NOTES AND CORRESPONDENCE

Evaluation of the Accuracy of a Ship-Mounted, Bottom-Tracking ADCP in a Near-Shore Coastal Flow

DEREK A. FONG AND STEPHEN G. MONISMITH

Environmental Fluid Mechanics Laboratory, Stanford University, Stanford, California

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ABSTRACT

The accuracy of an acoustic Doppler current profiler (ADCP) used with an internal bottom-tracking system is considered. The boat speed measured using bottom tracking is extremely accurate, comparable to the speeds measured by a high-resolution, real-time kinematic global positioning system (KGPS). The accuracy in the direction of boat motion reported by the bottom tracking is limited to the accuracy of the internal compass of the ADCP. Directional differences (after correcting for local magnetic declination) are about 3° between the ADCP bottom tracking and KGPS. An error of this magnitude is shown to result in a maximal measurement error in water velocity of less than 6%.

Nonetheless, an unexplained water velocity error is observed that is significantly larger than can be explained by a simple compass error. Repeated transects in opposing directions show a bias in measured water velocities in the direction of boat motion. The bias cannot be explained by an error in the compass or the bottom-tracked boat velocities. The difference in recorded velocity between two repeated transects with the boat moving in opposite directions exhibits an error of up to ± 5 cm s^{-1} that has vertical variability.

1. Introduction

Since its introduction in the early 1980s, the acoustic Doppler current profiler (ADCP) has revolutionized physical oceanography. As discussed in King et al. (2001), ADCPs have been used to map both the deep and near-surface circulation of the world's oceans, giving remarkably improved views of the structure and variability of flows found there. They have also been used to revolutionize stream gauging (Simpson and Oltmann 1993) and to record previously hard-to-measure flows in lakes (Rueda et al. 2003). In estuarine hydrodynamics, ADCPs have made possible new conceptual models of estuarine circulation (Geyer et al. 2000), especially highlighting the role of transverse variability in estuarine tidal flows (Valle-Levinson et al. 1998). More recently, as the technology has improved, ADCPs have been used to measure stratified turbulence (Stacey et al. 1999) and directional wave spectra (Terray et al. 1997).

Ship-mounted ADCPs are often used to infer spatial distributions of ocean currents in a vertical plane. The ADCP is first used to estimate the velocity of the ship relative to different layers (depths) of water; these estimates are measured in the ship's coordinates. In order to infer velocities in the earth coordinate (fixed) system, information regarding the ship's orientation (pitch, roll, and heading) and movement are required. Usually, the ship's pitch, roll, and heading are measured by the ship's gyrocompass. The vessel's velocity can be inferred using either a global positioning system (GPS), Loran-C satellite tracking (Trump 1986), or an internal bottom-tracking system built into the ADCP itself.

Previous studies have considered how errors in the ship's gyrocompass can contaminate ADCP speed estimates (e.g., Bowditch 1977; Trump 1986; Joyce 1989; Pollard and Read 1989). Most modern gyrocompasses have corrective mechanisms that attempt to account for these problems, but as Trump and Marmorino (1997) note, manual corrections and calibration of the gyro measurements may be necessary in order to ultimately obtain useful ADCP-derived water velocities in the earth coordinate frame.

In recent years, a new breed of bottom-track-enabled ADCPs have become available that are relatively economical and, perhaps more importantly, are intended to be more portable than the previous generation of ship-mounted ADCPs that were permanently installed in the hull of a vessel at a fixed orientation. The Workhorse ADCPs sold by RD Instruments, Inc. (RDI), for ex-

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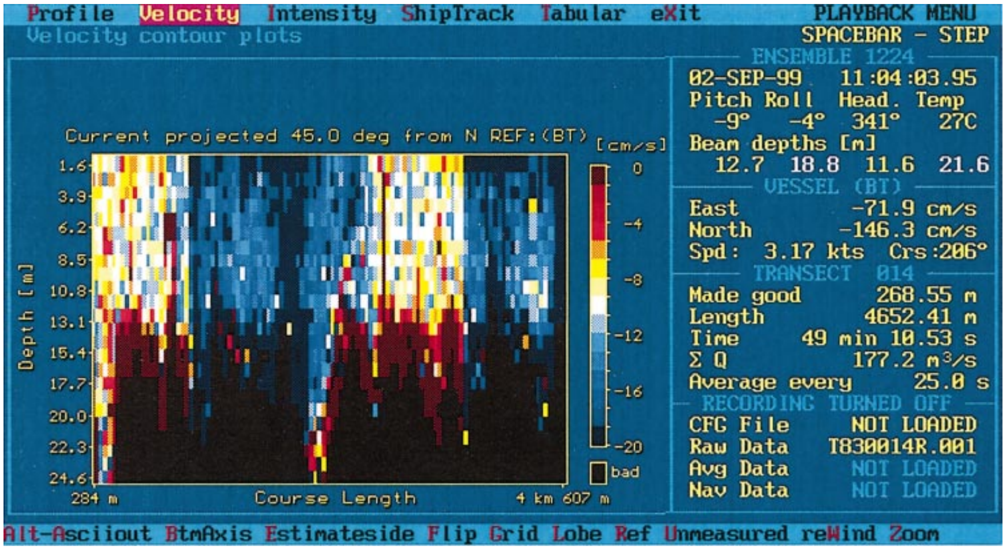
Corresponding author address: Dr. Derek Fong, Environmental Fluid Mechanics Lab, Dept. of Civil and Environmental Engineering, Stanford University, Stanford, CA 94305-4020.
E-mail: dfong@stanford.edu



