A Sound Ray Correction Method Based on Historical Data of Marine Acoustic Environment

Jian Li[1,2*], Zhen Zhang[1], Yue Pan[1], Ming-Yu Gu[1], Guang-Jie Han[1]

[1] College of Internet of Things Engineering, Hohai University, China
[2] Science and Technology on Underwater Vehicle Technogogy Laboratory, Harbin Engineering University, China
jian263@sina.com, golddwin@163.com, 782470917@qq.com, 211620010012@hhu.edu.cn, hanguangjie@gmail.com

Abstract

This paper proposes a new method for sound ray correction based on historical data, such as temperature, salinity, and depth of the sea area. The proposed method utilizes the Douglas-Peucker (D-P) algorithm to mine and extract features from sound velocity data processed using empirical orthogonal functions (EOF), completing the inversion of sound speed profiles (SSP). Compared to traditional EOF methods, an increase in the computational speed is achieved. Afterwards, this method quickly and linearly layers the processed sound speed profile, and uses the equivalent sound velocity method (ESVM) for sound ray equivalence to complete underwater target localization. Compared to the constant velocity method and the constant gradient method based on adaptive layering, the proposed method has higher accuracy and higher robustness to complex underwater environments. The effectiveness of the method is verified by applying it to the ultra-short baseline (USBL) positioning system.

Keywords: Sound ray correction, Data feature extraction, Equivalent sound velocity method

1 Introduction

Accurate location of underwater targets requires obtaining sound velocity data at different depths of the target water area. Sound speed profile inversion can mine a stable and accurate sound velocity function from the target water area's history data, thereby completing positioning and achieving civilian navigation, military strikes, and other purposes. Sound velocity data collection is a complex and difficult preparatory work. Han et al. proposed a few efficient data collection schemes using autonomous underwater vehicles (AUVs) [1-3], providing strong support for underwater positioning data collection in this paper. Munk et al. proposed the concept of acoustic velocity profile inversion for the first time [4], where the underwater sound ray data were used to retrieve the sound speed profile of the target sea area. Since then, many different sound speed profile inversion methods have been proposed by researchers. These methods include the simple wave model [5], the genetic algorithm [6], and the dictionary learning [7].

The ultimate goal of the inversion is to obtain a sound speed profile that can effectively reflect the characteristics of the target water area. In this process, it is necessary to extract the sound speed profile (SSP) characteristics, reduce the redundant parameters in the inversion process, and improve the speed, accuracy and reliability of the inversion. Davis [8] validated that the empirical orthogonal functions (EOF) have good performance for feature extraction of SSP, and can reduce the data dimensions and simplify the calculation process. Since then, many researchers have verified the feasibility of using the EOF to invert SSP and achieve good results [9]. The Douglas-Peucker (D-P) algorithm is a line feature compression algorithm [10-12]. This paper combines the D-P algorithm and the EOF method for SSP data, which significantly reduces the computational complexity of the SSP inversion process, and improves the speed of underwater positioning while retaining the data characteristics.

It is necessary to use specific underwater target data analysis methods after obtaining the sound speed profile of the target water area. The sound correction method used in this article relies on ray acoustics. The main idea of ray acoustics is to approximate the path of sound waves propagating through water in the form of sound rays. The sound rays will be refracted and reflected when they pass through the media formed by different water layers. When the sound rays are refracted, they will deflect towards the direction of lower velocity, thus forming a special path [13]. The underwater target can be located by using the sound ray propagation track.

The sound ray correction method is generally based on Snell's law [14-15], and the commonly used methods are constant sound velocity method and constant gradient method. The former considers a constant sound propagation speed in each water layer, while the latter regards the propagation speed of sound in each water layer as changing at a constant rate. Most of the traditional methods use adaptive layering of SSP, and then combine these two methods for location [16-19]. In this paper, a layered calculation method of equivalent sound velocity method (ESVM) is proposed. After the seawater medium layer is linearly stratified, the SSP of each layer becomes equivalent to the SSP with the same integral area. Next, we can perform sound ray simulation to complete the positioning This method improves the acoustic ray positioning accuracy and enhances the robustness for more complex SSP.

The rest of this paper is organized as follows: Sections 2 and 3 of this paper provide theoretical descriptions of the two

*Corresponding Author: Jian Li; E-mail: jian263@sina.com
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main proposed methods. Section 4 presents the experimental verification process of these two methods, as well as compares their effectiveness with other traditional methods. The flow chart of the sound line correction method in this article is shown in Figure 1. From the Figure 1, it can be seen that the basic structure and method used in this article.

