A Timing Noise Analysis Pipeline for HartRAO pulsars applied to PSR J1326-5859

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Abstract. Timing noise in long-term pulsar timing residuals is a challenge to our understanding of present pulsar models. The quest to understand on the emission mechanisms of radio pulsars has led to various key science projects ranging from the search for gravitational waves to the development of next-generation instruments for pulsar astronomy. Timing noise studies present an essential cornerstone in these projects. One possible explanation for the existence of timing noise is mode switching in the magnetosphere of the pulsar. In a long-term study we have investigated the timing noise phenomena seen in PSR J1326-5859. It was observed with the 26 m radio telescope of the Hartebeesthoek Radio Astronomical observatory (HartRAO) for several decades and exhibits a large variety of timing noise characteristics. In this paper we review the preliminary timing noise analysis pipeline used for PSR J1326-5859 which can be also used for other southern hemisphere pulsars observed with HartRAO.

1. Introduction

Pulsars can be considered as stable cosmic clocks that serve the purpose of testing fundamental theories and advancing computing technology [1]. Integrated pulses of pulsars can be used for timing purposes. However, careful inspection of the single pulses reveal a rather unstable picture regarding their emission modes [2]. Inspecting the integrated pulses and the timing residuals over a long time span (months to years) allow us to see possible signatures of mode switching [3], nulling [4], glitching [5], precession [6], timing noise [7] and the phenomenon of intermittent pulsars [1]. Anomalous pulse emission modes have unique longitudinal positions that require sophisticated observational hardware [8] and algorithms [9].

Most of these emission modes (or signatures in the residuals of the pulsar) can be linked to changes in the magnetosphere, plasma conditions and/or the pulse profile of the pulsar itself [3]. Theoretically, any changes in the magnetosphere of the pulsar also influence the spin-down ($\dot{\nu}$). Therefore, if the spin-down of the pulsar can be computed accurately over the total time span of the observed data, it will reveal the history of the spin-down and the magnetospheric conditions of the pulsar. One can then fit different models to the spin-down of the pulsar with the hope of linking the conditions of the magnetosphere (emission history) to changes in the pulse profiles. Lyne et al. [3] observed a correlation between the spin-down and pulse profile changes in several pulsars. These correlations are in the form of mode switching in the pulsar

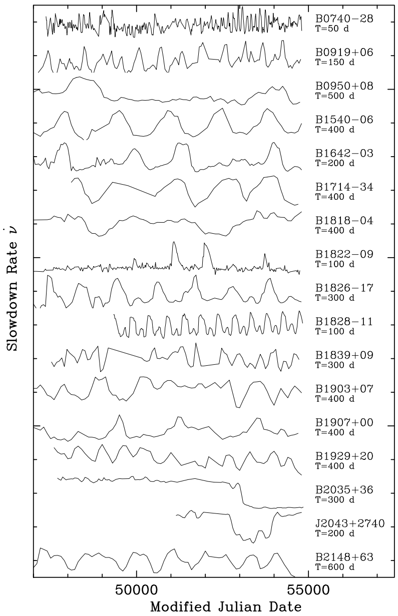

Figure 1. The spin-down history of 17 pulsars adopted from [3]. Clear mode switching between several states can be seen in the spin-down evolution of the pulsars. [3] also linked the mode switching seen in the spin-down evolution of the pulsars to pulse profile changes.

magnetosphere and could be a possible explanation for the observed timing noise signature seen in the timing residuals of several pulsars (Fig. 1).

In this paper we investigate the possible methods to link the observed timing noise signatures with possible changes in the magnetosphere and pulse profiles of the Hartebeeshoek Radio Astronomy Observatory (HartRAO) long term pulsar data sets. Timing noise analysis proves important for gravitational wave (GW) detection through the use of pulsar timing arrays, since both timing noise and GW signatures are considered to be red noise [10]. This paper is structured as follows: HartRAO Pulsar Data (Section 2), General Analysis Method (Section 3), Computing Algorithms (Section 4), Preliminary Results of spin-down Evolution of PSR J1326-5859 (Section 5) and an Discussion (Section 6).

