

Status Update of the Parkes Pulsar Timing Array

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Abstract. The Parkes Pulsar Timing Array project aims to make a direct detection of a gravitational-wave background through timing of millisecond pulsars. In this article, the main requirements for that endeavour are described and recent and ongoing progress is outlined. We demonstrate that the timing properties of millisecond pulsars are adequate and that technological progress is timely to expect a successful detection of gravitational waves within a decade, or alternatively to rule out all current predictions for gravitational wave backgrounds formed by supermassive black-hole mergers.

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1. Introduction

Pulsars are rapidly rotating neutron stars that emit beamed radio waves, probably from polar magnetic field lines. Due to a misalignment of the magnetic and rotation axes, this emission is observed as pulses of radiation whose times-of-arrival (TOAs) at a radio observatory can be measured accurately. Pulsar timing is a technique based on the comparison of these observed TOAs to those predicted by a timing model that describes the spin behaviour of the pulsar, its binary orbit, the interstellar medium and the solar-system ephemerides. The differences between the model-predicted TOAs and the actual observed TOAs are called the timing residuals and they contain all the information not properly described in the timing model, such as calibration errors, instrumental instabilities, higher-order ISM effects, instabilities intrinsic to the pulsar, gravitational waves (GWs) and radiometer noise.

The highly predictable nature of pulsars makes them useful tools for a variety of investigations in physics and astrophysics. One type of investigation was first proposed by Sazhin (1978) and Detweiler (1979), who claimed that pulsar timing might be used to detect GWs. Hellings & Downs (1983) expanded on that work and showed that a stochastic background of GWs (GWB) would introduce a quadrupolar correlation in pulsar timing residuals: the residuals of pulsars with separations on the sky close to 0° or 180° would be positively correlated, while those of pulsars separated by 90° would be anticorrelated. This insight triggered the concept of a pulsar timing array (PTA), proposed by Romani (1989) and Foster & Backer (1990). A PTA is an array of pulsars which are timed in order to investigate correlated signals between the timing residuals. Three causes of correlation are known to exist: a monopolar correlation due to reference clock errors; a dipolar correlation due to offsets in the solar-system ephemerides; and a quadrupolar correlation due to GWs.

In this paper we describe one of the three PTAs currently in operation: the Parkes Pulsar Timing Array (PPTA). In §2 we describe the overall project, its aims and observational requirements as derived by Jenet et al. (2005). §3 details current progress, both on scientific and technological fronts and in §4 our sensitivity to both a GWB and individual GW sources is discussed.

2. The Parkes Pulsar Timing Array Project

Founded in 2004, the PPTA project observes 20 millisecond pulsars (MSPs - pulsars with millisecond periods) on a bi-weekly basis with the 64-m Parkes radio telescope in NSW, Australia, at three different observing frequencies (centred on 685 MHz, 1369 MHz and 3128 MHz). For further technical details see Manchester (2008).

2.1. Aims

The main aims of the PPTA project are threefold:

- (i) Make a direct detection of GWs through pulsar timing and in so doing, develop the tools and methodologies required for the new era of full-fledged GW astronomy using pulsars, which is expected to commence with the commissioning of the Square Kilometre Array (SKA; Kramer et al. 2004).
- (ii) Construct a pulsar time-scale, thereby removing long-term dependence on Earth-based clocks, enabling further improvements in timing precision.
- (iii) Improve the solar-system ephemerides, both through improving precision of the masses of known solar-system objects and eventually through detection of currently unknown trans-Neptunian objects.

Of these aims, the one with the highest expected scientific value is GW detection. Because the most likely source of GWs to be detected by the PPTA is a GWB formed by super-massive black-hole mergers (Jenet et al. 2006), we will describe the observational requirements for a successful GWB detection in the following section, based on the semi-analytic work done by Jenet et al. (2005).

