DEVELOPMENT OF A PULSAR-BASED TIMESCALE

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ABSTRACT. In this paper we summarise how pulsar observations have been used to create a highly stable timescale. We review recent work from the Parkes Pulsar Timing Array team to create a timescale that has a stability comparable to existing atomic timescales. We discuss how this timescale will improve by combining data from more telescopes. We conclude by considering the long-term possibilities for pulsar-based timescales.

1. INTRODUCTION

In this review paper we describe how the regular rotation of millisecond pulsars can be used to create a highly stable timescale. Numerous observatories worldwide now carry out regular observations of such pulsars with the primary aim of searching for ultra-low-frequency gravitational waves formed from merging supermassive, binary black holes. Pulse times-of-arrival (ToAs) from the pulsars are measured. A model of each pulsar, that describes its rotation, position and orbit, is used to predict the ToAs for that pulsar. Discrepancies between the observed and predicted ToAs are known as the pulsar timing residuals. As gravitational waves are not included in the model for the pulsar, any such waves will induce timing residuals. Theoretical estimates predict timing residuals at the <100 ns level for a data set spanning $\sim$5 yr.

The observatory clock, to which the pulse ToAs are referenced, is normally based on a maser to provide a stable frequency standard and a system, now usually based on the Global Positioning Satellites, to provide absolute time. Using techniques such as the common view time transfer, the observatory timescale can be transferred to a realisation of Terrestrial Time, TT. For high precision timing, TT as realised by the Bureau International des Poids et Mesures is used, TT(BIPM).

Atomic time standards are becoming more and more stable. However, the stability over many years or decades is not well known. It is therefore possible that current terrestrial timescales are not sufficient for measuring pulse ToAs at the <100 ns level over many years. All pulsar observations referred to a given timescale will be affected by irregularities in that timescale. This provides the possibility that identical residuals in the data sets for different pulsars could be identified. Only recently have enough pulsars been observed with sufficient sensitivity to search for the timing residuals induced by irregularities in the terrestrial timescales. The Parkes Pulsar Timing Array (PPTA) project began during the year 2004 (Manchester et al. 2013). The PPTA currently observes 23 pulsars using the 64-m diameter Parkes radio telescope in Australia. The North American PTA (NANOGrav), described in McLaughlin (2013), formed in October 2007 and carries out observations with the Arecibo and Green Bank telescopes. The European PTA (EPTA; Kramer & Champion 2013) was established in 2004/2005 and includes telescopes in England, France, Germany, the Netherlands and Italy. In 2008 an agreement was made to share data sets between the three major PTAs. This led to the formation of the International Pulsar Timing Array (IPTA; see Manchester 2013 and references therein).

The basic methods for extracting a pulsar timescale have been known for many years (Guinot & Petit 1991, Petit & Tavella 1996, Rodin 2008, Rodin & Chen 2011, Hobbs et al. 2012). In brief, an ensemble of pulsars provides an Ensemble Pulsar Scale (EPS) that is analogous to the free atomic timescale Échelle Atomique Libre (EAL). The EPS can detect fluctuations in atomic timescales through the process of pulsar timing; the timing residuals for every pulsar in the sample will be affected by the timescale fluctuations in the same way. Identifying the signal common to all pulsars therefore allows the timescale fluctuations to be identified and corrected.

In this paper we initially describe an initial pulsar timescale produced using observations from the PPTA project. We then discuss a timescale likely to be produced using data from the IPTA. Finally, we discuss possibilities that arise from new telescopes that will begin observations in the near future.

