Anti-Jamming Algorithm Based on Spatial Blind Search for Global Navigation Satellite System Receiver

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Abstract: A novel subspace projection anti-jamming algorithm based on spatial blind search is proposed, which uses multiple single-constrained subspace projection parallel filters. If the direction of arrival (DOA) of a satellite signal is unknown, the traditional subspace projection anti-jamming algorithm cannot form the correct beam pointing. To overcome the problem of the traditional subspace projection algorithm, multiple single-constrained subspace projection parallel filters are used. Every single-constrained anti-jamming subspace projection algorithm obtains the optimal weight vector by searching the DOA of the satellite signal and uses the output of cross correlation as a decision criterion. Test results show that the algorithm can suppress the jamming effectively, and generate high gain toward the desired signal. The research provides a new idea for the engineering implementation of a multi-beam anti-jamming algorithm based on subspace projection.

Key words: global navigation satellite system (GNSS); anti-jamming; spatial blind search; subspace projection

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The characteristics of navigation and positioning systems are low received power of navigation terminal and complex electromagnetic environments. Navigation systems are faced with various kinds of jamming and more complex electromagnetic environments in military applications[1]. The focus of research in the field of navigation is on improving the anti-jamming ability of satellite navigation terminals[2].

The key to anti-jamming of satellite navigation terminals is to suppress interference signals and enhance satellite signals[3]. The anti-jamming technology of beamforming based on subspace projection is a hot spot in array signal processing[4-6].

The principle of anti-jamming techniques based on subspace projection is to form a signal subspace and a noise subspace by eigenvalue decomposition of the array signal covariance matrix. The signal subspace and the noise subspace are orthogonal. The received array signal is projected into the noise subspace to suppress jamming[7-8]. The anti-jamming algorithm based on subspace projection minimizes the total output power under the condition that the gain of the desired signal is constant[9-12]. However, to ensure the desired signal gain, the algorithm needs to impose constraints in the desired signal direction, which requires that the satellite position information be known or estimated to be relatively accurate[12]. Such methods are no longer applicable when satellite position information is unknown. Therefore, an improved blind adaptive jamming suppression algorithm based on the periodicity

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and autocorrelation of C/A codes is proposed in Ref. [12] and Ref. [13]. However, the algorithms are not suitable for P code signals, so they limited to civil receivers. Ref. [14] uses despreading and respreading techniques to form a high gain multibeam pointing to real satellites, but the algorithm requires accurate receiver tracking loop information, so the algorithm is unable to adapt to high-dynamic scenarios, and is difficult to guarantee in real time.

Based on the analysis of traditional subspace projection anti-jamming algorithms, a spatial blind search anti-jamming algorithm based on a combination of subspace projection filtering and acquisition is proposed in this paper. Each single-constrained filter takes the correlation output as the decision condition, and the optimal weight vector is obtained by searching the spatial direction of the satellite signal. The feasibility of using the captured correlation output as the direction decision for searching satellite signals is analyzed in this paper. Computer simulation and analysis show the effectiveness of the algorithm.

1 Signal Model of Subspace Projection Anti-Jamming Algorithm

The schematic diagram of anti-jamming based on subspace projection is shown in Fig. 1, where M is the number of elements and $\boldsymbol{R}(M \times M)$ is the covariance matrix of the received array signal. The covariance matrix $\boldsymbol{R}$ is decomposed; because the power of satellite signal is about 30dB lower than that of the noise, it has little influence on eigenvalue decomposition. Thus, two orthogonal subspaces of jamming and noise can be formed. Based on the noise subspace, the weights satisfying the optimal criterion are obtained. According to the orthogonal theory, the jamming can be suppressed from the received signal completely.

