IPTA 2011, Day 3
Pulsar Timing Practicum
Introduction to TEMPO2

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June 8, 2011

1 Introduction to Tempo2

TEMPO2 is the new version of TEMPO, a software package widely used in the pulsar timing community to find timing solutions for pulsars. TEMPO2 uses as input the times-of-arrival (TOAs) and the timing model for a particular pulsar, and outputs residuals. By inspecting the residuals, the TOAs and timing model can be refined and improved.

TEMPO2's advantages over TEMPO include the possibility of analyzing several pulsars at once (something important for the detection of gravitational waves which requires observing several pulsars in a pulsar timing array), as well as the use of "plug-ins" (think "app" for your iPhone). The most important TEMPO2 plug-in is "plk" ("plot-look"). With this plugin you can inspect, evaluate and improve your timing model and TOAs.

The exercises below will introduce you to some fundamental aspects of using the TEMPO2 pulsar timing software.

1.1 Inspecting Residuals: plk

1.1.1 Introduction to plk and Parameter Fitting

To inspect and "play around" with timing residuals, the PLK plug-in is generally used. Using the init.par and init.tim files, try:

```
tempo2 -gr plk -f init.par init.tim
```

Notice some standard input arguments of TEMPO2:

-gr: Determines the graphical interface or plug-in. In this tutorial, we will introduce the PLK plug-in. You can also relatively easily create your own plug-ins.

-f: Specifies the input file with the timing model (also called "par-file") and the file with the TOAs (also called the "tim-file"). The order ("par" followed by "tim") is important!

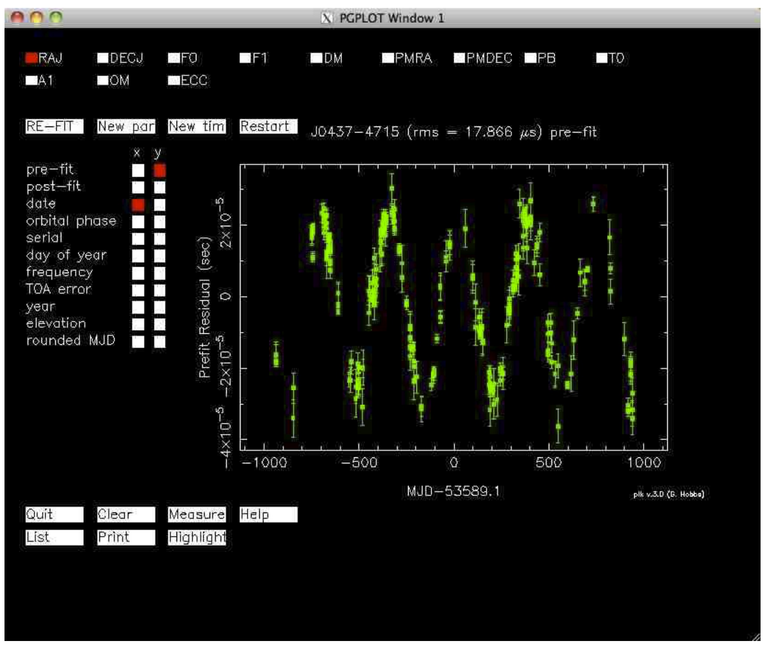

Figure 1: Startup display of the TEMPO2 PLK plug-in.

You should now see a display as in Fig. 1. There are three main components to the display:

A plotting area By default, the residuals are plotted with error bars as a function of their MJD. In the title of the plotting area, the pulsar name and the root-mean-square (rms) of the plotted residuals are shown and whether the plotted residuals are pre- or post-fit.

Switches There are two areas of switches: all on top of the graphics window there are switches to turn fitting on (red box) or off (white box) for different parameters in the timing model. Currently we are fitting for right ascension (RAJ) and declination (DECJ) only. The second set of switches selects which parameters you plot on the x and y axes. Currently we are plotting "pre-fit" residuals (y) against MJD or "date" (x).

Buttons There are two areas with buttons in the window. One near the top of the window and one on the bottom. The most important buttons to know are the "RE-FIT", "New par", "New tim" (all three on top) and "Quit" (bottom) buttons, which will be introduced shortly. Note that for all these buttons (as well as for the plotting switches) there are hotkeys (that can save you much time), which we encourage you to actively use.

Notice that the pre-fit residuals contain a yearly sine-wave. This is typical of a wrong pulsar position in the pulsar timing model. As you can see (red switches), we are fitting for position, so the post-fit residuals should have an updated position. To look at the residuals with the improved position, **plot the post-fit residuals against MJD/date.** There are two ways to do this: either by clicking the "post-fit" switch under "y", or by hitting '2' on the keyboard.

