Comparison of Different Bin-mapping Methods for a Bottom-mounted Acoustic Profiler

KARI PULKKINEN

Department of Geophysics, University of Helsinki, Helsinki, Finland

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ABSTRACT

Acoustic Doppler current profilers (ADCPs) can measure profiles of velocity components and some other properties of bodies of water. If the profiler is firmly mounted, the profiles can be recorded without immediate coordinate transform. This gives more flexibility to the instrument settings and increases the capabilities of the instrument. If the instrument tilts, some data cell positioning—bin mapping—is usually needed in the post-processing of the data. The errors during that procedure depend on the degree of the tilt and the method used. If there are high gradients in the profiles, maximum errors can easily be greater than the statistical accuracy of the ADCP. If the tilts are fixed, these errors occur systematically at equal distances. In this study it is shown that the errors can be made smaller by slicing the beam profiles or by taking weighted averages instead of straight nearest bin selections. The disadvantage of these methods is that all sharp changes will be smoothed.

1. Introduction

Acoustic profiling has recently become a new standard current-measuring method in physical oceanography and in physical limnology. The advantages of the method are known, and the instruments are rather reliable and accurate (Pettigrew et al. 1986; Chereskin et al. 1987; Derecki and Quinn 1987; Appell et al. 1988); thus, the instrument has been used widely (Schott and Johns 1987; Johns 1988; Schott and Leaman 1991). The internal errors of the acoustic Doppler current profilers (ADCP) have been studied in detail (Chereskin et al. 1989). In addition to velocity profiling, acoustic profilers have been used for the estimation of zooplankton abundance and aggregations (Flagg and Smith 1989; Smith et al. 1989).

These profilers are used in several ways: mounted on research vessels (Kosro 1985), on towed fish (Kaneko et al. 1990), on streamlined floats (Johns 1988), on bottom-mounted platforms (Flagg and Smith 1989), etc. If the instrument is vessel-mounted or floating, the effects of tilting and horizontal turning may require immediate coordinate transform inside the instrument or in the computer connected to the ADCP. Otherwise, if the instrument is firmly mounted on a lake or sea bottom, these transforms are not necessary, because any tilts of the instrument do not vary with time. The main advantage of this is diminished power consumption that in turn gives more flexibility to the instrument settings and perhaps allows longer deployments without special constructions; for example, external batteries.

"Aforementioned" also means that all the velocities are recorded in beam coordinates as radial velocities. Because users are usually interested in horizontal or vertical components of velocity, some algorithm is needed for this conversion. Unfortunately, it is almost impossible to deploy the instrument without any tilt, and as a result, the vertical spacing of measurement volumes (bins) varies from beam to beam. This happens because bin size along each beam is the same for all beams. (The preset value depends only a little on the velocity of sound.) Examples for the bin depths at different tilts for opposite beams are given in Table 1. It can be seen that even at small angles of tilt the bin depth varies considerably for distant bins. Also, the selection of the final cell depth will undoubtedly affect any experimental results.

The following investigations have been done with an RD Instruments narrowband 1200-kHz SC-ADCP. Similar results apply to ADCPs with a longer range and lower vertical resolution, if all the distances are multiplied accordingly. The 1200-kHz ADCP is capable of a short transmit pulse, and it records Doppler shifts and other properties of returning echoes. The maximum vertical resolution is about 1 m. The actual height of a measurement cell (bin) is most often two times the vertical resolution, that is, for an ADCP of 1200-kHz, usually 2 m. Because these bins are truncated both in space and time, the recordings of the neighboring bins have about a 16% common measurement volume (Brumley 1991). Two pendulums inside the pressure case of an SC-ADCP are used to measure tilts. These tilts and their standard deviations are recorded with each measurement.

Corresponding author address: Kari Pulkkinen, University of Helsinki, Department of Geophysics, Fabianinkatu 24 A, SF-00100 Helsinki, Finland.

TABLE 1. Examples of vertical bin-depth distances from the ADCP transducers for opposite beams with two angles of tilt. It is assumed that the bin size is 1 m at zero tilt and that the ADCP has 30° beam angles. Examples of where a bin of lower number passes one of higher number are printed in boldface.

