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INSTRUMENTS AND METHODS

Using a Lowered Acoustic Doppler Current Profiler for Measuring Current Velocities in the Black Sea

D. D. Aleinik[a,b], G. I. Shapiro[a,b], L. D. Mee[b], and E. M. Lemeshko[c]

[a] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia*
[b] *Marine Institute, Plymouth University, Plymouth, England*
[c] *Marine Hydrophysical Institute, National Academy of Sciences of Ukraine, Sevastopol, Ukraine*

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Abstract—The results obtained with the use of a lowered acoustic Doppler current profiler (LADCP) are presented. The use of the LADCP from a vessel was the first in the history of the study of the Black Sea. The measurements were carried out in the northeastern Black Sea under the auspices of the Black Sea Ecosystem Recovery Program (BSERP) in May 2004. The effect of the computation parameters on the quality and accuracy of the calculations of velocity profiles was studied. It was shown that the use of optimal parameters and reliable navigation data and setting the instrument as close to the bottom as possible could essentially enhance the accuracy of the measurements. The current velocity calculations from the LADCP data were compared with the data on the vessel drift under calm weather. The accuracy of the calculations reached 6–8 cm/s. Recommendations on the choice of the optimal parameters for processing the data on the current velocity are presented.

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INTRODUCTION

Acoustic Doppler current profilers (ADCP) built into the vessel bottom or deployed on the sea floor are widely used in oceanography (see, e.g., [4, 5]). These instruments represent effective means for obtaining time series of current velocity simultaneously at different levels near the bottom or the sea surface [7]. In the last fifteen years, ADCPs were used in a probing regime [1–3, 9] to obtain continuous current profiles when the sea depth exceeds the range of the acoustical sounding of the instrument, which generally ranges from 20 to 300 m depending on the carrier frequency of the acoustical signal and the characteristics of the scattering particles in the water.

For the first time, a lowered ADCP was used for the study of the Black Sea during the BSERP-3 expedition onboard the Bulgarian R/V *Akademik* in May 2004 under the auspices of the Black Sea Ecosystem Recovery Program (BSERP). The processing of the signal from the ADCP is more complex than that from stationary or onboard instruments due to the horizontal movements of the instrument with a velocity unknown in advance in addition to the vertical motion in the course of the sounding.

One of the previous methods for obtaining continuous profiles of the velocity was proposed in [2, 3]. The method is based on the differentiation of the individual velocity profiles obtained during the lowering of the instrument over the vertical and subsequent averaging of the velocity values in the layers over the domain where one profile overlaps another. The averaged profile of the velocity shear is then integrated over the vertical to obtain the relative, or baroclinic, current velocity profile. The barotropic current component, which is an integration constant, remains unknown at this stage. The level of the instrument is determined by integrating the measured vertical velocity (the velocity of lowering) over time. The barotropic component of the current is calculated by integrating the "apparent velocity" of the current, i.e., the water velocity with respect to the instrument, over time. In so doing, we should take into account that, during sounding from the surface to the maximum depth and backward, the instrument and the vessel cover the same distance. To carry out these calculations, it is necessary to have exact navigation data on the location of the vessel at the beginning and at the end of the sounding. Unfortunately, individual measurements of velocity are often noisy, which results in an unacceptably low accuracy of the measurements (about 10 cm/s).

To enhance the accuracy of the measurements of the current velocity, M. Visbeck proposed a new method that includes a procedure of rejecting outliers from the raw data and solving a set of equations in which the number of equations exceeds that of the unknowns [9]. The method was used in the LDEO LADCP Processing Software version 8b, a program package for data processing developed by M. Visbeck, who kindly permitted us to use it in the present study.

METHOD OF PROCESSING INDIVIDUAL VELOCITY PROFILES

Below, we present a simplified description of the method for the calculation of the horizontal current velocity. Each velocity value $\mathbf{U}_a$ measured with the use of the LADCP can be considered as a sum of three components: the velocity of the ocean water $\mathbf{U}_0$, the velocity of the frame $\mathbf{U}_r$ that carries the instrument, and the noise $\mathbf{B}$. The velocity of motion of the frame within one sounding pulse (ping) with a duration of 0.2–0.5 s is assumed to be constant. For the sake of simplicity, let us consider the case of a downward sounding.

