LETTER *Special Section on Intelligent Transport Systems and Wideband Systems*

Elevation Filter Design for Short-Range Clutter Suppression on Airborne Radar in MIMO System

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SUMMARY Short-range ambiguous clutter can seriously affect the performance of airborne radar target detection when detecting long-range targets. In this letter, a multiple-input-multiple-output (MIMO) array structure elevation filter (EF) is designed to suppress short-range clutter (SRC). The sidelobe level value in the short-range clutter region is taken as the objective function to construct the optimization problem and the optimal EF weight vector can be obtained by using the convex optimization tool. The simulation results show that the MIMO system can achieve better range ambiguous clutter suppression than the traditional phased array (PA) system.

key words: *MIMO system, short-range clutter, elevation filter design*

1. Introduction

Space-time adaptive processing is an important technique to suppress clutter in airborne radar platform [1], [2], and the accurate estimation of clutter covariance matrix (CCM) has great influence on STAP performance [3]. When the pulse repetition frequency (PRF) of radar system is high, the range ambiguous clutter will appear, and the SRC will be aliased with the long-range clutter. SRC is range-dependent, and the clutter characteristics of samples are different at different ranges. CCM estimated by range cells has deviation from the real CCM, thus affecting STAP performance.

In recent years, some studies have been done on SRC suppression. In [4], sparse recovery and orthogonal projection techniques were introduced to handle the SRC. Before STAP, L EFs were designed to generate zeros at corresponding short-range cells to eliminate SRC in each range cell, where L is the number of range rings [5]. In a PA radar system, an EF is designed to generate a certain zero-notch to suppress the SRC at one time [6]. When the number of elevation array elements is large, EF in PA system can suppress SRC better, otherwise, the performance deteriorates. In [7], the authors propose a vertical spatial frequency compensation and pre-STAP filtering method to separate range-ambiguous clutter with vertical frequency diverse array (FDA). An enhanced pre-STAP beamforming method is proposed using the priori knowledge of platform and radar parameters, and a covariance matrix tapering technique is introduced to widen the notches [8]. Different from previous SRC suppression methods, this letter uses sidelobe level control as an objective function to construct a convex optimization problem for EF design in airborne MIMO radar system, and the elevation beamforming weight can be solved by the convex optimization tool.

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2. EF Design in MIMO System

2.1 Signal Model

Consider an airborne radar platform flying along the y-axis at speed v and altitude H (see Fig. 1). A planar array is installed on the platform, and the normal direction of the array is consistent with the y-axis. There are N array elements in each row of the array, which transmit the same waveform, namely phased array mode. Each column has M array elements, which transmit orthogonal waveform, namely MIMO mode, and the array element interval is d. Then, the azimuth spatial frequency f_u, elevation spatial frequency f_e and Doppler frequency f_d corresponding to a scattering point P on the ground are respectively

$$\begin{cases} f_u(\theta,\varphi) = d/\lambda \sin\theta \cos\varphi \\ f_e(\theta,\varphi) = d/\lambda \sin\varphi \\ f_d(\theta,\varphi) = 2vT/\lambda \cos(\theta) \cos\varphi \end{cases} \tag{1}$$

where θ and φ are the azimuth angle and elevation angle of scattering point P relative to the platform respectively, T is the pulse repetition period of the MIMO system.

Assuming that there are K pulses in a coherent pulse interval (CPI), the clutter signal of the k^{th} pulse, the l^{th} range cell and the n^{th} column can be written as

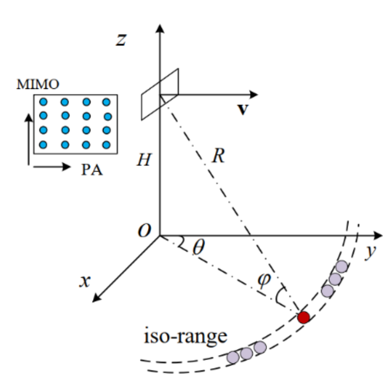


Fig. 1 Geometric structure of an airborne radar system.

