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Three-Dimensional Passive Source Localisation using the Flank Array of an Autonomous Underwater Vehicle in Shallow Water

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ABSTRACT

Researchers have become interested in autonomous underwater vehicles equipped with various kinds of sonar systems that can perform many of underwater tasks, which is encouraged by the potential benefits of cost reduction and flexible deployment. This paper proposes an approach to three-dimensional passive source localisation with the flank array of an autonomous underwater vehicle in shallow water. The approach is developed based on matched-field processing for the likelihood of passive source localisation in the shallow water environment. Inter-position processing is also used for the improved localisation performance and the enhanced stability of the estimation process against the lack of spatial gain due to the small physical size of the flank array. The proposed approach is presented and validated through simulation and experimental data. The results illustrate the localisation performance at different signal-to-noise ratios and demonstrate the build up over time of the positional parameters of the estimated source as the autonomous underwater vehicle cruises at a low speed along a straight line at a constant depth.

Keywords: Passive source localisation, flank array, autonomous underwater vehicle, matched-field processing, inter-position processing

1. INTRODUCTION

The technology of autonomous underwater vehicles (AUVs) has developed greatly over the last few decades, which is spurred by AUVs' low cost and ability to operate at sites that can rarely be reached by ship-based systems. AUVs are being extensively used in scientific research, defense, surveys, and industry today[1,2]. They have excellent characteristics such as low self-noise and vibration coupled with high stability all of which make AUVs become excellent platforms for quantitative acoustic measurements[1,3]. Shallow water acoustics is a very active area of underwater acoustic research as the continental shelves and slopes have great economic, social, and military importance to humans[4], and the flank of an AUV enlarges the aperture of the array and establishes a better foundation in weak signal detection[5]. Therefore, passive source localisation using the AUV's flank array in shallow water is also expected to obtain better performance.

Previous work has been done on the application of target motion analysis (TMA) to this localisation problem on the basis of exploiting receiver or source motion[6]. TMA is capable of determining the acoustic source's trajectory (i.e., bearing, range, speed, course, and possibly depth) in the open ocean where the ray assumption is valid[7,8]. Thus far, this method has been traditionally accomplished by conducting a series of maneuvers. Changes in relative motion are then analyzed using standard geometrical techniques and assumptions about limiting cases[9]. The flank array referred to here is usually less than ten meters due to the limited physical size of the AUV, so it is usually difficult to acquire sufficient spatial gain for localizing long-range sources. Researchers have been trying to apply the passive synthetic aperture sonar technique to the flank array by coherently combining the data from widely separated spatial sampling points[10-12]. One goal is to increase bearing resolution by synthesizing a longer array aperture. Although the combination of active synthetic aperture sonars with AUVs is well established[13], passive synthetic aperture processing is still more controversial where the large number of unknown source parameters may vitiate the technique[6]. The motion of the array can further increase the measurement uncertainty. It should be noted that both of the methods described above do not work well in shallow water.

The shallow water environment is extremely complex, and the assumption of plane waves in the processing scheme can lead to severe degradation of the estimation[8,9]. Matched-field processing (MFP) is a localisation technique that exploits the complexity of the ocean's structure to improve source localisation[14,15]. This process constitutes a depth-range ambiguity surface for the two-dimensional (2D) scenario, as it spatially correlates the actual field (measured at an array of sensors emitted from a point source at a particular location) with the replica field (computed by a numerical propagation model over a grid of hypothetical source locations). The maximum match on the ambiguity surface is regarded as the estimated source location. Given sufficient ocean environmental information, MFP has been shown to be a promising signal processing technique[8,9,16,17].

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The intent of this study is to combine MFP and the flank array of an AUV for three-dimensional (3-D) passive source localisation in shallow water. In MFP theory, increasing the array length to span more of the water column can significantly improve MFP performance in sidelobe reduction and peak resolution for the vertical linear array. The horizontal linear array usually requires much longer array length than the vertical array for the same localisation performance[14,18]. Therefore, the direct application of MFP to the flank array of an AUV would result in presumed failure in estimating the source positional parameters (i.e., depth, range, and cross-range). Thus, a localisation approach is proposed based on MFP for the likelihood of passive source localisation in shallow water. Furthermore, inter-position processing is employed for the improved localisation performance and the enhanced stability of the estimation process. It generally includes two steps: processing in space domain and parameter estimation in time domain. The positional parameters of the estimated source is built up over time through incoherent combination of the matched-field localisation (MFL) outputs generated at widely separated sampling positions as the AUV cruises at a low speed along a straight line at a constant depth. An additional merit is that this estimation process does not require compensation for a series of complex maneuvers, which is usually required in synthetic aperture processing. Compensating the motion requires additional costs and high fidelity, which may be not realistic in a harsh ocean environment, such as the Yellow Sea.

