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High-Precision Baseband Timing at Parkes

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Abstract. We present recent observations of three pulsars, PSR J1909-3744, PSR J1600-3053, and PSR J1022+1001, that demonstrate remarkable levels of timing precision and instrumental stability. Data were taken with CPSR2, a new baseband recording system at the Parkes radio telescope, during the first 12 months of operation.

1. Introduction

The experimental technique of pulsar timing has enabled some of the most precise measurements in the history of astronomy, with applications ranging from precise sky position measurements (Fomalont et al. 1984) to tests of strong-field gravity (Taylor & Weisberg 1989). Extracting physical parameters from pulsar arrival times requires fitting them to a model that describes the system in which the pulsar resides. External influences on the intrinsically stable spin rate manifest themselves as subtle perturbations that are detectable when the amplitude of their signature exceeds the scatter (due both to random noise and systematic errors) in the measured arrival times. Pulsars that time to within 1 μs are few and far between, thus much effort has gone into the development of instruments capable of more precise TOA estimates. In theory, the error in any arrival time estimate scales inversely with the signal-to-noise ratio of the observed profile. Thus given a fixed antenna gain it is useful to record a large bandwidth, although it is then necessary to correct for dispersion smearing. This involves channelisation or, more recently, baseband sampling and coherent de-dispersion (Stairs et al. 2000).

1.1. The Second Caltech–Parkes–Swinburne Recorder (CPSR2)

Incoherent detectors incorporate the dispersive smearing across one frequency channel into the observed profile, an undesirable effect known as instrumental smearing. In addition, traditional analogue filter-bank systems suffer from variations in the performance of each individual filter in the bank and auto-correlation spectrometers can suffer from flaws in their complicated channelisation circuitry. CPSR2 is an alternative software-based coherent de-dispersion system that uses a fast digitiser to Nyquist-sample 2 x 64 MHz bands, both with two orthogonal polarisations. Samples are sent to a cluster of computers for storage and online or offline processing. This processing is done using software capable of coherent de-dispersion, allowing almost complete elimination of dispersive smearing in the observed profile and minimising the need for specialised hardware. CPSR2 was installed at the Parkes radio telescope in August 2002 and has been taking data reliably since November 2002. The recorded samples are typically reduced to a 128 channel coherent filter-bank, in blocks spanning 16.7 seconds. In our standard mode of operation we record 1024 phase bins across the pulse profile.

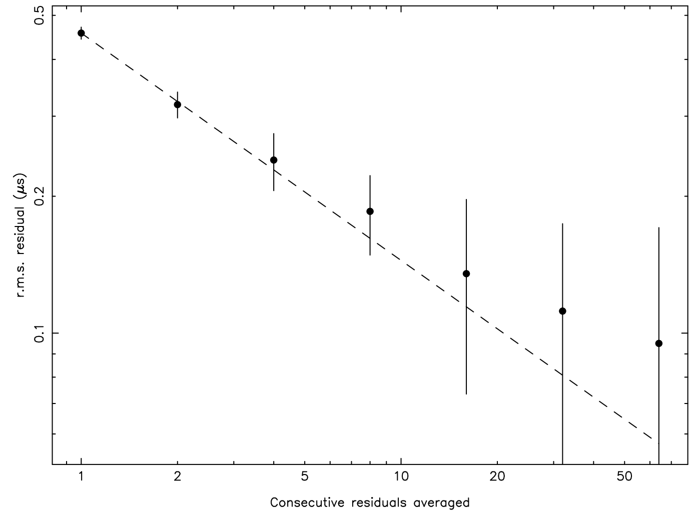

Figure 1. Decrease in RMS residual (after fitting to the J1909–3744 timing model) when averaging successive residuals. The RMS residuals calculated and presented in this plot do not weight TOAs according to their error estimates, which accounts for the initial increase when compared to the figure of 276 ns reported in this paper. The dashed line indicates the theoretical prediction for white noise residuals.

