Adaptive Mainlobe Interference Suppression in Sparse Distributed Array Radar Based on Synthetic Wideband Signal

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Abstract. This paper proposes a mainlobe interference suppression method in distributed array radar (DAR) based on stepped frequency synthetic wideband signal. Due to the equivalent large aperture of DAR, it is possible to cancel the mainlobe interference without target signal suppression. The applying of stepped frequency synthetic wideband signal can avoid the different time delays arriving at each array compared with the traditional instantaneous wideband Chirp (linear frequency modulation) signal. Moreover, it can reduce the computational complexity. This method employs the narrowband adaptive processing to each sub-pulse of the stepped frequency signal, and then synthesizes the high resolution range profile (HRRP). As a result, mainlobe interference suppression under wideband signal is accomplished. Mainlobe interference suppression experiment is carried out by using an S-band experimental radar system, an S-band noise jammer and a target simulator. The measured data is processed employing the proposed method, and the result verifies the effectiveness of this algorithm.

Keywords: Distributed array radar
Stepped frequency synthetic wideband signal
Wideband adaptive beamforming · Mainlobe interference suppression

1 Introduction

In modern battlefield, due to the wide application of electronic interference equipment, the electromagnetic signals in the battlefield space are extremely dense, forming a very complex electromagnetic environment. Radar will be faced with serious problems such as power, accuracy decline and even can not work properly. As a result, radar interference suppression has gradually become a hot issue. The effective approach of radar sidelobe suppression is introduced [1]. With the adaptive beamforming method, the radar system can suppress sidelobe interference effectively [1]. But for the mainlobe interference, the traditional adaptive beamforming will produce a nulling in the mainlobe, which leads to the distortion of the antenna pattern and reduces the radar detection capability greatly.

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In recent years, scholars are beginning to recognize the importance of mainlobe interference suppression and begin to study it. A mainlobe interference suppression method based on eigen-projection algorithm (EMP) is proposed [2]. Elimination of mainlobe interference based on the sum and difference channel is introduced [3]. For a large aperture distributed array, Mainlobe interference suppression algorithm based on auxiliary array is introduced [4]. Fresnel based frequency domain adaptive beamforming for large aperture distributed array radar is presented [5]. However, these methods only study the mainlobe interference suppression under narrowband signal, not including those under wideband signal.

For radar wideband signal, the conventional wideband adaptive beamforming algorithm includes incoherent subspace processing method (ISM) [6] and coherent subspace processing method (CSM) [7], which have a large amount of calculation.

Combining the above methods with my ideas, this paper presents a mainlobe interference suppression method in sparse DAR based on stepped frequency synthetic wideband signal. The equivalent large aperture of sparse DAR can eliminate the mainlobe interference with little loss of target signal energy. The stepped frequency synthetic wideband signal is an instantaneous narrowband and synthetic wideband signal, so it can effectively eliminate the time delay problem. In addition, it can reduce the computational complexity compared with the traditional wideband adaptive beamforming method. This paper is divided into the following sections. Section 1 describes the problems faced by radar in today's electromagnetic interference environment. Section 2 introduces the signal model of the radar based on the stepped frequency synthetic wideband signal in case of the mainlobe interference. Section 3 put forwards the signal processing method. This method utilizes the narrowband adaptive processing to each sub-pulse of the stepped frequency signal, and synthesizes the high resolution range profile by an inverse Fourier transform (IFFT). Section 4 designs the mainlobe anti-jamming experimental system, collects the echo data and then confirms the validity of this algorithm by processing the collected data. Section 5 concludes the full paper at last.

2 Signal Model

This paper uses the stepped frequency synthetic wideband signal. The stepped synthetic wideband frequency signal can reduce the system's instantaneous bandwidth in the premise of synthesizing a large bandwidth. It transmits the total signal bandwidth of $N\Delta f$ in N pulses as a frequency interval of Δf. Finally, synthetic wideband results are obtained by matching processing.

The i th pulse in time domain of the stepped synthetic wideband frequency signal is expressed as:

$$s_i(t) = \mathrm{rect}\left(\frac{t - iT_r}{\tau}\right)\mathrm{e}^{j2\pi(f_0 + i\Delta f)t}. \tag{1}$$

Where, $i = 0, 1, 2, \ldots, N-1$, T_r is the pulse repetition period, f_0 is the start frequency of the carrier frequency, Δf is the stepped frequency. N is the pulse number in a frame signal, M is the signal frame number, $\mathrm{rect}(t)$ is the rectangular function. Figure 1 shows the time-frequency feature of stepped frequency synthetic wideband signal.

