A Space-time Anti-interference Algorithm Based on Antenna Rotation

DU Ruiyan\textsuperscript{1,2,a}, YANG Jiaqi\textsuperscript{1,2,b}, WANG Xianchao\textsuperscript{1,2} and LIU Fulai\textsuperscript{1,2}

\textsuperscript{1}Engineer Optimization & Smart Antenna Institute, Northeastern University at Qinhuangdao, Qinhuangdao, China; \\
\textsuperscript{2}School of Computer Science and Engineering, Northeastern University, Shenyang, China.

E-mail: \textsuperscript{a}ruiyandu@126.com, \textsuperscript{b}yangjq316@163.com

Abstract. To inhibit interference, the conventional space-time adaptive processing technology can form nulling at both the interference coming angle and the interference frequency, inhibiting the interference in the development of satellite navigation anti-jamming technology. When the frequency of the signal source is equal or similar to the central frequency of the interference source and they are adjacent in the spatial domain, the desired signal will be suppressed in the traditional algorithms, which will lead to the decrease of the output signal-to-interference-noise ratio (SINR). To overcome this issue, a space-time joint anti-interference algorithm based on planar array steering is proposed in this paper. Specifically, the plane array steering is adjusted by calculating the spatial correlation coefficient of the desired signal and the interference signal. Simulation results show that the proposed algorithm can increase the output SINR by about 10dB under the same frequency, and the anti-interference ability of the system is enhanced.

1. Introduction

With the wide use of GPS system in military and civil fields, its poor anti-interference performance has become increasingly prominent. Satellite navigation signals are extremely weak and vulnerable to interference from the outside world when they reach the ground. Therefore, it is of great significance to study the anti-interference technology of navigation receivers.

Common anti-interference methods of GPS receiver include time domain filter, frequency domain filter [1] and space domain filter [2]. In 2000, the space-time adaptive processing (STAP) technology was applied in the field of GPS receiver anti-interference by Fante first, which carried on the joint filtering in the space-time domain [3] and increased the degree of freedom of processing. The conventional space-time anti-jamming forms nulling at the interference signal direction and disturbing frequency. Considering target self-nulling effects of the angle and Doppler frequency uncertainly of the target, a robust STAP method is proposed by reconstructing the clutter-plus-noise covariance matrix [4, 5]. However, when the frequency of the signal source is close to that of the interference source and both signals’ angle are near to each other, the previous adaptive beamforming algorithm show beam distortion, and the output signal-to-interference-noise ratio (SINR) may also drop seriously. Under the condition of limited number of channels, the structure of array antenna becomes an important factor which affects the performance of anti-interference algorithm [6].
The anti-jamming performance of space-time array depends not only on the optimization of anti-jamming algorithm but also on the optimization of the front-end array structure of anti-jamming module. H. v. an Trees pointed out that the spacing and relative position of array elements had been determined at the beginning of antenna design [7]. Therefore, the array flow pattern is fixed, which to some extent results in that the anti-interference performance of the array at some interference angles is not as flexible as that of the structure. In 1982, H.C.Lin proposed the concept of spatial correlation coefficient and the factors affecting the performance of the array antenna [8]. In 2014, Wang came up with the idea of reconfigurable array [9]. In 2018, Xiang [10] combined the spatial correlation coefficient with adaptive beamforming technology to improve the anti-interference ability by optimizing the array structure. Combined with the above analysis, a space-time anti-interference algorithm based on planar array rotation is proposed. In the case of fixed relative position, delay interval and number of array, the direction of jump frame array is changed by optimizing the spatial correlation coefficient of expected signal and interference signal. The proposed algorithm can be expected to overcome the serious signal-to-interference-noise ratio (SINR) drop problem caused by two signals coming close to each other when the central frequency of the signal and the interference signal are equal, and improve the output SINR of the space-time array.

2. Establishment of space-time adaptive anti-interference model
The idea of space-time two-dimensional processing is to extend time domain, frequency domain or spatial domain filtering into the two-dimensional domains of time and space to form a space-time two-dimensional processing structure. The structural model of space-time adaptive anti-interference processing is shown in Figure 1.