Bin number	Vertical distance of the middle of the bin from the transducers (m)			
	Tilt = 5°		Tilt = 10°	
	Beam 1	Beam 2	Beam 1	Beam 2
1	1.05	0.95	1.09	0.88
2	2.09	1.89	2.17	1.77
—	—	—	—	—
5	5.23	4.73	**5.43**	4.42
6	6.28	5.68	6.51	**5.31**
—	—	—	—	—
10	**10.47**	9.46	10.85	8.85
11	11.51	**10.40**	11.94	9.73

2. Comparison of bin-mapping methods

a. General

The bin-mapping method presented by RD Instruments (1988) selects bins closest to the actual (selected) measurement depths. This method is used when the profiler itself calculates the earth-oriented velocity components from radial velocity measurements. Because this is done for every ping prior to averaging, the procedure must be fast and economical. A disadvantage of this method is that some information is easily lost or used twice in the calculation, resulting in the loss of accuracy. This "gapping" or "doubling" happens because, when the instrument tilts, the vertical extent of the bins for the "lower" beam decreases, whereas that of the "higher" beam increases. An example of this is shown in Fig. 1. The same will happen at lower tilts in more distant depth bins.

The principles of the bin-mapping methods are shown in Fig. 1. The original bin-mapping method selects those nearest the actual depth for the calculation of the horizontal (and vertical) components. Notice that in using the data from beam 1, bin 4 is skipped (marked as A), whereas in using data from beam 2, bin 6 is used twice (B).

The bin-slicing method is technically identical to the original method but with the vertical resolution artificially increased so that each calculation depth is divided into two or more slices. The data from beams are selected for each slice, and the final result is the average of the slices. It is obvious that if the tilts and the "slicing factor" are small enough, the bin-slicing method gives exactly the same results as the original method. The example in Fig. 1 is for bin slicing with a factor of 2.

An alternative method uses a weighted average such that binned values are proportional to their effect on the calculated depth interval. Bin slicing is a rough estimate (discretization) of these weighted averages; that is, these two become equivalent if the number of slices becomes large enough.

The advantage of bin slicing and weighted averaging is that they use beam profile data more precisely than the original method. The same algorithms can be used in calculating other variable profiles, such as those for echo amplitude and spectral width.

b. Generated profiles

As these bin-mapping methods use the original data differently, they have rather different effects on the final calculated profiles. Although the alternative methods may yield better vertical positioning, they may also smooth the data a bit more. As the ADCP in some circumstances seems to underestimate the velocities (Appell et al. 1988; Appell 1989), this might be a problem in some applications.

In order to test the characteristics of the bin-mapping methods, a set of velocity profiles was generated. For these purposes, an estimation of how an ADCP would measure those profiles was first made. A depth cell (or bin) can be imagined to be a cylinder, the volume of which increases with distance from the transducer. As Brumley (1991) described, the ADCP takes samples from the returning echo so that neighboring bins overlap by about 16%. Therefore, a reasonable approximation of the bins is described in Fig. 2, although the actual impulse response of the ADCP's filter, which has not been taken into consideration, would increase the value somewhat (Brumley 1991). For testing the bin-mapping methods, the velocity estimates were re-

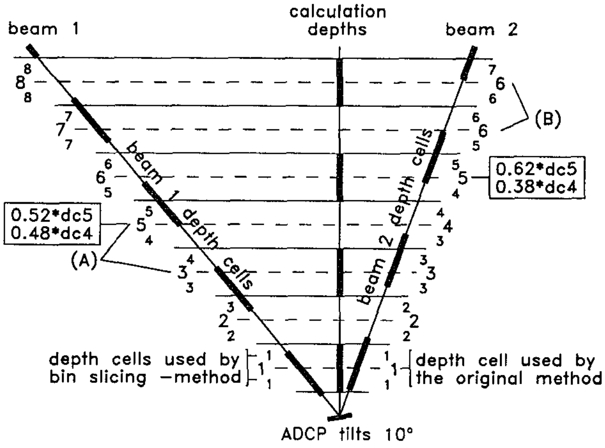

FIG. 1. Examples of the bin selection by different bin-mapping methods. Larger numbers correspond to the beam bin numbers, which are selected by the original bin-mapping method. Smaller numbers are the bin numbers selected by the bin-slicing method with a slicing factor of 2. The separate boxes contain two examples of the approximate weights that would be used if the results were calculated by weighted averages.