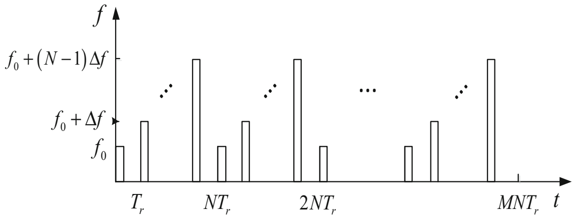


Fig. 1. Time-frequency feature of stepped frequency synthetic wideband signal

Supposing that DAR system has one transmitting antenna and m receiving antennas. The receiving antennas are on the same horizontal line, and their positions are respectively $\mathbf{d} = [d_1, d_2, \cdots, d_m]$, and $d_1 = 0$. The distance between the target and the transmitting antenna is R_0, and the distance between the target and m th receiving antenna are $R_1, R_2, \cdots, R_m$ respectively. For the i th pulse, the radar echo received by the 1st receiving antenna is:

$$s_{i1}(t) = s_i\left(t - \tau_1^s\right) = \mathrm{rect}\left(\frac{t - iT_r - (R_0 + R_1)/c}{\tau}\right)e^{j2\pi(f_0 + i\Delta f)\left(t - \frac{R_0 + R_1}{c}\right)}. \quad (2)$$

Assuming that the interference is R_{c0} away from the transmitting antenna, and the distance between the interference and m th receiving antenna are $R_{c1}, R_{c2}, \cdots R_{cm}$ respectively, so the actual signal received by the m th antenna is:

$$x_{im}(t) = s_i\left(t - \tau_m^s\right) + c\left(t - \tau_m^c\right) + w_m(t). \quad (3)$$

Where, t is time, $s_i\left(t - \tau_m^s\right)$ is the echo of target, the interference is $c(t)$, the time delays of the target echo signal and the interference signal in the m th antenna are $\tau_m^s = (R_0 + R_1)/c + d_m \sin\theta_0/c$ and $\tau_m^c = (R_{c0} + R_{c1})/c + d_m \sin\theta_1/c$, the direction of target signal and interference signal are θ_0 and θ_1. c is the speed of light. $w_m(t)$ is the noise.

Considering that each sub-pulse of the stepped synthetic wideband frequency signal is narrowband signal, the time delay difference between target and each antenna can be ignored [5]. Accordingly, the array received data becomes:

$$\mathrm{x}_i(t) = \mathbf{a}(\theta_0)s_{i1}(t) + \mathrm{X}_{i+n}(t) = \mathbf{a}(\theta_0)s_{i1}(t) + \mathbf{a}(\theta_1)c_1(t) + \mathrm{w}(t). \quad (4)$$

Where, $\mathrm{x}_i(t) = [x_{i1}(t), x_{i2}(t), \cdots, x_{im}(t)]^T$ is the vector of the echo signal, T expresses transpose. $\mathbf{a}(\theta_0) = \left[1, e^{-j2\pi d_2 \sin\theta_0/\lambda}, \cdots, e^{-j2\pi d_m \sin\theta_0/\lambda}\right]^T$ is the target steering vector, λ is the radar transmitting signal wavelength. $s_{i1}(t) = s_i\left(t - \tau_1^s\right)$ is the complex envelope representation of the target signal. $\mathrm{X}_{i+n}(t)$ is the signal vector synthesized by interference and noise. $\mathbf{a}(\theta_1) = \left[1, e^{-j2\pi d_2 \sin\theta_1/\lambda}, \cdots, e^{-j2\pi d_m \sin\theta_1/\lambda}\right]^T$ is the interference steering vector. The interference vector is $c_1(t)$. The noise vector is $\mathrm{w}(t)=[w_1(t), w_2(t) \cdots w_m(t)]^T$.