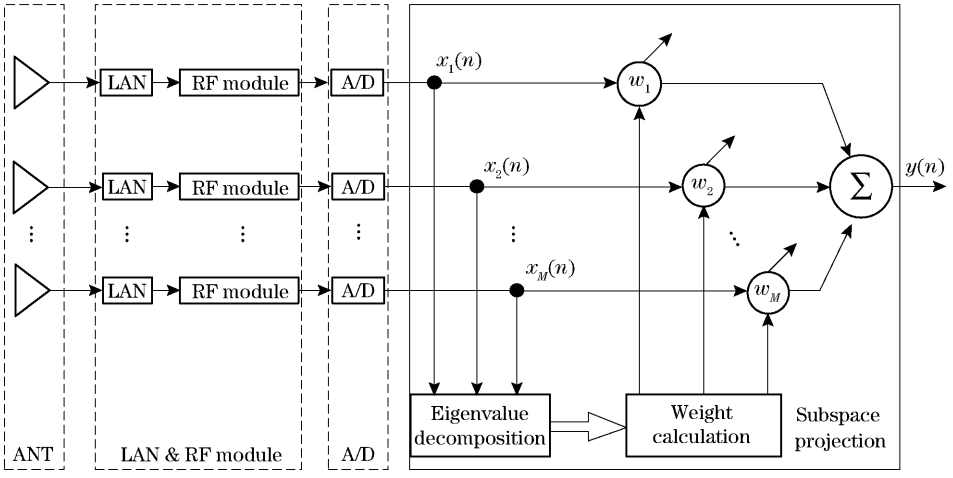

Fig. 1 Schematic diagram of anti-jamming algorithm based on subspace projection

If λ_i is the ith eigenvalue of $\boldsymbol{R}$ and $\boldsymbol{e}_i$ is its corresponding eigenvector, then

$$\boldsymbol{R}\boldsymbol{e}_i = \lambda_i \boldsymbol{e}_i \tag{1}$$

The eigenvalues are arranged from in decreasing order, the jamming subspace $\boldsymbol{Q}_{\mathrm{j}}(M \times r)$ is formed by the eigenvectors corresponding to r larger eigenvalues, the noise subspace $\boldsymbol{Q}_{\mathrm{n}}$ $(M \times (M-r))$ is formed by the eigenvectors corresponding to $M-r$ smaller eigenvalues, and $\mathrm{span}(\boldsymbol{Q}_{\mathrm{j}}) \perp \mathrm{span}(\boldsymbol{Q}_{\mathrm{n}})$.

The weight matrix should be satisfied as

$$\min_{\boldsymbol{W}} \boldsymbol{W}^{\mathrm{H}} \boldsymbol{R} \boldsymbol{W} \tag{2}$$

The constraint conditions are: $\boldsymbol{Q}_{\mathrm{j}}^{\mathrm{H}} \boldsymbol{W} = 0$, $\boldsymbol{C}^{\mathrm{H}} \boldsymbol{W} = f$.

Where, $\boldsymbol{C} = (\boldsymbol{a}(\theta_1), \boldsymbol{a}(\theta_2), \cdots\cdots, \boldsymbol{a}(\theta_p))$ is the constraint matrix, $\boldsymbol{a}(\theta_{\mathrm{i}})(i = 1, 2, \cdots, p)$ is the steering vector of satellite signals, $\boldsymbol{f} = (g_1, g_2, \cdots, g_p)$ is the response vector, $g_{\mathrm{i}}(i = 1, 2, \cdots, p)$ is

the receiving gain of a satellite signal, and $\boldsymbol{W}^{\mathrm{H}} = (w_1^*, w_2^*, \cdots, w_M^*)$ is the weight vector where H represents the conjugate transpose operation.

The objective function can be obtained from the Lagrange multiplier as

$$\boldsymbol{W} = \boldsymbol{Q}_{\mathrm{n}} \boldsymbol{\Gamma}_{\mathrm{n}} \boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}} \boldsymbol{C} [\boldsymbol{C}^{\mathrm{H}} \boldsymbol{Q}_{\mathrm{n}} \boldsymbol{\Gamma}_{\mathrm{n}} \boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}} \boldsymbol{C}]^{-1} \boldsymbol{f} \tag{3}$$

where $\boldsymbol{\Gamma}_{\mathrm{n}}$ is the diagonal matrix composed of noise eigenvalues.

