A primer to Pulsar Timing (tutorial)

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In this tutorial, we will go through basic pulsar timing using the tempo2 software and obtain the timing residuals. Tempo2 is a popular pulsar timing package developed to be used both for general pulsar timing applications and also for pulsar timing array analysis. It is very versatile and can be extended by plugins.

1 Introduction

Pulsar timing is a very powerful technique which has enabled tests of gravity, plasma physics and nuclear physics – extreme conditions that are not achievable in Earth-based laboratories.

A useful point to note here is that, many of the Tempo2 programs print out a brief help message when the -h command line option is used.

2 Tempo2 Usage

1. Simplest form
   tempo2 -f <parfile> <timfile>
2. Graphical Interface : plk plugin
   tempo2 -gr plk -f <parfile> <timfile>
3. Graphical Interface : splk plugin
   tempo2 -gr splk -f <parfile1> <timfile1> -f <parfile2> <timfile2>
4. Graphical Interface : fake plugin
   Create a fake parfile: fake.par
   tempo2 -gr fake fake.par
5. Graphical Interface : transform plugin
   tempo2 -gr transfrom tempo1.par tempo2.par [back]
6. Output format : general2 plugin
   tempo2 -output general2 -s "{BAT} {post} {err} " -f <parfile> <timfile>

3 Creating template

1. Using high SNR profile directly
2. Using psradd to add a few high SNR profiles
3. Using psrsmooth on any of the above two final profiles
4. Using paas

   paas -i <pulsar_profile>

   A graphical interface will open. Here we will fit multiple Gaussian waveform to model the

pulse profile

(a) Fist select the centre
(b) Second the width
(c) Third the peak
(d) Repeat to capture the full shape of the pulse profile
(e) Press "f" which means fit the model to the data
(f) Report the reduced χ^2 of the fit, make sure it should be ~ 1, but also you should not over fit.
(g) Press the key "q"
(h) Report what are the new files created in the directory.

4 Generating arrival time estimates with pat

pat -F -f tempo2 <files> -s <template> -A PGS > <timfile name>

5 Tutorials

5.1 Tut-1: Looking at parfiles and timfiles

In this folder, you will find a few parfiles and timfiles. Please open the files and have a look at them to see the differences in these files for isolated pulsars and millisecond pulsars.

5.2 Tut-2: Bad ToA removal

This folder contains a set of FITS files which were used to generate the ToA file. Use tempo2 plk plugin to look at the timing residuals. Try to identify the bad ToA files manually.

5.3 Tut-3: Wrong parameters

Use tempo2 with the parfiles given in this folder. Look for trends and identify which parameter needs to be fitted.

5.4 Tut-4: Phase connection

This folder contains a timfile where the phase connection needs to be achieved. Use tempo2 to do so.

Did you encounter an error? What does the error message says?

Put the ORT coordinates in your observatories directory.
Inside $TEMPO2/observatory/observatories.dat

```
1442712.95 6087044.73 1251052.35 ORT ort
```

5.5 Tut-5: DMMODEL and DMX

Implement DMMODEL and DMX (DM values obtained using DMcalc) in timing.

5.6 Tut-6: Use of other plugins

Try using general2, splk, fake, transform plugins of tempo2.

5.7 Tut-7: IPTA DR2 example

Use IPTADR2 pulsar data files for timing.

5.8 Tut-8: Check if IPTA DR2 solutions are the global minima

Perturb the solution of IPTADR2 and refit to see if the same parameter value is obtained.