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North          -146.3 cm/s
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Average every      25.0 s
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Avg Data      NOT LOADED
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FIG. 1. Screen capture from RD Instrument's Transect software. Color contoured is the along-coast component of velocity (the coastline is oriented roughly 45° from north). Four consecutively measured transects are shown (portions of the first and fourth transects are missing due to the software viewing window limitations). The blue contours indicate strong downcoast velocities when the boat is travelling in the downcoast direction while white/yellow contours indicate weak downcoast velocities when the boat is moving in the upcoast direction.

ample, contain their own compass (that monitors pitch, roll, and heading of the instrument), have an internal bottom-tracking system, and are designed to be mounted in a fairly quick and temporary fashion to the port or starboard side of the vessel. By being self-contained, problems related to the ship's gyrocompass are removed along with issues related to the orientation of the instrument with respect to the vessel.

During a summer 1999 experiment in the Red Sea at Eilat, Israel, a 600-kHz RDI Workhorse ADCP was mounted onto a small boat and alongshore sections of velocity were measured. In repeated transects with the boat traveling parallel to the coast along the 20-m isobath in both directions, different velocity fields were observed (Fig. 1). The water velocities (in the earth coordinate frame) showed a stronger downcoast (in the direction of Kelvin wave propagation) component when the boat was traveling downcoast than when the boat was moving in the upcoast direction (opposite of Kelvin wave propagation).

This note documents our exploration of this observed bias over a 3-yr period using several different ADCPs equipped with internal bottom tracking. We present a few of the datasets collected in different shallow-water settings and include one set of simultaneous measurements using a very-high-resolution, real-time kinematic global positioning system (KGPS) (Trimble Navigation, Limited) to evaluate the accuracy of the bottom-tracking system.

In the next section, we describe the instrumentation under consideration and the datasets collected. The observed velocity bias and bottom-tracking accuracy is evaluated in section 3. In section 4, we discuss the consequences of the observed bias for measuring weak and strong flows, followed by some concluding remarks in section 5.

2. Data and instrumentation

a. *RD Instruments BroadBand ADCP*

In this study several different RDI BroadBand ADCPs equipped with bottom tracking were evaluated. The description that follows is general to all of the different models used. The reader should consult an ADCP manual or contact RDI for additional details.

ADCPs work on the Doppler principle. Sound is transmitted from the instrument in four beam directions, intercepted by scatterers, either in the water column or by the bottom, and then scattered. A portion of this scattered signal is intercepted by the instrument and processed to compute a Doppler shift in frequency from the transmitted signal. The Doppler shifts are measured along the radial axis of each transmitted beam and can be converted into a velocity. With knowledge of the beam angles and information from the ADCP's internal compass, the along-beam velocities can be converted into an earth-based reference system. The RDI ADCPs equipped with bottom tracking can measure the velocity of the instrument relative to the water (known as water tracking), as well as the velocity of the instrument relative to the bottom (known as bottom tracking).

Water tracking is accomplished by transmitting a pulse of user-selected length (usually in units of depth). The scattered return signal from the water column arrives at different times, dependent on the distance of the scatters from the transducer faces. The return signal is broken up into user-selected lengths (called bins) and processed. The result is a unique velocity measurement for each bin; the different bins can be used to construct a velocity profile.

The current generation of RDI BroadBand ADCPs (including the Workhorse and Navigator ADCPs discussed in this study) operate as described above, but the pulse is filled with a wide band code consisting of alternating phase reversals of the carrier frequency. This results in many independent measurements of the velocity during the averaging interval of a bin. This dramatically improves the precision[1] of the velocity measurement.

Bottom tracking uses the same processing algorithms as water tracking. The major difference is in the transmit and averaging (bin) lengths (times). The transmission length for bottom tracking is typically 30% of the altitude (vertical distance to the bottom). This ensures that the beam, as it intercepts the bottom, is fully ''illuminated'' for an optimal averaging interval. The received signal is processed in two distinctly different ways. First, the bottom return is identified by the utilization of a sophisticated filtering technique; the objective is to avoid mistaking fish or life layers for the bottom. Second, the velocity processing is accomplished using essentially the same algorithms as are used for water tracking.

