A Satellite Navigation Signal Acquisition and Interference Suppression Method in a Complex Electromagnetic Environment

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Abstract. Under a complex electromagnetic environment, satellite navigation signals are affected by interference and the receiver cannot effectively locate them. A satellite navigation signal acquisition and interference suppression method is proposed. Prior to signal acquisition synchronization, the power inversion method is used to cancel interference, and then multiple half-bit information is used for incoherent accumulation to effectively capture satellite signals, and after satellite signals are captured, a parallel multi-beam method is used to beamform different satellites separately. The simulation results show that this method can not only suppress the interference signal, but also produce a large gain for the satellite signal, with its performance superior to the conventional methods.

1. Introduction
Since the distance between the navigation satellite and the ground is far, and the signal power at the end of the receiver is lower than the noise, the receiver is easily disturbed by the complex electromagnetic environment. Therefore, anti-jamming technology continues to develop, and the adaptive filter algorithm based on array antennas is the most common and most effective measure.

The power inversion (PI) method commonly used in GPS receivers can achieve a good anti-interference effect without the need to know the Direction of Arrival (DOA) of the desired signal[1]; in addition, reference[2,3] also studies the suppression methods of specific interferences, such as pulse interference, FM interference, etc. In the calculation process, to avoid matrix inversion, the rank reduction method using multi-stage Wiener filter has been widely used[4]; since GPS is a code division multiple access (CDMA) system, blind adaptive beamforming algorithm using PN code has also become a direction of research[5]. The reference[6] uses a multi-beam antenna to point the main beam toward the satellite, but the DOA of the desired signal must be known, so it is seldom used.

This paper proposes a signal acquisition and parallel multi-beam interference suppression method in a complex electromagnetic environment, which can achieve the best reception performance through high-sensitivity acquisition and main beam gain while cancelling interference.

2. Signal Acquisition in Complex Electromagnetic Environments

2.1. Interference power minimization
In a complex electromagnetic environment, the power of the interfering signal is high, and the direction is unknown. The GPS signal is from multiple satellites and cannot be accurately tracked.
Therefore, the direction is unknown. However, the power of the GPS signal to reach the ground signal is much lower than the natural noise. Thus, before the signal acquisition synchronization, the power minimization can be used as a calculation criterion, that is, the PI method[1] is used, and derived as follows:

\[ x(n) = \begin{bmatrix} x_1(n), x_2(n), \cdots, x_M(n) \end{bmatrix}^T \]  

(1)

The weighted output of the array is

\[ y(n) = w^H x(n) \]  

(2)

The output power can be expressed as

\[ P_{out} = E[y(n)]^2 = w^H E[x(n)x^H(n)]w \]  

(3)

The constraints are as follows:

\[ \text{Minimize } P_{out} = E[|y(n)|^2] \]  

\[ w^H a(r^\text{gps}_j) = 1 \]  

(4)

Where, \( w \) is for the antenna array weighting coefficient, \( a(r^\text{gps}_j) \) for the jth GPS signal, and H for the conjugate transpose.

After construction of a Lagrangian extremal function, the equation is solved to get the optimal weight:

\[ w_{opt} = \frac{R^{-1}s}{s^HR^{-1}s}, R = E[x(n)x^H(n)] \]  

(5)

In(5), the solution of the optimal weight requires matrix inversion. To avoid inversion, the initial weight \( w(0) \) can be set so that the weight is iterated along the direction in which \( P_{out} \) reduction is fastest. The recurrence formula is

\[ \text{Figure 1. The structure of the PI method} \]
\[
\begin{align*}
    w(0) &= (1,0,0,...)^T \\
    s &= (1,0,0,...)^T \\
    w(n+1) &= w(n) - 2\mu \left[ I - \frac{ss^T}{s^Ts} \right] x^T(n)x(n)w(n)
\end{align*}
\]

Where, \( w(0) \) is for the initial weight, \( s \) for the constraint condition, \( x \) for the input vector, \( \mu \) for the iteration step size, and \( w(n+1) \) for the updated weight value.

2.2. High sensitivity signal acquisition

The GPS signal uses a GOLD code with a length of 1023, a chip rate of 1.023 Mcps, and a data rate of 20 bps. Figure 2 shows the data model of the signal.

![Figure 2. Data model of the signal](image)

As shown in Figure 2, to improve the acquisition sensitivity, complete correlation processing can be performed on the entire bit length data to obtain a 43 dB spreading gain. However, before the signal acquisition, the bit flipping position is unknown. If the whole bit data is used for correlation, the bit flipping causes the correlation peak to be cancelled and the signal cannot be successfully captured.

