Cross correlation matched field localization for unknown emitted signal waveform using two-hydrophone

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ABSTRACT

Source localization is a crucial issue in underwater acoustics. Traditional matched field processing (MFP) use large vertical arrays to locate an underwater acoustic target. However, the use of the large arrays not only increases equipment and computational cost but also some problems such as element failures and array title degrades the localization performance. In this paper, the matched field localization method of using two-hydrophone is proposed for underwater acoustic pulse signals with unknown emitted signal waveform. Firstly, using the received signal of hydrophones and the ocean channel which can be calculated from an acoustic propagation model, the emitted signal for every grid location over search region can be estimated by using the least squares solution in the time domain. And then, the estimated signal is convolved with the ocean channel pulse for various trial source locations to generate the replica signal. Finally, matched field localization of using two-hydrophone for underwater acoustic pulse signals of unknown emitted signal can be estimated by comparing the difference between the cross correlation of the received signal and the cross correlation of the replica signal to construct the localization error function yielding the ambiguity surface of localization function. Theoretical analysis and numerical simulation demonstrate the effectiveness of the proposed matched field localization and the localization performance were analyzed under different signal to noise ratio (SNR) cases by simulation trial.

Key words: Underwater acoustic signal, Matched Field Processing, Source Localization

I-INCE Classification of Subjects Number(s): R2

1. INTRODUCTION

Source localization is a crucial issue in underwater acoustics. Considering the complexity of underwater acoustic environment, a number of literatures employ the matched field processing (MFP) technique to locate an acoustic source [1-6]. Traditional matched field processing methods mostly use vertical hydrophone arrays with significant apertures in order to obtain sufficient source location spatial discrimination. However, using hydrophone arrays with many elements, on the one hand, increases equipment and computational cost, on the other hand, some problems such as element failures in the array and array tilt degrades the acoustic source estimation performance. Therefore, the interest of researchers has been motivated by employing less number of elements to locate an underwater acoustic source[7-16].

The difficulty of using the less number of elements to locate a source location is the lack of spatial information. Many studies use the broadband signal with multi-frequencies and make the further assumption that the emitted signal is known, however, in many instances, especially in the passive location, the knowledge of the source signal may not be obtained, in addition, the complexity of the ocean environment will further increase the difficulty of the source localization.

In this paper, we propose a new source localization method known as cross correlation matched field (CCMF) localization for acoustic pulse signals with unknown emitted waveform using two-hydrophone. We draw lessons from the least square approach to matched field with a single hydrophone proposed by Chapin[13], and the key idea behind the proposed method is to compare the cross correlation of the

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measured signal and the cross correlation of the replica signal which can be realized by employing the method of least squares. The localization algorithm is theoretically derived and some results are presented by numerical simulation.

The paper is organized as follows. In section II, data model and replica signal is presented. In section III, the estimation algorithm of source location is described. Section IV, shows some of the simulation results. In section V, conclusions are drawn.

2. Data Model and Replica Signal

2.1 Data Model

We consider an array system consisting of two hydrophones. Each of the hydrophone received signal, for a fixed source-receiver position, can be expressed by a convolution integral, with additive Gaussian noise

$$\begin{aligned} r_j(t) &= s(t) * h_j(t) + n_j(t) \\ &= \int_{-\infty}^{\infty} s(\tau) h_j(t-\tau) d\tau + n_j(t)\ , \quad j = 1,2 \end{aligned} \tag{1}$$

where $s(t)$ is the emitted signal at location (r_0, z_0), $h_j(t)$ is the ocean impulse response, and $n_j(t)$ is the additive noise. In a discrete time system, equation (1) can be described as

$$r_j(n) = \sum_{m=0}^{N-1} s(m) h_j(n-m) + n_j(n) \tag{2}$$

where m and n indicate the value of $\boldsymbol{s}$ and $\boldsymbol{h}$ at discrete times m and n. Equation (2) can be written using matrix notation as

$$\boldsymbol{r}_j = \boldsymbol{H}_j \boldsymbol{s} + \boldsymbol{n}_j = \boldsymbol{r}_j + \boldsymbol{n}_j\ ,\ j = 1,2 \tag{3}$$

