much as they are in ship-mounted applications. In fact, due to lack of surface chop, vertical velocities measured on an AUV platform may be more useful for nonwavy conditions than those from a ship-mounted ADCP. In addition, as suggested in the previous section, the addition of an INS or more sophisticated sonar system may allow next-generation AUV DVL measurements to resolve wave-induced motions in both the vertical and horizontal directions.

There are other issues to consider when making AUV-based velocity measurements. Due to the presence of the vehicle and blanking distances, there is a significant portion of the water column (~1.4 m) where no water velocities are reported. In addition, to date, many of the water modes available for ship-mounted Workhorse ADCPs do not currently exist in the DVLs manufactured by RDI. One example is the fast-pinging water Mode 12. Mode 12 is a firmware upgrade for the Workhorse series of ADCPs that allows raw ping rates near 20 Hz (in comparison to 2-4 Hz possible with the standard water Mode 1 found on standard ADCPs and DVLs), and therefore a significant reduction in velocity measurement uncertainties. In theory, this water mode and others are readily transportable to DVL products and would improve measurements such as those presented here.

Finally, it should be noted that the deployment of upward and downward DVLs on an AUV potentially allows for up to twice the profiling range of a similar-frequency ship-mounted ADCP. The increased profiling range is available with no loss in accuracy or increased bin size, which are required when using a lower-frequency ship-mounted ADCP to increase the profiling range.

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