Generally, the precision of the bottom-track measurement is much better than that for water track. This is because the scatterers being illuminated during the averaging interval are less varying: during bottom-track pings, the changing scatterers are only the result of instrument motion (because the bottom is assumed to be immobile).

Obtaining a current profile from a moving boat requires at least two pings: a water-track ping, which measures the relative velocity of the instrument to the water, and a bottom-track ping, which measures the relative velocity of the instrument to the bottom. The instrument then subtracts the bottom velocity measurement from the water velocity measurement. This difference, in the absence of any acceleration between the pings, results in the water velocity relative to the bottom. It is possible, under certain conditions, to improve the temporal resolution by obtaining more water pings than bottom pings. This, however, increases the time between the water pings and bottom ping: accelerations during this time may result in increased noise.

b. *Trimble Navigation kinematic GPS*

In order to ascertain the inherent accuracy of boat speed and heading reported by the ADCP, we borrowed a real-time kinematic GPS system to log boat motions. The system used was the Trimble Navigation Total System 4700. The system consists of a base station, an L1/L2 GPS antenna, and a radio receiver (associated with the antenna). The latter two units were deployed on the same vessel as a 600-kHz RDI Workhorse ADCP during the San Clemente Island, California, experiment.

The GPS base station is installed and surveyed to a locally established geodetic monument. The radio link to the base station provides real-time kinematic GPS; not only does this avoid the need for postprocessing to accomplish GPS error corrections, but it also allows for real-time navigation. The kinematic GPS receiver measures the 3D position of the phase center of the antenna in the 1984 World Geodetic System (WGS84) datum and can make real-time corrections, and, thus, allows for nominally 3-cm horizontal position accuracy at a frequency of 5 Hz. If combined with an echo sounder, the system can also be used to infer depths (i.e., bathymetry) to within 10 cm, and tide levels to better than 5 cm (Dugan et al. 2001). A more detailed description of the system, its characteristics, and performance can be found in Dugan et al. (2001) or on the Trimble Web site (the Total System 4700 has recently been replaced by the Total System 5700).

3. Analysis

The velocity data shown in Fig. 1 exhibit a velocity measurement that is dependent on the direction the boat is traveling. When the boat is moving in the downcoast direction, the ADCP reports a significant downcoast velocity; in contrast, the ADCP reports a weak downcoast velocity while moving in the upcoast direction. One might normally speculate that the different velocities recorded are attributable to the temporal variability in the actual velocity field. The series of repeated transects shown in Fig. 1, however, indicate that the velocity fields reported in each transecting direction do not change appreciably in time. For each transecting direction, repeated twice, the velocity fields show a persistent bias toward the direction of boat motion. The curious behavior in Fig. 1 suggests that when operating with a bottom-tracking system (in this case, an RDI 600-kHz Workhorse ADCP), there is an error in velocity that is biased toward the direction the boat is traveling. The net difference is quite large, at times in excess of 10 cm s^{-1}. Plots of the cross-shore velocity (nominally perpendicular to the transects shown) from the same data show very similar recorded velocities for all four transects, independent of the direction of boat motion (not shown).

In order to verify that the behavior in Fig. 1 was not site or instrument specific, a different ADCP (same frequency and model) was mounted on a small vessel during an experiment at San Clemente Island in November 1999. Several transects were measured that replicated the behavior observed in Fig. 1. We focus below on one particular pair of transects (one transect with the boat

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[1] We define precision as the reciprocal of the standard deviation in short-term error.

