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Target detection method for reverberant environments in continuous-wave active sonar system based on group multichannel nonnegative matrix factorization

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Abstract

In the underwater environment, the active sonar system emits an acoustic wave and receives echo signals to detect a target. However, the echo signals consist of not only the echo from the target but also the reverberation from scatterers. If the target has a low speed, the detection problem is more difficult because the target echo is interfered by the reverberation severely. In this paper, the target detection method for the reverberant environment is developed based on multichannel nonnegative matrix factorization. To extract the target echo signal mixed with reverberations, received signal is transformed into bearing-time-frequency domain, and analyzed into bearing, frequency, and temporal basis by the multichannel nonnegative matrix factorization. The simulation was performed to evaluate the proposed method, and the result shows that the proposed method has good detection performance in the simulated reverberant environments.

Keywords: Active Sonar, Reverberation, Nonnegative Matrix Factorization, Target Detection

1 INTRODUCTION

In the underwater acoustics systems, the active sonar emits a ping signal and analyzes the reflected signal to detect the target. Because the active sonar system utilizes the emitted ping, the system has advantage to estimate the bearing and range of the target. However, the emitted ping signal also causes a problem: the reverberation from scatterers degrades the detection performance. The conventional target detection algorithm including the matched filter is sensitive to the reverberation, so several researches have been conducted to improve the detection performance of the active sonar system [1, 2, 3, 4, 5, 6, 7].

Because the target moves with a specific speed, we can classify the targets into two categories with respect to the Doppler shift: the high-Doppler and the low-Doppler targets. Detections of the high-Doppler targets are not severely affected by the reverberation because the beamformers can deal with the problem, but the reflected echo from the low-Doppler targets are easily interfered by the reverberations [1], so additional algorithms is required to tackle the problem. Some researchers designed the transmission pulse to robust to the reverberation [2, 3]. While these approaches are effective, designed new pulses may be incompatible with the conventional systems. Therefore, some signal processing algorithms have been developed to suppress the reverberation at the receiver, including auto-regressive (AR) pre-whitening[4], principal component inverse (PCI)[5], and signal subspace extraction (SSE)[6]. The AR pre-whitening algorithm shows good performances in the simulation, but the performance is degraded if the model does not match the actual signal environment. The PCI and SSE algorithms can be good alternatives, but the algorithms focus on the low-rank decomposition only and does not utilize a signal characteristic.

Recently, a reverberation suppression algorithm based on the nonnegative matrix factorization (NMF), which utilizes a time-frequency characteristic of the transmitted and received ping, has been developed [7]. The NMF decomposes a nonnegative matrix into a multiplication of two nonnegative matrices [8], and the method can decompose a magnitude spectrogram of an acoustic signal into frequency basis and temporal basis matrices[9]. The NMF-based reverberation suppression algorithm has been developed to take into account the fact that the NMF algorithm can analyze the time and frequency characteristics. The algorithm shows a good performance relative to the other signal processing algorithms, but the algorithm only utilizes the time and frequency char-

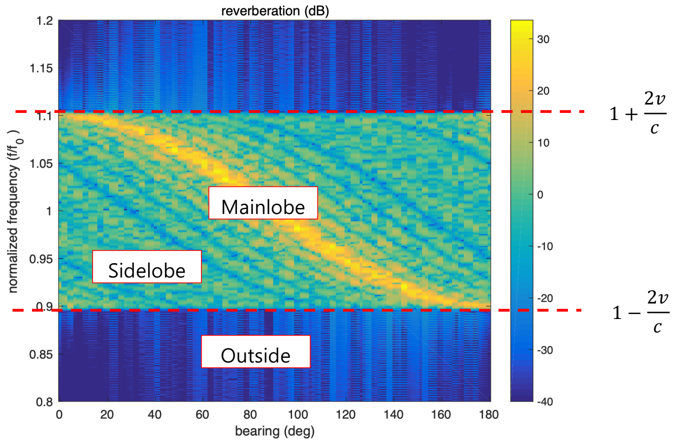

Figure 1. Simulated reverberation of a frequency-bearing domain. The receiver is assumed to use beamformers. The x-axis denotes a bearing and the y-axis denotes a relative frequency.

acteristics, and it does not use any inter-channel information e.g. bearing information.