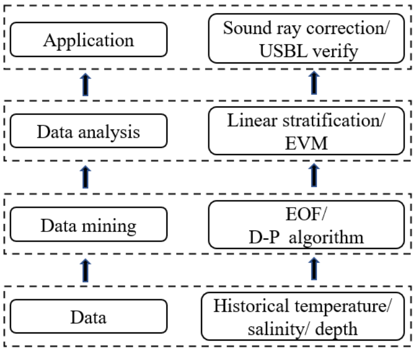

Figure 1. Sound ray correction process

2 EOF SSP Inversion Based on D-P Algorithm

2.1 Data Preprocessing

In practice, the function of sound velocity versus depth in water cannot be obtained directly, and researchers can only compute a similar SSP through data processing, approximation and other methods. The EOF is composed of function vectors, which are orthogonal to one another and can better reflect the characteristics of SSP changes. The authors in [20] point out that only the first three to six orders of the EOF can be obtained for the SSP inversion. The D-P algorithm is a data simplification algorithm. The combination of the two algorithms will produce good results, and considerably reduce the computational complexity at the expense of a slight reduction in accuracy. Next, this article will introduce the specific calculation process.

First, the temperature and salinity information at different depths of the target water area should be obtained, and the empirical formula of sound velocity is used to obtain the sound velocity information at the corresponding depths. According to the characteristics of the target water area in this paper, the empirical formula for calculating the sound velocity in China’s sea area given in the International Hydrographic Standards is used [21]. This formula is shown in (1), which provides the sound velocity data at the corresponding depth of the sea area. In Eq. (1), T and S represent the temperature and salinity corresponding to the depth of water, respectively.

$$V = 1449.2 + 4.6T - 5.5\times10^{-2}T^2 + 2.9\times10^{-4}T^3 + (1.34 - 0.01T)(S-35) + 0.17. \quad \textbf{(1)}$$

Due to the limitations of the actual water data acquisition, the obtained sound velocity data are not equidistant. Therefore, the sound velocity at equidistant points is obtained by carrying out cubic spline interpolation on the measured historical sound velocity data of each group at different depths in the same water area. As shown by matrix C in Eq. (2), each column represents a group of SSP data, where there are n groups. Furthermore, the depth distance between each point in each column is equal.

$$C = \begin{vmatrix} c_1(0) & c_2(0) & \cdots & c_n(0) \\ c_1(h) & c_2(h) & \cdots & c_n(h) \\ \vdots & \vdots & \vdots & \vdots \\ c_1(kh) & c_2(kh) & \cdots & c_n(kh) \end{vmatrix}. \quad \textbf{(2)}$$

Subsequently, Eq. (3) is used to process C and obtain the average value of the corresponding depth of each of its row, which is recorded as the average SSP $\overline{c}$.

$$\overline{c} = \frac{1}{n}\sum_{i=1}^{n} c_i(kh). \quad \textbf{(3)}$$

2.2 Extraction of Data Features

Next, the average SSP is processed using the D-P algorithm to simplify the data and obtain the sound velocity value of the corresponding depth, which can better characterize the SSP.

For the average SSP, a straight line is determined from the two points with the minimum and maximum depth values. The distance D_i, also called the offset, is calculated from the other points in the average SSP to the straight line in turn. The calculation method is shown as follows:

$$D_i = abs\left[\frac{(h_i - h_1)*(C_n - C_1)}{h_n - h_1} + c_1 - c_i\right]. \quad \textbf{(4)}$$

In Eq. (4), c_i and h_i are the sound velocity value and depth value corresponding to the ith point in the depth value of the average SSP $\overline{c}$ in the ascending order, respectively. After the distance D_i of each point is calculated, a distance threshold D_t is set according to the actual requirements.

The amplitudes of D_{imax} and D_t are compared, where the latter is the distance between each point and the line, and the former is the maximum of that distance. If $D_{\text{imax}} <= D_t$, only the first point D_1 and the last point D_n are retained. If $D_{\text{imax}} > D_t$, D_1, D_n and D_{imax} are reserved, and the average SSP is divided into two parts with respect to the point . This finishes the first calculation step. In the second calculation step, D_1 and D_i are connected to calculate the offset and determine the size of the threshold D_t. The above process is repeated until D_{imax} corresponding to all segments is less than D_t, which means that the selection of characteristic points of SSP is over.

