

Application and evaluation of layering shear method in LADCP data processing

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Abstract

The current velocity observation of LADCP (Lowered Acoustic Doppler Current Profiler) has the advantages of a large vertical range of observation and high operability compared with traditional current measurement methods, and is being widely used in the field of ocean observation. Shear and inverse methods are now commonly used by the international marine community to process LADCP data and calculate ocean current profiles. The two methods have their advantages and shortcomings. The shear method calculates the value of current shear more accurately, while the accuracy in an absolute value of the current is lower. The inverse method calculates the absolute value of the current velocity more accurately, but the current shear is less accurate. Based on the shear method, this paper proposes a layering shear method to calculate the current velocity profile by “layering averaging”, and proposes corresponding current calculation methods according to the different types of problems in several field observation data from the western Pacific, forming an independent LADCP data processing system. The comparison results have shown that the layering shear method can achieve the same effect as the inverse method in the calculation of the absolute value of current velocity, while retaining the advantages of the shear method in the calculation of a value of the current shear.

Key words: LADCP data processing, layering shear method, Western Pacific

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1 Introduction

The Acoustic Doppler Current Profiler (ADCP) is a kind of current measurement equipment developed in the early 1980s and is widely used in physical oceanography and other related research fields (Flagg and Smith, 1989). The traditional ADCP observation method is based on both mooring observation and shipboard ADCP (SADCP) observation. The mooring observation has the disadvantages of high risk, high cost, difficulty of deployment in rough ocean conditions, and unable to obtain a large-scale current field information. ADCP of shipboard field observation can only be limited to a measurement ship, and the maximum depth of measurement is only 500–800 m, which cannot obtain the vertical current field structure in full water depth. LADCP can provide a complete vertical profile of the ocean current, and it is free to operate with few constraints. The self-contained LADCP is generally loaded on the bottom of the frame of the Conductivity-Temperature-Depth (CTD) measuring instrument, and is lowered with the CTD from the sea surface to near bottom and then lifted to the surface to obtain the current profile

information of the entire water profile while keeping the ship as stable as possible (Xiong et al., 2003).

The first observation experiment of LADCP was conducted by Firing and Gordon (1990) in the sea area near Hawaii. Although the observation error was large, they concluded that the data contained valid information such as current shear values. Fischer and Visbeck (1993) conducted several observation experiments using LADCP in 1990 while cruising in tropical Atlantic Ocean, evaluated the performance of LADCP based on a large amount of test experiment data, and found that LADCP can restore most of the current information by certain methods. They provided a large number of current velocity profiles for the study of ocean circulation (Stramma et al., 1996; Beal and Bryden, 1997; Wilson and Johns, 1997; Wijffels et al., 1998).

Due to the unidirection of the LADCP transducer, the transducer cannot observe the surface layer when it is downward and cannot observe the near-bottom layer when it is upward, so a single LADCP measurement cannot observe both surface and near-bottom currents in a single observation, resulting in an in-

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complete current velocity profile of a water column (Xiong et al., 2006). In recent years, the dual LADCP observation system with simultaneous top-down observations has been widely used, and the LADCP/CTD bundled measurements are supplemented by high-precision GPS positioning and shipboard ADCP to correct the data, constituting a complete LADCP observation system.

At present, there are two main methods for LADCP data processing in the international ocean community: one is the shear method adopted by Fischer (Fischer and Visbeck, 1993) and the other is the inverse method adopted by Martin and Fischer (Fischer and Visbeck, 1993; Visbeck, 2002). The quality of the current velocity data of each layer calculated by using the shear method is theoretically independent of each other, and the reflected current conditions are more realistic. However, the integration of the shear values will make the errors accumulated, and finally the current velocity at the sea surface will differ greatly from the real value. The advantage of the inverse method is that it makes full use of additional information, such as high-precision GPS data and shipboard ADCP data, so that the obtained current velocity profile is closer to the real current field to a greater extent. However, since the principle of the inverse method is to consider the whole current velocity profile as a whole function, too much invalid data will lead to the lack of the whole profile. In addition, the accuracy of the current shear value calculated by the inverse method is slightly lower than that of the shear method, which is obviously unfavorable for obtaining important parameters that depend on the current shear, such as the diapycnal mixing rate.

The “layering shear method” in this paper retains the advantages of the shear method. That is, the current shear values obtained by LADCP are preserved as much as possible while restoring the full water depth current field. The absolute values of the current velocity are quality-controlled by the “layering averaging” method, so that errors are always not cumulated. Therefore, the “layering shear method” not only has the theoretical advantage of accurate calculation of current shear values by the shear method, but also has the advantage of accurate calculation of the absolute value by the inverse method. In addition, since ADCP has less effective data when observing a region with low echo in deep ocean, this paper proposes a further optimization of LADCP data post-processing.

2 LADCP observation and data

The data were obtained from LADCP observation experiments conducted during field observations in the western Pacific Ocean (12°–16°N, 154°–158°E) from 2014 to 2017. The two RDI 300 kHz self-contained ADCPs were bundled on a CTD frame with a transducer up and down. The ADCP has the measured layer thickness of 8 m (the first layer is 10 m) with 15 layers in total. It transmits sound waves and receives echo signals every second, and records them. In addition, the raw data also include the rolling, pitching, heading, echo amplitude (*EA*), horizontal velocity (*u*, *v*) and vertical velocity (*w*) of the instrument in water. The data quality of each profile observation was judged, and abnormal data (shear velocity >1.5 m/s) were rejected. The threshold value of the dip angle (a pitch was a longitudinal rocking angle and roll was a transverse rocking angle) of the LADCP was set to 18°, and the data larger than this range were rejected. The error of the first layer current velocity of LADCP was often large, so it was excluded (Visbeck, 2002; Komaki and Kawabe, 2007). Since there are few effective data after the fifth layer observed in the deep water, and considering that there is a large amount of data observed every second that overlaps with the data observed in the previous second in depth, we only select the observation data within

the fifth layer.

The observations were mainly concentrated on two areas in the Magellanic seamount, the Caiwei Guyot (denoted as MA) and its nearby seamounts (denoted as MC). Three LADCP observations were made near each seamount. The six observations were denoted as MA001, MA002, MA003, MC001, MC002 and MC003, respectively (Fig. 1).

In addition, this paper also uses the data of the current real-time global forecasting CMEMS system (<https://doi.org/10.48670/moi-00021>). The model component is the NEMO platform driven at surface by ECMWF ERA-Interim then ERA5 reanalyses for recent years. Observations are assimilated by means of a reduced-order Kalman filter. Along track altimeter data (sea level anomaly), satellite sea surface temperature, sea ice concentration and *in situ* temperature and salinity vertical profiles are jointly assimilated. Moreover, a 3D-VAR scheme provides a correction for the slowly-evolving large-scale biases in temperature and salinity. This data is used to validate the current velocity profiles calculated by different methods. Since it is the daily average forecast data, it can only be used as a reference.

3 Calculation method of flow velocity profile

3.1 Principle of LADCP observation

During the lowering and lifting processes of the LADCP, the corresponding current velocity profile is measured. The adjacent profiles are overlapped, which is called overlapping data because it resembles the iteration of roof tiles. The LADCP gets one relative current velocity profile for each operation. A series of overlapping relative profiles are recorded in one observation process. As shown in Fig. 2, the thick black line represents the lowering and lifting processes of LADCP, during which ADCP releases a signal (black dots on the thick black line) every certain time. The current velocity profile in a certain depth range below it is obtained according to the reflected signal strength and Doppler effect. An overlapping part of the current velocity profile is measured between two adjacent released signals. Although ship displacement and instrument sway can produce significant errors in the measurement of full-profile current velocity, the time to measure a single profile is only 0.1–0.3 s. The current shear velocity between water layers can be considered to be approximately constant during one measurement.

3.2 Inverse method

Martin developed an inverse method for calculating current profiles (Visbeck, 2002) and a corresponding matlab software package. His idea was to express the LADCP data post-processing in the form of a linear equation set, which was then solved by the least square method. An example is illustrated as follows.