The velocity of the water flow in the ocean is determined from the LADCP data by solving the set of linear equations

$$\mathbf{C} = A\mathbf{x} + \mathbf{B}, \qquad (1)$$

where $\mathbf{C}$ is the vector whose components are the measured velocities $\mathbf{U}_a$ and a set of additional conditions $\mathbf{H}$. The product of the matrix A by the unknown vector of velocities $\mathbf{x}$ and the vector $\mathbf{B}$ (noise) are on the right-hand side of the equation. The components of the vector $\mathbf{x}$ are the unknown values of the actual velocity of the water flow in the ocean, $\mathbf{U}_0$, and the vector of the frame velocity with respect to the bottom, $\mathbf{U}_r$. The dimension of the matrix A is $m \times N$ (here and below, the first term denotes the number of columns). The value of N is determined from the formula $N = n + p$, where n is the number of the velocity values $\mathbf{U}_a$ and p is the number of the additional conditions $\mathbf{H}$. The value of n is $n = nt \times nbin$, where nt is the number of pings, i.e., the profiles of velocity obtained for the entire sounding period, and $nbin$ is the number of the measured values of velocity obtained during one ping. The value of m is $m = nz + nt$, where nz is the number of layers in the profile of the ocean water velocity, and nt is the number of values of the frame velocity, which is equal to the number of pings.

The terms of Eq. (1) can be presented in the following form:

$$\mathbf{C} = \begin{bmatrix} U_{a1,1} \\ U_{a1,2} \\ \dots \\ u_{a1,nbin} \\ u_{a2,1} \\ \dots \\ u_{a2,nbin} \\ \dots \\ u_{ant,nbin} \\ \mathrm{H}_1 \\ \dots \\ \mathrm{H}_\mathrm{p} \end{bmatrix}; \quad A = \left[\begin{array}{ccccc|ccccc} 1 & 0 & 0 & \dots & 0 & 1 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 & \vdots & \vdots & \vdots & \ddots & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 & 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 1 & \dots & 0 & 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 & 0 & 0 & 0 & \dots & 1 \\ \hline \multicolumn{10}{c}{G} \end{array}\right]; \quad \mathbf{x} = \begin{bmatrix} U_{r,1} \\ U_{r,2} \\ \dots \\ U_{r,nt} \\ \hline U_{0,1} \\ \dots \\ U_{0,nz} \end{bmatrix}. \qquad (2)$$

The horizontal and vertical lines inside the matrices are presented for the sake of clearness. The matrix A is a block matrix and is composed of $2nt + 1$ blocks:

$$A = \begin{bmatrix} D^1 & E^1 \\ \vdots & \vdots \\ D^{nt} & E^{nt} \\ \multicolumn{2}{c}{G} \end{bmatrix}. \qquad (3)$$

The matrices D^k are composed of nt columns and $nbin$ rows. The elements of the matrices D^k are equal to unity only in the column $i = k$, where $1 \le k \le nt$, while other columns contain zeros:

$$D^k = \overset{i = k}{\underset{\longleftrightarrow\, nt}{\begin{bmatrix} 0 & 1 & 0 \\ \vdots & 1 & \vdots \\ 0 & 1 & 0 \end{bmatrix}}} \updownarrow nbin. \qquad (4)$$

The matrices E^k are composed of nz columns and $nbin$ rows, and, in turn, each of them represents a block matrix $E^k = [E_L^k E_C^k E_R^k]$. Each block of the matrix comprises *nbin* rows and a different number of columns

$$E^k = \overbrace{\begin{bmatrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{bmatrix}}^{E_L^k}_{k-1} \overbrace{\begin{bmatrix} 1 & 0 & 0 \\ \vdots & 1 & \vdots \\ 0 & 0 & 1 \end{bmatrix}}^{E_C^k}_{nbin} \overbrace{\begin{bmatrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{bmatrix}}^{E_R^k}_{nz-nbin-k+1} \updownarrow_{nbin}. \quad (5)$$

The left E_L^k and the right E_R^k matrices contain only zeros. The number of columns in the left matrix is equal to $k - 1$. The number of columns in the right matrix is equal to $[nz - nbin - k + 1]$. The intermediate matrix E_C^k has *nbin* rows and *nbin* columns. The main diagonal of the intermediate matrix contains units, and other elements are zeros.