3 Signal Processing

3.1 Narrowband Adaptive Processing

The narrowband adaptive processing method is employed to the i th sub-pulse of the stepped frequency synthetic wideband signal. For the echo signal data model, the signal covariance matrix R_S and R_{i+n} can be computed as:

$$R_S = E\left[s_{i1}(t)\mathbf{a}(\theta_0)\mathbf{a}(\theta_0)^H s_{i1}^*(t)\right] = \sigma_s^2\mathbf{a}(\theta_0)\mathbf{a}(\theta_0)^H. \tag{5}$$

$$R_{i+n} = E\left[X_{i+n}(t)X_{i+n}^H(t)\right] = \sigma_1^2\mathbf{a}(\theta_1)\mathbf{a}^H(\theta_1) + \sigma_n^2 I. \tag{6}$$

Where, $\sigma_s^2 = E\left[|s_{i1}(t)|^2\right]$ is the signal power, $\sigma_1^2 = E\left[|c_1(t)|^2\right]$ is the interference signal power, σ_n^2 is the power of the noise. The optimal weight vector is obtained in accordance with the principle of the best output SINR.

$$\mathrm{W}_{opt} = \alpha R_{i+n}^{-1}\mathbf{a}(\theta_0). \tag{7}$$

Where

$$\alpha = \sigma_s^2\mathbf{a}^H(\theta_0)\mathrm{W}_{opt}/\lambda. \tag{8}$$

However, in the realizable case, the covariance matrix of the optimal weight vector is hard to get. As a result, according to the temporal stability of the signal, the maximum likelihood estimation can be obtained from the snapshot data:

$$\hat{R}_{i+n} = \frac{1}{K}\sum_{k=1}^{K} X_{i+n}(nK+k)X_{i+n}^H(nK+k) = \frac{1}{K}XX^H. \tag{9}$$

$X = [X_{i+n}(nK+1), X_{i+n}(nK+2), \cdots, X_{i+n}(nK+k)]$, is n th snapshot data block, each block contains K snapshots. Replace R_{i+n} with $\hat{R}_{i+n}$, then we can obtain the adaptive weight vector of the SMI algorithm:

$$\mathrm{W}_{smi} = \frac{\hat{R}_{i+n}\mathbf{a}(\theta_0)}{\mathbf{a}^H(\theta_0)\hat{R}_{i+n}^{-1}\mathbf{a}(\theta_0)}. \tag{10}$$

So the output signal is:

$$\mathrm{y}_i(t) = \mathrm{W}_{smi}^H \mathrm{x}_i(t). \tag{11}$$

3.2 Synthesize HRRP

After the above process, we finish the interference suppression in each sub-pulse, then we synthesize the high resolution range profile (HRRP) with sub-pulses by an inverse Fourier transform (IFFT). For N pulses, the radar echo after the frequency mixing and the narrowband adaptive processing can be expressed as:

$$x'(t) = \sum_{i=0}^{N-1} \text{rect}\left[\frac{t - iT_r - (R_0 + R_1)/c}{\tau}\right] \mathrm{e}^{-j2\pi i\Delta f(R_0+R_1)/c} \mathrm{e}^{-j2\pi f_0(R_0+R_1)/c}. \tag{12}$$

For the echo of N PRT, the sampling points of the same distance are processed by an inverse Fourier transform (IFFT), then we derive:

$$\begin{aligned} y_{hrrp1}(l) &= \frac{1}{N}\sum_{i=0}^{N-1} x'(i)\mathrm{e}^{j2\pi\frac{1}{N}i} \\ &= \frac{\sin\pi(l - N\Delta f(R_0+R_1)/c)}{N\,\sin\pi(l/N - \Delta f(R_0+R_1)/c)} \mathrm{e}^{j2\pi f_0\frac{R_0+R_1}{c}} \mathrm{e}^{j\pi\frac{N-1}{N}}(l - N\Delta f(R_0+R_1)/c). \end{aligned} \tag{13}$$

The amplitude is:

$$\left|y_{hrrp1}(l)\right| = \frac{\sin\pi(l - N\Delta f(R_0+R_1)/c)}{N\,\sin\pi(l/N - \Delta f(R_0+R_1)/c)}. \tag{14}$$

$\left|y_{hrrp}(l)\right|$ is the HRRP, its mainlobe width is $1/(N\Delta f)$, thus the target range resolution is $c/(2N\Delta f)$, which is equivalent to the range resolution obtained by the signal of $B = N\Delta f$ transmitting bandwidth. The essence of the stepped frequency synthetic wideband signal processing is obtaining the time delay information of the target by utilizing an inverse Fourier transform (IFFT) to a string of sampling values in frequency domain.

