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Mainlobe jamming cancelation method for distributed monopulse arrays

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Dear editor,

Array antennas, which are able to adaptively generate the mainlobe in the target direction and notches in the jamming directions, are usually employed by modern radars [1–3]. A notch is adaptively placed in the mainlobe direction when mainlobe jamming (MLJ) exists, which changes the shape of the mainlobe and decreases the antenna gain on the target echo. Hence, in this scenario, it makes detecting the target or estimating its direction more difficult, and the problem becomes more serious when MLJ is closer to the target.

Multi-input-multi-output (MIMO) system with distributed antennas is an emerging technique for modern radar. The scattered echoes from identical target are uncorrelated [4] or partly correlated [5] on different antennas. In contrast, MLJ from identical transmitter is completely correlated on different antennas [6]. According to these correlation characteristics, the target echo can be identified even in the case where it comes from the same direction as MLJ [6]. However, when target echo is overlapped with MLJ, the correlation coefficient of the received signal could be much larger than that of the target echo. Thus, the overlapped signal could be denied as MLJ with large probability.

In a practical scenario, MLJ could be generated by both airborne jammer and accompanying jammer. Moreover, target echo and MLJ could overlap in time domain. To deal with this scenario, we propose a new target detection and direction estimation method on distributed monopulse arrays (DMA). An adaptive MLJ cancelation (MLC) filter is designed with a condition that the steering vector of target echo on DMA is perturbed by the partly correlated random vector. This filter on DMA can filter out MLJ and reserve target echo even in the case that target echo and MLJ come from the same position. The monopulse ratio is maintained while simultaneously performing MLC with the identical filter on Σ, Δ_e, and Δ_a beams of DMA. Hence, the direction of target echo can be estimated under the monopulse principle.

System model. Assume there are I mainlobe jammers and a target in the far field of DMA, as shown in Figure 1(a). The target is placed at T_0, and the i-th jammer ($0 < i \leqslant I$) is placed at T_i. There are N_s monopulse arrays placed parallel to each other at positions M_n ($n = 1, 2, \ldots, N_s$). For any two arrays with positions M_m and M_n, the system geometry relationship satisfies $|M_m M_n| \ll |M_n T_i|$. Each array forms Σ beam, Δ_e beam, and Δ_a beam simultaneously, and the monopulse axis intersects the axes of other arrays at predicted target position P. Hence, the Σ (or Δ_e, Δ_a) beam gain of each array on T_i can be approximated to be identical, which is derived in Appendix A. The gain of monopulse beams are defined as $g_\Sigma(\theta_{e_i}, \theta_{a_i})$, $g_{\Delta_e}(\theta_{e_i}, \theta_{a_i})$, and $g_{\Delta_a}(\theta_{e_i}, \theta_{a_i})$, respectively. The steering vector on DMA corresponding to position T_i can be expressed as

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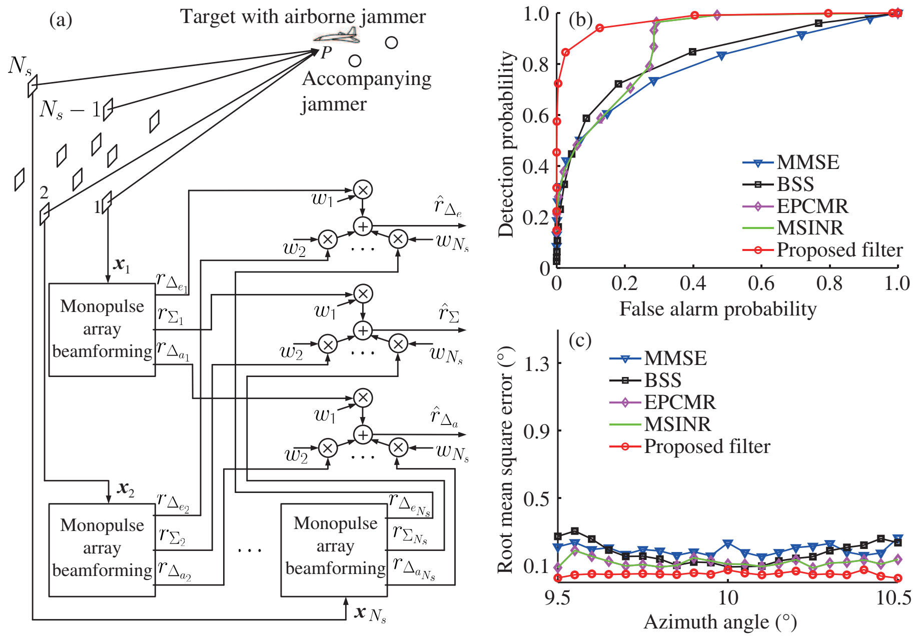

Figure 1 (Color online) (a) System model; (b) receiver operating characteristic curves; (c) angle estimation accuracy.

$$\boldsymbol{d}_i = \left[\mathrm{e}^{\mathrm{j}2\pi\frac{|M_1 T_i|}{\lambda}}, \ldots, \mathrm{e}^{\mathrm{j}2\pi\frac{|M_{N_s} T_i|}{\lambda}}\right]^{\mathrm{T}}, \tag{1}$$

where λ denotes electromagnetic wavelength.