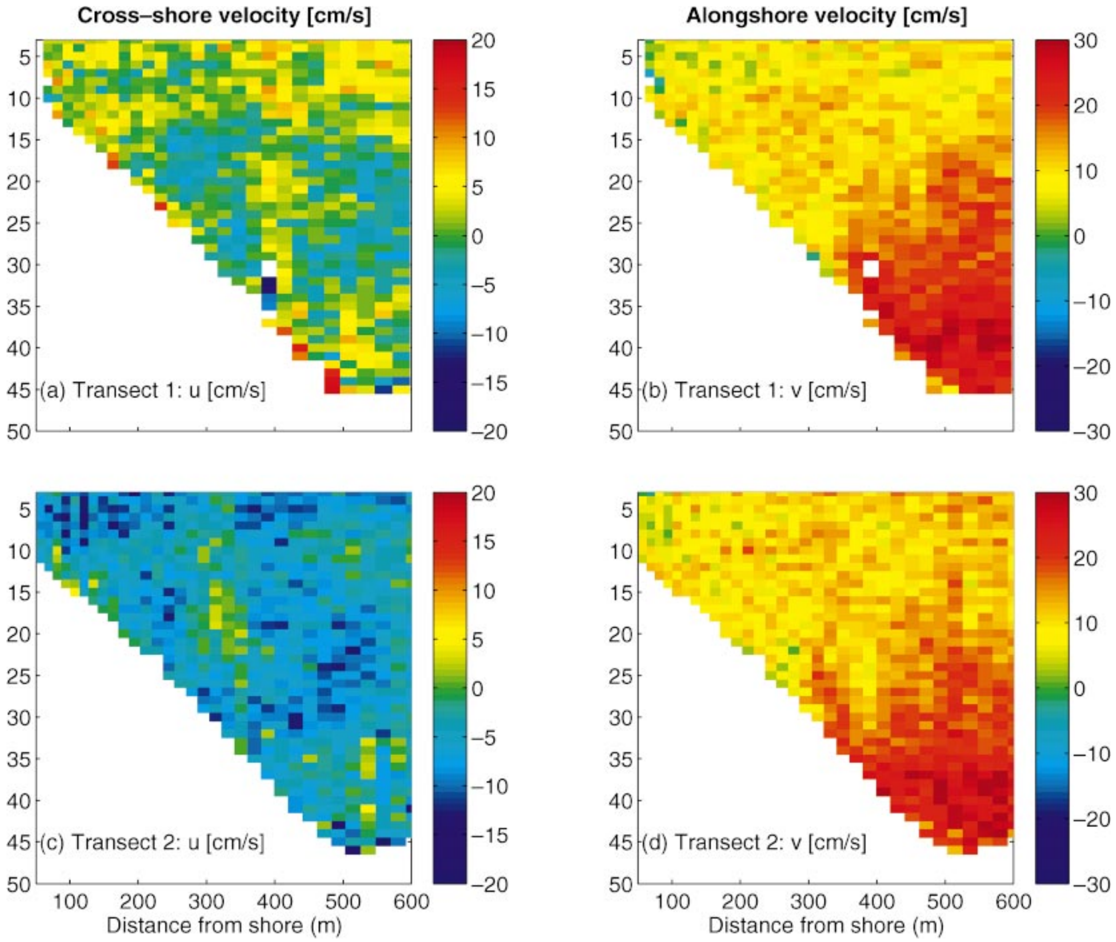

FIG. 2. ADCP-derived water velocities at San Clemente Island, Nov 1999: (a) cross-shore velocity for transect 1, (b) along-shore velocity for transect 1, (c) cross-shore velocity for transect 2, and (d) along-shore velocity for transect 2. The start times for each transect differs by less than 6 min.

traveling in the offshore direction immediately followed by an onshore transect across the same water), separated by about 5 min. We examine these particular transects because we were able to borrow a Trimble Navigation real-time KGPS to obtain high-resolution concurrent tracking of the boat motion for these particular transects. The KGPS dataset will be used to evaluate the accuracy of the internal bottom-tracking system of the ADCP later in this section.

a. Quantifying the bias error

Two transects of velocity measured with the boat moving in the off- and onshore directions are shown in Fig. 2. The transects were taken only about 5 min apart, well less than the time scale of variability usually observed at the site. A bias error is clearly evident in the cross-shore velocity contours shown Figs. 2a and 2c. For the first transect where the boat is moving offshore, there is a recorded offshore current of $O(5)$ cm s^{-1} in the surface layer and a more quiescent, near-zero cross-shore velocity below the 15-m depth. In contrast, the second transect taken with a shoreward-moving boat shows an onshore current over much of the water column, sometimes in excess of 10 cm s^{-1}. The depth-averaged cross-shore velocities in the sections differ by up to $O(5–10)$ cm s^{-1}.

The alongshore velocities are shown in Figs. 2b and 2d. There is a mean downcoast flow (in the direction of Kelvin wave propagation) in the waters above 15 m of $O(10)$ cm s^{-1}, and this current intensifies to over 25 cm s^{-1} at the deepest portions of the transect. Although there are some small differences in features, the depth-averaged alongshore currents of the two transects only differ by 1–2 cm s^{-1}. As we shall see later, this is consistent with a small error in the ADCP compass measurement.

Further inspection of Fig. 2 suggests that the differences in cross-shore velocities reported by the ADCP are not simply due to a depth-uniform offset. Table 1 shows the mean velocity (averaged from x = 200–600 m in the cross-shore direction) at 5- and 20-m depths

TABLE 1. Transect-averaged current properties and differences between the transects. All values are in centimeters per second and averaged over $x = 200–600$ m (see Fig. 2).