When dealing with the measured data, because of the condition $\Delta f < 1/\tau$, the spectrum of each pulse is overlapped, causing the range ambiguity. In order to obtain the real target distance information, we need to select some points from the IFFT results of all sampling points in a certain order, and then synthesize the high resolution range profile according to a certain rule. We employ the backward abandon method to solve the above problem.

The classic abandon method takes out $t_s N\Delta f$ (t_s is the sampling interval, N is the number of frequency points, Δf is the stepped frequency) points spectral line in turn from each group of IFFT results, synthesizes them continuously and abandons others, but it cannot determine the extraction starting point. The backward abandon method applied in the data processing finds the position of the peak value first according to the low resolution envelope feature of echo, and determines the extraction starting point in reverse derivation, then accomplishes the high resolution range profile (HRRP) by means of the classic abandon method.

4 Experiment

4.1 Experiment Design

To meet our need, we build a mainlobe anti-jamming experimental system and design a mainlobe interference suppression experiment. The experimental system includes an S-band radar, a sparse distributed array, a target simulator and a noise interference source. The S-band radar transmits stepped synthetic wideband frequency signal, the pulsewidth is 0.1 μs, the pulse repetition period is 10 μs, the starting frequency of the carrier frequency is 3.3 GHz, the stepped frequency is 5 MHz, the synthetic bandwidth is 320 MHz. The step frequency signal of a frame has 64 pulses and the sampling rate is 100 MHz. The sparse distributed array has one horn antenna for transmitting the signal and four horn antennas for receiving the signal. The aperture of each horn antenna is 0.12 m, for a single antenna, the beamwidth is so large that it reaches 43°. For purpose of reducing the influence of the grating lobe, the receiving antennas are arranged in a non-uniform array [8]. The length of the array is 6 m, the receiving antennas are on the same horizontal line, and their positions are respectively (0.125 m, 2.275 m, 2.575 m, 5.925 m), so the designed array can make the equivalent antenna beamwidth as 0.86°, as we can see, it is much smaller than the beamwidth of a single antenna. The transmitting antenna is located in the middle of the array, facing the target simulator. The target simulator is composed of two horn antennas and it is 40 m straight from the array. One of them is used to receive the radar signal, the other is used to amplify the received signal and send them back. The noise interference source is located 1.2 m from the target simulator, that is, 1.7° off the target. In this case, the interference is in the mainlobe of a single antenna, but inside the sidelobe of the synthetic array. We collect multiple sets of four channel data using a digital collector, and then perform off-line processing and analyze the experimental results. The simulative experiment scene is shown in Fig. 2, the actual experiment scene and the experiment equipment are shown in Fig. 3.

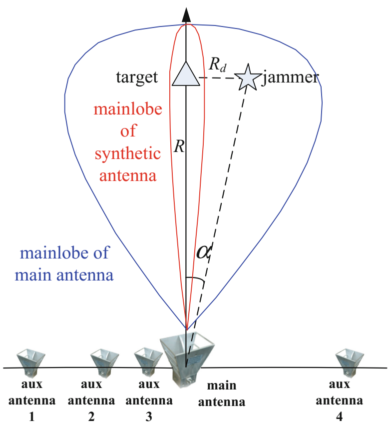


Fig. 2. Simulative experiment scene

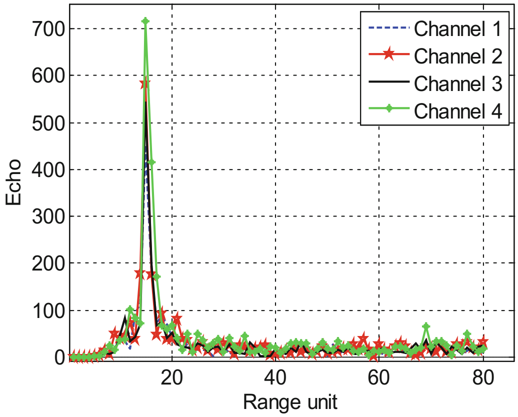
a S-band experimental DAR system b interference source and target simulator

