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Target detection algorithm using independent component analysis for pulse Doppler radar

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Abstract: Microwave pulse Doppler radar systems are useful tools for airplane tracking and velocity estimation in all-weather situations. However, Doppler radar often suffers from intrinsic difficulty when the target Doppler spectrum is buried amongst a cluttered background from clouds as lower pulse repetition frequencies (PRF) cause ambiguity in the Doppler spectrum. To address this issue, we propose a novel target detection method based on the independent component analysis (ICA) scheme. The results from numerical simulations validate the effectiveness of our method compared with those obtained by conventional methods based on principal component analysis (PCA).

Keywords: moving target detection, independent component analysis (ICA), principal component analysis (PCA), pulse Doppler radar

Classification: Sensing

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1 Introduction

Microwave pulse Doppler (PD) radar is one of the most useful tools for estimating range and velocity of a moving target by extracting the Doppler frequency difference from that of clutter [1]. One significant advantage in air-traffic control systems is its adaptability in all-weather conditions. However, the radar system often encounters difficulties in that the spectrum of the target experiences interference from clutter such as clouds because of the ambiguity in the Doppler velocity caused by lower pulse repetition frequencies (PRF), which is required for a long-range observation system. In trying to resolve this issue, various kinds of blind signal deconvolution methods have been developed, such as those based on the inverse filtering of a mixed system [2]. However, in an observation model typical to the Doppler radar, the number of source signals often exceeds that of observed signals; namely, the problem becomes ill-posed. To mitigate this difficulty, a method to separate source signals that focuses on the phase symmetry of the over-complete basis has been proposed [3]. However, when an observed signal includes many independent sources, the accuracy of this method is degraded because its evaluation function based on maximizing the posterior probability barely converges to an optimal solution.

As an alternative solution, we proposed the clutter suppression method based on principal component analysis (PCA) [4]. This method determines a target signal by extracting a principal component signal, which significantly upgrades the signal separation performance, especially in the cases mentioned above. However, with lower signal to clutter ratio (SCR), a principal component does not necessarily correspond to a target signal because the singular value (SV) of clutter also becomes larger.

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Thus, this paper proposes a novel target detection method based on the independent component analysis (ICA) scheme, which is extended to the complex-valued signal separation model [5, 6]. In this method, quasi-multichannels are generated using a time shift of the received signal with a single sensor. Moreover, to mitigate the ill-posed feature of this model, this method increases the number of quasi-multichannels to a maximum extent that is essential in extracting the maximum performance from the ICA separation. There are some literature using ICA scheme for clutter suppression aiming at ultrasound signal separation [7], ground penetrating radar (GRP) [8, 9] and the through-wall imaging issues [10]. However, these reports do not deal with severe SCR cases, where a target signal is completely buried into clutter signal in both time and frequency domain. To overcome such difficulty, this method adopts a synthesis scheme of selected signal from ICA processing, where the degree of energy concentration in the Doppler frequency domain as in [4] is used for selecting promising signals.

The results from numerical simulations demonstrate that the proposed method significantly enhances target detection performance compared with that from the conventional PCA-based method in terms of the receiver operating characteristic (ROC), even for extremely low SCR situations.

2 System and mathematical model

Fig. 1 illustrates a schematic diagram of PD radar. A mono-static radar and a single moving target is assumed. A number of pulses are transmitted after sinusoidal wave modulation. A target echo is received with a time delay and its Doppler frequency is calculated for the same range with the received pulses sampled over the pulse repetition interval (PRI). It also assumes that the radar beam width is adequately wider than the size of the target, and that the velocity of the target is regarded as constant in the data acquisition interval. Under this assumption, the received signal can be expressed as

$$s(n\Delta t_{\mathrm{PRI}}) = A_s \exp(\mathrm{j}2\pi f_{\mathrm{d}} n\Delta t_{\mathrm{PRI}}), \tag{1}$$

where A_s is the reflection amplitude of the target, f_{d} the Doppler frequency, and n the number of pulses. The clutter is formulated using a moving average model with identical independent distribution sources [11] as in

