

## TEMPO2: a New Pulsar Timing Package

G. Hobbs <sup>\*</sup>, R. Edwards and R. Manchester

Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 1710, Australia

**Abstract** TEMPO2 is a new pulsar timing package that provides the precision necessary for modern millisecond timing projects and should supersede all existing pulsar timing packages such as TEMPO and PSRTIME. As TEMPO2 is the only program available that can analyse multiple pulsar datasets simultaneously it will become an integral part of pulsar timing array projects which aim to detect the signatures of gravitational radiation in pulsar timing residuals. In this paper we describe the basic functionality of TEMPO2.

**Key words:** methods: data analysis — pulsars: general — ephemerides

### 1 INTRODUCTION

The aim of the Australian Pulsar Timing Array project is to detect gravitational waves by observing millisecond pulsars with the best possible timing precision. Any such detection will only be possible if systematic effects in the timing residuals are close to the  $\sim 1$  ns level, or smaller. However, commonly used pulsar timing packages such as TEMPO only provide a timing precision of  $\sim 100$  ns. We have developed TEMPO2, a new software package that implements the necessary algorithms with a level of precision suitable for such high-precision experiments. Full details of the TEMPO2 program will be published elsewhere; a first paper (Hobbs et al. submitted to MNRAS) will provide an overview of TEMPO2, a second will describe details of the algorithms used to achieve 1 ns timing precision and a third will explain methods for analysing multiple pulsars simultaneously. Here, we describe the basic functionality and usage of TEMPO2.

The ideas behind pulsar timing have been well described in the literature (for example, Manchester & Taylor 1977; Lorimer & Kramer 2005). In brief, the procedure starts by converting the measured pulse arrival times at the observatory to the pulse emission time in the solar system barycentric frame which is assumed to be inertial. Pulsar timing residuals are then calculated that represent the difference between the measured pulse phase and a predicted phase using a pulsar timing model. Terms corresponding to offsets in model parameters can subsequently be fitted to the timing residuals in order to improve the measurement of these parameters.

TEMPO2 requires, as input, a file containing the site-arrival-times and another file that contains an initial estimate of the pulsar timing model. We discuss in Section 2 the output from TEMPO2, Section 3 provides a short overview of graphical interfaces that add to the functionality of TEMPO2, Section 4 describes the fitting algorithms and Section 5 provides a basic overview of improvements over currently used pulsar timing packages. The software and documentation for TEMPO2 can be obtained from our web-site, <http://www.atnf.csiro.au/research/pulsar/tempo2>.

### 2 OUTPUT FORMATS

TEMPO2 has been written to provide user-definable output formats. By default, on completion of forming pre- and post-fit timing residuals, TEMPO2 tabulates the pulsar parameters. These are listed along with their pre- and post-fit values, the change in the parameter and its uncertainty. However, it is also possible to obtain more general output formats such as a  $\LaTeX$  tabular format. The parameters and their errors can be output either separately or the uncertainty can be written in parenthesis after the measurement indicating the error

---

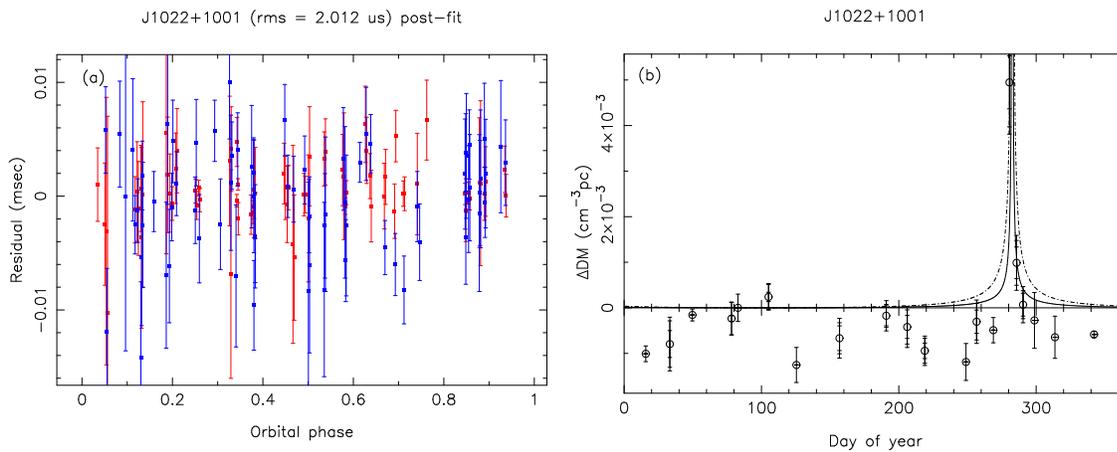
<sup>\*</sup> E-mail: [george.hobbs@csiro.au](mailto:george.hobbs@csiro.au)

