Required cadence for the 10/50cm dual band receiver for pulsar observations

Authors: G. Hobbs, M. Keith, W. Coles, R. Manchester, R. Shannon, V. Ravi

Purpose

ATUC has requested: "*ATNF staff to analyse and present quantitative information on appropriate science-driven receiver cadence for Parkes.*". This document provides input into the response by describing the science-case for the use of the 10-50CM receiver at Parkes for the Parkes Pulsar Timing Array (PPTA) observations. This document concentrates on the PPTA and makes use of analyses carried out for the specific PPTA pulsars, but similar arguments will apply for other high-precision pulsar timing experiments at Parkes.

Background material

Pulsar observations currently take up 56% of the time on the Parkes telescope (with maintenance taking up a further 15%). The Parkes Pulsar Timing Array (PPTA) project (see Manchester et al., 2012, submitted to PASA; a preprint is available on request) currently uses 16% of the available time. This project has received high grades from the Time Assignment Committee and it is expected that a large fraction of Parkes observing time will continue to be dedicated to this project.

It is in CASS's interest to continue the PPTA project for numerous reasons:

First, the PPTA research is closely aligned with the Astrophysics Theme within CASS. The vision statement for the Astrophysics Theme is "To conduct world-class research in astrophysics, retaining astronomy's position as Australia's highest impact science and furthering our understanding of the Universe through innovative use of CSIRO's telescopes". The September 2011 scientific program assessment of CASS noted "that pulsar science in Australia is at the leading edge of benchmark research" and "is a highlight of Australian scientific research, broadly acknowledged as dominant worldwide."

Second, CASS is actively engaged in the technology, science and site development for the Square Kilometre Array (SKA) telescope. This research topic is aligned with the SKA Phase I Key Science Goal that aims to study gravitational waves using pulsar observations. This project will ensure that CSIRO remains at the forefront of this research.

Third, the PPTA project is a major component of the International Pulsar Timing Array (IPTA) project allowing CASS to strengthen our collaborations with researchers Worldwide. Without funding for the LISA mission, the pulsar timing experiments are now the only probe of gravitational waves from massive black hole binary systems. The Parkes data set is currently the most sensitive available for searching for gravitational waves (Shannon et al., in preparation) and therefore is of huge importance to the IPTA project.

The PPTA project requests observations every ∼14 d and usually is scheduled every 2–3 weeks. Each set of observations requires at least two days to complete and requires both a 20 cm receiver (usually the central beam of the 13-beam multibeam receiver, but the H-OH receiver can also be used) and the dual-band 10/50 cm receiver. The 10/50 cm receiver is therefore required every 2 – 3 weeks for 2 – 3 days. This places stringent limitations on the availability of other receivers and on the number of receiver changes that are required each semester.

The purpose of this document is to address the science justification for the observing cadence requirement for the 10/50 cm receiver.

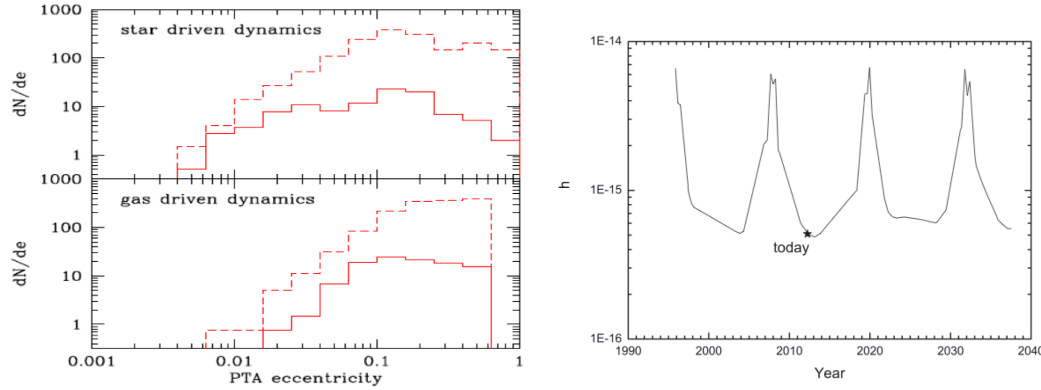

Figure 1: (left) Predicted eccentricity of GW sources detectable by pulsar timing (Sesana, private communication). (right) Predicted characteristic strain as a function of the observation time for OJ287. Figure taken from Liu et al. (2012).