2 Anti-Jamming Algorithm Based on Spatial Blind Search

According to Eq. (2) and Eq. (3), the anti-jamming algorithm based on subspace projection can minimize the total output power under the condition that the gain of the desired signal is constant. In theory, the pattern formed by the algorithm generates a nulling corresponding to the jamming bandwidth in the jamming direction and a gain in the desired signal direction. However, this method requires accurate satellite azimuth information to be known or estimated.

According to Eq. (3), the constraint matrix is simplified to a single constraint $\boldsymbol{f} = (1, 0, \cdots, 0)^{\mathrm{T}}$. Taking the steering vector of a satellite signal as $\boldsymbol{a}(\theta)$, the algorithm of the single-constraint subspace is

$$\boldsymbol{W} = \frac{\boldsymbol{Q}_{\mathrm{n}} \boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}} \boldsymbol{a}(\theta)}{\| \boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}} \boldsymbol{a}(\theta) \|^2} \tag{4}$$

According to Eq. (4), the single-constraint algorithm still needs to know the steering vector of the satellite signal in order to guarantee the gain in the desired direction of the satellite signal. But in the absence of external auxiliary information, the steering vector $\boldsymbol{a}(\theta)$ of the satellite signal is unknown. The steering vector $\boldsymbol{a}(\theta)$ needs to be estimated. If the steering vector is estimated to be $\boldsymbol{a}_{\mathrm{s}}(\theta)$ by spatial search, the optimal weight is

$$\boldsymbol{W}_{\mathrm{opt}} = \frac{\boldsymbol{Q}_{\mathrm{n}} \boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}} \boldsymbol{a}_{\mathrm{s}}(\theta)}{\| \boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}} \boldsymbol{a}_{\mathrm{s}}(\theta) \|^2} \tag{5}$$

In addition, in order to obtain information such as position and speed, at least four satellite signals need to be received.

Therefore, multiple single-constrained subspace projection algorithms can be used for parallel filtering. Each single-constrained subspace projection algorithm works independently to form a main beam in the direction of a single desired satellite and a null in the direction of jamming. The number of parallel filters is determined by the number of currently visible stars. In this way, multiple jamming signals can be suppressed effectively, and the gain of the desired satellite signal can be guaranteed. Taking 4-beam parallel anti-jamming as an example, the schematic diagram of parallel filtering algorithm is shown in Fig. 2.

After jamming suppression, the cross-correlation function between array output and local sig-

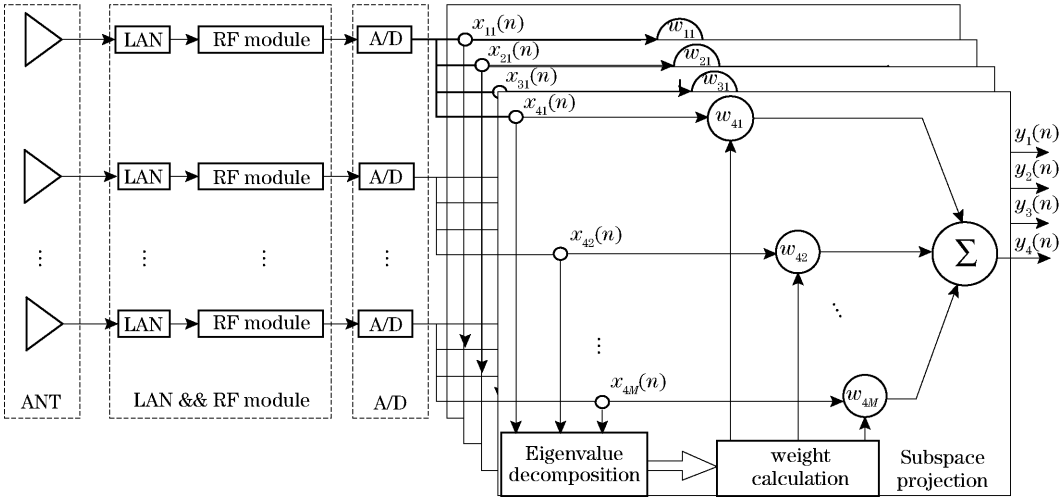

Fig. 2 Schematic diagram of the parallel filtering algorithm based on spatial blind search

