IPTA Student Week 2026

Bonus activity: Timing with Tempo2

Theme: Pulsar Safari

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Welcome to the Pulsar Safari! In this tutorial we will track down a millisecond pulsar through the wilderness of timing residuals and learn how to build a precise timing model using `tempo2`. Bring your binoculars (and your terminal).

Contents

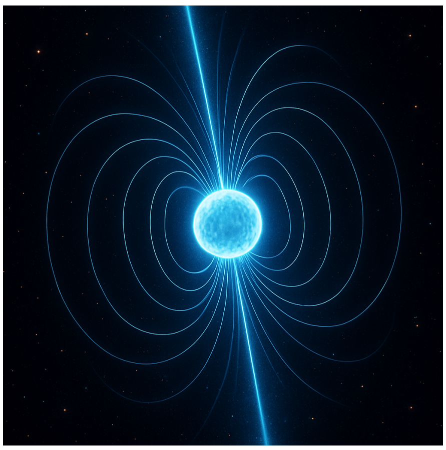
1 A short review of the basics

1.1 Pulsars as Cosmic Clocks

As you know by now, Pulsars are rapidly rotating, highly magnetised neutron stars whose radio beams sweep across our line of sight as they rotate, producing the regular train of pulses we observe – like a lighthouse.

Millisecond pulsars (MSPs) spin with periods of a few milliseconds and are very rotationally stable. Their stability rivals – and sometimes exceeds – that of the best atomic clocks on Earth, giving us a network of natural, ultra-precise clocks distributed across the Galaxy.

Why is pulsar timing so powerful? It is a deceptively simple measurement – arrival time of a pulse vs. model prediction – yet it can be used to probe **gravitation**, **nuclear physics**, **strong-field general relativity**, and **plasma physics**.



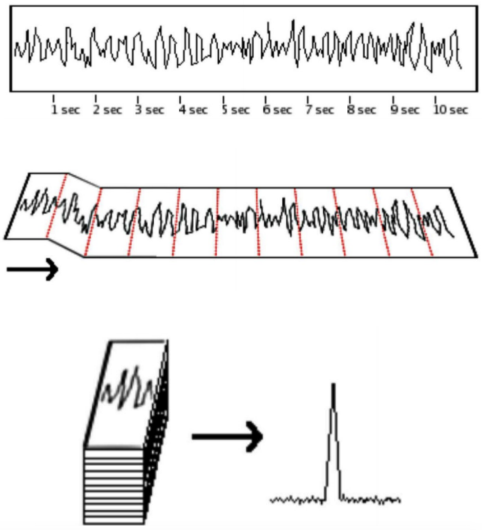
1.2 From Photons to Pulse Profiles: Pulse Folding and Pulse Profile

A single pulse is almost always too weak to detect against receiver, sky, and ground noise. But pulsars are exceptionally periodic. Given the rotational period P, we chop the data into P-length segments and add them: the signal adds coherently, the noise incoherently, and

$$S/N \;\propto\; \sqrt{N_{\text{pulses}}}. \tag{1}$$

This procedure – averaging many rotations of the pulsar in time and across the radio band – is called **pulse folding**, and yields a high signal-to-noise **integrated pulse profile** (see Lorimer & Kramer 2005).

Each pulsar has its own characteristic, stable profile – a unique **fingerprint**. Some show a single narrow peak; others have multiple components spread over the rotational phase.



The profile shape also depends on observing frequency, and some components are prominent only in certain frequency bands. For each band, we, therefore, usually build a separate noise-free **template**, typically by smoothing a high-S/N profile with `psrsmooth` in `PSRCHIVE`.

1.3 Times of Arrival: Template Matching

From an integrated profile and a template we want one number: the **Time of Arrival (TOA)** – the time at which the pulse reached the telescope.

We get it by **template matching**: we ask *by how much must we shift the template to best match the observed profile?* That phase shift converts directly into a time delay. The matching is done in the **Fourier domain**, where a phase shift is just a complex-exponential multiplication, by minimising

$$\chi^2(\Delta\phi, a) \;=\; \sum_k \frac{\left|P_k - a\,T_k\,e^{-2\pi i k \Delta\phi}\right|^2}{\sigma_k^2}, \tag{2}$$

with P_k, T_k the Fourier coefficients of profile and template, a an amplitude scale, $\Delta\phi$ the phase shift (TOA), and σ_k^2 the noise power in harmonic k. In `PSRCHIVE` this is done by the `pat` module.