$$\mathbf{c}_{n,k,l} = \sum_{j=0}^{N_r}\sum_{i=1}^{N_c} \alpha_{i,j,l} e^{j2\pi\left[(n-1)f_u(\theta_i,\varphi_{j,l})+(k-1)f_d\left(\theta_i,\varphi_{j,l}\right)\right]} \cdot \mathbf{a}_{\mathrm{MIMO}}\left(\varphi_{j,l}\right) \tag{2}$$

where N_r is range ambiguous multiplicity, N_c is the number of clutter patches on the l^{th} range ring, $\alpha_{i,j,l}$ is the amplitude of clutter patch after matched filtering. The elevation spatial steering vector $\mathbf{a}_{\mathrm{MIMO}}\left(\varphi_{j,l}\right)$ has the following form

$$\begin{aligned}\mathbf{a}_{\mathrm{MIMO}}\left(\varphi_{j,l}\right) &= \mathbf{a}_t\left(\varphi_{j,l}\right)\otimes\mathbf{a}_r\left(\varphi_{j,l}\right)\\ &= \left[1, e^{j2\pi d/\lambda\sin\varphi_{j,l}}, \cdots, e^{j2\pi(M-1)d/\lambda\sin\varphi_{j,l}}\right]^T\\ &\quad\otimes\left[1, e^{j2\pi d/\lambda\sin\varphi_{j,l}}, \cdots, e^{j2\pi(M-1)d/\lambda\sin\varphi_{j,l}}\right]^T\end{aligned} \tag{3}$$

where $\mathbf{a}_t\left(\varphi_{j,l}\right)$, $\mathbf{a}_r\left(\varphi_{j,l}\right)$ are the transmit and receive spatial steering vector in the elevation dimension, $\otimes$ is the Kronecker product.

The target signal can be written as

$$\mathbf{s}_{n,k,l_0} = \alpha_0 e^{j2\pi\left[(n-1)f_s(\theta_0,\varphi_0)+(k-1)f_d(\theta_0,\varphi_0)\right]}\mathbf{a}_{\mathrm{MIMO}}\left(\varphi_0\right) \tag{4}$$

where l_0 is the range ring of the target, α_0 is the target amplitude after matched filtering, φ_0 is the elevation angle of target, and θ_0 is the azimuth angle. Then the radar echo signal can be expressed as

$$\mathbf{x}_{n,k,l} = \begin{cases}\mathbf{s}_{n,k,l_0} + \mathbf{c}_{n,k,l} + \mathbf{z}_{n,k,l}, & l = l_0\\ \mathbf{c}_{n,k,l} + \mathbf{z}_{n,k,l}, & l \neq l_0\end{cases} \tag{5}$$

where $\mathbf{z}_{n,k,l}$ is gaussian white noise.

2.2 EF Design

After the MIMO array receives the signal, the elevation dimension beamforming is carried out first. Assuming that the elevation dimension beamforming vector is $\mathbf{w}_{\mathrm{MIMO}}$, then the data $\mathbf{y}_{n,k,l}$ after elevation dimension beamforming is

$$y_{n,k,l} = \mathbf{w}_{\mathrm{MIMO}}^H\mathbf{x}_{n,k,l}. \tag{6}$$

where $(\cdot)^H$ is a conjugate transposition operation. The CCM can be estimated by

$$\mathbf{R} = \frac{1}{L-1}\sum_{l=1, l\neq l_0}^{L}\mathbf{y}_l\mathbf{y}_l^H \in \mathbb{C}^{NK\times NK} \tag{7}$$

where $\mathbf{y}_l$ is expressed as

$$\mathbf{y}_l = \left[y_{1,1,l}, y_{2,1,l}, \cdots, y_{N,K,l}\right]^T \tag{8}$$

where $(\cdot)^T$ is a transposition operation. Then, the data is processed by reduced-dimension STAP (RD-STAP), and the optimal space-time filter weight vector can be obtained in the form of

$$\mathbf{w}_{\mathrm{STAP}} = \frac{1}{\mu}\left(\mathbf{D}^H\mathbf{R}\mathbf{D}\right)^{-1}\left(\mathbf{D}^H\mathbf{s}_{l_0}\right) \tag{9}$$

where, $\mathbf{D} \in \mathbb{C}^{NK\times 3N}$ is the reduced-dimension matrix and has the same form as $\mathbf{T}$ in [6], $\mu = \mathbf{s}_{l_0}^H\mathbf{R}^{-1}\mathbf{s}_{l_0}$, where $\mathbf{s}_{l_0}$ has the following form

$$\mathbf{s}_{l_0}^T = \mathbf{w}_{\mathrm{MIMO}}^H\left[\mathbf{s}_{1,1,l_0}, \mathbf{s}_{2,1,l_0}, \cdots, \mathbf{s}_{N,K,l_0}\right] \tag{10}$$