2.2. Pulsar timing array requirements

While the original PTA described by Romani (1989) and Foster & Backer (1990) only contained three pulsars, more recent work by Jenet et al. (2005) has demonstrated the strong dependence of PTA sensitivity on the number of pulsars included in the array. Specifically, they demonstrated that the detection significance a PTA would achieve, can be approximated as (Jenet et al. 2005, their Eq. 12):

$$S = \sqrt{\frac{M(M-1)/2}{1 + [\chi(1 + \bar{\xi}^2) + 2(\sigma_n/\sigma_g)^2 + (\sigma_n/\sigma_g)^4] / N\sigma_\xi^2}}, \quad (1)$$

where M is the number of pulsars in the timing array, N is the number of observations of each pulsar, σ_n is the RMS of the timing residuals (assumed identical for all pulsars), ξ , χ and σ_ξ are variables related to the correlation function, as defined in Jenet et al. (2005) and σ_g is the RMS residuals introduced by the GWB, derived by Jenet et al. (2005) to be:

$$\sigma_g^2 = \frac{A^2}{12\pi^2(2-2\alpha)} (f_1^{2\alpha-2} - f_h^{2\alpha-2}) \quad (2)$$

with $f_h = 2/\Delta t$ and $f_1 = 1/T$ the highest and lowest detectable GWB frequencies based on the span of the timing observations T , Δt the sampling interval, and A and α the amplitude and spectral index of the GWB in the characteristic strain spectrum: $h_c(f) = A(f/f_0)^\alpha$ where h_c is the characteristic strain and $f_0 = 1 \text{ yr}^{-1}$. While GW frequencies below T^{-1} are originally present in the timing data, they are effectively removed by the fitting process that estimates the timing model parameters (most importantly the pulse period and spindown) from the timing residuals.

In the weak-field limit where the GWB power at the lowest frequency, f_1 , is comparable to the noise power in the pulsar timing residuals, Equation 1 can be rewritten

into a scaling law for the GWB amplitude to which a PTA is sensitive:

$$A_{\text{GWB}} \propto \frac{\sigma_n}{T^{5/3} \sqrt{NM(M-1)}}. \quad (3)$$

Note that this relation only holds for the GWB originating from supermassive black hole binaries, which has a predicted spectral index of $\alpha = -2/3$ (see e.g. Sesana et al. 2008). This negative spectral index implies that PTAs are most sensitive to GWB frequencies of the order of the inverse of the data length: $T \approx 10$ years or $f_1 \approx 3$ nHz.

Equation 3 clearly delineates the four parameters that are fundamental to the success of a PTA: the number of pulsars M , the number of observing epochs N , the RMS of the timing residuals σ_n and the length of the data set T . Since any one telescope is limited in the number of available pulsars and the regularity with which it can observe them, M and N are practically fixed at around 20 MSPs and weekly to biweekly observations. International collaboration, however, has the potential to significantly improve on these numbers, as described elsewhere in these proceedings by Hobbs et al. (2009c).

3. Recent and ongoing progress

The previous section showed how PTA sensitivity scales with RMS residuals and with the length of the timing data sets. In this section we will investigate how these parameters can be used to improve our sensitivity to GWs. Specifically, in §3.1 we comment on continuing improvements to observing hardware and data analysis methods that will decrease receiver noise levels and reduce some systematic effects that currently contribute to the RMS residuals, σ_n . Since PTA sensitivity does not simply depend on σ_n , but rather on $\sigma_n/T^{5/3}$, it is important also to assess how the RMS residuals evolve over increasing time-spans. For many young pulsars it is known that timing deteriorates over long time-spans because of irregular spindown or “timing noise” (Arzoumanian et al. 1994). In §3.2 we will highlight some recent investigations into the presence of such low-frequency noise in our MSP timing data.

