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Original research article

Pulse template establishment with the consideration of the directional error of pulsar

Shijun Xin, Wei Zeng, Yidi Wang*

College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

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ABSTRACT

A pulse template establishment method considering the directional error of the pulsar is proposed in this paper. This method folds the series of photon time of arrival (TOA) of symmetric time intervals to reduce the impact of directional error on pulse template. Firstly, the characteristic of this error is analyzed. And then, its analytical formula of the average value for a whole year is derived as well as that for arbitrary time interval. Finally, the simulated and real data are employed to investigate the performance of the proposed method. Results have shown that this method can establish a relative high-accuracy pulse template.

1. Introduction

With the development of the space industry, there is a growing number of on-orbit spacecraft. If we still use the navigation mode relied on the ground measurement and control system, not only the operating costs would be increased but the survival ability of the spacecraft could not be guaranteed. Therefore, the autonomous navigation will be the central and key technology for the future spacecraft [1]. At present, the autonomous navigation for the lower orbit spacecraft has been basically realized by means of the Global Navigation Satellite System (GNSS) and some missions can be completed very well, such as rendezvous and docking autonomously, short-term autonomous operation and et al. Limited by the orbit altitude of navigation satellites and the radiation angle of electromagnetic signals, GNSS is difficultly applied to autonomous navigation missions of higher orbit spacecraft and deep space explorer [2]. And researching the autonomous navigation technology of these two kinds of spacecraft has been a current hotspot.

X ray pulsar navigation (XPNV) is a new autonomous navigation method, which has an advantage over the satellite navigation that can be applied to the spacecraft near earth as well as the deep space explorer. Building high-precision pulsar ephemeris is one of its key technologies [3]. Because of the broad application prospects, XPNV gets wide attention at home and abroad [4–7]. After the development of the last thirty years, XPNV has completed the concept studying stage and gradually enters the segment of critical technology.

The pulsar database is very basic and significant for XPNV, including the pulsars' spatial distribution parameters, periods, signal parameters and others. Thereinto, the pulse template is the basic input for pulsar signal processing and an important content for building the pulsar database. The pulse TOA is the basic measured quantity, which can be estimated by comparing the on-orbit recovering profile and the pulse template [8]. Therefore, the error of the pulse template can cause deviations

* Corresponding author.
E-mail address: wangyidi_nav@163.com (Y. Wang).

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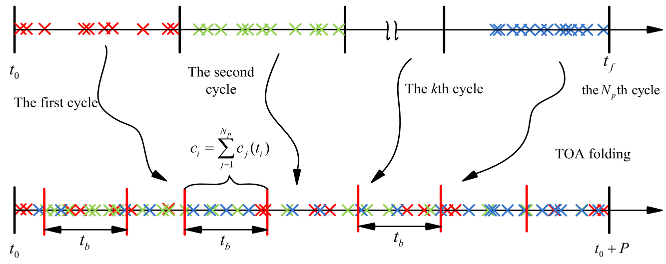

Fig. 1. Epoch folding: All photon TOAs are folded back into the first cycle $[t_0, t_0 + P]$.

of TOA and subsequently reduces the navigation performance. So analysing the influence factors of the pulse template and raising compensation method can strongly support for improving the navigation performance.

The remainder contents of this paper are organized as follows. Section 2 introduces the principle of building the pulse template. Section 3 analyses the impact of the pulsar's directional error. Section 4 proposes the compensation method and investigates the performance of the method via simulation and the real data provided by the Rossi X-ray Timing Explorer (RXTE).

2. The principle of building the pulse template

For actual measurement of X-ray pulsars, the observed quantity is X-ray photons radiated by pulsars. Because of the changing rotation frequency of pulsars and inaccurate orbital information of the spacecraft, it is difficult to build high-precision pulse template. Therefore, in order to remove the motion of spacecraft, relativistic effects and other impact, the photon TOA array detected by the spacecraft should be transformed to the solar system barycenter (SSB). Except for this, searching the best period and phase alignment are also needed [9].

2.1. Time transfer to solar system barycenter

Considering the relativistic and geometric effects and ignoring the movement of pulsar, denoting TOA of the detector and SSB as t_{SC} and t_{SSB} respectively, the corresponding time transfer model can be written as [10]

$$t_{SSB} = t_{SC} + \frac{1}{c}\left[\boldsymbol{n}\cdot\boldsymbol{r}_{SC} - \frac{r_{SC}^2}{2D_0} + \frac{(\boldsymbol{n}\cdot\boldsymbol{r}_{SC})^2}{2D_0} - \frac{(\boldsymbol{b}\cdot\boldsymbol{r}_{SC})}{D_0} + \frac{(\boldsymbol{n}\cdot\boldsymbol{b})(\boldsymbol{n}\cdot\boldsymbol{r}_{SC})}{D_0}\right] + \sum_{i=1}^{9}\frac{2\mu_i}{c^3}\ln\left|\boldsymbol{n}\cdot\boldsymbol{p}_i + \left\|\boldsymbol{p}_i\right\|\right| \tag{1}$$

where t_{SC} and t_{SSB} are respectively the TOA of the detector and SSB, t_{SC} is the pulse TOA of the spacecraft, $\boldsymbol{n}$ is the position vector of one pulsar, $\boldsymbol{r}_{SC}$ is the position vector from the SSB to the spacecraft, c is the light velocity, D_0 is the distance from the pulsar to the spacecraft at the reference time T_0, $\boldsymbol{b}$ is the position vector of SSB relative to the solar barycentre, $\boldsymbol{p}_i$ is the position vector from the ith planet to the spacecraft, and μ_i is the gravitational constant of the ith planet. If the pulsar's direction is (α, δ), then its position vector is

$$n = \begin{bmatrix} \cos\alpha\cos\delta \\ \sin\alpha\cos\delta \\ \sin\delta \end{bmatrix} \tag{2}$$

2.2. Period searching

Suppose that in the time interval $[t_0, t_f]$, a series of photon TOAs are received. Then the test period P is chosen to implement epoch folding, which is performed as follows [12]:

- **Step 1** the photon TOAs' time interval is divided into N_P segments which are all equal to one pulse period P.
- **Step 2** the period duration is divided into N_b equal-length bins and the number of photos in each bin is counted.
- **Step 3** the computed photon counts are folded back into the first period duration, then the photon counts of the ith bin is denoted as c_i (see Fig. 1).

Let the statistic χ^2 is

$$\chi^2 = \sum \frac{(c_i - \bar{c})^2}{\bar{c}} \tag{3}$$

where $\bar{c}$ is the average photon number.

Changing the test period P to search the maximum χ^2 and the corresponding period is exactly the pulsar's period.