2. LOCALISATION APPROACH

According to the above description of the proposed localisation approach, the MFL output is first generated using the selected matched-field processor as the AUV cruises along a straight line to each sampling position; it is constructed by stacking the depth-range ambiguity surfaces into one 3-D (depth, range, and cross-range) 'ambiguity cube'. Then, the source localisation output is formed by averaging all of the generated MFL outputs at previous sampling positions. Finally, the positional parameters of the source of interest are estimated using the simple 'peak picker' algorithm from these 'ambiguity cubes'.

In order to overcome the lack of spatial gain due to the small physical size of the flank array, the high resolution matched-field processor is chosen to discriminate the source of interest from the noise background at each sampling position. Incoherent broadband MFP is also used to increase the amount of available data and to stabilize the estimation process because there is no requirement for phase relationships across frequency; it is a widely used approach for taking advantage of the temporal complexity of the signal for an additional gain over narrowband processing[14,19]. Inter-position processing further exploits the spatial complexity of the signal for the improved localisation performance.

The minimum variance distortionless response (MVDR) processor is a high resolution adaptive MFP method, of which the essence is 'optimum in the sense that the output noise power be minimized subject to the constraint of unity undistorted signal response from the desired source location'[14,15]. Its weight vector $\boldsymbol{w}$ is determined by solving

$$\min_{w} \boldsymbol{w}^{*}\boldsymbol{R}\boldsymbol{w} \text{ subject to } \boldsymbol{w}^{*}\boldsymbol{d} = 1, \tag{1}$$

where $\boldsymbol{R}=E\{\boldsymbol{x}\boldsymbol{x}^{*}\}$ is the cross-spectral density matrix (CSDM) at the frequency of interest, $E\{\}$ denotes the expectation value operation, and $\boldsymbol{x}$ is the data vector. The superscript * represents the conjugate transpose operation, and $\boldsymbol{d}$ is the replica vector.

The well-known solution of this optimization problem is

$$\boldsymbol{w}_{MVDR} = \frac{\boldsymbol{R}^{-1}\boldsymbol{d}}{\boldsymbol{d}^{*}\boldsymbol{R}^{-1}\boldsymbol{d}}. \tag{2}$$

Then, the output of the MVDR processor is expressed by

$$\boldsymbol{P}_{MVDR} = \boldsymbol{w}^{*}_{MVDR}\boldsymbol{R}\boldsymbol{w}_{MVDR} = \frac{1}{\boldsymbol{d}^{*}\boldsymbol{R}^{-1}\boldsymbol{d}}. \tag{3}$$

Consider the noisy data vector $\boldsymbol{x}_{f_j} = \boldsymbol{s}_{f_j} + \boldsymbol{n}$ received by $\boldsymbol{N}$ hydrophones in the flank array at the jth frequency component. The signal vector $\boldsymbol{s}_{f_j}$ is normalized such that $\| \boldsymbol{s}_{f_j} \| = 1$, where $\| \boldsymbol{s}_{f_j} \|$ is the L_2 norm of $\boldsymbol{s}_{f_j}$. The additive noise vector $\boldsymbol{n}$ is white, Gaussian, zero-mean, and uncorrelated with the signal vector $\boldsymbol{s}_{f_j}$. Computationally, the components n_i are generated using the Box-Muller formula[20]:

$$n_i = \sigma_n \sqrt{-\log X_i}\, e^{i\,2\pi Y_i}, \tag{4}$$

where the noise strength $\sigma_n^2 = 1/(Nr)$, r denotes the input SNR averaged across the flank array, and X_i and Y_i are random variables with uniform distribution on the interval (0,1).