$$c(n\Delta t_{\mathrm{PRI}}) = \sum_{k=0}^{L} \alpha_k [e_{\mathrm{re}}\{(n-k)\Delta t_{\mathrm{PRI}}\} + \mathrm{j}e_{\mathrm{im}}\{(n-k)\Delta t_{\mathrm{PRI}}\}], \tag{2}$$

where $e_{\mathrm{re}}(n\Delta t_{\mathrm{PRI}})$, and $e_{\mathrm{im}}(n\Delta t_{\mathrm{PRI}})$ have a zero mean uniform distribution, and f_{c} and L denote the Doppler center frequency of $c(n\Delta t_{\mathrm{PRI}})$ and the length of a moving window, respectively. α_k is expressed $\alpha_k = \exp(\mathrm{j}2\pi f_{\mathrm{c}} k\Delta t_{\mathrm{PRI}}) \cdot \exp(-\{(k - L/2)\Delta t_{\mathrm{PRI}}\}^2/2\sigma^2)$, where σ determines the slope of the window. Note that Eq. (2) approximates the spectrum density of the clutter as a compound Gaussian distribution, where its statistical relevance for an actual clutter signal has been validated in [11]. For simplicity, a receiver noise is not considered, and therefore the observed signal $x(n)$ is then given by

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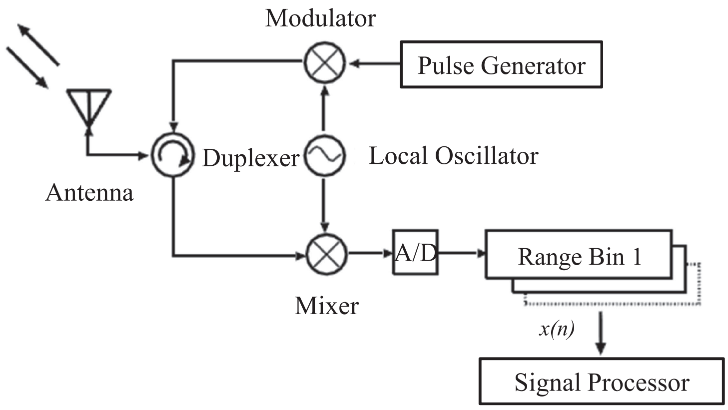

Fig. 1. System model.

$$x(n) = s(n\Delta t_{\mathrm{PRI}}) + c(n\Delta t_{\mathrm{PRI}}). \tag{3}$$

Here, the SCR is defined as

$$\mathrm{SCR} = 10\log_{10}\frac{|A_s|^2}{E[|c(n\Delta t_{\mathrm{PRI}})|^2]}, \tag{4}$$

where $E[*]$ denotes time averaging.

3 Target detection method

In target detection analysis using PD radar, there are various methods such as the constant false alarm rate (CFAR). We demonstrated in [4] that the PCA-based separation is more effective for target detection in low SCR instances compared with the CFAR method. However, if the Doppler spectrum of a target is completely buried within the clutter signal, these methods suffer significant degradation in target detection performance. To overcome this challenging problem, this letter introduces a novel target detection method based on ICA decomposition. The ICA is one useful tool used in blind source separation, and requires only the statistical independence of the source signals for signal reconstruction. As the target signal has a complex sinusoidal signal in the time domain, previous methods such as those using algorithms FastICA [5] or MLICA [6], specifying the sinusoidal wave separation, are also useful in target signal separation. Initially, to obtain multiply observed signals in mono-static observations, the observed signal matrix $\boldsymbol{X}$ is generated with a time shift of

$$\boldsymbol{X} = [\boldsymbol{x}_1, \boldsymbol{x}_2, \cdots, \boldsymbol{x}_M]^{\mathrm{T}}, \tag{5}$$

where $\boldsymbol{x}_m = [x_m(m), x_m(m+1), \cdots, x_m(m+N-1)]$, $x_m(n) = x(m+n-1)$, m denotes the channel number, M the total number of quasi-multichannels, and N the total data length. The whitened signal $\boldsymbol{Z}$ is decomposed by PCA processing described in [4]. In this method, the FastICA algorithm based on maximizing the non-Gaussianity is applied to $\boldsymbol{Z}$ [5] to obtain the reconstruction matrix $\boldsymbol{W}_{\mathrm{Fast}}$. The reconstruction signal matrix after FastICA is defined as

$$[\boldsymbol{y}_{\mathrm{F},1}, \boldsymbol{y}_{\mathrm{F},2}, \cdots, \boldsymbol{y}_{\mathrm{F},M}]^{\mathrm{T}} = \boldsymbol{W}_{\mathrm{Fast}}\boldsymbol{Z}. \tag{6}$$

