SCIENCE CHINA
Information Sciences

• LETTER •

March 2022, Vol. 65 139301:1–139301:3
https://doi.org/10.1007/s11432-020-3229-4

Suppression of dense false target jamming for stepped frequency radar in slow time domain

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Received 2 October 2020/Revised 30 December 2020/Accepted 23 March 2021/Published online 10 February 2022

Citation Zeng L, Zhang Z J, Wang Y-L, et al. Suppression of dense false target jamming for stepped frequency radar in slow time domain. Sci China Inf Sci, 2022, 65(3): 139301, https://doi.org/10.1007/s11432-020-3229-4

Dear editor,

The presence of jamming can drastically degrade the detection performance of a radar system [1]. Dense false target jamming is a paramount type of deceptive jamming, which is employed to counter pulse compression radar [2]. The jamming signal is obtained by storing and transmitting the radiated signal, and it produces a large number of false targets that are similar to target signals at the radar receiver [3].

In this study, we propose a method to suppress the dense false target jamming based on stepped frequency radar. This method can resist the jamming of the main lobe, even the jamming in the same direction. The innovation of this study is determining the steering vector by the phase difference between adjacent pulses on the distance dimension, and then suppressing jamming by processing on the distance gate.

The basic concept of the proposed algorithm. We consider the step frequency signal consisting of M transmitting pulses. The frequency of the mth pulse is $f_m = f_0 + (m-1)\Delta f$, $m = 1, 2, \ldots, M$, where f_0 is the initial transmitted signal pulse frequency, Δf is the frequency increment, which is minute compared with f_0. Taking the linear frequency modulated signal as a modulated signal, the transmitting signal can be expressed as

$$s_m(t) = \mathrm{rect}(t/T_p)\mathrm{e}^{\mathrm{j}\pi\mu t^2} \cdot \mathrm{e}^{\mathrm{j}2\pi f_m t}, \tag{1}$$

where t is the time sampling points within a single pulse. T_p is the pulse duration, μ indicates the chirp slope. $s(t) = \mathrm{rect}(t/T_p)\mathrm{e}^{\mathrm{j}\pi\mu t^2}$ indicates the complex envelope of the transmitted signal.

Considering a far-field point source at range r, the step frequency signal sent by an array element is reflected back when it reaches the target at the far-field point. The echo signal received by the array element can be expressed as

$$s_r(t) = \mathrm{rect}[(t-t_1)/T_p]\mathrm{e}^{\mathrm{j}\pi\mu(t-t_1)^2} \cdot \mathrm{e}^{\mathrm{j}2\pi f_m(t-t_1)}, \tag{2}$$

where $t_1 = \frac{2r}{\mathrm{c}}$. For narrow-band signals, the difference of signal envelope on each array element is negligible, so

$$s_r(t) = \mathrm{rect}(t/T_p)\mathrm{e}^{\mathrm{j}\pi\mu t^2} \cdot \mathrm{e}^{\mathrm{j}2\pi f_m(t-t_1)}. \tag{3}$$

Then the phase difference of the mth and 1st pulses is $\Delta\varphi_m = 2\pi(m-1)\Delta f(t - \frac{2r}{\mathrm{c}})$. Similar to array signal processing, the steering vector of each echo in the M coherent pulses is defined as $\boldsymbol{w}_0(r,t) = [\,1\ \mathrm{e}^{\mathrm{j}2\pi\Delta f(t-\frac{2r}{\mathrm{c}})}\ \cdots\ \mathrm{e}^{\mathrm{j}(M-1)2\pi\Delta f(t-\frac{2r}{\mathrm{c}})}\,]^{\mathrm{T}}$, which is the weighting vector of the pulses in the slow time domain, and the slow time is the time change between multiple pulses. The output signal after matched filtering is given by [4]

$$\begin{aligned} &s_{\mathrm{out}}^m(t) \\ &= T_p \cdot \sin\mathrm{c}(B(t-t_0)) \cdot \mathrm{e}^{\mathrm{j}2\pi f_m(t-t_0) - \mathrm{j}2\pi f_m\frac{2r}{\mathrm{c}}}. \end{aligned} \tag{4}$$

So the output phase difference of the mth and 1st pulses after matched filtering is expressed as

$$\Delta\varphi_m' = 2\pi(m-1)\cdot\Delta f\left(t - t_0 - \frac{2r}{\mathrm{c}}\right),$$

where t_0 represents the necessary delay time for achieving matched filtering. The steering vector between the pulses of the same array element can be expressed as $\boldsymbol{a}(r,t) = [1\ \mathrm{e}^{\mathrm{j}2\pi\Delta f(t-t_0-\frac{2r}{\mathrm{c}})} \ldots \mathrm{e}^{\mathrm{j}(M-1)2\pi\Delta f(t-t_0-\frac{2r}{\mathrm{c}})}]^{\mathrm{T}}$.

