IPTA 2010, Day 2:
Pulsar Timing Basics Practicum
Introduction to TEMPO2

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2 Tempo2

The exercises below will introduce you to some fundamental aspects of using the TEMPO2 pulsar timing software. The primary aim is to gain confidence with the way the package (and its plug-ins) work, though some introductory information about pulsar timing will of course also be covered.

We will use two main plug-ins in this tutorial:

plk: The most important plug-in of TEMPO2. With this plug-in you can inspect, evaluate and improve your timing model and TOAs.

fake: This plug-in allows you to simulate fake data sets, which can often come in handy when trying to understand or prove concepts.

2.1 Inspecting Residuals: plk

2.1.1 Introduction to plk and Parameter Fitting

To inspect and "play around" with timing residuals, the PLK ("plot-look") plug-in is generally used. Using the init.par and init.tim files (which you can find in /data/ipta/day2/tempo2data/), try:

```
C:/> tempo2 -gr plk -f init.par init.im
```

Notice some standard input arguments of TEMPO2:

-gr: Determines the graphical interface or plug-in. In this tutorial, we will introduce the PLK and FAKE plug-ins. 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 site-arrival-times (also called the "tim-file"). The order (par followed by tim) is important!

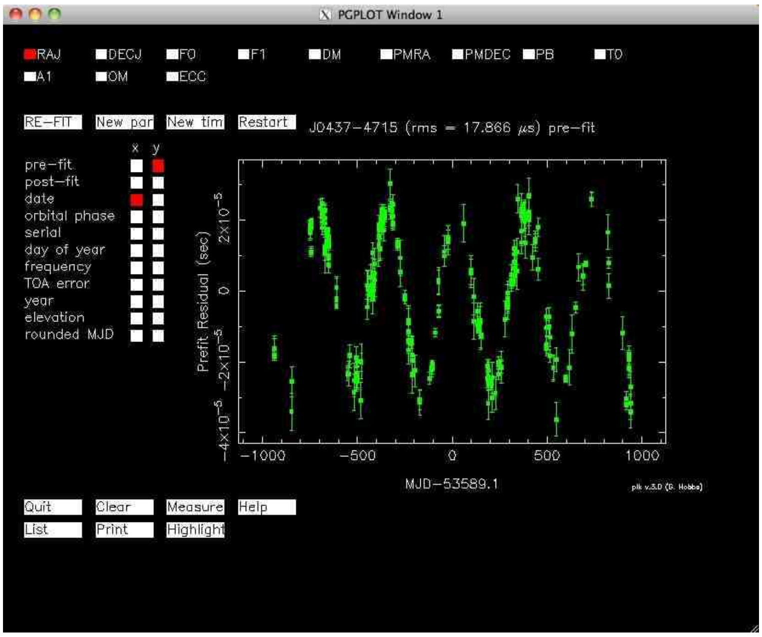

Figure 1: Startup display of the TEMPO2 PLK plug-in.

You should now see a display as in Figure 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').

2.1.2 Timing Signatures of Model Parameters

You have seen in the lectures that 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.

2.1.3 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.

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 Figure 2.

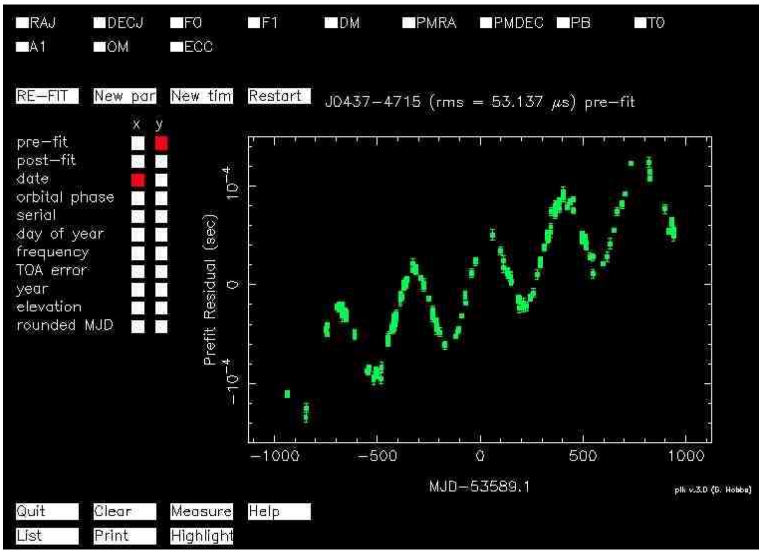

Figure 2: The timing residuals after changing from the DE200 Solar-System ephemeris model to the DE405 model, without any fitting.

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.