In this paper, we develop a target detection method in the reverberant signal environment, especially for a low-Doppler target with transmitting a continuous-wave ping signal. The proposed algorithm is developed by using the beamspace-domain multichannel NMF (BD-MC-NMF) [10], and dividing the basis vectors into two basis groups – echo and reverberation basis groups.

2 PROPOSED METHOD

2.1 Problem Description

If we assume the sonar receiver moves with the velocity of v and receives a reflected ping $s_T(t)$ which is caused by the transmitted ping $s(t)$ from the transmitter, the received signal can be expressed as [11]

$$s_T(t) = a\,|G(\psi-\psi_0)|\,s(t-t_d)\exp(j2\pi f_d t), \tag{1}$$

where a is an attenuation factor, t_d is a time delay, f_d is a Doppler frequency shift, ψ is an angle between the signal incidence and the receiver moving direction, and $G(\psi)$ is a directivity function of the beamformer. Then the spectrum $S_T(f)$ of the received signal is stated as [11]

$$S_T(f) = a\,|G(\psi-\psi_0)|\,S(f-f_d)\exp\left[-j2\pi(f-f_d)t_d\right], \tag{2}$$

where $S(f)$ is a Fourier transform of $s(t)$.

The reverberation can be modeled as a sum of several reflections from a large number of scatterers, so the spectrum $S_R(f)$ of reverberation can be expressed as [11]

$$S_R(f) = \sum_n \left\{a_n\,|G(\psi_n-\psi_0)|\,S(f-f_{d_n})\exp\left[-j2\pi(f-f_{d_n})t_{d_n}\right]\right\} \tag{3}$$

where a_n, f_{d_n}, and t_{d_n} are the attenuation factor, Doppler frequency shift, and time delay of n-th scatterer, respectively. It can be assumed that the velocities of the scatterers are very small relative to the velocity of the sonar receiver, or the ship, so the Doppler shift from each scatterer is

$$f_{d_n} = \frac{2v\cos\psi_n}{c} f_0, \tag{4}$$

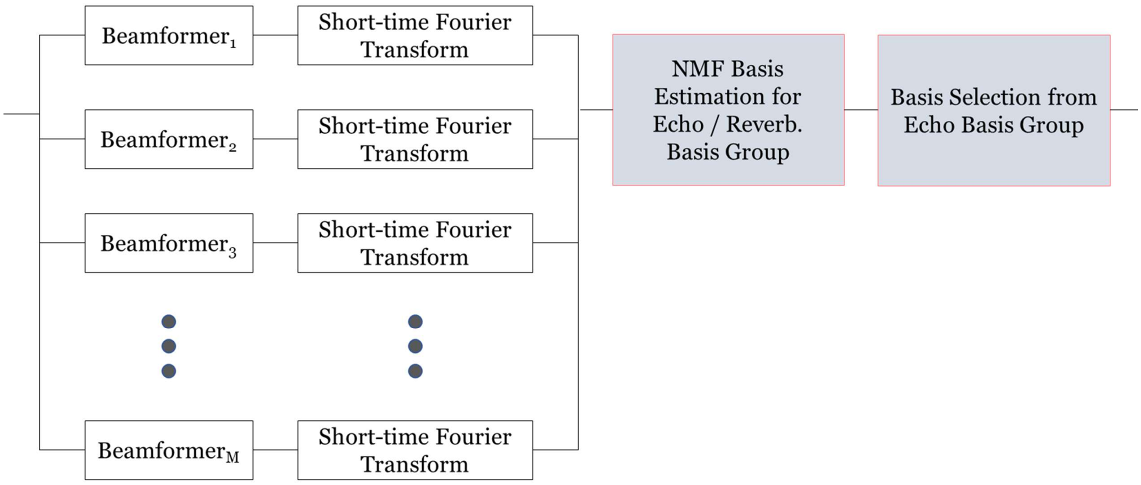

Figure 2. A block diagram of the proposed algorithm.

where f_0 is a center frequency of the transmitted ping. Therefore, the incidance angle of the reverberation with the Doppler frequency shift of f_{d_n} is

$$\psi_n = \cos^{-1}\left(\frac{cf_{d_n}}{2vf_0}\right). \tag{5}$$

Figure 1 shows that the magnitude of simulated reverberation in a frequency-bearing domain. It is clearly shown that the reverberation can interfere the detection of low-Doppler targets because the energy of reverberation is distributed around the zero-Doppler frequency. Considering $-1 \leq \cos\psi_n \leq 1$, equation (4) shows that the Doppler frequency of reverberation has the value from $-\frac{2v}{c}f_0$ to $\frac{2v}{c}f_0$, and Figure 1 shows that the range of the reverberation. Therefore, the faster the receiver moves, the more difficult it is to detect the low-Doppler target.

