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

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Introduction

The *Fermi* Large Area Telescope (LAT) is enabling a revolution in pulsar physics, having detected almost 300 gamma-ray pulsars. Many *Fermi* pulsars show glitches in one or more timing parameters. Therefore, we could benefit of a monitoring infrastructure that systematically studies the timing evolution of gamma-ray pulsars and detects glitches. For this purpose we are developing the Automated Pulsar Periodicity Looker, a Python-based analysis infrastructure for *Fermi*-LAT pulsars. Here we present the main features of the tool and show the results of a preliminary test.

Data management

The project contains tools used to periodically download *Fermi*-LAT data from the Fermi Science Support Center [1]. A script produces an index containing the analysis setups for a list of pulsars. Information about pulsars can be entered manually or imported as a catalog in FITS format. Data reduction and photon barycentering are automatically run for each pulsar in the index in order to keep the analysis up to date.

Periodicity monitoring

Pulsar periodicity is performed with a traditional method based on the H statistics [2]. Given a set of photon arrival times t_i and some test values for the rotational frequency and its derivatives at a chosen epoch t_0, the calculation of the H variable is performed with the following equations:

$$\phi_i = f_0(t_i - t_0) + \frac{1}{2!}f_1(t_i - t_0)^2 + \frac{1}{3!}f_2(t_i - t_0)^3 + \dots \quad (1)$$

$$Z_m^2 = \frac{2}{n}\sum_{k=1}^{m}\Big[(\sum_{i=1}^{n}\cos\, k\phi_i)^2 + (\sum_{i=1}^{n}\sin\, k\phi_i)^2\Big] \quad (2)$$

$$H = \max_{1\leq m\leq 20}(Z_m^2 - 4m + 4) \quad (3)$$

The maximum value of H over a grid in the multi-dimensional parameter space gives optimal values of the frequency and its derivatives. The test is performed on a list of short time windows covering the whole data set. The result is a time series representing optimal values of the frequency and its derivatives as a function of time.

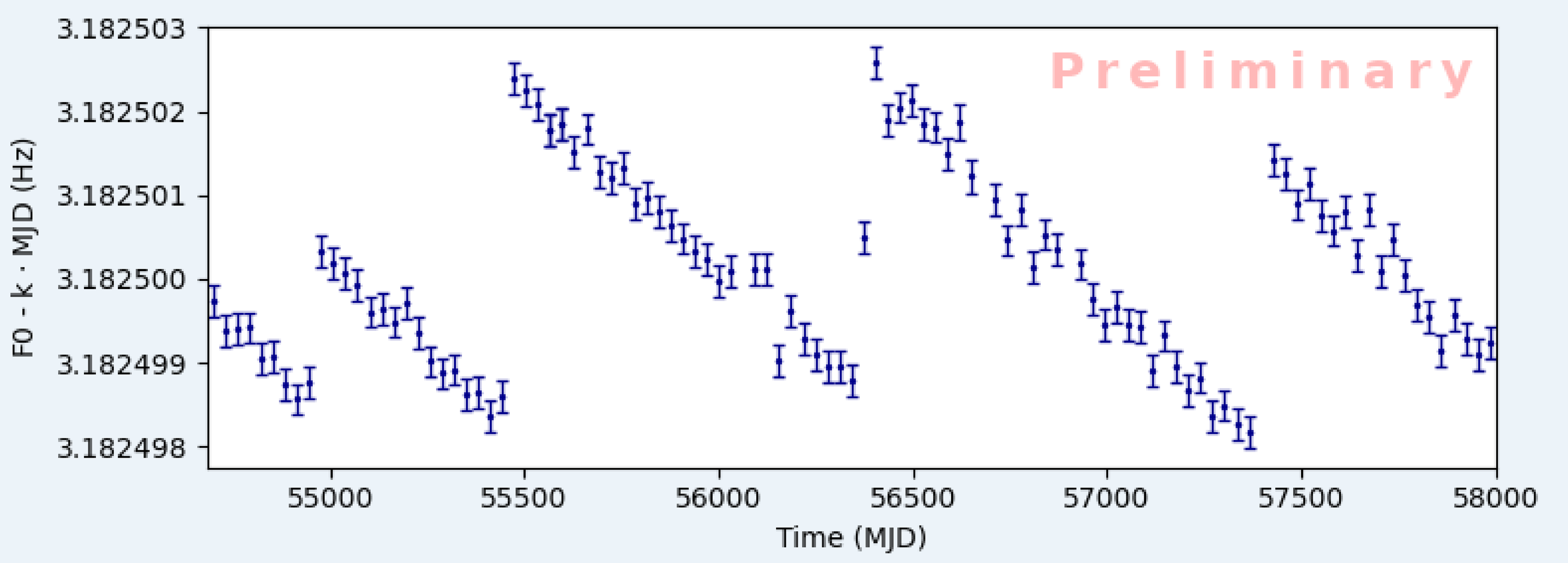

Fig. 1 Optimal frequency of the young radio-quiet PSR J0007+7303 as a function of time. Each errorbar is the result of an H test on a 30-day time interval. Photons were selected within a radius of 1.5° at energies > 200 MeV. A linear term was subtracted, with $k = 3.1 \cdot 10^{-7}$ Hz day^{-1}, to enhance the frequency changes.

Since iterating over the parameter space may require a long time, our tool performs the calculation on the whole grid simultaneously using numpy multi-dimensional arrays. This drastically reduces the computational time (from a few seconds to one minute, depending on the machine computational resources) at the expense of higher memory usage.
We introduced specific functions for data reduction that allow the selection radius to depend on both photon energy and data quality. The optimal time window and spatial cuts are automatically estimated by maximizing significance of the H test.