For the set of equations presented in the matrix form (2), the additional conditions (p elements of the vector $\mathbf{H}$ in the vector $\mathbf{C}$) correspond to the blocks G of the matrix A

$$\mathbf{H} = [H_1 \cdots H_p]; \quad G = [G_1 \cdots G_p]. \quad (6)$$

Each block matrix G_i comprises elements F_j with weight coefficients w

$$G_i = w[F_1 \cdots F_{nt} \cdots F_{nz}]. \quad (7)$$

The values of F_j represent additional conditions, or "restrictions," for the elements $\mathbf{H}$. The relative role of the equations that provide additional information is defined by the weight coefficients w. The additional conditions allow the frame velocity to be determined more exactly and include (i) the data on the GPS vessel navigation at the beginning and the end of the sounding, which are used for determining the shift of the vessel over the sounding time, and (ii) the measurements of the horizontal velocity of the instrument movement with respect to the bottom when the meter is located at a distance from the bottom within the measurement range (the so-called "bottom tracking"). The third of the conditions considered in this paper is smoothing the resulting profile of the ocean water velocity to reduce its noisiness.

It is evident that, during sounding from the surface to the maximum depth and backward, the instrument and the ship cover the same distance S_{ship} in the horizontal direction. This can be expressed as

$$S_{\text{ship}} = \int_0^T U_r dt. \quad (8)$$

To allow for this additional information, the vector $\mathbf{C}$ includes the element $\mathbf{H}_1$, and the matrix A includes the matrix G_1, $m \times 1$ in size. The matrix–row G_1 is composed of *nt* ratios of the individual time intervals $dt_i = t_{i+1} - t_i$, to which the current values of the frame velocity $U_{r,i} = U_r(t_i)$ correspond to the total time T of the measurements at the station multiplied by the weights of the w_{bar} and nz zeros

$$H_1 = [w_{\text{bar}} U_{\text{ship}}];$$

$$G_1 = w_{\text{bar}} \left[\frac{dt_1}{T} \; \frac{dt_2}{T} \; \cdots \; \frac{dt_{nt}}{T} \middle| 0 \; 0 \; \cdots \; 0 \right]. \quad (9)$$

Here and hereinafter, the weight w_{bar} is referred to as the barotropicity factor and defines how exactly the solution of the set of equations satisfies Eq. (8).

Similarly, the system of equations (1) contains the condition of consistency of the calculated velocities of the frame motion $\mathbf{U}_r$ and the measured velocities of the frame with respect to the bottom in the bottom-tracking regime $\mathbf{U}_{r,\text{bot}}$

$$H_2 = \begin{bmatrix} w_{\text{bot}} U_{r,\text{bot}}^1 \\ \dots \\ w_{\text{bot}} U_{r,\text{bot}}^q \end{bmatrix};$$

$$G_2 = \left[\begin{array}{cccccc|ccccc} 0 & \cdots & w_{\text{bot}} & 0 & \cdots & 0 & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \cdots & 0 & w_{\text{bot}} & & \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ 0 & \cdots & 0 & 0 & \cdots & w_{\text{bot}} & 0 & \cdots & 0 & \cdots & 0 \end{array} \right] \updownarrow_q, \quad (10)$$

where $\mathbf{H}_2$ is the vector composed of q elements that represent the measured values of the frame velocity with respect to the bottom $\mathbf{U}_{r,\text{bot}}$. The matrix G_2 consists of m columns and q rows, where q is the number of pings comprising information on the motion of the instrument with respect to the bottom, and m is described above. The weight factor of the bottom tracking, w_{bot}, determines how exactly the solution of the set of equations is in agreement with the obtained values of the instrument motion with respect to the bottom.

Similarly, the condition for smoothing the values calculated from the profile of the ocean water velocity $\mathbf{U}_0$ is introduced in the set of equations (1)

$$H_3 = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}; \quad G_3 = \left[\begin{array}{ccc|ccccccc} 0 & \cdots & 0 & -1w_{\text{sm}} & 2w_{\text{sm}} & -1w_{\text{sm}} & 0 & \cdots & 0 \\ 0 & \cdots & 0 & 0 & -1w_{\text{sm}} & 2w_{\text{sm}} & -1w_{\text{sm}} & \cdots & 0 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & 0 & 0 & 0 & 0 & \cdots & -1w_{\text{sm}} \end{array} \right] \updownarrow_{nz}. \quad (11)$$

Here, all *nz* elements of the vector $\mathbf{H}_3$ are equal to zero. The matrix G_3 has *m* columns and *nz* rows. The first *nz* elements of each row of the matrix G_3 are equal to zero, and the remainder *nz* elements provide smoothing of the values of the vector $\mathbf{U}_0$ with regard to the weight factor of smoothing w_{sm}.