	Offshore transect	Onshore transect	Difference between transects
u_5 (mean cross-shore velocity at $z = 5$ m)	2.1	−7.5	9.6
u_{20} (mean cross-shore velocity at $z = 20$ m)	−0.4	−4.7	4.3
Mean shear ($u_5 - u_{20}$)	2.5	−2.8	5.3
v_5 (mean alongshore velocity at $z = 5$ m)	7.7	7.6	0.1
v_{20} (mean alongshore velocity at $z = 20$ m)	12.9	13.1	−0.2
Mean alongshore shear ($v_5 - v_{20}$)	−5.2	−5.5	0.3

for each velocity component for each transect, and also shows the related velocity shear between these two depth layers. For the alongshore direction, the cross-shore-averaged velocities are similar, as well as the shear between the $z = 5$ and 20-m levels. The cross-shore currents and shear differ appreciably, however.

At the 5-m depth, the cross-shore currents measured during the different transects differ by 9.6 cm s^{-1} while at the 20-m depth, they differ by 4.3 cm s^{-1}. Not only are the general orientation of the velocities different between the transects, but also, the cross-shore-averaged shears are different. As indicated in Table 1, the mean shear in the cross-shore direction is 2.5 cm s^{-1} for the offshore transect and −2.8 cm s^{-1} for the onshore transect, a difference of 5.3 cm s^{-1}. For calculations such as a bulk Richardson number in a weakly stratified flow, this might be a significant error. Variations in the alongshore direction are much smaller, well within the range of expected current variability between the two transects.

b. Evaluating bottom tracking

The apparent mismeasurement of currents in the direction of boat motion motivates an examination of the ADCP's bottom-tracking system. If it is unable to accurately measure the motion of the boat, bottom tracking is likely to have an adverse effect on the reported water velocity. Because the boat's velocity is typically large in comparison to the actual water velocity, even a small error in boat speed can manifest itself as a significant error in the recorded water velocity.

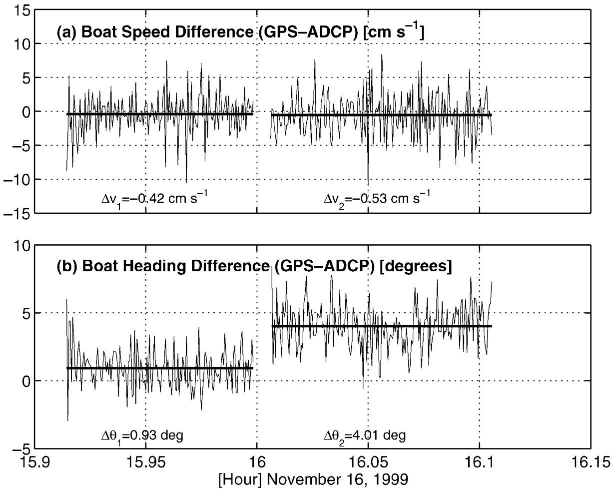

FIG. 3. A comparison of bottom-tracking and real-time kinematic GPS navigation systems: (a) difference in measured boat speed and (b) difference in measured boat heading. The bold lines indicate mean differences for each of the two transects, corresponding to the values noted within the panels.

In order to assess the accuracy of the bottom-tracking system for the 600-kHz Workhorse ADCP used at San Clemente Island, concurrent measurements of the boat's motion were measured by logging data from a Trimble Navigation KGPS system, as described in section 2b. The raw KGPS 5-Hz position data are averaged into 1.5-s ensembles for direct comparison with the 1.5-s ensemble data from the bottom-tracked velocities measured by the ADCP. Both the KPGS and ADCP had their clocks synchronized prior to the experiment to allow for a direct comparison of the boat displacement and speed measured by the KGPS and the boat velocity measured by the ADCP.

A comparison of the boat speed velocities is shown in Fig. 3a where the differences in measured boat speeds are plotted as a function of time. Although there are some instantaneous differences in measured boat velocity, the average boat speeds compare extremely well. For the offshore transect, the difference in velocity is only 0.42 cm s^{-1}, and the difference is only 0.53 cm s^{-1} for the onshore transect. This small error will have negligible impact on the reported cross-shore velocities. Moreover, the differences in velocities between the two transects are similar, only 0.09 cm s^{-1}; the bias induced by an error in boat speed is two orders of magnitude smaller than that observed in the reported water velocities.

The boat direction measured by the KGPS and the ADCP bottom tracking exhibit greater differences (Fig. 3b). After correcting for the magnetic declination used in the compass-assisted ADCP measurements, one finds that during the offshore transect, the mean boat heading differed by 0.93°; for the return transect, the difference was 4.01°. The difference between the two transects is appreciable, approximately 3°. This, however, is consistent with the published specifications of the internal ADCP compass, and is also similar to the root-mean-squared compass-heading errors found for a standard shipboard gyrocompass (Trump and Marmorino 1997).