![Figure 1. Structure model of space-time joint anti-interference processing](image)

The basic idea of space-time joint processing is to add delay units on each antenna array on the basis of spatial filter. From the perspective of a single array element, all levels of delay taps constitute a time domain filter. From the perspective of the same time delay node, different array elements form spatial adaptive filter. Therefore, the STAP technology has the ability of space-time two-dimensional anti-interference. It is assumed that the number of antenna array elements is M and the number of time delay elements is P. The delay of each time delay unit is T, and T is required to be less than 1/B, where B is the processing signal bandwidth, and the total delay length \((P-1)\cdot T\) after each matrix is greater than the multipath delay of the signal. Then the input signals of \(p\)-th tap on the \(m\)-th matrix is...
\( x_m(i(p-1)T) \). Among them \( m = 1,2, \ldots, M \; ; \; p = 1,2, \ldots, P \). Let the weight of the \( p \)-th tap on the \( m \)-th matrix be \( w_{mp} \). The output of the space-time adaptive filter is

\[
y(n) = \sum_{m=1}^{M} \sum_{p=1}^{P} w_{mp} x_{mp}(n)
\]

(1)

The input of the array and the corresponding weight are expressed as a vector as follows, corresponding to the moment \( i \)

\[
W = [w_{11}, w_{21}, \ldots, w_{M1}, w_{12}, w_{22}, \ldots, w_{M2}, \ldots, w_{1P}, w_{2P}, \ldots, w_{MP}]^T
\]

(2)

\[
X(i) = [x_{11}(i), x_{21}(i), \ldots, x_{M1}(i), x_{12}(i), x_{22}(i), \ldots, x_{M2}(i), \ldots, x_{1P}(i), x_{2P}(i), \ldots, x_{MP}(i)]^T
\]

(3)

Thus, the array output can be represented as

\[
Y = W^H \times X(i)
\]

(4)

Therefore, it can be found that the space-time adaptive processing is the extension form of the spatial antenna array in the time domain, which is equivalent to increasing the freedom degree of the filter without increasing the number of antennas.

3. **Space-time anti-jamming algorithm based on planar array steering**

By rotating the orientation Angle of the array antenna, the spatial correlation coefficient of the satellite navigation signal and the interference signal on the array can be reduced, and a better SINR can be obtained [7]. In reference [10], the array rotation technology is extended from uniform linear array to spatial planar array. On this basis, the planar array steering technique is extended to space-time array to study the effect of space-time array steering on output signal dry noise ratio under specific conditions.

Assuming that there is an uniform rectangular array of \( M \) rows and \( N \) columns with \( P \) taps on each antenna. The pitch angle and azimuth angle of the expected signal and the interference signal are \((\theta_i, \phi_i)\) and \((\theta_j, \phi_j)\) respectively. The pitch angle and azimuth angle of above two signals can be defined as \( s = [\sin \theta_i \cos \phi_i, \sin \theta_i \sin \phi_i]^T \) and \( j = [\sin \theta_j \cos \phi_j, \sin \theta_j \sin \phi_j]^T \). The space-time steering vectors of the satellite signal and the interference signal are respectively \( V_s = V_{\alpha} \otimes V_s \) and \( V_i = V_{\beta} \otimes V_i \). \( V_s \) and \( V_i \) are the space steering vectors of the expected signal and the interference signal, as shown below

\[
V_{\alpha} = e^{j2\pi \phi_i}
\]

(5)

\[
V_{\beta} = e^{j2\pi \phi_j}
\]

(6)

And the Steering vector in the time domain of the two signals are \( V_s \) and \( V_i \) which can be described as follows

\[
V_s = [1 \; e^{-j\Omega_1 T} \; \ldots \; e^{-j\Omega_{(P-1)T}}]^T
\]

(7)

\[
V_i = [1 \; e^{-j\Omega_1 T} \; \ldots \; e^{-j\Omega_{(P-1)T}}]^T
\]

(8)

