PULSAR TIMING AND A PULSAR-BASED TIMESCALE

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ABSTRACT Pulsar Timing Arrays in which precise timing observations are made for a large number of pulsars spread across the celestial sphere have many applications, including the direct detection of gravitational waves. They can be used to detect irregularities in the atomic timescale used as a reference for the timing observations, thereby establishing a pulsar-based timescale which is independent of the reference timescale. The Parkes Pulsar Timing Array (PPTA) project has been timing 20 millisecond pulsars at 2 – 3 week intervals using the Parkes 64-m radio telescope since 2005. The PPTA data set has been analysed together with earlier timing data from Parkes using TT(TAI) as the reference timescale. The resulting timescale which we call PT(PPTA10) has deviations from TT(TAI) which closely match the differences between TT(BIPM10) and TT(TAI). This both demonstrates the practicality of a pulsar-based timescale and verifies that TT(BIPM10) is an improvement on TT(TAI).

1. PULSAR TIMING BASICS

Pulsars are highly stable celestial clocks. They are identified by their broad-band and periodic pulse emission. The basic pulse periodicity P is typically between 100 ms and 1 s but a very important class known as millisecond pulsars (MSPs) have much shorter periods, mostly between 1.5 and 20 ms. Pulsars are identified as rotating neutron stars. Almost all of the ~ 2000 known pulsars are located within our Galaxy with typical distances of a few kpc (1 kpc = 1000 pc = 3.085×10^{19} m). Although other formation routes are possible, most neutron stars are believed to be formed in the core collapse of a massive star, resulting in a supernova explosion and the formation of a highly magnetised and rapidly rotating stellar remnant – the neutron star. This combination of rapid rotation and strong magnetic fields means that huge voltages are generated within the magnetosphere of the star, accelerating charged particles to ultra-relativistic energies. By mechanisms that are not fully understood, these ultra-relativistic particles radiate beams of electromagnetic radiation which rotate with the star. We see a pulse when one of these beams sweeps across the Earth.

Since pulsars are powered by their rotation, they slow down as they lose energy. The rate of slowdown is very small however, with $\dot{P}$ typically about 10^{-15} for "normal" (non-millisecond) pulsars; for MSPs it is even smaller, typically about 10^{-20}. Precise parameters for a pulsar are obtained by measuring a series of pulse times of arrival (ToAs) and then fitting a timing model to them. In practice, ToAs are obtained by synchronously averaging data for intervals typically between a few minutes and an hour to form a mean pulse profile. The averaging reduces the effects of both random receiver noise and pulse-to-pulse shape variations. The resulting mean pulse profile is then cross-correlated with a standard template to determine the effective arrival time at the telescope of a reference phase on the mean profile (normally at or near the profile peak). Observed pulse ToAs are initially with reference to the observatory time standard. At most observatories, GPS systems and published timescale offsets[1] are used to reference the ToAs to an international timescale, e.g., TT(TAI), giving observatory pulse arrival times $t_{\rm o}$.

Observed ToAs must also be corrected for the motion and varying gravitational potential of the observatory by referring them to an inertial frame, that is, one which is unaccelerated with respect to the distant Universe; in practice, the barycentre of the Solar system (SSB) is normally used. Pulse ToAs at the SSB are given by

$$t_{\rm o,b} = t_{\rm o} - \Delta_{\rm R} - \Delta_{\rm E} - \Delta_{\rm a} - \Delta_{\rm p} \qquad (1)$$

where $\Delta_{\rm R}$ is the Roemer delay or propagation time of a plane wavefront from the SSB to the observatory, $\Delta_{\rm E}$ is the "Einstein" delay resulting from the relativistic transformation from the observatory frame to

[1]Circular T from http://www.bipm.org/en/scientific/tai/

the SSB, $\Delta_{\rm a}$ is the additional propagation delay in the Earth's atmosphere and ionosphere and $\Delta_{\rm p}$ is the effective "parallax" delay resulting from the curvature in the wavefront due to a finite source distance.