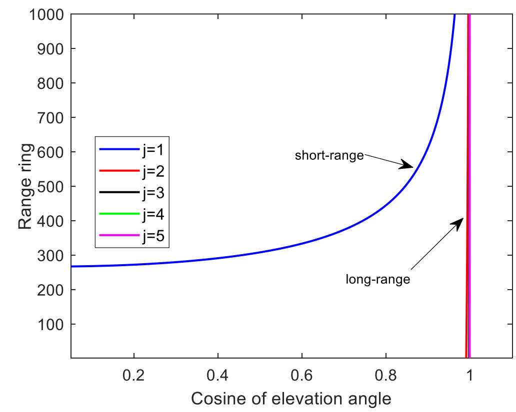


Fig. 2 Cosine of elevation angle with different range rings.

According to the RMB rule, $L = 6N$ range rings are required to estimate the CCM. The elevation angles corresponding to different range rings can be calculated by

$$\varphi_{j,l} = \frac{H}{R_{j,l}} + \frac{R_{j,l}^2 - H^2}{2r_eR_{j,l}} \tag{11}$$

where r_e is the earth radius.

Figure 2 shows the variation trend of elevation angle at different range rings when range ambiguity exists. It can be seen that the elevation angle changes dramatically in the short-range area, but little in the long-range area. When detecting long-range targets, and there is no range ambiguity, the range samples are independently and identically distributed. The CCM estimated by Eq. (9) is accurate, and STAP processing performance is good. However, in the case of range ambiguity, especially in the case of short-range ambiguity, the near-range sample data changes with the elevation angle, and the CCM is not accurate, thus affecting STAP performance. One solution is to design the elevation filter vector $\mathbf{w}_{\mathrm{MIMO}}$ based on the difference in elevation angle between the short-range area and the long-range, so that the SRC can be eliminated after the data $\mathbf{x}_{n,k,l}$ is acted by vector $\mathbf{w}_{\mathrm{MIMO}}$. Aiming at sidelobe level minimization in the SRC area, the following optimization problem is constructed

$$\min_{\mathbf{w}_{\mathrm{MIMO}}}\sum_{q=1}^{Q}\left|\mathbf{w}_{\mathrm{MIMO}}^H\mathbf{a}_{\mathrm{MIMO}}\left(\phi_q\right)\right|^2 \tag{12}$$

where ϕ_q ($q = 1, \cdots, Q$) is a random variable uniformly distributed in the short-range elevation angle area. The target should be guaranteed to have no loss output, and constraints need to be added

$$\begin{cases}\mathbf{w}_{\mathrm{MIMO}}^H\mathbf{a}_{\mathrm{MIMO}}\left(\varphi_{l_0}\right) = 1\\ \mathbf{w}_{\mathrm{MIMO}}^H\mathbf{a}_{\mathrm{MIMO}}\left(\phi_g\right) \leq 1\end{cases} \tag{13}$$

where ϕ_g ($g = 1, \cdots, G$) is a random variable uniformly

Table 1 Simulation parameters.

Parameters	value
Wavelength	0.25m
PRF	2.5kHz
Bandwidth	5MHz
Planar array rows	8
Planar array columns	8
Pulses in one CPI	64
Platform height	8km
Platform velocity	120m/s

distributed in the mainlobe area. In addition, the overall sidelobe level should not be too high, and the following constraints can be added

$$\mathbf{w}_{\mathrm{MIMO}}^{H}\mathbf{a}_{\mathrm{MIMO}}(\phi_z) \le \varepsilon \tag{14}$$

where is ϕ_z $(z = 1, \cdots, Z)$ a random variable uniformly distributed in the sidelobe area. Overall, the optimization problem can be established as

$$P_1 \begin{cases} \min_{\mathbf{w}_{\mathrm{MIMO}}} \sum_{q=1}^{Q} \left|\mathbf{w}_{\mathrm{MIMO}}^{H}\mathbf{a}_{\mathrm{MIMO}}\left(\phi_q\right)\right|^2 \\ \mathbf{w}_{\mathrm{MIMO}}^{H}\mathbf{a}_{\mathrm{MIMO}}(\varphi_{l_0}) = 1 \\ \mathbf{w}_{\mathrm{MIMO}}^{H}\mathbf{a}_{\mathrm{MIMO}}\left(\phi_g\right) \le 1 \\ \mathbf{w}_{\mathrm{MIMO}}^{H}\mathbf{a}_{\mathrm{MIMO}}(\phi_z) \le \varepsilon \end{cases} \tag{15}$$

According to [9], P_1 is a convex quadratic program problem and the solution can be calculated by CVX toolbox.