3.1. Technical improvements

One of the cornerstones of the PPTA efforts to improve RMS residuals values, is improving the observational hardware. Development has been undertaken along several lines:

Observing systems: Two new observing systems have been commissioned within the last year. The Parkes Digital Filterbank system (PDFB3 and PDFB 4) are a digital polyphase filterbank that are capable of 8-bit sampling at a rate of 2 GHz for an observational bandwidth of up to 1 GHz. They support a range of configurations including an online-folding mode with up to 2048 pulse phase and radio frequency bins, a search mode with up to 8192 frequency channels and a baseband sampling mode. The second newly-commissioned observing system is the

ATNF-Parkes-Swinburne Recorder (APSR). It receives up to 1 GHz of baseband data from the PDFB3 and performs real-time coherent dedispersion on a dedicated 16-node, dual quad-core computing cluster, providing real-time system diagnostic and observational information through a web-based user interface.

Real-time interference mitigation: A system for real-time mitigation of radio-frequency interference (RFI) as described by Kesteven et al. (2005) has been implemented at the Parkes radio observatory to work with the PDFB3 during folded and baseband data taking.

Besides development of observational hardware, the PPTA team is investigating various ways of improving the timing analysis itself:

Improved timing software: As part of the PPTA efforts, the TEMPO2 pulsar timing software package was created (Hobbs et al. 2006). Based on the original TEMPO software, it implements all known relevant effects down to a precision of 1 ns, which is several orders of magnitude more precise than most previous timing software packages. Recently, TEMPO2 has been expanded with GW simulation capabilities (Hobbs et al. 2009a), allowing realistic evaluation of timing model fitting effects on GW sensitivity.

ISM and solar wind: The effect of the changing interstellar medium density on pulsar timing residuals and an optimal way to correct for these variations was published by You et al. (2007a). The varying electron density caused specifically by the solar wind was investigated in more detail by You et al. (2007b).

Full polarimetric calibration: Imperfect calibration of the instrumental polarisation causes systematic errors in arrival time estimation. Calibration errors are mitigated through measurement equation modelling (MEM; van Straten 2004), a technique that uses observations made over a wide range of parallactic angles to better determine the instrumental response. When used in combination with matrix template matching (MTM; van Straten 2006), which exploits the additional timing information in the polarisation of the pulsar signal, the RMS residuals of recent data from PSR J0437–4715 is reduced by up to 50% (Verbiest et al. 2008).

Improved solar-system parameters: Pulsar timing has reached a precision where accurate solar-system ephemerides crucially affect both timing precision and the resulting timing model parameters (Verbiest et al. 2008). This implies that, rather than correcting for the position and mass of solar-system bodies, PTA data sets are now able to add information to solar-system models. An initial investigation of this capability, including a precise measurement of the Jovian system mass, is about to be published (Champion et al. 2009).

Frequency-dependent template profiles: The 1 GHz bandwidth that the newly-commissioned observing systems can record, is increasing the amount of possible pulse profile evolution across a single observing band. Ignoring this issue would artificially broaden the pulse profile when integrated over the observed frequency

range - and therefore worsen TOAs and timing residuals. Research on profile evolution and observing-frequency-dependent template profiles to time against is ongoing.

Pulse stabilisation time-scales: The shape of the pulses received from a radio pulsar, changes from one pulse to the next. Luckily, integration of many subsequent pulses results in a stable, reproducible profile. With increased bandwidths and future timing programs at highly sensitive telescopes such as the SKA, it is important to know the precise stabilisation time and therefore the shortest pulse-integration time suitable for high-precision timing. Using the new APSR backend (see §3.1), we have recently commenced such a study of single pulses and pulse-stabilisation time-scales.

3.2. Intrinsic pulsar properties

The improvements outlined in §3.1 are guaranteed to reduce the radiometer noise and systematic contributions to the RMS residuals. The ultimate potential of PTAs does, however, not depend exclusively on hardware and processing techniques: eventually, timing will be limited by the intrinsic characteristics of the pulsars themselves. There are two specific properties of pulsars that are of relevance to the future potential of PTAs: the lowest achievable RMS residuals ($\sigma_{n,\min}$) and the ‘timing stability’ of the pulsars, defined by Verbiest et al. (2009) as “the potential of an MSP timing data set to maintain a constant, preferably low RMS residuals at all time-scales up to the time-span of a PTA project, which is typically envisaged to be 5 years or longer.”