At this time, the number of points in the average SSP is reduced from the original k+1 to g, and the average SSP is recorded as $\overline{c_1}$. The SSP matrix C is simplified. It only retains the points at the same depth as $\overline{c_1}$, and the SSP matrix C_1 is obtained. At this time, C_1 is not only smaller in dimensions than C, but it also retains the points that can better reflect the SSP characteristics. The matrix C_1 is subtracted from the average SSP $\overline{c_1}$ to obtain disturbance matrix ΔC, as shown in Eq. (5):

$$C = \begin{bmatrix} \Delta c_1(0) & \Delta c_2(0) & \cdots & \Delta c_n(0) \\ \Delta c_1(mh) & \Delta c_2(mh) & \cdots & \Delta c_n(mh) \\ \vdots & \vdots & \vdots & \vdots \\ \Delta c_1(kh) & \Delta c_2(kh) & \cdots & \Delta c_n(kh) \end{bmatrix}. \quad \textbf{(5)}$$

The covariance matrix R' of ΔC is calculated, and decomposed into eigenvalues, as shown in Eqs. (6) and (7), respectively:

$$R' = \frac{\Delta C \Delta C^T}{n}. \quad \textbf{(6)}$$

$$R' F = D. \quad \textbf{(7)}$$

In Eq. (7), F matrix is composed of eigenvectors of covariance matrix R', and D matrix is composed of eigenvalues of covariance matrix R', as shown in Eqs. (8) and (9), respectively:

$$D = diag\left[\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_n\right]. \quad \textbf{(8)}$$

$$F = \left[f_1(kh) \quad f_2(kh) \quad \cdots \quad f_N(kh)\right]^T. \quad \textbf{(9)}$$

The sound velocity at any point in the target water area can be expressed by EOF, as shown in Eq. (10):

$$c(h) = \overline{c}(h) + \sum_{i=1}^{g} \alpha_i f_i(h). \quad \textbf{(10)}$$

In Eq. (10), α_i is the EOF coefficient of the SSP, which can be determined by other values. During inversion, all the obtained eigenvalues can be arranged in descending order, and the eigenvectors corresponding to the eigenvalues are recorded as the -order EOF mode in this order. As mentioned above, the SSP of the water area in general scenarios can be more ideally retrieved by selecting the first three to six orders of the EOF. Using Eq. (10), we can obtain all the points from 1 to g according the parameter i, and subsequently carry out the cubic spline difference on these points to get the SSP after inversion.

3 Sound Ray Correction Based on ESVM

3.1 ESVM

Figure 2 demonstrates the schematic diagram of three SSP processing methods. The figure shows a layer of SSP with a small depth difference. It can be observed that the constant sound velocity method processes the SSP directly by treating the SSP in the layer as a constant sound velocity region. The calculation is simple; however, when the layer is slightly larger, it will cause a larger deviation in positioning. The constant gradient method approximates the SSP in the layer by directly connecting the head and tail sound velocities of the SSP layer. Compared with the former, it obviously increases the computational complexity and accuracy, but will suffer from a large deviation for a slightly complex section in the layer.

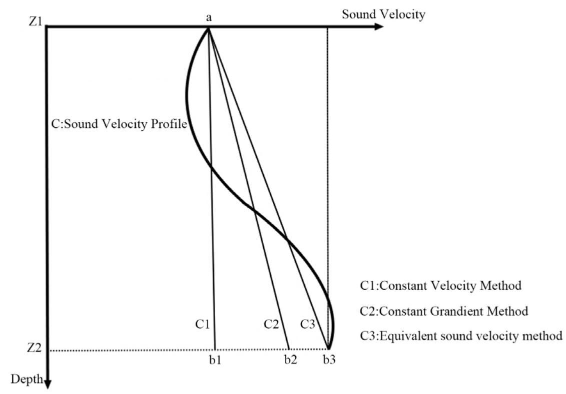

Figure 2. Schematic diagram of three SSP processing methods

The layered positioning of the ESVM proposed in this paper is different. It integrates the layered SSP segments to obtain an equivalent area of SSP segments, thus increasing positioning accuracy. Theoretically, the accuracy of the three methods is the same when the SSP is infinitely stratified. However, in practice, it is necessary to ensure the positioning accuracy under a certain computational complexity. Obviously, the sound ray location based on the ESVM is closer to the original SSP for an equal number of layers, which results in a higher accuracy. Moreover, in the previous SSP inversion, the functions of each segment of the SSP are obtained through the cubic spline interpolation. Therefore, the computational complexity is considerably reduced during the integration operation.