The CSDM at the jth frequency component is constructed as follows:

$$\boldsymbol{R}_{f_j} = \boldsymbol{E}\{\boldsymbol{x}_{f_j}\boldsymbol{x}^{*}_{f_j}\} = \sum_{l=1}^{L} \boldsymbol{x}^{l}_{f_j}\boldsymbol{x}^{l\,*}_{f_j}, \tag{5}$$

where L is the total number of realizations (snapshots).

Then, the normalized CSDM at the vth sampling position is expressed by

$$\boldsymbol{K}^{v}_{f_j} = \frac{\boldsymbol{N}\boldsymbol{R}^{v}_{f_j}}{(1+\sigma_n^2)L}, \tag{6}$$

which yields

$$\boldsymbol{P}^{v}_{f_j} = \boldsymbol{w}^{v\,*}_{f_j}\boldsymbol{K}^{v}_{f_j}\boldsymbol{w}^{v}_{f_j}. \tag{7}$$

If M is the number of discrete frequencies considered, then the final source localisation output at the vth sampling position is

$$P_{output} = \frac{P^{1}_{f_1} + P^{1}_{f_2} + \cdots + P^{1}_{f_M} + \cdots + P^{v}_{f_1} + P^{v}_{f_2} + \cdots + P^{v}_{f_M}}{v} \tag{8}$$

3. PERFORMANCE SIMULATION

A 3-D coordinate system is employed as shown in Fig. 1, where z is the depth below the ocean surface, the range r is the horizontal distance in the array broadside direction, and the cross-range cr is the horizontal distance in the array endfire direction. The test scenario is described as follows. An AUV cruises towards the source at a speed of 2 m/s along a straight line at 50 m depth. Its right flank array comprised of 6 hydrophones that are evenly spaced at 1 m intervals is used to localize the source. A single stationary acoustic source located at 26 m depth, 4502 m range, and 4498 m cross-range measured from the start position of the flank array emits multitone signals at 75 Hz, 100 Hz, 150 Hz, and 250 Hz. The search

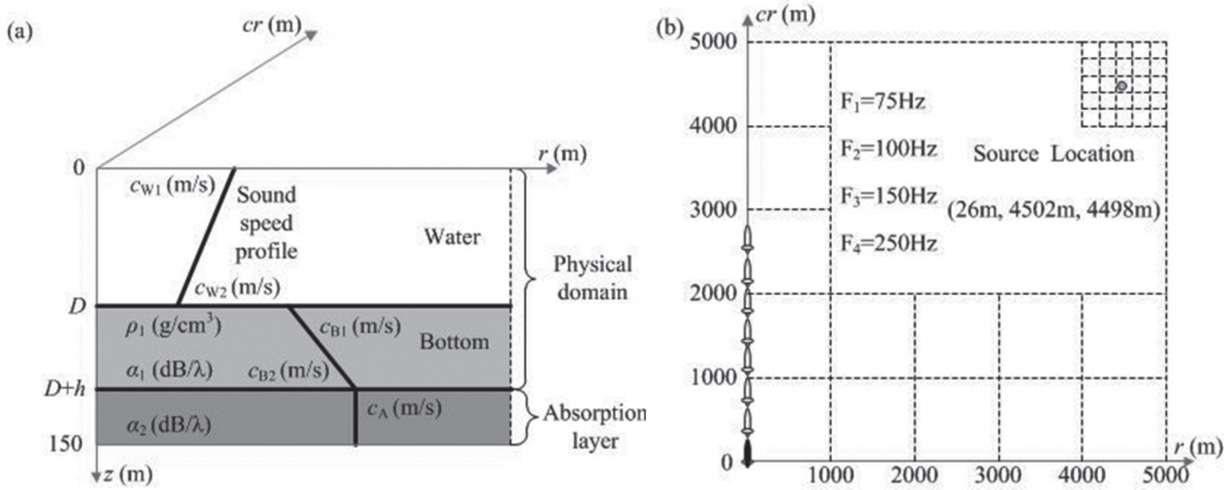

Figure 1. (a) The coordinate system and the schematic of the ocean environment and (b) the geometric configuration of the source and the flank array.

region extends from 0 m to 100 m in depth, from 4 km to 5 km in range, and from 4 km to 5 km in cross-range (as measured from the start position of the flank array). The corresponding search grid spacing is 4 m in depth, 50 m in range, and 50 m in cross-range. The horizontal distance between the adjacent uniformly separated sampling positions is 100 m.

