A New Algorithm of Energy Suppression for Satellite Navigation

JI Yuanfa¹², SUN Xiyan¹

¹. Satellite Navigation Lab, Guilin University of Electronic Technology, 1 Jinji Road, Guilin 541004, China
². National Astronomical Observatory, Datun Road, Beijing 100012, China

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Abstract The satellite navigation anti-interference technique, especially space anti-interference technique, is subjected to many restrictions, such as cost, energy depletion, and so on, and the satellite signal strength is limited by the International Radio Advisory Committee, the International Telecommunication Union (ITU) and satellite companies. This paper focuses on satellite navigation systems, especially satellite navigation systems adopting direct sequence spread spectrum (DSSS). The notch filter is used to remove some frequencies from the pseudorandom code frequency spectrum making use of its cyclostationarity first, then the filtered pseudorandom code is modulated by the carrier to attain energy suppression, but the pseudorandom code autocorrelation characteristic stays unchanged. The feasibility of this algorithm is verified by simulation results.

Keywords satellite navigation; CA code; anti-interference; notch filter; cyclostationarity; parasitizing

CLC number P228

Introduction

The direct sequence spread spectrum (DSSS) is adopted by some satellite navigation systems, such as GPS (Globing Positioning System) and CAPS (China Area Positioning System), which have certain anti-interference ability. However, the spreading gain can be acquired only after the code correlation in the signal processing of the receiver; the actual strength of satellite navigation signal is very low. Therefore, the satellite receivers are vulnerable to intentional and unintentional interference, and signal-to-interference ratio is up to 40dB [1]. Currently, the anti-interference methods are mainly divided into space anti-interference and receiver anti-interference [2]. Three anti-interference methods are mainly adopted by GPS, which are enhancing GPS satellite signal power, developing new navigation satellites and setting up independent GPS systems for the military. However, these three kinds of methods have high cost and need large amounts of material resources. The receiver anti-interference methods are divided into the self-adaptive filter method [3,4], antenna method [5,6], time-frequency domain method [7] and sub-space method [8]. The selection of the method for anti-interference is mainly decided by cost, space limitation, energy depletion and application environment, etc. Currently, anti-interference techniques mainly involve the receiver anti-interference being subjected to a lot of restrictions; however, space interference aims at navigation satellite directly. Therefore, it is more dangerous, and also is...
more difficult to be realized.

The navigation satellites of CAPS are geostationary satellites and there are lots of communication satellites. The signals from different satellites can possibly affect each other. The strength of satellite navigation signal is limited strictly for this. The International Radio Advisory Committee and the International Telecommunication Union (ITU) also ruled the space communication systems to produce the international standard of “flux density” on the ground in order to prevent interference of ground communications. They also restricted a value of “flux density” of -152 dBws/m² in the C band inside each 4 kHz. In addition to this, corresponding satellite companies have put forward more strict limitations of satellite signal strength for the normal working of satellites. Therefore, the strength, namely signal energy, of satellite navigation signal should be controlled strictly. Moreover, if the navigation signal is weak enough, the navigation signal can be parasitized on other satellites. Then, space anti-interference can be carried out without a big price.

A novel energy suppression algorithm is put forward aimed at the limitation of satellite navigation signal energy and space anti-interference. The algorithm is based on the “hidden” cyclostationary characteristics of the DSSS signal of navigation satellites. First, the navigation pseudo-random code is translated by Fourier transformation, and the notch filter is used in frequency domain, then, the filtered code is translated to time domain and modulated by the carrier. As a result, the energy of filtered satellite navigation signals is reduced greatly in comparison to that without filtering.

1 GPS signal frequency and its modulation mode

As showed in Fig.1, GPS signal includes three components: carrier, pseudo-random code and navigation data. GPS satellite signal is the modulated wave from GPS satellites to the vast numbers of users for navigation and positioning, and the wave is a combination of code modulated by satellite navigation message and pseudo-random code. The signal is a typical DSSS: the coded pulse (navigation message or information code) is modulated by the pseudo-random code first, then, L-band carrier is modulated by binary phase-shift-keying (BPSK), and the modulated signal is finally transmitted by the GPS satellites. Pseudo-random codes in GPS satellite signal are divided into two kinds: CA (coarse acquisition) code used for civilian systems and P (precise) code used for military systems. They are both pseudo-random codes (pseudorandom noise, or PRN). The main characteristics of this kind of code sequence not only takes on good autocorrelation characteristic similar to random code, but also takes on a certain coding rule. Propagation delay from the GPS satellite receiver and the satellite can be accurately determined because of its good autocorrelation single peak value and replicability. All satellite signals can be transmitted at the same frequency without causing interference because of their low cross-correlation characteristic.