In the reference frame of the pulsar, the pulse phase may be described by a truncated Taylor series

$$\phi = \phi_0 + \nu t_{\rm p} + \frac{1}{2}\dot{\nu} t_{\rm p}^2 \tag{2}$$

where the pulse frequency $\nu = 1/P$ and $t_{\rm p}$ is the proper time at the pulsar (ignoring the effect of the pulsar's gravitational field). The reference phase ϕ_0 is chosen so that $\phi = 0$ for emission times which correspond to the reference phase of the observed ToAs. For comparison with the observed ToAs, the pulse emission times must also be transformed to the SSB:

$$t_{\rm p,b} = t_{\rm p} + \Delta_{\rm IS} + \Delta_{\rm B} \tag{3}$$

where $\Delta_{\rm IS}$ is the "interstellar" delay, primarily the dispersive delay in the interstellar medium and in the Solar system (the vacuum propagation delay and its first time derivative are unmeasurable and are ignored) and $\Delta_{\rm B}$ is the relativistic transformation from the pulsar-centred frame to the barycentre frame of the binary system. See Edwards et al. (2006) for a full description of all of the terms in Equations (1) and (3).

The differences $t_{\rm o,b} - t_{\rm p,b}$ are known as timing residuals. A series of timing residuals will have systematic variations related to errors in the terms in Equations (1) – (3) together with any perturbations which are not included in these equations. A least-squares fit of functions describing the effect of errors in these terms using a program such as Tempo2 (Hobbs et al. 2006) can determine improved values and uncertainties for the various parameters, including the pulsar position and proper motion through the term $\Delta_{\rm R}$. Unmodelled terms such as higher-order variations in the intrinsic pulse frequency ν, perturbations due to gravitational waves (GWs) passing over the pulsar and the Earth, errors in Solar-system ephemeris used to compute $\Delta_{\rm R}$ and irregularities in the reference timescale will remain after such a least-squares fit. However, because of the fitting of Equation (2), any perturbations which are linear or quadratic in time will be absorbed into ν and $\dot{\nu}$.

2. PULSAR TIMING ARRAYS

With observations of just a single pulsar it is not possible to separate the unmodelled perturbations described above. However, with observations of many pulsars spread across the sky, a so-called "pulsar timing array" (PTA), it is possible to separate these effects. Irregularities in the reference timescale affect all pulsars equally, in effect a monopole term with reference to position on the sky. Errors in Solar-system ephemeris correspond to a displacement of the SSB from its true position and so introduce a dipole term, whereas GWs passing over the Earth result in residuals which have a quadrupolar dependence on sky position. Therefore, in principle, these three sources of perturbation can be separated from intrinsic pulse frequency variations and the effect of GWs passing over each pulsar; these are of course different for every pulsar. Our ability to achieve this separation in practice is limited by the precision with which we can measure pulse ToAs, the number and sky distribution of pulsars for which sufficiently accurate ToAs can be obtained and the cadence and total data span of the ToA measurements.

Because GWs induce a frequency perturbation but pulsar timing is essentially a phase measurement, PTAs are most sensitive to long-period GWs. Furthermore, since linear and quadratic phase perturbations are not detectable, PTAs are most sensitive to GWs with periods comparable to the data span. Estimates of the strength of GWs in the Galaxy from likely astrophysical sources (e.g., Sesana et al. 2008) show that weekly ToAs with precision of order 100 ns for about 20 pulsars over a 5-year data span are necessary to make a significant detection of astrophysical GWs (Jenet et al. 2005). Possible errors in the Solar-system ephemeris arise from uncertainties in the mass of planets relative to the Sun, especially those in the outer Solar system, and the presence of Solar-system objects not included in the ephemeris. Recent ephemerides from the Jet Propulsion Laboratory, for example, DE421 (Folkner et al. 2008), include more than 300 of the largest asteroids in their model. Errors and omissions in the ephemeris may induce timing residuals of order 100 ns in observed ToAs (see, e.g., Champion et al. 2010). The most accurate timescales based on atomic frequency standards are those produced by the BIPM by retroactive reweighting of the various atomic clocks that are used to form TAI (Arias et al. 2011). Successive revisions of the TT(BIPMYY) timescale[2] result in timescale differences of order 50 ns. It is clear that significant detections of any of

[2]Obtainable from ftp://tai.bipm.org/TFG/TT(BIPM)