where

$$H_j = \begin{bmatrix} h_j(0) & h_j(1) & \cdots & h_j(N-1) & \cdots & 0 \\ 0 & h_j(0) & \cdots & h_j(N-2) & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & h_j(0) & \cdots & h_j(N-1) \end{bmatrix}^T$$

$$\boldsymbol{s} = \left[\ s(0), s(1), \cdots, s(N-1)\right]^T$$

$$\boldsymbol{r}_j = \left[\ r_j(0), r_j(1), \cdots, r_j(2N-2)\right]^T$$

$$\boldsymbol{n}_j = \left[\ n_j(0), n_j(1), \cdots, n_j(2N-2)\right]^T$$

where $\boldsymbol{H}_j$ is the convolution matrix formed from the elements of $\boldsymbol{h}_j$, $\boldsymbol{s}$ is the source signal vector with length N, $\boldsymbol{r}_j$ is the received signal vector with length $2N$-1, the noise vector $\boldsymbol{n}_j$ is of length $2N$-1.

2.2 Replica Signal

If the environmental parameters such as the sound speed profile of the water, water column depth and sediment characteristics are known, the ocean impulse response can be calculated for various trial locations of source by an acoustic propagation model. Thus, we can obtain a set of trial convolution matrix $\hat{\boldsymbol{H}}_j(r,z)$ over search region of possible source locations.

Assuming that the source-emitted waveform $s(t)$ is known, the replica signal can then be calculated by convolving the emitted signal with an impulse response, $h_j(t)$ or multiplying the source-emitted waveform by convolution matrix $\boldsymbol{H}_j$. However, if the emitted signal waveform is assumed to be unknown, then the replica signal could not be obtained directly. This problem can be solved by employing the method of least squares[13]. The emitted signal waveform for every grid location over search region can be estimated by the convolution matrix of the ocean channel pulse response and the received signal of hydrophones.

The least squares solution of the emitted signal can be written as follows[13]

$$\hat{\boldsymbol{s}} = (\hat{\boldsymbol{H}}_j^T \hat{\boldsymbol{H}}_j)^{-1} \hat{\boldsymbol{H}}_j^T \boldsymbol{r}_j = \hat{\boldsymbol{H}}_j^+ \boldsymbol{r}_j \tag{4}$$

where $\hat{\boldsymbol{H}}_j^+$ is the pseudo-inverse of $\hat{\boldsymbol{H}}_j$. The replica signal is generated by multiplying convolution matrix $\hat{\boldsymbol{H}}_j$ by the estimated signal $\hat{\boldsymbol{s}}$

$$\begin{aligned} \hat{\boldsymbol{r}}_j &= \hat{\boldsymbol{H}}_j \hat{\boldsymbol{s}} = \hat{\boldsymbol{H}}_j \hat{\boldsymbol{H}}_j^+ \boldsymbol{r}_j = \hat{\boldsymbol{H}}_j \hat{\boldsymbol{H}}_j^+ (\boldsymbol{H}_j \boldsymbol{s} + \boldsymbol{n}_j) \\ &= \hat{\boldsymbol{H}}_j \hat{\boldsymbol{H}}_j^+ \boldsymbol{H}_j \boldsymbol{s} + \hat{\boldsymbol{H}}_j \hat{\boldsymbol{H}}_j^+ \boldsymbol{n}_j \\ &= \hat{\boldsymbol{x}}_j + \hat{\boldsymbol{n}}_j, \quad j = 1,2 \end{aligned} \tag{5}$$

3. Cross Correlation MFP

In this section, we show how to use the cross correlation matched field processing to locate an acoustic source with unknown emitted signal waveform. The basic idea of the proposed method is to calculate the cross correlation of received signals and replica signals of two hydrophones respectively.

The cross correlation between the received signals of two hydrophones can be written as

$$\begin{aligned} \rho_{12} &= r_1(n) \odot r_2(n) \\ &= \left(x_1(n) + n_1(n)\right)\left(x_2(n) + n_2(n)\right) \\ &= x_1(n) \odot x_2(n) + x_1(n) \odot n_2(n) + \\ &\quad n_1(n) \odot x_2(n) + n_1(n) \odot n_2(n) \end{aligned} \tag{6}$$

where $\odot$ represents the cross correlation operation.