Another thing you should notice, is the amount by which the different parameters have changed. Looking at the table in your x-term, you can see that the difference for the binary parameters is always smaller than the parameter uncertainty, indicating that any change in these parameters was insignificant. The non-binary parameters, however (position, period, proper motion) *have* changed significantly. This means that the values derived using the DE200 model were wrong by a tiny amount, or rather: it means that the uncertainties of the parameters contained in the DE200 model were not properly accounted for in our timing results.

2.1.4 Expanding the Timing Model

The timing model we've been using so far was reasonably simple: it only contained astrometric, spin and basic binary parameters. In order to expand a timing model, we have to hack the par-file. So now that you have implemented the DE405 model and refitted, save the par-file again (as, say, DE405.par), quit PLK and open the newly saved par-file with your favourite text editor.

First, we'll add the parameters we want to add, but we don't fit for them yet. On the line right above[1] "BINARY", add: "PX 0 0 ": parallax with a value of 0 and we are not fitting for it (as the second zero indicates). If we now run TEMPO2 with PLK again, you can see a new switch has appeared, to allow fitting for parallax. If you turn on fitting, however, you can see in the x-term that the measurement uncertainty is larger than the measured value. This means we have an insignificant measurement: the parallax signature is too small and we cannot confidently claim any size for the parallax, we can only place an upper limit. In this case there is no legitimate reason to include parallax in your timing model so we should quit PLK and remove the PX line from the par-file.

Next, we will try a post-Keplerian parameter. On the first line after the one that says "BINARY", add: "OMDOT 0 0 " for $\dot{\omega}$, the periastron advance. If you now rerun PLK, you'll see the PX switch has disappeared but an OMDOT switch has appeared instead. Before proceeding, make sure you are looking at the *post-fit* residuals (hit '2'). Now, click the OMDOT switch and re-fit (hit 'x'). As you can see, after a first iteration of fitting, the residuals are actually getting worse! This is a consequence of the covariance between P_{b} (the orbital period) and $\dot{\omega}$. There are more rigorous techniques to figure out this correlation, but for now, you can discover it by inspecting the table given in the x-term. In that table, you can see that the only parameter that has been significantly changed (i.e. the difference between post- and pre-fit is larger than the uncertainty), is the orbital period. Because of this correlation, you'll have to re-fit a couple of times (hit 'x' repeatedly), until the rms residual remains constant. As you can see from the x-term table, you now have a $3.5\,\sigma$ detection of periastron advance!

[1] In fact it doesn't matter on which line in the par-file you add things: TEMPO2 will read each line and interpret it in itself. However, it makes sense to group parameters logically.

2.1.5 Adding in New Data

Now copy the addit.tim tim file. This is additional simulated data with higher precision - as you might get from, e.g. another telescope or a new back-end. In order to add this new data to our timing, simply concatenate the two files:

```
C:/> cat init.tim addit.tim >> all.tim
```

Now run PLK again, but add the

```
-nofit
```

command-line argument for reasons that will become clear in a second:

```
C:/> tempo2 -gr plk -f DE405.par all.tim -nofit
```

As you can see, the residuals of the two files do not line up. If we were to fit for any parameters now (which you can try), this offset between the data sets would totally corrupt your results. In order to correct for this, we will have to add a "jump" between the two data sets. To do this, quit from TEMPO2 and edit the par-file with your favourite text editor. All at the bottom of that file, add:

```
JUMP MJD 54529 55100 0 1
```

This line tells TEMPO2 to jump all the data that falls between MJDs 54529 and 55100. The 0 indicates that the current jump value is 0 (since we don't know any better) and the 1 at the end of the line implies that we want to fit for the jump. If you now run TEMPO2 with PLK again, we get the same result but 54529 has appeared in red on the bottom of the screen. This is a switch with which you can fit for this jump. If you click on the MJD, it turns green and in the next fit you will be fitting for the jump. Try to do this (make sure to look at the "post-fit" residuals!)

2.1.6 Weighting and Uncertainty Estimation

Now that we have a data-set with a wide range in TOA uncertainties (hit '@' to plot the TOA uncertainties), it would make sense to perform a weighted fit. To do this (as 'h' will tell you), press 'w' and re-fit (by pressing 'x'). Right above the table in the x-term, you will now also find the reduced χ^2 value: "Chisqr/nfree". This value would be unity if the noise in the residuals is Gaussian and the uncertainties on the TOAs are the right size. Generally, we assume this to be true, but sadly it often isn't. This may be because the TOA-determination algorithm underestimates uncertainties in the low-signal-to-noise case or because calibration uncertainties distort the pulse shape or because of many more reasons, many of which are instrument-related. For this reason, we should make sure to "correct" the uncertainties of different back-ends to ensure the backends are properly weighted against each other. To do so, we first have to evaluate the reduced χ^2 value for each of the data sets individually.