2. HartRAO pulsar data

We investigate the timing noise signature seen in the 21 year long data set of PSR J1326-5859. This is a 478 ms [11] pulsar with a dispersion measure of $DM = 287\,\mathrm{pc\,cm^{-3}}$ [12] and an average spin-down of $-1.415 \times 10^{-14}\ \mathrm{s^{-2}}$ [13]. The data contains both 18cm and 13cm observations that were performed with the 26m HartRAO radio telescope. Timing of PSR J1326-5859 was done with the help of the packages TEMPO2 and PSRCHIVE [10,14]. Each time of arrival (and subsequently every residual) was produced via single polarization observations with an integration time of 20 minutes (Fig. 2).

3. General method of analysis

Timing residuals are produced by comparing the observed times of arrival (TOA) to the predicted ones, this process can be done with a combination of software: DSPSR (folding of raw data) [15], PSRCHIVE (manipulating of folded data) and TEMPO2 (timing analysis). Raw data are folded according to a pulsar ephemeris and the integrated pulse is used as a standard pulse to determine the TOA. A timing model is then fitted to the list of TOA and factors that are not

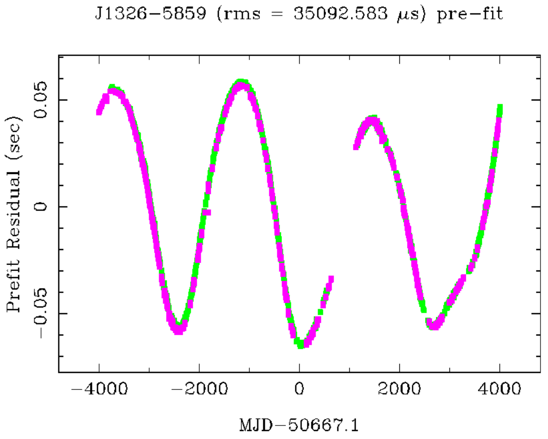

Figure 2. Timing residuals of J1326-5859 showing a timing noise signature that is quasi-periodic. The break in the residuals was due to telescope maintenance. Purple and green points represent observations at 13cm and 18cm.

predicted in the model will produce a unique signature in the residuals. In PSR J1326-5859 the signature is in the form of long time scale quasi-periodic timing noise.

When trying to connect the observed timing noise signature (or residuals) to the spin-down evolution of the pulsar, the immediate complexity that arises is that of computing the second derivative of the signature. This is done by reconstructing a function (F) that fits the residual signature. If the function F is not fitted in an accurate way, then the second derivative ($\ddot{F}$) will resemble false history of the spin-down of the pulsar. Any behaviour that is not considered as normal mode of emission, will be reflected in the spin-down history, like for example: glitches, mode switching, encounters with secondary masses and nulling. In the next section we investigate the possible methods to reconstruct the function F.

[16] developed novel methods and techniques to correlate the short term variability seen in both the pulsar spin-down and pulse profile variations by implementing Gaussian processes. We closely follow their recipe for determining the spin-down evolution using Gaussian process reconstructions of the residuals.

4. Algorithms

There are several methods to compute the spin-down evolution by using the timing residuals of a pulsar. One such method is to use the glitch plugin provided with the TEMPO2 code [10]. This plugin accepts hand-selected regions of residuals and computes the spin-down for each of these regions. However, the second derivative ($\ddot{F}$) is sensitive to the size of the chosen regions. Consequently, this method is restricted by the prerequisites of knowing what type of emission history to look for in the spin-down history (such as mode switching).

Another popular method to reconstruct the function F is the use of Gaussian fits. The main benefit of this fitting process is that the sizes of regions are optimized and the error in the reconstructed function decreases if the residuals are locally predictable. The Gaussian fitting process requires no assumptions of whether F is related to a specific model. The value of F when evaluated at any point x is a Gaussian random variable with mean $\mu(x)$ and variance $Var(x)$. The function values at a point x and some other point x' are related by the covariant function, $k(x, x')$. Thus, the latter indirectly implies that fitting a semi-predictable signature will produce a good fit to the residuals. The GaPP (Gaussian process in python) code [17] is