nal in frequency domain is expressed as[11]

$$r(\tau) = \int_{-\infty}^{\infty} P(f)H(f,\theta)\mathrm{e}^{-\mathrm{i}2\pi f\tau}\mathrm{d}f \qquad (6)$$

where $P(f)$ is the power spectral density function of the navigation signal. $H(f,\theta)$ is the Fourier transform of the unit impulse response function of anti-jamming

$$H(f,\theta) = \int_{-\infty}^{\infty} \boldsymbol{W}^{\mathrm{H}}\boldsymbol{P}_{\perp}\boldsymbol{a}(\theta)\mathrm{e}^{-\mathrm{i}2\pi ft}\mathrm{d}t \qquad (7)$$

where $\boldsymbol{P}_{\perp} = \boldsymbol{Q}_{\mathrm{n}}\boldsymbol{Q}_{\mathrm{n}}^{\mathrm{H}}$ is the projection matrix for noise subspace and $\boldsymbol{a}(\theta)$ is the space-time steering vector of satellite signal. From Eq. (5) and Eq. (7), when the adaptive weights are consistent with the projection of the orthogonal space of the interference subspace, the correlation peak of the array output and the local PN code is largest and has no distortion. Therefore, the correlation output can be used as a decision condition of the directed vector $\boldsymbol{a}(\theta)$ search.

The acquisition of a satellite signal is a two-dimensional estimation of carrier Doppler and code phase[15]. Doppler f_d includes a carrier Doppler and frequency offset due to the estimation error of the steering vector. Therefore, the algorithm is a three-dimensional estimation of the steering vector $\boldsymbol{a}(\theta)$, carrier Doppler, and code phase. Recording the maximum correlation output for each θ, the decision condition of the steering vector $\boldsymbol{a}(\theta)$ is

$$\max_{\boldsymbol{a}_{\mathrm{s}}}\max_{(D,K)} |g(f_{\mathrm{d}})|_{W_{\mathrm{opt}}} \qquad (8)$$

where $\boldsymbol{a}_{\mathrm{s}}$ is the searching space, D is the number of frequency units, and K is the number of correlation values per time.

Based on the above analysis, let the search range for the direction of the signal be $\theta \in [\theta_1 \quad \theta_2]$ and the search step be $\Delta\theta$. Then, the blind anti-jamming algorithm based on subspace projection is shown in Fig. 3. The searching range of θ can be estimated based on Fig. 3, where $\boldsymbol{a}(\theta_{\mathrm{s}})$ is the steering vector of the satellite signal for each search.

The maximum cross correlation value recorded in the algorithm is that in the case of successful acquisition. Because each steering vector estimation corresponds to a traditional acquisition process, a traditional acquisition scheme is still applicable. The complexity and resource consumption of the algorithm will not significantly increase, but the number of calls to the acquisition and weight calculation modules will increase.

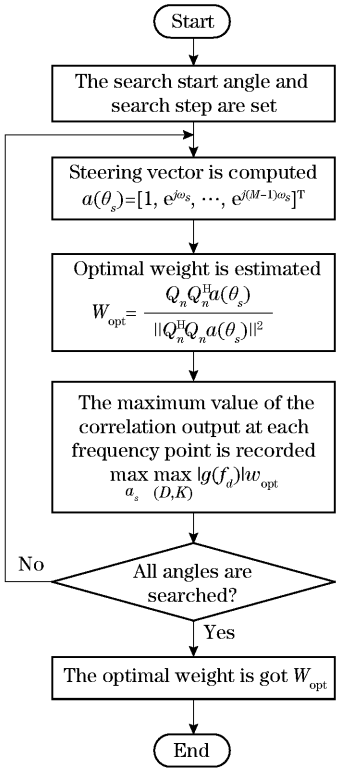

Fig. 3 Anti-jamming algorithm based on spatial blind search

3 Algorithm Simulations and Analysis

The following simulations are based on four elements of a uniform linear array. The carrier frequency is 1 268.52 MHz, the signal bandwidth is 20 MHz, the analog IF is 46.5 MHz, the sampling rate is 62 MHz, the estimation of autocorrelation matrix using 500 samplings, and the noise is Gauss white noise. The signal-to-noise ratio (SNR) is −32 dB, and the suppression jamming bandwidth is 20 MHz.

