Tempo2 Tutorial - MeerKAT Pulsar Timing Workshop

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September 17, 2021

Abstract

In this tutorial, we will learn to use the TEMPO2 software to analyse timing residuals of a pulsar. TEMPO2 is a high-precision pulsar timing software and provides a generic set of tools to analyse and visualise pulsar timing residuals. For background reading, please refer to Hobbs et al. (2006). The software repository is hosted here:
`https://bitbucket.org/psrsoft/tempo2/src/master/`

1 Introduction

Pulsars spin with remarkable rotational stability, which allows us to use them as highly accurate clocks, distributed across the galaxy. Pulsar timing is a powerful technique which has enabled tests of gravity, plasma physics and nuclear physics – extreme conditions that are not achievable in Earth-based laboratories.

We have learnt the basics of pulsar data analysis in the previous exercises. Here we will be analysing pulsar timing residuals. Pulsar timing residuals show us how well we are able to predict the arrival times of a pulsar's pulses.

All the relevant files for this exercise will be in the **PulsarTiming** directory.

2 Pulsar ephemerides

We learnt that a time of arrival (TOA) is computed by comparing the observed pulse profile with a noise-free reference template. This process is called 'template matching'.

These arrival times are then compared with the predicted arrival times to generate the timing residuals for a pulsar. A pulsar model is used to predict arrival times and as our understanding of the pulsar improves, so does the prediction of the arrival times. Unmodelled or imprecise parameters produce structures in the timing residuals providing insights into missing parameters in the model.

A pulsar model consists of several parameters that describe the pulsar system. Take a look at the *J0835-4510.par* in the **Part1** directory.

The first set of parameters as shown below provide information on the position of the pulsar on the sky (RAJ, DECJ), it's rotational frequency (F0), the rate at which it slows down due to dissipation of energy (F1), higher-order frequency derivatives (like F2) and the dispersion measure of the pulsar (DM). If the pulsar is in a binary system, then there are additional parameters that describe the orbital properties.

The first column is the parameter, the second column is the value, the third column describes if the parameter is fitted for in TEMPO2 and the final column provides the uncertainty in the measurement of that parameter.

```
PSRJ  J0835-4510
RAJ   08:35:20.5554429         1  0.00000479120352431585
DECJ  -45:10:33.38894           1  0.00005350998986295085
F0    11.188233045353667218     1  3.5161673561672063491e-13
F1    -1.5463446874179076243e-11 1  7.4410865651184824406e-21
F2    9.1268920254487347502e-22 1  7.0906746758831428687e-29
DM    67.844558268051564053
```

The rest of the parameters in the ephemeris file are relevant to various aspects of the fitting or clock conversions which are important but beyond the scope of this exercise.

If you have a question about a particular parameter in the ephemeris file, please ask.

3 Pulsar times of arrival

In the previous PSRCHIVE exercise, we generated arrival times by cross-correlating the pulse profile with a template. This was stored as a *.tim* file. There is a similar file in the **Part1** directory that lists the arrival times: *J0835-4510.tim.*

This file records the arrival time of every pulse profile of the pulsar along with information about the recording system, the length of each observation, the backend etc. Read each column of this file carefully and if you have any questions, please ask.

4 Using tempo2

Once we have the generated the arrival times and have an initial model (*.par* file) for the pulsar, we can compute the timing residuals using TEMPO2.