2. Analysing Pulse Arrival Times

Pulsar timing, in its distilled form, involves combining the time tag attached to the beginning of an observed profile with a measurement of the precise position of the pulse within the profile. Measuring the position of the pulse usually involves correlating the profile amplitudes with a standard template, the point of maximum correlation being the location of the pulse. In practice it is possible to implement correlation algorithms in either the time or frequency domain. In either case it should be possible to resolve positions to less than one phase bin, using either interpolation or the shift theorem. The results presented below all use standard template profiles derived from the entire CPSR2 data set, Fourier domain arrival time estimation methods and the standard TEMPO[1] timing package.

2.1. Results From Observations of PSR J1909–3744

Discovered in a recently completed high latitude survey (Jacoby et al. 2003), this 2.9 ms pulsar resides in an edge-on binary system with a white-dwarf companion. It has an intrinsically narrow pulse profile, with a measured width of only 42 μs and a dispersion measure of approximately 10.4 cm^{-3} pc. This makes it a prime candidate for precision timing, and coherent de-dispersion in particular. This pulsar scintillates markedly on time scales of a few hours, however during favourable episodes it is possible to obtain a signal-to-noise ratio in excess of 100 in just a few minutes. PSR J1909–3744 was discovered in a 4.5-minute pointing and is not particularly bright, with a time averaged flux density of about 2 mJy at 20 cm. This indicates that modern instrumentation may hold the key to increasing the number of pulsars that can be precisely timed.

[1] http://www.atnf.csiro.au/research/pulsar/timing/tempo

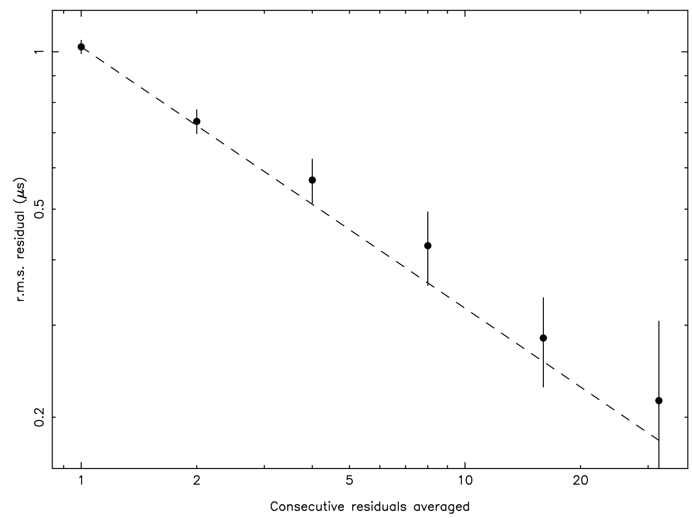

Figure 2. PSR J1600–3053 RMS timing residual trend.

Timing residuals already reveal a large Shapiro delay (Jacoby et al. 2003), making PSR J1909–3744 a candidate system for obtaining a precise recycled pulsar mass. With an integration time of only 5 minutes per TOA, the timing model produces an RMS residual of 276 ns when applied to 677 arrival times from both 64 MHz CPSR2 bands. A reduced chi-squared of unity can be achieved with an error scaling factor (TEMPO's EFAC) of just 1.11. Successive averaging of residuals indicates that systematic errors only begin to dominate at a level of around 150 ns, which means that PSR J1909–3744 can be timed to a precision comparable to that of PSR J0437–4715, which has a flux density around 60 times greater at 20 cm.

2.2. Results From Observations of PSR J1600–3053

PSR J1600–3053 was discovered in the same high-latitude survey as PSR J1909–3744 and also boasts a narrow pulse feature that has a full width at half maximum of approximately 77 μs. This pulsar has a rotation period of 3.6 ms and measurements of its dispersion measure yield a value of approximately 52 cm^{-3} pc. Although not as bright as PSR J1909–3744, the higher dispersion measure mitigates the effects of scintillation, ensuring that observations have a predictable relationship between signal-to-noise and integration time. Although this pulsar orbits a white dwarf companion, no Shapiro delay has yet been detected, which may indicate that the system has a small inclination angle. The current timing model produces a RMS residual of 840 ns and requires an EFAC of 1.59 when fitted to 10-minute integrations. Given the weak nature of the source, longer integration times are expected to yield a significant improvement, as Figure 2 suggests. The fact that the errors in arrival times appear to be significantly underestimated may be related to the poor signal-to-noise in a 10-minute integration, or is perhaps characteristic of a deficiency in the analysis or model. This will be investigated in future.