According to the definition of coherent accumulation in the slow time domain, the output of each coherent pulse after weighted accumulation can be expressed as

$$\begin{cases} y(t) = \boldsymbol{w}^{\mathrm{H}}(r,t)\boldsymbol{s}_{\mathrm{out}}(t), \\ \boldsymbol{s}_{\mathrm{out}}(t) = \boldsymbol{a}(r,t)s_{\mathrm{out}}^1(t). \end{cases} \tag{5}$$

The matched filter output of M pulses can be expressed as $\boldsymbol{s}_{\mathrm{out}}(t) = [\,s_{\mathrm{out}}^1(t)\ s_{\mathrm{out}}^2(t)\ \cdots\ s_{\mathrm{out}}^M(t)\,]^{\mathrm{T}}$, where $\boldsymbol{w}(r,t)$ is the weighting coefficient of each pulse in the slow time domain. Even if it is weighted by constant weight $\boldsymbol{w}(r,t_0) = [1\ \mathrm{e}^{-\mathrm{j}2\pi\Delta f\frac{2r}{c}}\ \cdots\ \mathrm{e}^{-\mathrm{j}(M-1)2\pi\Delta f\frac{2r}{c}}]^{\mathrm{T}}$ or distance gate $\boldsymbol{w}(r,t) = \boldsymbol{a}(r,t)$, at $t = t_0$ time, the coherent accumulation output is $|y(t_0)| = MT_p$.

The basic principle of dense false target jamming is that the jammer samples, stores and forwards the radar signals in a certain period, forming multiple false targets with different distances [5]. If the number of dense false targets is K, the jamming of multiple false targets can be expressed as follows:

$$s_j(t) = \sum_{k=1}^{K}\beta_k s_m(t-\tau_k), \tag{6}$$

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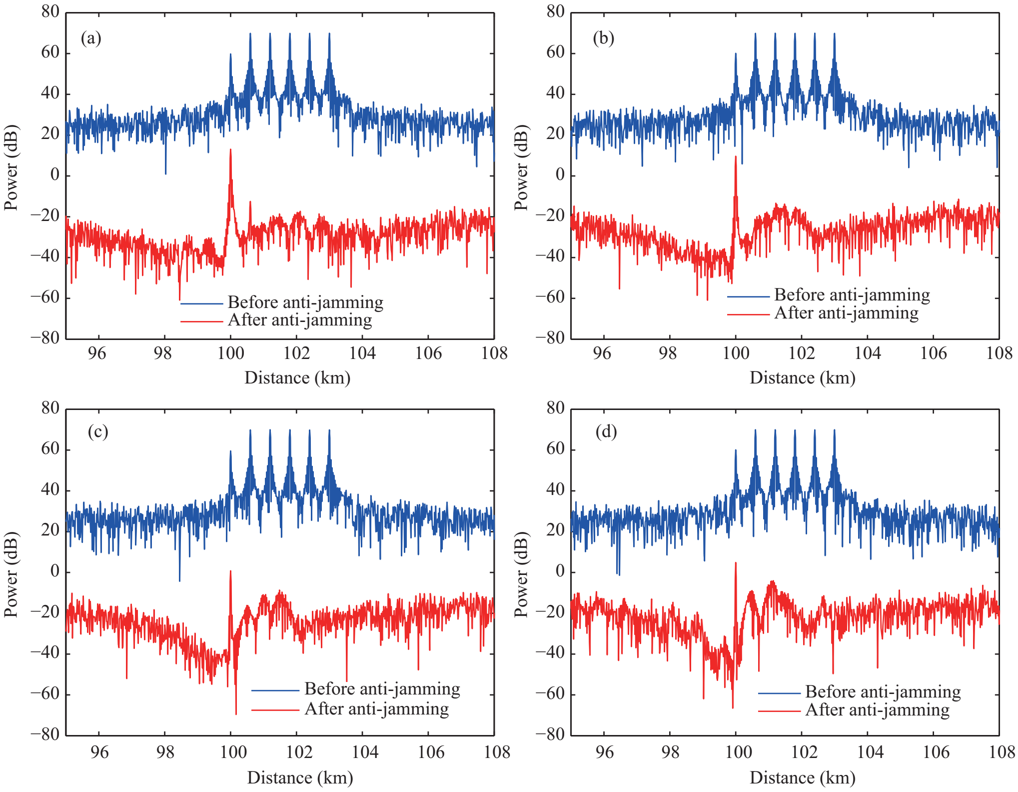

Figure 1 (Color online) The blocking output of mixed signal weighted by distance gate at different frequency intervals. (a) $\Delta f = 0.5$ kHz; (b) $\Delta f = 1$ kHz; (c) $\Delta f = 2$ kHz; (d) $\Delta f = 3$ kHz.

where τ_k, $k = 1, 2, \ldots, K$, represents the delay of false target jamming relative to the true target. The jamming peak indicating distance is $r_{j_k} = r_e + c\tau_k$, where r_e is the distance of the target and β_k is the coefficient of jamming amplitude.