The ADCP is lowered to the sea bottom at a uniform speed, and then raised to the sea surface at the same speed. It is assumed that the instrument observes *n* layers at a time. Each layer thickness is L_{bin} , and the water depth is *m* times as much as the layer thickness. That is, the unknown current velocity is divided into *m* layers. The layer interval and the layer thickness of ADCP are the same ($R_{res} = 1$). If one thickness of layer is devolved in the adjacent observation time interval, the ADCP is carried out for a total of $nt = 2 \times m$ observations, and $2 \times m \times n$ observation values are obtained. If $2 \times n$ observations below the bottom observation range are excluded, there are $d = 2 \times m \times n - 2 \times n$ effective observation

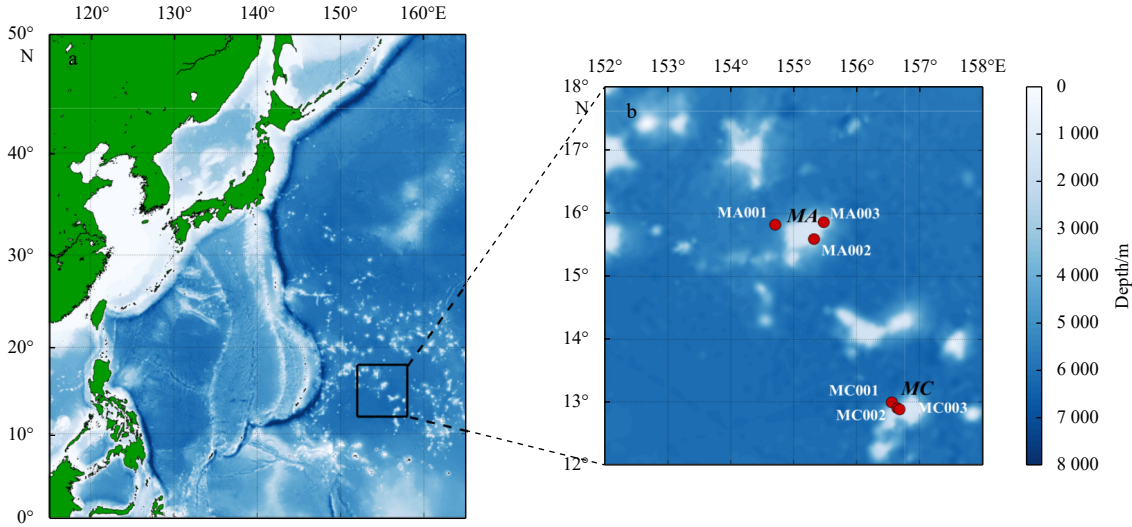


Fig. 1. Topography and station location in western Pacific Ocean. Red dots denote the six observation stations.

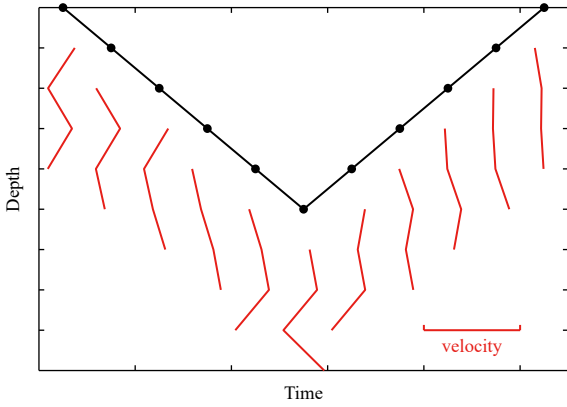


Fig. 2. Schematic diagram of the LADCP overlapping profile.

values. Since the difference in the current velocity between the n layers observed at one time is known, there are $M = nt + m$ unknown numbers. d and M can be expressed as Eq. (1) and Eq. (2):

$$d = [u_{1,1}, u_{1,2}, \dots, u_{1,n}, u_{2,1}, \dots, u_{2 \times m, n}]^T, \quad (1)$$

$$M = [u_{CTD,1}, u_{CTD,2}, \dots, u_{CTD,2 \times m}, u_{ocean,1}, u_{ocean,2}, \dots, u_{ocean,m}]^T. \quad (2)$$

The velocity observation of LADCP can be taken as the sum of three components (Visbeck, 2002):

$$U_{ADCP} = U_{ocean} + U_{CTD} + U_{noise}, \quad (3)$$

where U_{CTD} is the velocity of the motion of the ADCP mounted on the CTD frame. U_{ocean} represents the unknown real current velocity field, which is usually taken as a constant at each layer. The perturbation variation superimposed on it is represented by U_{noise} . U_{ADCP} is the observed data of ADCP.

In the inverse method, the above equation can be rewritten as a linear equation set of the following form:

$$d = GM + N, \quad (4)$$

where N denotes the random and systematic errors; G is the model matrix with the following expressions (here, $n = 3$ is assumed):

$$G = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 1 & 0 & 0 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 & 1 & 0 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 & 0 & 1 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 & 0 & 1 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 1 & \dots & 0 & 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 & 0 & 0 & 1 & \dots & 0 \end{bmatrix}. \quad (5)$$

The solution of the linear equation set can be constrained by inputting additional information (e.g., GPS data), which in turn obtains the entire current profile. Visbeck (2002) stated that the equation set had a solution if a ratio (F) of known to unknown quantities was greater than 1. It can be inferred from this that the observation accuracy is related to the number of layers in a vertical direction. That is, the slower the lowering speed of the LADCP, the more accurate the observation. However, due to the limitation of ship time, the lowering speed of LADCP should be controlled reasonably.

3.3 Shear method

The relative current velocity profile can be calculated directly from the raw data.

The current velocity of the j -th water layer (n layers in total) of the profile obtained by the i -th acoustic emission is U_{ij} . If the thickness of the water layer between two adjacent observation values on the same profile is b , the current shear velocity within the profile is S_{ij} :

$$S_{ij} = \frac{U_{i,j+1} - U_{ij}}{b}, \quad 1 \leq j \leq n - 1. \quad (6)$$

Based on the time and the pressure data recorded by CTD, the position Z_i of ADCP at the time of the i -th acoustic emission can be obtained.

The position $Z_{i,j}$ of the j -th water layer is defined by Eq. (7):

$$Z_{i,j} = Z_i + b_j. \quad (7)$$

Since the velocity profile observed by LADCP each time overlaps with the depth observed at the previous time in a certain range, $S_{i,j}$ should be arranged from surface to bottom according to its corresponding depth $Z_{i,j}$ to obtain the whole water column current shear value $S(z)$ and the corresponding water depth Z of the n_z -th layer. When the sound wave emitted by ADCP reaches the bottom of sea, the stronger echo signal will be obtained. The real near-bottom velocity (the observed data here is commonly referred to as “bottom tracking” data) can be obtained from the relative velocity of the near-bottom current and the sea bottom. The current shear velocity of each layer of seawater will be vertically integrated (U_{bc}) and then superimposed on the reference velocity U_{ref} (“bottom tracking” data) to finally obtain the current velocity profile of the entire water column by the following equations:

$$U_{bc}(z) = \sum_{i=1}^{n_z} S(i), \quad (8)$$

$$U = U_{bc} + U_{ref}. \quad (9)$$

3.4 Layering shear method

For the layering shear method, the reference velocity U_{ref} can be obtained from the GPS data or bottom tracking data (if it is to calculate the bottom layer), record the errors caused by changes in the working ship position during the observation. The entire water depth will be divided into N layers with a B_k thickness (N is different from n). The effective data of the current velocity of each layer is subtracted from the U_{ref} of the corresponding depth and then averaged. Then, the current shear values are superimposed on average velocities of the corresponding layers after integration. As long as the layer thickness B_k is reasonably adjusted, a more accurate current velocity profile can be obtained. Let n_k be the number of points for averaging the current velocity in the k -th layer. The average current velocity U_k in the k -th layer is calculated by Eq. (10):

$$U_k = \frac{1}{n_k} \sum (U_{i,j} - U_{ref}), \quad \sum_{i=1}^k B_k(i) < Z_{i,j} < \sum_{i=1}^{k+1} B_k(i). \quad (10)$$

It is assumed that S_k is the current shear velocity in the k -th layer:

$$S_k(z) = \sum S(n_z), \quad \sum_{i=1}^k n_k(i) < n_z < \sum_{i=1}^{k+1} n_k(i). \quad (11)$$

The final absolute current velocity profile U can be obtained by superimposing the current shear velocity on the average current velocity of each layer:

$$U = U_k + S_k. \quad (12)$$

The calculation of the current shear velocity $S_{i,j}$ of the layering shear method is similar to the shear method. The difference between the two is as follows: for the shear method, after the current shear velocity is calculated, the bottom tracking data from

the bottom are integrated to the sea surface, and the errors may be accumulated at the surface. However, for the layering shear method, the current shear velocity of each layer is superimposed on the average current velocity of the corresponding layer, which circumvents the shortcomings of the shear method.

According to this method, a LADCP data processing system was built independently. The lowering process of LADCP was compared with the lifting process. The information of the process of observation depth changed with time and the position of the ship during the observation was provided, as shown in Fig. 3.

4 Comparison between the layering shear method and the traditional method

4.1 Comparison of the layering shear method and the shear method

The advantage of the traditional shear method for the calculation of the current velocity profile is that the current shear value obtained is more accurate, but the absolute velocity of each layer of seawater will accumulate large errors as a distance from the sea bottom or the sea surface increases.