Assume that signal and noise are completely unrelated, and the cross correlation between n_1 and n_2 of two hydrophones are also completely unrelated, then equation (6) can be rewritten as

$$\rho_{12}(m) = x_1(n) \odot x_2(n) = \sum_{n=0}^{2N-2} x_1(n) x_2(n+m) =$$

$$\begin{bmatrix} 0 & \cdots & x_2(0) & \cdots & x_2(2N-2) \\ 0 & \cdots & x_2(1) & \cdots & 0 \\ \vdots & \cdots & x_2(2) & \cdots & 0 \\ 0 & \cdots & \vdots & \cdots & \vdots \\ x_2(0) & \cdots & x_2(2N-2) & \cdots & 0 \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} x_1(0) \\ x_1(1) \\ x_1(2) \\ \vdots \\ x_1(2N-2) \end{bmatrix}$$

$$= W_2^T x_1, \quad m=-2N+2,\cdots,2N-2 \tag{7}$$

Similarly, the cross correlation between replica field signals of two hydrophones can be written as

$$\begin{aligned} \hat{\rho}_{12}(m) &= \hat{x}_1(n) \odot \hat{x}_2(n) = \sum_{n=0}^{2N-2} \hat{x}_1(n) \hat{x}_2(n+m) \\ &= \hat{W}_2^T \hat{x}_1 \end{aligned} \tag{8}$$

Then, the error sum of squares between the cross correlation of measured signals and the cross correlation of replica signals can be written as

$$\begin{aligned} \|e\|_2^2 &= \|\rho_{12} - \hat{\rho}_{12}\|_2^2 \\ &= \left\|\mathbf{W}_2^{\mathbf{T}} \mathbf{x}_1 - \hat{\mathbf{W}}_2^{\mathrm{T}} \hat{\mathbf{x}}_1\right\|_2^2 \\ &= \left\|\mathbf{W}_2^{\mathrm{T}} \mathbf{H}_1 \boldsymbol{s} - \hat{\mathbf{W}}_2^{\mathrm{T}} \hat{\mathbf{H}}_1 \hat{\mathbf{H}}_1^+ \mathbf{H}_1 \boldsymbol{s}\right\|_2^2 \\ &= \left\|(\mathbf{W}_2^{\mathbf{T}} - \hat{\mathbf{W}}_2^{\mathbf{T}} \hat{\mathbf{H}}_1 \hat{\mathbf{H}}_1^+) \mathbf{H}_1 \boldsymbol{s}\right\|_2^2 \end{aligned} \tag{9}$$

Thus, the localizer of the cross correlation matched field processing can be formed as follows

$$L(r,z) = 1/\|e\|_2^2 = 1/\|\rho_{12} - \hat{\rho}_{12}\|_2^2 \tag{10}$$

when the convolution matrix for various possible source locations is same as the convolution matrix for true source location, we have $\hat{\mathbf{H}}_j(r,z) = \mathbf{H}_j(r_0, z_0)$ and

$$\begin{aligned} \hat{\mathbf{x}}_j &= \hat{\mathbf{H}}_j \hat{\mathbf{H}}_j^{+} \mathbf{H}_j \mathbf{s} = \mathbf{H}_j \mathbf{H}_j^{+} \mathbf{H}_j \boldsymbol{s} \\ &= \mathbf{H}_j \boldsymbol{s} = \mathbf{x}_j \end{aligned} \tag{11}$$

Therefore, $\hat{\mathbf{W}}_2 = \mathbf{W}_2$.

Now, the equation (9) becomes

$$\begin{aligned} \|e\|_2^2 &= \|(\mathbf{W}_2^{\mathrm{T}} - \mathbf{W}_2^{\mathrm{T}} \mathbf{H}_1 \mathbf{H}_1^{+}) \mathbf{H}_1 \boldsymbol{s}\|_2^2 \\ &= \|\mathbf{W}_2^{\mathrm{T}} (\mathbf{I} - \mathbf{H}_1 \mathbf{H}_1^{+}) \mathbf{H}_1 \boldsymbol{s}\|_2^2 \\ &= \|\mathbf{W}_2^{\mathrm{T}} \mathbf{P}_{\mathbf{H}_1}^{\perp} \mathbf{H}_1 \boldsymbol{s}\|_2^2 = 0 \end{aligned} \tag{12}$$

where $\mathbf{P}_{\mathbf{H}_1}^{\perp}$ is the orthogonal projection matrix of the matrix $\mathbf{H}_1$.