An ocean environmental model representative of the shallow water[16] was chosen for this study as shown in Fig. 1(a). The model consists of a water column of depth (D) and a seabed with a sediment layer of thickness (h) over a semi-infinite basement. The seabed geoacoustic parameters include the sound speed at the top (c_{B1}) and bottom (c_{B2}) of the sediment layer, density (ρ_1) and attenuation (α_1) in the sediment, and the constant sound speed equal to (c_{B2}) and attenuation (α_2) in the basement. The sound speed profile (SSP) in the water column is described by two parameters, (c_{w1} and c_{w2}) at depths of 0 m and D m. The sound propagation for this environmental model is modeled based on parabolic equation theory[21, 22].

The ocean environmental mismatch is unavoidable and is likely the most outstanding obstacle to the general experimental application based on high resolution adaptive MFP[14,15]. Table 1 shows the detailed values of the ocean environmental parameters used in simulation study. Different ocean environmental parameter sets are used for calculating the data vector and the replica vectors, which simulate the ocean environmental mismatch. In addition, actually the positions of the flank array cannot be estimated exactly every time when the replica vectors are calculated. Therefore, the errors of the estimated flank array positions in depth, range, and cross-range always exist, and their errors are all assumed to be 2 m in this study. It should be noted that all of the nodes in the 3-D search region miss the true source location, which also challenge the localisation performance.

The authors intend to find out how the convergence over time of the estimated source location to the true source location and how the ocean environmental mismatch and the position errors of the flank array affect the localisation performance in this problem. To address this question, 300 snapshots are generated for each sampling position and each frequency component, and 30 sampling positions are processed. Thus, the source localisation output is updated every 50 s, and the interval for the updated localisation outputs between the first and the last sampling positions is 1450 s. For each updated localisation output, the source location is estimated with respect to the current position of the flank array.

Figures 2 and 3 display the depth versus range ambiguity surfaces all of which involve the peak (the maximum match) in their corresponding 'ambiguity cubes' at signal-to-noise ratios (SNRs) of 40 dB and 10 dB, respectively. The four plots in each figure are extracted and selected from 30 source localisation outputs generated at 30 sampling positions. The circles denote the true source location in these plots. Figure 2 shows that the source of interest gradually appears at the correct location and that sidelobes are better suppressed over time even in the presence of various ocean environmental mismatch and position errors of the flank array. It means that the MVDR processor exploits the information well arising from the source of interest at each sampling position and that its shortcoming of sensitivity to ocean environmental mismatch and position errors of the flank array can be overcome through inter-position processing. Figure 3 shows that the source of interest can be also localized at the true source location but with higher sidelobes compared to the results as shown in Fig. 2. It can be seen that localisation performance degrades as the noise level increases and that

Table 1. Ocean environmental parameters used in simulation study

Parameter (unit)	c_{W1} (m/s)	c_{W2} (m/s)	c_{B1} (m/s)	c_{B2} (m/s)	c_A (m/s)	α_1 (dB/λ)	α_2 (dB/λ)	ρ_1 (g/cm^3)	D (m)	h (m)
data vector	1475	1471	1512	1573	1573	0.30	10.0	1.64	115.5	13
replica vector	1469	1465	1494	1547	1547	0.14	10.0	1.36	114.5	11

