InPTA Student Week 2022

A primer to Pulsar Timing (Tutorial)

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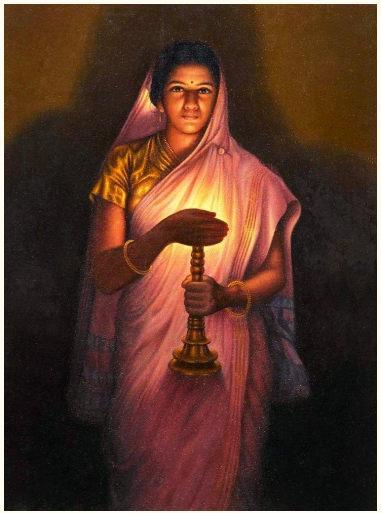
Great Indian Sitarist, Ravi Sankar

An exponent of Bharatnatyam, Rukmini Devi

The Great Wave off Kanagawa : a woodblock print by Japanese ukiyo-e artist Hokusai

"Pulsar Timing is an art....."

~ Bhal Chandra Joshi



Glow of Hope : painting by S. L. Haldankar

Disclaimer: These tutorials on pulsar timing will only introduce you to the basics of pulsar timing. To master the art of timing radio pulsars, we need to practice with different types of pulsar data (isolated pulsars, binary pulsars, etc).

Quick Recap of Pulsar Timing (Refer to Manjari's Talk)

- Track the rotation of pulsar : Estimate the Time of arrival (ToA)
- Various complications and corrections : Clock corrections, ISM effects, STR, GTR, Binary systems, etc.
- ToA Generation : Cross-correlation with template
- Timing : Multi-parameter fitting

For more pulsar timing details one can always refer to Handbook of Pulsar Astronomy (Lorimer and Kramer)

Timing analysis of pulsars: Fitting Procedure-3

- P_s = time difference between consecutive pulses
  f_s = rate of change of pulse number

$$f_s(t_i) = \frac{1}{t_{i+1} - t_i} = \frac{N_{i+1} - N_i}{t_{i+1} - t_i}$$

$$N_{i+1} = f_s(t_i) \times (t_{i+1} - t_i) - N_i$$

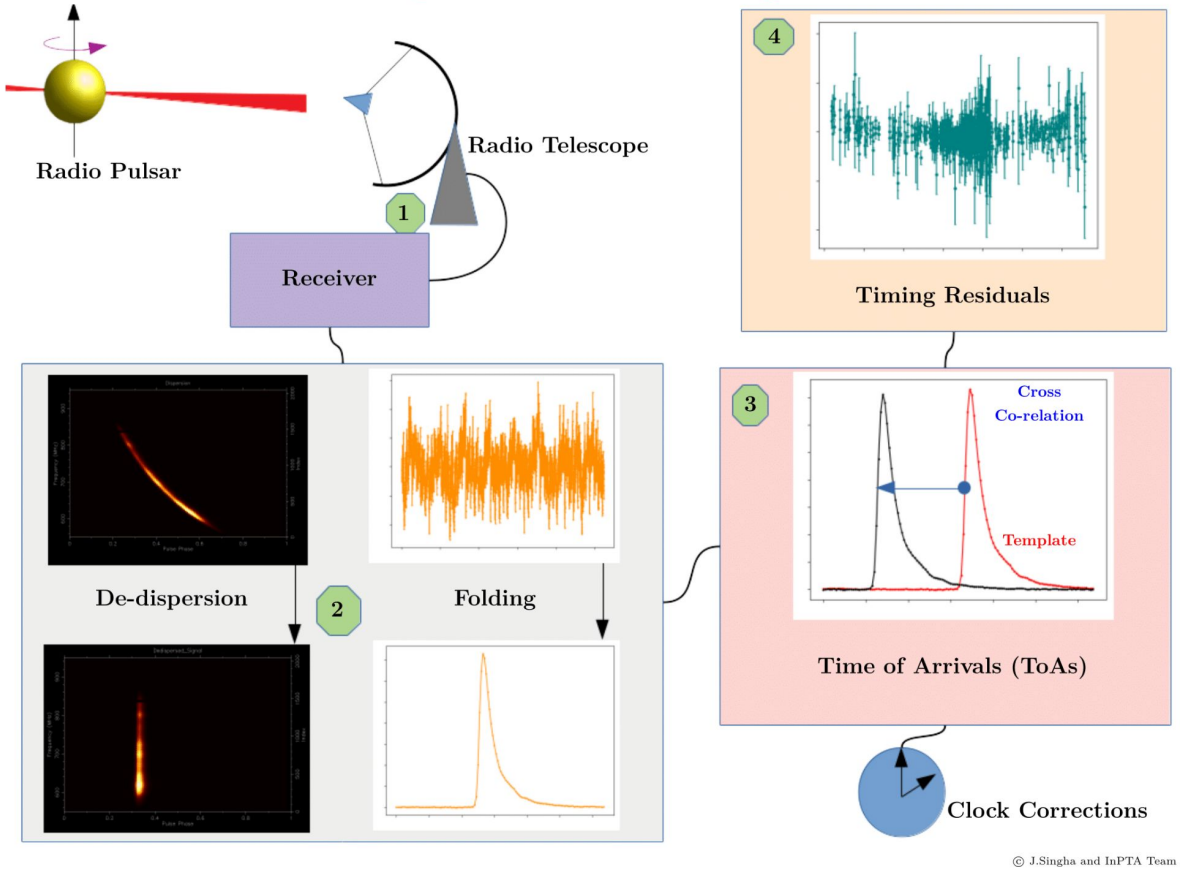
- We have a set of t_is that corresponds to N_is. We correct these measured t_is for all effects (delays) discussed earlier. We calculate $f_s(t_i) = f_s(t_0) + \dot{f}_s(t_0)(t_i - t_0) + (1/2!)\,\ddot{f}_s(t_0)(t_i - t_0)^2 \cdots$ by fitting parameters in tempo2. We insert those in the RHS of the above equation to obtain a value of the LHS $\mathcal{N}_{i+1} = \mathcal{N}(t_{i+1})$. Pulse number should always be integer, say the nearest integer is N_{i+1}.
- We minimise, i.e., change model parameters