The layering shear method in this paper is similar to the traditional shear method in principle. However, the concept of “layering averaging” is added, aiming to improve the accuracy of the calculation of the absolute value of the current velocity in each layer. Figure 4 shows the comparison between the traditional shear method and the layering shear method in three random tests. It is assumed that ADCP is descended at a uniform speed of 1 m/s. A total of 50 observations are made from surface to bottom. Five current velocity measurements are obtained for each observation, with a distance of 1 m between the measurements. The layer thickness $B_k = 25$ m is set in the layering shear method. The gray dashed line in the figure is a computer-generated sequence of random numbers between -1 m/s and 1 m/s to simulate the real current velocity profile in ocean. The individual scattered gray solid lines represent the current velocity values observed by LADCP during a descent process. Their absolute values have an error of ± 5 m/s from the real current velocity (gray dashed lines). The current shear values obtained by LADCP at the same observation time are more accurate, but also have an error of ± 1 m/s. The current velocity closest to the bottom has an accurate value, indicating that the bottom tracking data are used. For a more visualization in the figure, the values of the remaining variables, except for the real current velocity profile (gray dashed lines), are enlarged appropriately. Figure 5 indicates the absolute values of the deviation of the results obtained according to the two methods and the real current velocity profile.

As can be seen in Figs 4 and 5, the results of the traditional shear method in the near-bottom layer perform excellently and are still fitted with the real current velocity profile from the bottom up in these three simulations usually until near 40 m. However, the errors in the absolute values of the current velocity become cumulatively larger with small errors in the current shear value obtained by ADCP each time, and are more obvious in the upper layers. In real ocean conditions, the depth of seawater is usually much larger than the bin value of ADCP (i.e., a distance between observation values in one ADCP observation). The number of errors is much larger than that in simulations, so the errors of the traditional shear method cannot be ignored.

The layering shear method reduces the errors in the absolute value of current velocity in the traditional shear method by “layering averaging”. As can be seen in Fig. 5, although there are some errors in this method, the errors are not accumulated with

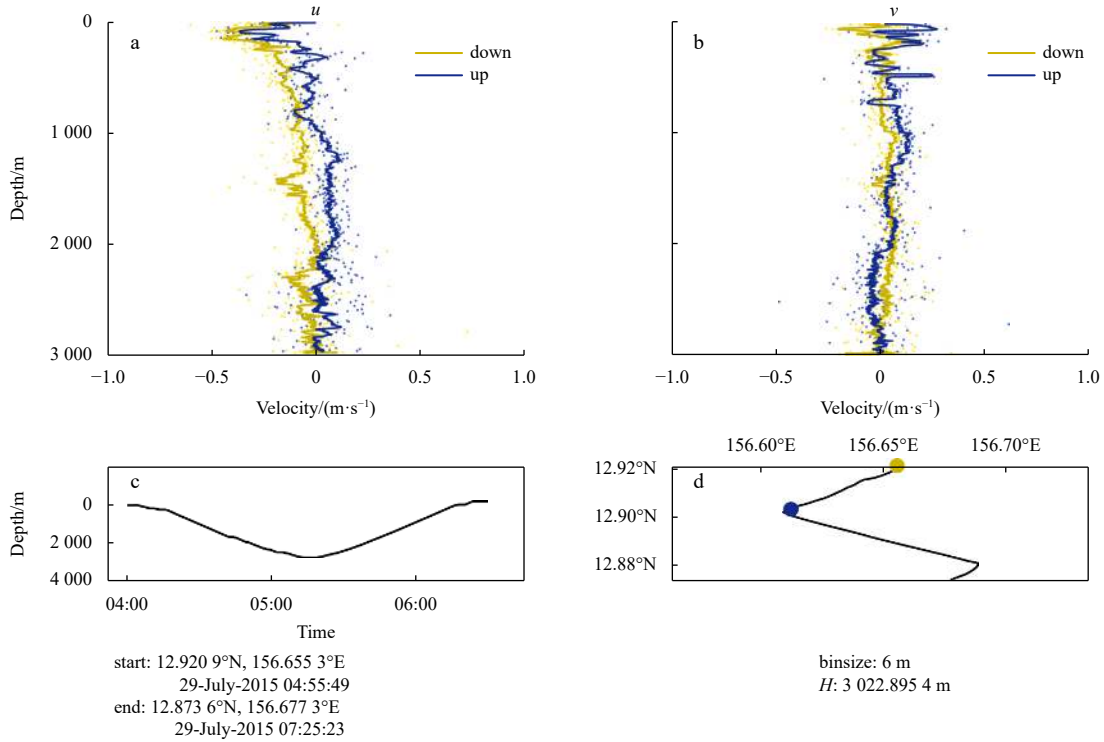


Fig. 3. Processing results of LADCP data. a. The results of the inversion of the eastern component of the current velocity, where yellow represents the calculated results of an instrument during a descent process, and blue represents the calculated results of the instrument during an ascent process; b. the results of the inversion of the northern component of the current velocity; c. the time series of the water depth of the instrument obtained by integrating the vertical velocity; d. the ship displacement during the observation process. Yellow dot: initial position; Blue dot: the maximum depth position.

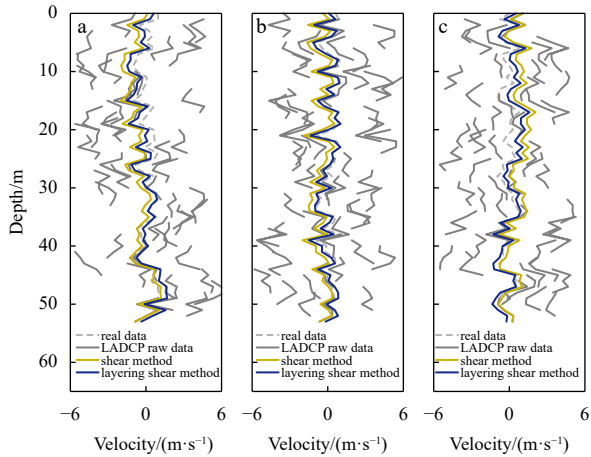


Fig. 4. Comparison diagram of simulation results between shear method and layering shear method.

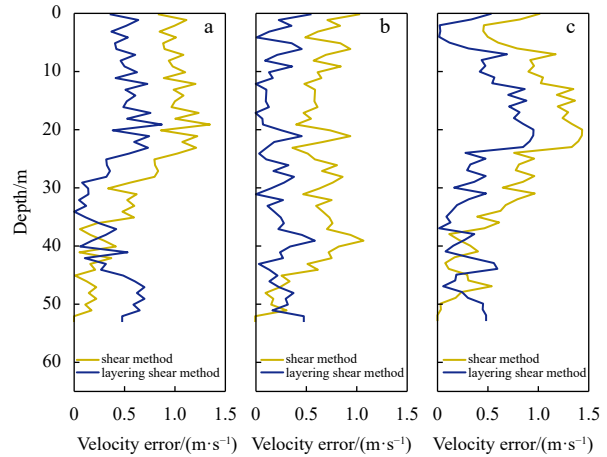


Fig. 5. Error comparison of real current velocity and current velocities calculated by shear method and layering shear method.

depth. That is, the errors between layers are not correlated with each other. In the three random tests, the average of the absolute value of the errors of the shear method and layering shear method are shown in Table 1. If we judge the accuracy of the calculation of the absolute value of the current velocity according to the size of the average value of these errors, then obviously the result of the layering shear method is better. The calculation of the near-bottom currents in the simulation does not use the bottom tracking data as the exact values. However, in practice, calculation can be conducted with the traditional shear method in the near-bottom layer under the premise of bottom tracking data in

Table 1. Average of the absolute value of the error of the current velocity in the whole depth calculated by the shear method ($\epsilon u1$) and layering shear method ($\epsilon u2$)

| Test | $\epsilon u1/(\text{m}\cdot\text{s}^{-1})$ | $\epsilon u2/(\text{m}\cdot\text{s}^{-1})$ |
|--------|--|--|
| Test 1 | 0.66 | 0.43 |
| Test 2 | 0.61 | 0.23 |
| Test 3 | 0.72 | 0.42 |

actual operations, which will greatly improve the calculation accuracy of the layering shear method.

4.2 Comparison of layering shear method and inverse method

Compared with the shear method, the inverse method has the improved calculation of the absolute value of the current velocity, but the calculation of the current shear velocity is poorer. This is unfavorable for high-precision ocean vertical mixing and other related studies. It is assumed that the relevant settings of LADCP in the three simulations are the same as the shear method above.

