IPTA Student Week, Sèvres

Timing Analysis of Pulsars using Tempo2: Worksheet

James McKee
Max Planck Institute for Radio Astronomy
jmckee@mpifr-bonn.mpg.de

27th June 2017

1 Introduction

Following yesterday's tutorial, where you learned how to extract a TOA from a folded observation, we will now learn some of the basics of how to use the Tempo2 software (Hobbs et al. 2006) to analyse pulsar timing data.

Initially, we will be using an ephemeris (the .par file) based on analysis of PSR J1918−0642 using the EPTA Data Release 1.0 (Desvignes et al. 2016), together with fake TOAs (much greater precision and recorded at higher cadence than real data for this pulsar). Later, we will try to find a timing solution for an imaginary pulsar.

An ephemeris is a set of parameters that are used to model timing observations of a pulsar. By looking at the provided .par file for PSR J1918−0642, we can see some things about the pulsar.

Q1.1: What do the following parameters in the .par file describe: RAJ, DECJ, F0, F1, DM, PMRA, PMDEC, PB, T0, A1, OM, ECC, M2, SINI? What are their units?

Q1.2: What is the projected semi-major axis and its uncertainty, in metres?

Q1.3: Using the eccentricity and the projected semi-major axis listed in the .par file, what is the difference in length of the semi-major axis (a) and the semi-minor axis (b) of the orbital ellipse?

Hint: Eccentricity is defined as: $e = \sqrt{1 - \frac{b^2}{a^2}}$

2 Timing Parameter Signatures

(Note: The PGPLOT server, which is required for displaying TEMPO2 graphics, may not start automatically on the Virtual Machine. Before we start the exercises, we should manually start it). Type the following into the terminal:

```
/opt/pulsar/pgplot/pgxwin_server &
```

We will now try to reproduce some of the signatures induced in residuals by unmodelled timing parameters. This is a good way to qualitatively understand how the timing software creates the timing solutions. We'll make use of TEMPO2 and the PLK graphical interface plugin. The general procedure is:

Run TEMPO2 using the .par file and the .tim file, and using the PLK graphical interface:

```
tempo2 -gr plk -f J1918-0642_exercise.par J1918-0642_exercise.tim
```

Your timing residuals should be clustered around zero (i.e. only white noise remains in the residuals), indicating an accurate timing solution. We will now break the timing solution in different ways, to see what structure appears in the residuals, then try to recover the original solution. First, let's see what happens when we change the spin-frequency parameter:

With the graphical interface selected, press the `p` key

Switch to the terminal and select a parameter by typing `F0`

TEMPO2 tells us that the value of F0 is 130.78951412338 Hz (rounded up to the first uncertain figure). Change this to `130.78951412339` (i.e. introduce a spin-frequency error of +0.00000000001 Hz, or 0.01 nHz). We can see that even a 'tiny' error in the spin-frequency is easily noticeable! Let's fit for F0 now, to recover the original solution:

In the PLK interface, click the 'F0' box, click 're-fit', and change the y-axis to 'post-fit' (you can toggle between pre-fit and post-fit axes quickly using the `1` and `2` keys). Your residuals should once again be clustered about zero.

Q2.1: What is the difference in the structure of the residuals when introducing an error of +0.01 nHz and −0.01 nHz?

Let's now see what happens when we introduce a larger error into the spin-frequency. Click 'restart', and repeat the previous steps, but instead change the spin-frequency value

to `130.78951411338` (i.e. introduce an error of -10 nHz).

The residuals should now look like several diagonal lines, called 'phase wraps' (that is, the residuals are now greater than the pulse phase of the pulsar). Try fitting for F0 once again (hint: it doesn't fix things...). To fix things, let's zoom into a smaller section of the data and fit for F0.

We can zoom in on sections of the data (that is, change the range of the x-axis) by hovering the mouse over the plot and pressing the `s` and `f` keys ('start' and 'finish'). We can un-zoom with the `u` key.