$$\chi^2 = \sum_i \left(\frac{\mathcal{N}(t_{i+1}) - N_{i+1}}{\sigma_i} \right)^2$$

- The best fit model parameters: timing solution!
- Residuals $R_i = (\mathcal{N}(t_{i+1}) - N_{i+1})/f_s(t_{i+1})$

From Manjari's Talk

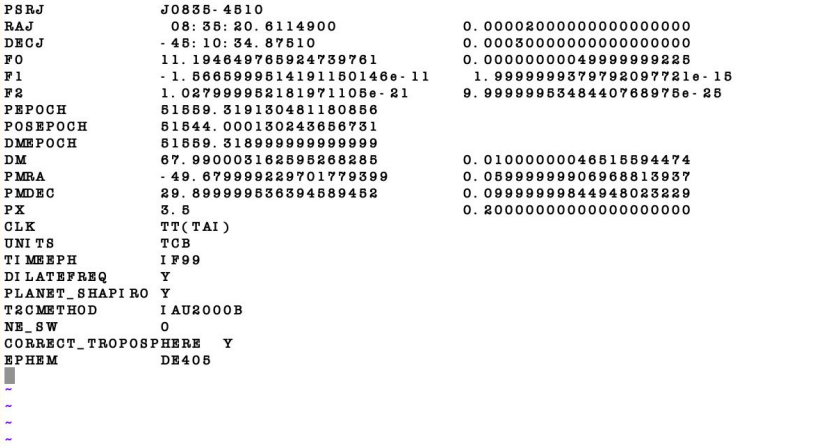
Schematic Diagram of Pulsar Timing Observations



The Pulsar Ephemeris (par file)

Right Ascension
Declination
Frequency
Frequency Derivative
Epoch when F0 is measured
Dispersion Measure
Proper Motion
Parallax

Clock standard
Units
Timing Ephemeris
Solar Ephemeris
Etc



The Pulsar Ephemeris (par file)

Binary parameters:

T2, BT, DD, MS, ELL1, DDH etc.
Binary Period (days)
Epoch of periastron passage
Projected semi-major axis

Clock standard

```
PSRJ            J2145-0750
RAJ               21:45:50.4606057          1  0.0000065832920569209 5
DECJ            -07:50:18.48768             1  0.0002707279251224778 1
F0              62.29588783738383187        1  0.0000000000144545151
F1              -1.1563551169321617895e-16 1  9.4909581393480609126e-21
PEPOCH          55000
POSEPOCH        55000
DMEPOCH         58400
DM              9.0051
PMRA            -9.58299395022203061 99     1  0.0253815591784000288 4
PMDEC           -8.87179936567136088 93     1  0.0692649425506764865 3
PX              1.5346509610735751529       1  0.0952840153268259409 9
BINARY          T2
PB              6.838902615426344 49        1  0.0000000000319018975 6
A1              10.164108024319806264       1  0.0000000802528132944 1
PBDOT           1.2740878501840923706e-13 1  2.8300251478235610462e-14
XDOT            7.5171540724755761786e-15 1  4.8784761068738545289e-16
TASC            53558.375983405215582       1  0.0000000094153858832 6
EPS1            -6.8707864931387065228e-06 1  0.0000000093942954987 1
EPS2            -1.8054550416325962692e-05 1  0.0000000099141487182 3
EPHVER          5
NE_SW           0
CLK             TT(BIPM2015)
MODE 1
UNITS           TCB
TIMEEPH         IF99
DILATEFREQ      Y
PLANET_SHAPIRO  Y
T2CMETHOD       IAU2000B
CORRECT_TROPOSPHERE   Y
EPHEM           DE436
~
~
```

The ToA file (tim file)

FITS file name

Frequency of observation (MHz)

ToA (in MJD?)