3.2 Linear Stratification

The SSP can be reasonably stratified in the sound ray correction process. Therefore, the underwater positioning can be carried out more quickly and accurately. Based on the aforementioned inversion process, the layering method proposed in this paper mainly relies on the dichotomy method for fast layering. The threshold correlation is determined based on the depth value of the water layer and the linear correlation coefficient of the least squares method. The steps of this method are as follows:

First, the number of points obtained from the above inversion is divided into two SSPs based on the depth value. If g is an odd number, the point corresponding to (g+1)/2 is the partition point used by the upper and lower segments. If g is an even number, the point corresponding to g/2 is the dividing point used by the upper and lower segments. The depth of the divided water layer is determined by the characteristics of the target water area. The default is one tenth of the water depth, which can be adjusted independently. If this depth is less than the threshold, no stratification will be carried out. Otherwise, the least square method will be used to calculate the linear correlation coefficient of the profile function of the upper and lower sections. The value of the correlation coefficient is compared with the preset threshold value. The default is 0.90, which can be adjusted independently. If their linear correlation coefficient is greater than the threshold value, no stratification will be performed. If there is a water layer with a linear correlation coefficient that is less than the threshold, the water layer is continued from the central data of the water layer and the threshold is determined. This process stops when the depth of all layers is less than the threshold value, or the absolute values of the corresponding linear correlation coefficients are greater than the threshold value, which completes the rapid linear stratification of the SSP. Although the ESVM has a high robustness for complex SSP, its accuracy positioning is better for a higher linearity. In order to fully utilize the advantages of the ESVM, the depth of the water layer is set as a threshold criterion. When the depth is small, the ESVM can also obtain its position more accurately despite its relative complexity. Moreover, due to the particularity of the SSP, the profiles in the upper and lower layers of the water area are generally more complex and simpler, respectively. Therefore, positioning calculation can be carried out without extensive layering, thus improving the underwater positioning speed and accuracy.

In the above, the functions of SSP and the stratification of SSP are obtained. These layered functions are known as they are obtained from the cubic spline interpolation. Therefore, the ESVM can be used to further process the SSP: First, the area of each layer is obtained using integration, and a rectangular trapezoid with the same area is obtained. In the first layer, the height of the trapezoid is the height of the layer, the length of its upper base is the length of the upper base of the layer, and the length of the lower base can be calculated from the above known values. For the second layer, the length of the upper base of trapezoid is equal to the length of the lower base of the first layer of trapezoid. A final equivalent SSP consisting of multiple equivalent SSPs will be obtained after performing the sound velocity equivalence in turn.

3.3 Sound Ray Correction

Once the layering is completed and the final equivalent SSP is determined, sound ray tracking is required to determine the underwater position of the target. The left part in Figure 3 shows the SSP of a layer processed by the ESVM, and the processed SSP, where each layer is a constant gradient SSP. The underwater propagation track of the sound ray of each layer can be seen as an arc with radius r_i. As shown in the right-side of Figure 3, r_i can be obtained using Eq. (11) as follows:

$$r_i = -\frac{1}{pg_i}. \quad \textbf{(11)}$$

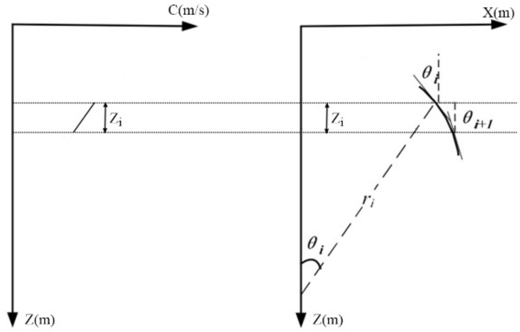

Figure 3. Sound ray propagation path of the processed SSP

In Eq. (10), p and g_i are the Snell constant and sound velocity gradient, which are derived from Eqs. (12) and (13), respectively.

$$p = \frac{\sin\theta_i}{c_i} = \frac{\sin\theta_{i+1}}{c_{i+1}}. \quad \textbf{(12)}$$

$$g_i = \frac{c_{i+1} - c_i}{z_i}. \quad \textbf{(13)}$$

In Eqs. (12) and (13), c_i and c_{i+1} are the first sound velocity of the equivalent SSP of the current layer and the next layer, respectively, θ_i is the incident angle of the sound ray of the SSP of the current layer, and θ_{i+1} is the incidence angle of the sound ray of the SSP of the next layer.