2.2 Basis-Group Beamspace-Domain Multichannel Nonnegative Matrix Factorization

The proposed algorithm consists of NMF basis estimation and basis selection modules, as shown in Figure 2. The basis groups consist of bearing, frequency, and time bases, and each basis is estimated by beamspace-domain multichannel NMF algorithm. If we gather the magnitude spectrogram of the output signals from the beamformers, the element $v_{m,kn}$ of the 3-dimensional spectrogram tensor $\mathbf{V} \in \mathbb{R}^{M\times K\times N}$ is [10, 12]

$$v_{m,kn} = \sum_j u_{mj} p_{j,kn} + e_{m,kn}, \tag{6}$$

where u_{mj} is a gain for m-th beamformer output of j-th source, $e_{m,kn}$ is a noise of (k,n)-th time-frequency bin of a spectrogram of m-th beamformer output, and $p_{j,kn}$ is a (k,n)-th bin of a spectrogram $\mathbf{P}_j$ of j-th source. $p_{j,kn}$ can be expressed as

$$p_{j,kn} = \sum_{r\in C_j} w_{kr} h_{rn}, \tag{7}$$

where w_{kr} is a (k,r)-th element of a frequency basis matrix $\mathbf{W}$, and h_{rn} is a (r,n)-th element of a time basis matrix $\mathbf{H}$. If we divide the basis matrix to the echo and reverberation basis groups, equation (6) can be modified as [12]

$$v_{m,kn} = \sum_{j=1}^{J_R} u_{mj} p_{j,kn} + \sum_{j=J_R+1}^{J_R+J_E} u_{mj} p_{j,kn} + e_{m,kn}, \tag{8}$$

where J_R and J_E are number of basis vectors in the reverberation and echo basis groups, respectively.

2.3 Estimation of the reverberation basis group

In order to develop the estimation algorithm of the NMF bases, the reconstructed spectrogram $\hat{v}_{m,kn}$ is defined as

$$\hat{v}_{m,kn} = \sum_{j=1}^{J_R} u_{mj} p_{j,kn} + \sum_{j=J_R+1}^{J_R+J_E} u_{mj} p_{j,kn}. \tag{9}$$

The estimation algorithms of u_{mj}, w_{kr}, and h_{rn} have to minimize the distance between $v_{m,kn}$ and $\hat{v}_{m,kn}$. Therefore, we define the cost function $C(\Theta)$ with the distance measure as

$$C(\Theta) = d(v_{m,kn}|\hat{v}_{m,kn}), \tag{10}$$

where $\Theta = \left\{u_{mj}, w_{kr}, h_{rn}\right\}$. The distance measure is defined by the Itakura-Saito divergence as

$$d(x|y) = \frac{x}{y} - \log\left(\frac{x}{y}\right) - 1. \tag{11}$$

In order to derive the update equation for u_{mj} that minimize the cost function (10), the cost function is differentiated with respect to u_{mj} as [10]

$$\frac{\partial C}{\partial u_{mj}} = \sum_{k=1}^{K}\sum_{n=1}^{N}\left(\frac{p_{j,kn}}{\hat{v}_{m,kn}} - \frac{v_{j,kn} p_{j,kn}}{\hat{v}_{m,kn}^2}\right), \tag{12}$$