ToA error

Telescope name

Additional flags

```
FORMAT 1
J2145-0750_59156.584211_1460.gptool.col.fits 1447.597656 59156.603414292191933  16.885  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1422.597656 59156.603414299508135  14.969  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1397.597656 59156.603414307298769   4.488  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1372.597656 59156.603414315394340   5.079  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1347.597656 59156.603414324086706   4.997  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1322.597656 59156.603414333080804   5.572  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1297.597656 59156.603414342825221   5.253  gmrt
J2145-0750_59156.584211_1460.gptool.col.fits 1272.597656 59156.603414352861320  14.325  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1447.597656 59175.472569231093042  68.667  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1422.597656 59175.472569129129542  81.292  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1397.597656 59175.472569163828811  32.735  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1372.597656 59175.472569171416613   8.734  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1347.597656 59175.472569180037334   4.623  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1322.597656 59175.472569189028600   4.528  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1297.597656 59175.472569198742269   3.405  gmrt
J2145-0750_59175.455059_1460.gptool.col.fits 1272.597656 59175.472569208909574   7.796  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1447.597656 59264.218055475437526  71.895  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1422.597656 59264.218055482550714  12.966  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1397.597656 59264.218055490466362  12.402  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1372.597656 59264.218055498235349  11.546  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1347.597656 59264.218055507370602  18.959  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1322.597656 59264.218055516330428  20.206  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1297.597656 59264.218055526450508  29.773  gmrt
J2145-0750_59264.198873_1460.gptool.col.fits 1272.597656 59264.218055536224893  40.939  gmrt
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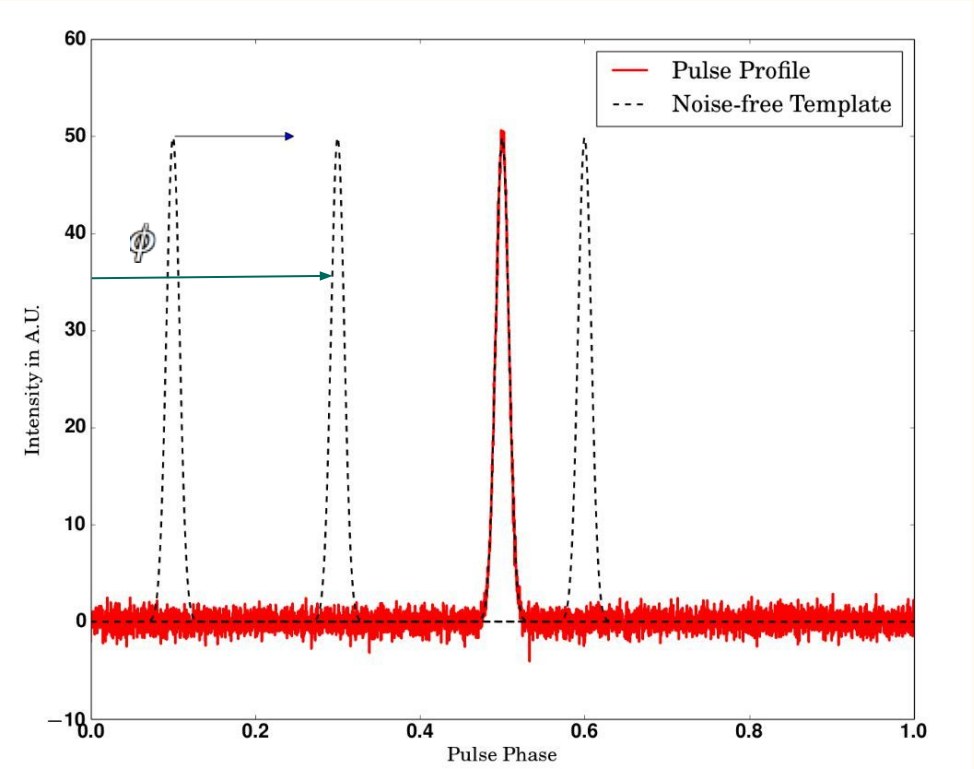
Recap: Generating the Time of Arrival



$$p(t) = a + bs(t - \tau) + g(t)$$

Recap: Template generation

1. Any high SNR profile
2. Addition of few profiles
3. Any high SNR profile + psrsmooth
4. Addition of few profiles + psrsmooth
5. Paas

Tempo2

Tempo2 is a software package, widely used by pulsar astronomers, to analyse the times of arrivals (ToAs) of the pulsar signals from observations, along with a timing model accounting for various time delays, a solar system ephemeris, and clock corrections from the observatory.....

- **Hobbs et al., 2006, Edwards et al., 2006, etc....**

Useful resources:

1. Tempo2 user manual : George Hobbs, Russell Edwards (documentation V2.0)
2. Tempo2 Examples : George Hobbs (PPTA)

Libstempo

Libstempo is a Python wrapper around the tempo2 pulsar timing package.

https://github.com/vallis/libstempo

More about Libstempo in PINT tutorial by Sai.

Let us start the hands-on.....