At this time, the horizontal displacement of sound ray of each layer can be obtained, as shown in Eq. (14).

$$x_i = r_i(\cos\theta_{i+1} - \cos\theta_i) = \frac{\cos\theta_i - \cos\theta_{i+1}}{pg_i}. \quad \textbf{(14)}$$

4 Experimental Verification

4.1 SSP Inversion

The SSP data obtained in this paper are located in a certain area of the Yellow Sea of China [1-3]. The time is around March 2021. There are 10 groups basic profile data. The basic data are temperature, salinity and depth data. The depth range is 0 m to 2000 m. As Figure 4 shows, the SSP is drawn using the original 10 sets of data. The data of each group are similar since the location is a fixed target and the time is at the end of winter. The SSP data of the corresponding time period of the location can be obtained through the inversion of the SSP, which completes the accurate positioning of the target water area.

Figure 5 shows the SSP inversion effect Specifically, Figure 5(a) and Figure 4(b) show the effects of SSP inversion using the EOF and the D-P algorithm, respectively, and Figure 5(c) compares the results shown in Figure 5(a) and Figure 5(b). In Figure 5(a), the water layer is divided into 80 layers on average, where there is one layer every 25 meters. In Figure 5(b), the threshold is set to 0.05, and the water layer is divided into 27 layers with different distances between them. As Table 1 shows, the former needs to calculate the 80-dimensional matrix multiple times for SSP inversion, while the latter only needs to calculate the 27-dimensional matrix multiple times for the inversion. This significantly reduces the computational complexity and increases the speed of underwater positioning.

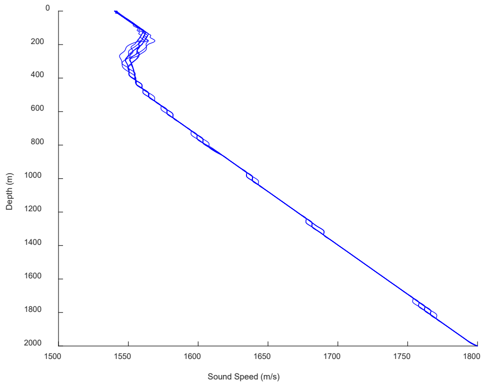

Figure 4. Ten groups of original SSPs

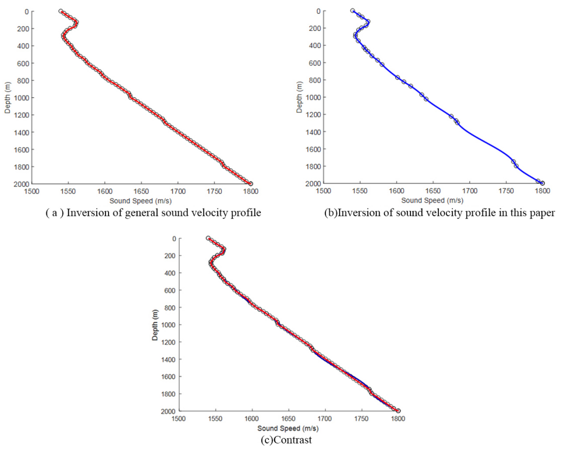

Figure 5. Inversion effect of SSP

After the calculation of the matrices, the root mean square errors of the former and latter are approximately equal to 2.430 m/s and 3.342 m/s, respectively. As the processor used in the calculation in this paper is a PC-based processor, the calculation speed is considerably higher than that of the processor used in the ultra-short baseline (USBL) positioning system. Therefore, although the computational time is lower by only 0.14 seconds, the time saved in the actual calculations will be significantly higher, thus increasing the timeliness of positioning. The maximum errors with the former and latter inversions are 14.77 m/s and 14.79 m/s, respectively. Note that the inversion result of the latter has no significant error. It can be observed that in the target water area, the inversion method of SSP proposed in this paper can significantly reduce the computational complexity of the SSP inversion process. This accelerates the underwater positioning speed while the root mean square error increases by only 0.912 m/s. Table 2 shows the actual positioning results of the two sound velocity inversion methods in Figure 5, both of which use the ESVM based on linear stratification. From Table 2, it can be seen that this inversion method can improve the speed while still ensuring the accuracy of positioning. Figure 6 shows the first three orders of EOF corresponding to the SSP inversion. It can be observed that the characteristics of the first three orders of EOF in Figure 6(a) and Figure 6(b) are highly similar. Thus, we conclude that the SSP proposed in this paper has considerably reduced the underwater positioning time while retaining the main characteristics of the SSP.