Each CA code is a unique sequence of 1023 bits, called chips, which is repeated each millisecond. The duration of each CA code chip is about 1 μs. Each CA code is periodic, repeating a 1023-chip pattern. There is a different CA code PRN for each navigation satellite.

It is widely used in Code Division Multiple Access systems, and it is also used in GPS Gold Code as part of the CA’s main reason for its desired autocorrelation and cross correlation properties.

\[ S(t) = A_c C(t) D(t) \cos(\omega t + \varphi) \]
Where $S(t)$ is the modulated signal, $A_c$ is the amplitude of CA code, $C(t)$ is CA code transmitted from satellite, $D(t)$ is satellite navigation message, $w$ is the angular frequency of carrier wave, $\varphi$ is the initial carrier phase of satellite $i$.

Because the rate of navigation message is much less than that of CA code, $D(t)$ can be omitted from Eq.(1) and the item $A_i=1$, then Eq.(1) becomes:

$$S(t) = C(t) \cos(w t + \varphi)$$

(2)

Because $C(t)$ is the binary code of $+1$ and $-1$, Eq.(2) can be denoted by discrete form

$$S(t) = \sum_{n=1}^{N_c} C_n(t) \cos(w t + \varphi_n), \quad 0 \leq t \leq N \tau$$

(3)

Where $N = 1, 2, \cdots; \tau$ is a CA chip duration; $\varphi_n = 1$ or $\pi$.

From Eq.(3), we can see that there is a fixed frequency signal in signal $S(t)$ making the signal have a cyclostationary characteristic. However, this cyclostationary characteristic is not obvious, and some non-linear transformations (such as secondary conversion) should be done, and then the spectral lines will appear. The goal of this paper is to attempt to suppress the hidden periodicity present in the satellite signal. The suppression of periodicity will be attempted by filtering out frequency components from the frequency spectrum of the CA code itself. The filtering of certain frequency components in the frequency spectrum of CA code will result in energy suppression in the neighborhood of twice the carrier frequency present in the squaring of satellite signal. It should be noted that any filtering of frequency components should cause no degradation of the narrow central peak characteristic of the coded signal’s auto-correlation to ensure satellite signal acquisition successfully.

### 2 Design of notch filter

The Fourier transform of $C(t)$ (CA code) is

$$C(f) = \mathcal{Z}\{C(t)\}$$

(4)

The filtered CA code is named $m(t)$, and the Fourier transform of $m(t)$ is

$$M(f) = \mathcal{Z}\{m(t)\} = H(f)C(f)$$

(5)

Where $H(f)$ is the Fourier transform of the energy filter. The filtered CA code is modulated by carrier wave and its result is

$$p(t) = m(t) \cos(2\pi f_0 t)$$

(6)

Squaring $p(t)$ results in information of unknown spectral lines, and therefore, the form of energy filter is decided by squaring of Eq.(6).

Squaring of Eq.(6) is denoted in frequency domain

$$\mathcal{Z}\{p^2(t)\} = \mathcal{Z}\{p(t)\} \otimes \mathcal{Z}\{p(t)\} = \mathcal{P}(f) \otimes \mathcal{P}(f)$$

(7)

Where $\otimes$ denotes convolution, $\mathcal{P}(f)$ is the result of $p(t)$, Fourier transformation. Convolution can be denoted as

$$R(\alpha) = \mathcal{P}(f) \otimes \mathcal{P}(f) = \int \mathcal{P}(f) \mathcal{P}(\alpha-f) df$$

(8)

The Fourier transformation of Eq.(6) is

$$P(f) = \mathcal{Z}\{p(t)\} = \mathcal{Z}\{m(t) \cos(2\pi f_0 t)\}$$

$$= \frac{1}{2}[M(f - f_c) + M(f + f_c)]$$

(9)

Substituting Eq.(9) into Eq.(8), we can obtain

$$R(\alpha) = \frac{1}{4} \left[ M(f-f_c) + M(f+f_c) \right]$$

$$\left[ M(\alpha-f_c) + M(\alpha+f_c) \right] df$$

(10)

Eq.(10) can be written as

$$R(\alpha) = \frac{1}{4} \left[ M(f-f_c) + M(f+f_c) \right]$$

$$\left[ M(\alpha-f_c) + M(-f_c+\alpha) - M(-f_c-\alpha) \right] df$$

(11)

Eq.(10) can be divided into two terms $[M(f-f_c) + M(f+f_c)]$ and $[M(f+f_c) + M(\alpha-f) + M(-f_c+\alpha-f)]$, which correspond to two figures in Fig.2(a) respectively, and the integral of the product of those two terms can be seen in Fig.2(b). $R(\alpha)$ can be divided into three parts which can be seen from Fig.2, and there

![Fig.2](image-url)
are spectral lines at $\pm 2f_c$ frequency which shows the signal’s periodicity. Since $-2f_c$ is the mirror of $2f_c$, then for the purpose of problem simplification and without loss of generality, the frequency components of interest in the right positive spectrum only are considered, and therefore, the frequency components that will be examined are those in the neighborhood of $\alpha = 2f_c$.