1.4 TOA Precision: the Radiometer Equation

TOA precision depends on the telescope, the backend, and the pulsar's intrinsic properties. The pulsar is detectable only if its mean flux density exceeds the receiver noise floor (the **radiometer equation**; Lorimer & Kramer 2005):

$$\Delta S_{\text{sys}} \;=\; \frac{T_{\text{sys}}}{G\,\sqrt{n_p\,t_{\text{obs}}\,\Delta f}}, \qquad \sigma_{\text{TOA}} \;\propto\; \frac{\Delta S_{\text{sys}}}{S_{\text{mean}}}\,P\,\sqrt{\delta}, \tag{3}$$

with $T_{\rm sys}$ the system temperature, G the gain, n_p the number of polarisations, $t_{\rm obs}$ the integration time, Δf the bandwidth, $S_{\rm mean}$ the mean flux density, P the period, and δ the duty cycle (pulse width / period). **Good TOAs therefore want a cold receiver, large collecting area, dual polarisation, wide bandwidth, long integrations, and a bright pulsar with a short period and narrow pulse.**

1.5 The Timing Model and Residuals

Once we have a set of TOAs, we want to predict them further. We do this by constructing a **timing model** – a set of physical parameters describing everything we know about the pulsar and the geometry of the observation: **astrometric** (RA, DEC, proper motion, parallax), **spin** (F_0, F_1, occasionally F_2), **dispersion** (DM and its time variation), **binary parameters** (orbital period P_b, projected semi-major axis $A_1 = a \sin i$, eccentricity etc), and **post-Keplerian** terms in relativistic systems. Clock corrections and the Solar System ephemeris also enter.

The timing model produces a predicted TOA for each measurement; the difference is the **timing residual,** $r_i = t^{(i)}_{\rm obs} - t^{(i)}_{\rm pred}$. **A perfect timing model leaves residuals consistent with white noise around zero; an imperfect model leaves *systematic structure*, and the shape of that structure tells us *which* parameter is wrong or missing, see table below**:

Wrong / missing parameter	Signature in timing residuals
F_0 (spin frequency)	linear trend in time
F_1 (spin-down rate)	quadratic trend in time
RA, DEC	annual sinusoid
PMRA, PMDEC (proper motion)	annual sinusoid, amplitude growing with time
PX (parallax)	6-month sinusoid
P_b, A_1 (binary parameters)	sinusoid at the orbital period
e (eccentricity)	harmonics of the orbital period
Dispersion Measure (DM)	radio-frequency-dependent residuals ($\propto \nu^{-2}$)

When we discover a new pulsar we typically know only crude initial values for the timing parameters. We refine the model *iteratively*: fit, look at the residuals, identify the dominant remaining structure, add the next parameter, and repeat. This is exactly what we will do – *by hand* – with a real pulsar.

2 Pulsar Safari: Timing a MSP with Tempo2

You have been handed a TOA file, `J1909-3744.tim`, from the MeerKAT Pulsar Timing Array (MPTA), together with an initial timing solution, `start.par`. The `start.par` file already contains every timing parameter (spin, astrometry, binary, post-Keplerian) but each value is only *approximately* known. *Our job is to refine each parameter* by enabling its fit one (or a few) at a time and watching the timing residuals shrink with `TEMPO2`.

2.1 What is TEMPO2?

`TEMPO2` (Hobbs, Edwards & Manchester 2006) is the standard pulsar-timing package. Given a TOA file (`.tim`) and a timing model (`.par`), it applies all the corrections needed to translate observatory-frame TOAs into the inertial Solar System barycentre (SSB) frame, produces **timing residuals**, and performs a weighted least-squares fit of timing parameters. Its `plk` plugin (`-gr plk`) lets us inspect the residuals interactively – which is what we will use throughout this safari.

