BRIEF NOTE

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Underwater acoustic source localization using closely spaced hydrophone pairs

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Underwater sound source position is determined using a line array. However, performance degradation occurs owing to a multipath environment, which generates incoherent signals. In this paper, a hydrophone array is proposed for underwater source position estimation robust to a multipath environment. The array is composed of three pairs of sensors placed on the same line. The source position is estimated by performing generalized cross-correlation (GCC). The proposed system is not affected by a multipath time delay because of the close distance between closely spaced sensors. The validity of the array is confirmed by simulation using acoustic signals synthesized by eigenrays.

In the ocean, the received signal, which is emitted from an underwater source, has a multipath time delay caused by the surface/bottom reflection. Multipath propagation is a drawback of a positioning system using the time difference of arrival for estimating the target bearing and range.[1)] This problem has been the focus of research on source localization accuracy improvement in wireless communication, passive localization systems, and sonar systems.[2,3)] For source position estimation in a multipath environment, other systems require the advantages of various signal processing systems.[4–7)] In this study, a line array is proposed. The array has three pairs of sensors, which are composed of closely spaced and widely spaced hydrophones. The signals transmitted from an underwater object undergo different propagation paths that cause distortion of the signals through reflections and diffractions on the sea surface and bottom. Consequently, each received signal on widely spaced sensors has noncoherent characteristics, which cause performance degradation in the estimation of the time delay. However, by using the proposed array structure, we can obtain the time difference of received signals from generalized cross-correlation (GCC) in a multipath environment without degradation. The signals acquired from the sensor pairs are coherent owing to the sufficiently short distance between the closely spaced hydrophones, such that different propagation paths can be ignored.

The geometry of the proposed array is shown as Fig. 1. The ranges of the acoustic source from the array, R_1 and R_6, are respectively,

$$R_1 = R + c\tau_1, \tag{1}$$

$$R_6 = R + c\tau_6, \tag{2}$$

where c is the sound speed and τ is the time delay. Each time delay can be written as

$$c\tau_1 = \sqrt{R^2 + L^2 + 2RL\sin\theta} - R = R\left[\left(1 + \frac{L^2}{R^2} + \frac{2L}{R}\sin\theta\right)^{1/2} - 1\right], \tag{3}$$

$$c\tau_6 = R\left[\left(1 + \frac{L^2}{R^2} - \frac{2L}{R}\sin\theta\right)^{1/2} - 1\right]. \tag{4}$$

We can use the Taylor series expansion for the time delay by substituting $x = L^2/R^2 + 2L\sin\theta/R$ in Eq. (3). The time delay is replaced with the following equations:

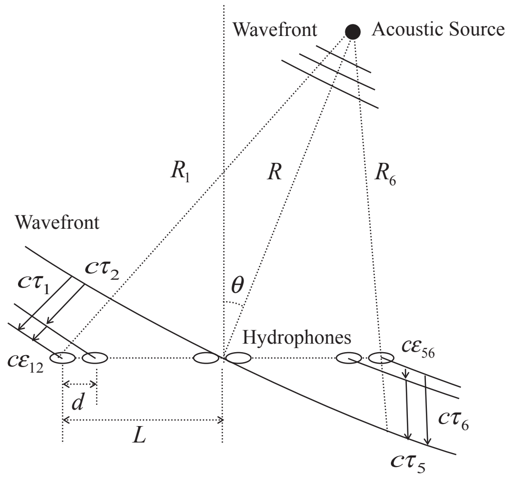

Fig. 1. Geometry of proposed array.

$$c\tau_1 \cong L\sin\theta + \frac{L^2}{2R}\cos^2\theta, \ \frac{L}{R} \ll 1, \tag{5}$$

$$c\tau_6 \cong -L\sin\theta + \frac{L^2}{2R}\cos^2\theta. \tag{6}$$

As shown in the equation below, the range of the underwater source can be obtained by solving simultaneously Eqs. (5) and (6).

$$R = \frac{L^2\cos^2\theta}{c(\tau_1 + \tau_6)} \tag{7}$$

The time delays τ_1 and τ_6 are replaced with the time delays ε_{12} and ε_{56} for closely spaced hydrophone pairs.