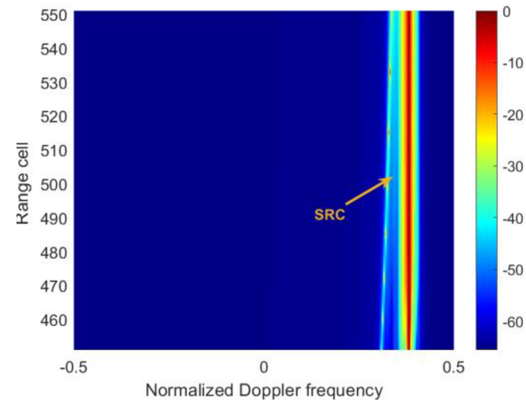
3. Simulations

In this section, the performance of the proposed algorithm is evaluated by MATLAB simulation, and the simulation parameters are given in Table 1. The input signal-to-noise ratio (SNR) is 10 dB, and the clutter-to-noise ratio (CNR) is 40 dB. The range resolution of MIMO system is $\Delta R = c/2B = 30\,m$, and the range ambiguous interval is $\Delta R_a = c/2f_r = 60$ km. The target range is set to 75 km, and the target elevation angle is $\varphi_0 = -6.46°$. The sidelobe area is $[-90°, -8°] \cup [-4°, 90°]$, and the mainlobe area is $[-8°, -4°]$. It needs $L = 48$ range cells to estimate the CCM. The short-range area is 14.28 ∼ 15.72 km, and the corresponding elevation angle area is $-30.65°$ ∼ $-34.07°$. The short-range rings are from 476 to 524.

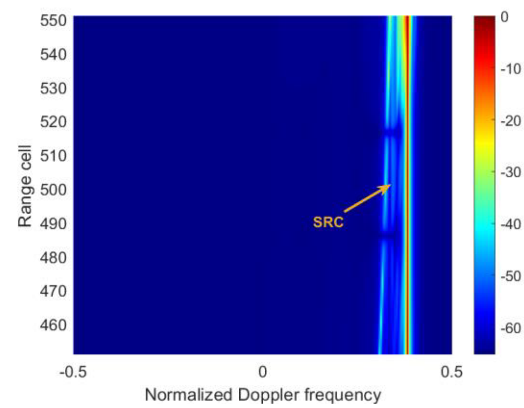
We compare the effects of static processing (i.e., no processing), phased array mode and MIMO mode on short-range clutter suppression. Figure 3 shows the range-Doppler spectrum of several methods. By comparing the results, it can be obviously found that the clutter is strong in the short-range region without any processing. In phased array mode, the short-range clutter is slightly suppressed due to the effect of EF. In MIMO mode, short-range clutter is fully suppressed due to the increase of available degrees of freedom of EF filter.

4. Conclusion

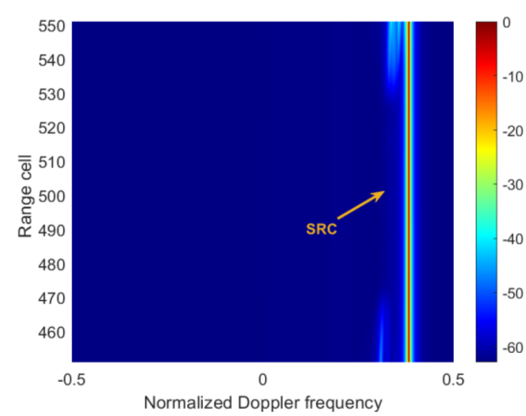
In this letter, an EF in MIMO system is designed to suppress SRC. The simulation results show that MIMO array can achieve better SRC suppression than PA array with the same number of array elements. Of course, MIMO system is more complex than PA system, and the computation is higher. It's worth looking forward to solving this problem as hardware improves in the future.



(a)



(b)



(c)

Fig. 3 Range-Doppler spectrum: (a) static mode, (b) PA mode, (c) MIMO mode.

Acknowledgments

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