Zoom in on a section of data so that there is only a single diagonal line of residuals, with no phase wraps, and now fit for F0. The residuals should once again be clustered around zero for this range of MJDs. Un-zoom and inspect the overall results.

Q2.2: Is the RMS of the residuals and the value for F0 the same as when you started? Is the F0 signature completely removed from the residuals? Can you explain what you see?

Activity: Producing Residual Signatures
Now let's try to produce signatures in the residuals due to errors in some other parameters. (Hint: Are any other choices of x-axis better for seeing some of these effects?)

1. The spin-down rate
2. The sky coordinates
3. The proper motion
4. The orbital period
5. The projected semi-major axis of the orbit
6. The Shapiro delay (hint: which parameters could be changed to see this?)

Try to introduce an error that is large enough for the signature to be clearly seen, but not so large that phase wraps are introduced (this may require a little trial and error). For each of the above, save a new .par file with the error included (click 'new par', and name the file e.g. J1918-0642_F1.par).

Q2.3: Explain qualitatively why errors in each of these parameters induce these specific structures in the residuals.

3 Printing Results

Following the analysis, it can be useful to print residuals to a file e.g. so they can be plotted. To do this, we can use the GENERAL2 plugin:

```
tempo2 -output general2 -s "{bat}\t{post}\t{err}\n" -f
J1918-0642_exercise.par J1918-0642_exercise.tim > output.file
```

This prints out the following columns: the barycentric arrival time (bat), the post-fit residual (post), and the TOA error (err). The `\t` and `\n` parts of the above command tell TEMPO2 to delimit the columns with spaces and to start a new line, respectively.

Q3.1: What are the units for each of these three values? (Hint: you might need to look at the data using the PLK plugin to check)

Activity: Plotting the Results (*optional*)
Use your favourite plotting software to make plots of the signatures for each of the .par files you saved in the previous section. Make sure the axes are properly labelled (and the correct units are used!). (Hint: some of the plots will require {binphase} (binary phase) instead of the barycentric arrival time).

If you're unsure how to produce plots in Linux, remain calm and ask an instructor for help!

4 Finding the Timing Solution for a Pulsar

When a pulsar is discovered, an initial value for the period, DM, and sky coordinates are derived from folding the observation, but it may take many months or years of timing data for the signatures of other parameters to become apparent in the timing residuals. In this exercise, we will illustrate this by deriving a timing solution for an imaginary pulsar, PSR J1234−5678. Our starting .par file has only the parameters that can be derived from the initial observations, and the precision of these parameters is not high.

Activity: Find a Timing Solution for PSR J1234−5678
Starting with the J1234-5678_initial.par file, analyse the timing data and update your timing model to describe data sets of length 3 months (data1.tim), then 6 months (data2.tim), then 4 years (data3.tim), then finally 11 years (data4.tim) for this pulsar. This is an iterative process, you will need to update your timing model (.par file) as you move on to longer data sets. Note that you will eventually need to manually add some parameters to your timing solution when their effect becomes significant. Think about which parameters these could be, based on remaining signatures in the residuals that cannot be removed by fitting any of the other parameters. Email your final timing solutions to jmckee@mpifr-bonn.mpg.de.

5 Useful Resources

- TEMPO2 overview paper (Hobbs et al. 2006): `arxiv.org/abs/astro-ph/0603381`
- TEMPO2 timing model description (Edwards et al. 2006): `arxiv.org/abs/astro-ph/0607664`
- EPTA data release 1.0 overview (Desvignes et al. 2016): `arxiv.org/abs/1602.08511`
- TEMPO2 user manual: `http://www.jb.man.ac.uk/~pulsar/Resources/tempo2_manual.pdf`
- TEMPO2 wiki page (tutorials, documentation, etc.): `http://www.atnf.csiro.au/research/pulsar/tempo2/index.php?n=Main.HomePage`