To run tempo2,

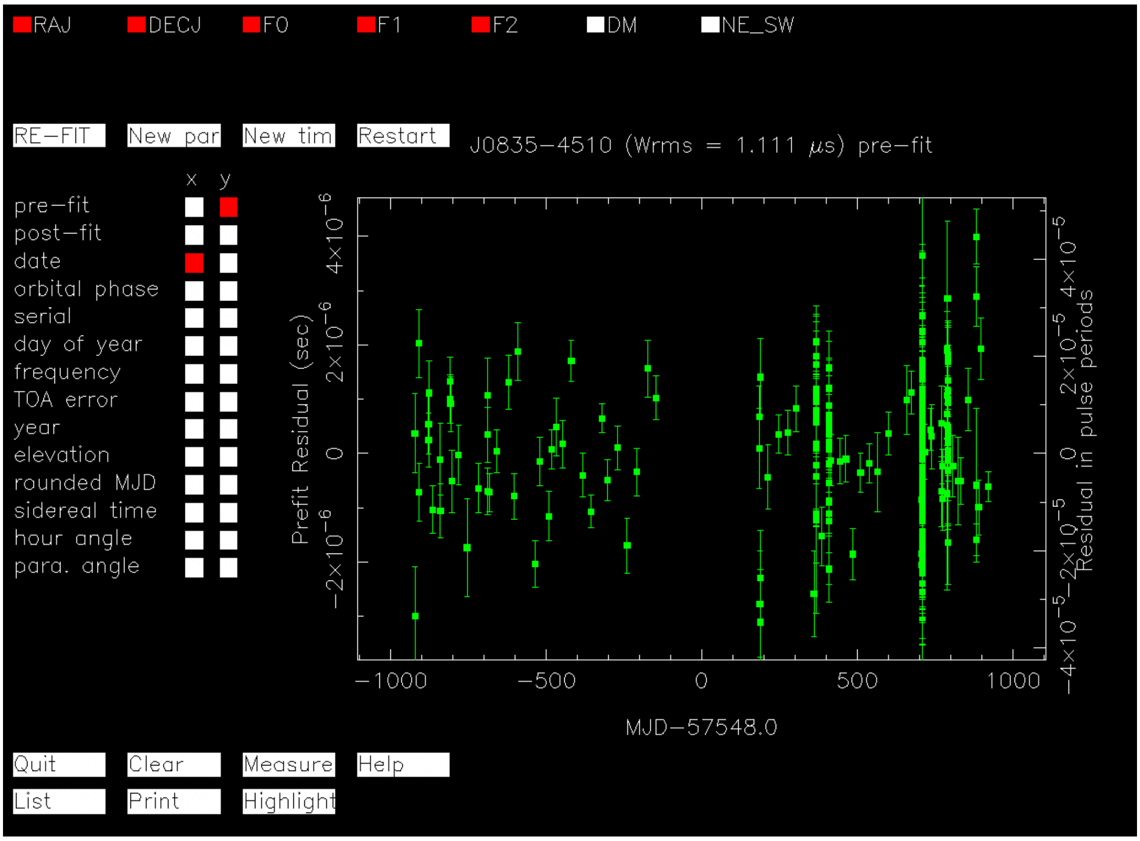

Figure 1: The TEMPO2 graphical interface.

```
In the Part1 directory,
tempo2 -gr plk -f J0835-4510.par J0835-4510.tim
```

The *-gr plk* command launches a graphical interface that allows interactive visualisation and analysis of the timing residuals.

On running the above command, you should see a window as shown in Figure 1.

- The parameters listed on the top describe the pulsar model (as listed in the *.par* file).
- The highlighted parameters (with red squares) indicate those that are fitted for.
- The plot with green squares show the timing residuals. When the pulsar model accurately describes the properties of the pulsar, the timing residuals would be scattered around a mean value of 0 – which is the case here.

- The scatter in the timing residuals seen here is due to radiometer noise (i.e., noise due to system electronics). There are typically additional processes that also contribute to the scatter in the timing residuals.
- The weighted root mean square value (Wrms) listed above the timing residuals describes the goodness of the fit and in this case, it is ~ 1 microsecond.
- The various buttons on the left side of the timing residuals allow us to interactively view and analyse the data.

Try plotting the timing residuals as a function of:

- ToA error
- Serially
- Orbital phase

Apart from the graphical interface, TEMPO2 displays a wealth of information on the terminal. Were you able to spot it? If so, try answering the following questions:

- What is the time span of the data set?
- What is the age of the pulsar?
- What is the reduced chi-sq value?
- How many parameters are fitted for?
- How many data points are in the fit?

```
Time span of the data:
Age of the pulsar (in years):
Reduced chi-sq value:
Number of fitted parameters:
Number of data points in the fit:
```

5 Trends in the timing residuals

What happens if the pulsar model is incorrect? In the **Part2** directory, you will find a couple of ephemerides (*wrongF0.par and wrongRAJ.par*). Try running TEMPO2 with each of these ephemerides.

How do the pre-fit timing residuals look like when using wrongF0.par?

How do the pre-fit timing residuals look like when using wrongRAJ.par?

To update the incorrect timing model, we fit various parameters to check what best describes the observed data. In the above cases, try clicking on the *RE-FIT* button in the graphical interface. Does that make the timing residuals flat? Take a look at the output in the terminal and note down the pre-fit and the post-fit values for the relevant parameters.

```
Incorrect F0:
Trend in the timing residuals:
Pre-fit value:                     Post-fit value:

Incorrect RAJ:
Trend in the timing residuals:
Pre-fit value:                     Post-fit value:
```

6 Is there a glitch in the data?

Analyse the timing residuals using the files in the **Part3** directory.

How do the pre-fit residuals look?

Do you see an abrupt change in the spin-period of the pulsar in the pre-fit timing residuals? Pulsars, especially younger pulsars, typically experience a sudden increase in their rotational period which are called *glitches*. Glitches are thought to be caused due to turbulence in neutron star interiors – starquakes. Read more about glitches here: `https://arxiv.org/pdf/1801.04332.pdf`.

In order to fit for the glitch, edit the ephemeris file (J0835–4510.par) and add the following lines:

```
GLEP_1 57500
GLPH_1 0 1
GLF0_1 0 1
```

GLEP is the glitch epoch and *GLF0* is the change in the spin-frequency due to the glitch. We initially set this to 0 and fit for it in TEMPO2.

Were you able to fit for the glitch parameters using *tempo2*? If so, try answering the following questions:

- What is the value of GLFO?

- How do the post-fit timing residuals look like?

References

Hobbs G. B., Edwards R. T., Manchester R. N., 2006, http://dx.doi.org/10.1111/j.1365-2966.2006.10302.x , https://ui.adsabs.harvard.edu/abs/2006MNRAS.369..655H 369, 655