# 5. Noise in the IPTA data

## Aims and objectives

- Understand the different noise processes that affect pulsar timing data
- Study the PSRs J1939+2134 and J1909−3744 data sets from the Parkes Pulsar Timing Array
- Determine the relative importance of different noise processes
- Consider the cause of pulsar timing noise

## Background reading

- Dispersion measure variations and their effect on precision pulsar timing, You et al. (2007; MNRAS)
- High signal-to-noise ratio observations and the ultimate limits of precision pulsar timing, Oslowski et al. (2011; MNRAS)
- Pulsar timing analysis in the presence of correlated noise, Coles et al. (2011; MNRAS)
- Developing a pulsar-based timescale, Hobbs et al. (2010arXiv1011.5285H)
- Measuring the Mass of Solar System Planets Using Pulsar Timing, Champion et al. (2010; ApJ)
- Switched Magnetospheric Regulation of Pulsar Spin-Down, Lyne et al. (2010, Science)
- An analysis of the timing irregularities for 366 pulsars, Hobbs et al. (2010, MNRAS)
- Assessing the role of spin noise in the precision timing of millisecond pulsars, Shannon & Cordes (2010, ApJ).
- Timing stability of millisecond pulsars and prospects for gravitational-wave detection, Verbiest et al. (2009, MNRAS)

## Who to find if you get stuck

For implementation issues in tempo2, speak with George Hobbs, Ryan Shannon or Mike Keith

For general discussion on noise in pulsar data sets, speak with: Ingrid Stairs, Jim Cordes, Dan Stinebring, and David Champion.

## Experts to discuss this with during the science meeting

Many of the science meeting talks will be dedicated to the topics of noise in the timing residuals. Experts include William Coles, Dick Manchester, Joris Verbiest, Stefan Osłowski and David Nice.

# 1 Overview

The aim of this worksheet is to determine what noise processes affect pulsar timing residuals and may hinder gravitational wave detection. The noise processes that we will study are:

- Receiver noise
- Dispersion measure variations
- Irregularities in terrestrial time standards
- Unknown objects in the Solar System
- A stochastic background of gravitational waves
- Pulsar timing noise

What other phenomena can affect the observed timing residuals?

Give two explanations for the possible cause of pulsar timing noise

# 2 The data set

We will make use of observations of PSRs J1939+2134 and J1909−3744 from the Parkes Pulsar Timing Array. The observations include data taken using the 10/50CM dual band feed that simultaneously provides a pulse profile in the 10 cm and the 50 cm bands (note: the most recent data were actually taken in the 40 cm band, but for this project we will not distinguish between the 40 and the 50 cm bands). Separately observations are also made in the 20 cm band. The ephemeris that is provided does not include any dispersion measure correction.

The data files can be accessed from

```
/data/module5/J1909.par
/data/module5/J1939.par
/data/module5/J1909.tim
/data/module5/J1939.tim
```

The timing residuals can be viewed using tempo2:

```
$ tempo2 -gr plk -f J1939.par J1939.tim
```

(and similarly for PSR J1909−3744).

By default the red indicates observations in the 50 cm band, the green in the 20 cm band and the blue in the 10 cm band.

Which observing band shows the largest variations? Why?

If these variations are caused by dispersion measure variations, how does the size of the variation scale with the observing frequency?

## 3 Hands-on approach to measuring dispersion measure variations

For this part we will measure the dispersion measure by hand in different regions of the data and then plot the dispersion measure as a function of time. To do this, we need to choose two observing bands (we can choose the 10 cm and the 50 cm bands) by:

```
$ tempo2 -gr plk -f J1939.par J1939.tim -nofit -pass "-B 10CM 40CM 50CM"
```

Now you should only see the two bands in the resulting plot. Click on the "post-fit" box to show the post-fit residuals (which, as no fitting has been undertaken, should look the same as the pre-fit residuals).

Now we must select a short section of data that includes both 10 cm and 50 cm observations. You need to draw a box around the observations that you want to include. Move the mouse to one corner of the box and press 'z' (for zoom). Now release the mouse button and drag the box around the required observations and then click the mouse button again. You should now only see the observations that you have selected.

Click using the left mouse button on one of the central observations in this region and write down the MJD of that observation. Then turn on fitting for DM and click on re-fit. Record the post-fit value of the dispersion measure and its uncertainty. Then press 'u' to unzoom and return to the original plot.

Repeat this process with a different section of data until you have multiple measurements of the dispersion measure as a function of time (you may find clicking with the middle mouse button on an observation helps you keep track of which regions of the data you have already processed). Record all these values in a file and plot them with the error bars using any plotting package (gnuplot would work well).

Is the dispersion measure changing? If yes, what is the physical origin for these changes?

Do you get the same answer if you use the 20 cm and 10 cm observing bands or the 20 cm and 50 cm bands? Why are there differences?

What happens if your region covers a year or more when you fit for the dispersion measure?

Are the dispersion measure variations for PSR J1909−3744 similar to PSR J1939+2134?

## 4 Looking at the timing residuals after the dispersion measure variations have been removed

The dispersion measure variations can be removed from the data by adding the following into your parameter file:

```
DMMODEL DM 0
DMOFF <mjd> <val> <err>
DMOFF <mjd> <val> <err>
```

For instance:

```
DMMODEL DM 0
DMOFF 53451 0.001975 8e-5
DMOFF 53551 0.001621 5e-5
...
```

The DMOFF parameters give the difference between the dispersion measure at the specified MJD and the nominal dispersion measure given in the parameter file. Instead of calculating the offsets by hand you could use `awk`:

(assuming that your file containing the dispersion measure values and errors is called dmlist_1939)

```
awk '{print "DMOFF ",$1,$2-71.023911,$3}' dmlist_1939
```

(NOTE: these DMOFF parameters interpolate between adjacent points to determine the value of the dispersion measure at a given time. You will need to ensure that the first DMOFF has an MJD that is earlier than your first observation and the last DMOFF has an MJD that is after than the last observation.)