2.2 Setup

The two files `J1909-3744.tim` and `start.par` are provided alongside this tutorial inside `safari-J1909-3744` folder. The starting par file contains a realistic initial timing solution: every timing parameter is present and all fit flags are off (column 3 set to 0). The most important entries look like:

```
PSRJ      J1909-3744
RAJ       19:09:47.424761     0
DECJ      -37:44:14.9098      0
F0        339.315686657896    0
F1        -1.6144e-15         0
PEPOCH    59018
DM        10.395              0
PMRA      -9.39               0
PMDEC     -35.29              0
PX        1.30                0
BINARY    ELL1
PB        1.53344947460       0
A1        1.8979916614        0
TASC      53630.72321500      0
EPS1      1.68e-7             0
EPS2      -1.25e-7            0
M2        0.214               0
SINI      0.99911             0
EPHEM     DE440
UNITS     TCB
```

We will run `tempo2` on it, see how the residuals look, and refine the parameters group by group.

Running `tempo2`. Throughout the safari, we use the `plk` graphical plugin to inspect residuals interactively. Run the following on your terminal:

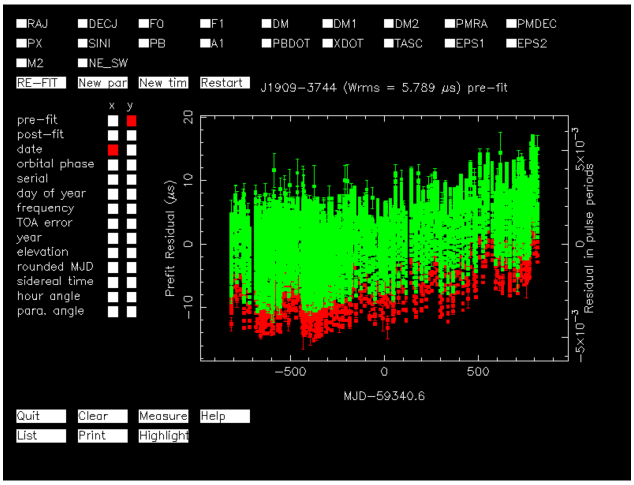
```
$ tempo2 -gr plk -f start.par J1909-3744.tim
```