2.3. Results From Observations of PSR J1022+1001

PSR J1022+1001 has a rotation period of 16.5 ms, so it is unlikely to be a candidate for extremely precise timing. However, it is regularly observed as part of the Swinburne timing program, both because of its relative brightness and the paucity of other sources at this hour angle. Previous authors have reported intrinsic profile variability on short

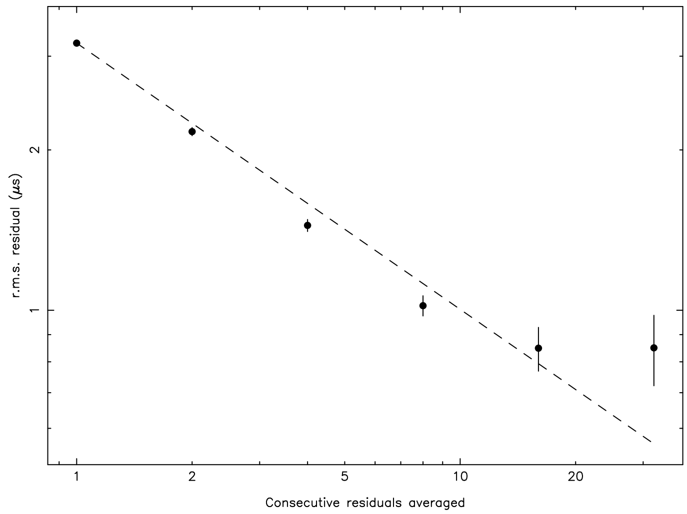

Figure 3. PSR J1022+1001 RMS timing residual trend.

time scales that results in a RMS timing residual of order 20 μs (Kramer et al. 1999). In sharp contrast, the existing 12 months of CPSR2 data is well suited to a Blandford-Teukolsky (Blandford & Teukolsky 1976) model containing only Keplerian parameters. The fitted RMS residual corresponding to this new model is 2 μs and a reduced chi-squared of unity can be achieved with an EFAC of 1.13, negating the need to invoke profile variations to explain any timing irregularities. In fact, as Figure 3 and Figure 4 show, the residuals appear to be dominated by Gaussian noise down to a level near 1 μs. This is just 0.006% of the pulsar period, amongst the most precise RMS/p values ever obtained.

3. Conclusions

With the maturation of software processing techniques and digital recording technology, millisecond pulsar timing is reaching new levels of precision. Modern pulsar surveys are also increasingly sensitive to rapid pulsation rates, expanding the sample of suitable timing sources available for study.

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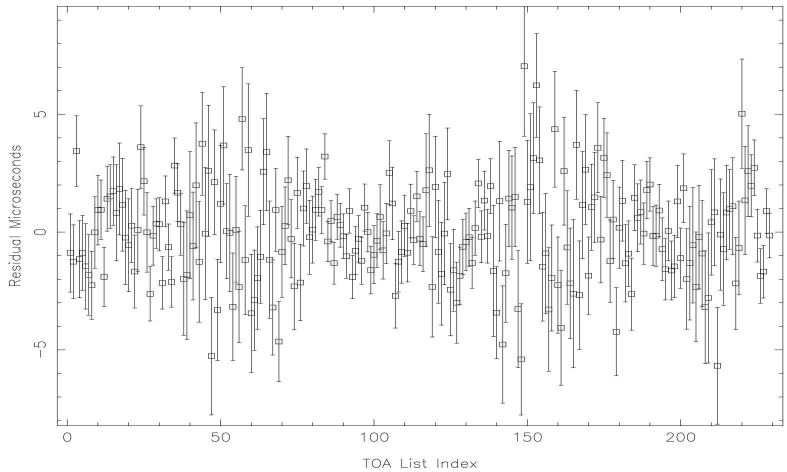

Figure 4. 230 arrival times from observations of PSR J1022+1001, plotted against their list index.

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