Getting help in Tempo2

There are two main ways of interacting with the TEMPO2 software: through command-line arguments (like '-gr' and '-f' as described before) and through key-board interaction (like hitting '2' to get post-fit residuals versus MJD). The third way (through switches and buttons) is (currently) unique to plk and does not contain any help beyond what's written on the buttons and next to the switches.
In order to obtain a list of possible command-line arguments along with brief descriptions of these, add "-h" to the command line:

```
C:/> tempo2 -gr plk -h
```

The same works for the basic TEMPO2 code, which will give you general TEMPO2 command-line arguments as well as a list of all installed plug-ins:

```
C:/> tempo2 -h
```

To obtain information on the possible hotkeys available in a plug-in, hit 'h' inside the graphics window. In the case of the PLK plug-in, there are a vast amount of keys you can press. **Type 'h' in the plk graphics window and have a look through the key presses. Some of these are for very specific purposes and may not be useful for the data you are currently working on, but others you will use very soon. Try out a few of these, especially try the keys 1 to 9, a and @ to see the different plotting options and play around with zooming (s, f, z, u), indicating points (o) and deleting points (d, Ctrl+d, mouse scroll, right mouse button).**

Now, you can improve your timing model. Do this by turning on fitting for various parameters (click the switches next to the timing model parameters, at the top of the graphics window) and re-fitting the timing model by clicking the "RE-FIT" button, or (preferably) by hitting 'x' while the graphics window is active. Typically you would only gradually turn on fitting for one or two parameters at a time, to allow the model to converge before introducing a new variable. The data set you are currently working with, however, is well-behaved and this is not a problem. As you fit for an increasing number of parameters, notice how the rms of the residuals goes down (you can find this number right above the residual plot in the graphics window).

The x-term text of Tempo2

Besides the graphics window, PLK also provides a lot of information in the x-term from which TEMPO2 was started. Typically, you would get information like this:

```
Results for PSR J0437-4715

RMS pre-fit residual = 18.058 (us), RMS post-fit residual = 4.131 (us)
Number of points in fit = 262

PARAMETER       Pre-fit                   Post-fit                  Uncertainty   Difference   Fit
---------------------------------------------------------------------------------------------------
RAJ (rad)       1.20979414670511          1.20979421910139          1.0835e-09    7.2396e-08    Y
RAJ (hms)       04:37:15.8636846           04:37:15.8646801         1.4899e-05    0.00099552
DECJ (rad)      -0.824711371731622        -0.824711367110639        7.9645e-10    4.621e-09     Y
DECJ (dms)      -47:15:08.93130           -47:15:08.93035           0.00016428    0.00095315
F0 (s^-1)       173.687945948429          173.687945948429          0             0             N
F1 (s^-2)       -1.72842582491239e-15     -1.72842582491239e-15     0             0             N
PEPOCH (MJD)    53589                     53589                     0             0             N
POSEPOCH (MJD)  53589                     53589                     0             0             N
DMEPOCH (MJD)   53589                     53589                     0             0             N
DM (cm^-3 pc)   2.64490234304054          2.64490234304054          0             0             N
PMRA (mas/yr)   121.158622391678          121.158622391678          0             0             N
PMDEC (mas/yr)  -71.2981347824207         -71.2981347824207         0             0             N
PB (d)          5.74104245756631          5.74104245756631          0             0             N
T0 (MJD)        53588.6529714743          53588.6529714743          0             0             N
A1 (lt-s)       3.36670891281376          3.36670891281376          0             0             N
OM (deg)        2.09201272756846          2.09201272756846          0             0             N
ECC             1.99907163499582e-05      1.99907163499582e-05      0             0             N
START (MJD)     52649.7294699937          52649.7294699937          0             0             N
FINISH (MJD)    54528.5009999717          54528.5009999717          0             0             N
TRACK (MJD)     0                         0                         0             0             N
TZRMJD          53567.3124999919          53567.3124999919          0             -1.4552e-11   N
TZRFRQ (MHz)    1341                      1341                      0             0             N
TZRSITE         7
TRES            3.981                     4.13105662058684          0             0.15006       N
EPHVER          5                         5                         0             0             N
---------------------------------------------------------------------------------------------------

Derived parameters:

P0 (s)      = 0.00575745193219635       0
P1          = 5.7294296106505e-20       0
tau_c (Myr) = 1593.2
bs (G)      = 5.8119e+08

Binary model: T2
Mass function                 = 0.001243133916  +- 0.000000212341
solar masses
Minimum, median and maximum companion mass: 0.1403 < 0.1637 < 0.3493
solar masses
Total proper motion = 140.58 +/- 0 mas/yr
Total time span = 1878.770 days = 5.144 years
```