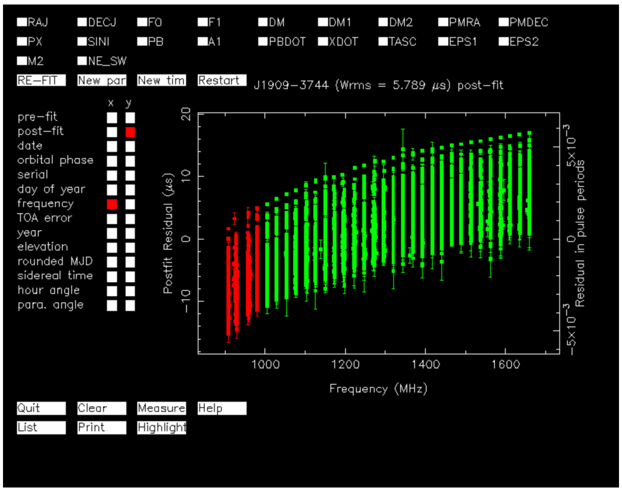
You should see something like this on your terminal, let's stare at these creatures and try to understand them:

```
Results for PSR J1909-3744

RMS pre-fit residual = 5.789 (us), RMS post-fit residual = 5.789 (us)
Fit Chisq = 4.563e+07   Chisqr/nfree = 45630460.98/7198 = 6339.32      pre/post = 1
Number of fit parameters: 1
Number of points in fit = 7199
Offset: 1.40531e-07 6.82361e-08 offset_e*sqrt(n) = 5.78962e-06 n = 7199


PARAMETER       Pre-fit                   Post-fit              Uncertainty   Difference   Fit
---------------------------------------------------------------------------------------------------
RAJ (rad)       5.01690710229713          5.01690710229713           0             0       N
RAJ (hms)       19:09:47.424761           19:09:47.424761            0             0
DECJ (rad)      -0.65864318916942         -0.65864318916942          0             0       N
DECJ (dms)      -37:44:14.9098            -37:44:14.9098             0             0
F0 (s^-1)       339.315686657896          339.315686657896           0             0       N
F1 (s^-2)       -1.6144e-15               -1.6144e-15                0             0       N
PEPOCH (MJD)    59018                     59018                      0             0       N
POSEPOCH (MJD)  59018                     59018                      0             0       N
DMEPOCH (MJD)   59000                     59000                      0             0       N
DM (cm^-3 pc)   10.395                    10.395                     0             0       N
DM1 (cm^-3 pc y 0.00027                   0.00027                    0             0       N
DM2 (cm^-3 pc y -0.000333                 -0.000333                  0             0       N
PMRA (mas/yr)   -9.39                     -9.39                      0             0       N
PMDEC (mas/yr)  -35.29                    -35.29                     0             0       N
PX (mas)        1.3                       1.3                        0             0       N
SINI            0.99911                   0.99911                    0             0       N
PB (d)          1.5334494746              1.5334494746               0             0       N
A1 (lt-s)       1.8979916614              1.8979916614               0             0       N
PBDOT           5.246e-13                 5.246e-13                  0             0       N
XDOT            -1.32e-15                 -1.32e-15                  0             0       N
```

```
TASC (MJD)       53630.723215             53630.723215             0             0      N
EPS1             1.68e-07                 1.68e-07                 0             0      N
EPS2             -1.25e-07                -1.25e-07                0             0      N
M2               0.214                    0.214                    0             0      N
START (MJD)      0                        58526.2138891553         0         58526      N
FINISH (MJD)     0                        60154.9489721363         0         60155      N
TZRMJD           59334.1186939729         59334.1186939728         0     -4.3656e-11    N
TZRFRQ (MHz)     1659.335                 1659.335                 0             0      N
TZRSITE          meerkat
TRES             0                        5.78922277182178         0          5.7892     N
EPHVER           0                        TEMPO2
NE_SW (cm^-3)    0                        0                        0             0      N
DM_SERIES        TAYLOR
------------------------------------------------------------------------------------------------------------
[textOutput.C:305] Notice: Parameter uncertainties multiplied by sqrt(red. chisq)

Jump 1 ( -MJD_58526_59621_1K -1 -1.1962616822e-06 0): -1.1962616822e-06 0 N
Jump 2 ( -MJD_58550_58690_1K -1 -0.000306243 0): -0.000306243 0 N
Jump 3 ( -MJD_58526.21089_1K -1 -2.4628e-05 0): -2.4628e-05 0 N
Jump 4 ( -MJD_58550.14921_1K -1 2.463e-05 0): 2.463e-05 0 N
Jump 5 ( -MJD_58550.14921B_1K -1 -1.196e-06 0): -1.196e-06 0 N
Jump 6 ( -MJD_58557.14847_1K -1 -4.785e-06 0): -4.785e-06 0 N
Jump 7 ( -MJD_58575.9591_1K -1 5.981308411e-07 0): 5.981308411e-07 0 N

Derived parameters:

P0 (s)       = 0.00294710807463557       0
P1           = 1.40217840281831e-20      0
tau_c (Myr) = 3332.4
bs (G)       = 2.0571e+08

Binary model: ELL1
Mass function                    = 0.003121955330
Minimum, median and maximum companion mass: 0.1954 < 0.2288 < 0.5065 solar masses
Pulsar Mass (Shapiro Delay): 1.55541 (+/- 0) Msun.

Parallax distance is 769.231 (+/- 0) pc.
Pbdot distance is 1222.25 (+/- 0) pc.
MTOT derived from sin i and m2 = 1.7694597138251
Inclination angle (deg)          = 87.582509094309 (+ 0 - 0)

Conversion from ELL1 parameters:
------------------------------------
ECC = 2.09401528170164e-07 +/- 0
OM  = 126.651003660144 +/- 0 degrees
T0  = 53631.2626953195 +/- 0
------------------------------------
Total proper motion = 36.518 +/- 0 mas/yr
Total time span = 1628.735 days = 4.459 years

Tempo2 usage
Units:                  TCB (tempo2)
Time ephemeris:         IF99 (tempo2)
Troposphere corr.?      Yes (tempo2)
Dilate freq?            Yes (tempo2)
Electron density (1AU) 0
Solar system ephem      DE440
Time scale              TT(BIPM2020)
Binary model            ELL1
```

Next, let's stare at the interactive `pgplot` window to look at timing residuals, they should look like the following:





Q1. What shape do the residuals take as a function of MJD and radio-frequency, and which parameters from the table in §1.5 explain it?