The calculation of the velocities of the ocean water flow U_0 was carried out by solving the set of equations (1) with regard to additional Eqs. (9), (10), and (11). When $N > m$, the set of equations becomes overestimated. The solution of such sets of equations is based on a well-known method of least squares (see, e.g., [6]). It should be noted that, when we solve an overestimated set of equations, it is impossible to satisfy all the equations exactly.

The experiments on the processing of the raw data obtained with a lowered ADCP show that the numerical velocity value in the final velocity profile can essentially depend on the values of the weight coefficients w_{bar}, w_{bot}, and w_{sm}. Unfortunately, Visbeck's method does not provide any recommendations on the choice of such coefficients. The problem on the choice of optimal parameters for the processing of the results of the measurements remains open up till now. The next section is devoted to an analysis of the sensitivity of the velocity profiles to the variations of the weight coefficients and formulation of criteria for choosing the optimal parameters that can provide higher accuracy of the determination of continuous velocity profiles with the use of a sounding acoustic profiler.

EXPERIMENTS

The measurements were carried out with the use of an RDI-WH300 velocity profiler manufactured by the RDI firm (United States). The operating frequency of the meter is 300 kHz, the frequency of the pings is 2 Hz, the nominal working range of the measurement distance is 135–175 m, and the housing is designed to withstand the pressure down to a depth of 1000 m. The accuracy of the velocity measurements with respect to the instrument is 5×10^{-3} m/s, the resolution is 1×10^{-3} m/s, the precision of the compass readings is 2°, the resolution is 0.5°, the number of layers for the measurements is 1–128, and the resolution in the vertical direction is proportional to the number of layers.

Most of the parameters used for the processing of an LADCP station (e.g., the weight of the instrument) have clear meanings and their values are evident. The values of other parameters need to be chosen individually. In the series of our experiments, the main attention was paid to the three most important parameters: the profile smoothing factor, the bottom-tracking factor, and the barotropicity factor.

The instrument was not provided with an RDI bottom-tracking system, which allows sending and processing an additional acoustic pulse. Therefore, to trace the bottom, the information on the intensity of the general "sounding" measuring pulses was processed. The previous studies showed [9] that the accuracy of such a method is only slightly lower than that of the RDI system, and the method has a series of advantages (e.g., reduced power consumption).

When the instrument is located at a distance of the acoustic "visibility" from the bottom, which is determined by the acoustical transparency of the water (suspension, gas bubbles, plankton, and so on), the data on the reflection from the bottom are recorded in the file for the raw data [9]. In all the runs of processing the signals from the lowered profiler, we always used the bottom-tracking regime. In such a case, the information on the "bottom movement velocity" with respect to the meter can be taken into account in the calculation of the total velocity profile, with a weight factor w_{bot} not equal to zero.

The experiments for testing the method were carried out with the use of a set of actual LADCP stations obtained in May 2004 in the region of intensive anticyclonic eddy in the vicinity of the shelf edge in the northwestern area of the Black Sea [8]. Seven stations performed under a very weak wind (up to 5 m/s) or calm weather conditions were selected from the full set of stations performed during the expedition (more than 60). This allowed the comparison of the results of the calculations of the current velocity inferred from the LADCP data with the independent estimations of the velocity at the surface obtained from the vessel drift data. The GPS vessel navigation data were used for determining the mean velocity and direction of the vessel movement during the expedition at these stations (see the first four columns in the table).

The continuous velocity profile was calculated from the data obtained with a lowered ADCP by the method described in the previous section and with the use of various combinations of the values of three factors (w_{sm}, w_{bot}, and w_{bar}), each of which was 0, 0.5, 1, and 2. Totally, for each of the seven stations (nos. 08, 09, 11, 44, 48, 49, and 50), we calculated 64 variants of the velocity profile. As was expected, different values of the weight factors resulted in different velocity profiles at the same station, although the initial data of sounding were identical.

Figure 1 shows an example of the vertical profiles of the zonal and meridional velocity components at station 11 from the results of 64 runs with sets of the values of the weight smoothing factors w_{sm}, the bottom factor w_{bot}, and the barotropicity factor w_{bar}. The sounding at station 11 was carried out down to a level of 325 m with the bottom depth equal to 380 m under absolutely calm weather conditions. The discreteness of the data records over the vertical was 10 m, and the range of the measurement distances varied from 100 m at the surface to 50 m at the bottom.