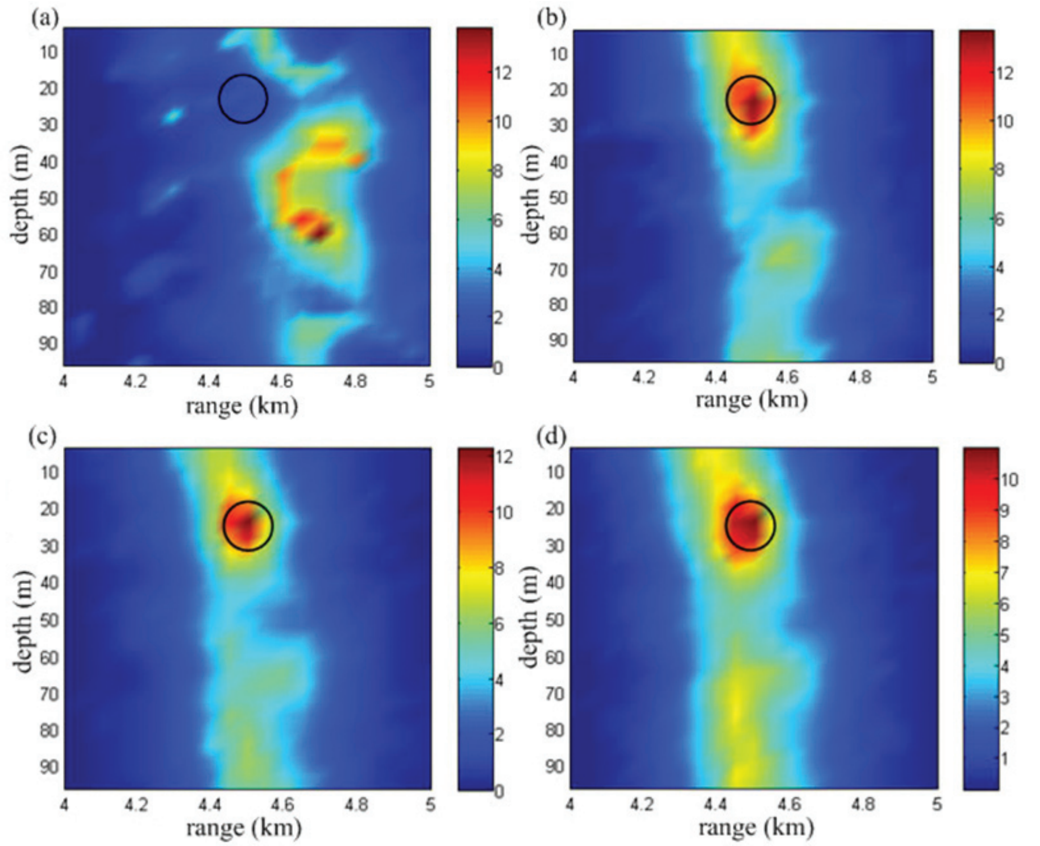

Figure 2. Depth versus range ambiguity surfaces at a SNR of 40 dB after (a) 0 s, (b) 450 s, (c) 950 s, and (d) 1450 s.