Fig. 3. Actual experiment scene and experiment equipment

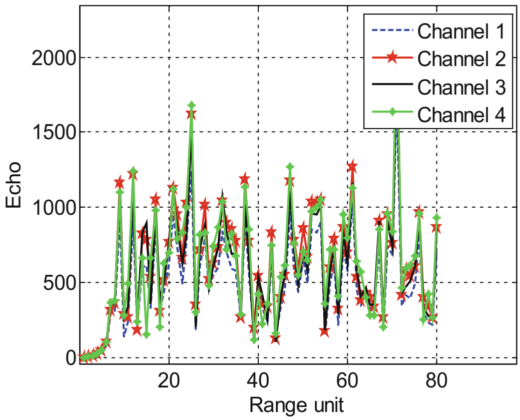
4.2 Measured Data Processing

Figure 4 shows the echo data collected. Among them, Fig. 4a is the echo of the target simulator, Fig. 4b is the echo of the target as well as the interference. We can see that the target signal are suppressed seriously by the interference and disappear. According to the Neyman-Person criterion, the detection probability depends on the signal energy to noise ratio, so we can calculate the signal energy to noise ratio to reflect whether the original echo signal is affected by interference. One frame stepped frequency synthetic wideband signal which contains 64 pulses is utilized to process. In general, we use SNR, INR, and SINR to evaluate the suppression result by quantitative analysis. After calculation, the SNR of the original target signal is 39.5 dB, the INR of the interference is 28.9 dB, so the initial SINR is 10.6 dB.

Then we employ the narrowband adaptive processing to each sub-pulse of the four channels collected data, and synthesize the HRRP. The result of the narrowband adaptive processing in time domain is shown in Fig. 5. The result of the synthetic wideband processing in time domain is shown in Fig. 6. As we can see, in two figures, the mainlobe interference is basically suppressed after processed, the target can be clearly distinguished. After processing, we obtain that the output SINR is 36.1 dB, that is, the SINR has increased by 25.5 dB, so the improvement works well. As a consequence, the proposed method in this paper can suppress the mainlobe interference based on the stepped frequency synthetic wideband signal while keeping the target signal energy basically intact and reducing the relative calculation.



a Original target echo



b Original target echo affected by the interference source

Fig. 4. Echo data collected

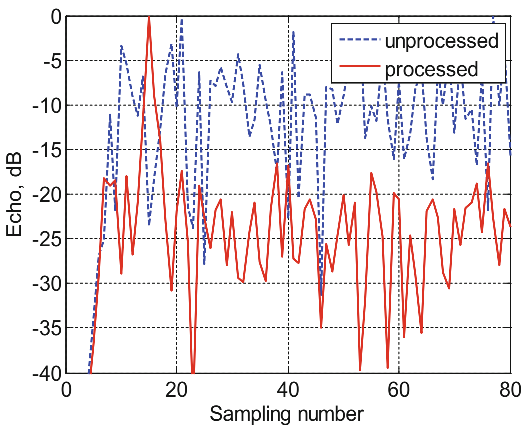


Fig. 5. Narrowband adaptive processing result

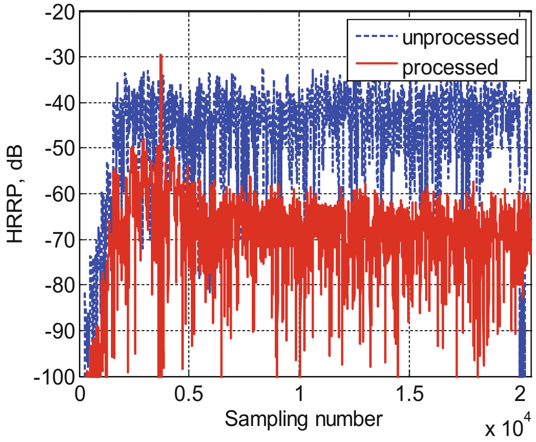


Fig. 6. Synthetic wideband processing result

5 Summary

This paper presents a mainlobe interference suppression method in sparse DAR based on stepped synthetic wideband frequency signal. This method utilizes the equivalent large aperture of DAR to keep the target signal energy basically intact. It contains two steps. Step 1 is employing the narrowband adaptive processing to each sub-pulse of the stepped frequency signal, and Step 2 is synthesizing the high resolution range profile by an inverse Fourier transform (IFFT). Whats more, a mainlobe interference suppression in sparse distributed array radar experiment is implemented by using an S-band radar, a noise interference source and a target simulator. At last, the result of the collected data processed by the presented method confirms the validity of the algorithm.

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