Figure 1 shows three clearly distinguishable groups of velocities (denoted by numerals) in the plots of the zonal component **u**. The groups were composed of neg-

Velocity and direction of the drift of R/V *Akademik* from the navigation data and values of the current velocity at the surface from the LADCP data (weight factors $w_{sm} = 0$, $w_{bot} = 1$, $w_{bar} = 1$) for seven stations in the Black Sea in May 2004 (BSERP-3 expedition)

Station no.	Vessel drift from the GPS data				LADCP ($w_{sm} = 0$, $w_{bot} = 1$, $w_{bar} = 1$)				Wind, m/s
	u_s m/s	v_s m/s	$\|V\|_s$ m/s	Angle°	u_{ladcp} m/s	v_{ladcp} m/s	$\|V\|_{ladcp}$ m/s	Angle°	
8	–.362	–.004	.362	269.4	–.443	.070	.448	278.9	3
9	–.475	–.092	.484	259.0	–.408	.076	.415	280.5	5
11	–.376	.148	.404	291.5	–.288	.180	.340	301.9	0
44	.239	–.061	.247	104.3	.172	–.008	.172	92.7	0
48	–.414	–.006	.414	269.2	–.361	–.050	.364	262.7	0
49	–.310	.162	.350	297.6	–.317	.015	.317	272.6	0
50	–.297	.140	.329	295.2	–.444	.048	.447	276.1	0

Note: The positive values of u and v correspond to the eastward and northward currents, respectively. $|V|$ is the absolute velocity value. The angle is measured clockwise from the northward direction.

ligibly different profiles. The first group comprises profiles with the minimum absolute value of the velocity at the surface and the maximum value at the bottom. This group corresponds to the cases when both of the factors, w_{bot} and w_{bar}, are equal to zero. The second group comprises the cases when the factor w_{bar} is zero and $w_{bot} > 0$. In the second group, the absolute velocity value is much higher (by a factor of two) at the surface and is lower at the bottom than that in the first group. The third group of profiles comprises the cases when both of the factors w_{bar} and w_{bot} are higher than zero. The absolute values of the current velocities at the surface in this group are higher, and, near the bottom, they differ negligibly from those from the second group. In spite of the difference in the absolute values, the shape of the velocity profile in the top 150 m is similar to that from the other three groups. Between 150 and 300 m, the shapes of the profiles from the second and third

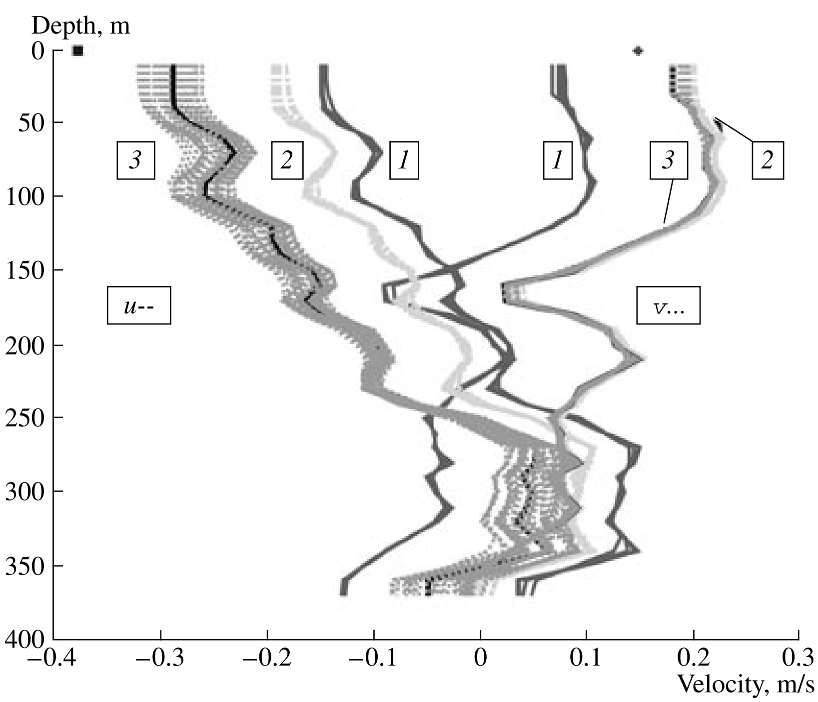

Fig. 1. Vertical profiles of the zonal (u) and meridional (v) current velocity components for 64 variants of the weight factors (w_{sm}, w_{bot}, and w_{bar}) inferred from the data obtained with the LADCP, station 11. The squares and diamonds denote the values of u_s and v_s calculated from the vessel drift using navigation data. The bold lines denote the values of the factors $w_{sm} = 0$, $w_{bot} = 1$, and $w_{bar} = 1$. The numerals inside the squares denote the groups: (*1*) $w_{bot} = 0$, $w_{bar} = 0$; (*2*) $w_{bot} > 0$, $w_{bar} = 0$; (*3*) $w_{bot} > 0$ and $w_{bar} > 0$.