The most important part of this is the table which lists all the parameters in the timing model, their pre- and post-fit values, the measurement uncertainty on the post-fit value, the difference between pre- and post-fit and whether the parameter in question is being fitted (Y) or not (N). Above this table, the residual rms of the pre- and post-fit residuals is given, along with the number of points in the fit and (in case of a weighted fit), the reduced χ^2 value for the fit. Look through the help (hit 'h') and try to figure out how to turn weighting on and off. Compare the residual rms for the weighted and unweighted fit. Do you expect this difference?

Once you have improved the timing model through fitting for all parameters, write out a new timing model (par file) either by pressing the relevant button on the graphics window or by hitting the appropriate hotkey (see the help - 'h').

1.1.2 Timing Signatures of Model Parameters

Every timing model parameter has a unique timing signature. With PLK it is easy to find out what these different signatures look like. To do so, turn off fitting for all parameters (by clicking the switches or by pressing the hotkey 'c' and following the instructions on the x-term). Next, hit 'p' in the graphics window. In the original x-term, you will be asked to select a parameter to change - type "PMRA" and hit enter. Subsequently, give in the new value of '100' and hit enter again. You now see the timing residuals with a faulty proper motion in right ascension. Do you understand the shape of these residuals?

Turn fitting for PMRA on (by hitting the switch or typing 'c' in the graphics window), re-fit (by hitting 'x') and compare the pre- and post-fit residuals by hitting '1' and '2'. Repeat this exercise for some more parameters to get a feeling for what the different timing signatures look like. For the binary parameters, you may want to look at the pre- and post-fit residuals as a function of binary phase (hit '3' and '4' for pre- and post-fit residuals as a function of binary phase respectively). Also, make sure to be careful not to change parameters too much because if the signature grows too large you may experience phase-wraps, which will be very hard to recover from. In case this happens, the best you can do is to quit the program (press 'q' in the graphics window, Ctrl+c in the x-term or hit the "Quit" button) and restart TEMPO2 with your most recent par-file.

1.1.3 The Parameter File

Now we'll have a closer look at the parameter file. Quit PLK and open the par-file you've just created with your favourite text editor. This should look something like this:

```
PSRJ           J0437-4715
RAJ            04:37:15.8636846           1  0.21011137467902116769
DECJ           -47:15:08.93130            1  34.78324101756007952213
F0             173.68794594842935443      1  0.00000000000111788754
F1             -1.7284258249123948464e-15 1   5.7230740822669443999e-20
PEPOCH         53589
POSEPOCH       53589
DMEPOCH        53589
DM             2.6449023430405429367      1  0.00246579734298233268
PMRA           121.15862239167792101      1  0.11290275671340979646
PMDEC          -71.29813478242066806      1  0.13587334030220266090
```

```
BINARY         T2
PB             5.7410424575663080568      1  0.00000000132561712661
T0             53588.652971474344913      1  0.01015645370511947601
A1             3.3667089128137608045      1  0.00000037891156380237
OM             2.0920127275684644651      1  0.63687421134468769068
ECC            1.999071634995824611e-05   1  0.00000023205093714752
START          52649.729469993733801
FINISH         54528.500999971678539

TZRMJD         53567.312499991897074
TZRFRQ         1341
TZRSITE        7
TRES           3.981
EPHVER         5
CLK            TT(TAI)
EPHEM          DE200
NITS           1
NTOA           262
```

The par-file shows you the post-fit value and measurement uncertainty for all the parameters in the timing model, along with a '1' in the third column if the parameters were fitted for at the time the par-file was created. There are also some constants:

PSRJ: the J2000.0 name of the pulsar

PEPOCH: the reference epoch for the pulse period. Similarly, POSEPOCH is the reference epoch for the pulsar position and DMEPOCH is the reference epoch for the dispersion measure (DM).

BINARY: determines the binary model used. As was briefly mentioned in the lectures this morning, historically there have been several different models for binary orbits. The T2 model is TEMPO2's attempt at replacing all of these, but previous models (BT, DD, ELL1,...) still work as well.

START: the MJD of the first TOA in the tim-file. Similarly, FINISH is the MJD of the last TOA in the tim-file.

TZRMJD: together with TZRSITE and TZRFRQ, this parameter defines the phase-zero point.