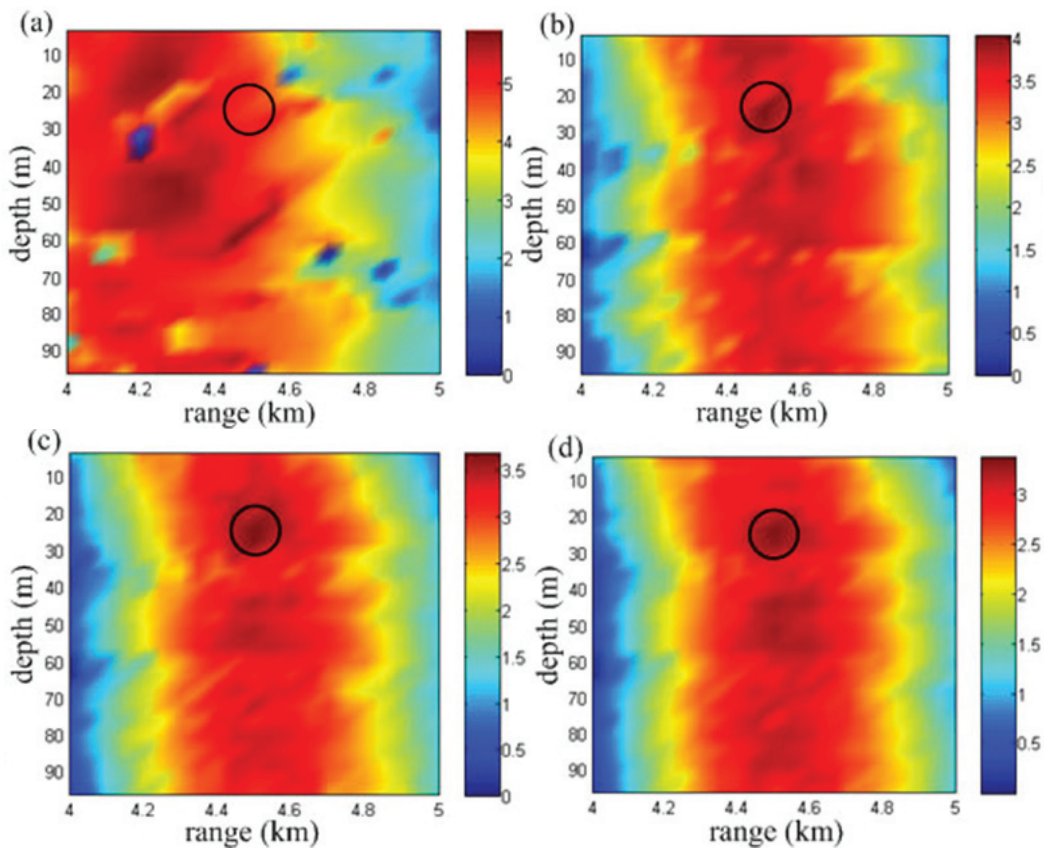

Figure 3. Depth versus range ambiguity surfaces at a SNR of 10 dB after (a) 0 s, (b) 450 s, (c) 950 s, and (d) 1450 s.

source depth estimation is still problematic for the horizontal linear array.

To get better localisation performance, more information arising from the source of interest is going to be required. Utilization of the additional information provided by an acoustic vector sensor (AVS) array may be a good choice. An acoustic vector sensor consists of two or three identical but orthogonally oriented velocity hydrophones plus one pressure hydrophone, so it can measure the three components of the acoustic particle velocity and the pressure field at a single point in space. The characteristic has been introduced into MFP which is adapted to incorporate the particle velocity for better estimation performance[23,24]. Nowadays 100-meter-long vector sensor arrays capable of acoustically detecting and tracking other vessels are carried by AUVs[25]. However, an AVS array usually takes more room than a scalar sensor array, so how to place an AVS array in a small AUV still needs more consideration.

Figure 4 presents the source depth estimation, range estimation, and cross-range estimation versus time at SNRs of 40 dB and 10 dB. The circles denote the true source positional parameters and the asterisks denote the estimated source positional parameters. The parameter estimation is considered to be acceptable if the absolute depth error is less than 6m and the absolute range and cross-range errors are both less than 600 m[16]. It is seen that the estimated source positional parameters appear within the acceptable estimation range after 6 min in this simulation study.

4. EXPERIMENTAL RESULTS

An experiment to study acoustic localisation and tracking using an AUV was conducted in a lake in the year 2010. The experimental scenario is described as follows. An acoustic source is suspended at a depth of about 5 m by a ship. The AUV moves towards the source at a speed of 4 kn along a straight line at about 10 m depth. The source is at the endfire of the flank array of the AUV, so two positional parameters (depth and range) are estimated. The initial distance between the source and the AUV is about 700 m. The average water depth of the lake is about 80 m. The sound speed profile is measured by a hydrological information collecting instrument, and the bottom geoacoustic parameters are not very clear. Figure 5 shows the environmental parameters for calculating the replica vectors. Due to practical constraints, the measured data here are only at a frequency of 150 Hz, only five hydrophones of the flank array are used, and the spacing of the hydrophones is about 0.5 m. The search region extends from 0 m to 80 m in depth, and from 600 m to 800 m in range (as measured from the start position of the flank array). The corresponding search grid spacing is 1 m in depth, and 2 m in range. The horizontal distance between the adjacent uniformly separated sampling positions is 50 m, and 12 sampling positions are processed.

Figure 6 presents the depth versus range ambiguity surfaces generated from the fifth sampling position to the last one. The

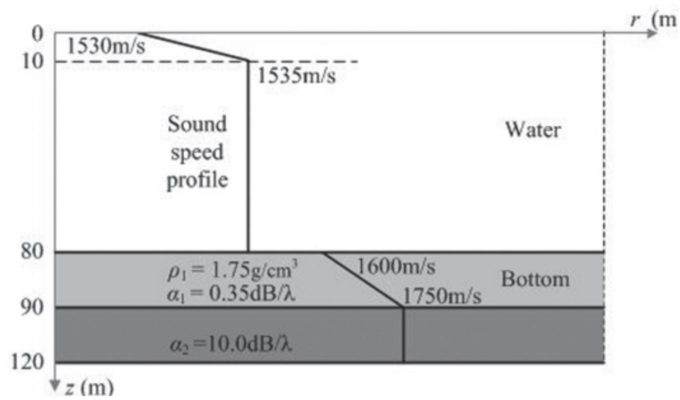

Figure 5. Environmental model for the replica vectors.