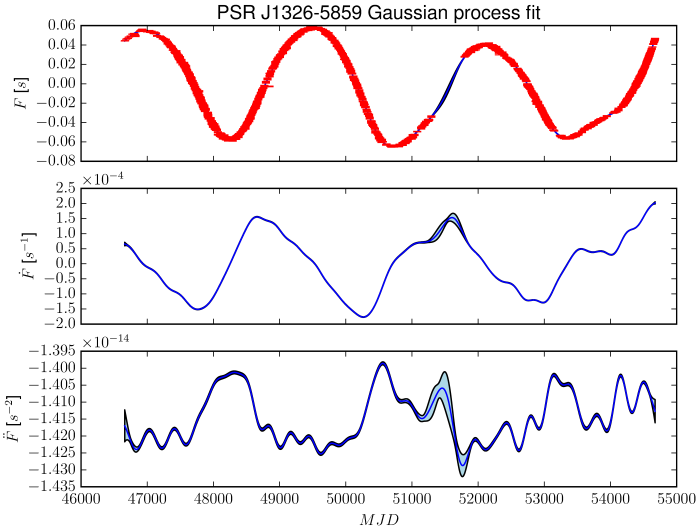

Figure 3. Spin-down evolution of PSR J1326-5859. Upper panel: Fitted timing noise residual. Middle Panel: Spin-down ($\dot{F}$). Lower Panel: Spin-down evolution ($\ddot{F}$). Errors of the fit are indicated by the shaded regions. The scaling of $\ddot{F}$ arises through the process of partial derivatives with time, see [16].

used to perform the Guassian process regression on the residuals. The GaPP is used for the reconstruction of dark energy data.

After computing the spin-down history of the pulsar, one can look at the history to identify certain signatures worth investigating and link that to any pulse profile changes. This can be done by a self developed python code that loads, fits and cleans the integrated pulses that were produced for each observation. One can afterwards plot, manipulate or stack pulses in certain regions of time. The only limitation of this process is the quality of the pulse profile itself.

5. Preliminary spin-down evolution of PSR J1326-5859

A list of residuals and TOA errors can be produced for the total data set using the TEMPO2 code. These residuals and TOA errors serve as input for the GaPP code. The GaPP code initializes the Gaussian process with initial parameters for the mean and the variance according a kernel:

$$k(x, x') = \sigma_f^2 \exp\left(-\frac{(x - x')^2}{2\ell^2}\right). \tag{1}$$

One important part of the process is the optimization of the step length (l). Lastly follow the training of the hyper-parameters, reconstruction of the function F and its second derivative $\ddot{F}$ (Fig. 3). The parameters for the Gaussian process were optimized to be $l = 232$ days and $\sigma_f = 2.8 \times 10^{-2}$.

We used the pipeline to stack pulses in two temporal regions ($48000 - 48500$ MJD and $49000 - 49500$ MJD) of different spin-down values (Fig. 4). A constant number of pulses were added in both regions to ensure a consistent S/N. In this paper the stacking was done for only the first part of the data set. The investigation of the second half will be left for future work.

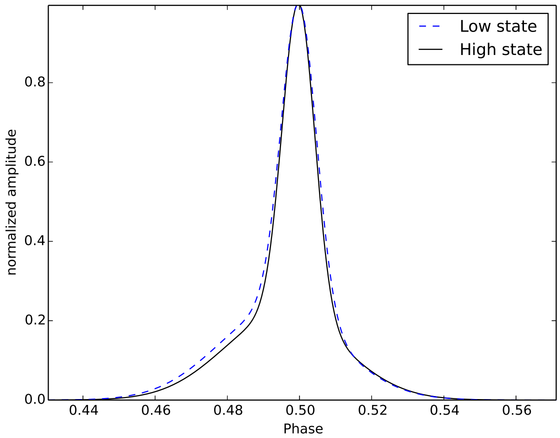

Figure 4. Stacking of 1644 MHz integrated pulses of PSR J1326-5859 in two different regions. The high and low state correspond to the largest and lowest spin-down observed in PSR J1326-5859.