$$R = \frac{L^2\cos^2\theta}{c(\tau_2 + \tau_5) + c(\varepsilon_{12} - \varepsilon_{56})} \tag{8}$$

$$R = \frac{(L-d)^2\cos^2\theta}{c(\tau_2 + \tau_5)} \tag{9}$$

Finally, similarly to the equations below, underwater acoustic source location can be written as

$$R = \frac{2L(d^2 - c^2\varepsilon_{34}^2)}{cd(\varepsilon_{12} - \varepsilon_{56})}, \tag{10}$$

$$\theta = \sin^{-1}\left(\frac{c\varepsilon_{34}}{d}\right). \tag{11}$$

The bearing of the underwater target shown in Fig. 2 and Eq. (11) is expressed as a time difference and distance between two sensors.

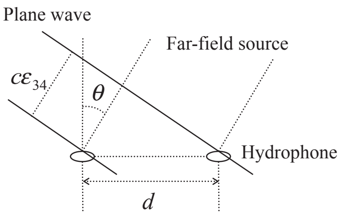

Fig. 2. Geometry of closely spaced hydrophone pair.

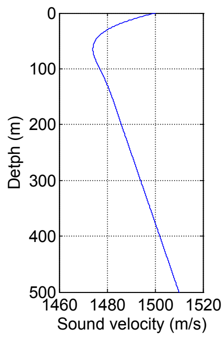

Fig. 3. (Color online) Sound velocity profile.

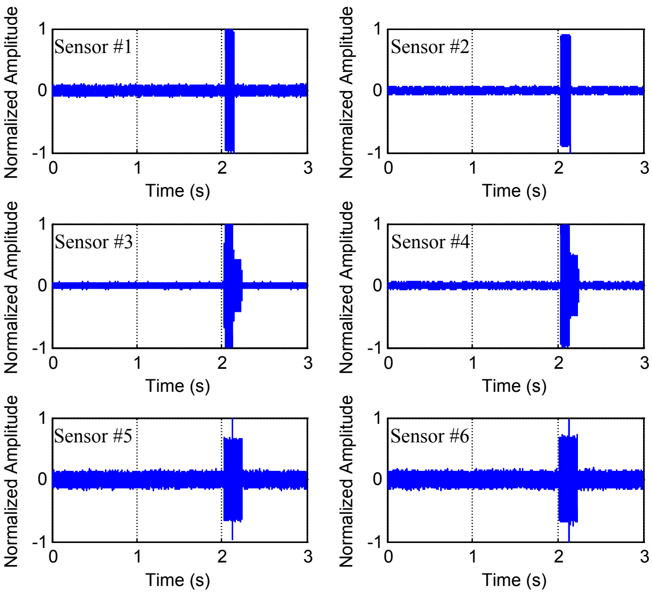

Fig. 4. (Color online) Examples of synthesized signals ($R = 3$ km, $\theta = 30°$, SNR = 20 dB).

For verification of the proposed array, we perform simulation using acoustic signals synthesized from eigenrays considering single-path and multipath environments. The depth of the sea is 500 m. Figure 3 shows a sound velocity profile. The bearings and ranges of the target are assumed to be 0–45° and 1–3 km from hydrophones. The underwater source depth and receiver depth are both 50 m. The distance between widely spaced hydrophones is 20 m and that between closely spaced hydrophones is 1 m. The signal-to-noise ratios (SNRs) are 0–20 dB. The center frequency of the signal and the length of a continuous wave (CW) pulse are 10 kHz and 100 ms, respectively. The white Gaussian noise is used to synthesize signals. Figure 4 shows the synthesized signals that show cancellation and amplitude increase owing to out-of-phase and in-phase phenomena. The time delay of the received signal on the sensor pair is calculated by GCC.[8]