It can be seen clearly from the equation (12) that the error sum of squares is then equal to zero when trial source location corresponding to actual source location, therefore, the output of the cross correlation matched field processor achieve a maximum value. However, the replica signal $\hat{\mathbf{x}}_j$ is not equal to the measured signal $\mathbf{x}_j$ when trial source location not corresponding to actual source location, then the error sum of squares $\|e\|_2^2 \neq 0$, therefore, the output of cross correlation matched field processor could not achieve maximum value.

Finally, the true source location can be found by

$$(\hat{r}_0, \hat{z}_0) = \arg\max_{r,z} L(r,z) \tag{13}$$

4. Simulation Results

In this section, we present the simulation results of the proposed CCMF processor. For comparison, the classical Bartlett MFP is simulated as well under the same waveguide environment condition. The simulated shallow-water environment is a stratified waveguide model, which consists of a water column, multilayer sediment and half-space basement. The water column depth is 110m and water density is 1.0g/cm^3, the sound speed profile of the water and geoacoustic properties shown in Fig1. Let us consider a LFM pulse with duration 20ms and frequency band from 150 to 350Hz. A sound source is assumed to be located at (r,z)=(5km,60m), two hydrophones at depth of 50m and 70m , respectively.

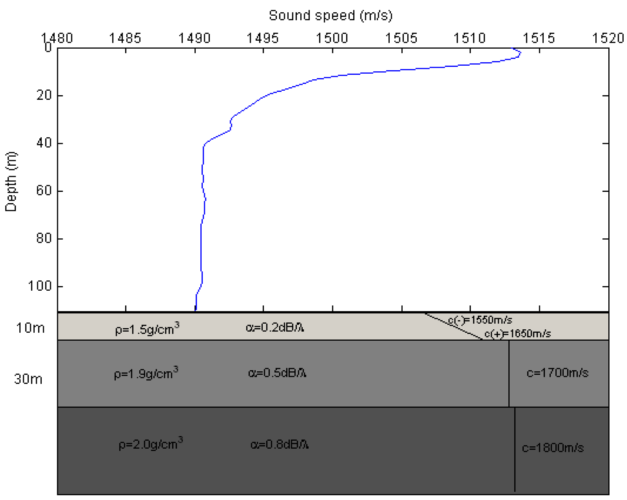


Figure1—Simulated ocean environment model

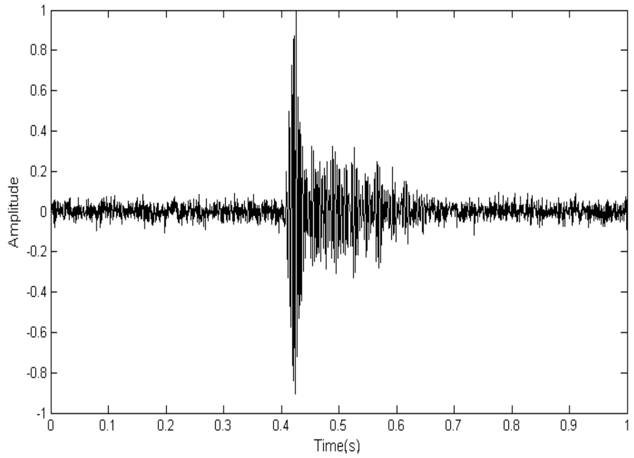


Figure2—Received signal at 50m depth and 5Km range

The received signal of two hydrophones are calculated by multiplying the convolution matrix for the actual source location by the emitted signal and adding a white Gaussian noise with the signal to noise ratio(SNR) of 10dB. The received signal of a single hydrophone is shown in Figure2.

Replica signal were computed for 100m increments in range from 2km to 7km, for 2.5m increments in depth from 5 to 105m. Figure3 (a) shows the ambiguity surface for the CCMFP. It is easily seen from the result that the CCMFP is able to accurately localize, target and peek position more clearly. For comparison, the Bartlett MFP ambiguity surface is shown in Figure3 (b). From Figure3 (b), we see that the Bartlett MFP is not able to localize an acoustic source due to lack of the number of hydrophones.