Long-term solution

The PPTA project limits the availability of receivers for other observing projects at Parkes. The long-term solution for this problem is to commission a sensitive, wide-band feed that covers from the 40 cm band to the 10 cm band (and includes the 20 cm band). Such a receiver would therefore be the only receiver required for most pulsar observations at Parkes (except multibeam searches) and would be useful for many other non-pulsar projects. In this document we only consider the short-term application to the PPTA project where we are restricted to the 10/50 cm receiver and one of the 20 cm receivers.

1 Use of the 10/50 cm receiver for the PPTA project

The main goal of the PPTA observations is to produce high quality pulsar timing data sets that can be used to search for gravitational wave signals (Yardley et al. 2010, 2011). The project has many secondary goals, e.g., establishment of a pulsar-based timescale (Hobbs et al., submitted to MNRAS; a preprint is available on request) and investigation of ISM properties (Keith et al., submitted to MNRAS; a preprint is available on request). These applications require (1) precise estimates of the pulse arrival times, (2) the ability to remove model dispersive effects and (3) the ability to identify (and correct) instrumental errors in the data quickly.

1.1 Justification for the required observing cadence

Here we first justify the observing cadence for PPTA observations (typically one observation every 2-3 weeks). Then we justify the need for having the same number of 10/50 cm observations as 20 cm observations. Therefore we justify the requirement for the 10/50 cm observing cadence.

1.2 Justification for the observing cadence for the PPTA project

Requirements for the observing cadence exist for the following:

Producing high quality data sets for scientific analysis: The main PPTA goal is to make what may be the first direct detection of gravitational waves (GWs). The expected GW signal is thought to come from a large number of supermassive binary black holes that produce a background of GWs. Jenet et al. (2005) provided the first in-depth analysis of the number of pulsars needed to detect the background and the required observing cadence. In Jenet et al. (2005), we showed that around 20 pulsars were required to detect the background with a sampling of one observation per week over a data span of 5 yr and an rms timing residual around ∼100 ns. We have not achieved the required observing cadence, nor the required rms timing residual. In order to detect the GW background we therefore have to increase our data spans. If we reduce the observing cadence then the time taken to become sensitive to expected GW signals will further increase.

Ravi et al. (in preparation; pre-print available on request) have shown that the expected signal will not take the form of an isotropic, stochastic background. It is likely that individual GW sources may dominate the background. Recent numerical simulations have also shown that such binary black hole systems will be in highly eccentric systems (see the left-hand panel in Figure 1). For instance, the candidate binary supermassive binary black hole, OJ 287 (Valtonen et al. 2011) is modelled with an orbital eccentricity of 0.7. This will lead to bursts of gravitational wave emission. Figure 2 from Liu et al. (2012) has been reproduced here in the right-hand panel of Figure 1. This Figure shows that the emission will be "cuspy" and the detectable signal may only last for weeks or months. In order to provide a confident detection of any such burst we therefore require multiple pulsars to have been observed, ideally with an observing cadence of ∼ 2 weeks or better.[1]

One of the largest challenges for the PPTA project is to deal with unmodelled irregularities in the pulsar periodicity. Such irregularities generally take the form of low-frequency noise. Lyne et al. (2010) showed that such irregularities for young pulsars could be modelled as a two-state process in which the pulsar's spin-down rate flipped between the values. There is tentative evidence (Petroff private communication) to suggest that PSR J1939+2134, a pulsar in the PPTA sample, also shows the same effect. If true, it may be possible to model and subsequently remove the low-frequency noise. However, this will only occur if sufficient observations exist to enable the particular state to be identified. The time scale for such variations in millisecond pulsars is not known, but young pulsars are known to vary on time scales of weeks (such as PSR B1828−11; see Lyne et al. 2010). Pulsars are also known to undergo sudden discrete changes in their spin-down rate. These are known as "glitch events". One pulsar in our sample (PSR J1824−2452A) is known to have suffered a small glitch. To model any such events in the future it is necessary to have observations as close to the glitch event as possible.

