国家空间科学中心在脉冲星时间噪声估计与预报研究方面取得进展

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脉冲星由于具有稳定的周期性辐射信号和近似不变的空间位置，在被发现后不久人们便意识到可将其用于航天器自主导航。由于脉冲星在X射线频段的辐射更利于探测设备的小型化，现阶段对脉冲星导航的研究主要集中在X射线脉冲星自主导航。

X射线脉冲星自主导航的基本观测量为基于脉冲星时间模型的预报脉冲到达时间与基于X射线探测器实测的测量脉冲到达时间之差，即脉冲到达时间残差。脉冲到达时间残差中含有航天器位置、速度以及时钟等误差信息，因此利用数值方法将上述误差信息估计出来，便能实现对航天器的自主导航。虽然脉冲星辐射信号具有稳定的周期，但是几乎所有脉冲星的脉冲到达时间残差中均存在低频噪声即时间噪声，该噪声会显著影响脉冲到达时间的预报精度，进而影响到X射线脉冲星自主导航精度。由于对时间噪声的认识有限，现有的研究均忽略脉冲到达时间残差中的时间噪声，因此得到的理论研究结果与真实情况差距较大。

为获得更为真实可信的研究结果，国家空间科学中心系统仿真与论证技术研究室X射线脉冲星自主导航团队邓新坪博士，前往澳大利亚联邦科学与工业研究组织国家望远镜中心（ATNF, CSIRO），在世界一流的脉冲星研究团队中进行了为期一年的访问学习。在此期间，邓新坪博士及其合作者们基于Parkes射电望远镜的真实观测数据，对脉冲到达时间残差中存在的时间噪声进行研究，并基于最大似然给出了时间噪声的估计与预报方法。

该方法能显著提高脉冲到达时间的预报精度，对于提高X射线脉冲星导航精度具有重要意义，该项成果已正式发表于英国皇家天文月刊(MNRAS)。

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（供稿：系统仿真与论证技术研究室）

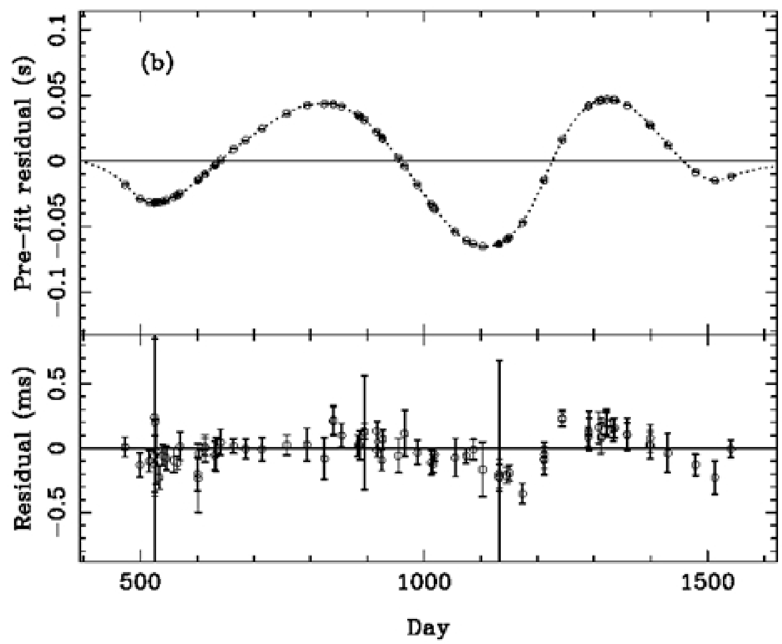

图1 基于最大似然方法对Vela脉冲星射电观测数据时间噪声进行估计与预报结果

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Optimal interpolation and prediction in pulsar timing

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ABSTRACT

For pulsar projects it is often necessary to predict the pulse phase in advance, for example when preparing for new observations. Interpolation of the pulse phase between existing measurements is also often required, for example when folding X-ray or gamma-ray observations according to the radio pulse phase. Until now these procedures have been done using various ad hoc methods. The purpose of this paper is to show how to interpolate or predict the pulse phase optimally using statistical models of the various noise processes and the phase measurement uncertainty.

Key words: methods: data analysis – pulsars: general.

1 INTRODUCTION

Pulsars are rapidly rotating neutron stars. Each rotation of a radio pulsar leads to the characteristic pulse of radiation that can be detected using a radio telescope. Because the rotation of pulsars is exceptionally stable, the time of arrival (ToA) of each pulse can be precisely predicted from a timing model that includes the motions of the pulsar and the Earth and the various propagation effects between the pulsar and the Earth. Comparing the actual pulse arrival time with the prediction of a timing model, whose parameters are adjusted using a least-squares procedure, is the essence of pulsar timing. The timing model and the least-squares procedure are implemented in software packages, e.g. TEMPO2 (Edwards, Hobbs & Manchester 2006; Hobbs, Edwards & Manchester 2006). A preliminary timing model is obtained with the discovery of the pulsar. When a series of observations have been made over a period of years, the timing model can be refined with great precision. The deviations between the actual and the predicted arrival times are known as 'timing residuals'. Ideally, these residuals would simply reflect the ToA measurement uncertainty, but in fact they will include various unmodelled effects. Residuals often exhibit slow variations which appear to be a red stochastic process, which is referred to as 'timing noise'. Timing noise may be caused by many phenomena including those intrinsic to the pulsar (e.g. Hobbs, Lyne & Kramer 2010b; Lyne et al. 2010, and references therein), effects in the interstellar medium (e.g. You et al. 2007), the interplanetary medium (You et al. 2012) or even irregularities in terrestrial time standards (Guinot & Petit 1991; Petit & Tavella 1996; Rodin 2008; Hobbs et al. 2010a).

Being able to remove the timing noise is important for numerous applications. For instance, in order for Hobbs et al. (2004) to measure accurately pulsar proper motions, it was necessary to remove timing noise without affecting any signal with a periodicity close to 1 year. This was done using the FITWAVES algorithm (described in the appendix of Hobbs et al. 2004) which fits a sequence of harmonically related sinusoids to the data, where the period of the highest frequency wave was constrained to be >1.5 years. Recent work (Coles et al. 2011) showed that improved parameter measurements could be made by obtaining and using a simple, analytic model of the power spectrum of the timing noise in order to calculate the covariance matrices of the red and white noise processes. With the covariance matrices one can find a linear transformation that whitens the observations. If this transformation is applied to both the observations and the timing model, the least-squares problem is greatly simplified. With the covariance matrices, the red timing noise can also be interpolated or predicted using a maximum likelihood estimator. It is this interpolation and prediction scheme that we will discuss in the following sections.

In order to obtain the characteristic pulse profile for a pulsar, it is necessary to sum many individual pulses during the observation. For radio observations this is often carried out 'online' by folding the incoming data stream at the known topocentric period of the pulsar. Over short data spans, this can be done with sufficient accuracy by assuming that the timing model is perfect. However, if a pulse profile is obtained from a data set that spans many months or years, then it is often necessary to model the timing noise. For instance, obtaining a pulse profile using the Large Area Telescope (LAT) on the *Fermi Gamma-ray Space Telescope* requires the gamma-ray photons to be added together according a timing model that must be valid over many years (Abdo et al. 2010). This is commonly done using a timing model from observations of the pulsar obtained with

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图2 时间噪声估计与预报论文首页