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X-ray pulsars time delay estimation using GSO-based bispectral feature points

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ABSTRACT

In order to reduce the calculation time and improve the performance of X-ray pulsar-based navigation (XNAV), we choose the bispectral feature points by the glowworm swarm optimization (GSO) algorithm, and to estimate the time delay for the pulsar integrated pulse profile. The proposed method is used to extract the bispectral feature points of the standard pulsar integrated pulse profile by the GSO algorithm on the ground control center, and store these feature points into the spacecraft's database. Then to estimate the time delay, it is only necessary to calculate the self-bispectrum and the cross-bispectrum of the standard pulsar integrated pulse profile and the observed one at the extracted bispectral feature points during flying. The results showed that the proposed method not only has the advantages of the traditional bispectrum algorithm that it can suppress the Gauss noise completely, but also reduced the calculation time greatly.

1. Introduction

As a new technology in the field of celestial navigation, X-ray pulsar navigation (XNAV) has a very important military purpose and wide engineering application [1]. In this technology, the measurement of the pulse time of arrival (TOA) is the basis of spacecraft's timing and positioning [2]. The TOA of pulsar is obtained after a long time of observation and procured by epoch folding (EF) according to the arrival time of received photons on the detector [3], therefore the measurement of the pulse TOA depends on the time delay estimation of X-ray pulsar integrated pulse profile [4]. Liu et al. developed an extended Kalman filter (EKF) with correlated measurement bias and state estimation error to improve the accuracy of navigation [5]. Liu et al. also used non-linearly constrained least square to estimate the spacecraft velocity and position according to the variation of TOAs based on the relationship between the TOA and the spacecraft velocity [6]. In order to improve the navigation's accuracy, Rinauro and Zhang calculated the phase of X-ray pulsar by the near-maximum likelihood estimation and the maximum likelihood estimation respectively [7,8]. Emadzadeh compared the standard pulsar integrated pulse profile with the observed one to estimate the time delay by non-linear least squares estimation and cross correlation [3,9]. Taylor proposed the FFT algorithm for the time delay estimation of X-ray pulsar [10], which makes the accuracy of the time delay only depends on the SNR of the integrated pulse profile. Su proposed a new method to estimate the time delay of pulsars with the three-order cross wavelet cumulants [11]. In order to estimate more accurately, Xie et al. used the bispectrum algorithm for the time delay estimation [12]. The bispectrum algorithm not only can suppress the additive white noise in the pulsar integrated pulse profile, but also has good suppression on the multiplicative noise, multiplicative and additive noise.

The existing literatures indicate that researches in the area of navigation focus on the accuracy of the time delay estimation for the pulsar integrated pulse profile. Little attention has been paid to the calculation which also affects the accuracy of navigation. Although the traditional bispectrum algorithm has high accuracy for the time delay estimation even under low SNR, the two dimensional operation in the bispectrum causes so large amount of data of pulsar's signal that the algorithm runs slowly and the spacecraft can not position in real time.

In the paper, the glowworm swarm optimization (GSO) algorithm is introduced into the time delay estimation [13]. To solve the large amount of computation in the traditional bispectrum algorithm, we used GSO to extract the suitable bispectral feature points on the ground, calculated the bispectrum on these feature points in the spacecraft. Then a new method for the fast time delay estimation is formed by reducing a large amount of calculation in the real time positioning.

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In Section 2 of this paper, we introduced the traditional bispectrum algorithm and the GSO algorithm briefly. Section 3 described the new method we proposed to estimate the time delay of X-ray pulsar integrated pulse profile. In Section 4, we did some experiments to evaluate the calculation and accuracy of time delay estimation on different pulsars, by using the traditional bispectrum algorithm and the new method proposed in this paper respectively. Section 5 summarized this paper.

2. The bispectrum algorithm and the GSO algorithm

2.1. The bispectrum algorithm

The bispectrum which has the lowest order in high-order spectrum contains the phase information, and can suppress the Gauss noise [12]. As it can improve the estimation performance, the bispectrum algorithm is widely used in the signal processing to estimate the time delay. The bispectrum algorithm is introduced briefly as follows.

Assuming that the observation data $\{x(0), x(1), \ldots, x(N-1)\}$ and $\{y(0), y(1), \ldots, y(N-1)\}$ is a data sequence with length N, the direct method can be used to carry out the bispectrum estimation, and the specific process is as follows.

Assuming that $X(\lambda)$, $Y(\lambda)$ is the discrete Fourier transform (DFT) of data $\{x(0), x(1), \ldots, x(N-1)\}$ and $\{y(0), y(1), \ldots, y(N-1)\}$, and $\lambda = 0, 1, \ldots, N/2$.

According to the DFT, the expression of bispectrum is:

$$B_{xxx}(\lambda_1, \lambda_2) = X(\lambda_1) \cdot X(\lambda_2) \cdot X^*(\lambda_1 + \lambda_2) \quad (1)$$

$$B_{xyx}(\lambda_1, \lambda_2) = X(\lambda_1) \cdot Y(\lambda_2) \cdot X^*(\lambda_1 + \lambda_2) \quad (2)$$

Assuming that the function $I(\lambda_1, \lambda_2)$ is:

$$I(\lambda_1, \lambda_2) = \exp\, j[\Phi(\lambda_1, \lambda_2)] \quad (3)$$

where $\Phi(\lambda_1, \lambda_2) = \Psi_{xyx}(\lambda_1, \lambda_2) - \Psi_{xxx}(\lambda_1, \lambda_2)$, $\Psi_{xxx}(\lambda_1, \lambda_2)$ and $\Psi_{xyx}(\lambda_1, \lambda_2)$ are the phase functions of self-bispectrum $B_{xxx}(\lambda_1, \lambda_2)$ and the cross-bispectrum $B_{xyx}(\lambda_1, \lambda_2)$ respectively.