According to Lee and Seung [13], u_{mj} can be updated using equation (12) based on the multiplicative update rule as

$$u_{mj} \leftarrow u_{mj} \frac{\mathbf{1}_{1\times K}\left[\hat{\mathbf{V}}_m^{-2} \otimes \mathbf{V}_m \otimes (\mathbf{W}_j \mathbf{H}_j)\right]\mathbf{1}_{N\times 1}}{\mathbf{1}_{1\times K}\left[\hat{\mathbf{V}}_m^{-1} \otimes (\mathbf{W}_j \mathbf{H}_j)\right]\mathbf{1}_{N\times 1}}, \tag{13}$$

where $\hat{\mathbf{V}}_m^{-1}$ and $\hat{\mathbf{V}}_m^{-2}$ are element-wise inverse and squared inverse of $\hat{\mathbf{V}}_m$, respectively, $\otimes$ is an element-wise multiplication (Hadamard product), the fraction is an element-wise division, and $\mathbf{1}_{a\times b}$ is a $a \times b$ matrix whose elements are ones. In the same way, w_{kr} and h_{rn} can be updated as [12]

$$\mathbf{W}_j \leftarrow \mathbf{W}_j \frac{\sum_{m=1}^{M} u_{mj}\left(\hat{\mathbf{V}}_m^{-2} \otimes \mathbf{V}_m\right)\mathbf{H}_j^T}{\sum_{m=1}^{M} u_{mj} \hat{\mathbf{V}}_m^{-1} \mathbf{H}_j^T}, \tag{14}$$

and

$$\mathbf{H}_j \leftarrow \mathbf{H}_j \frac{\sum_{m=1}^{M} (u_{mj}\mathbf{W}_j)^T \left(\hat{\mathbf{V}}_m^{-2} \otimes \mathbf{V}_m\right)}{\sum_{m=1}^{M} (u_{mj}\mathbf{W}_j)^T \hat{\mathbf{V}}_m^{-1}}. \tag{15}$$

2.4 Estimation of the echo basis group

The bearing and time bases, u_{mj} and h_{rn}, can be updated by the same method as the reverberation basis group case. However, the frequency bases can be contructed in advance if we know the frequency structure of the transmitted ping signal, because the received ping can be assumed as a Doppler-shifted replica of the transmitted ping, as shown in equation (2). Therefore, the frequency bases are constructed in the proposed method as [12]

$$\mathbf{W}_j = \mathbf{w}_{p,\uparrow\{j-J_R-1-(J_E-1)/2\}}, \qquad J_R + 1 \leq j \leq j_E, \tag{16}$$

where $\mathbf{w}_j$ is a frequency spectrum of transmitted ping signal, and $\mathbf{w}_{p,\uparrow\Delta k}$ is a vector with $\mathbf{w}_p$ shifted upward by Δk bins.

2.5 Own-Doppler compensation

The NMF bases can be updated iterativly using equations (13)-(16). However, the estimated bearing basis tends to have large value at the own-Doppler reverberation (which is denoted by "Mainlobe" in Figure 1). From equations (3) and (5), the beamformer gain of the own-Doppler reverberation is

$$G_{OD}(m,j) = G_m\left\{\cos^{-1}\left(\frac{c}{2v}\frac{\Delta k_j \Delta f}{f_0}\right)\right\}, \tag{17}$$

where Δk_j is a number of bins for the Doppler shift and Δf is a frequency resolution between the adjacent bins. Considering the own-Doppler gains, equation (13) for the echo basis group is modified as

$$u_{mj} \leftarrow \alpha u_{mj} + (1-\alpha)\left\{1 - \frac{G_{OD}(m,j)}{\max_{m,j} G_{OD}(m,j)}\right\}, \tag{18}$$

where α is a tuning constant for the own-Doppler compensation whose value is between 0.0 and 1.0.

2.6 Basis selection

To detect the bearing, frequency, and the range of the target from the estimated NMF bases, we choose a proper basis which can represent the reflected echo from the target. As shown in the previous research [7], the energy of the reflected echo signal is concentrated in a short time period. Therefore, the target basis is selected by the energy of continuous short duration as [12]

$$r_{target} = \arg\max_r \bar{h}(r), \qquad r \in \{C_{J_R+1}, \ldots, C_{J_R+J_E}\}, \tag{19}$$

where,

$$\bar{h}(r) = \max_i \sum_{n=\max(i-n_p+1,1)}^{i} h_{rn}. \tag{20}$$

The target bearing number m_{target}, target frequency bin number k_{target}, and target time frames n_{target} is calculated as

$$m_{target} = \arg\max_m u_{mj}\|_{C_j \ni r_{target}}, \tag{21}$$

$$k_{target} = \arg\max_k w_{kr_{target}}, \tag{22}$$

$$n_{target} = \{n \| h_{r_{target}n} > \eta\}, \tag{23}$$

where η is a pre-defined threshold to determine that target echo exists.