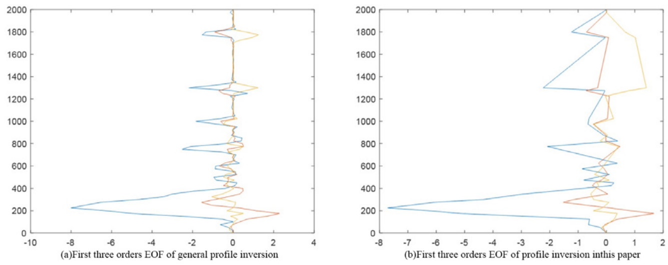

Figure 6. First three orders of EOF for SSP inversion

Table 1. Inversion efficiency comparison

SSP inversion	Main calculation	Calculation time*	RMSE	Maximum error
EOF method	80-dimensional matrix multiplication	0.35s	2.430m/s	14.77m/s
EOF method based on D-P algorithm	27-dimensional matrix multiplication	0.21s	3.342m/s	14.79m/s

*: CPU: i7-10870H Software: MATLAB

Table 2. Comparison of inversion positioning effect

Incidence angle (degrees)		10	20	30	45
Actual horizontal distance (m)		180.8	375.9	600.0	1063.0
SSP inversion -EOF	Distance	180.59	374.95	598.21	1059.13
	Error	0.12%	0.25%	0.30%	0.36%
SSP inversion -EOF & D-P	Distance	181.06	374.84	598.15	1058.91
	Error	0.14%	0.28%	0.31%	0.38%

The general SSP has the following characteristics: the profile function of the upper part of the water layer is relatively complex, while that of the lower part is relatively simple. In general, in terms of feature extraction of SSP, it can be found through comparison that using the SSP inversion method proposed in this paper can mainly reduce the feature extraction of the lower half of the SSP. Despite this reduction, it can still invert the SSP that can better reflect the sound velocity law. The SSP proposed in this paper significantly reduces the time of underwater positioning but retains the main characteristics of the SSP. The positioning accuracy of the SSP inversion method is almost the same, which improves the positioning efficiency.

4.2 Linear Stratification and ESVM

Figure 7 shows the linear stratification of the SSP in the sea area and the performance of the ESVM, while Figure 8 separately shows the performance of the ESVM. The blue curve in Figure 7 represents the SSP obtained after inversion, while the red line segment represents the SSP processed using the layering and ESVM, which is also shown in Figure 8. Although the shape of the processed SSP differs from that of the original one, the positioning effect of sound rays on underwater targets is equivalent. This article uses the layering method mentioned above, with a threshold set to an absolute value of 0.95 for the linear correlation coefficient and a depth of 100 meters. In Figure 7, the SSP is divided into six layers, where their linear correlation coefficients/depths from top to bottom are 0.9999/125 m, -0.9544/100 m, -0.9999/50 m, 0.9990/75 m, and 0.9997/1475 m.

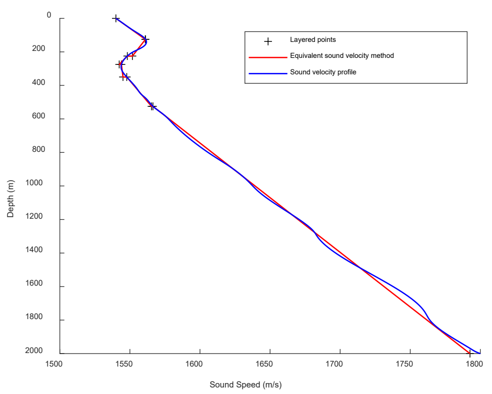

Figure 7. Performance of linear layering of SSP and ESVM

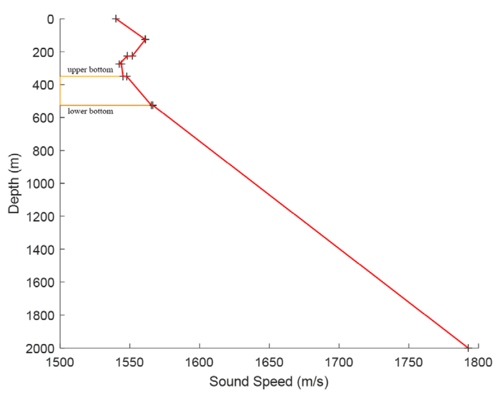

Figure 8. Performance of ESVM

After layering, the ESVM needs to be used to generate the SSP of each layer equivalent to a line segment. As the function of the SSP is obtained from the cubic spline interpolation described previously, the function of each SSP section is known, and its specific value can be obtained through integration. As explained in Section 3, the SSP's area of the profile section is equivalent to a trapezoid. These six trapezoids will form a 6-layer SSP, and their data are shown in Table 3.