Then we can get the estimated time delay D when $T(\tau)$ get the max value according the following equation:

$$T(\tau) = \sum_{\lambda_1=0}^{N-1} \sum_{\lambda_2=0}^{N-1} I(\lambda_1, \lambda_2) \exp(j\lambda_2 \tau) \quad (4)$$

2.2. The GSO algorithm

The glowworm swarm optimization algorithm (GSO) is a new swarm intelligence optimization algorithm which was proposed to solve the multiple local extreme values optimization and the global optimization problem [13]. Because the GSO algorithm can capture the extreme value with high efficiency and speed, it has gradually become a hot topic in academic research in recent years.

The basic principle of the GSO algorithm is that the glowworm attracts a mate or prey by giving out light using luciferin. Assuming that in the m dimension of the target search space, there is a group with n glowworms. According to the similar degree of luciferin, the group is divided into n neighborhoods. In each neighborhood, the glowworm i moves to the glowworm j in the decision domain $r_d^i (0 < r_d^i \le r_s)$ where r_s is the radial sensor range of the glowworm i. The position n of the glowworm i is a solution. We can get the value of the fitness function $f(x_i)$ by putting x_i into an objective function, the value of luciferin l_i will thus be obtained at the same time because it is corresponding to the fitness function. Then, the optimal degree of solutions can be measured according to the size of the luciferin's value, and the glowworm moves to the luciferin with higher value. To sum up, the glowworm can determine the optimal value of the fitness function by searching the highest luciferin in the dynamic decision domain.

3. Time delay measurement based on GSO and the bispectrum algorithm

In the paper, it will take a lot of time if the traditional bispectrum algorithm for the time delay estimation of X-ray pulsar integrated pulse profile in the spacecraft is considered. As a result, the real-time and the accuracy of positioning are greatly affected. Because the GSO algorithm can search the optimal value quickly, we proposed a new method combined the GSO algorithm with the bispectrum algorithm. First, we extracted the bispectral feature points of the standard pulsar integrated pulse profile by the GSO algorithm on the ground control center, and store these feature points into the spacecraft's database. Then during the spacecraft flies, by comparing the self-bispectrum and the cross-bispectrum of the standard pulsar integrated pulse profile and the observed one at the extracted bispectral feature points, we can also obtain the information of the time delay. This method can not only suppress the Gauss noise and improve the accuracy of the measurement, but also reduce the computation greatly when the data in spacecraft is transformed into the bispectrum form and searched for the value of the time delay, so the efficiency of the time delay measurement in the spacecraft can be improved.

3.1. Algorithm for ground control center

Assuming the standard X-ray pulsar integrated pulse profile is $s(k)$, and its DFT $S(\omega)$ is:

$$S(\omega) = \sum_{k=0}^{N} s(k) e^{-jk\omega} \quad (5)$$

According to Eq. (1), the self-bispectrum of the standard integrated pulse profile $s(k)$, $B_{sss}(\omega_1, \omega_2)$, is:

$$B_{sss}(\omega_1, \omega_2) = S(\omega_1) \cdot S(\omega_2) \cdot S^*(\omega_1 + \omega_2) \quad (6)$$

where ω_1, ω_2 is the frequency parameter of the bispectrum, $\omega_1 \in [0, N]$, $\omega_2 \in [0, N]$, and N is the sampling number.

For the X-ray pulsar integrated pulse profile, N is usually large, and the amount of calculation will increase because of the two-dimensional transform in the traditional bispectrum algorithm. However, there are a lot of ordinary bispectral points [14]. Meanwhile, the energy of the X-ray pulsar integrated pulse profile is concentrated in the low frequency part in the bispectrum, so the paper introduced the GSO algorithm to extract the frequency sampling points in the low frequency part of the integrated pulse profile.

Because the bispectrum function of the X-ray pulsar integrated pulse profile is a two-dimensional function with a number of extreme points, it becomes a two-dimensional optimization problem by introducing the GSO algorithm. In the paper, we sets the objective function $f(\omega_{1t}(t), \omega_{2t}(t))$ as:

$$f(\omega_{1t}(t), \omega_{2t}(t)) = \log(|B_{sss}(\omega_{1t}(t), \omega_{2t}(t))|) \quad (7)$$

where t is the times of iterations in the GSO algorithm.

Assuming that n is the number of glowworms, we can get the luciferin $l_i(t)$, transition probability $P_{ij}(t)$, and the decision domain of the ith glowworm according to Eqs. (8)–(12),

$$l_i(t) = \max\{[0, (1-\rho) \cdot l_i(t-1) + \gamma \cdot f(\omega_{1i}(t), \omega_{2i}(t))]\} \quad (8)$$

$$P_{ij}(t) = \frac{l_j(t)}{\sum_{k \in N_i(t)} l_k(t)} \quad (9)$$