plk plugin options

```
b          Bin TOAs within certain time bin
c          Change fitting parameters
C          run unix command with filenames for highlighted observations
ctrl-c     Toggle between period epoch and centre for the reference epoch
d (or right mouse) delete point
D (or middle mouse) view profile
ctrl-D     delete highlighted points
e          multiply all TOA errors by given amount
f          finish of zoom section
F          run FITWAVES
ctrl-F     remove FITWAVES curve from residuals
g          change graphics device
G          change gridding on graphics device
h          this help file
H          highlight points with specific flag in .tim file
i (or left mouse) identify point
j          draw line between each points
l          list all data points in zoomed region
L          add label to plot
ctrl-l     add line to plot
m          measure distance between two points
M          toggle removing mean from the residuals

   ctrl-m     toggle menu bar
   o          obtain/highlight all points currently in plot
   p          Change model parameter values
   P          write new .par file
   ctrl-P     Toggle fitting versus pulse phase
   q          quit
   r          Reset (reload .par and .tim file)
   s          start of zoom section
   S          save a new .tim file
   ctrl-S     Overplot Shapiro delay
   u          unzoom
   U          unhighlight selected points
   v          view profiles for highlighted points
   V          define the user parameter
   ctrl-V     for pre-fit plotting, decompose the timing model fits
   w          toggle fitting using weights
   x          redo fit using post-fit parameters
   ctrl-X     place periodic marks on the x-scale
   y          Rescale y-axis only
   z          Zoom using mouse
   +          add positive phase jump
   -          add negative phase jump
   ctrl-=     add period to add residuals above cursor
   <          in zoom mode include previous observation
   >          in zoom mode include next observation
   1          plot pre-fit  residuals vs date
   2          plot post-fit residuals vs date
   3          plot pre-fit  residuals vs orbital phase
   4          plot post-fit residuals vs orbital phase
   5          plot pre-fit  residuals serially
   6          plot post-fit residuals serially
   7          plot pre-fit  residuals vs day of year
   8          plot post-fit residuals vs day of year
   9          plot pre-fit  residuals vs frequency
   a          plot post-fit residuals vs frequency
```

general2 plugin options

```
        {sat}   site-arrival-times
        {bat}   barycentric arrival times
        {clock0 -> clock4}  various clock correction values
        {shapiro} the solar Shapiro delay
        {shapiroJ} the Shapiro delay due to Juptier
        {shapiroS} the Shapiro delay due to Saturn
        {shapiroV} the Shapiro delay due to Venus
        {shapiroU} the Shapiro delay due to Uranus
        {shapiroN} the Shapiro delay due to Neptune
        {tropo} the tropospheric delay
        {roemer} the solar system Roemer delay
        {tt}    correction to TT

    {tt2tb} correction from TT to TB
    {earth_ssb} magnitude of vector from Earth to barycentre
    {earth_ssb1} magnitude of 'x' component from Earth to barycentre
    {earth_ssb2} magnitude of 'y' component from Earth to barycentre
    {earth_ssb3} magnitude of 'z' component from Earth to barycentre
    {sun_earth1} magnitude of 'x' component from Sun to Earth
    {sun_earth2} magnitude of 'y' component from Sun to Earth
    {sun_earth3} magnitude of 'z' component from Sun to Earth
    {ism}        interstellar medium dispersion delay
    {elev}       Source elevation
    {npulse}     pulse number
    {clock}      complete clock corrections to TT
    {ipm}        interplanetary medium dispersion delay
    {freq}       observing frequency
    {pre}        prefit timing residual in seconds
    {pre_phase}  prefit timing residual in phase
    {post}       postfit timing residual in seconds
    {post_phase} postfit timing residual in phase
    {err}        TOA error
    {binphase}   binary phase
```

6 Introduction to Pulsar Timing using libstempo2

1. **timing_libstempo1.ipynb** : libstempo tutorial taken from libstempo website.
2. **timing_libstempo2.ipynb** : libstempo tutorial with data sets given in Tut2 and Tut3 above.

7 More exercises to try

1. Scrunch the fits file to a lower number of frequency subbands. What happens to the ToA erros? What do you expect from theory?
2. Use IPTA DR2 parfile and remove the jumps. Run Tempo2. What do you notice? Try to fit for variuos jumps.
3. Create templates using various methods and do timig separately. What differences do you notice?
4. Go through the juppyter notebook **timing_libstempo2.ipynb** (libstempo tutorial to simulate datasets from Viper Summer School 2022).
5. Try the HD corelation jupyter notebook