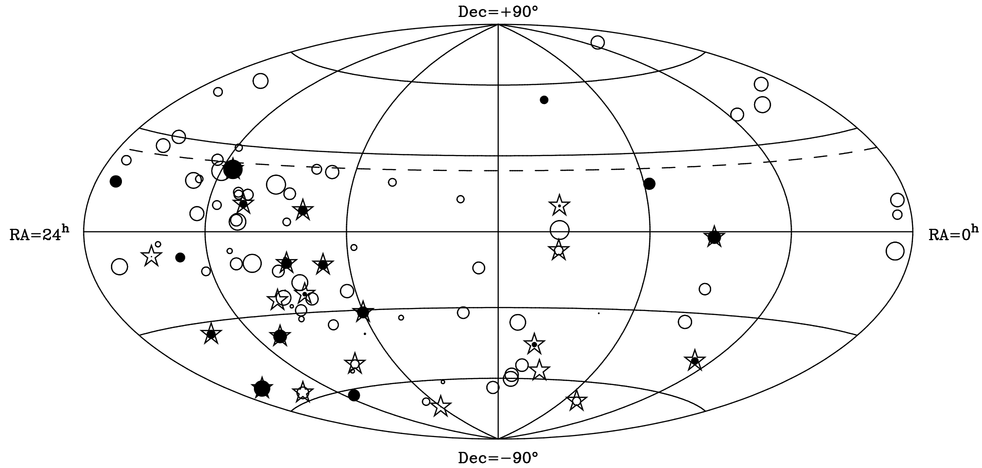

Figure 1: Distribution on the celestial sphere of pulsars suitable for PTA projects. The size of the circle is inversely related to the pulsar period and circles are filled if the pulsar mean flux density is greater than 2 mJy. The dashed line marks the northern limit for the Parkes radio telescope. Pulsars observed by the PPTA project are marked with stars.

these effects require observations of a large sample of pulsars for which ToA precisions are of order 100 ns. With current instrumentation, this is possible only for MSPs and indeed only for a subset of the known MSPs that have relatively narrow pulse features and relatively large flux densities. Since all of the expected signals are very "red", i.e., the signal spectrum is dominated by low frequencies, detection is aided by long data sets.

There are currently three main PTA projects world-wide. The European Pulsar Timing Array (EPTA) is based on the large radio telescopes in Europe: the Effelsberg 100-m telescope in Germany, the Nançay radio telescope in France, the Westerbork Synthesis Radio Telescope in the Netherlands and the Jodrell Bank radio telescope in England (Ferdman et al. 2010). The EPTA currently has high quality observations (rms residuals $< 2.5\ \mu$s) for nine MSPs. The NANOGrav project is based in North America and makes use of data from the 100-m Green Bank Telescope in West Virginia and the 300-m Arecibo radio telescope in Puerto Rico (Jenet et al. 2009). NANOGrav has high quality observations for 17 MSPs. The third main PTA is the Parkes Pulsar Timing Array (PPTA) which uses data from the Parkes 64-m radio telescope in New South Wales, Australia (Manchester 2008; Hobbs et al. 2009). Each of these PTAs is timing about 20 MSPs, with some overlap between the samples. The main goal of these projects is to detect nanoHertz GWs but they have many secondary goals. One of the most important of these is to establish a pulsar-based timescale (Hobbs et al. 2011; Rodin 2011).

3. THE PARKES PULSAR TIMING ARRAY

The PPTA project uses the Parkes 64-m radio telescope to make precise timing measurements of 20 MSPs. The project is a collaboration primarily between CSIRO Astronomy and Space Science and Swinburne University of Technology, with important contributions from colleagues based in North America, China and Europe. Observations commenced in 2004 and regularly-sampled high-quality data have been obtained since 2005 March. Observations are made in three radio-frequency bands, 50 cm (~ 700 MHz), 20 cm (~ 1400 MHz) and 10 cm (~ 3000 MHz), typically at 2 – 3 week intervals. On-line signal processors use 8-bit digitisation to Nyquist-sample the full bandwidth for each band, 64 MHz at 50 cm, 256 MHz at 20 cm and 1024 MHz at 10 cm. Two types of dedispersion are used. The Parkes digital filterbank systems use polyphase digital filters to split the data into many (typically 1024) frequency channels which are incoherently summed off-line to provide dedispersed profiles. For the 50 cm band and high DM/P pulsars (DM is dispersion measure) at 20 cm, baseband recording systems and quasi-real-time coherent dedispersion give superior results. Off-line signal processing uses the PSRCHIVE suite of programs (Hotan et al. 2004)[3] and TEMPO2 (Hobbs et al. 2006)[4]. Figure 1 shows the sky distribution of MSPs suitable for