From the indicating distance, the jamming can only form a few false spots behind the jammer without cross period and frequency shift. When the jamming traces are accumulated according to the distance gate, the actual weighted output signal at $t = t_0$ can be expressed as follows:

$$y_j(t) = \boldsymbol{w}^{\rm H}(r_{j_k})\boldsymbol{s}_{\rm j\_out}(t) = \boldsymbol{w}^{\rm H}(r_{j_k})\boldsymbol{a}(r)s^1_{\rm j\_out}(t) = \sum_{k=1}^{K} \frac{\sin(2\pi M\Delta f\tau_k)}{\sin(2\pi\Delta f\tau_k)} {\rm e}^{{\rm j}2\pi(M-1)\Delta f\tau_k} \cdot s^1_{\rm j\_out}(t), \quad (7)$$

where $\boldsymbol{w}(r_{j_k}) = [1\ {\rm e}^{-{\rm j}2\pi\Delta f\frac{2r_{j_k}}{c}}\ \cdots\ {\rm e}^{-{\rm j}(M-1)2\pi\Delta f\frac{2r_{j_k}}{c}}]^{\rm T}$ is the steering vector attached to the jamming traces by weighting according to the distance gate, $\boldsymbol{a}(r) = [1\ {\rm e}^{-{\rm j}2\pi\Delta f(2r_e/c)}\ \cdots\ {\rm e}^{-{\rm j}(M-1)2\pi\Delta f(2r_e/c)}]^{\rm T}$ is the actual steering vector of the jamming, $\boldsymbol{s}_{\rm j\_out}(t) = [s^1_{\rm j\_out}(t), s^2_{\rm j\_out}(t), \ldots, s^M_{\rm j\_out}(t)]^{\rm T}$ represents the output signal of the jamming signal after matched filtering. At $t = t_0$, the coherent accumulation output is $|y_j(t_0)| = T_p\sum_{k=1}^{K} (\sin(2\pi M\Delta f\tau_k)/\sin(2\pi\Delta f\tau_k))$. Therefore, false traces formed by jammer can be seen as an amplitude modulation after mutual accumulation by distance gate, which does not get an amplitude accumulation like real traces. Although the dense false target jamming is generated by replication and forwarding, its indicating distance is jamming distance. However, the steering vectors of the jamming signal in the slow time domain are still the same as the actual steering vector of the true target, so we can use this characteristic to suppress jamming.

The proposed algorithm. The Wiener filtering theory can be employed for null-forming in the distance domain of the slow time domain to suppress jamming [6]. The method is weighting the echo signal received in each pulse to form a pattern related to distance in the slow time domain, form null-forming at a jamming distance, and keep the gain at the true target distance. Considering that a target is located at r_e, there are P jamming sources whose spatial positions are r_{j_i}, $i = 1, 2, \ldots, P$. Then the received signal of the array can be expressed as

$$\boldsymbol{x}(t) = \boldsymbol{a}(r_e)s(t) + \boldsymbol{x}_{j+n}(t) = \boldsymbol{a}(r_e)s(t) + \sum_{i=1}^{P}\boldsymbol{a}(r_{j_i})s_j(t) + \boldsymbol{n}(t), \quad (8)$$

where $\boldsymbol{x}_{j+n}(t)$ is the jamming plus noise vector, which is not related to the target signal. The maximum signal-to-jamming-plus-noise ratio maximizes the output signal to the jamming ratio of the system. We can obtain the optimal weight vector $\boldsymbol{w}_{\rm opt} = \alpha\boldsymbol{R}^{-1}_{j+n}\boldsymbol{a}(r_e)$, where α is a constant, and $\boldsymbol{a}(r_e)$ represents the steering vector at the true target distance r_e. $\boldsymbol{R}_s = \sigma^2_s\boldsymbol{a}(r_e)\boldsymbol{a}^{\rm H}(r_e)$ is the covariance matrix of the true target signal, $\boldsymbol{R}_{j+n} = \sum_{i=1}^{P}\sigma^2_i\boldsymbol{a}(r_{j_i})\boldsymbol{a}^{\rm H}(r_{j_i}) + \sigma^2_n\boldsymbol{I}$ is the covariance matrix of jamming signal and noise. The distance gates are weighted seriatim in the distance domain, the blocking matrix can be used to block the signal from this distance. The blocking matrix has the form

$$\boldsymbol{B}(r_d) = \begin{bmatrix} 1 & -{\rm e}^{{\rm j}2\pi\Delta f(2r_d/c)} & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \cdots & -{\rm e}^{{\rm j}2\pi\Delta f(2r_d/c)} \end{bmatrix}. \quad (9)$$