3.1 Basic performance of the algorithm

There are two jammings and satellite signals from different directions. In the first group, the

azimuth of a jamming is −40°, and the azimuth of the satellite signal is 20°; in the second group, the azimuth of the jamming is −30°, and the azimuth of the satellite signal is 0°. The jamming to signal ratio (JSR) is 80dB. The antenna pattern of the two scenes is shown in Fig. 4 and Fig. 5, respectively. As shown in the figures, the algorithm in this paper has obvious gain in the direction of satellite signal at the same time that the jamming direction forms a null.

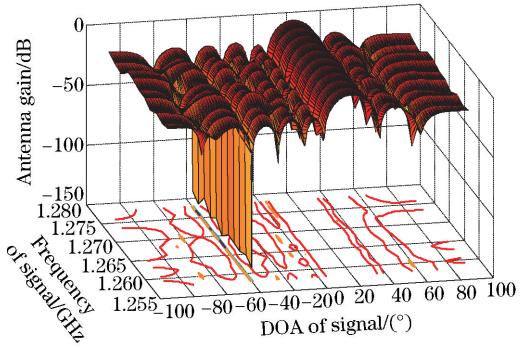

Fig. 4 Antenna pattern of the azimuth of the jamming is −40° and the azimuth of the satellite signal is 20°

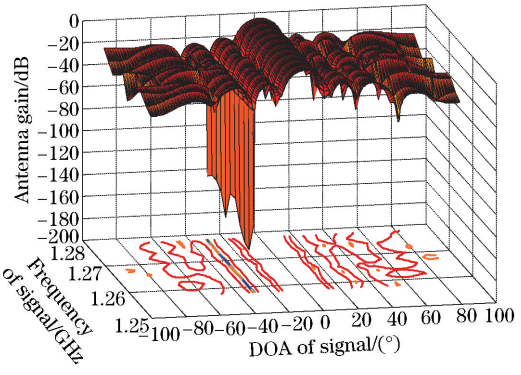

Fig. 5 Antenna pattern of the azimuth of the jamming is −30° and the azimuth of the satellite signal is 0°

3.2 Performance comparison with unconstrained algorithm

In order to verify the performance improvement of the proposed algorithm, the output signal to jamming and noise ratio (SJNR) after jamming suppression is compared between the proposed algorithm and the unconstrained subspace projection algorithm. The azimuth of the jamming is −40°, and the azimuth of the satellite signal is 20°. Fig. 6 shows the output SJNR of the two algorithms when the JSR varies from −45 dB to −80 dB.

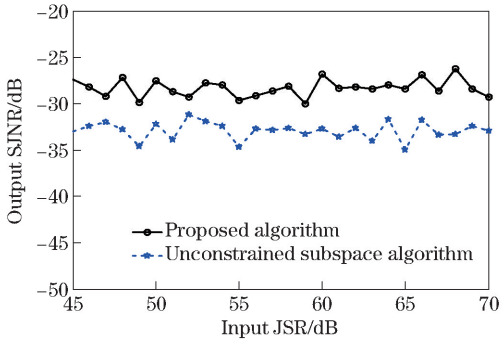

Fig. 6 Output SJNR of jamming azimuth angle −40° and satellite signal azimuth angle 20° with JSR variation

From Fig. 6, the output SJNR of the proposed algorithm is obviously superior to that of the unconstrained subspace projection anti-jamming algorithm, by about 5 dB. The fluctuation of output SJNR of the two algorithms is about 1 dB, which is due to the random error of the estimation of the jamming subspace.

