HIGH PRECISION PULSAR TIMING: NANCAY AND THE EUROPEAN PULSAR TIMING ARRAY

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ABSTRACT. Pulsars are highly stable celestial rotators used in many different applications, from tests of the theories describing the gravitation to the search for a Gravitational Waves background. They could even play a role in time scales definition and those point sources are also used to link the different reference frames. Nancay radiotelescope is involved in high precision timing since 20 years. Since 2004, a coherent dedispersion instrumentation enables numerous routine observations on more than 200 pulsars using half of the time of this 100-meters class radiotelescope. Two main programs are currently conducted. A large set of young and old pulsars is timed for a multi-wavelength approach, complementary to the very successful high energy observations of pulsars done by the instrument FERMI/LAT (Abdo et al., 2009). A set of highly stable millisecond pulsars is monitored as our contribution to the European Pulsar Timing Array in order to probe any kind of Gravitational Waves background.

1. INTRODUCTION

Highly magnetized neutron stars are called pulsars when we receive collimated radio beams from them on every rotation. The most stable pulsars are used as clocks for many different kind of studies. Such pulsars located in a relativistic binary are used to put constrains on the theories of gravitation (Kramer et al., 2006). An array of highly stable pulsars distributed over the sky is used to search for a gravitational waves background (Jenet et al., 2006). An effort towards an international Pulsar Timing Array is taking place in every large telescope in the world in order to share all the observations and set the best limit on a gravitational waves background coming from the early Universe.

With a collecting area corresponding to a 100m dish, the Nançay radiotelescope is a centimetric telescope among the largest in the world. Based on a Kraus design, the telescope has two receivers providing a continuous coverage from 1.1 to 3.5GHz. The 1.4 to 2GHz range is a good choice to observe pulsars between embarrassing interstellar effects at the lower frequencies and faint emission received from pulsars at higher ones.

2. A COHERENT PULSAR DEDISPERSION INSTRUMENTATION

A quasi-perfect way to remove the dispersion introduced by the ionized part of the interstellar medium, called the coherent dedispersion, is to apply a transfer inverse function in the complex Fourier domain of the data time series (Hankins & Rickett, 1975). This operation needs a huge computing power since we need to do direct and inverse Fast Fourier Transforms in real-time on the Nyquist sampled data stream. At Nançay, we were among the very first in June 2008 to routinely use the Graphical Processing Units (GPU) instead of standard processors (CPU) to dedisperse pulsar data (Figure 1). With the now fairly old Nvidia GeForce 8800GTX, we are able to coherently dedisperse a 128MHz bandwidth having 2 computers hosting 2 GPU units each. The two GPUs we put in each computer are water-cooled to increase their lifetime. Presently the folding of the data in phase with the pulsar rotation is done in the CPUs. and the overall load of each computer during observations is around 60%. We are already testing the next generation which is able to coherently dedisperse a 512MHz bandwith (Figure 1), the maximum currently available at the Nançay telescope. While the current version is based on a Serendip5 board, we are now using a ROACH board also designed by the CASPER group (http://casper.berkeley.edu/).