In the formula, \( Q = [q_1, q_2, \ldots, q_M, N]^T \in R^{M \times N+2} \) contains the position information of the matrix element. Assuming that the noise of each array element is independent from each other and the signal is independent, besides the power of satellite navigation signal is far less than that of the interference signal, and the covariance matrix of the spatial adaptive array obtained by redundancy is as follows.

\[
R_n = \sigma^2 I + P_i V_i \times V_i^H + \sum_n P_j V_j \times V_j^H
\]

(9)

\[
R_n = \sigma^2 I + \sum_n P_j V_j \times V_j^H
\]

(10)

In the above two formulas, \( \sigma^2 \) is the thermal noise power of each channel, \( P_i \) is the power of expected navigation signal, and \( P_j \) is the power of interference signal. According to the classical covariance matrix [11], equation (10) can be written as follows in the case of single disturbance.
describes the ratio of interference and noise. The desired signal correlation coefficient is defined to present the ratio of expected signal power to noise power. 
\[ \text{INR} = \frac{P_j}{\sigma^2} \]

Where \( K = M \times N \times P \). Get spatial correlation coefficient expression by definition [10]
\[ \alpha_{ij} = \frac{V_j^H \times V_{in}}{|V_j^H||V_{in}|} = \frac{V_j^H \times V_{in}}{\sqrt{V_j^H V_j^H V_{in}^H V_{in}^H}} = \frac{V_j^H \times V_{in}}{M \times N} \]

At the same time, \( \alpha_i = V_j^H V_j / P \). The spatial correlation coefficient \( \alpha_{ij} \) represents the spatial separation degree of the desired signal and the interference signal on the array. Combined with equation (12), the optimal weight vector of the spatial array can be obtained
\[ w_{opt} = \mu R_{ij}^{-1} \times V_s = \frac{\mu}{\sigma^2} (V_s - \frac{V_j \alpha_j \alpha_i}{\sigma^2}) \]

The output signal-to-interference-noise ratio (SINR) of the array can be defined as [12].
\[ \text{SINR}_{out} = PV_j \times R_{ij}^{-1} \times V_j^H = \frac{P}{\sigma^2} (K - \frac{N^2 |\alpha_j|^2 |\alpha_i|^2}{\sigma^2}) = K \cdot \text{SNR}(1 - |\alpha_i|^2 |\alpha_j|^2 \rho) \]

Where \( P_j \) represents the expected signal power, and \( \rho \) describes the ratio of interference and noise power. \( \text{SNR} = P_j / \sigma^2 \) is defined to present the ratio of expected signal power to noise power. \( \text{INR} = P_j / \sigma^2 \) is defined to present the ratio of interference signal power to noise power.
\[ \rho = (KP_j / \sigma^2) / (1 + KP_j / \sigma^2) = \frac{K \cdot \text{INR}}{1 + K \cdot \text{INR}} \]

At first, not consider \( \alpha_i \). It can be found from equation (16) that when the interference is larger than the noise power, \( \rho \) is close to 1, and the interference has a greater impact on the performance of SINR. At the same time, it can be found that SINR is a decreasing function of spatial correlation coefficient. In the case of high INR, the correlation coefficient of the output SINR is obviously affected. Therefore, as long as the desired signal and the interference signal are known, the array structure can be optimized by the spatial correlation between the desired signal and the interference signal, so as to improve the jamming capability of the satellite navigation system. The spatial correlation coefficient of the signal can be changed through array steering. So the SINR can be improved by adjusting the rotation Angle of the signal.

Rotate the array \( \phi \) degrees with the origin as the central. Assuming the antenna original position is \((x, y)\). After rotating, it turns out to be
\[ (\sqrt{x^2 + y^2} \cos(\arctan \frac{y}{x} + \phi), \sqrt{x^2 + y^2} \sin(\arctan \frac{y}{x} + \phi)) \]

Think of \( \alpha_i \) as the adjustment factor. \( \alpha_i \) is larger when the central frequency of the two signals is equal or similar. Otherwise, \( \alpha_i \) is smaller. In this paper, the SINR can be improved by optimizing the configuration of the spatial array structure form the perspective of space-time array structure. And the anti-interference ability of satellite navigation systems is improved to some extent. The desired signal can be obtained by inertial navigation information and satellite ephemeris calculation. As to the problem of obtaining the orientation information of the interference signal, different direction-finding methods can be used for different environments.