In practical scenarios, the target echoes received by distributed antennas are not completely correlated [4,5]. Hence, the steering vector of the target echo on DMA can be modeled as a random vector with the form

$$\tilde{\boldsymbol{d}}_0 = \boldsymbol{\eta} \circ \boldsymbol{d}_0, \tag{2}$$

where $\circ$ denotes Hadamard product, $\boldsymbol{\eta}$ is a random vector satisfying $\mathrm{E}[\boldsymbol{\eta}\boldsymbol{\eta}^{\mathrm{H}}] = \boldsymbol{C}$, and the elements of $\boldsymbol{C}$ are modeled according to [5] in this article. In the presence of MLJ, the received signals of the monopulse beams are the summation of target echo, MLJ, and thermal noise following the models

$$\boldsymbol{r}_{\Sigma} = \tilde{\boldsymbol{d}}_0 g_{\Sigma_0} s_0 + \sum_{i=1}^{I} \boldsymbol{d}_i g_{\Sigma_i} s_i + \boldsymbol{n}_{\Sigma}, \tag{3}$$

$$\boldsymbol{r}_{\Delta_e} = \tilde{\boldsymbol{d}}_0 g_{\Delta_{e0}} s_0 + \sum_{i=1}^{I} \boldsymbol{d}_i g_{\Delta_{ei}} s_i + \boldsymbol{n}_{\Delta_e}, \tag{4}$$

$$\boldsymbol{r}_{\Delta_a} = \tilde{\boldsymbol{d}}_0 g_{\Delta_{a0}} s_0 + \sum_{i=1}^{I} \boldsymbol{d}_i g_{\Delta_{ai}} s_i + \boldsymbol{n}_{\Delta_a}, \tag{5}$$

where s_0 and s_i are the target echo and the i-th jamming, respectively; in addition, $\boldsymbol{n}_{\Sigma}$, $\boldsymbol{n}_{\Delta_e}$, and $\boldsymbol{n}_{\Delta_a}$ are the thermal noise vectors.

Proposed MLJ filter. Because classical spatial filtering algorithms [1–3] are designed based on the target steering vector model (1), the algorithms could not achieve their optimum performance in the case of the random steering vector as model (2). Hence, we propose a new filter to deal with this case

$$\max \quad \frac{\boldsymbol{w}^{\mathrm{H}} \boldsymbol{r}_{\Sigma} \boldsymbol{r}_{\Sigma}{}^{\mathrm{H}} \boldsymbol{w}}{\boldsymbol{w}^{\mathrm{H}} \boldsymbol{R}_{\Sigma_{\mathrm{JN}}} \boldsymbol{w}}, \tag{6}$$

$$\text{s.t.} \quad \boldsymbol{w}^{\mathrm{H}} \boldsymbol{G}_{\Sigma_J} \mathrm{E}\left[\boldsymbol{s}_J \boldsymbol{s}_J^{\mathrm{H}}\right] \boldsymbol{G}_{\Sigma_J}^{\mathrm{H}} \boldsymbol{w} = 0, \tag{7}$$

$$\boldsymbol{w}^{\mathrm{H}} \boldsymbol{w} = 1, \tag{8}$$

where $\boldsymbol{R}_{\Sigma_{\mathrm{JN}}}$ is the covariance matrix of jamming-plus-noise in the Σ beams of DMA.

From some theoretical derivations, the optimization model (6)–(8) is solved as

$$\boldsymbol{w} = \frac{\left(\boldsymbol{I}_{N_s \times N_s} - \boldsymbol{U}_1 \boldsymbol{U}_1^{\mathrm{H}}\right) \boldsymbol{r}_{\Sigma}}{\sqrt{\boldsymbol{r}_{\Sigma}^{\mathrm{H}} \left(\boldsymbol{I}_{N_s \times N_s} - \boldsymbol{U}_1 \boldsymbol{U}_1^{\mathrm{H}}\right) \boldsymbol{r}_{\Sigma}}}, \tag{9}$$

where $\boldsymbol{U}_1$ represents the jamming signal subspace (JSS) of $\boldsymbol{R}_{\Sigma_{\mathrm{JN}}}$, and $\boldsymbol{I}_{N_s \times N_s}$ represents identity matrix.