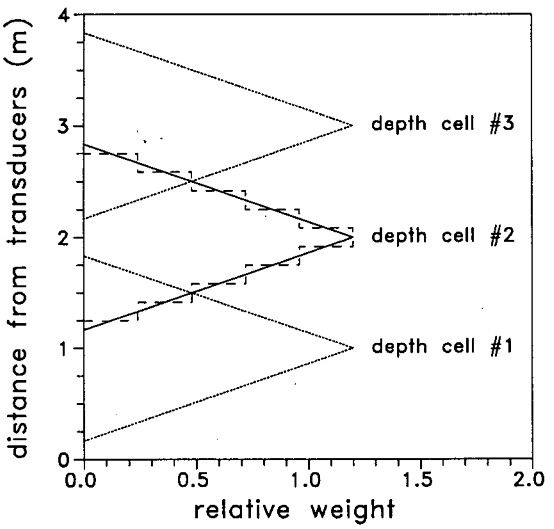

FIG. 2. Estimation of an ADCP bin. The solid line represents the estimate of the weighting function of an ADCP as described by Brumley (1991), and the dashed line represents the function used in the generation of the profiles. The dotted lines show the weights of the neighboring bins.

corded along the two beams separately by using the weighting function presented in Fig. 2. Positioning and scaling were done using the normal procedure.

The bin-mapping methods were tested with velocity profiles for ADCP tilts from 0° to 20°. The original velocity profiles are shown in Fig. 3. These profiles are scaled so that in each case the velocity at a distance of 20 m from the ADCP would be 20 cm s^{-1}. Velocities were calculated over a depth range from 0 to 20 m. The bin depths were estimated as an average of the corresponding beam-depth bin depths. As the actual measurements are usually affected by tilts in two directions, the selection of the ideal bin depth may be more difficult.

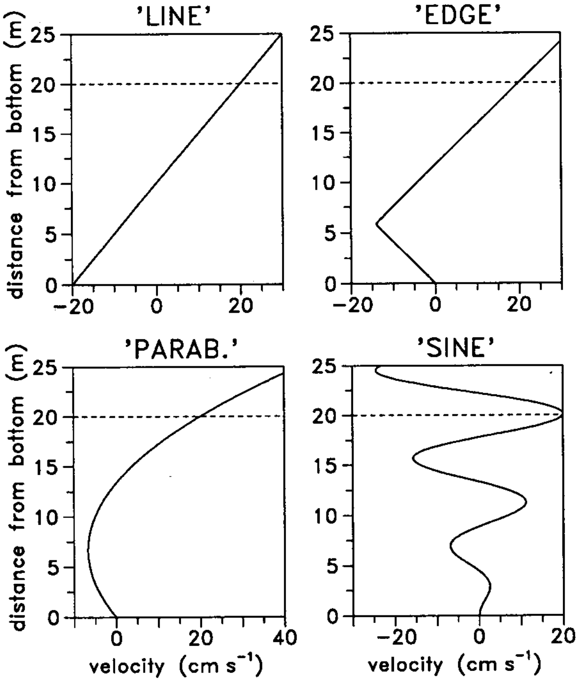

FIG. 3. Generated test profiles. The dashed line shows the upper limit of 20 m for the calculations.

Figure 4 gives the rms errors of the profiles as a function of tilt. For tilts greater than a few degrees, the original method is clearly the worst, whereas weighted averages are usually slightly better for all the tested velocity profiles. Bin slicing seems to fall somewhere between the original and the weighted average methods mentioned earlier. The rms errors increase with tilt, especially for the simple velocity profiles. In Fig. 5, the maximum error within a profile is shown as a function of tilt. In actual measurements this error can be serious because for fixed or slowly varying tilts the error occurs systematically at the same depth and may bias the results. If the profile has no discontinuities, the original method seems to have considerably greater maximum errors than the other methods.

