An Improvement in the Calculation of ADCP Velocities

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ABSTRACT

Acoustic Doppler current profilers are used to measure currents in a variety of aquatic conditions. When nonzero pitch and roll angles occur, a number of complications arise in the conversion from beam velocities, which are measured parallel to the acoustic beams, to earth velocities. One such difficulty is correcting for the vertical difference between bins in each beam. It is demonstrated that the default algorithm may lead to errors in the recovered velocity field, particularly in the presence of strong shears. An alternative correction is proposed, one which reduces the error by an order of magnitude for a flow field recently measured in an estuary.

1. Introduction

The ability to measure oceanic currents has been greatly improved over the past decade with the development of acoustic Doppler current profilers (ADCPs). They offer numerous advantages over conventional rotary-type current meters, including increased spatial resolution and the ability to measure the third component of the velocity field. In addition, ADCPs measure the backscatter intensity, and, with significant correlation between these observations and those of zooplankton abundance taken directly from tows (e.g., Heywood et al. 1991), for example, acoustic techniques can be useful in combined studies of biomass productivity and currents. More recently, ADCPs have also been used to study oceanic turbulence by directly measuring the horizontal contributions ($\overline{u'u'}$ and $\overline{v'v'}$) to the turbulent kinetic energy (Gargett 1994) as well as the $\overline{u'w'}$ and $\overline{v'w'}$ components of the Reynolds stress (e.g., Lohrmann et al. 1990; van Haren et al. 1994; Lu and Lueck 1999b; Stacey et al. 1999a,b; Ott et al. 2002, hereafter ODG).

Given the capabilities of the ADCP to measure currents and Reynolds stresses, it is not surprising that considerable effort has been made in quantifying the various sources of error associated with the technique. Deviations from zero in the ADCP pitch and roll angles slightly modify the algorithm for recovering the three-dimensional flow field (Lu and Lueck 1999a). The correction algorithm is more complicated in the measurement of Reynolds stresses, although it has been shown that for typical tilt angles the effect is small (van Haren et al. 1994; Lu and Lueck 1999b).

A basic complication introduced by nonzero tilt angles is that, at any instant of time, each beam ensonifies water at different depths. The resulting vertical ''bins,'' determined by the time delay of the returned acoustic signal, are therefore no longer in the same horizontal plane. Not only does the ''bin-mapping'' correction software supplied by RD Instruments (RDI), the manufacturer, not correct for the fact that beam velocities covering different vertical ranges are combined in producing earth velocities, it also results in the duplication and loss of data. A proposed refinement of the bin-mapping algorithm that more accurately recovers the currents is described in section 2. In section 3, a realistic three-dimensional flow field is used to determine the errors associated with each of these methods. Section 4 compares these errors to other sources typically associated with the measurement of currents by ADCP.

2. The bin-mapping algorithms

Consider a four-beam bottom-mounted upward-looking ADCP in which the beams are oriented 20° below the vertical and with an azimuthal separation of 90°. In a deployment for which the pitch and roll angles are identically zero, the bins in opposing beams of each beam pair sample the same water depths. In the case of a nonzero tilt angle, however, this is no longer the case,

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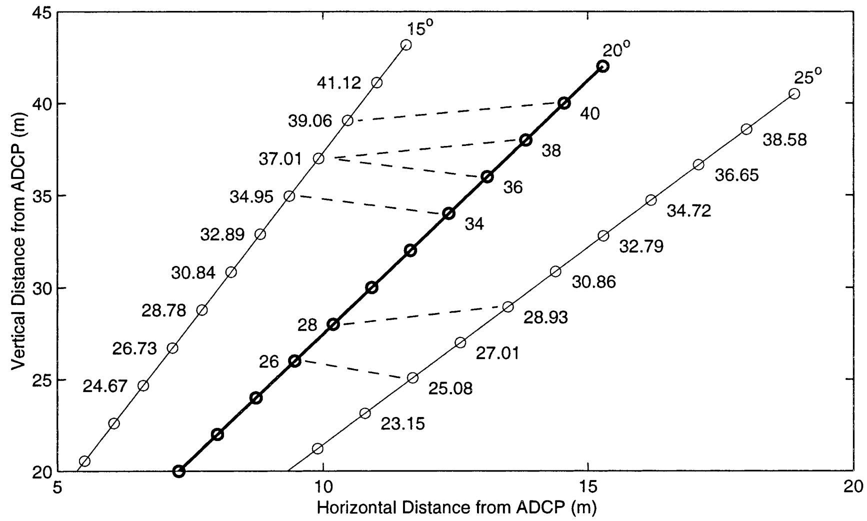

FIG. 1. The effect of nonzero tilt angle on bin height. Nominal bin centers (thick circles) are moved (thin circles) higher and lower for smaller and larger declinations, respectively. Numbers indicate the height (m) of the bin center above the ADCP unit.

and the vertical separation of corresponding bins in a beam pair increases with height above the ADCP (Fig. 1). For a pitch of 5° and with 2-m bins, for example, the bin nominally centered at 26 m above the ADCP is found at 26.72 and 25.08 m in the shallower and deeper beams, respectively—a separation of 1.64 m. At 36 m above the ADCP, the separation increases to 2.29 m and there is no overlap in the bins. To correctly calculate the velocity, or stress, from these beam pairs, a correction must therefore be applied.