4. Simulation verification of space - time anti - jamming algorithm
The experiment takes two rows and four columns of uniform rectangular array as an example, and the interval of elements is half the wavelength of the navigation signal. The relationship between the
spatial correlation coefficient and the rotation angle of the array is studied under different central frequency difference, and the influence of the optimal and the worst turns of the array on SINRout is analysed.

In this experiment, SNR=20 and INR=70 were set. The position information of the satellite signal and interference signal were (70°, 40°) and (70°, 45°). The rotatable angle range of the planar array was set as 0-180°. Figure 2 verifies the relationship between the spatial correlation coefficient and the rotation angle of the array.

Figure 2. The relation between steering Angle and spatial correlation coefficient

Figure 3. The relation between steering Angle and SINRout (fj=fc)

Figure 3 presents the relationship between SINRout of the STAP algorithm and array rotation angle. fj is the central frequency of the navigation signal, and fj is the central frequency of the interference signal. During the experiment, the navigation signal and the interference signal were set at the same central frequency. It can be seen from Figure 3 and Figure 4, there is still a relationship between the array rotation angle and SINRout. The spatial correlation coefficient is the minimum when $\phi = 50$ and the SINRout is the maximum. When $\phi = 140$, the spatial correlation coefficient is the largest, and the SINRout is the smallest. SINRout is approximately 12dB higher when $\phi = 50$ than $\phi = 140$. So in the case of the same central frequency, the optimal steering method of planar array can overcome the problem that the expected signal is adjacent to the interference signal space, which leads to a serious decline in the anti-interference performance, and improve the anti-interference ability of navigation.

Figure 4. The relation between steering Angle and SINRout (fj=1.02fc)

Then the effect of the array steering on SINRout under different signal central frequencies was analysed. Figure 4 shows the effect of array steering when the central frequency of the disturbance
signal is 1.02 times as much as the central frequency of the navigation signal. We found that when $f_j = 1.02 f_s$, the value of SINR$_{out}$ is still related to the spatial correlation coefficient. But the change in SINR$_{out}$ decreases. At this point, the SINR$_{out}$ at the best angle rotation is about 2dB higher than that at the worst angle of rotation. When the expected signal is greatly different from the center frequency of the interference signal, the space-time anti-interference algorithm can effectively suppress the interference signal in the time domain.

5. Conclusion
The complex electromagnetic environment makes the satellite navigation system vulnerable to the interference from the outside, which leads to the performance degradation and even failure of the satellite navigation system. Therefore, it is very important to improve the anti-interference ability of satellite navigation system. In the space-time navigation anti-jamming system, the anti-jamming performance depends not only on the optimization of space-time anti-jamming algorithm, but also on the optimization of space-time array structure. In this paper, in the case that the central frequency of the navigation signal and the interference signal is the same or similar, the space-time navigation anti-interference technology based on the array steering is studied in view of the spatial proximity of the two signals.

By introducing spatial correlation coefficient evaluation, a space time adaptive anti-interference algorithm based on planar array steering is proposed. By changing the structure of the array antenna, the spatial correlation coefficient of the desired signal and the interference signal is optimized to control the optimal direction of the planar array. This method overcomes the problem that the expected signal is similar to the interference signal in frequency and the anti-interference performance is seriously decreased when the space is adjacent, and improves the SINR$_{out}$. Simulation results show that the proposed algorithm can effectively improve the SINR$_{out}$ when the direction angles and frequencies of signal source and interference source are close.

Acknowledgments
This work was supported by the Natural Science Foundation of Hebei Province (No. F2016501139) and the Fundamental Research Funds for the Central Universities under Grant No. N162304002 and No. N172302002, and the National Natural Science Foundation of China under Grant No. 61501102 and No. 61473066.

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