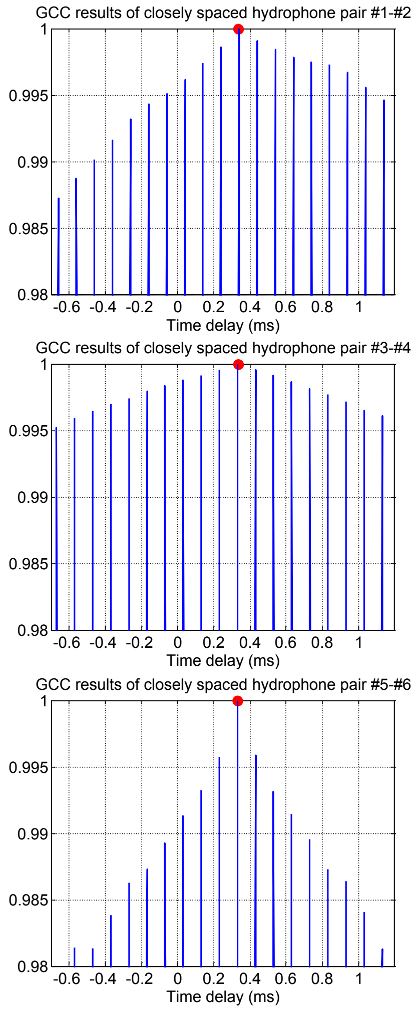

Fig. 5. (Color online) Examples of generalized cross-correlation between closely spaced hydrophone signals ($R = 3$ km, $\theta = 30°$, SNR = 20 dB).

Figures 5 and 6 show generalized cross-correlation results for estimating the time-delay on the proposed array and conventional array at $R = 3$ km, $\theta = 30°$, and SNR = 20 dB, respectively. The GCC results in Figs. 5 and 6 are obtained from signals shown is Fig. 4. In the figures, a red point indicates the true time delay between sensor signals. Despite the multipath delay, the time difference between closely-spaced receiver signals can be obtained stably by GCC. Figures 7–9 are simulation results of the conventional array, which is composed of three widely spaced hydrophones, and the proposed array for estimating the time difference between received signals, underwater source bearing, and range from the array. We had assumed the multipath and single-path environments for each array. The RMSEs are compared by changing SNR to confirm the efficiency of the array of closely spaced hydrophone pairs under multipropagation condition. For the time delay estimation, in a multipath environment, the proposed array shows better performance than the conventional array at SNRs above 10 dB. The closely spaced hydrophone pair array showed better performance in the multipath environment. It is due to the improvement of signal coherence by cancellation and amplitude increase. Under the multipath condition, the closely spaced sensor array performs better than the conventional array in terms of bearing and range estimations. At SNRs = 10–15 dB, the proposed array under multi-/single-

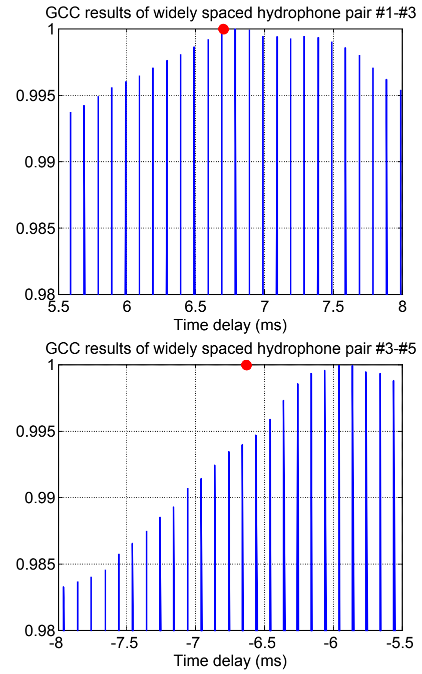

Fig. 6. (Color online) Examples of generalized cross-correlation between widely spaced hydrophone signals ($R = 3$ km, $\theta = 30°$, SNR = 20 dB).