Table 3. Layered parameter data of SSP

Sound velocity profile	Upper bottom (m/s)	Bottom (m/s)	Height (m)
First layer	1540.00	1560.95	125
Second layer	1561.15	1551.78	100
Third layer	1548.16	1542.37	50
Fourth layer	1543.96	1545.07	75
Fifth layer	1547.75	1565.41	175
Sixth layer	1566.44	1792.62	1475

The actual reference position of the positioning target is the specific known position at which the device is installed in water, where its depth is about 1000 m. In order to verify the effectiveness of the algorithm proposed in this paper, the depth data is set as a fixed value to reduce influencing factors. In practical applications of USBL, depth information can be obtained through pressure sensors or calculated using the results of slant distance and direction. The horizontal distance is determined by changing the position of the ship and using the data available from satellites. Here, the determined horizontal distance and depth values are regarded as true values to determine the positioning performance of various positioning methods. Different degrees of incidence are obtained by changing the position of the ship, and the average value over multiple positioning times is calculated for each positioning method.

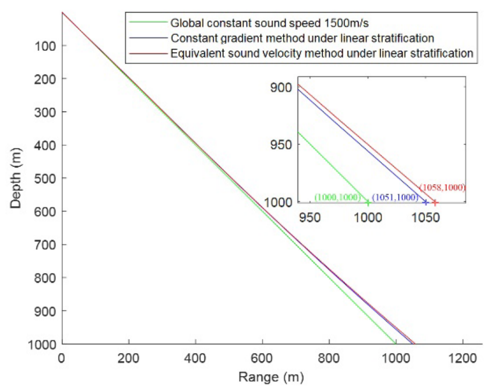

Figure 9. Schematic diagram of three types of sound paths

Figure 9 shows a schematic diagram of the paths of three types of sound rays. The incident angle, i.e., the angle between normal and sound ray is 45 degrees in the figure, the target depth is 1000 meters, and the target true horizontal distance is 1063.0 meters. The red, blue, and green sound rays represent the ESVM using linear layering, constant gradient method using linear layering, and global constant sound velocity method of 1500 m/s. It is obvious that the positioning accuracy of the red sound ray is higher than that of the other two sound rays, exhibiting a horizontal accuracy improvement of approximately 8 meters and 58 meters, respectively.

4.3 Comparison of Experimental Results

Table 4 compares the positioning performance of various sound line correction methods in the experiment. Their SSPs are all inverted using the method proposed in this paper, with six layers of SSPs. It can be observed from this table that the positioning results of various sound ray correction methods differ from the true values at different incident angles.

Table 4. Localization effects of four sound ray correction methods

Incidence angle (degrees)		10	20	30	45
Actual horizontal distance (m)		180.8	375.9	600.0	1063.0
ESVM under linear stratification	Distance	181.06	374.84	598.15	1058.91
	Error	0.14%	0.28%	0.31%	0.38%
Constant gradient method under linear stratification	Distance	180.43	374.03	596.36	1051.43
	Error	0.20%	0.50%	0.77%	1.1%
Constant sound velocity method under linear stratification	Distance	179.23	368.46	585.48	1014.31
	Error	0.87%	1.98%	2.42%	4.58%
Constant gradient method under equal-interval stratification	Distance	180.06	372.25	592.26	1039.61
	Error	0.41%	0.97%	1.29%	2.20%

Figure 10 compares the positioning errors of four sound ray correction methods. It can be observed that the ESVM proposed in this paper is superior to the constant gradient method and significantly superior to the constant sound velocity method under the same layered conditions [13-15]. It also has a higher accuracy compared with the constant gradient method of equal interval layering method with the same number of layers.