In Figs 6 and 7, the inverse method shows a better fitting in all layers without the accumulation of errors in the traditional shear method. However, the current shear velocity calculated by the inverse method differ from the actual ones, as shown by the low smoothness of the error values of the inverse method in Fig. 7. The mean values of the errors of the inverse method and the layering shear method in three random tests are shown in Table 2. If

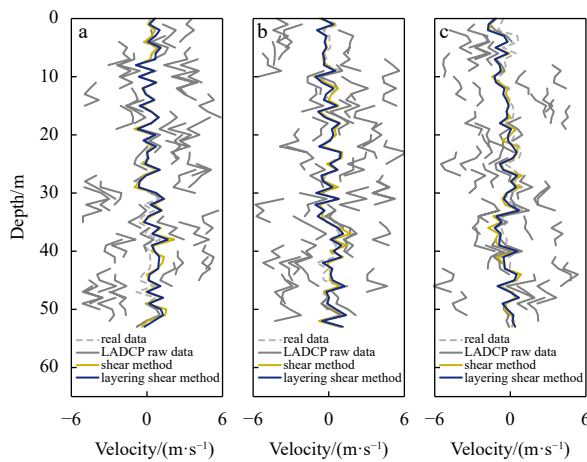


Fig. 6. Comparison diagram of simulation results between inverse method and layering shear method.

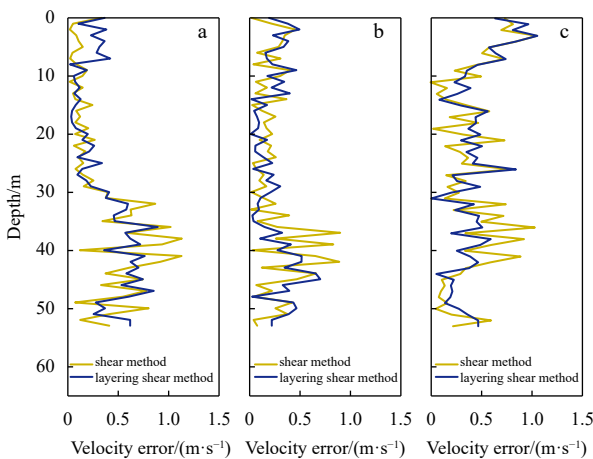


Fig. 7. Error comparison of real current velocity and current velocities calculated by inverse method and layering shear method.

Table 2. Average of the absolute value of the error and the standard deviation of the error of the current velocity in the whole depth calculated by the inverse method ($\varepsilon u1$, $\text{dev}1$) and layering shear method ($\varepsilon u2$, $\text{dev}2$)

| Test | $\varepsilon u1/(\text{m}\cdot\text{s}^{-1})$ | $\varepsilon u2/(\text{m}\cdot\text{s}^{-1})$ | $\text{dev}1/(\text{m}\cdot\text{s}^{-1})$ | $\text{dev}2/(\text{m}\cdot\text{s}^{-1})$ |
|--------|---|---|--|--|
| Test 1 | 0.32 | 0.33 | 0.32 | 0.24 |
| Test 2 | 0.24 | 0.23 | 0.22 | 0.16 |
| Test 3 | 0.42 | 0.41 | 0.28 | 0.19 |

the standard deviation of error is used to indicate how accurate the current shear value calculation is, then we can clearly see the difference between the two methods. Although the results obtained by the layering shear method do not differ much from the inverse method in terms of the errors of the real current velocity profile, the calculation of the current shear velocity inherits the accuracy of the traditional shear method. Therefore, the layering shear method takes into account the calculation of the two key elements of the absolute current velocity and the current shear velocity, which makes up for the problems that have been existing in the post-processing of LADCP.

5 Optimization of flow velocity profile calculation

The principle and advantages of the layering shear method are briefly compared and analyzed by ideal experiments above. In order to obtain better current calculation results, the preliminarily processing results obtained after the above steps can still be optimized in the following aspects. In practice, several of these optimization options can be selected for the current velocity profiles until the profiles calculated during descent and ascent processes of LADCP are fitted better.

5.1 Optimization of layering thickness

The reasonable division of the profile thickness (B_k) for calculating the average current velocity of each layer is a key step in the layering shear method. If the layer thickness is too small, and the number of samples for calculating the average current velocity of the layer is too small, there will be a large error between the calculated average value and the real value. If the layer thickness is too large, there will be a problem similar to that of the traditional shear method: the error will be accumulated as the layer thickness increases, and the current velocity between two layers will have a large shear value that does not conform to common sense. Usually, the near-surface seawater has more suspended particulate matters, high echo rate, abundant valid data and greater data confidence. However, due to the large current velocity and strong current shear, LADCP is extremely unstable in the up-and-down moving process (shown as a large change in a dip angle with a depth). Therefore, B_k can be reduced appropriately. With the decreased current velocity and the reduced shear in a deep-sea region, the LADCP moving process is more stable. However, because the scattering intensity is smaller, the echo rate is lower, and the effective data are reduced. Therefore, the B_k can be increased appropriately. However, this may not be the case in the actual marine environment. In order to divide the layer thickness more reasonably, this paper adopts a way to divide the layer thickness based on the proportion of effective data in a certain depth range and the dip angle of ADCP.

Taking Station MC001 as an example, the following shows the way to divide the layer thickness by a change rate of a dip angle with a depth recorded by ADCP. The change rate of the dip angle of the instrument with a depth can be expressed as: $d\text{tilt}/dz$. The change rate of a dip angle with a depth during the ascent process of LADCP at this station is shown in Fig. 8. In a range of 0–200 m of a water depth, the change rate of the dip angle with the depth is larger near the ocean surface, near a region with a water depth of 75 m, and near a region with a water depth of 150 m, indicating that the current shear at these depths may be larger or the cable is under greater tension, which requires subdividing the layer thickness. Therefore, the following division of the layer thickness in this range is taken: $B_1 = B_2 = 10$ m, $B_3 = 40$ m, $B_4 = B_5 = B_6 = 10$ m, $B_7 = 30$ m, $B_8 = B_9 = B_{10} = B_{11} = 10$ m, $B_{12} = 40$ m. In practice, the program can be set to determine the change rate of

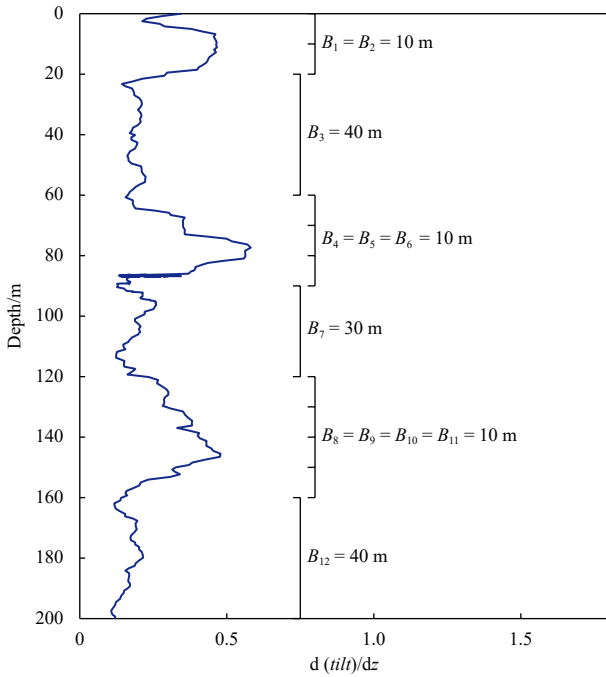


Fig. 8. Schematic diagram of layer thickness division in layering shear method.

the dip angle of LADCP with a depth for a certain depth range. The program automatically divides the layer thickness B_k . Such a layer thickness division can replace the empirical division of a dense upper layer and a sparse lower layer, and the problem of layer thickness selection is solved in a quantitative way.