2. CURRENT STATUS

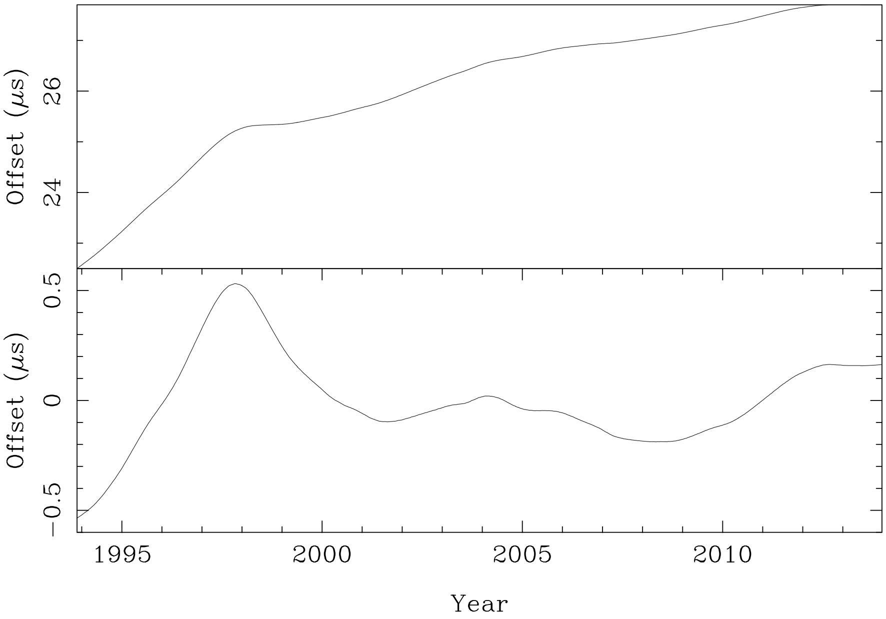

Figure 1: (top panel) The difference between the TT(TAI) and TT(BIPM2013). (bottom panel) The same, but after a quadratic polynomial has been fitted and removed.

The most stable and precise realisation of terrestrial time currently available is TT(BIPM2013). This timescale is obtained by retroactively applying a set of corrections to International Atomic Time, TT(TAI). For high precision pulsar timing it is usual to refer the pulsar ToAs to the best available realisation of TT, such as TT(BIPM2013). However, for our recent work we specifically chose to refer the ToAs to TT(TAI). The main reason for doing this was to confirm that we could recover the known irregularities in TT(TAI), i.e., could we recover TT(BIPM2013) from TT(TAI).

All attempts to use pulsars to search for irregularities in a terrestrial timescale are limited as we do not know the intrinsic pulsar pulse periods. Many phenomena, such as the pulsar slowing down, having a radial velocity from Earth, gravitational waves and drifts in the terrestrial timescale will also lead to an apparent change in that period. Hence, as part of the pulsar timing procedure it is necessary to fit for the pulse period and its first time derivative, i.e., to fit a quadratic polynomial to the timing residuals. The fitted parameters lead to new estimates of the pulsar's period and its time derivative. Post-fit timing residuals derived from the new parameters will not contain a quadratic polynomial and therefore, any errors in a timescale that induce residuals which follow a quadratic polynomial would be absorbed into the parameter fit and hence undetectable.

In the top panel of Figure 1 we show the expected signal TT(TAI)-TT(BIPM2013) before removing a quadratic polynomial. In the bottom panel we show the same, but after a quadratic polynomial has been fitted and removed. For observations spanning the years 1994 to 2014 and referred to TT(TAI) we would expect residuals at the $< 500\,\mathrm{ns}$ level induced by errors in the time standard.

In Hobbs et al. (2012) we used observations from the PPTA project. The sampling for each pulsar is shown in the top panel of Figure 2. All the pulsars are different. For some pulsars, observations exist since the year 1994. These pulsars have wide-ranging properties. They have different data spans,