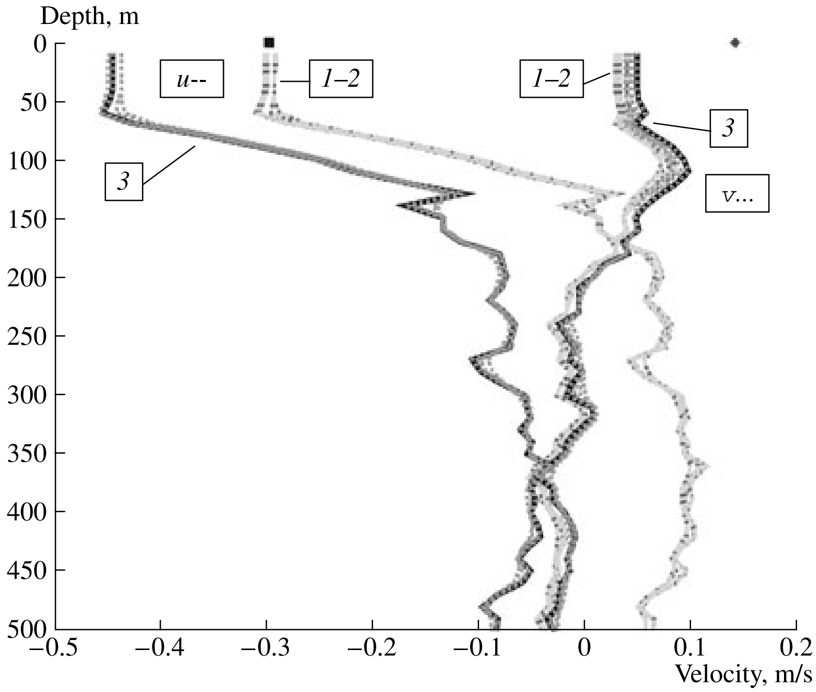

Fig. 2. Vertical profiles of the zonal (u) and meridional (v) current velocity components for 64 variants of the weight factors (w_{sm}, w_{bot}, and w_{bar}) from the LADCP data, station 50. The marks (square and diamond) show the values of u_s and v_s calculated from the vessel drift. The bold lines correspond to $w_{sm} = 0$, $w_{bot} = 1$, $w_{bar} = 1$. The numerals inside the squares denote the groups: (*1*)–(*2*) $w_{bar} = 0$, $w_{bot} \geq 0$; (*3*) $w_{bot} > 0$ and $w_{bar} > 0$.

groups differ negligibly, whereas the velocity value in the first group increases as one approaches the bottom. The meridional component v in groups 2 and 3 is virtually the same.

The values of the calculated velocities at the surface are closest to the value of the vessel drift velocity in the third group. When $w_{bot} = 1$ and $w_{bar} = 1$ (bold lines in Fig. 1), the absolute value of the velocity inferred from the LADCP measurements is 0.34 m/s, whereas the vessel drift gives 0.4 m/s (see table). Thus, the discrepancy of the current velocities is 0.06 m/s in the absolute value and 10° in the direction. A similar situation for the three groups of the velocity current profiles was revealed at stations 8 and 44, where the discrepancies of the velocities at the surface were 0.08 and 0.07 m/s, respectively. The difference in the velocities can be explained in part by the fact that the velocity value closest to the surface obtained with the use of the profiler corresponds to depths of 10–20 m, whereas the vessel draft was much smaller.

Another situation was observed at stations 9, 48, 49, and 50, where the calculated current velocity profiles can be joined only in two groups. Figure 2 shows the current velocity profiles (u and v) for station 50. The measurements at this station, where the bottom depth was more than 1000 m, were carried out down to a level of 476 m under absolutely calm weather conditions. The discreteness of the data record over the vertical was reduced down to 5 m, and the range of the measurement distances below the 100-m level was reduced down to 25 m. All the variants of the calculation of u and v show that the shapes of the vertical profiles are absolutely similar: high values at the surface, a two- or threefold drop of the velocity u in the layer from 70 to 200 m, and uniformly low values below 200–250 m.