Also taking the measured LADCP data at this station as an example, two different stratification methods for the same LADCP data are compared. The first stratification method approach follows the above principles. That is, stratification is performed by calculating the rate of change of a dip angle with a depth, and the minimum layer thickness is not less than 10 m. The second stratification method is as follows: if the depth is less than 500 m, $B_k = 50$ m; if it is between 500–1 500 m, $B_k = 200$ m; if it is between 1 500–2 900 m, $B_k = 500$ m, and if it is between 2 900–3 031 m, $B_k = 25$ m. As can be seen in Fig. 9, generally speaking, both methods provide more ideal current velocity profiles, without major discrepancies, except for the second stratification, which results in some “step” faults due to too large B_k of the deeper layers. However, if a region with a water depth of 0–500 m is zoomed in Fig. 9 (Fig. 10), the difference between the two stratification methods becomes evident. Figure 10 shows that the current velocity changes sharply in a region with water depth of above 500 m. In response to this change, the finer stratification is more conducive to reflecting the real current velocity profile. In the first strat-

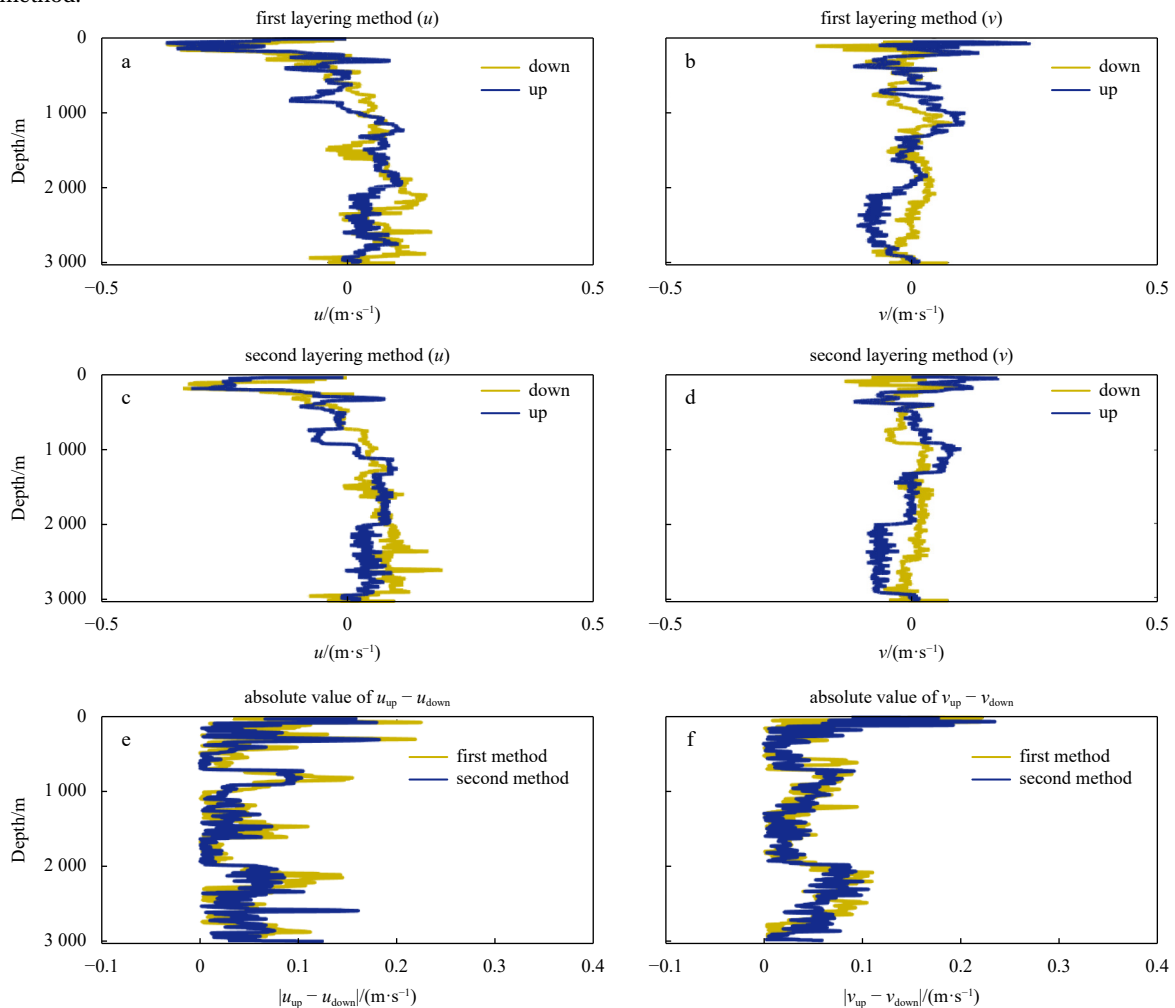


Fig. 9. Current velocity profiles obtained with different values B_k (a–d) and the difference in current velocity calculated during the lowering and lifting processes (e, f).

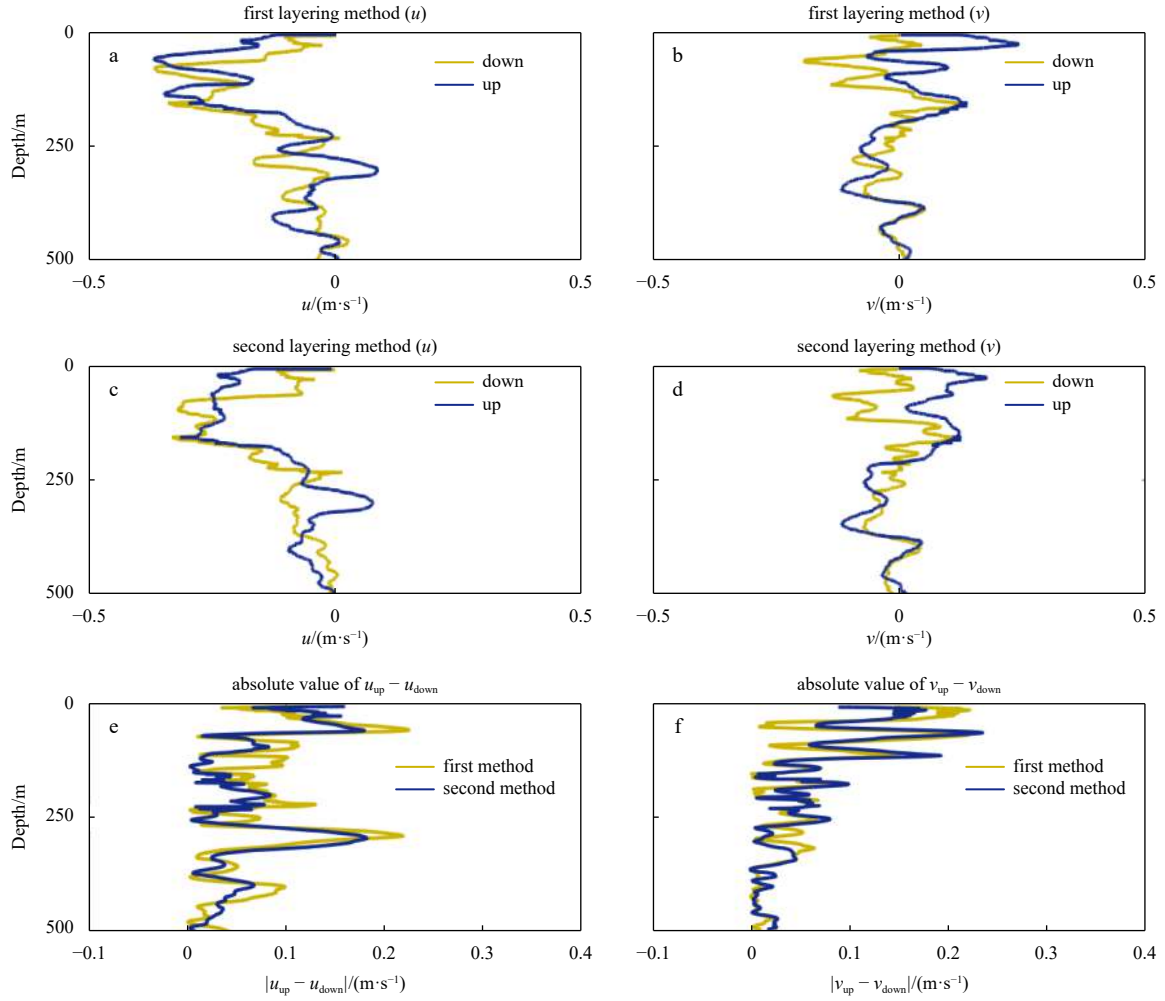


Fig. 10. Current velocity profiles obtained with different values B_k (a–d) and the difference in current velocity calculated during the lowering and lifting processes (e, f) (0–500 m).

ification method, the current velocity profiles measured by the lowering and lifting processes have a very similar structure. Usually, it is assumed that the change in the current field during one observation is very small. Therefore, the current velocity profile of the first stratification method has a larger degree of reduction. Although the current velocity profile calculated by the second stratification method ($B_k = 50$ m) can provide the approximate change of the current velocity, the current velocity calculated at individual depths during the lowering and lifting processes is somewhat different. We evaluated both stratification methods by averaging the difference in current velocity calculated during the lowering and lifting processes of LADCP: the value of the first stratification method is about 0.04 m/s in the u component, and the second is 0.06 m/s; the value of the first stratification method in the v component is 0.05 m/s, and the second is 0.06 m/s. The accuracy of the second stratification method can be inferred to be lower than that of the first stratification method.