The algorithm supplied by RDI uses the beam velocity from the bin nearest the nominal (i.e., with zero tilt angle) bin center. For example, the current at 26 m above the ADCP head is calculated using the velocity recorded for heights 26.72 and 25.08 m from the shallow and deeper beams, respectively. For the shallower beam, however, this leads to a situation in which two consecutive calculated velocities use the recorded beam velocity from the same bin. For a pitch of 5°, this occurs at the nominal heights of 36 and 38 m above the transducer head (Fig. 1). Conversely, in the opposite deeper beam, one recorded bin is skipped entirely. In this case, the data recorded at a height of 27.01 m are effectively discarded (Fig. 1). That is, the bin at 26-m height uses the data recorded for 25.08 m, while the bin at 28 m uses the beam velocity at 28.93 m; there is almost a 4-m (vertical) distance between bin centers at this location.

In addition to omitting or duplicating data, this procedure does not actually correct for the fact that beam velocities averaged over different depth ranges are combined to calculate the flow field.

As an alternative to the default bin-mapping method, consider one in which the beam velocities are linearly interpolated from the measured values. For example, for the beam oriented 15° below the vertical (Fig. 1), the beam velocity for a bin centered at 38 m is the interpolation between the data recorded at 37.01 and 39.06 m.

Implicit in this interpolation algorithm is the assumption that the beam velocities, and therefore the actual currents, vary smoothly between bin levels. Since the beam velocities measured are actually weighted averages over a depth range equal to 130% of the bin size (RDI 1996), implying an overlap of 0.6 m between adjacent 2-m bins, significant smoothing of the currents is already present in the measured beam velocities. At any rate, the assumption of smoothly varying currents is clearly more tenable than one in which currents at different depths are identical, as the nearest neighbor algorithm requires.

3. Evaluation

To estimate the magnitude of the differences between the two methods, the beam velocities corresponding to the 21-day mean residual flow (ODG) measured in Juan de Fuca Strait in 1996 using a 300-kHz broadband ADCP with 2-m bins (Fig. 2) are combined to recalculate the earth velocities. The ADCP unit was bottom mounted at a depth of 130 m and was operated in mode 1 (i.e., burst mode), with ensemble averages of 35 pings (about 11 s in duration) recorded every 30 s. The mean pitch and roll angles over the deployment were 1.0° and 4.6°, respectively (Ott 2000).

The three-dimensional velocity is first interpolated to yield currents every 0.01 m. For the measured pitch and roll angles, the actual height of the center of each 2-m bin was calculated for each beam independently, as in the RDI software; the heights for beams 1 and 2 were similar to those in Fig. 1. The beam velocities were then determined via the conversion matrix supplied by RDI,