To solve this problem, techniques such as half-bit data matching filtering and incoherent accumulation (HDMF-IA) are used, as shown in Figure 3.

![Figure 3. The structure of the HDMF-IA method](image)

The length of each segment of the matching filter is designed to be half of the data bit period, so that the correlation result of one of the adjacent two segment matching filters is not affected by the bit flipping. The length of the matching filter is related to the data bit period, which creates conditions for incoherent accumulation.

The power-minimized I and Q baseband signals, i.e. \( S_{bI} \) and \( S_{bQ} \), are sent to a matching filter for processing. Each segment has a length of 10,230 chips. Assume that the cumulative number of segments is \( N \), each segment performs related calculations.
\[ Z_{1,k}(n) = \sum_{i=0}^{10230} S_{1,i} (n-i) \times h(-i), k = 1 \sim 2N \] (7)

\[ Z_{Q,k}(n) = \sum_{i=0}^{10230} S_{b,Q} (n-i) \times h(-i), k = 1 \sim 2N \] (8)

Where, \( Z_{1,k}(n) \) and \( Z_{Q,k}(n) \) represent the matching results of the k-th segment of I and Q baseband data respectively.

After incoherent accumulation of matching filter results where k is an odd segment, we can obtain:

\[ G_o(n) = \sum_k (Z_{k,1}(n) + Z_{k,0}(n)) \] (9)

After incoherent accumulation of matching filter results where k is an even segment, we can obtain:

\[ G_e(n) = \sum_k (Z_{k,1}(n) + Z_{k,0}(n)) \] (10)

Where, \( G_o(n) \) and \( G_e(n) \) are the incoherent accumulated value of the matching filtering results of the odd and even segments respectively. Through peak search and real-time comparison of the two correlation results, the correlation peak value of a large value is compared with the capture threshold, and if the correlation peak value exceeds the threshold value, the satellite signal is considered to have been successfully captured.

3. Parallel multi beam (PMB) interference suppression

The PI method and high-sensitivity signal acquisition method ensure the effective capture of GPS signals, but in the tracking stage, if the PI method is still used, and when the interference is high, the gain of the useful signal direction cannot be satisfied, resulting in decline of reception performance.

Therefore, multiple parallel beams can be used to obtain adaptive weights for multiple satellites and perform beamforming independently. Using the despreading and re-spreading method[5], a main beam is formed at the direction of a single desired receiving satellite through the beamformer, and nulling is formed at the interference of other directions. Figure 4 shows the structure of the PMB method.

The number of antennas of the receiver is M, and each satellite corresponds to an adaptive beamformer. By adaptively processing the weights, the method minimizes the square-error between the array output and the expected response. The cost function is defined as

\[ D(w_i) = \sum_{k=1}^{K} |w_i^H X(k) - r_i(k)|^2 \] (11)

Where, K is the size of the data block. For the GPS synchronizing with spreading code and data bit, to obtain the best spread-spectrum processing gain, K is taken as sampling data within one bit period.
Figure 4. The structure of the PMB method

After the satellite signal is captured and steadily tracked, the data bits of the i-th satellite are detected. If the n-th data bit is detected correctly, the signal waveform of the i-th satellite transmitted within the time interval \( [(n-1)T_b, nT_b] \) can be considered to be obtainable through respread of the detected data bits \( \hat{b}_i \) using the \( c_i \) code of the i-th satellite, i.e.

\[
r_i(t) = \hat{b}_i c_i, \quad (n-1)T_b \leq t \leq nT_b
\]

The i-th beamformer uses this respread signal to adaptively process the weight vector of the i-th satellite. Since the \( c_i \) code repeats once every bit period, \( c_i \) and \( r_i(t) \) have the same period \( T_b \). For iteration at each step, a different input data block may also be used to adaptively process the weight vector. Let

\[
X(j) = [x((1+j)K), x((2+j)K), \ldots, x((l+1)K)], \quad j = 0, 1, \ldots, J
\]

Where, \( J \) is the number of iterative steps required for the convergence of the algorithm; \( K \) is the number of data samples per bit, and all data samples in one bit period are used in the adaptive process. The output data of beamforming corresponding to the i-th satellite is as follows:

\[
y_i(j) = [w_i^H(j) X(j)]^T = [y_i((1+j)K), y_i((2+j)K), \ldots, y_i((1+l)K)]^T
\]

\( \hat{b}_j \) is the estimate of the j-th data bit of the signal transmitted from the i-th satellite, and the respread signal can be written as

\[
r_i(j) = \hat{b}_j c_i^T
\]