5.2 Optimization of shear values between adjacent layers

Since the calculation of the current velocity profiles between layers do not interfere with each other, the current shear values between adjacent layers may show abrupt changes from the measured ones when the proportion of limited data is low or when the strong current has a large influence on ADCP. Usually, such abrupt changes can be reduced by reducing the layer thick-

ness and adding one or more layers in the corresponding depth range. But according to the previous section, the layer thickness shall not be too small. The following smoothing approach is adopted in this paper when it is not appropriate to continue subdividing the layers.

With the current velocity U_a of the upper layer at the middle point of the thickness where the sudden change in current shear velocity occurs, and the current velocity U_b of the lower layer at the middle point of the thickness, there are n current velocity values and $n + 1$ current shear values between the two points (excluding these two points). If $U_a > U_b$, the k -th current velocity value needs to be subtracted from $(U_a - U_b) \cdot k / (n + 1)$ starting from the next current velocity value of U_a . If $U_a < U_b$, the k -th current velocity value needs to be added to $(U_a - U_b) \cdot k / (n + 1)$ starting from the next current velocity value of U_a . A comparison of the current velocity profile before and after adjustment is shown in Fig. 11. The figure shows that this method takes into account the absolute value of the current velocity and the accuracy of the value of the current shear velocity. The illogical strong current shear between two layers is reasonably smoothed by this method.

5.3 Optimization of calculation of LADCP depth

There are usually two methods to estimate the depth where LADCP is located at present: one is obtained by integrating the vertical velocity w recorded by ADCP, and the other is to use CTD

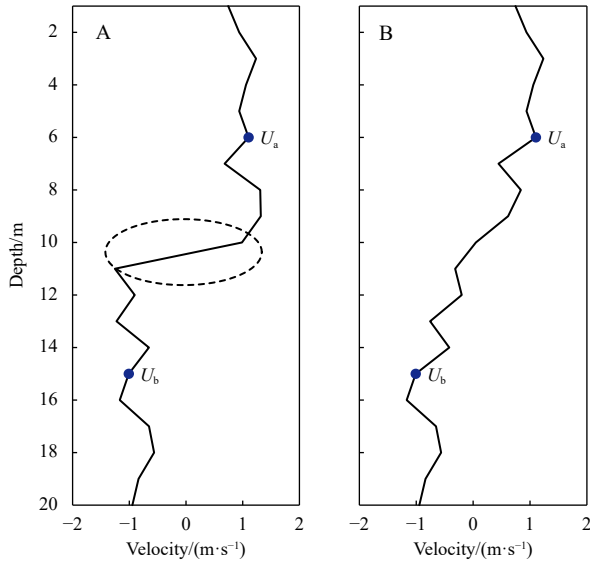


Fig. 11. Schematic diagram of optimization method for anomalous strong current shear between two layers. A. Before optimization (the dashed line range is the abnormally strong current shear between two layers); B. after optimization.

to observe the depth at the same time. However, after integrating the vertical velocity w in a large amount of LADCP data, it is found that it is difficult to maintain a good uniform speed when LADCP is lowered. A large amount of observation data will be lost in deeper water layers due to the reduction of scatterers. The first method is sure to cause errors in the calculation of depth. The method in this paper is to use the CTD depth calculated by the seawater software package to obtain the depth at which the LADCP is located at the same time. Due to the problems of unsynchronized time of CTD and LADCP and possible data loss of CTD, the time of maximum vertical integration of the vertical velocity w of LADCP is calibrated with the time of CTD located at the deepest depth. The depth obtained by CTD is interpolated to the time recorded by LADCP, so that the depth and the current velocity can correspond each other by one to one. Taking Station MA001 as an example, comparing the vertical integration results of the vertical velocity w with the observed depth of CTD, it can be seen (Fig. 12) that the current velocity w is not integrated to the maximum depth because more data are lost in the deeper water. The final integration deviates from the sea surface by nearly 800 m. Therefore, this paper adopts the second method to calculate the depth corresponding to the current velocity.

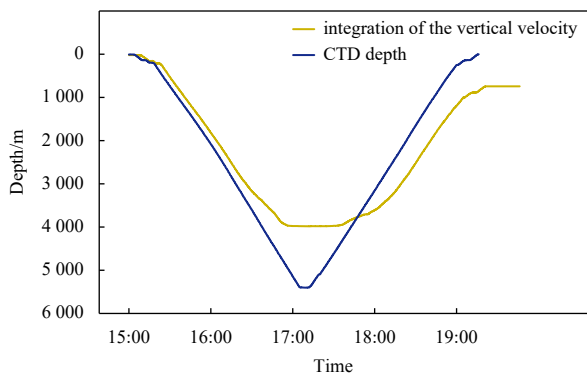


Fig. 12. Comparison of two depth acquisition methods.

5.4 Optimization of calculation of reference velocity

The determination of the reference current velocity requires additional information from the LADCP observation system, such as bottom tracking data or GPS information. The principle of a bottom tracking method to determine the reference current velocity is to consider the near-bottom current velocity as the movement speed of the sea bottom relative to the LADCP. The widely used method of GPS is to determine the reference current velocity based on a distance between LADCP start and end position divided by the time of the whole process. However, in the actual situation, the movement of the ship on the sea surface is not linear and uniform (Fig. 13, Stations MC001 and MC002). The movement of the ship in the upper figure appears an included angle, while the ship in the lower figure drifts a longer distance in the latter half of the time. This poses a difficulty for the determination of the reference current velocity. Xiong et al. (2003) pointed out that the most direct method was to apply the GPS positioning information directly to the LADCP observation system. However, this method was eventually discarded because GPS could not achieve the required accuracy and there was also relative motion between a GPS signal receiver and the LADCP.

In view of the above two reasons, in this paper, the reference current velocity is calculated in segments after the quality of GPS positioning data is controlled, and then the reference current velocity of each segment is superimposed on the LADCP observation system for the same time period. This is compared with the traditional method of using GPS positioning information (Fig. 14 uses the observation data of Station MC001, corresponding to the

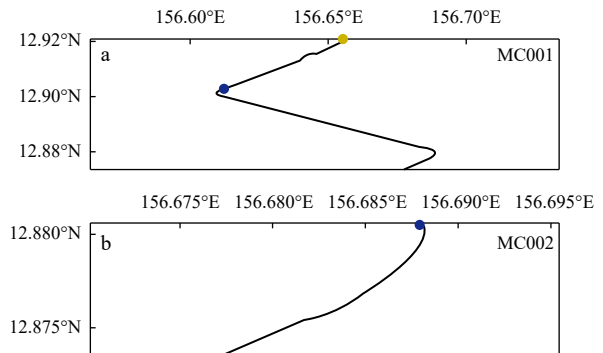


Fig. 13. Movement of the ship during observation period of MC001 and MC002. Yellow dot: initial position; blue dot: the maximum depth position.

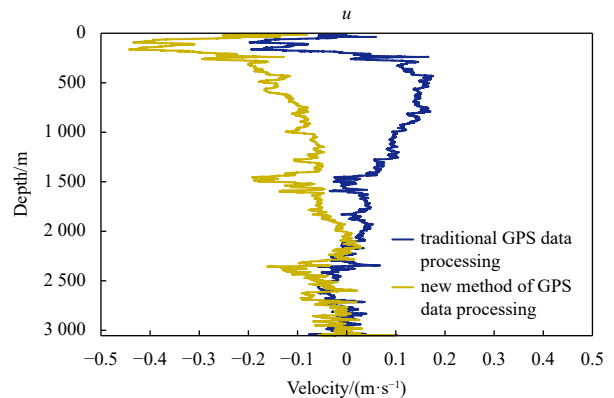


Fig. 14. Current velocity profiles obtained by two GPS processing methods.

ascent process of LADCP in the upper part of Fig. 13). It can be seen that a better current velocity profile can also be obtained using GPS positioning data with segmentation and quality control. The overall trends are relatively similar between the two methods, but there are large differences in a region with a water depth of above 1 300 m, which is most likely due to the large errors in the traditional GPS positioning data when the observation ship moves non-linearly.

5.5 Optimization of calculation of current velocity of water layer with low echo rate

Xiong et al. (2006) pointed out that optimizing the setting value of the LADCP blind zone length according to the size of the lowering speed and the length of the sampling interval can significantly improve the information quality of the first observation layer. However, in the deeper layers of the deep ocean, the seawater becomes more “clear” and the scatterers are greatly reduced, making the echoes less intense. In some deeper waters, an ADCP transducer can only receive one echo signal for a single observation, while at least two echo signals are needed to calculate the current shear velocity. This makes the effective data for calculating the current velocity profile reduced, and sometimes about 1/2 of the data cannot be used. In the deeper water layer, the seawater current velocity itself is smaller and the current shear is weaker. Therefore, the data processing method different from the upper seawater can be used to calculate the current velocity of the water layer with a low echo rate and improve the efficiency of using the data.

