PROCEEDINGS OF SCIENCE

An automated and interactive tool for gamma-ray pulsar monitoring and glitch detection

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The *Fermi* Large Area Telescope is enabling a revolution in pulsar physics, having detected more than 300 gamma-ray pulsars. *Fermi*-LAT pulsars are typically highly energetic, and hence they are very likely to show *glitches*. Moreover, a significant fraction of *Fermi*-LAT pulsars are not detected by radio telescopes. Among radio-quiet pulsars there's the peculiar example of PSR J2021+4026, which is variable on a time scale of a few years. Hence, a monitoring infrastructure is required in order to systematically study the timing evolution of gamma-ray pulsars. For this purpose we are developing GLIMPSE, an analysis pipeline for *Fermi*-LAT pulsars, based on Python and on the official Fermitools. This pipeline periodically runs data reduction and periodicity tests for each gamma-ray pulsar in the catalog, then performs a glitch search with different approaches. The computational time is reduced thanks to an optimized usage of memory, which renders the tool suitable for a systematic timing analysis of Fermi pulsars. Moreover, a web application allows users to visualize the results and to interactively manage analysis setups. Here we present a preview of the infrastructure, and we discuss future applications in the multi-messenger framework, focusing on searches for gravitational waves from pulsars.

**** 27th European Cosmic Ray Symposium - ECRS ****
**** 25-29 July 2022 ****
**** Nijmegen, the Netherlands ****

[*] Speaker

PoS(ECRS)111

1. Introduction

Pulsar astronomy was born half a century ago with the discovery of the first pulsating radio source [1]. This event triggered a prolific search throughout the following decades, and today ~ 3000 pulsars have been observed at radio wavelengths [2]. Later, multiwavelength pulsar emission has also been observed spanning the whole electromagnetic spectrum. Today, the *Fermi* Large Area Telescope (LAT) [3], launched in 2008 and still in operation, is enabling a revolution in gamma-ray pulsar astrophysics, with ~300 gamma-ray pulsars discovered so far[1]. Pulsars are also potential emitters of continuous gravitational waves (GWs), and thus promising multi-messenger sources [4].

Although pulsars are know to be very precise astrophysical clocks, they undergo a *spin-down* evolution, with the rotational frequency slowly decreasing in time. Occasionally, a pulsar may deviate from the regular spin-down regime and undergo a sudden increase in frequency. These rapid changes are usually followed by a recovery phase that brings the frequency evolution back to the normal state. Such events are called *glitches* and occur preferentially in young, energetic pulsars with different rates [5]. Pulsar timing techniques have the goal of producing a model that accounts for every rotation in the pulsar. In order to do this, a model should take glitches into account. Unfortunately, gamma-ray pulsars are affected by their intrinsically low photon flux, which requires long integration times. This dramatically limits the precision on timing parameters whenever a radio timing solution is not available. Therefore, glitches in radio-quiet pulsars can only be characterized with a limited resolution [6]. Moreover, pulsar glitches are considered as possible emitters of detectable GWs [7, 8] and probes of neutron star (NS) interiors [9]. Due to the large uncertainties in the glitch parameters, it is currently difficult to perform targeted searches for transient GW signals [10] on radio-quiet gamma-ray pulsars.

In an attempt to overcome these limitations, we have developed the Glitch Monitoring and Periodicity Search (GLIMPSE) toolkit, a Python pipeline for the analysis of gamma-ray pulsars. The main features of this project are: a timing analysis algorithm for high-energy pulsars based on Bayesian parameter estimation; an automated and interactive monitoring software for *Fermi*-LAT pulsars. Here we provide an overview on the GLIMPSE analysis pipeline. The outline of the paper is as follows. In Section 2 we describe the main analysis steps, i.e. data reduction, periodicity monitoring and glitch parameter estimation. Section 3 describes the multi-messenger applications of our work. In Section 4 we draw conclusions and discuss future prospects.