Q2. How do the timing residuals depend on the observing radio frequency?

Notes: Pre-fit vs. post-fit:

Note that `TEMPO2` reports two flavours of residual in its output.
The **pre-fit residuals** are computed using the parameter values exactly as they appear in your `start.par` file.
The **post-fit residuals** are computed after `TEMPO2` has performed its weighted least-squares fit and updated every fitted parameter. They show what the residuals would look like with the new best-fit values plugged back in.
If you do not enable any fits (all flags `0`), the pre-fit and post-fit numbers are identical – as in the example above.

2.3 Spin parameters - F_0 and F_1, and Dispersion measure - DM, $DM1$, $DM2$

Notes:

The F_0 and F_1 are the spin frequency and spin down rate of the pulsar.

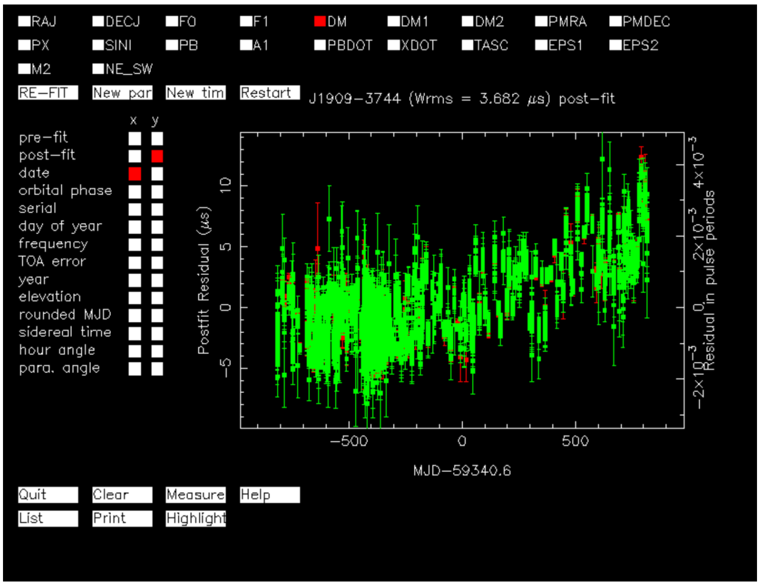
The dispersion measure (DM) is the line-of-sight column density of free electrons in the ISM (cold plasma), which delays low frequencies relative to high ones. The DM also drifts on weeks-to-years timescales as the line of sight changes; `TEMPO2` models this as a Taylor expansion around `DMEPOCH`:

$$\mathrm{DM}(t) \;=\; \mathrm{DM} \;+\; \mathrm{DM1}\,(t - t_{\mathrm{DMEPOCH}}) \;+\; \tfrac{1}{2}\,\mathrm{DM2}\,(t - t_{\mathrm{DMEPOCH}})^2 + \ldots$$

A wrong DM gives residuals depending on ν only; unmodelled DM1/DM2 gives residuals depending on both ν *and* t.

Step 1

Let's first fit `DM` using the interactive `pgplot` window using the RE-FIT button, and note that change in fitted `DM` value on your terminal. Also note the change in residual shape as a function of frequency and MJD.
Do you now see a left over linear trend in timing residuals as a function of MJD as shown below?



Note that you should be looking at **post-fit residuals** once you start fitting any timing parameter.