Referring back to Equation 3, the importance of these two properties is evident: $\sigma_{n,\min}$ uniquely defines the minimal GWB amplitude to which a PTA with given number of pulsars and observing cadence can be sensitive to within a given length of time. The timing stability, on the other hand, specifies if $\sigma_n T^{-5/3}$ decreases as a function of time or not - and hence if the PTA gains sensitivity because of longer time-spans, or loses sensitivity because of intrinsic low-frequency instabilities in the timing data.

An upper bound on $\sigma_{n,\min}$ can most readily be determined as the lowest RMS residuals obtained so far. Initial data from the PDFB2 pulsar backend (the immediate precursor to the PDFB3 mentioned in §3.1) on PSR J0437–4715 in the $\nu \sim 3$,GHz observing band, have already achieved weighted RMS residuals of 73 ns over 0.7 years, with 126 TOAs (see Figure 1). A somewhat more involved analysis (Verbiest et al. 2009) that used multi-frequency data to separate out several contributions to the RMS residuals, established a bound of 80 ns on a time-scale of 5 years for PSRs J1909–3744 and J1713+0747. A third type of analysis was presented by Hobbs et al. (2009b) who investigated how the TOA uncertainty varies with the signal-to-noise ratio (S/N) of the observation. While this approach is only sensitive to a subset of contributions to the RMS residuals, it does have the ability to highlight systematic problems in the data analysis. In their Figure 2, Hobbs et al. (2009b) demonstrated how TOA uncertainties grew dramatically worse for S/Ns above ~ 1000 , suggesting systematic effect at levels

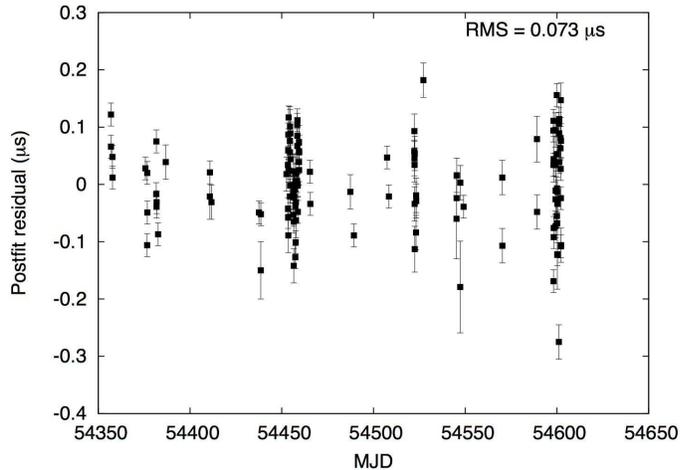


Figure 1. Timing residuals for PSR J0437–4715, obtained with the PDFB2 observing system at the Parkes Radio Observatory. The timing model of Verbiest et al. (2008) was used and only the pulse period and spindown rate were refitted.