2. The GLIMPSE package

2.1 Data reduction

GLIMPSE comes with a script that automatically performs the full data reduction procedure for each entry in the *Fermi*-LAT pulsar catalog. *Fermi*-LAT data are downloaded from the official Fermi Science Support Center[2] (FSSC) in the form of weekly FITS fits. Data reduction is performed using the official *Fermi*-LAT software suite, *Fermitools*[3]. For a chosen *Fermi*-LAT pulsar, GLIMPSE

[1]Public list of *Fermi*-LAT pulsars: https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars

[2]https://fermi.gsfc.nasa.gov/ssc/

[3]https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/

uses the `gtselect` tool to select photons within 10° of the source, with energies in the range 100 MeV - 300 GeV and zenith angles $\theta_z < 90°$. Then, the `gtmktime` tool is run to apply a filter based on the data reconstruction quality and the status of the detector. Finally, the `gtbary` tool is used to apply corrections to the photon arrival times and measure them in the Solar System barycenter (SSB). This is the standard data preparation procedure for the reduction of *Fermi*-LAT pulsars.

Further data selection can also be performed by the user with dedicated Python classes that manage data through *Pandas*[4] `DataFrames`. GLIMPSE contains different data selection methods: a *cookie cutter*, that selects a circular region around the center of the pulsar position; a *power-law cutter*, that allows the radius to depend on the energy as a power-law function; a *PSF-like cutter*, that uses the energy-dependent point spread function of the LAT. GLIMPSE also allows the usage of photon probabilities, which can be computed using a gamma-ray spectral model of the pulsar.

2.2 Quick periodicity monitoring

GLIMPSE includes a method to perform a periodicity scan based on H-test [11]. We approximate the timing model $\phi(t)$ as a Taylor series,

$$\phi(t) = \phi_0 + \sum_{k=0}^{k_{\max}} \frac{1}{k!} f_k (t - t_0)^{k+1} , \tag{1}$$

with $k_{\max} = 1$ and $\Phi_0 = 0$. Then, for each photon arrival time t_i we take the fractional part, $\varphi_i = \mathrm{frac}\,[\phi(t_i)]$. The H variable is defined by the following equations:

$$Z_m^2 = \frac{2}{N} \sum_{k=1}^{m} \Big[\big(\sum_{i=1}^{N} \cos\, 2\pi k \varphi_i\big)^2 + \big(\sum_{i=1}^{N} \sin\, 2\pi k \varphi_i\big)^2 \Big] , \tag{2}$$

$$H = \max_{1 \le m \le 20} (Z_m^2 - 4m + 4), \tag{3}$$

with N being the total number of photon. We define a $N_0 \times N_1$ grid in the $f_0 - f_1$ parameter space within some chosen boundaries. The resolution of the grid, $\Delta f_0 \times \Delta f_1$, is determined by the Nyquist limit, and therefore on the observation time T: in particular, $\Delta f_0 \sim 1/T$ and $\Delta f_1 \sim 1/T^2$. H is calculated for each point of the grid, and the optimal solution is the point that maximizes H.

The strength of this tool is its computational speed. An algorithm that relies on loops would require $O(20 \times N \times N_0 \times N_1)$ iterations to perform one scan, and it may become computationally prohibitive for large grids. Instead, our implementation is based on *NumPy*[5] multi-dimensional arrays. This dramatically reduces the computational time, as NumPy deals with operations between arrays by means of vectorization. The typical computational time on an average laptop varies from few to tens of seconds, depending on the number of arrival times and on the size of the grid. The speed of this tool allows us to rapidly produce time series of f_0 and f_1 covering the whole *Fermi*-LAT mission. As a preliminary step, GLIMPSE iteratively runs H-tests for different choices of T and different selection methods to find the best combination of cuts. The combination that maximizes H is then used to produce the time series. The full procedure is included in a script.

[4] https://pandas.pydata.org/docs/
[5] https://numpy.org/doc/stable/

As an example, we tested the tool on PSR J0007+7303 [12], a 315 ms pulsar that can be seen within the shell of the CTA1 supernova remnant. It is one of the first pulsars discovered by *Fermi*-LAT and it is still radio-quiet. Our choice is motivated by the fact that PSR J0007+7303 is a young gamma-ray pulsar, and it has undergone 3 significant glitches during the first 7 years of mission [13]. Hence, it falls into the group of pulsars that we would be particularly interested in monitoring. We provide the output of the test in Figure 1.