One of the main goals of the PPTA project is to search for irregularities in terrestrial time standards by comparing them with a pulsar-based reference timescale (Hobbs et al., submitted to MNRAS). Terrestrial time standards are formed by combining the signals from multiple clocks and frequency standards around the world. It is possible that errors may exhibit as step-changes in terrestrial time. Identifying and correcting such errors by comparison with the pulsar-based timescale requires frequent observations. In Figure 2 we show the difference between our pulsar-based time scale TT(PPTA11) and TT(TAI). We see variations between the timescales around the year 1998, but the poor data sampling around this time (shown in the upper panel) means that it is very challenging for us to confirm this discrepancy.

Removing the effect of dispersion measure variations: The gravitational wave detection experiments rely on variations in the dispersion measure to be measured and corrected. The required sampling is determined by the size and structure of structures in the interstellar medium and the precision with which the 10/50 cm observations are made. Keith et al. (in preparation; pre-print available) have shown, that with present data sets, the optimal time smoothing time to be used for the dispersion measure correction is as small as 50 d for several pulsars. We therefore need more frequent sampling than this obtain sufficient precision in the correction.

Studying the interstellar medium: The PPTA data sets cover six years and are well sampled both spatially and temporally. Numerous analyses have been carried out on these data (such as You et al. (2007a), You et al. (2007b), Coles et al. (2010), You et al. (2012), Keith et al. (2012)). We have identified inhomogeneities in the ionised interstellar medium (IISM) on time scales even finer than our present sampling. Such studies not only enhances our understanding of turbulence in the interstellar medium, but potentially allows us to develop methods for scattering correction that would be applicable to other pulsars and other PTAs.

[1] Note that producing an upper bound on the existence of a gravitational wave signal of known functional form can be carried out using observations of a single pulsar (see e.g., Jenet et al. 2004 who refuted the existence of a binary black hole system in the radio galaxy 3C66B. However, an unambiguous detection of the gravitational waves can only be made by measuring the correlation between a large number of pulsar data sets.

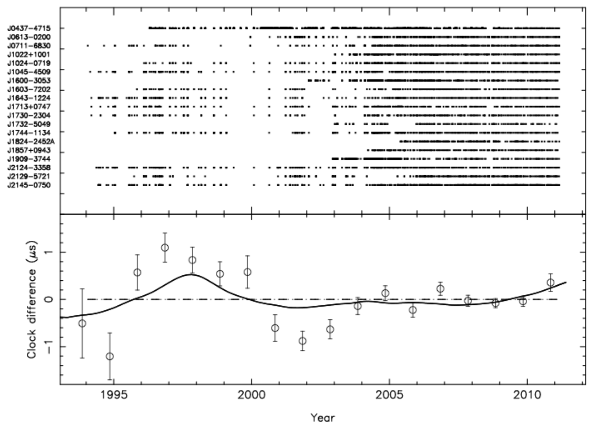

Figure 2: The top panel shows the sampling for 19 of the 20 PPTA pulsars. The lower panel shows the difference between TT(BIPM11) and TT(TAI) as the solid line. The data points indicate the difference between TT(PPTA11) and TT(TAI). Figure from Hobbs et al. (submitted to MNRAS).

Identifying instrumental errors: It is hard to quantify the sampling necessary to enable the efficient detection and correction of instrumental errors. However, it is clear that frequent, regular observations using different receivers are required to calibrate our data sets and to identify unexpected errors. If, for instance, measurements were made at very infrequent intervals then it would be difficult or impossible to identify slow variations in the time delays through the observing system.