The significant difference in measured boat heading does not, however, explain the bias error noted earlier. A simple analysis (see the appendix) shows that a compass error of 3° should manifest itself as an error in water velocity of about 5% when using bottom tracking. For the peak currents of 30 cm s^{-1} observed in this dataset, this represents a maximum bias, due to compass error, of about 1.5 cm s^{-1}. The error induced by the compass is significant, and may possibly explain the small differences in alongshore velocity observed. Nonetheless, it is too small to explain the observed bias error in the cross-shore velocity measurements.

c. *Additional observations*

Recently, we investigated whether RDI's changes to the transducer angle (to increase range at the expense of precision) or the transducer housing and pressure case material (to cut instrument weight and production costs) were responsible for the bias reported here.

In June 2002, we measured velocities in Monterey Bay using both a 600-kHz Workhorse ADCP and a 600-kHz Workhorse Navigator ADCP. The former unit has 20° angled transducers housed in a polyurethane case, and the latter has 30° transducers in an aluminum pressure case. The data collected with both instruments (not shown) both exhibit a bias error in the direction of boat motion. The depth-averaged and transect-averaged shift in velocity due to change in boat direction was 4.5 cm s^{-1} for the Workhorse Navigator and 6.0 cm s^{-1} for the Workhorse ADCPs, respectively. The shears were not compared because the severe slope of the bottom over the course of the transect made discerning the vertical structure of the bias difficult. In short, the mean bias, for this dataset, is slightly smaller for the Workhorse Navigator, but the differences are not statistically significant, thus suggesting that the bias error cannot be linked to the transducer housing, pressure case material, or transducer angle.

The results presented in the previous section do not appear to be limited to only the 600-kHz series of Workhorse ADCPs; there is evidence from other published studies that suggest that the bias is a recurring issue for transecting in several near-coastal environments. For example, in a recent paper by Epifanio and Garvine (2001), their 1200-kHz Workhorse ADCP–derived velocity field shown in their Fig. 7 demonstrates a bias similar to the one discussed here: velocities between adjacent on- and/or offshore transects are biased toward the direction of boat motion. In Fig. 10 of Dugan et al. (2001), measured currents within the shipping channel at Oregon Inlet, North Carolina, are shown to oscillate between transects, dependent on the direction in which their jet ski (to which a 1200-kHz Workhorse ADCP is mounted) is moving. It is worth nothing that Dugan et al. claim no significance bias in the text of their paper; we speculate that insufficient averaging was used to reach this conclusion.

In addition to other datasets we have collected using 300- and 600-kHz Workhorse ADCPs, some of our colleagues have noted qualitative observations of the bias error in their measurements using their Workhorse ADCPs in coastal or estuarine environments when operating in bottom-tracking mode: 1200 (N. Jones 2003, personal communication), 600 (A. Genin 2000, personal communication) and 300 kHz (J. O'Donnell 2000, personal communication).

Finally, RD Instruments reports that they have conducted several tests on small, inland freshwater lakes, trying to reproduce the bias error we observed. While they have, on some occasions, found errors similar in magnitude to the San Clemente Island dataset, many of their collected data do not exhibit appreciable bias error (J. Gast 2002, personal communication). Nevertheless, for salt water coastal environments the bias error seems to be a prevalent problem, suggesting the measurement conditions may play an important role in the bias error.

4. Discussion

The analysis of the previous section reveals that in spite of a very accurate bottom-tracking system, BroadBand ADCPs may still exhibit a significant bias that manifests itself as an overestimated velocity in the direction of boat motion. As was demonstrated, this bias is several centimeters per second in magnitude and can exhibit a vertical structure; a simple barotropic offset correction cannot be used to correct for the problem. The importance of the bias error will depend on the energetics of the flow environment.

Obviously, for situations where the currents are weak, that is, less than 10 cm s^{-1}, the bias can be comparable to the size of the actual water velocities. In these circumstances, the best measurement strategy would be to make transects in the direction perpendicular to the dominant flow direction (i.e., the major axes of a velocity ellipse). This should ensure that the major current signature will be resolved with minimal influence of a bias. Unfortunately, this also means that measured currents in the axis of the transect (i.e., the minor velocity axis) will have to be discarded because it is likely that the bias error will overwhelm any meaningful current signature. In the case where the predominant flow direction is unknown, exploratory measurements, with transects along a few different directional axes, will be required to establish an appropriate measurement strategy.

For strong flows, one might suspect that a bias of $O(5–10)$ cm s^{-1} should be less important. For example, in many estuaries, along-estuary currents can often exceed 100 cm s^{-1} and cross-estuary currents may exceed 30 cm s^{-1}, thereby making the bias less of an issue for inferring net discharge and circulation patterns (e.g., Lacy and Monismith 2001). Nonetheless, the bias may still be important in situations where flow parameters, such as vertical velocity shears, vorticity, salt and momentum fluxes, and the Richardson number, are of interest. In calculations such as these, the reduction or increase in shear attributable to the bias error may be significant.