6. Discussion

Switching in the spin-down evolution of PSR J1326-5859 is clearly visible (Fig. 3). The observed switching reveals itself as changing between two extreme states in the first half of the data set and becomes less predictable in second half. The stacking of pulses (of equal stacking length) in different states of the spin-down evolution proves to be insufficient for correlation searches. Thus, correlating the observed spin-down evolution to the pulse profiles, will require more sophisticated techniques that will be done in future work. In addition to the switching, we also observe an increase in the mean of the spin-down from MJD = 53000. Spin-down activity in the second half of the data becomes less clear. Similar results can be seen in the spin-down evolution of several pulsars reported in [3] (see Fig. 1-3 in their paper) and [16]. Recently a numerical model was developed for the evolution of non-spherical pulsar parameters (period and inclination angle) with plasma filled magnetospheres [18]. This MHD model was used to fit the observed residuals of PSR B1828-11 and the Crab pulsar according to a precession model. As future work we will be fitting different models to the spin-down evolution of PSR J1326-5859 (especially the second part of the data set) to test possible signatures such as MHD precession or encounters with massive objects.

7. Acknowledgments

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References

[1] Lorimer D R 2005 *Handbook of pulsar astronomy* (Cambridge, UK New York: Cambridge University Press) ISBN 978-0-521-82823-9

[2] Osłowski S, van Straten W, Hobbs G B, Bailes M and Demorest P 2011 *Monthly Notices of the Royal Astronomical Society* **418** 1258–1271 (*Preprint* `1108.0812`)

[3] Lyne A, Hobbs G, Kramer M, Stairs I and Stappers B 2010 *Science* **329** 408–412 (*Preprint* `1006.5184`)

[4] Backer D C 1970 *Nature* **228** 42–43

[5] Lyne A G, Smith F G and Pritchard R S 1992 *Nature* **359** 706–707

[6] Frescura F and Flanagan C S 2003 *Radio Pulsars* (*Astronomical Society of the Pacific Conference Series* vol 302) ed Bailes M, Nice D J and Thorsett S E p 237

[7] Chukwude A E 2007 *Chinese Journal of Astronomy and Astrophysics* **7** 521–530

[8] Karuppusamy R, Stappers B and van Straten W 2008 *Publications of the Astronomical Society of the Pacific* **120** 191–202

[9] Jones D I 2012 *Monthly Notices of the Royal Astronomical Society* **420** 2325–2338 (*Preprint* `http://mnras.oxfordjournals.org/content/420/3/2325.full.pdf+html`) URL `http://mnras.oxfordjournals.org/content/420/3/2325.abstract`

[10] Hobbs G, Edwards R and Manchester R 2006 *Chinese Journal of Astronomy and Astrophysics Supplement* **6** 020000–192

[11] D'Alessandro F, McCulloch P M, King E A, Hamilton P A and McConnell D 1993 *Monthly Notices of the Royal Astronomical Society* **261** 883–894

[12] Hobbs G, Faulkner A, Stairs I H, Camilo F, Manchester R N, Lyne A G, Kramer M, D'Amico N, Kaspi V M, Possenti A, McLaughlin M A, Lorimer D R, Burgay M, Joshi B C and Crawford F 2004 *Monthly Notices of the Royal Astronomical Society* **352** 1439–1472 (*Preprint* `astro-ph/0405364`)

[13] Manchester R N, Hobbs G B, Teoh A and Hobbs M 2005 *VizieR Online Data Catalog* **7245**

[14] Hotan A W, van Straten W and Manchester R N 2004 *Publications of the Astronomical Society of Australia* **21** 302–309 (*Preprint* `astro-ph/0404549`)

[15] van Straten W and Bailes M 2010 (*Preprint* `1010.006`)

[16] Brook P R, Karastergiou A, Johnston S, Kerr M, Shannon R M and Roberts S J 2016 *Monthly Notices of the Royal Astronomical Society* **456** 1374–1393 (*Preprint* `1511.05481`)

[17] Seikel M, Clarkson C and Smith M 2012 *Journal of Cosmology and Astroparticle Physics* **6** 36 (*Preprint* `1204.2832`)

[18] Arzamasskiy L, Philippov A and Tchekhovskoy A 2015 *ArXiv e-prints,1504.06626*