TRES: the rms residual of the tim-file from which this par-file was derived.

EPHVER: determines which format this file is in. For historic reasons, 5 denotes TEMPO2 format while 2 denotes TEMPO format.

CLK: determines the clock reference that was used.

EPHEM: determines which Solar-System ephemeris model is being used.

NITS: gives the number of fitting iterations a "re-fit" performs.

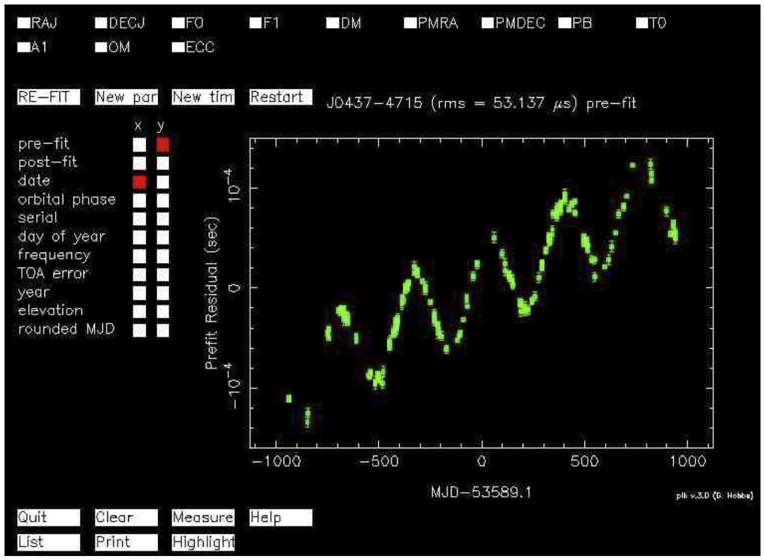

Figure 2: The timing residuals after changing from the DE200 Solar-System ephemeris model to the DE405 model, without any fitting.

NTOA: determines the number of TOAs in the related tim-file.

The Solar-System ephemeris model that we are currently using (DE200) is slightly outdated and currently it is more common to use the more up-to-date DE405 model. In order to do so, you can simply manually change your par-file by changing DE200 into DE405 on the EPHEM line. Once you've done that, run plk again and look at the residuals. You should see something like Fig. 2.

You can clearly see a linear drift along with a sine-like wave. Relabelling the X-axis into calendar years (hit 'Ctrl+x' then '0'), you can easily see that the wave has a yearly period. This is because the differences in the Solar-System ephemerides slightly changed the Solar-System barycentre, which in turn implies the relative position of the Earth (or, to be specific, the transformation from site arrival times to barycentric arrival times) was corrected wrongly. This difference can most readily be modelled as a difference in pulsar position, which is why the signal wasn't seen earlier: the errors in the Solar-System ephemeris model were absorbed in the parameter fits for position and period. If everything is correct, fitting was turned on for all (sensible) parameters in your par-file, so a fit has already been performed. To see the result of this fit, display the post-fit timing residuals (hit '2').

Notice the residual rms, which is now lower (though not much) than it was with the DE200 model - this indicates the improved quality of DE405 over DE200.

1.2 Other plug-ins

- If you are dealing with "red" pulsars (pulsars with timing noise at the low-frequency end of the spectrum), you can use the spectralModel plugin to plot the power spectrum of pulsar residuals, separating red noise from white noise. The plug-in ouputs the covariance function which can then be used to better fit model parameters. The command is:

  ```
  tempo2 -gr spectralModel -f filename.par filename.tim
  ```

- The "fake" plug-in is used to make fake data.

- You can also write your own plug-ins.

1.3 Simulating Gravitational Waves: GWsim and GWbkgrd

One can "inject" a gravitational wave using the GWsim or GWbkrd plug-ins. See Justin's slides.

1.4 Further Information

More can be found in Joris Verbiest's practicum from IPTA 2010 (available on the preparation page of the IPTA 2011 website). This includes sections on:

- How to add binary parameters, since most millisecond pulsars are in binary systems.

- How to add in new data using jumps

- Weighting and uncertainty estimation

- Using the "fake" plugin

  A full TEMPO2 user manual can be found on-line at http://www.atnf.csiro.au/research/pulsar/tempo2. Specifically, under "Documentation" in the left-hand menu, you can find most (if not all) of the information covered in this tutorial, along with a complete description of the file formats, timing model parameters etc. Appendix A of the documentation provides an introduction into writing your own TEMPO2 plug-ins, which unleashes the true power behind Tempo2. Under "Download tempo2" (also in the left-hand menu), you can find full instructions on installation of the latest sourceforge version, which includes several gravitational-wave simulation plug-ins in addition to the more traditional plug-ins.