After including these lines in the .par file you can then re-run tempo2 as normal.

What is the rms timing residual before and after removing the dispersion measure variations?

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Has this method removed all of the dispersion measure variations? Is it possible to completely remove the effects of dispersion measure variations?

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## 5 Studying clock files

The pulsar timing procedure relies converting measurements of site-arrival-times to times of arrival at the Solar System barycentre as measured in Coordinated Barycentric Time (TCB). To do this timing packages (such as tempo2) use a series of data files to convert from the observatory time standard to a realisation of terrestrial time (TT). If, however, any of these corrections is wrong, or the realisation of TT itself is not perfect then timing residuals will be induced. The goal of this section is to determine whether the likely errors in TT will induce timing residuals that could affect our ability to detect gravitational waves.

To see the effect we need to simulate a data set with a long data span. This project should only be attempted after you have completed module 4.

Create a simulated pulsar .par file that contains within it the command:

```
CLK TT(BIPM2011)
```

This will tell tempo2 to relate all the pulsar arrival times to the BIPM2011 realisation of terrestrial time (which is the best available terrestrial time standard). Now you should use this parameter file (and the fake plugin) to simulate 20 years of data with 100 ns of white noise and one observation every 14 days (note ensure that the last observation has an MJD of around 55700). Use the plk plugin to view the timing residuals and ensure that the rms of the timing residuals is $\sim 100$ ns.

What is BIPM and where is it located?

Now update the parameter file to change CLK TT(BIPM2011) to CLK TT(TAI). This will change the realisation of terrestrial time to TAI which is the best real-time time standard. Now view the timing residuals use plk.

What is the pre- and post-fit rms timing residual for the induced timing residuals caused by irregularities in TT(TAI)?

Is the effect of an error in the terrestrial time standard larger or smaller than the effect of not correcting for the dispersion measure variatons?

Anyone who therefore uses TT(TAI) as their time standard will have induced timing residuals at this level present in their data sets (assuming this data span). However, there is no reason why the post-corrected time standard TT(BIPM2011) should not be used instead.

You have shown the size of the errors in TT(TAI). How would you calculate the size of the errors in TT(BIPM2011)?

## 6 Errors in the planetary ephemeris

Conversion from site-arrival-times to barycentric-arrival-times requires the use of a planetary ephemeris that can give the vector between the centre of the Earth and the Solar System barycentre. Of course, the planetary ephemeris will not be perfect. Any errors in the planetary ephemeris will lead to induced timing residuals that may affect our ability to detect gravitational waves. In this section we estimate the size of any possible effect by comparing two planetary ephemerides.

We generally use the planetary ephemeris published by JPL. The most up-to-date ephemeris called DE421. Following the procedure above (used to study the clock files), you should now simulate a long (∼20 yr) data set using DE421 (by including `EPHEM DE421` in the parameter file). Look at the resulting timing residuals when you change the planetary ephemeris to an earlier version (`EPHEM DE414`).

Describe the main features of the induced timing residuals

Can you identify which Solar System body is inducing the difference between DE421 and DE414?

Use a web search to find the difference between DE421 and DE414

Is the effect of errors in the planetary ephemeris larger or smaller than errors in the terrestrial time standard and uncorrected dispersion measure variations over a 20 year data span?

You have identified errors in DE414 compared with DE421. How would you search for errors in DE421?

## 7 Adding in a gravitational wave background signal

Various predictions have shown that an isotropic, stochastic gravitational wave background is likely to have an amplitude of $A_g \sim 10^{-15}$. Use the GWbkgrd plugin to simulate such a background for the same data span that you have used above.

Are the induced residuals caused by the gravitational waves larger or smaller than those from dispersion measure variations, clock errors or errors in the Solar System ephemeris?

By eye can you distinguish the induced timing residuals caused by a gravitational wave background, clock errors or planetary ephemeris errors?

## 8 What is causing the noise that we see in the residuals?

Make a plot of the post-fit timing residuals for both PSR J1939+2134 and PSR J1909−3744.

Are the timing residuals caused by gravitational waves, dispersion measure variations, clock errors, Solar System errors, or something else?

## 9 Challenge: What is causing the dispersion measure variations?

Most analyses of dispersion measure variations are based around obtaining a power-spectrum or structure function of the variations. Develop some software that can obtain either a power-spectrum or structure function of your measurements of the dispersion measure variations.

Are the variations consistent with that expected from (Kolmogorov) turbulence in the interstellar medium?

## 10 To think about

- Will you remove any gravitational wave signal when you are removing the dispersion measure variations?
- How correlated would the timing residuals be for two pulsars if the residuals were dominated by 1) dispersion measure variations, 2) clock errors, 3) planetary-ephemeris errors or 4) gravitational waves?
- Can we use our data sets to measure the errors in the terrestrial time standards or in the planetary ephemeris?
- Do we expect a pulsar's dispersion measure to change if the line-of-sight to the pulsar passes close to the Sun?

## 11 Publication

Find a publication on ADS that is related to this worksheet and summarise the basic conclusions of that paper.

## 12 Mistakes

How many mistakes did you find in this worksheet?