The zonal velocity components are grouped into two groups, and only one group exists for the meridional component. The first group includes the profiles for the zero factors w_{bar} and/or w_{bot}. The second group includes the profiles calculated for $w_{bar} > 0$ and $w_{bot} > 0$. A comparison with the appropriate components of the velocity obtained from the data on the vessel drift shows essential deviations from the results of the calculations of v (~0.1 m/s) for both of the groups and good agreement with the results of the calculations of the profiles u ($w_{bar} = 0$, $w_{bot} = 0$) for the first group.

The reason for the formation of a two-cluster structure of the velocity profiles at station 50 is the absence of information on the bottom "movement" with respect to the meter in the file of the raw data due to the fact that the measurements do not reach the levels where the acoustic reflection from the bottom is sufficient for the formation of the "bottom tracking." Therefore, the calculations virtually do not use the module responsible for the calculation of the bottom-tracking factor (w_{bot}).

This experiment shows that the choice of the most optimal parameters for the calculation does not guarantee the obtaining of exact results when sounding far from the bottom. The experiments at station 50 show

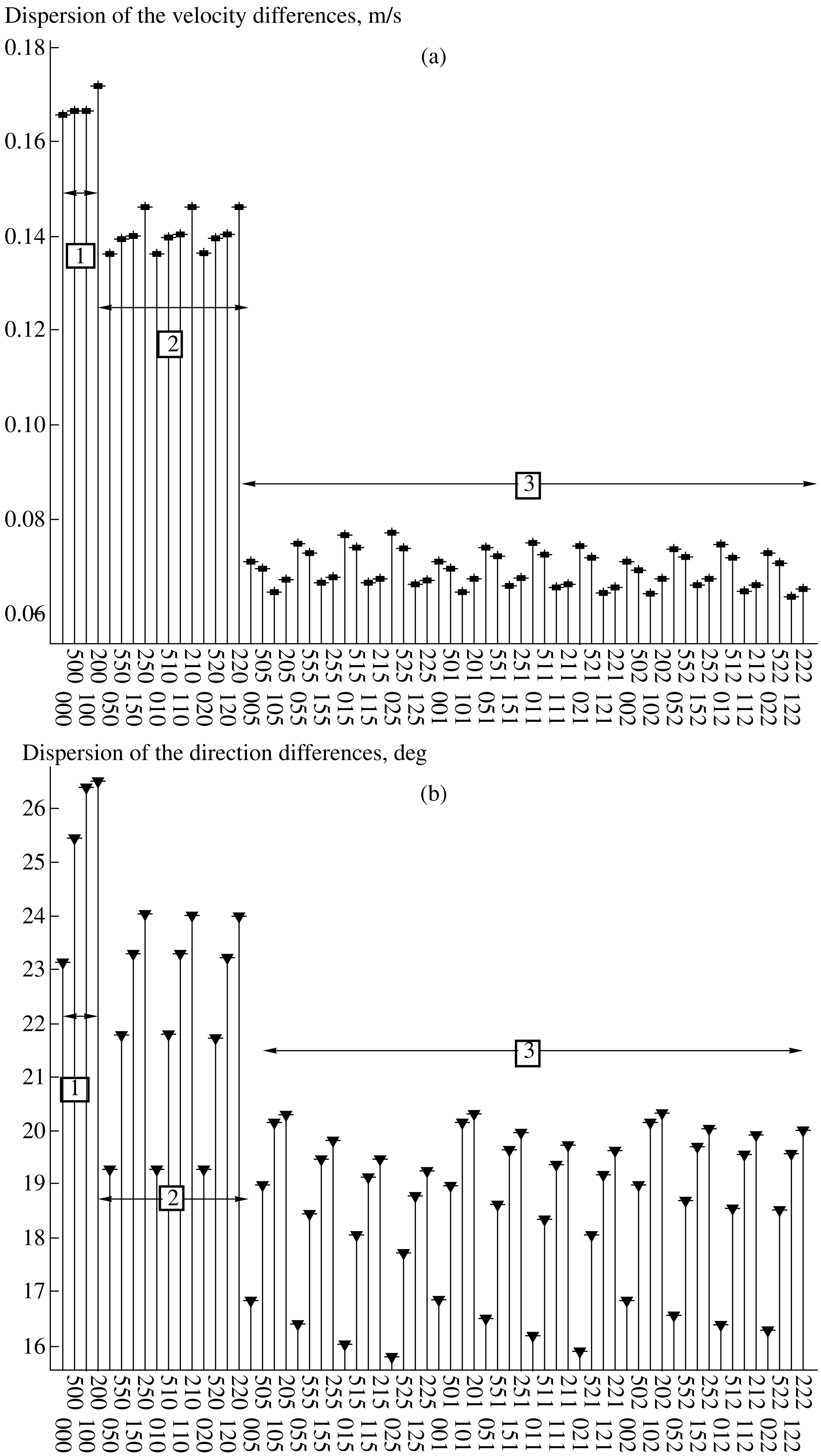

Fig. 3. Dispersion of the difference between (a) the absolute value and (b) the direction of the velocity for 64 variants of the weight factors (w_{sm}, w_{bot}, and w_{bar}) from the data obtained at seven LADCP stations at a level of 0 m and the values of the drift velocity of the vessel at these stations. The indices along the *x*-axis denote the variants of sets of the factors where ‘0’ = 0, ‘5’ =0.5, ‘1’ = 1, and ‘2’ = 2.

that the proper choice of the parameters allows us to obtain satisfactory results only for one of the components of the measured velocity: the value of u (zonal velocity) at the surface is very close to the value of the zonal projection of the vessel drift velocity, u_s, whereas, for the meridional components, v and v_s, the discrepancies are very large (> 0.1 m/s). In addition, the errors in the determination of the direction of the current may be caused by both insufficient depth of sounding for the bottom tracking and, e.g., the effect of the metallic body of the vessel on the magnetic compass of the meter in the near-surface water layers.

We performed the calculation of the differences between the absolute values and directions of the current velocity at the surface (top level) and the absolute values and directions of the vessel drift velocity from the GPS data for all 64 variants of the sets of the values of the weight factors (w_{sm}, w_{bot}, and w_{bar}) for each of seven LADCP stations under consideration. Then, we calculated the dispersions of the differences for each variant. The results are shown in Figs. 3a and 3b.