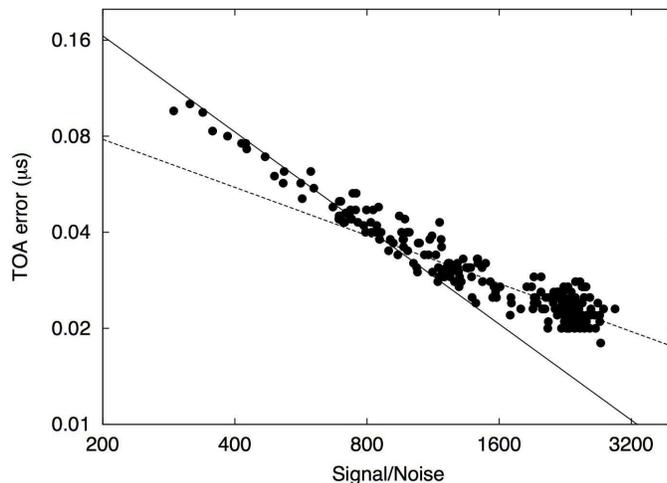


Figure 2. TOA uncertainty versus signal-to-noise ratio (S/N) for PDFB2 data on PSR J0437–4715 (dots), timed against a fully-calibrated, high-S/N CPSR2 (Caltech-Parkes-Swinburne Recorder 2) template profile. The full line shows the theoretically expected inverse relationship, the dashed line scales σ_{TOA} as $1/\sqrt{S/N}$. In contrast to the similar plot shown by Hobbs et al. (2009b), these data demonstrate the potential to achieve TOA precisions down to 20 ns. The departure from theoretical scaling in the high S/N regime suggests the presence of data analysis imperfections such as calibration errors, or limits in precision caused by variations in observing frequency, for example.

up to 100 ns. We present a re-analysis of their data in Figure 2, improving the pulse template used in the cross-correlation from which the TOA uncertainty is derived. Our results still contain systematic worsening of the TOA uncertainties at high S/N, but these effects now only occur at the 20 – 30 ns level.

Verbiest et al. (2009) also investigated the long-term timing behaviour of the

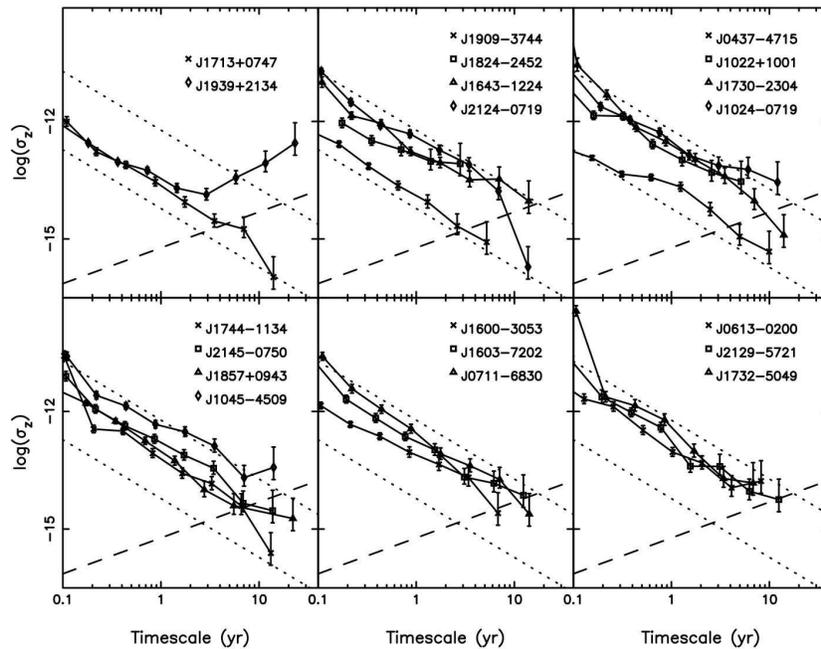


Figure 3. σ_z stability curves for the 20 MSPs that constitute the PPTA, as in Verbiest et al. (2009). The downward sloping, dotted lines are theoretical white noise levels at 100 ns (lower line) and 1 μ s (upper line). The upward sloping, dashed line is a theoretical curve for a hypothetical GWB. These graphs demonstrate the large excess of low-frequency noise in the PSR J1939+2134 data set, which could easily obscure a GWB. For some other pulsars (PSR J1045-4509, for example) there is some indication of low-frequency noise, though more data would be required to verify this. Overall, the lack of clear low-frequency noise bodes well for long-term GW detection efforts.