[3]See http://psrchive.sourceforge.net
[4]See http://tempo2.sourceforge.net

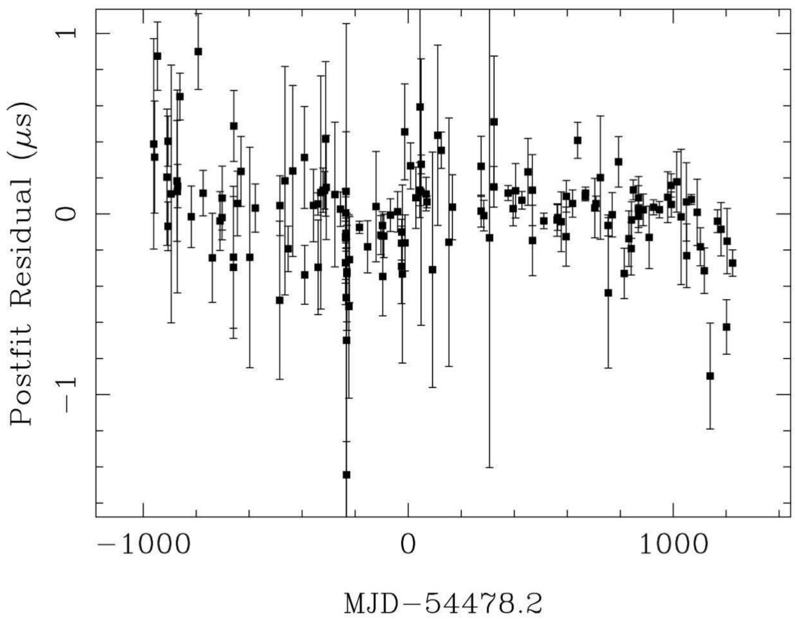

Figure 2: Timing residuals over a six-year data span for PSR J1909−3744. The ToAs were obtained using data from the 10 cm system and have been corrected for variations in interstellar dispersion using ToAs from the 20 cm and 50 cm systems.

PTA observations and the PPTA sample. While not fully isotropic, the PPTA pulsars do sample nearly two thirds of the celestial sphere.

After correction for variations in interstellar dispersion and fitting for parameters in Equations (1) – (3), 19 of the 20 PPTA pulsars have rms timing residuals of less than 2.5 μs over a six-year data span. However, for more than half of the pulsars, the post-fit residuals are dominated by a cubic term. Figure 2 shows the post-fit timing residuals for one of our best-performing pulsars, PSR J1909−3744, which has a pulse period of 2.95 ms and a pulse width of just 43 μs (Jacoby et al. 2003). It is clear that the rms timing residual, 137 ns, is dominated by a cubic term. Fitting to a 1-year span of recent data gives a "white" rms timing residual of just 61 ns. Similar fits to the other PPTA pulsars show that all have rms residuals of less than 1.5 μs and for more than half, the rms residual is less than 500 ns. These results are approaching those needed to achieve the PPTA goals. We can expect some reduction in these rms residuals from further improvements in signal processing algorithms and the development of new and more sensitive receiving systems.

4. A PULSAR-BASED TIMESCALE

We have combined the PPTA data sets for 13 pulsars with earlier Parkes data from Verbiest et al. (2008, 2009) to give data sets covering about 16 years from mid-1994 to mid-2011. The upper part of Figure 3 shows the distribution of ToAs over this interval for the 13 pulsars. To extract the timescale offsets or "common-mode signal" from the observed residuals, the standard Tempo2 analysis was extended to simultaneously process ToA data from multiple pulsars, solving for the optimal parameters for each pulsar as well as for the common-mode signal. The Cholesky method (Coles et al. 2011) was used to properly deal with the red noise in the residual spectrum of each pulsar. The timescale offset signal was sampled at intervals of 300 days and constrained to have zero mean and no linear or quadratic components. The resulting offsets and their uncertainties are shown in the lower part of the plot. These define a pulsar-based timescale which we name PT(PPTA11). Also plotted is the difference between TT(BIPM10) (extended) and TT(TAI) after subtraction of a second-order polynomial to mimic the effect of fitting Equation (2) to the pulsar data.