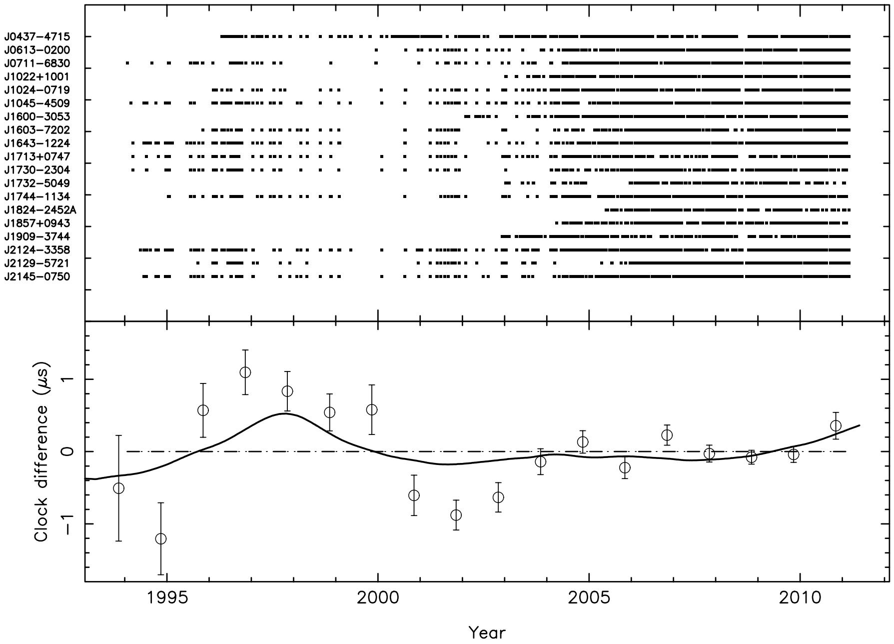

Figure 2: This figure is reproduced from Hobbs et al. (2012). The top panel shows the observing cadence for each of the pulsars in our sample. The lower panel shows the difference between the pulsar timescale and TT(TAI) as points with error bars. The solid line indicates the difference between TT(TAI) and TT(BIPM11) after a quadratic polynomial has been fitted and removed. Full details are available in Hobbs et al. (2012).

timing precision and sampling. Some pulsars are significantly affected by noise processes that induce low-frequency noise into the timing residuals. It was therefore necessary to develop a method for extracting the common signal that accounts for all these effects. The resulting algorithm is described in section 4 of Hobbs et al. (2012) and the result from applying the algorithm to the data is shown in the lower panel of Figure 2. We refer to the pulsar timescale as TT(PPTA2011). The difference between TT(PPTA2011) and TT(TAI) is shown in the figure as points with error bars. The expected signal, the difference between TT(BIPM2011) and TT(TAI) is shown as the solid line. In general there is good agreement between TT(PPTA2011)-TT(TAI) and TT(BIPM2011)-TT(TAI).

The largest deviation occurs between the years 1995 and 2003. During this time deliberate corrections were made to steer the TAI frequency to correct for changes in the primary frequency standards (Petit 2004). There is therefore a possibility that slight inaccuracies were introduced around this time. The PPTA data set has sparse sampling around this time and so it is also possible that these discrepancies come from the determination of the pulsar timescale. As shown below the use of data sets from the International Pulsar Timing Array project should be able to identify the reasons for the discrepancy.

3. THE INTERNATIONAL PULSAR TIMING ARRAY

The International Pulsar Timing Array (IPTA) team are in the process of combining data sets from the three current PTAs. The final data sets are not complete, but the pulsar names and their expected data spans have been published in Manchester (2013). For some of these pulsars it is possible to determine ToAs with < 50 ns precision. However, other pulsars are more poorly timed and may only achieve $\sim 1\ \mu$s timing precision. Some pulsar data sets will be dominated by jitter noise and other pulsars by timing noise. It is therefore currently not trivial to predict how sensitive the IPTA data set will be to clock errors. In order to provide an initial prediction we have simulated data sets with the expected data spans,

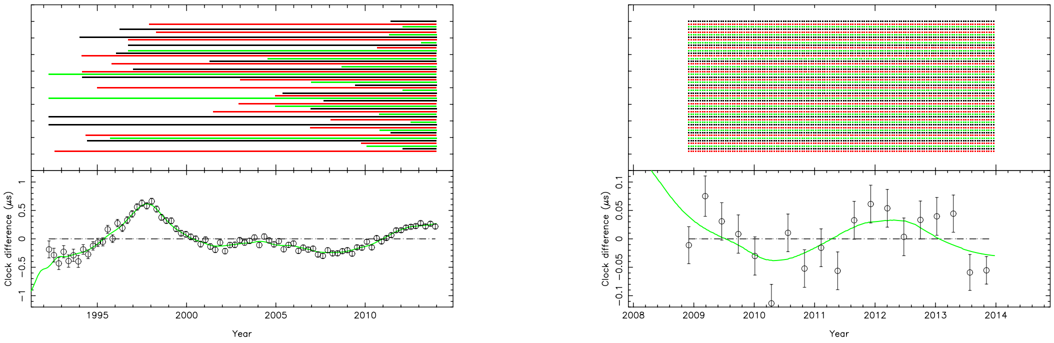

Figure 3: As in Figure 2, but using simulated data of the 50 pulsars being observed as part of the IPTA. In all cases the pulsars were assumed to be regularly sampled with a ToA precision of 500 ns. In the left hand panel the true data spans are used. In the right-hand panel only the last five years of data are simulated. For legibility the pulsar names, given in Figure 2, are not provided here. The pulsars simulated are listed in Manchester (2013).

but assume that all pulsars have a timing precision of 500 ns and are observed every 14 days. No low frequency noise processes are included in the simulation. The result is shown in the left-hand panel of Figure 3. With such a data set the expected discrepancies between TT(TAI) and TT(BIPM2013) can easily be identified.