Without knowledge of the actual source of the bias error, it is difficult to prescribe an explicit and effective remedy for the problem. As suggested above, careful choice of the direction of transecting can help reduce much of the bias problem because it appears to be a predominantly along-transect-directed error. Nonetheless, in conditions where low flow speeds are of interest, and, moreover, the smaller component of velocity (e.g., cross-shore currents in a coastal circulation study) is the one of physical significance, discarding the minor axis velocity component is not a welcomed solution. One potentially useful strategy is to take repeated transects of opposing directions (as was done in all of the tests presented in this study) and average them to obtain an estimate of ''unbiased velocity.'' While this calculation assumes that the bias is direction invariant (i.e., independent of the boat direction with respect to the compass rose), it should be a reasonable first guess for the actual velocity field as long as the transects are significantly close enough in time such that the currents can be assumed synoptic and one can assume that the bias is not strongly a function of the actual water velocity. Nonetheless, all of these suggestions are kludges, at best. Additional work must be done to deduce the source of the error. Only then, can one expect to derive an actual solution.

5. Concluding remarks

To summarize, we have documented a bias error when operating an ADCP with its internal bottom-tracking algorithm in near-coastal environments and identified some important issues to consider when inferring information from bottom-tracked, ADCP-derived current fields. We have shown, however, that the bias error is not directly related to the bottom-tracking system. In fact, we have demonstrated that bottom tracking is excellent at measuring a boat's speed. The boat direction measured is limited by the accuracy of the internal compass. For most conditions, use of a differential GPS to log the starting point of a transect is the only ancillary navigation data necessary to map a velocity field. The net boat displacements measured by bottom tracking are comparable in accuracy to those measured by a real-time kinematic global positioning system.

We speculate that one possible area that requires further investigation is the potential for interaction between the water and bottom pings. Given the nature of the bias suggested here, it is clear that the instrument is measuring something in the water column that is inhomogeneous in nature. Subsequent investigations should focus on the magnitude of the bias as a function of bottom substrate material, wave conditions, and scattering environment; focusing on these issues may help illuminate the source of the bias error.

The exploration of this bias error is one of continuing work that will undoubtedly be helped by the participation of other ADCP users in the oceanographic community. A sharing of time and resources will be necessary to eventually achieve a full resolution of the problem presented here.

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APPENDIX

Contribution of Compass Error to Velocity Bias Error

Let $\mathbf{u}' = (u', v')$ define the horizontal velocity components with respect to the orientation of ADCP transducers, and $\mathbf{u} = (u, v)$ denote the zonal and meridional velocity components of velocity with respect to magnetic north. The choice of magnetic north is simply one of convenience for the analysis that follows. The results are generalizable for use with any orthogonal coordinate system (e.g., true north or a local reference frame).

Using ϕ to denote the actual transformation angle (for a perfect compass) between the coordinate systems and ϕ_E for the compass angle error, a set of transformation equations can be written:

$$u = (\hat{u} - u_B)\cos(\phi + \phi_E) - (\hat{v} - v_B)\sin(\phi + \phi_E), \tag{A1a}$$

$$v = (\hat{u} - u_B)\sin(\phi + \phi_E) + (\hat{v} - v_B)\cos(\phi + \phi_E), \tag{A1b}$$

where it has been noted that $u' = \hat{u} - u_B$ and $v' = \hat{v} - v_B$, and $(\hat{u}, \hat{v})$ and (u_B, v_B) are the earth and the bottom-track velocities, respectively, measured by the ADCP. Using the laws of sines and cosines, the velocity components can be rewritten as

$$\begin{aligned} u = {} & (\hat{u} - u_B)(\cos\phi \cos\phi_E - \sin\phi \sin\phi_E) \\ & - (\hat{v} - v_B)(\sin\phi \cos\phi_E + \cos\phi \sin\phi_E), \end{aligned} \tag{A2a}$$

$$\begin{aligned} v = {} & (\hat{u} - u_B)(\sin\phi \cos\phi_E + \cos\phi \sin\phi_E) \\ & - (\hat{v} - v_B)(\cos\phi \cos\phi_E - \sin\phi \sin\phi_E). \end{aligned} \tag{A2b}$$