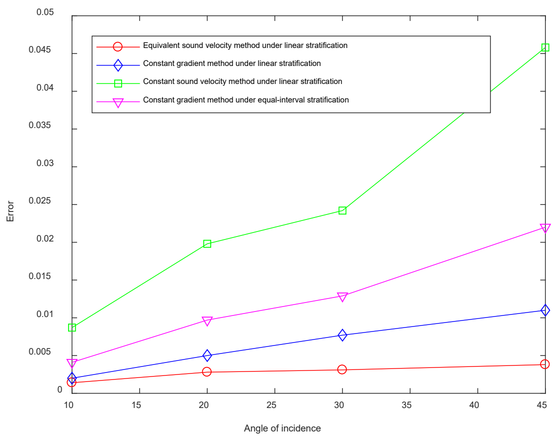

Figure 10. Positioning errors of four sound ray correction methods

Overall, the positioning errors of various sound ray correction methods keep on increasing as the incident angle increases. Under the profile inversion method and linear layering method proposed in this article, the positioning accuracies of the ESVM, constant gradient method, and constant sound velocity method decrease sequentially. The error of the results obtained using the constant gradient method with equal interval layering is only lower than that of the constant sound velocity method with linear layering. It can be observed that the method proposed in this article has a good performance, with a horizontal error of only 0.14% at an incidence angle of 10 degrees, and the maximum error of only 0.38% at an incidence angle of 45 degrees. Compared to other methods, the accuracy improves by 0.06% to 4.20%.

5 Conclusion

Efficient data processing methods are needed to achieve ideal positioning results from complex historical data of marine acoustic environments. The sound line correction method in this article improved the speed, accuracy and robustness of underwater positioning by starting from the SSPs inversion and the ESVM. The inversion of SSP based on EOF and D-P algorithm showed good data mining performance in the target water area. The inversion process involved many matrix multiplications, which were reduced by 66.25% ((80-67)/80=66.25%) in the proposed method, thus significantly improving the inversion speed. Further data analysis showed that the proposed method exhibited good robustness for complex SSPs due to the integral characteristics of the ESVM. Combined with the linear layered method, the horizontal error was 0.38% when the incident angle reached 45 degrees. When the incident angle decreased, the positioning performance of the proposed method was better, and the error was only 0.14% at 10 degrees. The positioning results showed that under the same number of layered methods, the accuracy was higher than other traditional positioning methods. It is obvious that the theory of sound line correction method proposed in this paper is universal. It is not only limited to target waters, but also applicable to different waters, and has certain engineering application value.

The proposed method also needs some improvement. For example, there may be a more suitable layering method for linear layering of the SSP. The judgment threshold used in this paper is based on the linear correlation coefficient and depth value of the SSP in this layer. Although it is relatively consistent with the situation of the SSP proposed in this paper, more reasonable layering is needed to improve the speed and accuracy for a more specific SSP. Currently, we can consider setting the threshold as a function of layering depth and linear coefficient to effectively avoid this situation. The specific setting needs further discussion and research based on the actual situation.

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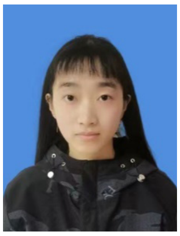
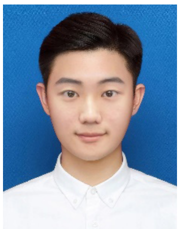
Biographies

Jian Li, PhD, Associate Professor. College of Information Science and Engineering, Hohai University. Member of the China Acoustics Society, Jiangsu Ocean Society. Research interests include: underwater acoustic communication, detection, positioning and navigation, etc. Current projects: National Natural Science Foundation of China(NSFC), NSF of Jiangsu Province, National Key R&D Plan, etc.

Zhen Zhang received his bachelor's degree from North China University of Water Resources and Electric Power in 2021, He is currently a master's student in the College of Information Science and Engineering at Hohai University. His research topics include applications in Underwater acoustic communication, computational ocean acoustics.



Yue Pan received his bachelor's degree from Hebei University of Engineering in 2022, He is currently a master's student in the College of Information Science and Engineering at Hohai University. His research topics include applications in Underwater acoustic communication, IoT.



Ming-Yu Gu received his bachelor's degree from Jinling Institute of Technology in 2020. He is currently a master's student in the College of Information Science and Engineering at Hohai University. His research topics include applications in Underwater acoustic communication, ocean acoustics.

Guang-Jie Han is currently a Professor with the College of Information Science and Engineering, Hohai University, China. He is a Fellow of the UK Institution of Engineering and Technology. He has been awarded 2020 IEEE Systems Journal Annual Best Paper Award and the 2017-2019 IEEE ACCESS Outstanding Associate Editor Award.