Acknowledgements

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Bayesian glitch search

Due to the low count rate typical of gamma-ray observations, traditional methods for timing model optimization are usually unable to estimate glitch parameter with good precision. Attempting to overcome this limitation, we are developing a new analysis pipeline based on Bayesian parameter estimation.
The input is a set of unbinned barycentered *Fermi*-LAT photon times. The analysis framework assumes a periodic signal of unknown shape where the pulse profile is modeled with a stepwise function [3]. We include different glitch models, allowing permanent or transient changes in one or more timing parameters [4]:

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

The estimation is performed with an adaptive Metropolis-Hastings sampling algorithm, that performs an online scaling of the proposal distribution based on the empirical acceptance rate [5]. Therefore, the analysis does not require a fine preliminary tuning.
Tests on *Fermi*-LAT data proved that the algorithm is able to estimate the frequency and its derivative with good precision. Tests also show that sampling the posterior distribution allows to detect sharp features in the parameter space that would not otherwise be observable. Anyway, the accuracy is limited by correlations between glitch parameters that may be removed introducing different parameterizations.

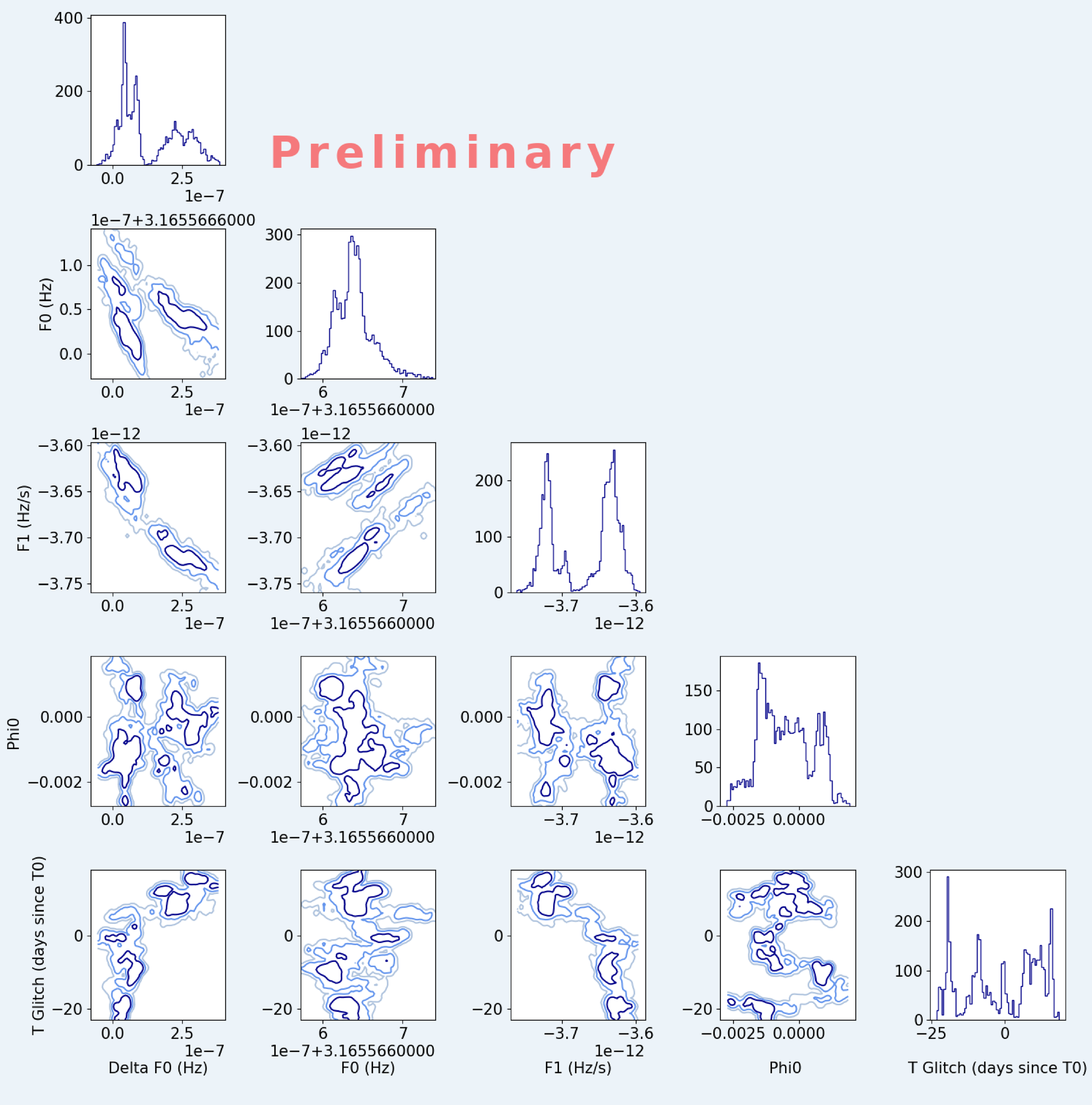

Fig. 2 Triangle plot showing the posterior distribution for the PSR J0007+7303 glitch at MJD 54953. The sample was obtained using 100 days of data around MJD 54953. We applied the same spatial cuts reported in Fig. 1. The model includes a linear spin-down evolution with a permanent change in f_0.

Conclusions

The periodicity monitoring tool already shows good performance, while the Bayesian parameter estimation needs to be refined and optimized. The first step will be running the analysis to precisely characterize high significance glitches in well known pulsars. We then intend to generate simulated pulsar signals that include timing noise and test the glitch detection capabilities of our algorithm.
Our tool may also be used as a reference in future searches for transient gravitational waves. In fact, it could produce parameter estimates for models of gravitational wave emission from pulsar glitches. Therefore, the infrastructure may become a powerful resource for pulsar physics and multi-messenger astrophysics.

References

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