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Here, we empirically demonstrate that this FastICA-based separation is often insufficient to recognize a target signal in an extremely lower SCR cases. Therefore, to obtain greater reliability in target detection, the evaluation value introduced in [4] is applied to each $\boldsymbol{y}_{\mathrm{F,i}}$ in the form

$$e(\boldsymbol{Y}) = \frac{\max_f |\boldsymbol{Y}(f)|^2}{\displaystyle\int_{-1/2\Delta t_{\mathrm{PRI}}}^{1/2\Delta t_{\mathrm{PRI}}} |\boldsymbol{Y}(f)|^2 \mathrm{d}f}, \tag{7}$$

where $\boldsymbol{Y}$ is the Fourier transform of $\boldsymbol{y}$. This evaluation value denotes the energy concentration ratio in the frequency domain. Here, if $\boldsymbol{y}$ forms a sinusoidal wave in the time domain, $e(\boldsymbol{Y})$ is close to 1. The reconstruction signals $\boldsymbol{y}_{\mathrm{F,i}}$ with a comparatively higher $e(\boldsymbol{Y}_{\mathrm{F},i})$ are selected as $\boldsymbol{y}_{\mathrm{S},i}$ $(i = 1, \cdots, Q)$, where Q is the total number of selected signals. Next, for each $\boldsymbol{y}_{\mathrm{S},i}$, the quasi-multisignals are generated with a time delay

$$\boldsymbol{X}_{\mathrm{S},i} = [\boldsymbol{x}_{\mathrm{S},i,1}, \boldsymbol{x}_{\mathrm{S},i,2}, \cdots, \boldsymbol{x}_{\mathrm{S},i,M}]^{\mathrm{T}}, \tag{8}$$

where $\boldsymbol{x}_{\mathrm{S},i,m} = [y_{\mathrm{S},i}(m), y_{\mathrm{S},i}(m+1), \cdots, y_{\mathrm{S},i}(m+N-1)]$. Then, the MLICA-based separation process [11] is applied to each selected signal $\boldsymbol{X}_{\mathrm{S},i}$. The reconstruction signal matrix obtained is where $\boldsymbol{x}_{\mathrm{S},i,m} = [y_{\mathrm{S},i}(m), y_{\mathrm{S},i}(m+1), \cdots, y_{\mathrm{S},i}(m+N-1)]$. Then, the MLICA-based separation process [8] is applied to each selected signal $\boldsymbol{X}_{\mathrm{S},i}$. The reconstruction signal matrix obtained is

$$[\boldsymbol{y}_{i,1}, \cdots, \boldsymbol{y}_{i,M}]^{\mathrm{T}} = \boldsymbol{W}_{\mathrm{ML},i}\boldsymbol{X}_{\mathrm{S},i} \ (i = 1, \cdots, Q). \tag{9}$$

Finally, all separated signals are synthesized with weights $e(\boldsymbol{y})$,

$$\boldsymbol{Y}_{\mathrm{all}} = \frac{\sum_{i=1}^{Q}\sum_{m=1}^{M} e(\boldsymbol{Y}_{i,m})|[\boldsymbol{Y}_{i,m}]|}{QM}. \tag{10}$$

A target is judged as present if $e(\boldsymbol{Y}_{\mathrm{all}}) > V_0$ holds with V_0 an empirically determined threshold.

4 Performance evaluation in numerical simulation

We present the performance evaluation using numerical simulations of the conventional PCA-based [4] and the proposed ICA-based methods. The target and clutter signals are generated using Eqs. (1) and (2), respectively. Here, $f_{\mathrm{d}} = 0.3f_{\max}$, $f_{\mathrm{c}} = 0.1f_{\max}$, $f_{\max} = 1/\Delta t_{\mathrm{PRI}}$ and $L = 4$ are used in this case.