It is not uncommon to fail to observe a source during regular observations due to scintillation, equipment failure, or operator error. Taking fewer but longer observations significantly enhances the probability of lost data. Lost data degrades the sensitivity of the array for all purposes.

Note that the sensitivity of our observations to all gravitational waves, clock, ephemeris errors and interstellar medium effects increases with increasing data span. We therefore require continued observations at the cadence described above to achieve the project goals.

1.3 Justification for the requirement for equal numbers of 10/50cm and 20cm observations

Above we justified the required cadence for the PPTA project. Here we justify the requirement for equal (or more) 10/50CM observations compared with 20CM observations.

Producing high quality data sets for scientific analysis: The strongest source, PSR J0437−7415, provides the best data set at 10 cm and is critical to the PPTAs overall sensitivity. Three of the four strongest sources are best observed with $> 90\%$ of the observation time at 10/50CM because, although the signal is not strongest at 10cm, the 10/50CM backend allows DM correction in a single observation.

The sensitivity of our data set to gravitational waves increases with the number of observations. Including 10 cm, 50 cm and 20 cm observations for each session for each pulsar significantly increases our detection sensitivity compared with a single observation in the 20 cm band. The sensitivity to various physical phenomena (such as gravitational waves) is also very dependent upon the regularity and uniformity of the observations. Currently our data sets are the best in the world and are significantly better than those from North American telescopes (Demorest et al., 2012, arXiv:1201.6641) and European telescopes (van Haasteren et al. 2011, MNRAS, 414, 3117). This is illustrated by the fact that the PPTA limit on the stochastic GW background in the Galaxy (Shannon et al., in preparation) is more than a factor of three better than the limits published by the North American and European groups. This is largely due to these groups having less frequent and less regular observations than we are currently able to obtain at Parkes.

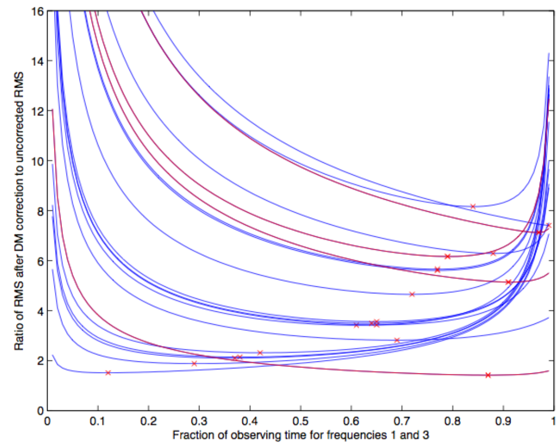

Figure 3: Increase in white noise versus the fraction of observing time devoted to dispersion measure correction for the PPTA pulsars. The four "best" pulsars are shown in red. The optimal observation-time division is marked with a red 'x' symbol in each case.

Removing the effect of dispersion measure variations: Keith et al. (submitted to MNRAS; preprint available on request) have shown that correcting for dispersion measure variations to the level required for GW detection entirely with the 20 cm receivers is impossible; a wider frequency span is essential to measure the variations with sufficient precision. The 10/50 cm receiver is therefore necessary for dispersion measure correction.

The Keith et al. paper includes a plot (reproduced in Figure 3) that shows the optimal observing time at 10/50 cm as a fraction of the total time (this plot makes use of real measured parameters). The fraction is greater than 0.5 for 16 out of the 20 PPTA pulsars, implying that we actually require more 10/50 cm observations than we are currently obtaining!

Studying the interstellar medium: Five of the PPTA pulsars are significantly affected by scattering effects. To date, we have been unable to correct for this effect, but regular sampling is essential for all ideas that have been proposed for dealing with this correction.

2 Conclusion

The above justification shows that, with the present receiver suite, we have a continuing need for observations with the 10/50 cm receiver at intervals ~ 14 d. We emphasise the importance of developing a sensitive, wide-band receiver system for Parkes. Such a system will provide superior data to that from the current 3-receiver system and will give the best possible solution to both PPTA requirements and the long-term optimisation of Parkes operations.