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Observation range-based compressive sensing and its application in TOA estimation with low-flux pulsars

Jin Liu [a,*], Jian-cheng Fang [b], Gang Liu [b]

[a] College of Information Science and Engineering, Wuhan University of Science and Technology, Wuhan 430081, People's Republic of China
[b] School of Instrumentation Science & Opto-electronics Engineering, Beihang University (BUAA), Beijing 100191, People's Republic of China

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ABSTRACT

In the traditional compressive sensing methods, to realize highly-accurate pulsar time-of-arrival (TOA) estimation, a large-size measurement matrix has to be adopted due to the low radiation flux of X-ray pulsars. However, a large-size measurement matrix results in a large computational load. To estimate the pulsar TOA fast and accurately, an observation range-based compressive sensing (ORCS) method with a small-size measurement matrix is proposed in this paper. In this method, the observation range (OR) of a measurement vector is developed, which is defined as the variation range of the corresponding observation values that are equal to the inner products between the measurement vector and each atom in the dictionary. The larger the observation range is, the smaller the number of atoms corresponding with the same measurement value is, and vice versa. We also find that the observation ranges of only a few measurement vectors are large. Using several measurement vectors with large observation ranges, we can construct the OR-based measurement matrix with a small size, and then obtain the most matching atom in the dictionary. Besides, according to the heuristic knowledge, the size of the dictionary and the bin number of the accumulated pulsar profile can decrease, which results in a small computational load. The simulation results demonstrate that even though the size of the measurement matrix is very small, the observation range-based compressive sensing method provides highly-accurate and real-time TOA estimation with low-flux pulsars.

1. Introduction

X-ray pulsar navigation is an innovative autonomous navigation technique for deep space exploration [1,2]. Currently, it has become a hot subject of research. In 2004, the Defense Advanced Research Projects Agency of United States has developed "X-ray Source-based Navigation for Autonomous Position Determination" [3]. The European Space Agency has also studied the feasibility of an autonomous navigation system using the pulsar timing information [4]. In November 2016, China has launched the X-ray pulsar navigation (XPNAV) satellite, which is utilized to test the autonomous navigation using X-ray pulsars.

* Corresponding author.
E-mail address: liujin@wust.edu.cn (J. Liu).

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The X-ray pulsar navigation system utilizes the signals from X-ray pulsars to provide the position information for the spacecraft [5,6]. The pulse phase can be divided into the integer and the fractional parts. According to the heuristic knowledge, the X-ray pulsar navigation system can provide the pre-estimation position information, and obtain the integer part of the pulse phase [7]. The navigation system uses the X-ray sensor at the spacecraft to receive the X-ray pulse signals from X-ray pulsars, and processes these signals by the epoch folding to construct the accumulated X-ray pulsar profile. The fractional part of the pulse phase can be obtained by comparing the accumulated pulsar profile with the standard one. The sum of the integer and the fractional parts is the pulse phase, which can be transferred into the pulsar time-of-arrival (TOA). The pulsar TOA is the measurement information for the X-ray pulsar navigation system. And the navigation performance is highly dependent on the accuracy of the pulsar TOA. To obtain three-dimensional position information, at least three pulsars must be adopted [8]. However, the radiation flux of all X-ray pulsars except the Crab pulsar is very low, which affects the accuracy of the pulsar TOA. Besides, due to the limitation of the spacecraft computer's relatively low processing ability [9], the pulsar TOA estimation algorithm with only a small computational load can operate normally. Therefore, how to estimate the pulsar TOA fast and accurately is crucial for the X-ray pulsar navigation system.