The dimension of $\boldsymbol{B}(r_d)$ is $(M-1)\times M$, where r_d represents the indicating distance corresponding to the radar range gate. So, the output signal is given by $\boldsymbol{z}(t) = \boldsymbol{B}(r_d)\boldsymbol{x}(t)$. The blocking matrix blocks the signal enters from the distance gate r_d, calculates the covariance and inverse of the remaining signal, and then multiplies by the steering vector of the distance gate at r_d, which has a jamming suppression effect. The adaptive weight vector can be expressed as follows:

$$\boldsymbol{w}_{\boldsymbol{B}}(r_d) = \left[\boldsymbol{R}_z^{-1}\widehat{\boldsymbol{a}}(r_d)\right] \Big/ \left[\widehat{\boldsymbol{a}}^{\mathrm{H}}(r_d)\boldsymbol{R}_z^{-1}\widehat{\boldsymbol{a}}(r_d)\right], \tag{10}$$

where $\boldsymbol{R}_z = E[\boldsymbol{z}(t)\boldsymbol{z}^{\mathrm{H}}(t)]$ is the sample covariance matrix after blocking matrix, and $\widehat{\boldsymbol{a}}(r_d) = [\,1 \;\; \mathrm{e}^{-\mathrm{j}2\pi\Delta f\frac{2r_d}{c}} \;\; \cdots \;\; \mathrm{e}^{-\mathrm{j}(M-2)2\pi\Delta f\frac{2r_d}{c}}\,]^{\mathrm{T}}$ is the steering vector at the distance gate r_d. After processing by blocking matrix, the number of available arrays reduces from M to $M-1$, and the corresponding received signal is $\boldsymbol{z}(t)$. According to the adaptive weight vector $\boldsymbol{w}_{\boldsymbol{B}}(r_d)$, the output signal of single array element can be expressed as follows $y_{\boldsymbol{B}}(r_d) = \boldsymbol{w}_{\boldsymbol{B}}^{\mathrm{H}}(r_d)\boldsymbol{z}(t)$.

Simulation. There is a target at a distance of 100 km, the number of pulses is 100, and the pulse duration is 100 μs. It is assumed that the false target generator generates five false targets. The replicas generated are at range bins of 100.6, 101.2, 101.8, 102.4, 103 km.

Figure 1 shows the result of the blocking output of mixed signal weighted by distance gate. From Figures 1(a) and (b), $\Delta f = 1$ kHz is better than $\Delta f = 0.5$ kHz in jamming suppression. From Figures 1(c) and (d), the effect of jamming suppression becomes worse with the increase in Δf. Notably, Δf should be suitable. If Δf is too small, the theoretical steering vector is very close to the actual steering vector, so it cannot suppress the jamming well. Moreover, if Δf is too large, the whole correlation process will be difficult.

Conclusion. We considered the problem of suppressing dense false target jamming for stepped frequency radar. In the distance domain, the true and dense false target jamming can be discriminated from each other because the frequency difference of the adjacent pulse signal in the stepped frequency radar is range-dependent. Since the time-delay modulations change only the range bins of the false targets and the steering vectors of the false targets contain the actual range parameters of the dense false targets jamming, the dense false targets can be suppressed due to range mismatch. The proposed method can effectively resist the main lobe jamming when the frequency difference is suitable, which cannot be achieved by the traditional phased array, whether the main lobe jamming is self-defense or accompanying jamming.

Acknowledgements This work was supported by National Natural Science Foundation of China (Grant Nos. 62071482, 62001510).

References

1 Liu W J, Liu J, Hao C P, et al. Multichannel adaptive signal detection: basic theory and literature review. Sci China Inf Sci, 2022, 65: 121301

2 Hao Z M, Yu W, Chen W. Recognition method of dense false targets jamming based on time-frequency atomic decomposition. J Eng, 2019, 20: 6354–6358

3 Wang H Y, Lv Y K, Wu Y H. Study on digital multidelay dense preceded jamming. In: Proceedings of IEEE International Conference on Information and Automation (ICIA), Macau, 2017. 688–691

4 Wang X S, Xiao S P, Feng D J, et al. Modeling and Simulation of Modern Radar and Electronic Warfare Systems (in Chinese). Beijing: Publishing House of Electronics Industry, 2009

5 Xu J W, Liao G S, Zhu S Q, et al. Deceptive jamming suppression with frequency diverse MIMO radar. Signal Process, 2015, 113: 9–17

6 Wang Y-L, Ding Q J, Li R F. Adaptive Array Processing. Beijing: Tsinghua University Press, 2009