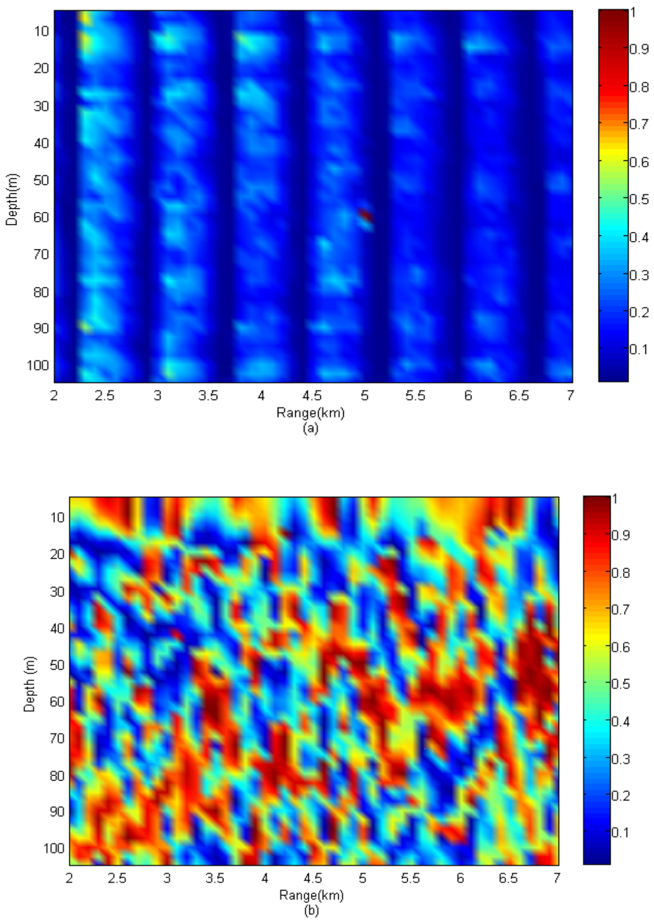


Figure3—Ambiguity surface for (a) CCMFP (b) Bartlett MFP

To assess the effect of environmental uncertainty on the proposed localization algorithm, we introduced the uncertain environmental case which contained six uncertain environmental parameters whose ranges of uncertainty are given in Table1.

Table 1—Uncertain environmental parameters

water depth	sediment attenuation	sediment density	sediment thickness	sediment upper-sound speed	sediment lower-sound speed
110±2.5m	0.1~0.3dBλ	1.4~1.6g/cm3	10±2.5m	1550±2m/s	1650±2m/s

The localization performance was tested using the Monte Carlo simulation trials, 50 environmental realizations were randomly selected from the uncertainty intervals of the parameters given in Table1 to generate a trial data. A correct localization was defined as a estimate within a region of ±500m in range and ±10m in depth of the true source location. The histograms of the localization results in range and depth plot of the localization error for the proposed localization algorithm are shown in Figure4, respectively.