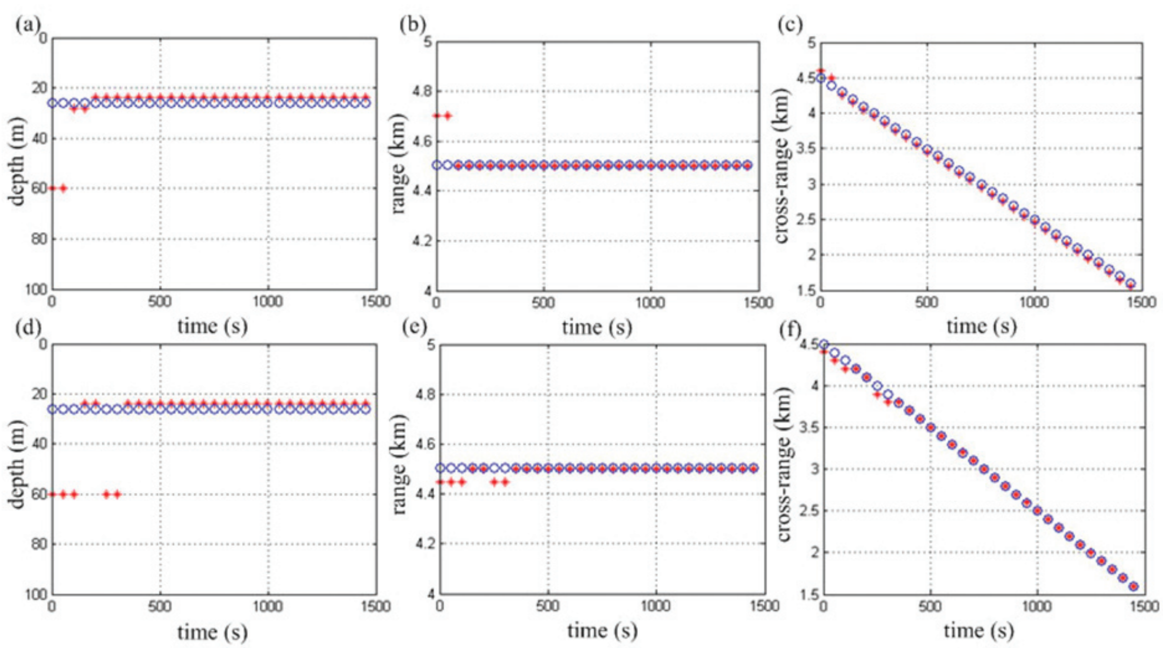

Figure 4. Depth estimation versus time at SNRs of (a) 40 dB and (d) 10 dB, range estimation versus time at SNRs of (b) 40 dB and (e) 10 dB, and cross-range estimation versus time at SNRs of (c) 40 dB and (f) 10 dB.

circles denote the true source location, and the arrows denote the estimated source location. It can be seen that the source of interest is gradually discriminated from the background, which is consistent with the simulation results, though the estimated source does not appear at the correct location over time. The acoustic environment of the lake is relatively stable. The source location is known in advance. SSP information is relatively accurate, and SNR is also high. All of above conditions are advantageous to localisation, but uncertain geoacoustic parameters degrade the localisation performance.