To determine the reduced χ^2 value for each of the data sets, add the line "MODE 1" to your most recent par-file (unless this line is already included). This tells TEMPO2 to perform a weighted fit, as opposed to an unweighted fit. Then you can run TEMPO2 without plug-in on each of the tim-files (init.tim and addit.tim):

```
C:/> tempo2 -f par.par init.tim
C:/> tempo2 -f par.par addit.tim
```

When you run TEMPO2 without plug-in, it simply provides the x-term information you've seen while using the PLK plug-in; and subsequently quits. In the textual output, note the Chisqr/nfree values for each data set and calculate the square root of these values. Next, open the all.tim file in your favourite browser and add on the second line:

```
EFAC 2.361
```

where in the place of 2.361 you should fill in the square root of the Chisqr/nfree value for the init.tim file. The "EFAC" line tells TEMPO2 to multiply the TOA uncertainties of all following TOAs with the given factor (2.361 in the example above). Because the reduced χ^2 is calculated based in the square of the TOA uncertainties (see the equation given in the lecture earlier today), multiplying the TOA uncertainties by $\sqrt{\chi^2}$ will result in a reduced χ^2 of unity. In order to also get the uncertainties of the new, high-quality data correct, move down until you find the place where the additional data begins. There, add

```
EFAC 34.136
```

where 34.136 should be replaced with the square root of the Chisqr/nfree value you found for the addit.tim file.

At this point, both sub-sets of data provide a reduced χ^2 of roughly unity and so we can be confident that the relative weighting of the two instruments is reasonable. Run TEMPO2 with PLK again on the EFAC'ed data and you'll find that the reduced χ^2 value of the combined data set is now much closer to unity and the uncertainties of the timing model parameters have gone up slightly, making them more reliable.

If you've made it this far, you should be familiar with the most important basics of Tempo2 and the plk plug-in. What follows is slightly more advanced but I encourage you to go through if you have the time because this *will* prove useful.

2.2 Creating Fake Data-Sets: fake

When investigating the possible effects of various parameters, gravitational waves, Solar-System ephemerides and such more, simulations are a fundamental tool that only increases its importance as (super)computing power keeps increasing. To simulate timing residuals, TEMPO2 provides the FAKE plug-in. There are two ways of running fake: either through command-line options (which can easily be used in scripts) or interactively. Have a look at

```
tempo2 -gr fake -h
```

to get an idea of what is possible.

Try to simulate TOAs interactively through:

```
tempo2 -gr fake -f init.par
```

and use PLK to have a look at the residuals. You can achieve the same result via the command-line, for example using this command (all on one line):

```
tempo2 -gr fake -f DE405.par -start 54530 -end 55000 -rms 0.0003
       -group 2 31 -idum -713 -red n -nobsd 2 -ndobs 1 -randha y
```

One thing you could try to do with FAKE, is to see how hard it would be to measure the Shapiro delay for this system. To do so, you can add the companion mass (M2) and the sine of the inclination angle (SINI) to your par file:

```
M2 0.1637 0
SINI 1.0 0
```

To get a reasonable value for the companion mass, you can look at the textual output of TEMPO2. Underneath the table, the mass function (which only depends on the Keplerian parameters) is used to determine minimum, median and maximum companion masses. These values you can use to obtain pessimistic, most likely and optimistic scenarios. The value for SINI can vary between 0 and 1, where 1 (edge-on: the pulsar passes directly behind the companion and therefore the line-of-sight passes directly past the companion) gives the strongest Shapiro delay signature and 0 (face-on, the pulsar and companion move in the same plane and the line-of-sight always passes through the same gravitational field) does not provide any measurable signature. Using this extended par-file, you can simulate a tim-file with high timing precision (say 50 ns or 0.00005 ms). Next, you fit for M2 and SINI (along with all other binary parameters) in PLK and you can see if this data is sufficient to achieve a significant detection of these parameters.

When you succeed in simulating a data-set that provides a significant detection, you can use this set to investigate the signature of Shapiro delay and its correlation with other parameters. To do so, make sure you are plotting the post-fit timing residuals as a function of orbital phase (hit '4') and aren't fitting for anything. Next, change the value of M2 to 0 (hit 'p' and follow the instructions in the x-term). What you see is the typical signature of Shapiro delay. Now turn on fitting for all binary parameters except M2 and SINI. As you can see, this absorbs most of the Shapiro delay signature, explaining why this is such a hard effect to measure accurately.

2.3 Getting Further Information and Help

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.

If all else fails, you can resort to e-mail. pulsarastronomy.net hosts a TEMPO2 mailing list to which you can (un)subscribe via http://www.pulsarastronomy.net/mailman/listinfo/tempo2_lists.pulsarastronomy.net. As you can find from the above-mentioned papers, the main author of TEMPO2 can be contacted via george.hobbs@csiro.au. Finally, the author of this tutorial can be contacted on joris.verbiest@gmail.com.