**Table 1** An example of the TEMPO2 output

```

RAJ (rad)           & 10:22:05.195(4) \\
DECJ (rad)          & +09:25:49.86(12) \\
F0 (s-1)           & 60.77944841072(4) \\
F1 (s-2)           & 1.70684E-15(17) \\
PEPOCH (MJD)        & 50571.17041 \\
DM (cm-3 pc)       & 1868.1(6) \\
DM1 (cm-3 pc yr-1) & -0.55284(16) \\
PMRA (mas/yr)       & -8349.6(6) \\
PB (d)              & 7.8051214324(18) \\
A1 (lt-s)           & 16.7651824(4) \\
TASC (MJD)          & 49776.2949420(8) \\
EPS1                & 0.00003164(4) \\
EPS2                & -0.00015749(6)

```

**Fig. 1** (a) An example of the PLK plugin to analyse the timing residuals for Parkes Pulsar Timing Array observations of PSR J1022+1001 and (b) the CALCDM plugin; figure courtesy of X-P You.

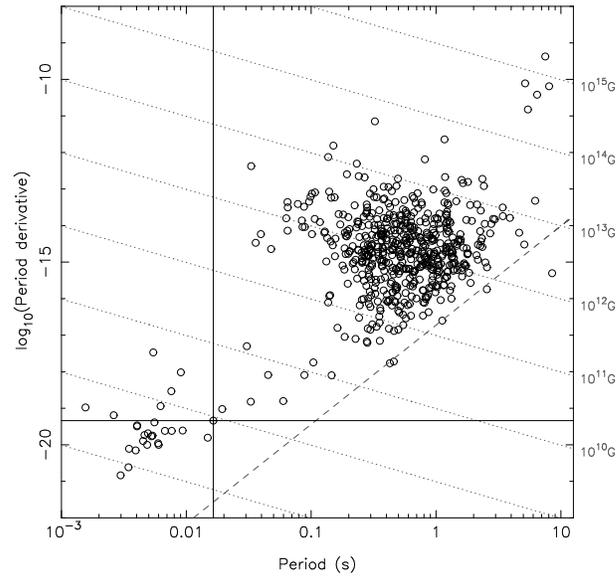
on the last quoted digit (see Table 1). It is also possible to obtain, for each observation, parameters such as the calculated Roemer delay, the extra delay due to interplanetary dispersion or the clock corrections that have been applied.

### 3 THE GRAPHICAL INTERFACES

A wide selection of graphical interfaces add to the functionality of TEMPO2. For instance, the PLK plugin allows the user to view the pre- and post-fit timing residuals versus parameters such as the observation date, binary phase, day of year or parallactic angle. Facilities to zoom in on specific regions of the timing residuals, to view the profiles of any observation and to delete observations that have been clearly affected by interference are provided. Specified observations, such as those obtained using a particular receiver system, can also be highlighted. Figure 1a shows output from the PLK plugin.

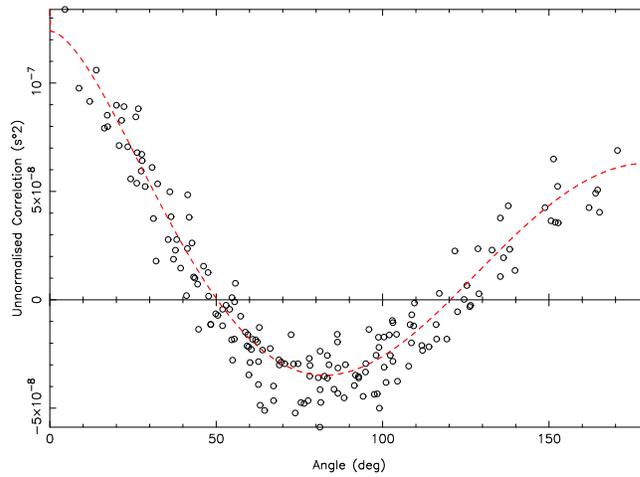
It is often useful to fit for a pulsar's dispersion measure (DM) over given time intervals. In Figure 1b we show the CALCDM plugin being used to obtain the DM of PSR J1022+1001 at one week intervals (the DM is calculated with respect to the value in the initial pulsar timing model). This pulsar lies in the ecliptic plane and as it passes the Sun, we clearly observe an increase in the DM that is predicted by the solar system interplanetary model implemented in TEMPO2 (two such models are plotted as a solid and a dashed line in the Figure).