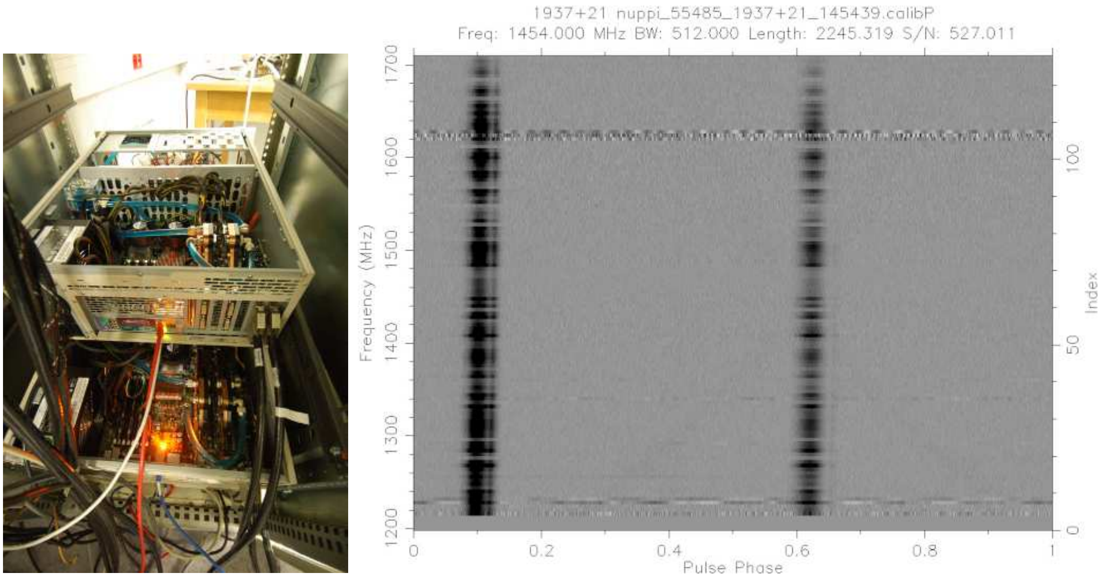

Figure 1: View of the 128MHz coherent dedispersion instrumentation based on GPUs. Profiles from the pulsar B1937+21 shown as function of the frequency and integrated for more than half an hour with the new 512MHz version of the instrumentation.

3. AN INTERNATIONAL EFFORT

The Nançay radiotelescope is part of an European consortium called the European Pulsar Timing Array (EPTA) which gather people from the five main radiotelescopes in Europe (Janssen et al. 2008): Cagliari (IT), Effelsberg (G), Jodrell Bank(GB), Nançay (F) and Westerbork (NL). The 64 meters antenna in Sicilia (Cagliari) is still under construction. We do have regular short workshops, usually at one of the radiotelescopes. During a few days, we closely interact to make progress on the different actions we planned together : coordinations of project and publications for students and post-docs, coordinations of source lists and joined observing sessions, sharing among partners of Time of Arrival (ToAs) and templates (used to derive ToAs), building a library of common synthetic multi-frequency templates. We are also open to international collaboration to share ToAs for joined goals, and we are presently preparing a Memorandum of Understanding being signed with the Australian Parkes Pulsar Timing Array (PPTA). We hope to reach the same level of agreement with the US NanoGrav consortium.

Lead by Michael Kramer (MPIfR, Bonn and University of Manchester), an advanced grant from the European Research Council called LEAP (for Large European Array for Pulsars) was obtained to coherently add the pulsar signal from the five large European radiotelescopes. Based on the high concentration of large antennae in central Europe, the aim is to get an Arecibo-like radiotelescope able to observe all the Northern sky.

4. THE NANCAY CONTRIBUTION

The Nançay pulsar coherent dedispersor is producing high quality timing data on a number of stable millisecond pulsars. Figure 2 shows an example of a daily profile and a template obtained on the ultra-stable pulsar PSR J1909-3744. From the coherently dedispersed profiles, we derive a ToA using a χ^2 fit in the Fourier domain (Taylor, 1992). A fit for the pulsar parameters (period and derivatives, position, proper motion and potentially several orbital parameters) is done from the ToAs using the code 'tempo2' (Hobbs et al., 2006) producing ToA residuals (differences between calculated and measured ToAs). We then carefully inspect them to make sure all the needed parameters are included in the analysis. A set of ToAs residuals is shown Figure 3 for pulsar J1909-3744. A summary of the ToAs residuals rms obtained at Nançay are shown in Table 1 (Desvignes, 2009). The excellent quality of the Nançay data can be

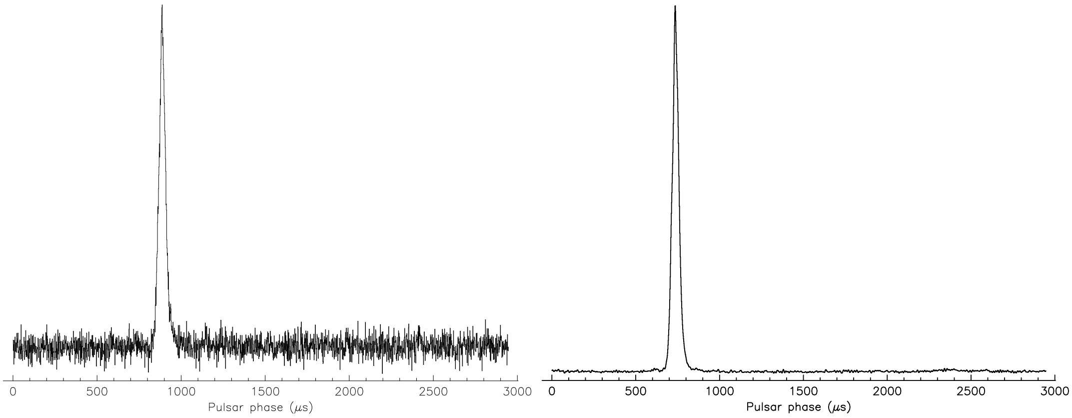

Figure 2: Exemple of a daily profile for pulsar J1909-3744, along with the template used to accurately determine the Times of Arrivals.

emphasized observing that half of the residuals are characterized by an rms below 1 μs and few of them are even below 500ns. Nançay is now an important partner to build a Pulsar Timing Array, within the EPTA first, and then the EPTA being part of the International Pulsar Timing Array.