Step 2

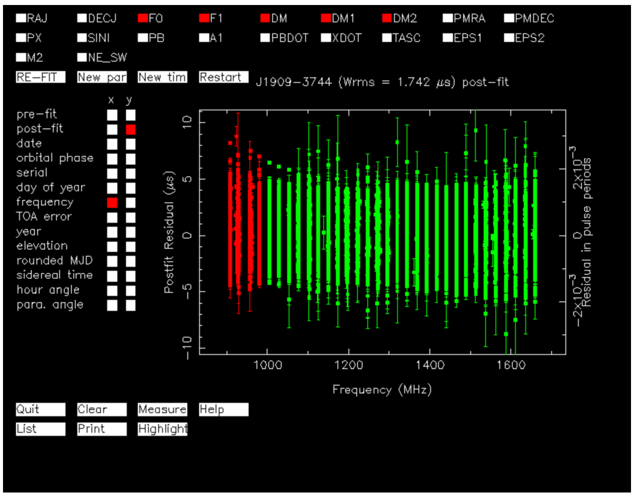
– Fit `F0` using the interactive `pgplot` window, and note the change in `F0` value on your terminal. Again note the change in residual shape as a function of MJD.
– Let's also fit `DM1` as that should also show linear trend in time (can you tell why?).
Do you now see a quadratic trend in the timing residuals?

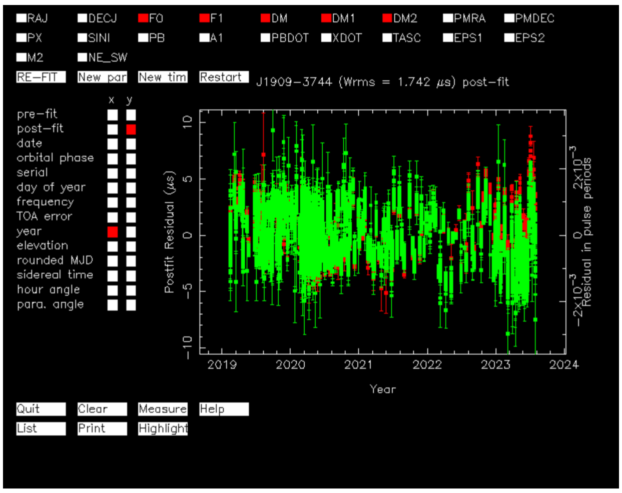
Q3. What is the change in F0 value in the units of sigma? Which parameter(s) should be fitted to remove the quadratic trend?

Step 3

– Fit `F1`, and note that change in `F1` value on your terminal. Again note the change in residual shape as a function of MJD.
– Fit `DM2`, and follow the same instructions as above.

Do your timing residuals now look like the following?





Q4. How does the left over structures look like in timing residuals?

Notes:

The most important numbers in the printed summary are the **post-fit RMS residual** (in μs – for J1909−3744 with MPTA data this should be of order 0.1–0.3 μs), the χ^2/dof (close to 1 means residuals are consistent with the TOA error bars; much larger usually means unmodelled signal or under-estimated TOA errors), and the **pre-fit / post-fit values** for each parameter, with formal uncertainties. After every step, look at all three – they tell a coherent story about what your model is doing.

2.4 Sky position and proper motion

Now let's try something different and fun this time. We will save the parfile and edit it manually.

Step 4

Let's save a new parfile where you have already fitted `F0`, `F1`, `DM`, `DM1`, `DM2`; you can save it using "New par" button on your `pgplot` window. Let's call this parfile as "J1909-intermediate1.par" and quit the `pgplot` window.

Step 5

Open "J1909-intermediate1.par" using any text-editor, and change `RAJ` and `DECJ` values inside the parfile to:

`RAJ` 19:09:47.42

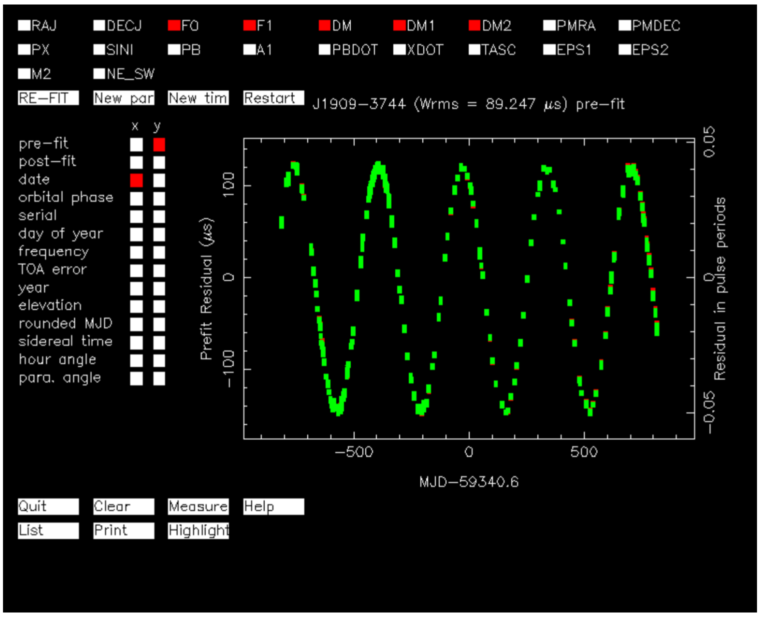
`DECJ` -37:44:14.9

Save the parfile.

Let's run tempo2 again using this new parfile.

```
$ tempo2 -gr plk -f J1909-intermediate1.par J1909-3744.tim
```

Now you will see the effect of wrong RAJ and DECJ.



Q5. What is the period of the residual oscillation, and where does that period come from physically?

Step 6

Fit `RAJ` and `DECJ` one by one. Note the change in parameter values on your terminal. Again note the change in residual shape as a function of MJD. The sinusoid trend should go away. Again save a new parfile, let's call it as "J1909-intermediate2.par", quit the `pgplot` window.

Step 7

Open "J1909-intermediate2.par" using any text-editor, and change (or perturb) `PMRA`, `PMDEC`, and `PX` values inside the parfile to:

`PMRA` -5

`PMDEC` -20

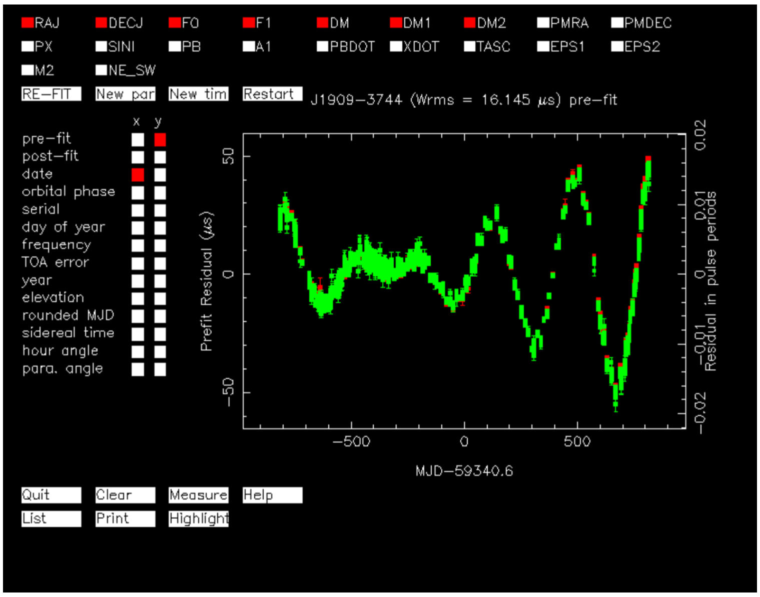
`PX` 0.1

Save the parfile.

Let's run tempo2 again using this new parfile.

```
$ tempo2 -gr plk -f J1909-intermediate2.par J1909-3744.tim
```

Do you now see the following trend in the timing residuals?



Step 8

Now fit `PMRA` and `PMDEC` one by one. Next, fit `PX`. The residual structures shown above should go away.

Save a new parfile, let's call it "J1909-intermediate3.par" and quit the `pgplot` window.

Q6. Why does the amplitude of sinusoid increase over time due to incorrect proper motion?