The weighted-average method usually gives the smallest maximum errors. However, if the there is a discontinuity in the profile, its maximum error is of about the same magnitude as that for the original

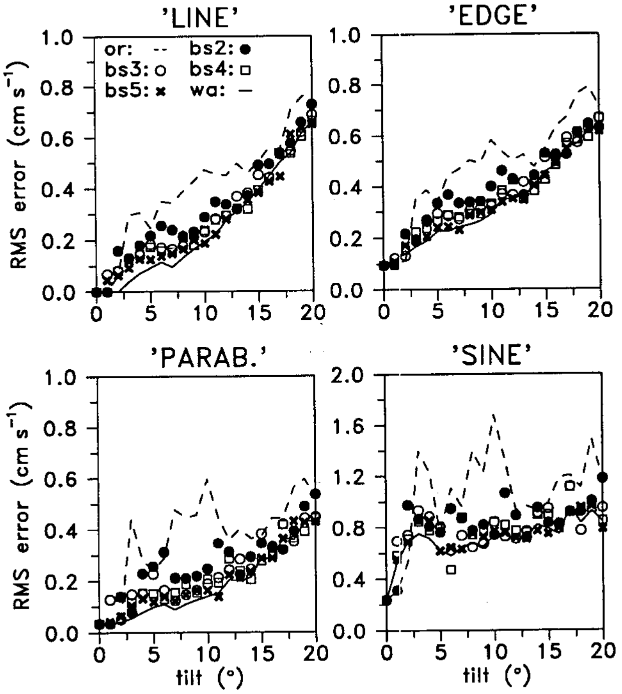

FIG. 4. The rms errors for the test profiles of the different bin-mapping methods as a function of tilt. The original method (dashed line), weighted averages (solid line), bin slicing with two slices (●), bin slicing with three slices (○), bin slicing with four slices (□), and bin slicing with five slices (×).

method. This seems to happen because the weighted averages smooth the resulted profiles most. For smoothly varying profiles, using weighted averages is clearly better. In these examples, the errors are about the same magnitude as the statistical error of a 1200-kHz narrowband ADCP (1-m ping length and an average of 100 pings will give a statistical error of about 1.3 cm s^{-1}); thus, the errors are by no means insignificant.

In normal applications the situation is usually more complex as the recorded velocities are calculated from the data from all four beams and the results are therefore affected by two (usually different) tilts.

c. Estimates with real data

Two real datasets were also used for comparing these methods:

1) The first dataset was recorded in Lake Päijänne (area of 1100 km^2) at 61°45.5′N, 25°25.5′E for the period from 7 June to 4 July 1989. The measurement interval was 10 min, and the magnitudes of the ADCP tilt were 3.3° and 3.3°. The velocity component presented was calculated in the direction the mean current. The maximum velocities were typically between 20 and 30 cm s^{-1}. The bin size was about 1 m. The results of the first bin were rejected because of some erroneous values.

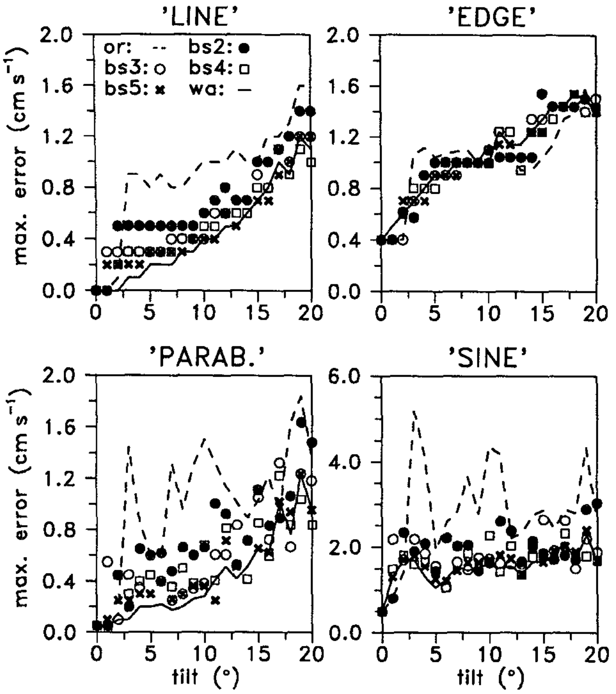

FIG. 5. Maximum errors for the test profiles of the different bin-mapping methods as a function of tilt. The original method (dashed line), weighted averages (solid line), bin slicing with two slices (●), bin slicing with three slices (○), bin slicing with four slices (□), and bin slicing with five slices (×).