Fig. 2(a) shows the Doppler spectrum of the observed signal $x(n)$ at $\mathrm{SCR} = -23.6\,\mathrm{dB}$ and verifies that the target Doppler spectrum is completely buried with the clutter signal. Fig. 2(b) shows the Doppler spectrum of the reconstructed signal obtained by the conventional method, and indicates that the PCA-based method fails to identify a target because of a false detection around the peak caused by clutter. This is because in such low SCR instances the SV of the clutter becomes larger than that of the target. In contrast, Fig. 2(c) shows the Doppler spectrum of the separated signal using the proposed method, namely $\boldsymbol{Y}_{\mathrm{all}}$. Here, $M = 20$, $N = 2000$ and $Q = 5$ are set. As the separation performance is improved by MLICA specifying the complex sinusoidal signal separation, the synthesized Doppler spectrum, $\boldsymbol{Y}_{\mathrm{all}}$, has a maximum peak around the actual Doppler frequency of the target, $f_{\mathrm{d}} = 0.3f_{\max}$.

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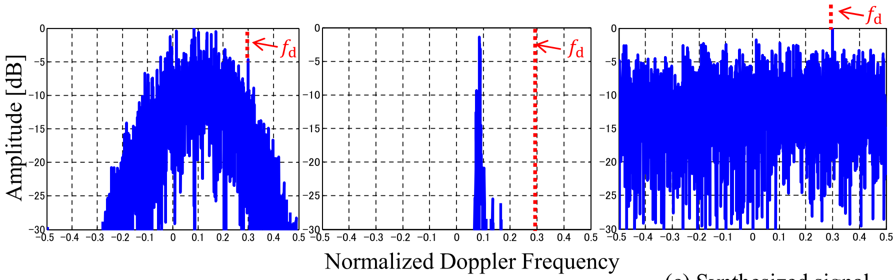

(a) Observed signal

(b) Reconstructed signal
by the conventional method

(c) Synthesized signal
by the proposed method

Fig. 2. Doppler frequency spectrum of observed signal (a), reconstructed signal by the PCA-based method (b) and synthesized signal by the proposed method (c) at SCR $= -23.6\,\text{dB}$.

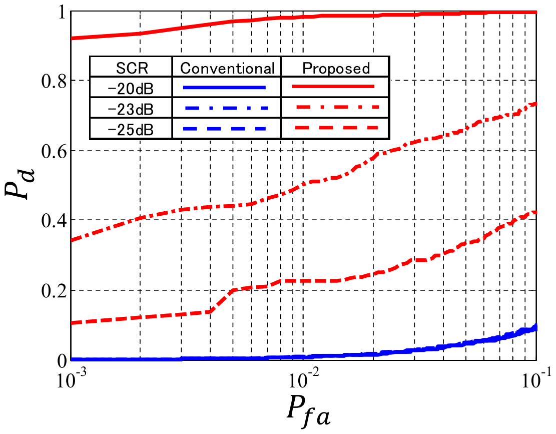

Fig. 3. ROC for each method at three different SCR cases.

Finally, for the statistical analysis, the ROC for each method is investigated. In this case, 1000 different clutter patterns with a target present or absent are investigated for three different SCR values. Fig. 3 presents the ROC of each SCR value for both methods and shows the proposed method considerably enhances the target detection probability compared with that obtained using the conventional method. For example, at SCR $= -23\,\text{dB}$, with $P_{fa} = 10^{-2}$, the proposed method returns $P_d = 0.50$ whereas the conventional method returns $P_d = 0.01$. Furthermore, the calculation times of the conventional and the proposed methods are 1.0 second and 400 second, respectively, in using Intel(R) Xeon(R) E5-2643 3.30 GHz processor.

5 Conclusion

For PD radar systems, we proposed a novel target detection method based on the ICA separation. The method employs a statistical feature of the ICA-based separated signal for target detection when the Doppler spectrum of the target experiences interference from that of clutter. The results from numerical simulations verified that our method does enhance the ROC feature compared with that obtained from the conventional PCA method.

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