2.5 The Orbital parameters and Solar wind

Notes:

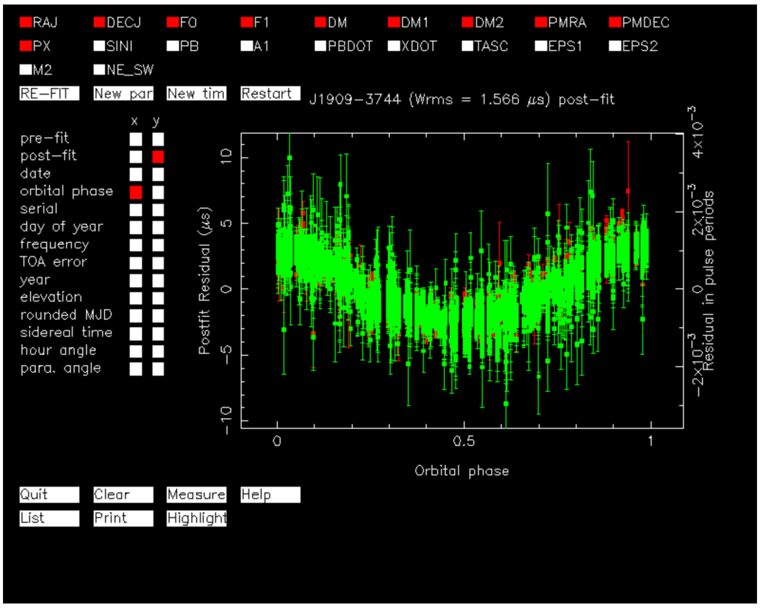
PSR J1909−3744 is in a binary system. Its orbit is modelled by the **ELL1** binary model (Lange et al. 2001, MNRAS 326, 274). The orbital parameters inside the parfile (`ELL1` block) are:

- `PB` – orbital period (days).
- `A1` – projected semi-major axis $a_p \sin i/c$ (light-seconds).
- `TASC` – epoch of ascending node passage (MJD).

- `EPS1`, `EPS2` – $e \sin \omega$ and $e \cos \omega$ (dimensionless).
- `PBDOT` – time derivative of P_b (s/s); orbital decay.
- `XDOT` – time derivative of A_1 (s/s).
- `M2` – companion mass ($M_\odot$); enters via the Shapiro delay.
- `SINI` – $\sin i$ where i is the orbital inclination.

The effect of incorrect orbital parameters appear as a function of orbital phase of the binary as shown below.

`NESW` – the electron density of the solar wind at 1 AU from the Sun, in units of cm^{-3}. As the Earth orbits the Sun and the pulsar's line of sight passes through different parts of the heliosphere, the radio signal accumulates an extra, time-variable dispersive delay from the solar-wind plasma. This delay is largest when the pulsar is at small angular separations from the Sun (the line of sight grazes denser plasma close to it) and is essentially zero when the pulsar is at solar opposition.
TEMPO2 uses `NESW` to compute and subtract this solar-wind delay from each TOA, assuming a simple spherically-symmetric ($1/r^2$) density profile. Typical values are a few cm^{-3}.



Step 9

Fit all orbital parameters (listed above) one by one starting from `PB`, `A1`, `PBDOT` and so on. Note the change in orbital parameter values. The residual structures as a function of orbital phase shown above should go away.

Step 10

Finally fit `NESW`.
Save the final parfile, and you may name it as "J1909-3744-final.par".

Q7. Check the timing residuals as the function MJD, frequency, orbital phase, day of the year; After fitting all parameters, do you see any left over structures left in the timing residuals? Note down the final **post-fit Weighted RMS** – it should be close to 0.255 μs (incredible precision!!).

Q8. The semi-major axis $A_1 = (a_p \sin i)/c$ tells us the projected size of the pulsar's orbit. Use Kepler's third law (assume $\sin i = 1$ and a pulsar mass $M_p = 1.4\,M_\odot$) to estimate the companion mass M_c. What kind of astronomical object could the companion be?
Hint: Use the definition of binary mass function.

Further Reading

- Lorimer, D.R. & Kramer, M., *Handbook of Pulsar Astronomy*, CUP, 2005.
- Hobbs, G., Edwards, R. & Manchester, R., *tempo2, a new pulsar timing package*, MNRAS 369, 655 (2006).
- McKee, J., *Introduction to Pulsar Timing and Tempo2*, IPTA Student Week lecture, 2018.
- Miles, M. T. et al., *The MeerKAT Pulsar Timing Array*, MNRAS, 2023.
- Liu, K. et al., *High-precision timing of PSR J1909−3744*, MNRAS 499, 2276 (2020).