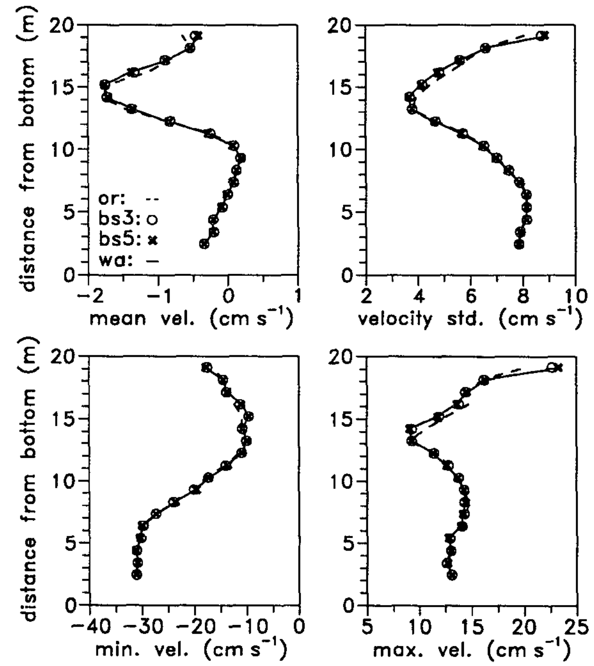

FIG. 6. Mean value, standard deviation, and minimum and maximum of the velocity component to the direction of the sound as calculated from 1-h means from Lake Päijänne. The original method (dashed line), weighted averages (solid line), bin slicing with three slices (○), bin slicing with five slices (×).

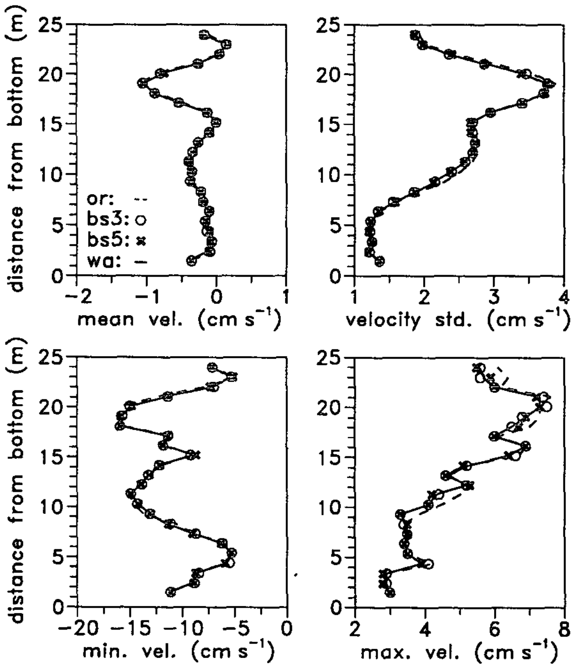

FIG. 7. Mean value, standard deviation, and minimum and maximum of the velocity component to the estimated main direction of the current as calculated from 1-h means from Lake Pääjärvi. The original method (dashed line), weighted averages (solid line), bin slicing with three slices (○), bin slicing with five slices (×).

TABLE 2. Mean velocities and standard deviations over the profiles as measured with different methods.

	Päijänne		Pääjärvi	
Bin-mapping method	Mean velocity ($cm\ s^{-1}$)	Mean velocity standard deviation ($cm\ s^{-1}$)	Mean velocity ($cm\ s^{-1}$)	Mean velocity standard deviation ($cm\ s^{-1}$)
Original	−0.5363	6.524	−0.2755	2.361
Bin slicing (3)	−0.5308	6.487	−0.2869	2.305
Bin slicing (5)	−0.5354	6.474	−0.2831	2.303
Weighted averages	−0.5366	6.473	−0.2873	2.300

2) The second dataset was recorded in Lake Pääjärvi (area of 13 km^2) at 61°04.1′N, 25°05.8′E for the period from 6 June to 24 June 1990. The measurement interval was 10 min, and the magnitudes of the ADCP tilt were 4.8° and 0.2°. The velocity component was calculated again in the direction of the mean current. Maximum velocities were typically less than 20 $cm\ s^{-1}$. The bin size was about 1 m.