Target detection and direction estimation. Theoretically, JSS is the signal subspace of the covariance matrix corresponding to MLJ-plus-noise. However, the signal subspace of received signal may be a span of JSS and the steering vector of target echo in practical scenarios. Generally, the energy of target echo is much weaker than that of MLJ. Based on this assumption, we propose a joint JSS and target estimation method. This method and its robstness is presented in Appendixes B–C.

For the purpose of target direction estimation, we calculate the voltage ratio of $\hat{r}_{\Delta_a}$ to $\hat{r}_{\Sigma}$ as

$$\begin{aligned}\hat{f}_a(\theta_{e_0}, \theta_{a_0}) &= \frac{\boldsymbol{w}^{\mathrm{H}}\boldsymbol{r}_{\Delta_a}}{\boldsymbol{w}^{\mathrm{H}}\boldsymbol{r}_{\Sigma}} \\ &= \frac{\boldsymbol{w}^{\mathrm{H}}\tilde{\boldsymbol{d}}_0 g_{\Delta_a}(\theta_{e_0}, \theta_{a_0}) s_T + \boldsymbol{w}^{\mathrm{H}}\boldsymbol{n}_{\Delta_a}}{\boldsymbol{w}^{\mathrm{H}}\tilde{\boldsymbol{d}}_0 g_{\Sigma}(\theta_{e_0}, \theta_{a_0}) s_T + \boldsymbol{w}^{\mathrm{H}}\boldsymbol{n}_{\Sigma}}. \quad (10)\end{aligned}$$

For target echo with sufficient signal to noise ratio (SNR), the noise term in (10) can be ignored, and the ratio $\hat{f}_a(t)$ is approximately expressed as

$$\hat{f}_a(\theta_{e_0}, \theta_{a_0}) \approx \frac{g_{\Delta_a}(\theta_{e_0}, \theta_{a_0})}{g_{\Sigma}(\theta_{e_0}, \theta_{a_0})}, \quad (11)$$

which means the monopulse ratio is maintained while performing MLJ cancelation. Hence, the target direction in the azimuth dimension can be estimated from $\hat{f}_a(\theta_{e_0}, \theta_{a_0})$ with the help of monopulse principle. Because of the symmetrical array architecture on the azimuth and elevation dimensions, the target direction in elevation dimension can also be estimated with the same method.

Simulations. Monte Carlo simulations are taken to evaluate target detection and direction estimation performances under different MLC algorithms. The algorithms are the proposed filter and other algorithms including filtering methods as per minimizing mean square error (MMSE) or maximizing signal to interference-plus-noise ratio (MSINR) criterion [1, 2], eigen-projection matrix pre-processing based covariance matrix reconstruction (EPCMR) algorithm [3], and blind signal separation (BSS) algorithm [7].

The basic parameters of the system are $N_s = 10$, $\lambda = 3$ cm, and an equivalent target diameter of $D = 10$ m. Each array is randomly placed on the xy plane of cartesian coordinate system in the region $\{(x, y)|x \in [-300, 300]$ m, $y \in [-300, 300]$ m$\}$. The number of elements of each array in elevation and azimuth directions are $N_e = 32$ and $N_a = 64$, respectively. The monopulse axes intersect at P ($\theta_{e_P} = 30°$, $\theta_{a_P} = 10°$, $R_P = 100000$ m). The coordinates of the jammers are T_1 ($\theta_{e_1} = 30°$, $\theta_{a_1} = 10°$, $R_1 = 100000$ m), T_2 ($\theta_{e_2} = 29.9°$, $\theta_{a_2} = 9.9°$, $R_2 = 100000$ m), and T_3 ($\theta_{e_3} = 29.5°$, $\theta_{a_3} = 10.1°$, $R_3 = 100000$ m). MLJ from T_1 is set as deceptive jamming, whose jamming to noise ratio (JNR) is 10 dB and the number of false targets is 400; MLJs from T_2 and T_3 are set as independent noise, whose JNRs are both 50 dB.

To evaluate target detection performance in the presence of both airborne and accompanying jammer, the target position T_0 is set to the same position as T_1, and the SNR of target echo is set to 10 dB. Figure 1(b) shows the receiver operating characteristic curves under 2000 independent Monte Carlo simulations, which indicates that the system will get higher detection performance under the proposed filter.

To evaluate target direction estimation accuracy, the target is set to the positions uniformly sampled from the arc ($\theta_{e_0} = 30°$, $\theta_{a_0} \in [9.5°, 10.5°]$, $R_0 = 100000$ m), whose SNR is 10 dB. At each target position, 200 independent Monte Carlo simulations are taken. Figure 1(c) shows the target direction estimation performance, which indicates that the system gets better direction estimation performance under the proposed filter.

Conclusion. In this article, an adaptive filtering algorithm for DMA is proposed to cancel MLJ. Based on this filter, the system will be able to detect the target and estimate its direction even if the target echo is submerged by MLJ. The simulation results show that the system can achieve better performance under the proposed filter.

Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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