It can be shown that if $\phi_E \ll 1$, then $\cos\phi_E \approx 1$ and $\sin\phi_E = \phi_E$, simple algebraic manipulation of (A2a) and (A2b) yields

$$\begin{aligned} u \approx {} & (\hat{u} - u_B)\cos\phi - (\hat{v} - v_B)\sin\phi \\ & + (\hat{u} - u_B)\phi_E \sin\phi - (\hat{v} - v_B)\phi_E \cos\phi, \end{aligned} \tag{A3a}$$

$$\begin{aligned} v \approx {} & (\hat{u} - u_B)\sin\phi + (\hat{v} - v_B)\cos\phi \\ & + (\hat{u} - u_B)\phi_E \cos\phi + (\hat{v} - v_B)\phi_E \sin\phi. \end{aligned} \tag{A3b}$$

Finally, noting that the actual velocities (assuming no compass error) are given by $u_a = (\hat{u} - u_B)\cos\phi - (\hat{v} - v_B)\sin\phi$ and $v_a = (\hat{u} - u_B)\sin\phi + (\hat{v} - v_B)\cos\phi$, the zonal and meridional velocities measured by the ADCP are given by

$$u = u_a + (\hat{u} - u_B)\phi_E \sin\phi - (\hat{v} - v_B)\phi_E \cos\phi, \tag{A4a}$$

$$v = v_a + (\hat{u} - u_B)\phi_E \cos\phi + (\hat{v} - v_B)\phi_E \sin\phi. \tag{A4b}$$

Equations (A4a) and (A4b) quantify the error in reported velocity as a function of water velocity, compass error, and transformation angle. The error induced by a less-than-perfect compass is $O(v_a \phi_E)$. In other words, for a small compass error, the deviation in actual measured velocity is small. For even a compass error as large as 5°, the error in measured velocity is less than 9% of the actual current speed.

REFERENCES

Bowditch, N., 1977: *American Practical Navigator.* Vol. I. Defense Mapping Agency Hydrographic Center, 1386 pp.

Dugan, J. P., W. D. Morris, K. C. Vierra, C. C. Piotrowski, G. J. Farruggia, and D. C. Campion, 2001: Jetski-based nearshore bathymetric and current survey system. *J. Coastal Res.,* **17,** 900–908.

Epifanio, C. E., and R. W. Garvine, 2001: Larval transport on the Atlantic Continental Shelf of North America: A review. *Estuarine Coastal Shelf Sci.,* **52,** 51–77.

Geyer, W. R., J. Y. Trowbridge, and M. M. Bowen, 2000: The dynamics of a partially mixed estuary. *J. Phys. Oceanogr.,* **30,** 2035–2048.

Griffiths, G., 1994: Using 3DF GPS heading for improving underway ADCP data. *J. Atmos. Oceanic Technol.,* **11,** 1135–1143.

Joyce, T. M., 1989: On in situ ''calibration'' of shipboard ADCPs. *J. Atmos. Oceanic Technol.,* **6,** 169–172.

King, B. A., E. Firing, and T. M. Joyce, 2001: Shipboard observations during WOCE. *Ocean Circulation and Climate,* G. Siedler, J. Church, and J. Gould, Eds., Academic Press, 99–121.

Lacy, J. R., and S. G. Monismith, 2001: Secondary currents in a curved, stratified, estuarine channel. *J. Geophys. Res.,* **106,** 31 283–31 302.

Pollard, R., and J. Read, 1989: A method for calibrating shipmounted acoustic Doppler profilers and the limitation of gyro compasses. *J. Atmos. Oceanic Technol.,* **6,** 859–865.

Rueda, F. J., S. G. Schladow, and S. O. Palmarrsson, 2003: Basin-scale internal wave dynamics during a winter cooling period in a large lake. *J. Geophys. Res.,* **108,** 3097, doi:10.1029/2001JC000942.

Simpson, M. R., and R. N. Oltmann, 1993: Discharge-measurement system using an acoustic Doppler current profiler with applications to large rivers and estuaries. U.S. Geological Survey Water-Supply Paper 2395, 32 pp.

Stacey, M. T., S. G. Monismith, and J. R. Burau, 1999: Measurements of Reynolds stress profiles in unstratified tidal flow. *J. Geophys. Res.,* **104,** 10 933–10 949.

Terray, E., R. L. Gordon, and B. Brumley, 1997: Measuring wave height and direction using upward-looking ADCPs. *Proc. Oceans '97,* Halifax, NS, Canada, IEEE, 287–290.

Trump, C. L., 1986: Estimating absolute current velocities by merging shipboard Doppler current profiler data with LORAN-C data. *Proc. IEEE Third Working Conf. on Current Measurement,* Airlie, VA, IEEE, 177–183.

——, and G. O. Marmorino, 1997: Calibrating a gyrocompass using ADCP and DGPS data. *J. Atmos. Oceanic Technol.,* **14,** 211–214.

Valle-Levinson, A., C. Li, T. Royer, and L. Atkinson, 1998: Flow patterns at the Chesapeake Bay entrance. *Cont. Shelf Res.,* **18,** 1157–1177.