Expanding Eq.(11) and substituting $\alpha = 2f_c$ into Eq.(11) we get
\[
R(2f_c) = \frac{1}{4} \left[ M(f - f_c)M(3f_c - f) + M(f - f_c)M(f_c - f) + M(f + f_c)M(3f_c - f) + M(f + f_c)M(f_c - f) \right] df
\]

Since only the neighborhood of $2f_c$ is considered, Eq.(12) reduces to
\[
X_{2f_c}(\alpha) = \frac{1}{4} \left[ M(f - f_c)M(-f_c + \alpha - f) \right] df
\]

For maximum energy suppression in the CA code signal, the result of Eq.(13) should be minimized. Energy is mainly located in neighborhood of CA code frequency main-lobe, as Fig.3, therefore the best energy suppression filter is notch filter. The notch filter can be easily constructed and its bandwidth is easily varied as needed[10].

3 Simulation results

The bandwidth of the notch filter is closely related to the bandwidth ($\frac{2}{\tau}$) of CA code. The bandwidth of the notch filter is chosen, $BW = \frac{1}{100} \left( \frac{2}{\tau} \right)$, in this paper.

The center frequency of the notch filter is the dc frequency. The frequency of the carrier wave is chosen as 4.309MHz to simplify the simulation, and the actual frequency of the carrier wave is 1575.42MHz, therefore the sampling frequency of 16MHz can be chosen, and this process will not affect the results.

The energy is compared by their respective average in frequency bandwidth computed before filtering and after filtering of the square signal. The energy in frequency bandwidth of the square signal should equal to that in the main-lobe ($\frac{2}{\tau} = 2.046$MHz) of CA code spectra and energy concentrates on the twice frequency ($4.309 \times 2 = 8.618$MHz) around, which can be seen from Fig.4 and Fig.5. The filtering caused the large change of the shape of CA code (see Fig.6), but its auto-correlation (see Fig.7 and Fig.8) is almost not changed. Moreover, with the notch filter bandwidth increase, the energy after filtering gradually decreases by comparison with the one before filtering, and the shape of the CA code will also become larger, the autocorrelation properties will deteriorate.
on the following theory: the satellite navigation signals of the DSSS satellite navigation system have cyclostationary characteristics. The filtered pseudo-random code modulated by the carrier can greatly reduce the energy of the modulated signal. The satellite signal energy can be decreased to a certain degree and the satellite signal can be parasitized on the other satellites without their awareness, so as to achieve the anti-interference capability of satellite navigation systems.

References

[1] Di Minmin, Zhang Eryang (2005) Designing of a multi-stage anti-jam GPS receive [J]. Journal on Communications, 26(11): 82-86
[2] Hou Zhefei, Wang Xuedong, Chen Guojun (2004) Research on interference and anti-interference of GPS[J]. Modern Electronic Technique, 23: 99-104
[3] Laurence B Milstein (1988) Interference rejection techniques in spread spectrum communications [J]. Proceedings of the IEEE, 76(6): 657-671
[4] Haimovich A, Vadhri A(1994) Rejection of narrow-band interferences in PN spread spectrum systems using an eigenanalysis approach [C]. IEEE Seventh SP Workshop on Statistical Signal and Array Processing, Quebec, Canada
[5] Christopher Ward, Philip J Hargrave, J&m G Mewhirter (1986) A novel algorithm and architecture for adaptive digital beamforming [J]. IEEE Trans on AP, 34(3): 338-346
[6] Compton R T C, J R (1979) The power-inversion adaptive array: concept and performance[J]. IEEE Trans on AP, AES, 15(6): 803-814
[7] Robert C D iPietro (1989) An FFT based technique for suppressing narrow-band interference in PN spread spectrum communications systems[C]. ICASSP-89, Glasgow, Scotland
[8] Lian Zhao, Moeness G Amin, Alan R Lindsey (2002) GPS anti-jam via subspace projection: a performance analysis for FM interference in the C/A code[J]. Digital Signal Processing, 12: 175-192
[9] Gardner W A(1994) Cyclostati onarity in communications and signal processing[M]. New York:IEEE Press
[10]Mohsin Benghuzzi (2006) Passive detection suppression of cyclostationary phase coded waveforms [C]. Proceedings of the 38th Southeastern Symposium on System Theory Tennessee Technological University Cookeville, TN, USA

4 Conclusion

The notch filter is used to filter the frequency spectrum of pseudo-random code, and it is mainly based...