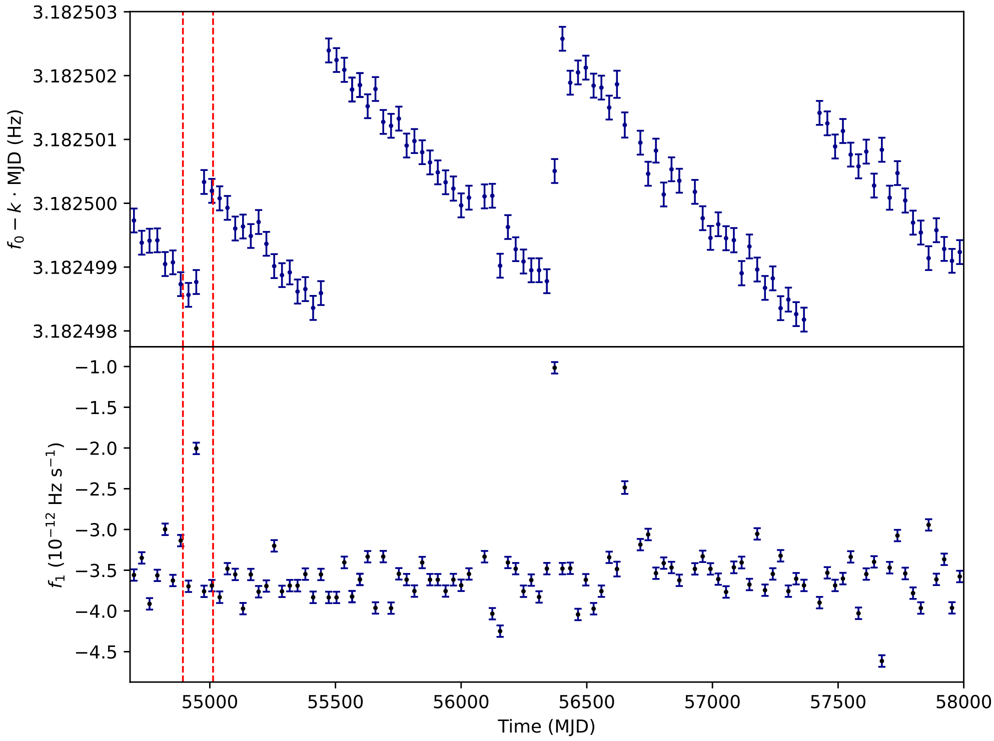

Figure 1: Optimal frequency (*top*) and spin-down rate (*bottom*) of PSR J0007+7303 as a function of time. Each errorbar is the result of an H test on a 30-day time interval. Photons were selected within a radius of 1.8° at energies $E > 200$ MeV. A linear term was subtracted from the frequency, with $k = 3.1 \times 10^{-7}$ Hz day^{-1}, to enhance the frequency changes. The red dashed lines indicate the boundaries of the time interval used for the Bayesian parameter estimation.

2.3 Bayesian glitch parameter estimation

GLIMPSE allows to perform Bayesian parameter estimation to characterize pulsar glitches. Our framework is based on the search for periodic signals of unknown shape for photon counting experiments [14]. The main advantage of this approach is that of being an unbinned analysis, i.e. no time binning is required. This grants a better resolution on critical parameters such as the epoch of the glitch.

The initialization of the Bayesian analysis requires a timing model. The base model must include a spin-down evolution term, as in Equation 1. To model glitches we allow for permanent changes in phase ($\Delta\Phi$), frequency (Δf_p) and spin-down rate ($\dot{f}_p$), and for transient changes in the frequency (Δf_t) with an exponential recovery over a timescale τ. These terms can be summarized as

$$\Delta\phi(t) = \Delta\Phi + \Delta f_p(t - t_g) + \frac{1}{2}\Delta\dot{f}_p(t - t_g)^2 + \Delta f_t \tau\left[1 - \exp\left(-\frac{t - t_g}{\tau}\right)\right], \tag{4}$$

where we t_g indicates the glitch epoch. The model can be defined including any combination of these terms, and each parameter can be fixed or set free to vary.