When a new pulsar has been discovered and TEMPO2 has been used to determine its parameters then the BASIC plugin (see Figure 2a) can be used to identify whether this pulsar is similar to previously known pulsars or is unique in its rotational properties.



(a)

Correlation analysis



(b)

**Fig. 2** a) An example of the BASIC plugin indicating the rotational parameters of the pulsars being analysed and b) obtaining the correlation coefficient between different simulated pulsar data sets versus their angular spacing on the sky.

#### 4 THE FITTING ALGORITHMS

The default fitting routines in TEMPO2 are based on a linear singular-value decomposition, weighted least-squares algorithm. TEMPO2 can do both weighted and non-weighted fits. TEMPO2 obtains the uncertainties

on the fitted parameters either using the formal least-squares fitting uncertainties or by using a bootstrapping technique (see, for instance, Wall & Jenkins 2003). As well as the pulsar's astrometric and pulse parameters, TEMPO2 can fit for an arbitrary number of glitch events and orbital companions. The binary models implemented in TEMPO2 are similar to those in the original TEMPO, but also include improvements for edge-on binary systems, orbital timing parallaxes (Kopeikin 1995) and secular variations of the orbital parameters due to the system's proper motion (Kopeikin 1996).

The fitting algorithms implemented into TEMPO2 allow multiple pulsars to be analysed simultaneously. In Figure 2b we plot the correlations between 20 simulated pulsars whose residuals are dominated by a stochastic gravitational-wave background (Jenet et al. 2005) versus the angular separation of the pulsars on the sky. It is also possible to carry out global fits where the rotational and astrometric parameters are obtained individually for each pulsar along with global parameters that are common to each pulsar in a simultaneous fit.

## 5 IMPROVEMENTS OVER EXISTING TIMING PACKAGES

The TEMPO2 is the only timing package that is compliant with the IAU 2000 resolutions and hence uses up-to-date precession and nutation models, the International Celestial Reference System (ICRS) and Barycentric Coordinate Time (TCB). TEMPO2 also 1) corrects for polar motion, 2) includes the Shapiro delay due to the planets, 3) includes the second-order Shapiro delay due to the Sun, 4) implements frequency-dependent fitting (not simply DM delays), 5) allows an arbitrary number of glitch events, orbital companions, pulse frequency derivatives and dispersion measure derivatives, 6) can 'whiten' the timing residuals using a Fourier technique (Hobbs et al. 2004) and 7) includes the annual orbital parallax for binary models.

## 6 CONCLUSIONS

We have described, TEMPO2, a pulsar timing package that we expect will become the package of choice for the new generation of high precision pulsar timing experiments. The TEMPO2 software has been written in a manner allowing new additions to be easily added both by the original developers of the software and, as plugins, by the general pulsar community.

**Acknowledgements** The TEMPO2 package is based on the original TEMPO Fortran code. This software was developed over many years by multiple authors including J. Taylor, R. Manchester, D. Nice, W. Peters, J. Weisberg, A. Irwin and N. Wex.

## References

- Hobbs G., Lyne A. G., Kramer M., Martin C. E., Jordan C., 2004, MNRAS, 353, 1311
- Jenet F. A., Hobbs G. B., Lee K. J. Manchester R. N., 2005 ApJ, 625, L123
- Kopeikin S. M., 1995, ApJ, 439, L5
- Kopeikin S. M., 1996, ApJ, 467, L93
- Lorimer D., Kramer M., 2005, Handbook of Pulsar Astronomy, Cambridge: Cambridge University Press
- Manchester R. N., Taylor J. H., 1977, Pulsars. San Francisco: Freeman
- Wall J. V., Jenkins C. R., 2003, Practical Statistics for Astronomers, Cambridge: Cambridge University Press