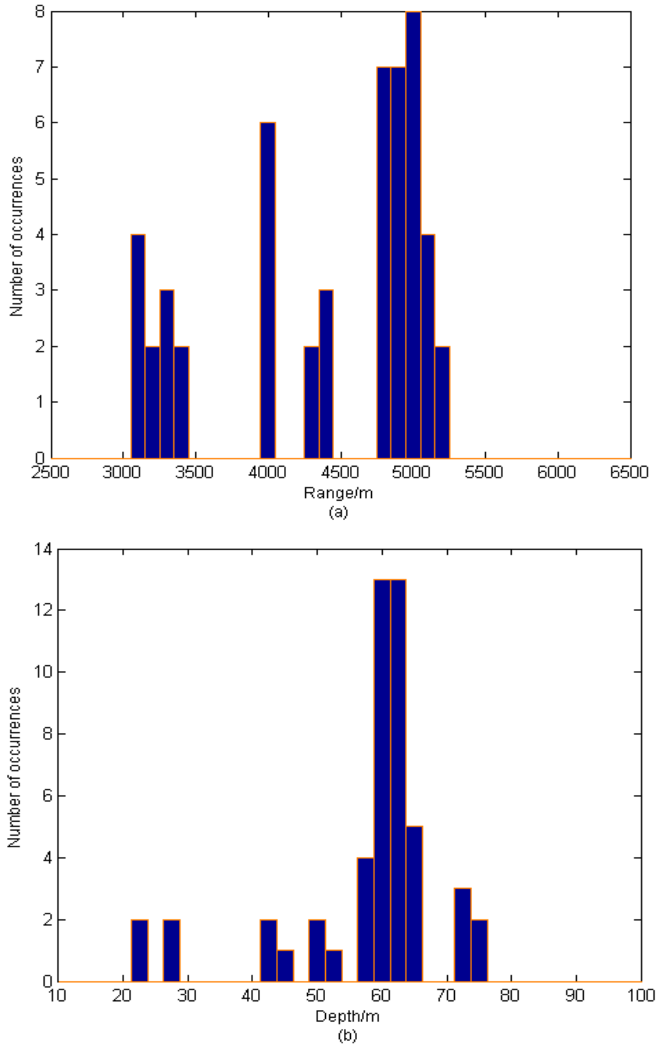
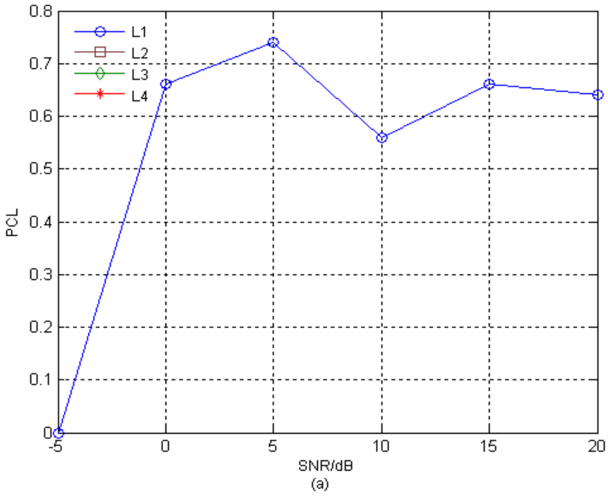


Figure4 Histogram of localization for environmental uncertainty (a) Depth estimation (b) Range estimation

It can be seen from the simulation results that the range and depth estimates are independent for the proposed algorithm. The performance of the proposed algorithm is degraded due to the environmental uncertainty. However, in 50 environmental realizations, we can observe that approximately 60% of the trials the source location estimates in range and approximately 75% of the trials the source location estimates in depth are within 500m and 10m respectively.

In order to determine the localization performance under different SNR case, simulation trials were run over a range of SNR from -5dB to 20dB. The probability of correct localization (PCL) and PBR for the localizer are shown in Figure5.



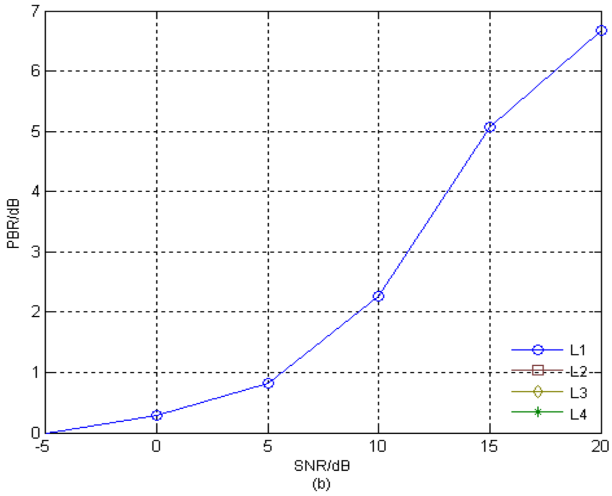


Figure5—Probability of correct localization (PCL) and Peak-to-background ratio (PBR) for different SNR values (a)PCL (b)PBR

We can observe from the results, the performance of the localizer was improved with the SNR increases. When the SNR is greater than 5dB, the PCL of the localizer is approximate to or slightly higher 0.6. In terms of the PBR, the PBR approximately up to 6.5dB at the SNR of 20dB.

5. CONCLUSIONS

We have presented a cross correlation MFP (CMFP)for the acoustic source with unknown emitted signal waveform based on two hydrophones. The key idea of the CCMFP is to compare the different between the cross correlation of the received signal and the cross correlation of the replica signal.

Simulation results indicate that the CCMFP is able to localize an acoustic source and overcome the problem of the higher sidelobes of the traditional Bartlett MFP due to lack of the number of hydrophones.

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