PPTA pulsars based on the σ_z stability parameter defined by Matsakis et al. (1997): $\sigma_z(\tau) = \frac{\tau^2}{2\sqrt{5}} \sqrt{\langle c_3^2 \rangle}$, with τ the timescale considered, c_3 the amplitude of a third-order polynomial fitted to a subset of the timing residuals of length τ , and $\langle \rangle$ denotes averaging over different subsets if τ is less than the time-span of the observations. Figure 3 summarises their results: on a 5 yr time-scale only PSR J1939+2134 shows non-white noise at high enough levels to obscure a GWB. On longer time-scales (~ 10 yr) the data also show potential low-frequency excess power shows in some other pulsars. For most pulsars in our sample it therefore appears likely that the GWB signal will dominate our timing on time-scales between 5 and 10 years, provided timing residuals are decreased further. While detection would be based on cross-correlations of timing residuals instead of the timing residuals of a single pulsar, unmodelled low-frequency noise as present in the PSR J1939+2134 data would render any GW-induced correlation less significant.

4. Sensitivity to GWs

There are two main classes of GW sources that may be detectable by PTAs: GWBs and single sources of GWs. In both cases the best studied sources are super-massive black-holes binary systems (SMBHBs): with low enough RMS timing residuals, nearby

SMBHBs may be strong enough to be detected individually and the combined effect of a large number of weaker, more distant ($z \approx 1 - 2$) SMBHBs is expected to be detectable as a GWB. In the following section, the PPTA’s sensitivity to single sources of SMBHBs will briefly be discussed, while projections of sensitivity to GWBs will be described in §4.2, assessing realistic time-scales for a positive detection of the GWB.

4.1. Sensitivity to Single Sources of GWs

The long-term timing of the PPTA pulsars (Verbiest et al. 2009) was recently used by Yardley et al. (2009) to determine the sensitivity of the PPTA to GWs emitted by SMBHBs. The conclusion of this research is that most[‡] $10^{10} M_{\odot}$ SMBHBs with orbital frequencies of order 10^{-9} to 10^{-6} Hz at distances out to the Virgo cluster can already be excluded, with sensitivity falling sharply with distance. They further predict that the high-mass ($\sim 5 \times 10^9 M_{\odot}$), high-redshift ($z \geq 2$) end of SMBHB merger rates will be constrained by pulsar timing within a decade.

4.2. Predicted GWB Detection Time-scale

Using the same long-term data sets and building on the analysis of Jenet et al. (2005), Verbiest et al. (2009) constructed the first GWB sensitivity curve for a PTA with a realistic spread in RMS residuals for the different pulsars. That sensitivity curve showed a 3σ detection sensitivity for GWB amplitudes $A \geq 2 \times 10^{-14}$, nearly equal to the best limit on the GWB amplitude: $A < 1.1 \times 10^{-14}$ (Jenet et al. 2006). Assuming a conservative noise floor of $\sigma_{n,\min}^{\text{est}} = 80$ ns, Verbiest et al. (2009) subsequently scaled their RMS residuals values with telescope sensitivity to make straightforward predictions for the sensitivity of other PTA efforts and projected the PPTA’s sensitivity on a decadal time-scale. They concluded that within another five to ten years, the PPTA is likely to obtain a 3σ sensitivity level throughout most of the predicted amplitude range of GWBs composed of SMBHBs. While this analysis does not predict detection significances beyond 3σ , this is mainly due to the bound of $\sigma_{n,\min}^{\text{est}}$, which may be too restrictive, especially in the light of the material presented in §3.2.

5. Conclusions

We have provided an overview of recent and ongoing work involved with the Parkes Pulsar Timing Array, focussing on hardware and software development and on investigations of fundamental pulsar properties that may be crucial to an eventual PTA-based detection of GWs. We have presented results of sensitivity calculations for the current PPTA data set to both single sources and a background of GWs. Making reasonable assumptions about the continued improvement of our data quality, we predict that the PPTA has a reasonable chance of detecting either the GWB or the GWs

[‡] Because of the need to fit the parameters of the pulsar timing model, the sensitivity at yearly and half-yearly periods is much reduced.

from a single, nearby SMBHB system within the next decade. This sensitivity will only be helped by various other projects, such as ongoing and planned pulsar surveys, the international PTA collaboration described elsewhere in these proceedings (Hobbs et al. 2009c) and new, highly sensitive telescopes such as the SKA and its pathfinder telescopes.

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