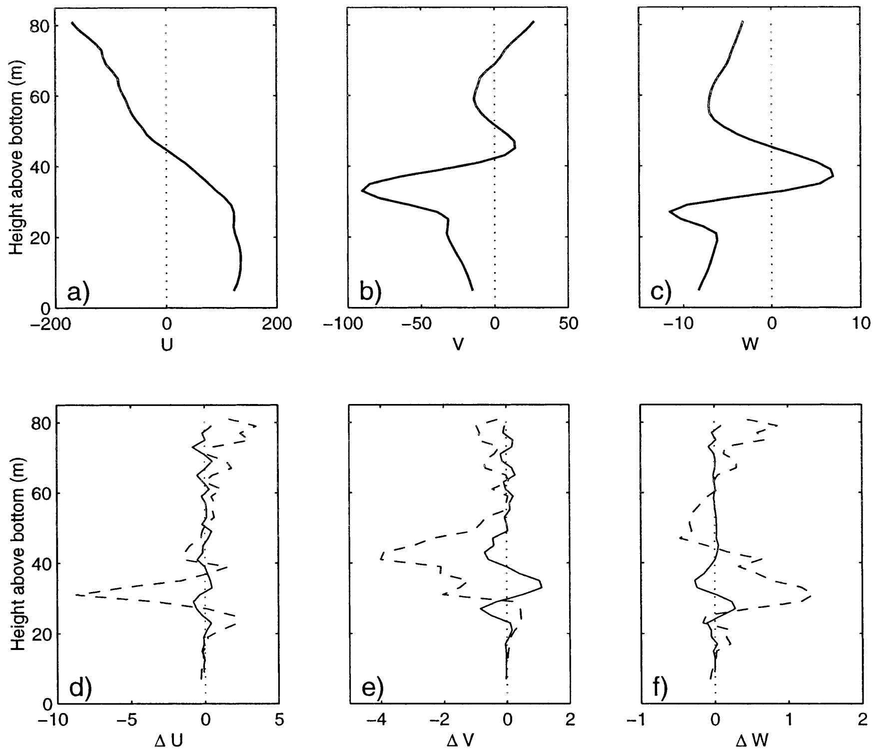

FIG. 2. The effect of the bin-mapping algorithm on calculated velocities. For the three-dimensional velocity depicted in (a), (b), and (c), the corresponding errors are shown in (d), (e), and (f), with dashed lines for the RDI nearest neighbor bin mapping and solid lines for linear interpolation. All currents are in units of 10^{-3} m s^{-1}.

which accounts for slight imperfections in the azimuthal and elevation angles. At the same time, the resolution was reduced to 2 m by averaging the velocities with a triangular filter of width 2.6 m, centered at the calculated bin centers (RDI 1996). Finally, these beam velocities were used to recalculate the three-dimensional velocity, which was then subtracted from the input velocity.

Whereas errors for the linear interpolation scheme are less than 0.001 m s^{-1} (i.e., the precision with which the ADCP records velocities) in magnitude at all depths, the RDI routine produces errors approaching 0.01 m s^{-1} in the horizontal velocity (Fig. 2). The error in the nearest neighbor algorithm should be greatest at depths with strong vertical shear in addition to depths where the separation between the actual and nominal bin centers are largest. Shears in both along- and cross-channel currents are large and fairly constant throughout the depth range 30–40 m above the bottom (Figs. 2a and 2b).

For the along-channel velocity u (calculated from beams 1 and 2), the peak in the error for the RDI algorithm (Fig. 2d) is found at a height of 36 m, the depth at which the bin separation is largest (Fig. 1). That is, the error is a direct result of the fact that in beam 2, the shallower beam for a roll angle of $+4.6°$, the same recorded beam velocity is used twice. The effect at 26-m height is much less pronounced because, although information from beam 1 is omitted, the shear in this region is considerably weaker. The cross-channel velocity v is calculated from beams 3 and 4. The pitch angle, $+1.0°$, with positive indicating that beam 3 is shallower than beam 4, is less than the roll angle, implying that the peak error occurs higher in the water column.

4. Error comparison

The errors found to be associated with the nearest neighbor bin-mapping routine are comparable to two types of error inherent in evaluating currents measured with an ADCP: instrument errors and those associated with inhomogeneities in the flow.

According to RDI, the single-ping standard deviation for a 300-kHz broadband ADCP with 2-m bins is 0.059 m s^{-1}. Ensemble averages of 35 pings reduce this to 0.01 m s^{-1}, the error associated with the nearest neighbor bin-mapping algorithm. Biases in the measured pitch and roll angles also lead to errors in the measured velocities. Although the recorded ADCP angles have a precision of 0.1°, the accuracy of these measurements is only 1°. The effect on the horizontal components is very small, because the vertical velocity is an order of magnitude less than (u, v). The vertical velocity, on the other hand, can be greatly affected; a roll bias of 1° in the presence of horizontal currents of magnitude 0.5 m s^{-1} leads to errors of approximately 0.01 m s^{-1} in *w*.

In a homogeneous flow field, only three beam velocities are required to recover the three-dimensional flow field. Rather than discard the additional information contained in the fourth beam velocity, an ''error velocity'' *e* is defined. When there are current inhomogeneities in the horizontal direction, *e* will not, in general, equal zero. A beam elevation angle of 20° implies that opposite beam pairs measure currents at a horizontal separation equal to 75% of the vertical height above the ADCP unit. Since the assumption of spatial homogeneity therefore becomes more unrealistic, error velocities should increase with height. In the 1996 deployment, for example, the 21-day mean magnitudes of the error velocities are 0.021, 0.030, and 0.037 m s^{-1} at heights of 10, 30, and 50 m above the ADCP, respectively.

5. Summary

The default bin-mapping correction for nonzero ADCP tilt angles has been shown to incorrectly calculate the velocity field, particularly in the presence of strong shear where the errors can approach 0.01 m s^{-1}. These errors, comparable in magnitude to several others inherent in the measurement process, can be reduced by an order of magnitude by linearly interpolating between the measured beam velocities rather than using beam velocities at different heights above the ADCP transducer.

The linear interpolation scheme requires that velocities vary smoothly with depth, a less restrictive condition than uniformity over depths of one-half the bin size, as the nearest neighbor routine implies. This latter condition is clearly violated to a greater degree in flow regimes with strong shears, as was demonstrated in the present case. Thus, the improvements expected with the new technique will be more important in boundary flows, such as at the bottom or sidewalls, where mean currents and log-layer dynamics are sometimes used to determine stresses acting on the flow. Similar situations arise at interior boundaries, such as those between the inflow and outflow of estuaries.

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