It is striking that the variations of PT(PPTA11) relative to TT(TAI) closely match the deviations of TT(BIPM10) relative to TT(TAI). This demonstrates both that it is possible to define a pulsar-based timescale of comparable accuracy to the best available atomic timescale and that the revisions used to

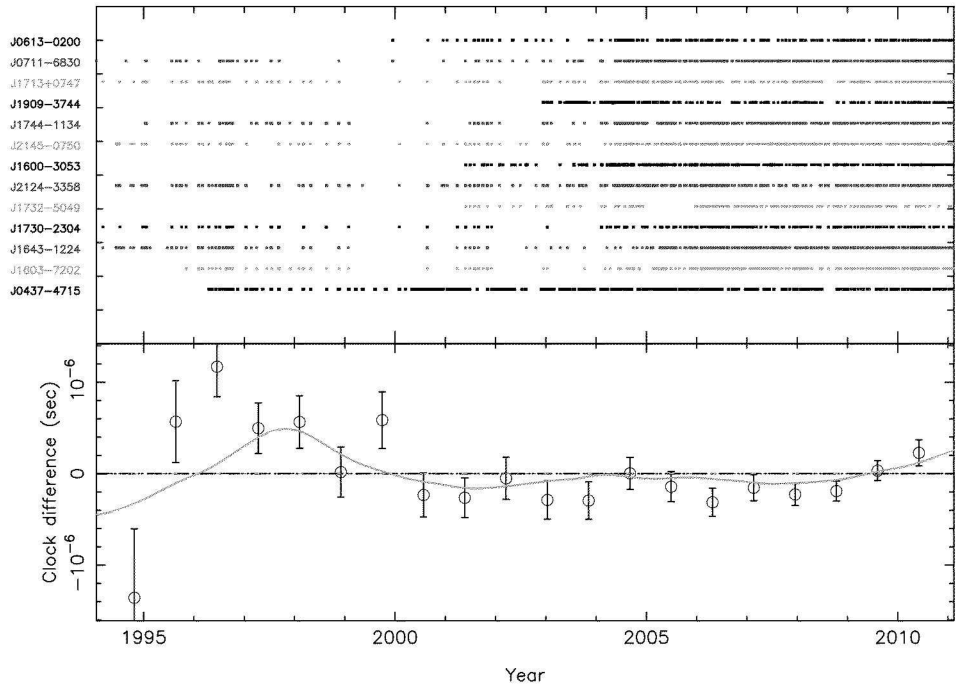

Figure 3: The upper part of the figure shows the distribution of ToAs for 16-year data sets for 13 PPTA pulsars. Timescale offsets relative to TT(TAI) derived from the pulsar timing data are shown in the lower part of the figure. The curved line is the deviation of TT(BIPM10) from TT(TAI) after subtraction of a second-order polynomial.

form TT(BIPM10) do result in a more stable timescale. There are some marginally significant deviations of PT(PPTA11) relative to TT(BIPM10) in the late 1990s. Definition of the pulsar timescale will be enhanced by combining the PPTA and earlier Parkes data sets with those from other PTAs. A collaborative project between the three main PTAs, known as the International Pulsar Timing Array (IPTA), has been established (Hobbs et al. 2010) and this will facilitate progress toward the common goals. In the more distant future, the Square Kilometre Array (Kramer et al. 2004) will provide enormously increased sensitivity for PTA observations, resulting in much improved results for all of the PTA objectives.

Acknowledgements. We acknowledge the contributions of our colleagues in the PPTA project and the staff of Parkes Observatory to the results presented here. The Parkes radio telescope is part of the Australia Telescope which is funded by the Commonwealth Government for operation as a National Facility operated by CSIRO.

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