We model the pulse profile as a piecewise constant function, which is defined by m different constant values in distinct phase bins. This defines a class of models that is uniquely parameterized by the number of bins m. Although in principle one could treat m as a free parameter, we choose to keep it fixed. The optimal number of bins, i.e. the one that produces the most significant pulsations at fixed timing parameters, is obtained by comparing models with different choices of m to a constant model ($m = 1$). The odds ratio is defined as

$$O_{m1}(\boldsymbol{\theta}) = \frac{1}{m_{\max} - 1}\binom{N + m + 1}{N}^{-1}\frac{m^N}{W_m(\boldsymbol{\theta})}, \tag{5}$$

where $W_m(\boldsymbol{\theta})$ is the multiplicity of the binned distribution of N events,

$$W_m(\boldsymbol{\theta}) = \frac{N!}{n_1!n_2!\dots n_m!}, \tag{6}$$

and $\boldsymbol{\theta}$ is the full set of parameters of the timing model. The optimal number of bins is the one that maximizes O_{m1} between 2 and $m_{\max}$.

Since we would like to apply the algorithm to the full catalog of *Fermi*-LAT pulsars, we need the sampling algorithm to be automatic. Among the large number of choices, we tested an Adaptive Metropolis Hastings Monte Carlo [15]. Unlike its traditional version, this does not require a fine tuning of the transitional kernel of the random walk. Instead, it is based on sequentially updating the scale of the transitional kernel to achieve the convergence of the acceptance rate to a theoretical asymptotic value. This reduces the necessary interaction of the user with the algorithm, at the cost of a longer convergence time. We tested this algorithm on the PSR J0007+7303 glitch at MJD 54953, and we report the results in Figure 2.

3. Pulsars glitches and multi-messenger astrophysics

Pulsar glitches are potential sources of transient GWs. So far, searches have focused on two different type of signals: short-term burst-like GWs concurrent with spin-up events [16]; long-term transient continuous waves occurring in the post-glitch phase [17]. Both types of signals depend on the pulsar timing parameters and on the distance, and they require assumptions on NS interiors. For example, the amplitude of post-glitch transients [8] can be approximated as

$$h_0 = 6 \times 10^{-26}\left(\frac{\Delta\Omega/\Omega}{10^{-4}}\right)\left(\frac{f}{10^2\ \mathrm{Hz}}\right)^3\left(\frac{D}{1\ \mathrm{kpc}}\right)^{-1}, \tag{7}$$

where D is the distance of the source and the change in angular velocity, $\Delta\Omega/\Omega$, is related to $\Delta f/f$ through models for NS glitches. Unfortunately, the upper limits on this amplitude are still below the sensitivity of the current GW detectors. The current generation of interferometers are only expected to detect glitches with $\Delta f/f \gtrsim 10^{-5}$ from close pulsars (D ~ 10^2 pc) [18]. Future interferometers,