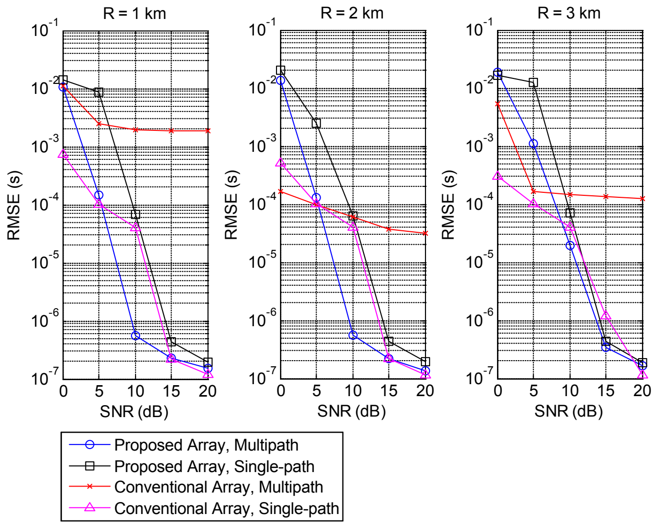

Fig. 7. (Color online) Time-delay estimation (RMSE vs SNR) ($R = 1$, 2, 3 km, $\theta = 0$–45°).

path conditions more correctly estimates the time delay than the conventional array under the single-path condition. However, in the bearing and range estimations, the widely spaced sensor array under the single-path condition is better than the proposed array. In this paper, an array of pairs of hydrophones was proposed for underwater acoustic source localization. We derive the equation that describes the time delay on closely spaced hydrophone pairs. We can confirm by simulation using simple signal processing that this line array system can find the target efficiently in a multipath environment. It is necessary to verify the proposed method under more severe conditions,[9–11] because the simulations in this study were conducted under limited conditions. Future works are needed to verify the proposed method under stronger interferences by multipaths at shallower seas. Also,

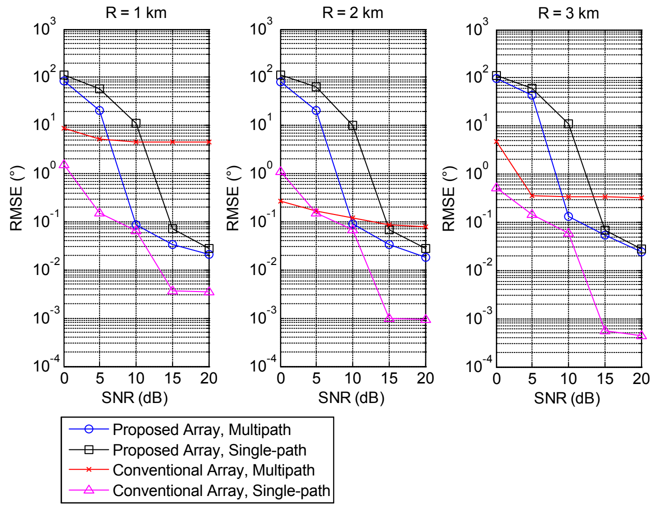

Fig. 8. (Color online) Bearing estimation (RMSE vs SNR) ($R = 1$, 2, 3 km, $\theta = 0$–45°).

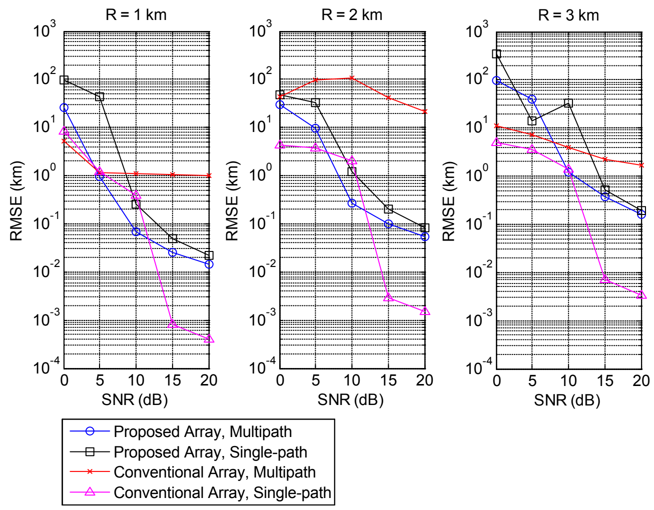

Fig. 9. (Color online) Range estimation (RMSE vs SNR) ($R = 1$, 2, 3 km, $\theta = 0$–45°).

we have to use various methods to find the time difference between signals and compare the results with those obtained using other systems.

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