As clocks improve, TT(TAI) is becoming more stable. In order to determine whether recent errors in TT(TAI) could be determined we have simulated IPTA data covering the last five years (all pulsars are simulated to have the same rms timing residual of 500 ns, same data span and same sampling). The result is shown in the right-hand panel of Figure 3. With such a short data span the clock errors are small, with a peak to peak amplitude of $\sim$ 100 ns. As seen in the Figure, it would be possible to detect the expected variation with the IPTA data sets, but it is unlikely that any smaller errors in TT(BIPM2013) could be identified.

The major purpose of the upcoming IPTA data sets will therefore be to 1) improve the pulsar-based timescale in the years before 2000 in order to confirm or deny the possible discrepancies seen using the PPTA data and 2) provide a long-term baseline for future, more precise data sets.

4. THE FUTURE

New telescopes are currently being designed and built. With its massive collecting area, the Five-hundred-meter Aperture Spherical Telescope (FAST) in China will provide high quality pulsar data sets on a large number of pulsars (see Nan et al. 2011). In the Southern Hemisphere the Square Kilometre Array (and its precursor telescopes such as MeerKAT) will also carry out large-scale pulsar timing array projects. Already existing telescopes are also being upgraded to provide more sensitive receivers covering much wider bandwidths. It is likely that the data sets from the larger telescopes will become limited by noise processes such as jitter noise on short time scales (see e.g., Shannon & Cordes 2012) and timing noise on longer time scales (e.g., Hobbs et al. 2010). However, with a careful choice of pulsars it seems likely that these telescopes would be able to provide combined data sets for at least 50 pulsars with an rms timing residual of $\sim$50 ns over a five year observing span. In Figure 4, we show the result that would be obtained if such telescopes had been observing for the last five years. The clock signal could be determined at the $\sim$ 10 ns level easily allowing the differences between TT(TAI) and TT(BIPM2013) to be identified.

Determining the pulsar time scale at this precision will lead to a long-term time standard that is competitive with the world's best atomic timescales. Combining the atomic time standards with the pulsar time standard will enable the development of a new timescale that is stable over decades. As emphasised in Hobbs et al. (2012) a pulsar-based timescale provides 1) an independent check on terrestrial time scales using astrophysical objects, 2) a timescale based on macroscopic objects of stellar mass instead

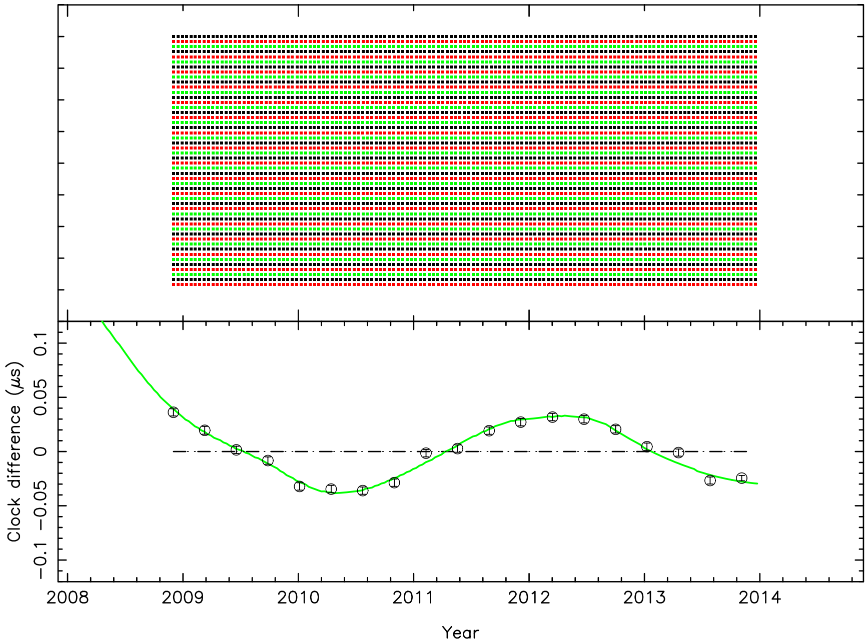

Figure 4: As in the right-hand panel of Figure 3, but using simulated data in which 50 pulsars are timed with a timing precision of 50 ns.

of atomic clocks and 3) a timescale that is continuous and will remain valid for millions of years.

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