It is assumed that a region with a water depth of 1 000 m and below and above the sea bottom is the “layers with low echo rate”, the number of valid data obtained in one observation of the transducer in the water layer above 1 000 m is first determined. If there are less than two valid data, this observation will be excluded. If there is less than one valid data for the water layer below 1 000 m, the data will be excluded. If most of the “water layers with a low echo rate” has only one valid data, “layers with low echo rate” can first be divided into several water layers D_k according to certain methods. The average value of all the current velocities in each D_k is calculated. Each observed current velocity is added to the relative current velocity calculated by GPS at the same time, which is used to replace the current velocity of this layer. Since the current velocity and the current shear value of the deeper water layer are smaller, as long as the D_k is reasonably divided, the current velocity can be effectively calculated, which greatly improves the efficiency of using LADCP data.

Taking Station MA001 as an example (Fig. 15), if at least two

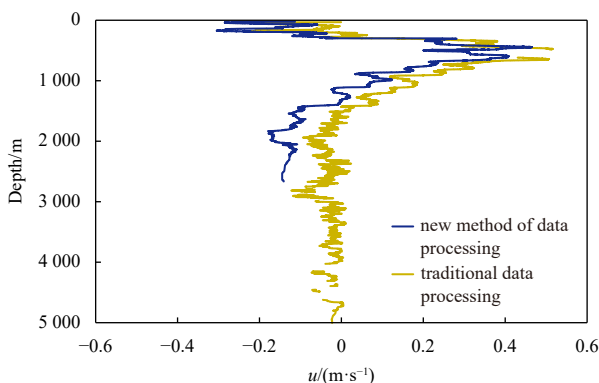


Fig. 15. Method improved to obtain water layer velocity profile with low echo rate.

valid data are required to be obtained from one observation of the transducer, the data of a region with a water depth below 2 700 m cannot be used. After using the improved method, the maximum depth at which the current velocity can be calculated exceeds 5 000 m, and the obtained deep seawater current velocity is same as the empirical one, indicating that the method is desirable to some extent (there is zero valid observation data at a breakage). A more accurate calculation method needs to be further researched.

5.6 Vertical filtering method to reduce effect of cable traction

When LADCP is used to observe the velocity profile of seawater, the observation errors caused by the traction of a cable is the most difficult to eliminate. If only the force from the cable, the gravity and the buoyancy of the instrument are considered, there will be a periodic oscillation of the ADCP during its lowering and lifting processes, resulting in the observed current velocity including the periodic speed signals. This periodic signals can be hidden in the actual flow velocity and a drift speed of the ship. After the GPS data is used to correct the ship position, the effect of the cable traction on the observation of the current velocity can be further reduced significantly by vertical filtering.

Firstly, the average of the current velocity data in layers 2–5 obtained from each observation of ADCP is taken and arranged as a one-dimensional array from an ocean surface to bottom. It is assumed that the period of ADCP oscillation is between 3 s and 40 s under the influence of the cable traction. Since the period of ADCP oscillation also increases slowly when the ADCP is lowered, a segmented vertical filtering method is used to filter out the current signals with a stable period in each segment. In the filter design, a 3rd order Butterworth analog filter is used to band-pass-filter the current data. Figure 16 shows the comparison of the current velocity profiles of Station MC001 before and after being filtered. In Fig. 16a, although the shear shapes of the current velocity profiles observed in the upper and lower processes are relatively similar, the absolute values of the current velocities differ significantly and can exceed 0.2 m/s at the maximum. Figure 16b shows that after the vertical filtering processing, the current velocity profiles measured by the lowering and lifting processes are fitted more closely. The duration of these processes is about 4 h. The current velocity usually is not changed significantly during

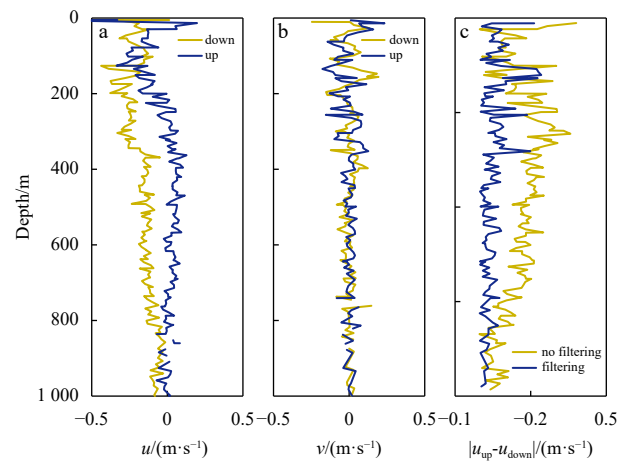


Fig. 16. Comparison diagram of current velocity profiles before (a) and after (b) vertical filtering (Sta. MC001), and the difference in current velocity calculated during the lowering and lifting processes (c).

this period. The average difference of the current velocity of the corresponding lowering and lifting processes at each standard depth is 0.16 m/s before vertical filtering and 0.05 m/s after vertical filtering. Therefore, the vertical filtering method can effectively improve the accuracy of the current velocity profile.

6 Comparison of velocity calculated by different methods with SADCP and CMEMS data

Based on the principle of the inverse method, Martin et al. developed the LDEO software package (<https://www.ldeo.columbia.edu/~ant/LADCP/>) specifically for processing LADCP data. This paper uses LDEO_IX version to process the same LADCP measured data, analyzes them against the calculation results of the layering shear method, and uses the SADCP current velocity profile as the standard to compare with the two. The results are shown in Fig. 17. The shipboard ADCP is fixed on the bottom of the ship for simultaneous observation. Compared with LADCP, it is not affected by a cable and has better stability. However, due to the limited observation range of SADCP, it can only observe the current velocity within 400 m depth. Therefore, SADCP can be only used to compare with the near-surface current velocity calculated by LADCP. The LDEO software package is used without calling the SADCP data for correction. The SADCP current velocity data have been superimposed on the GPS data at the same time to remove the effect of ship movement. The average difference between the calculation results of LDEO/layering shear method and the SADCP data in the *u* component are shown in

Table 3. It is obviously that the current velocity profiles processed by the layering shear method are closer to the observed results of the SADCP, while the results calculated by the inverse method have some deviations compared with SADCP. However, the difference between the results calculated by the two methods and the SADCP data cannot be eliminated in theory. The LADCP measures the instantaneous velocity of each layer of seawater, and these measured values do not occur at the same time. In terms of the observation range of SADCP, it takes about 250–400 s. While the SADCP velocity profile we obtained is the average of SADCP measurements during this period.

In addition, the current velocity profiles of the 6 stations were calculated using the layering shear method and inverse method and compared with the velocity profiles from CMEMS data. All of these velocity profiles are subtracted of the average tidal current for the same period predicted by the TPX09 (Egbert and Erofeeva, 2002). The results are shown in Fig. 18. Most of the results processed by the LDEO software package are close to those processed by the layering shear method (except for the station MC002). The velocity profile calculated from the CMEMS data is smoother for two reasons. First, it is a daily average data; second, there are many small and medium scale processes in the ocean, which usually exhibit greater current shear in instantaneous observations. The differences are larger in the upper layer. On the one hand, this area have always been difficult points for LADCP velocity processing, and a difference between the results of different methods are magnified; on the other hand, the vertical posi-