3 SIMULATION RESULTS

To evaluate the proposed algorithm, a simulation was performed with a simulated reverberant signal environment. The target echo was simulated by a attenuated and delayed replica of transmitted ping signal, and the received reverberation signal was synthesized by the reverberation model of Abraham and Lyons[14]. The transmitted ping was a 500 ms continuous-wave signal with a Doppler frequency ratio (f/f_0) of 1.015. The system was assumed to have 37 beamformers between 0°and 180°, and the null-to-null beamwidth of each beamformer was set to 10°. The output signal of each beamformer was short-time-Fourier-transformed, as shown in Figure 2, by 133 ms Hamming window with 25% overlap.

The number of sources in the reverberation group J_R was set to 10, and the number of basis per source in the reverberation group was set to 4. The number of sources in the echo group J_E was set to 27. Because each source of the echo group has one basis vector, the total number of the basis vectors was 67. The own-Doppler compensation constant α was set to 0.5, and the threshold for activation of target echo η was set as

$$\eta = 0.2 \max_n h_{r_{target}n}. \tag{24}$$

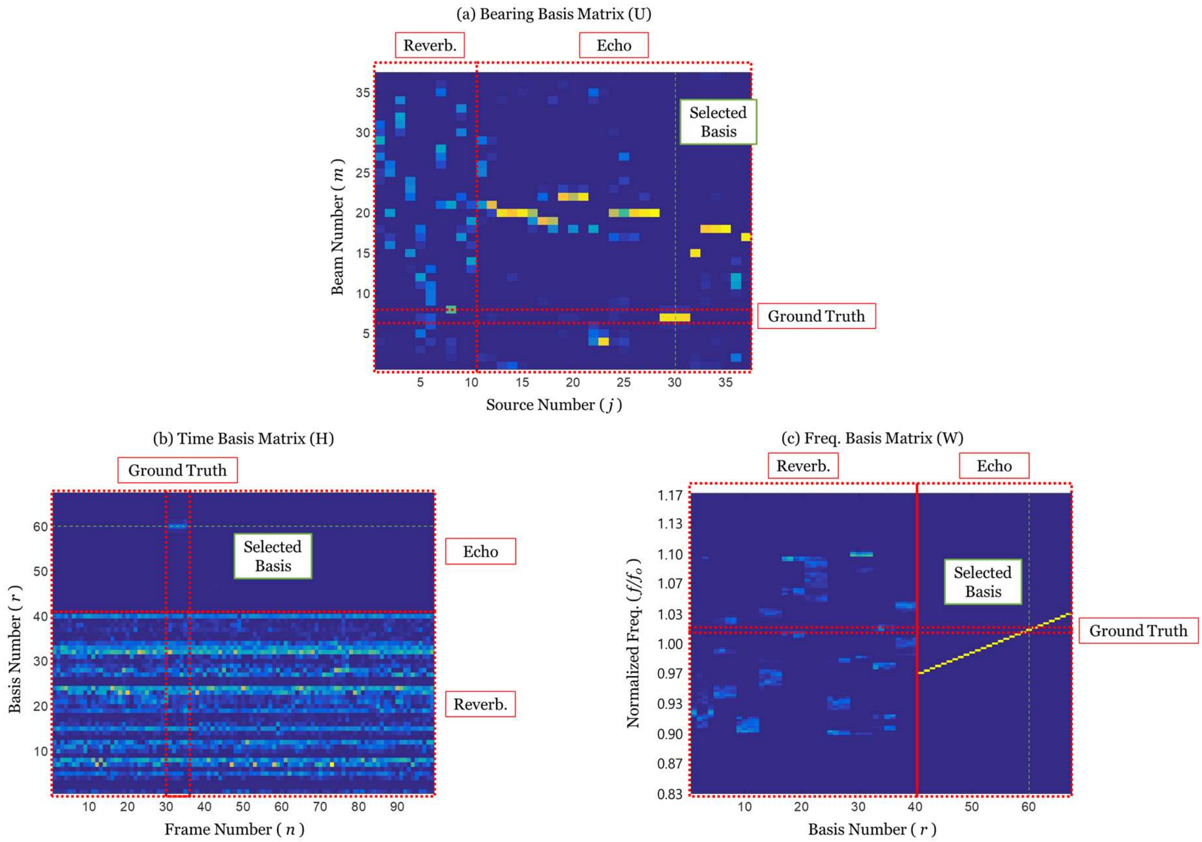

Figure 3. Results of estimated (a) bearing, (b) time, and (c) frequency basis matrices. Red doted rectangles denotes the reverberation and echo basis groups, and the ground truth to be estimated. Green dashed line denotes the selected basis r_{target} by the proposed algorithm.

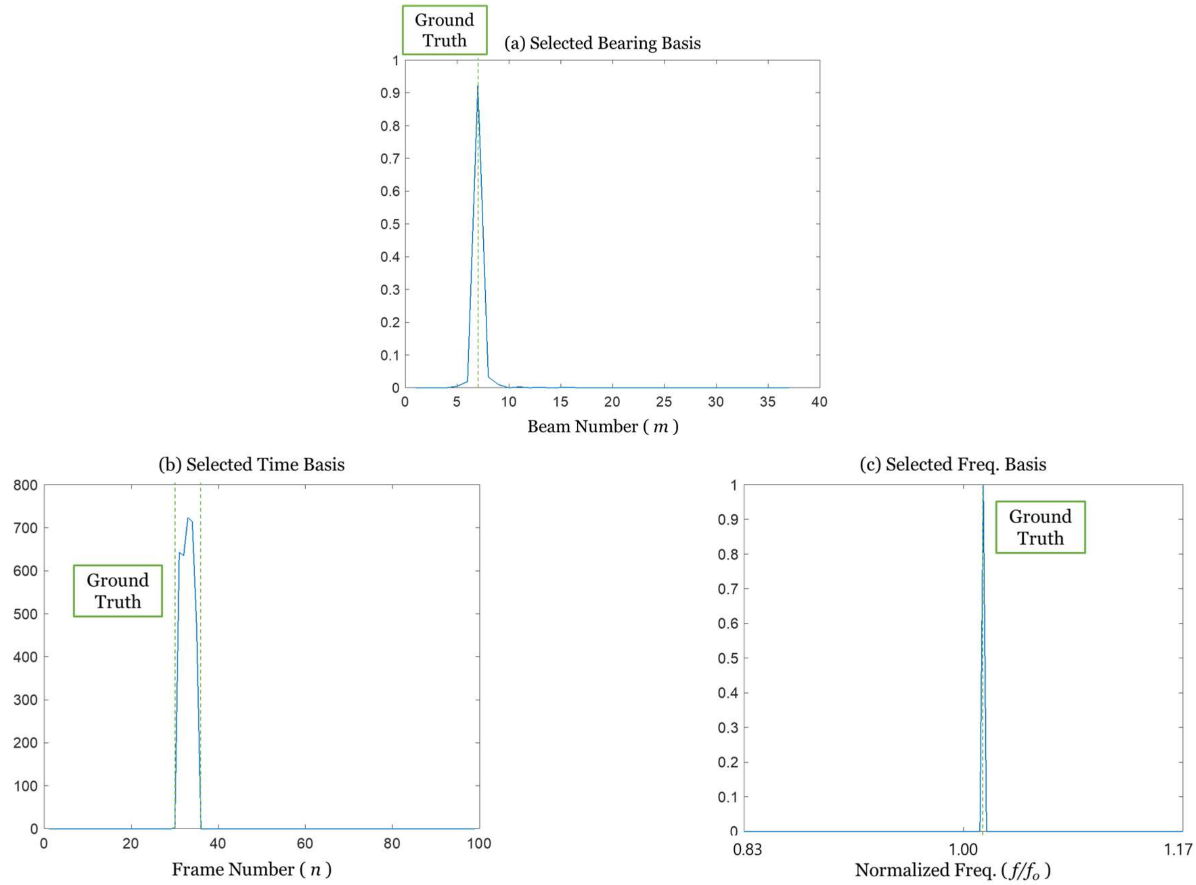

Figure 4. Selected (a) bearing, (b) time, and (c) frequency basis vectors. Green dashed line denotes the ground truth.

