4. Simulating pulsar data sets

Aims and objectives

- Learn how to simulate data sets using TEMPO2
- Consider how to limit the maximum size of a signal in a data set
- Understand the effects of fitting a pulsar timing model on gravitational wave signals
- Learn how to simulate a gravitational wave background

Background reading

- TEMPO2: a new pulsar timing package - III. Gravitational wave simulation, Hobbs et al. (2010; MNRAS)
- Upper Bounds on the Low-Frequency Stochastic Gravitational Wave Background from Pulsar Timing Observations: Current Limits and Future Prospects, Jenet at al., (2006; ApJ)
- Placing limits on the stochastic gravitational-wave background using European Pulsar Timing Array data, van Haasteren et al. (2011; MNRAS)
- The sensitivity of the Parkes Pulsar Timing Array to individual sources of gravitational waves, Yardley et al. (2010; MNRAS)

Who to find if you get stuck

For tempo2 implementation speak with: George Hobbs, Ryan Shannon or Mike Keith.

For general questions on gravitational waves speak with: Fredrick Jenet, Jim Cordes or Yuri Levin.

Experts to discuss this with during the science meeting

The TEMPO2 simulation software has been put together by Fredrick Jenet, George Hobbs, Ryan Shannon, Mike Keith, William Coles, Jingbo Wang and Sarah Burke Spolaor.

There will be many people at the science meeting that are experts on how gravitational waves affect pulsar timing residuals. Such people include William Coles, Rutger van Haasteren, Fredrick Jenet, Paul Demorest, Jim Cordes, Kejia Lee, Andrea Lommen and Yuri Levin.

1 Simulation of a perfect data set

We will first simulate a nearly perfect set of site arrival times for a single pulsar. These arrival times will be regularly sampled and all have an arrival time measurement precision of 100 ns. To start you need an ephemeris for the pulsar that you wish to simulate. As this is not real data, we can simulate a perfect pulsar. Let's make an ephemeris called psr1.par that contains:

```
PSRJ J1234-1234
RAJ 12:34:00 1
DECJ -12:34:00 1
F0 1  1
F1 0  1
PEPOCH 52000
DM 100
```

Note that this pulsar has a period of 1 second.

```
$ tempo2 -gr fake -f psr1.par -nobsd 1 -ndobs 14 -randha y -ha 8
      -start 50000 -end 53000 -rms 1e-4
```

(use `tempo2 -gr fake -h` to get information on what these command line arguments mean.) This will produce a file `psr1.simulate` that contains the simulated arrival times at the Parkes observatory for this pulsar. View the timing residuals using the plk plugin to ensure that they have an rms residual close to 100 ns.

Try running exactly the same command again to run the fake plugin. This time the residuals will look different. Each time you run the fake plugin a different set of random numbers is chosen and so the results will always be different.

2 Adding in a sinusoidal signal

A single, non-evolving gravitational wave source will induce sinusoidal timing residuals. Tempo2 can simulate such a source (see the challenge below), but for a single pulsar we can simulate a simple sinusoid. To do this we update the ephemeris (let's call it psr1_update.par) to contain:

```
PSRJ J1234-1234
RAJ 12:34:00 1
DECJ -12:34:00 1
F0 1 1
F1 0 1
PEPOCH 52000
DM 100
WAVE_OM 1e-2 0
WAVE1 1e-6 0
```

(WAVE_OM is an angular frequency of the sinusoid and is in units of radians/day. The amplitude of this sinusoid is 1μs.)

Now run the fake plugin with this new parameter file to get psr1_update.simulate.

What do you see when you run tempo2 with psr1.par and psr1_update.simulate?

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What do you see when you run tempo2 with psr1_update.par and psr1_update.simulate? Why?

After running tempo2 with psr1.par and psr1_update.simulate you should see a clear sinusoidal curve. Click on post-fit to see the effect of fitting for the pulsar's position, spin frequency and its first derivative.

What is the amplitude of the sinusoid in the data? How low can you reduce the amplitude of the sinusoid in the simulation before it is undetectable in the data?

Now update your ephemeris to:

```
PSRJ J1234-1234
RAJ 12:34:00 1
DECJ -12:34:00 1
F0 1 1
F1 0 1
PEPOCH 52000
DM 100
WAVE_OM 0.017202423 0
WAVE1 1e-6 0
```

and again simulate a data set using the fake plugin and display the pre- and post-fit timing residuals.

What is the period of the wave that has been simulated?

The pre-fit residuals should clearly show a sinusoidal signal. However, the post-fit residuals will simply be white noise.

Why has the sinusoid been absorbed during the fitting procedure?

Try simulating sinusoids with different periods.

What is the longest-period sinusoid that can still be detected in the post-fit timing residuals?