\( r_i(j) \) is used as the reference value for calculation of the weight, and \( y_i(j) \) is the output data corresponding to the weight \( w_i \) at iteration j. The weights are adaptively updated to minimize the cost function in equation (11).

\[
w_i(j+1) = [X(j) X_i^H(j)]^{-1} X(j) r_i^*(j)
\]

In (16), the method uses matrix inversion, since the PI method has already calculated the initial weight, to reduce the amount of calculation, an iterative method can be used instead of the matrix inversion. The steps are as follows:
\[
\begin{align*}
    w_i(j + 1) &= w_i(j) + \mu X_j (j) E_i(j + 1)^H \\
    E_i(j) &= r_i(j) - y_i(j)
\end{align*}
\] (17)

Where, \( \mu \) is for the step size; \( X_j(j) \) for the array receiving vector of the current bit; \( r_i(j) \) for the local reference signal; \( E_i(j) \) for the weight vector correction error vector of current bit; \( y_i(j) \) for the current bit data output.

4. Simulation results
To verify the effectiveness of the method, the simulation uses a 4-element uniform linear array with half-wavelength spacing. Assume that a singleton interference is located at \(-60^\circ\) and the interference-to-noise ratio (INR) is 60dB; an equal bandwidth DSSS-BPSK modulation signal is located at 50° and the INR is 50dB. The desired GPS satellite 1(Sat.1) is located at 18° and the signal to noise ratio (SNR) is -30 dB; the desired GPS satellite 2(Sat.2) is located at -25° and the SNR is -27 dB.

The frequency spectrum before the interference cancellation is shown in Figure 5, and the frequency spectrum after cancellation is shown in Figure 6. The PI method can suppress the narrowband interference and the broadband interference well.

The GPS signal acquisition uses a matching filter and takes N=8 segments for incoherent accumulation, i.e. the HDMF-IA method. The matching filter produces correlation peaks when the received signal is aligned with the local PN code, and approximates noise when not aligned. Therefore, the peak to mean ratio (PMR) of the correlation value is an important basis for capture. The result is shown in Figure 7.

![Figure 5. The frequency spectrum before PI method](image)
![Figure 6. The frequency spectrum after PI method](image)
![Figure 7. The PMR of the correlation](image)

Figure 5. The frequency spectrum before PI method
Figure 6. The frequency spectrum after PI method
Figure 7. The PMR of the correlation

After the satellite signal is captured, different satellites are beamformed using a parallel multibeam method, with the directional pattern as shown in Figure 8. Compared with the PI method, the PMB
method not only does not affect the nulling of the interference direction, but also can obtain greater gain in the desired direction. Figure 9 is comparison of correlation peaks before and after use of the method, showing that the method suppresses narrow-band and wide-band interference and also improves the SNR of satellite signals.

5. Conclusion
This paper presents a satellite navigation signal acquisition and interference suppression method under complex electromagnetic environment. Before the satellite signal is captured, the PI method is used to cancel the interference, and then the half-bit incoherent signal acquisition method is used to increase the acquisition sensitivity. After satellite signals are captured, a different beamformer is used for each satellite, and the adaptive weights are respectively obtained through the despreading and respreading method, so that a main beam can be formed at the direction of the desired receiving satellite and nulling formed at other directions of interference.

The simulation results show that the proposed method can effectively implement interference suppression and signal acquisition for multiple satellites in the airspace under the condition that the desired satellite and interference direction are unknown, and the performance is superior to conventional methods.

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References
[1] Schwegman C W and Compton R T 1972 Power inversion in a two-element adaptive array AD0758690 (Ohio State, USA: Ohio State Univ Columbus Electroscience Lab) pp 1-40
[2] Fante R L and Vaccaro J J 2000 Wideband cancellation of interference in a GPS receiver array IEEE Trans. on Aerospace and Electronic System 36(2) pp 549-564
[3] Amin M G Zhao L and Lindsey A R 2004 Subspace array processing for the suppression of FM jamming in GPS receivers IEEE Trans. on Aerospace and Electronic System 40(1) pp 80-92
[4] Werner S With M and Koivunen V 2007 Householder multistage Wiener filter for space-time navigation receivers IEEE Trans. on Aerospace and Electronic System 43(3) pp 975-988
[5] SANG Huai-Sheng LI Zheng-Rong and YONG Shao-Wei 2002 The blind adaptive beamforming algorithms using PN code Journal of China Institute of Communications 23(11) pp 103-108
[6] Miura Ryu Tanaka Toyohisa and Chiba Isamu 1997 Beamforming experiment with a DBF multibeam antenna in a mobile satellite environment IEEE Transactions on Antennas and Propagation 45(4) pp 707-714