Temperature profile data were used to calculate the speed of sound. The hourly mean of vertical profiles of horizontal velocity and mean profiles for the period using various bin slicing and averaging methods were calculated. The mean values, standard deviations, and absolute minimums and maximums of the velocity component are given in Fig. 6 and Fig. 7. The effects of the sidelobe reflection from the surface were not taken into account in any way in the following discussion.

All the methods generally give equivalent results. The differences are greatest at the minimums and maximums of the profiles at the distances where skipping and doubling should occur with the original method—at the distances near 15 m in the Lake Päijänne data and at the distances near 10 and 20 m in the Lake Pääjärvi data.

Table 2 shows the mean values for the various methods and their standard deviations. The differences between the methods are very small; only the original method seems to be systematically a bit higher than the others. Whether this is because of errors in the original method or because of smoothing caused by the other methods cannot be assessed. In comparison, the statistical accuracy of the Doppler calculation is about 0.005 $cm\ s^{-1}$ (about 1.3 $cm\ s^{-1}$ in 10-min averages averaged over about 70 000 measurements).

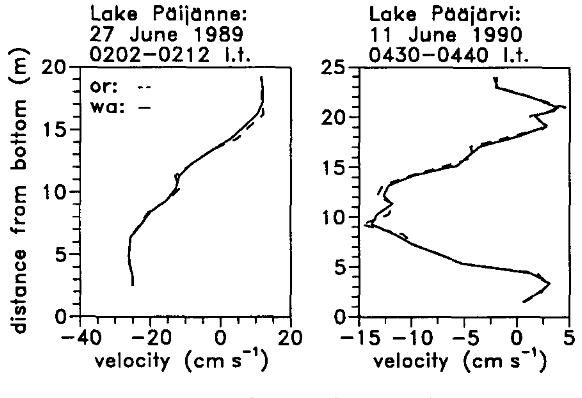

FIG. 8. Examples of two single profiles (10-min averages) as estimated with different bin-mapping methods. The original method (dashed line) and weighted averages (solid line).

Examples of two single profiles are presented in Fig. 8. There are only minor differences between the two bin-mapping methods presented. The profile from Lake Pääjärvi is smoother when estimated with weighted averages.

3. Conclusions

In most cases it will not be necessary to modify the bin-mapping method used, but the experimenter should be aware of the possibility of obtaining large errors in profiles with significant gradients. If the ADCP tilts are greater than a few degrees, the selection of the bin-mapping method may be critical at certain depths. If it is possible to record data without immediate coordinate transformations and if light smoothing of the data is not critical, then bin-mapping methods other than the original one offer much smaller errors. The study is by no means a perfect test concerning the bin-mapping methods presented, but some overall conclusions can be made concerning their advantages and disadvantages.

- The original bin-mapping method is quite safe at small tilts and with profiles with low gradients. The method is also the same as in VM-ADCP and in real-time coordinate transforms. It is also fast, since it does not involve complex calculations. However, this study has shown that unfortunate bin depths combined with highly sheared currents can produce significant errors for tilts greater than a few degrees.
- The bin-slicing methods use the profile data more efficiently. For very small tilts and small bin-slicing factors, the results are exactly the same as those of the original method. These methods, however, yield smaller maximum errors with high tilts and varying profiles than the original method. Application of the method to real data indicates that the methods might

smooth the ADCP measurements somewhat. The usefulness of these methods is dependent on the combination of the tilt and slicing factor.

- Using weighted averages gives the best profile estimate since it uses the beam profile data most efficiently. Without large shears, the method yields considerably smaller maximum errors than the original one. The cost of this is that the method does the most smoothing and also increases the computation time required.

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