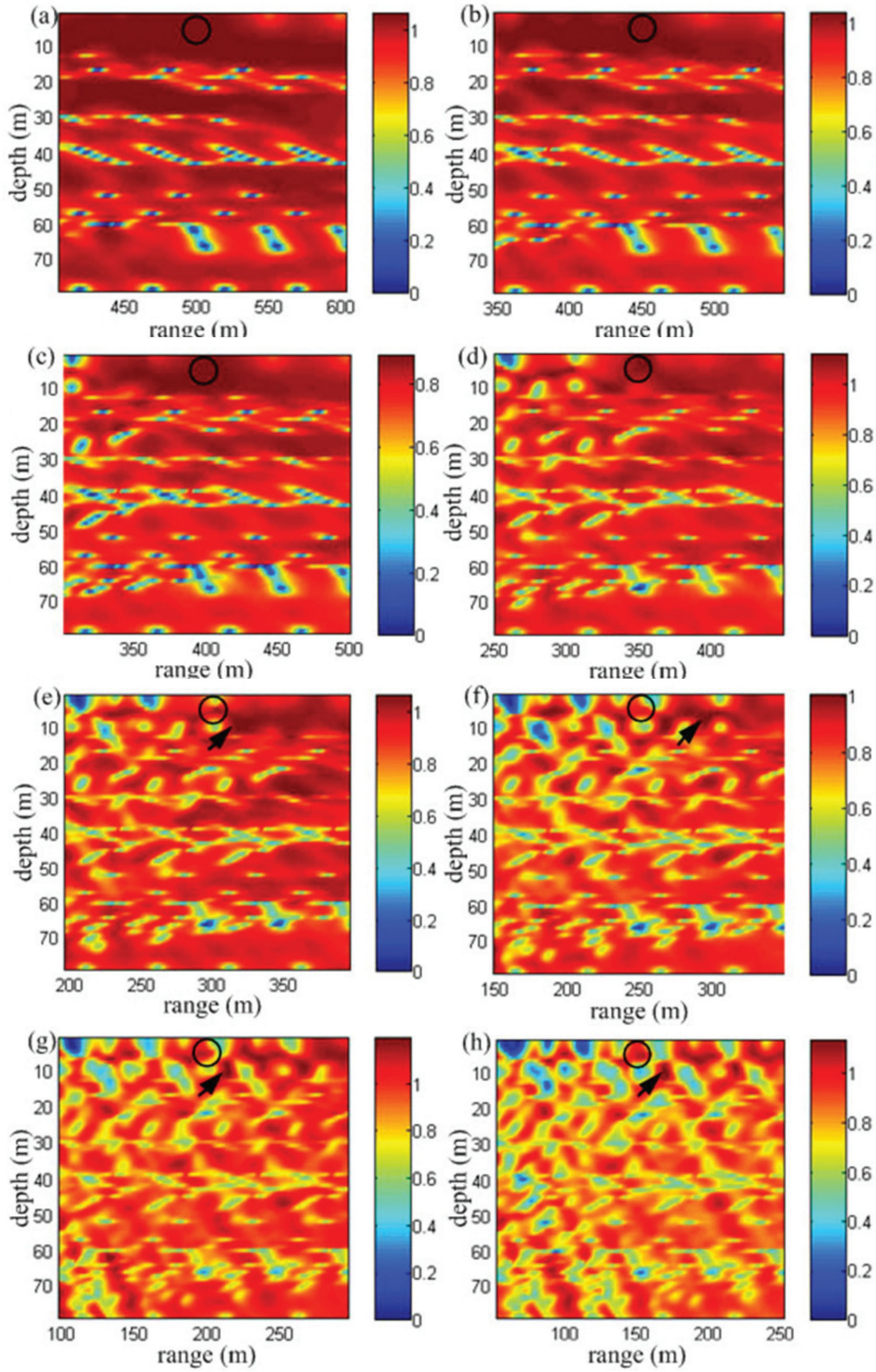

Figure 6. Depth versus range ambiguity surfaces at the (a) 5th, (b) 6th, (c) 7th, (d) 8th, (e) 9th, (f) 10th, (g) 11st, and (h) 12nd sampling position.

6. CONCLUSIONS

This paper presents a localisation approach to 3-D passive source localisation using the flank array of an AUV in shallow water. The proposed approach is based on matched-field processing which enables the use of the flank array of an AUV for passive source localisation in the shallow water environment. The approach also employs inter-position processing to improve its localisation performance and enhance the stability of the estimation process. The proposed approach was applied to synthetic data in a simulated environment at different SNRs. The results show that the source positional parameters can be built up over time as the AUV cruises at a low speed along a straight line at a constant depth. The high resolution MVDR processor is required in the proposed localisation approach to exploit the information as much as possible arising from the source of interest at each sampling position, and its shortcoming of high sensitivity to ocean environmental mismatch and position errors of the flank array can be gradually restrained over time. The approach was further applied to measured data to show to have the prospect of engineering application.

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