3.3 Influence of difference between the DOA of jamming and satellite signal on algorithm performance

In order to verify the relationship between the algorithm performance and relative DOA of the jamming and the satellite signal, the azimuth of the jamming was set to −30° and the azimuth of the signal was to −70°, 50°, −30°, −15°, −10°, 10° and 20°. The simulation results are shown in Fig. 7. It can be seen that if the signal and jamming are in the same direction, the algorithm is invalid, and the angle difference of signal and interference is greater, the jamming suppression effect is better, but the performance of the

Fig. 7 Influence of difference of direction angle between jamming and signal on the performance of the algorithm

algorithm whose angle difference between jamming and satellite signal is greater than 40° is no longer obviously changed.

3.4 Influence of estimation error on the algorithm performance

The estimation error of the DOA of the satellite signal is inevitable. In order to verify the influence of estimation error of the DOA of the satellite signal on the performance of the algorithm, further simulation was carried out. The azimuth of the jamming was set to −40° and the azimuth of the signal was set to 20°. The algorithm's performance at 0°, 5°, 10°, and −10° angle estimation errors from the steering vector was simulated. The other simulation conditions were the same as in simulation 1. Fig. 8 shows the correlation output after jamming suppression on the condition that Doppler search range of ±5 kHz, steps of 500 Hz, an estimation error of the steering vector of 10°. Fig. 9 shows the relationship between the estimation error of the steering vector and the correlation peak. The simulation results show that the estimation error of the steering vector of the satellite signal result in the loss of signal power and the decrease of the correlation peak. When the error is ±10°, the correlation peak is reduced by about 2.5 dB.

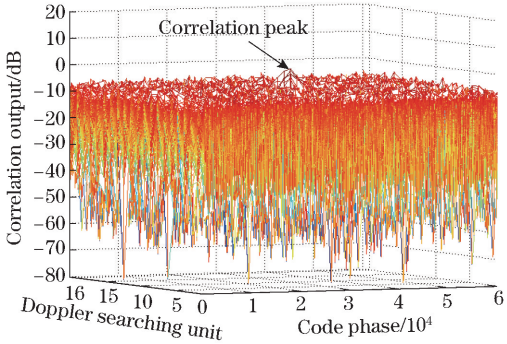

Fig. 8 Acquisition correlation output

The estimation error is related to the search step $\Delta\theta$. The smaller the $\Delta\theta$ is, the smaller the estimation error is, but also the slower the convergence of the algorithm is. The larger the $\Delta\theta$ is, the faster the algorithm converges, but the bigger the error is. Therefore, the $\Delta\theta$ of the algorithm should be used according to the actual situation.

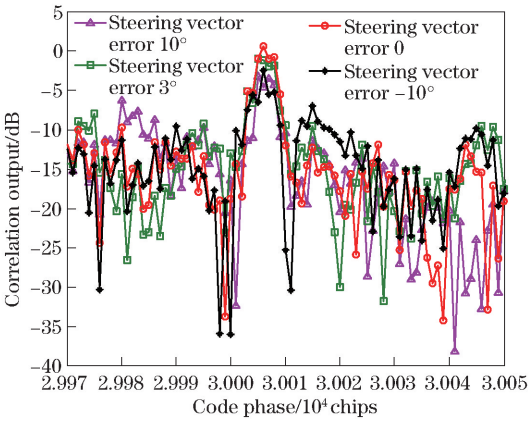

Fig. 9 Relationship between the correlation peak and estimation error of the steering vector of the satellite signal

4 Conclusion

A spatial blind search anti-jamming algorithm based on a combination of subspace projection filtering and acquisition is proposed in this paper. Each single-constrained filter takes the correlation output as the decision condition, and the optimal weight vector is obtained by searching the spatial direction of the satellite signal. The simulation results show that the performance of the algorithm is better than that of the unconstrained subspace projection anti-jamming algorithm because the directional gain of the satellite signal is guaranteed. The algorithm is easy to implement in engineering. The research provides a new idea for the engineering implementation of a multi-beam anti-jamming algorithm based on subspace projection.

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