The TEMPO2 software package and its differences with the TEMPO software are described by Hobbs, Edwards & Manchester, MNRAS Vol. 369, p. 655, 2006. The timing model is described by Edwards, Hobbs & Manchester, MNRS Vol. 372, p. 1549, 2006 and the gravitational-wave simulation code is described by Hobbs, Jenet, Lee et al., MNRAS Vol. 394, p. 1945, 2009.

2 Finding a timing solution for an isolated pulsar

In addition to pulse phase, there are four basic parameters to fit in TEMPO2:

1. F0 - spin frequency
2. F1 - frequency derivative i.e. spin down of the pulsar (we won't consider higher derivatives here)
3. RAJ - Right ascension (J2000)
4. DECJ - Declination (J2000)

When we have data at multiple frequencies, we normally fit for dispersion measure (DM), but we won't do this here.

For each of the first 3 sets of example parameter (.par) and TOA (.tim) files in your folder [example1, example2, example3]:

1. Identify a closely-separated set of TOAs in the "tim" file (e.g., pick 3 neighboring TOAs taken the same day or very close). Isolate the set using SKIP/NOSKIP.
2. Run tempo2:

   ```
   tempo2 -gr plk -f example1.par example1.tim -tempo1
   ```

(we use the TEMPO emulation mode here "-tempo1" because the tim files are in TEMPO format).

3. Fit for F0 and take note of the rms. If the rms is less than or about 1 % of the period, go to the next step. Otherwise find another set of closely spaced TOAs.
4. Add neighboring TOAs and look at the pre-fit residuals.
   If the rms increases dramatically, then you may need to fit for one of the following: F1, RAJ or DECJ before adding more points. Try fitting only one new parameter at a time.
5. Save your work prior to fitting any new parameter: click on "New par" to save intermediate par files and "New tim" to save intermediate tim files. You need to input a filename at the prompt.
6. Repeat steps above: including more points (until you have included all of them) and fitting for all parameters. The key is to do both of these things iteratively so that the fits converge.
7. Weigh the fit at the end by pressing "w" in the plk and note your final rms. Print a plot of your final residuals.
8. Check your ephemeris (the parameters in your final "par" file) with the ATNF catalog. You should find the name of the pulsar you've been working on, and see that the parameters match well with your prediction. Voila!
9. Now that you have a solution, reproduce the plots in Fig. 3 by setting the relevant parameter to 0 in the par file and show the residuals without fitting.

If you have time, go ahead and work on Examples 4 and 5. They are more challenging. Hint: Example 4 needs 2 jumps, which can be placed in the "tim" file by writing "PHASE +1" for each jump.

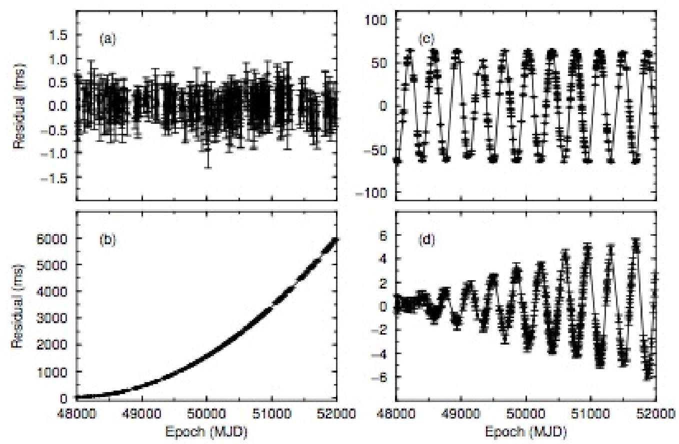

Fig. 8.2. (a) Timing residuals for the 1.19 s pulsar B1133+16. A fit of a perfect timing model should result in randomly distributed residuals. (b) A parabolic increase in the residuals is obtained if $\dot{P}$ is underestimated, here by 4 per cent. (c) An offset in position (in this case a declination error of 1 arcmin) produces sinusoidal residuals with a period of 1 yr. (d) The effect of neglecting the pulsar's proper motion, in this case $\mu_{\rm T} = 380$ mas yr^{-1}. In all plots we have set the reference epoch for period and position to the first TOA at MJD 48000 to show the development of the amplitude of the various effects. Note the different scales on each of the vertical axes.

Figure 3: From Lorimer & Kramer