3 Simulating a gravitational wave background

Instead of simulating a non-evolving, individual gravitational wave source, we will now simulate a gravitational wave background containing many thousands of sources. We start with your perfect data set (psr1.par and psr1.simulate).

```
$ tempo2 -gr GWbkgrd -f psr1.par psr1.simulate -dist 0.8 -gwamp 1e-14 -ngw 1000
```

(note that the distance estimate is given in kpc and the plugin automatically simulates a background with spectral exponent of $-2/3$ which corresponds to a background caused by supermassive binary black holes.)

This produces a new arrival time file (J1234-1234.gwsim.tim) that contains site arrival times affected by the gravitational wave signal. Use

```
$ tempo2 -gr plk -f psr1.par J1234-1234.gwsim.tim
```

to view pre- and post-fit the timing residuals. Note that the background is random and running the GWbkgrd plugin again will lead to a new set of timing residuals.

What is the effect of fitting on the timing residuals induced by the gravitational wave background?

What is the smallest gravitational wave amplitude that is still detectable in the residuals?

How do the post-fit pulsar parameters (such as F0, F1 and position) compare with those that you simulated?

4 Simulating multiple pulsars

If you produce ephemerides for 3 pulsars (psr1.par, psr2.par and psr3.par) with different positions for each pulsar (and ensure that you have different pulsar names) then you can simulate the perfect site-arrival-times by running the fake plugin for each pulsar separately. Here we want to simulate the effect of the same gravitational wave background for each pulsar. Once you have run the fake plugin (separately for each pulsar) you can then use:

```
$ tempo2 -gr GWbkgrd -f psr1.par psr1.simulate -f psr2.par psr2.simulate
   -f psr3.par psr3.simulate -dist 0.8 -dist 1.3 -dist 0.4 -gwamp 1e-14 -ngw 1000
```

You can view the timing residuals for all three pulsars simultaneously using the splk plugin:

```
$ tempo2 -gr splk -f psr1.par <name1>.gwsim.tim -f psr2.par <name2>.gwsim.tim
    -f psr3.par <name3>.gwsim.tim
```

If you simulate two pulsars at the same position (but with different names), do you get identical timing residuals? Why not?

5 Challenge: testing the tempo2 implementation of continuous gravitational wave sources

S. Burke Spolaor, G. Hobbs and R. Shannon have been updating the tempo2 source code to allow continuous gravitational wave sources to be included as part of the pulsar timing model. They think that their implementation is correct, but it would be good to check.

First we need to produce ephemerides for 3 or more pulsars (psr1.par, psr2.par ...). We will simulate the same gravitational wave source for all pulsars. To do this you need to create a new *global* ephemeris file (called `global.par`). In this file include:

```
GW_SINGLE 7e-8 0
GW_POSITION 0.2 -0.5
GW_APLUS 1e-12 0
GW_ACROSS 0 0
GW_EPOCH 52000
```

GW_SINGLE gives the gravitational wave frequency (in Hz), the GW_POSITION is the position of the source in right ascension and declination (radians), GW_APLUS is the real (1e-12) and imaginary (0) components of the A_+ polarisation state. GW_ACROSS is the same for the $A_\times$ polarisation state. GW_EPOCH is used to define a central MJD value (for now this can be any value). With this implementation only the effect of the gravitational wave signal passing the Earth is taken into account. If you wish to include the effect of the gravitational wave signal passing the pulsars then you must include the pulsar distance for each pulsar (in the individual pulsar ephemerides) with GW_PSR_DIST (where the value is given in kpc).

Now simulate the timing residuals including this gravitational wave source

```
$ tempo2 -gr fake -f psr1.par -nobsd 1 -ndobs 14 -randha y -ha 8
      -start 50000 -end 53000 -rms 1e-4 -global global.par
```

(repeat for each pulsar and note the addition of -global global.par on the end of the command line). You can view the residuals using splk:

```
$ tempo2 -gr splk -f psr1.par psr1.simulate -f psr2.par psr2.simulate
     -f psr3.par psr3.simulate
```

(note: you can plot the different pulsars using the same axis-scaling by pressing 'y' followed by 'x').

Are the induced residuals the same for each pulsar? If not, why are they different?

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How do the induced residuals change if you change the input gravitational wave source to be polarised in $A_\times$?

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How do the induced residuals change if you change the position of the gravitational wave source?

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What tests would you carry out to prove that the tempo2 simulation is correct (or incorrect)?

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6 To think about

- Your simulations have included white noise and a gravitational wave signal. What other noise processes should be simulated to create data sets that are similar with the actual data?
- What is the difference between detecting a gravitational wave signal and limiting the amplitude of any gravitational wave signal that may be in the data?
- Can you calculate the expected values of A_+ and $A_\times$ for a supermassive binary black hole system at a given distance and with known black hole masses?

7 Publication

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

8 Mistakes

How many mistakes did you find in this worksheet?