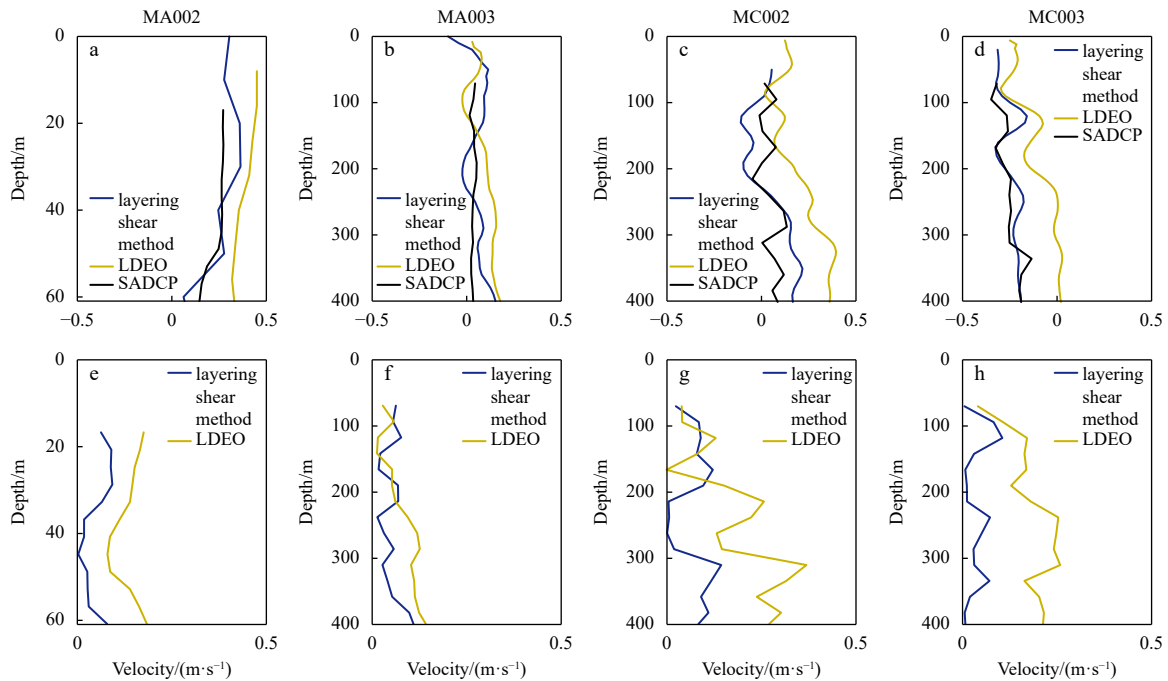


Fig. 17. Comparison of the current velocity profiles processed by layering shear method, inverse method and the current velocity profiles observed by the SADCP (a–d), and the difference between the results calculated by the two methods and the SADCP data (e–h).

Table 3. Average of the absolute value of the error with SADCP of the current velocity in the whole depth calculated by the LDEO ($\epsilon u1$) and layering shear method ($\epsilon u2$)

| Station | $\epsilon u1/(m \cdot s^{-1})$ | $\epsilon u2/(m \cdot s^{-1})$ |
|---------|--------------------------------|--------------------------------|
| MA002 | 0.13 | 0.05 |
| MA003 | 0.07 | 0.05 |
| MC002 | 0.17 | 0.07 |
| MC003 | 0.17 | 0.04 |

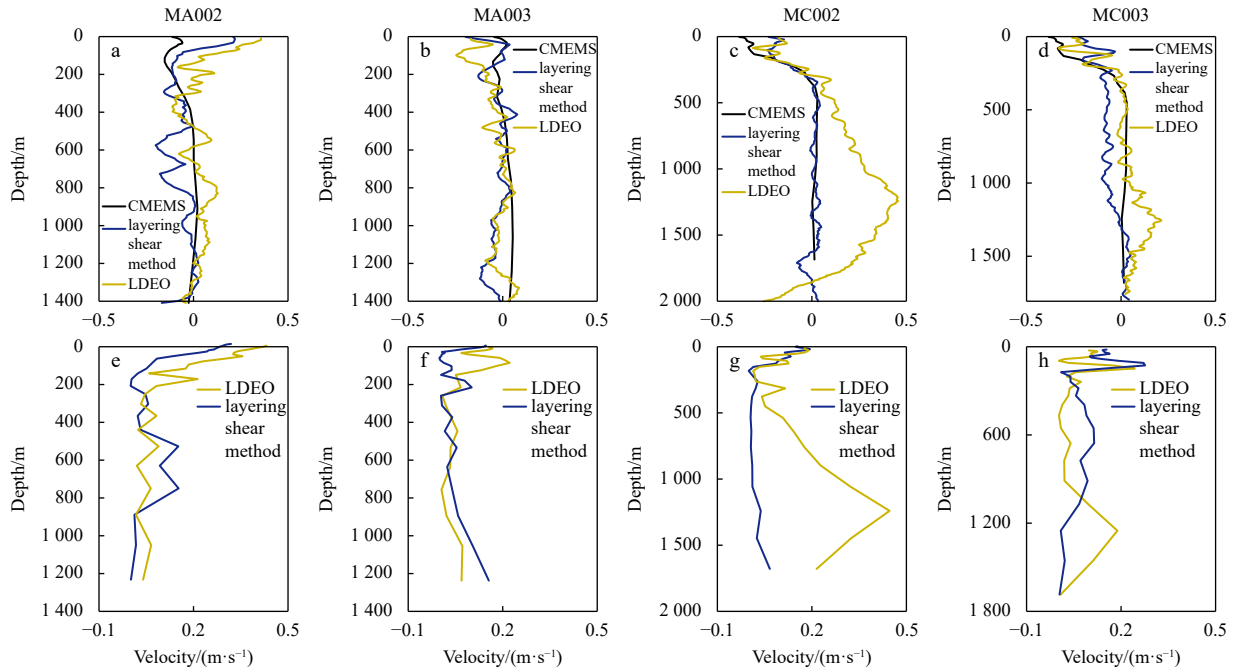


Fig. 18. Comparison of the current velocity profiles processed by layering shear method, inverse method and the CMEMS data (a–d), and the difference between the results calculated by the two methods and the CMEMS data (e–h).

tion of the current velocity profiles may be slightly deviated due to the different calculation methods for depth. The average difference between the calculation results of LDEO/layering shear method and the CMEMS data in the u component are shown in Table 4. Overall, the current velocity profiles calculated by the layering shear method are closer to the CMEMS results than the inverse method.

The inverse method provided by the LDEO software package does not work well when dealing with individual stations with a lot of missing data. For example, in the deeper water layer of Stations MA001 and MC001, the echo rate is extremely low and the data available for calculation by the LDEO software package is limited. Therefore, the current velocity of the whole profile cannot be calculated correctly. With the current velocity calculation method for the low echo rate water mentioned below, the current velocity even below 5 000 m can be calculated without affecting the surface-layer current velocity calculation.

7 Conclusions and discussion

In this paper, the current measurement principle of LADCP is studied, and the layering shear method is proposed. The simulation tests show that the method has the advantages of both the shear method and the inverse method while making up for the shortcomings of the both in calculating values of the absolute current velocity and the current shear velocity, respectively. In addition, based on the common problems in the actual measurements, further optimization solutions are proposed in this paper

Table 4. Average of the absolute value of the error with CMEMS of the current velocity in the whole depth calculated by the LDEO ($\epsilon u1$) and layering shear method ($\epsilon u2$)

| Station | $\epsilon u1/(\text{m}\cdot\text{s}^{-1})$ | $\epsilon u2/(\text{m}\cdot\text{s}^{-1})$ |
|---------|--|--|
| MA002 | 0.23 | 0.17 |
| MA003 | 0.1 | 0.08 |
| MC002 | 0.15 | 0.09 |
| MC003 | 0.08 | 0.09 |

from several perspectives.

Based on the LADCP observations in the western Pacific Ocean, this paper compares the processing results with those of the LDEO software package prepared by Visbeck (2002) based on the inverse method, and finds that the LDEO software package does not work well when dealing with situations with little effective data, such as deep water, and even fails to provide current velocity profiles. In this paper, the calculation results for deep seawater are smoother, which is more consistent with the real ocean current field, and has higher error tolerance and operability. The inverse method adopts a least square method in the calculation. Therefore, compared with the shear method and the layering shear method, it cannot get the high precision current shear velocity value; while the method in this paper takes the actual observation data as the most important point, and strives to restore the most realistic current velocity profile via reasonable data processing methods, so as to reduce the errors to the minimum. Therefore, when the inverse method is used for calculation, if the results contain a large amount of invalid data because of the problem of the previous observation, it will lead to the solution of the equation set to deviate greatly from the real velocity. Meanwhile, it has been mentioned before that if the inverse method has a solution for the equation set, the amount of known data should be greater than the unknown data (Visbeck, 2002). Compared with the inverse method, the layering shear method is equivalent to a segmental solution. There is little interference between the calculation results of different layers, which increases the operability of the actual calculation as well as the usage rate of the data.

We have compared the calculation results of the layering shear method with the SADC observation results, and the results show that the layering shear method can calculate the current velocity profile that is very close to the practical. If we can obtain the real current velocity below 400 m, the layering shear method can also obtain the calculation results similar to those of the upper layer. Assuming that U_{ref} is obtained from GPS data,

the velocity of each layer calculated by layering shear method does not affect each other. This is also the advantage of layering shear method, that is, the error will not accumulate with the increase of the depth of water. In theory, the error caused by the choice of U_{ref} has the greatest impact on the shear method, while it has less impact on the inverse method and layering shear method.

At present, the observation results of the conventional LADCP are only verified by the SADCP data, but the maximum observation depth of SADCP is usually less than 800 m, so the simultaneous observation is not possible in deeper sea area. Future research can combine multiple current measurement methods to test the layering shear method in more details from multiple perspectives.

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