In recent years, compressive sensing (CS) [10,11] has been a research hotspot in the field of signal processing [12,13]. Using the CS algorithm to estimate the pulsar TOA is a novel research idea. In 2011, compressive sensing is firstly applied in the X-ray pulsar profile construction by Su [14]. Su has merely reconstructed the X-ray pulsar profile but ignored the TOA estimation. In 2014, Li has proposed a CS-based method for the pulsar profile construction and the TOA estimation [15]. In this method, a column vector-based matching pursuit algorithm is developed. However, this method cannot fully guarantee the pulsar profile construction in high-efficiency. In 2015, Yu has developed a sparse representation-based TOA estimation method [16]. In 2016, Shen has proposed a robust compressive sensing for the pulsar profile construction [17], where the first m row vectors of the Hadamard matrix are selected to construct the measurement matrix. The reason why the Hadamard matrix is adopted is that compared with the random 0–1 matrix and the random Gaussian matrix, the Hadamard matrix can reconstruct the pulsar profile more completely, when the number of the row vectors in the measurement matrix is on the order of hundreds.

However, there are two common problems in these CS-based pulsar TOA estimation methods. (1) The traditional methods are not suitable for low-flux pulsars. The navigation pulsar in these traditional methods is only the Crab pulsar, which has the highest radiation photon flux in all pulsars. And the radiation photon flux of other pulsars is far lower than the background radiation photon flux. Besides, to make the X-ray pulsar navigation system observable, at least three pulsars should be adopted. Namely, at least two low-flux X-ray pulsars must be adopted. Therefore, it is significant to research the pulsar TOA estimation method with low-flux pulsars. (2) The computational load of these traditional CS-based TOA estimation methods is very large due to the large size of the measurement matrix. In these traditional methods, the number of measurement vectors is on the order of hundreds, even thousands. To reduce the computational load, the size of measurement matrix must decrease greatly. However, a small-size measurement matrix means that the low accuracy for low-flux pulsars. Therefore, how to accurately and fast obtain the TOA estimation with low-flux pulsars is difficult.

In this paper, to estimate the pulsar TOA fast and accurately with low-flux pulsars, an observation range-based compressive sensing method is proposed. In traditional compressive sensing methods, the size of the measurement matrix is in direct proportion to the computational time and the estimation accuracy. Namely, it is very difficult to fast obtain high accuracy, especially for low-flux pulsars. To do this, we develop the concept of the observation range (OR), and design the OR-based measurement matrix whose size is very small. The observation range of one measurement vector is defined as the variation range of the corresponding observation values that are equal to the inner products between this measurement vector and each atom in the dictionary. Using the observation range as criterion, we can select a few effective measurement vectors to construct the OR-based measurement matrix. And then the observation range-based compressive sensing method is applied in the pulsar TOA estimation to improve its performance. Besides, the size of the dictionary and the bin number of the pulsar profile decrease to improve the real-time of the proposed method.

This paper is organized into six sections. After the introduction, the traditional CS-based pulsar TOA estimation method is reviewed in Section 2. The observation range and the OR-based CS are then proposed in Section 3 and 4, respectively. Finally, the simulation results in Section 5 demonstrate the accuracy and real-time of the proposed method. And conclusions are drawn in Section 6.

2. Review of compressive sensing-based pulsar TOA estimation

Compressive sensing has been a research hotspot in the field of signal processing. It is an efficient signal recovery framework. The CS model can be described as follows [10,11]:

$$\hat{\boldsymbol{a}} = \min \|\mathbf{a}\|_0 \text{s.t.} \mathbf{y} = \boldsymbol{\Phi x} = \boldsymbol{\Phi \Psi a} = \boldsymbol{\Theta a} \tag{1}$$

where $\|\mathbf{a}\|_0$ denotes the zero-norm. $\boldsymbol{y}$ is an M*1 observation vector. $\boldsymbol{x}$ is an unknown N*1 signal vector, which can be sparsely represented as $x = \Psi a$ in an basis Ψ (N*N). If only K ($K \ll N$) components of the sparse coefficient vector, $\boldsymbol{a}$, are non-zero, $\boldsymbol{x}$ can be defined as being K-sparse. Φ denotes an M*N matrix called measurement matrix. Θ denotes the sensing matrix, and can be expressed as:

$$\boldsymbol{\Theta} = \boldsymbol{\Phi \Psi} \tag{2}$$