Figure 3 show results of the simulation. Figure 3(a) shows that the echo basis group includes the ground truth of bearing, and the selected basis has a large value at the ground truth. Figure 3(b) shows that the echo basis matrix have distinctive large values in the ground truth frames, and proper time basis is selected. Figure 3(c) shows that the echo basis group consists of the frequency-shifted replica of the transmitted ping, and the selected frequency basis indicates the ground truth well. Figure 4 show the selected basis vectors, and the results show that the large values of each selected basis vector are matched to the ground truth.

4 CONCLUSION

In this paper, a target detection method for a continuous-wave active sonar in the reverberant environment is developed. The proposed target detection method is developed based on the BD-MC-NMF, and by utilizing a priori information of the received target echo. To evaluate the proposed algorithm, a simulation is performed with a synthesized reverberation. The simulation results show that the proposed algorithm can estimate the bearing, time, and frequency basis matrices, and the target basis is selected well to detect the target echo.

REFERENCES

[1] Doisy, Y.; et al. Reverberation suppression using wideband Doppler-sensitive pulses, IEEE Journal of Oceanic Engineering, Vol 33 (4), 2008, pp.419-433.

[2] Cox, H.; Lai, H. Geometric comb waveforms for reverberation suppression, in Proceedings of 28th Asilomar Conference on Signals, Systems and Computers, Vol 2, 1994, pp. 1185-1189.

[3] Collins, T.; Atkins, P. Doppler-sensitive active sonar pulse designs for reverberation processing, IEE Proceedings-Radar, Sonar and Navigation, Vol. 145 (6), 1998, pp. 347-353.

[4] Li, W.; et al. Detection in reverberation using space time adaptive prewhiteners, Journal of Acoustic Society of America, Vol 124 (4), 2008, pp.236-242.

[5] Ginolhac, G.; Jourdain, G. "Principal component inverse" algorithm for detection in the presence of reverberation, IEEE Journal of Ocenic Engineering, Vol 27 (2), 2002, pp. 310-321.

[6] Li, W.; et al. Active sonar detection in reverberation via signal subspace extraction algorithm, EURASIP Journal on Wireless Communication and Network, Vol. 2010 (1), 2010, pp. 1-11.

[7] Lee, S.; Lim, J. Reverberation suppression using non-negative matrix factorization to detect low-Doppler target with continuous-wave active sonar, EURASIP Journal on Advances in Signal Processing, Vol 2019 (1), 2019, pp. 1-11.

[8] Lee, D. D.; Seung, H. S. Learning the parts of objects by non-negative matrix factorization, Nature, Vol 410 (6755), 1999, pp.788-791.

[9] Vincent, E.; Bertin, N.; Badeau, R. Harmonic and inharmonic nonnegative matrix factorization for polyphonic pitch transcription, in Proceedings of IEEE Conference on Acoustics, Speech and Signal Processing 2008 (ICASSP 2008), 2008, pp.109-112.

[10] Lee, S.; Park, S. H.; Sung, K.-M. Beamspace-domain multichannel nonnegative matrix factorization for audio source separation, IEEE Signal Processing Letters, Vol 19 (1), 2011, pp. 43-46.

[11] Burdic, W. S. Underwater acoustic system analysis, Prentice Hall, NJ, 1991.

[12] Lee, S. Target detection method of the narrow-band continuous-wave active sonar based on basis-group beamspace-domain nonnegative matrix factorization for a reverberant environment (in Korean), The Journal of the Acoustical Society of Korea, Vol 38 (3), 2019, pp. 290-301.

[13] Lee, D. D.; Seung, H. S. Algorithms for non-negative matrix factorization, in Proceedins of Advances in Neural Information Processing Systems (NIPS), 2001, pp.556-562.

[14] Abaraham, D. A.; Lyons, A. P. Simulation of non-Rayleigh reverberation and clutter, IEEE Journal of Oceanic Engineering, Vol 29 (2), 2004, pp.347-362.