The plots reveal three groups. The first group comprises the cases when both of the factors w_{bot} and w_{bar} are equal to zero, the dispersion of the differences of the absolute value of the velocity exceeds 16 cm/s, and the dispersion of the direction differences ranges from 23 to 27°.

The second group comprises the cases when the barotropicity factor w_{bar} is equal to zero and other weight factors are positive. The dispersion of the differences of the absolute velocity values ranges from 13 to 15 cm/s, and that of the direction is within 19–24°.

The third group comprises all the other cases, when both of the factors, the bottom-tracking w_{bot} and the barotropicity w_{bar} factors, are not equal to zero, whereas the factor w_{sm} is zero or positive. Here, the deviation of the absolute velocity value obtained with the LADCP from the velocity of the vessel drift at the surface ranges from 6 to 8 cm/s, whereas that of the direction differences ranges from 15 to 21°. The variations of the values of the factors w_{bot} and w_{bar} in the rage from 0.5 to 2 slightly affect the final result. In particular, the differences of the absolute velocity values at the surface and the velocity of the vessel drift for all these cases vary within no more than 1 cm/s, and the values of the differences in the current directions vary within a band of 4°.

The effect of the smoothing factor of the velocity profile w_{sm} on the results of the calculations is minimum for all the series of the calculations. The use of the factor results in a negligible decrease in the peaks and a slight reduction of the velocity profile noisiness.

CONCLUSIONS

The most acceptable cases for the calculation of the current velocities from the data obtained with the LADCP in our experimental set are the cases when the values of the weight factors for taking into account the bottom-tracking effect w_{bot} and the barotropicity w_{bar} are not equal to zero. The specified values of these factors do not essentially affect the results of the calculation. Thus, the following values of the parameters for the Black Sea can be recommended: the bottom-tracking factor w_{bot} = (1–2), the barotropicity factor w_{bar} = (1–2), and the smoothing factor of the velocity profile w_{sm} = 1. The final analysis of our experiments on the processing of the data of measurements showed that the use of the optimal parameters and the sounding with the LADCP from the surface down to small distances from the bottom allows us to obtain an actual profile of the current velocity with an error in the velocity at the surface of 6–8 cm/s and in the direction of 15–21°.

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