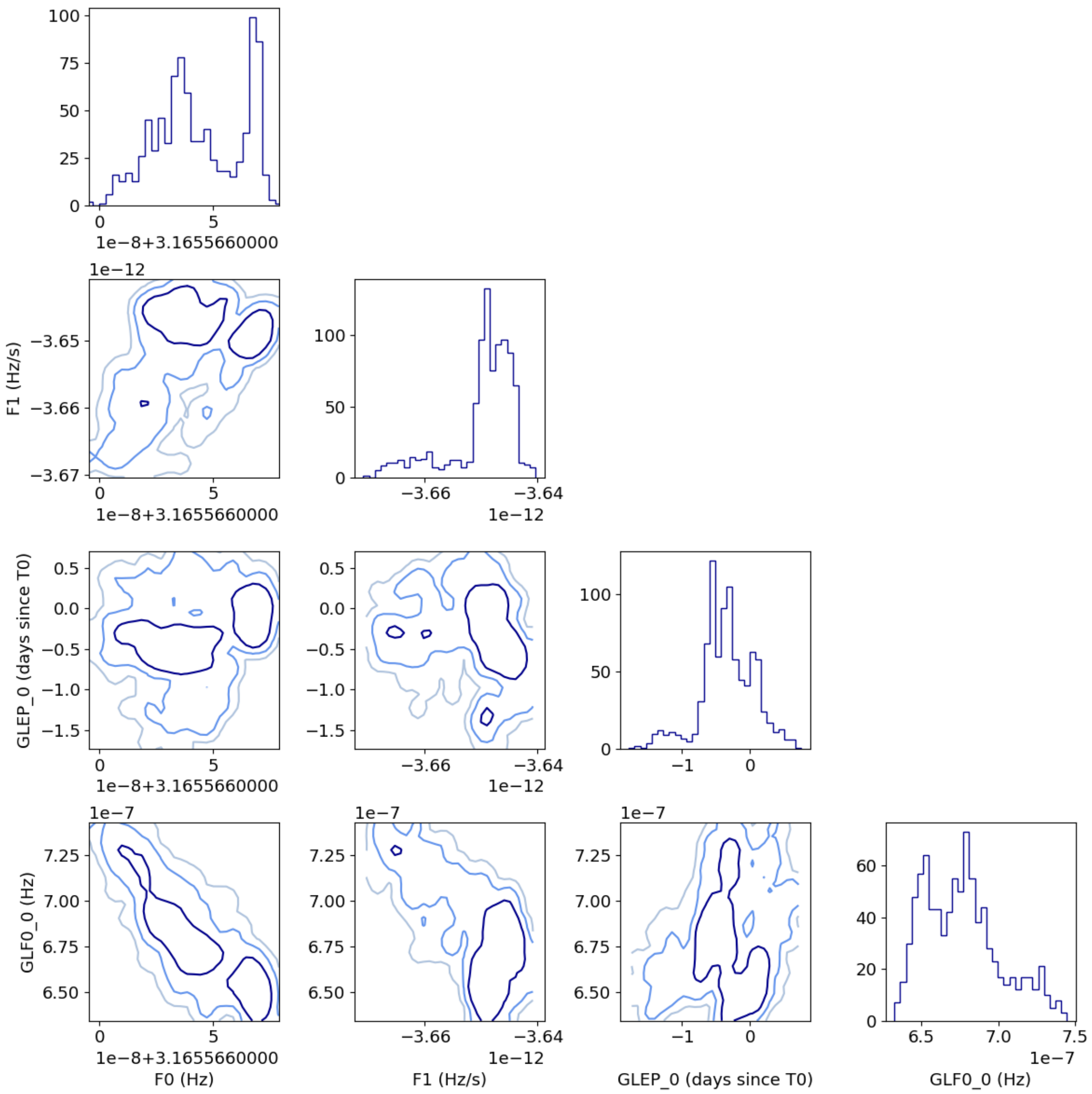

Figure 2: Triangle plot showing the sampled posterior distribution for the PSR J0007+7303 at MJD 54953. The model includes a Taylor series up to f_1 and a permanent change in f_0. We modeled the pulse profile as a piecewise constant function with $m = 11$. We included photons within 50 days before and after the glitch epoch. 1σ, 2σ and 3σ credibility contours are reported as shaded blue lines. The distribution was marginalized over the pulse profile parameters.

such as the Einstein Telescope, are expected to have a better sensitivity and hence a larger detection probability.

Targeted and narrow-band searches for transient GWs have only been performed on radio pulsars using LIGO-Virgo data. We believe the number of targets suitable for GW searches could increase if one were able to produce precise pulsar timing solutions for radio-quiet gamma-ray pulsars. Our tool includes an interactive web app for data visualization. We will include tables with the estimated timing parameters and the inferred GW amplitudes for each glitch in *Fermi*-LAT pulsars, and we plan to make our results public. Therefore, we think our analysis will be of use in multi-messenger astrophysics. In particular, it could be a reference for planning future targeted GW searches with the next generation of GW interferometers.

4. Conclusions and future prospects

We reported on the development of GLIMPSE, a tool for the timing monitoring and the characterization of glitches in *Fermi*-LAT pulsars. Our preliminary analysis of PSR J0007+7303 shows that GLIMPSE is able to sample the parameter space for pulsar glitches with good resolution. Unfortunately, the complexity of the posterior distribution is evident, with strong correlations between the parameters and the presence of multiple degenerate peaks. The most straight-forward approach to reduce correlations would be to increase the time window of the observation. This would require the addition of more terms in the spin-down component of the model, hence increasing the number of free parameters. Anyway, this solution is not suitable for pulsars with frequent glitches, such as J0007+7303, as multiple events could occur within the observation. The results also highlight the fact that a Metropolis Hastings algorithm is not the best choice to sample very complex distributions. Therefore, we plan to test other algorithms that may be better able to sample the parameter space uniformly. Finally, our goal will be to run the tool on simulated pulsar data, in order to test the detection capabilities of the algorithm.

Acknowledgments

The *Fermi*-LAT Collaboration acknowledges support for LAT development, operation and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. This work performed in part under DOE Contract DE-AC02-76SF00515.

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