5. AN EPTA LIMIT ON A GRAVITATIONAL WAVES BACKGROUND

As already mentioned, the direct detection of low-frequency gravitational waves (in the range $10^{-9} - 10^{-8}$Hz) is the main goal of the different Pulsar Timing Array projects around the world. High precision timing measurements will be processed to measure the stochastic background of gravitational waves (GWB) whose characteristic strain is expected to approximately follow a power-law of the form $h_c(f) = A(f/yr^{-1})^{\alpha}$, where f is the gravitational-wave frequency. A recent work (van Haasteren et al., 2010), used the current data from the European PTA along with a Bayesian algorithm to determine an upper limit on the GWB amplitude A as a function of the unknown spectral slope. For the case $\alpha = 2/3$, which is expected if the GWB is produced by supermassive black- hole binaries, a 95% confidence upper limit on A of 6×10^{-15} was obtained, which is 1.8 times lower than the 95% confidence GWB limit obtained by the Parkes PTA in 2006.

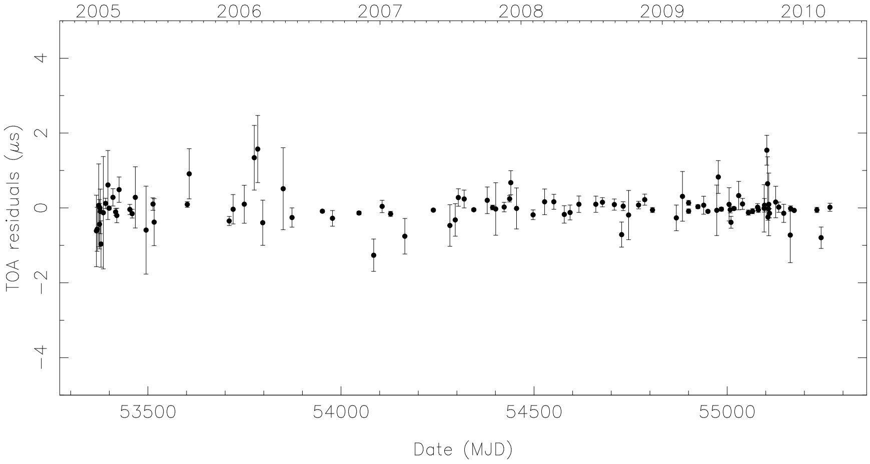

Figure 3: Timing residuals for the pulsar J1909-3744 observed with the Nançay radiotelescope. The residuals are characterized by a weighted rms of only ∼120ns.

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Pulsar	Period (ms)	P$_{orb}$ (jours)	Span (yr)	N$_{toa}$	σ (μs)
J0030+0451	4.87	–	4.6	402	1.84
J0613−0200	3.06	1.2	4.5	280	0.913
J0751+1807	3.48	0.26	4.5	158	1.73
J0900−3144	11.10	18.7	2.0	199	2.87
J1012+5397	5.25	0.6	4.3	107	0.771
J1022+1001	16.45	7.8	4.5	136	1.97
J1024−0719	5.16	–	3.6	128	1.23
J1455−3330	7.99	76.2	4.5	139	2.33
J1600−3053	3.60	14.3	2.8	211	0.576
J1643−1224	4.62	147	4.5	271	1.7
J1713+0747	4.57	67.8	4.5	260	0.350
J1730−2304	8.12	–	4.5	85	1.55
J1744−1134	4.07	–	4.5	87	0.343
J1751−2857	3.91	110.7	3.5	36	0.948
J1824−2452	3.05	–	4.5	313	2.63
J1857+0943	5.36	12.3	4.5	51	0.860
J1909−3744	2.95	1.53	4.5	109	0.119
J1910+1256	4.98	58.4	3.5	31	1.04
J1939+2134	1.55	–	4.5	277	0.483
J2145−0750	16.05	6.84	4.5	159	0.993

Table 1: Timing residuals rms for different pulsars monitored with the Nançay radiotelescope. Columns are pulsar's name, period, orbital period if binary, data span, number of ToAs and ToA residuals rms.

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