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NANÇAY CONTRIBUTION TO THE WORLDWIDE PULSAR PROGRAMS

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Abstract. The Nançay radio telescope is involved in two main scientific pulsar programs. Monitoring observations of various types of pulsars provide high quality rotational parameters, full radio polarization profiles and ephemerides to support observations taking place at high energy (*Fermi* LAT). Dense and precise timing measurements of a set of ultra-precise millisecond pulsars is carried out within a European collaboration (EPTA) to search for the subtle effect of gravitational waves, such as emitted by super-massive binary black holes at the center of galaxies.

Keywords: pulsar, Nançay, high energies, gravitational waves

1 Introduction

Radio pulsars are magnetized neutrons stars detected as periodic pulses produced by the intersection of collimated radio beams with radio telescopes on Earth. Detectable from the ionospheric cutoff around 10 MHz to more than 100 GHz, radio pulsars are essentially studied between 100 MHz and 3 GHz while the optimal frequency range for precise timing being 1.4-2 GHz. It is high enough to minimize interstellar scattering effects proportional to ν^{-4}, and not too high to keep signal strong enough despite a mean pulsar spectra following ν^{-2}.

The meridian Nançay radio telescope, equivalent to a ∼100m dish, is still among the 5 most sensitive decimetric telescopes. Having been built on a Kraus design in the 1960s (Lequeux et al. 2010), a given source can be observed for ∼1 hour using receivers moving along a 80m track. Two receivers covering 1.1 to 1.8GHz and 1.7 to 3.5GHz respectively can transmit ∼500MHz of bandwidth to the instrumentation. At 1.4GHz, the telescope is characterized by a system temperature of about 35K and an antenna gain of 1.4K/Jy.

Pulsar observations using the Nançay decimetric radio telescope started in the late 1980s. A swept local oscillator system was designed and built to observe the two millisecond pulsars (MSPs) B1937+21 and B1821-24. Very dense high precision timing measurements were conducted, leading to the detection of an Extreme Scattering Event interpreted as a ionized 'cloud' crossing the line of sight (Cognard et al. 1993), and to the discovery of the first micro-glitch in a millisecond recycled pulsar (Cognard & Backer 2004). Since the mid-2000s, the launch of the *Fermi* LAT and the growing Pulsar Timing Array for gravitational waves detection, the Nançay pulsar programs expanded to 50% of the telescope time with a state of the art instrumentation developped in parallel.

2 Instrumentations

Pulsar observations are hampered by dispersion produced by the free electrons of the interstellar medium. The narrow radio pulses are delayed inversely proportional to the square of the observing frequency and dedicated instrumentations are built to be able to integrate the signal both in frequency and time. Modern instrumentations are using the coherent dedispersion approach where the dispersion is removed directly on the phases of the digitized voltages received by the radio telescope (which are proportional to the electric field of the electromagnetic wave). The dedispersion process is done in the complex Fourier domain of the signal applying an adequate filter. Powerful GPUs (Graphic Processing Units) are used to calculate direct and inverse FFTs in real time over a bandwidth of 512 MHz. Currently at Nançay, the NUPPI 4 nodes - 8 GPUs system is able to process a 16Gbs data stream and provide radio pulse profiles for 128 4 MHz channels every 30 sec (Fig. 1).

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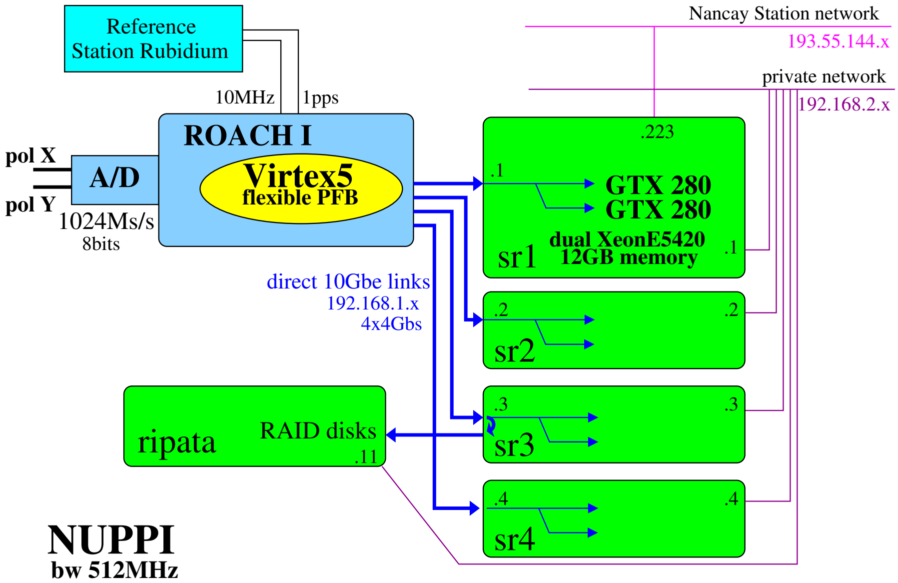

Fig. 1. Schematic of the Nançay NUPPI coherent dedispersion pulsar instrumentation. The two polarizations coming from the receiver of the telescope are 8-bit digitized at 1024Ms/s, pre-processed in a ROACH board to split the whole 512 MHz bandwidth into 128 more manageable 4MHz channels. Four 10Gbs links send data to the four nodes where 8 GPUs GTX 280 are used to dedisperse and fold the pulsar signal. A Rubidium clock provides reference frequency and 1pps signal to accurately time stamp the data stream.

3 Decimetric observations with the Nançay radio telescope

Pulsars can be used for a wide variety of physics and astrophysics problems (Ransom 2013). Connection to High Energy physics (related to the French PNHE Programme National Hautes Energies) mainly comes from the young and energetic pulsars (but also recycled millisecond pulsars since the recent *Fermi* LAT detections) showing complex gamma-ray emission, while connection to Cosmology (related to the French PNCG Programme National de Cosmologie et Galaxies) is through the potential direct detection of gravitational waves from Super-Massive Black Holes Binaries (SMBHB) using very precise timing measurements of a set of ultra-stable millisecond pulsars spread in the Galaxy.

3.1 Multi-wavelength study of pulsars from radio to TeV photons

The main idea of this program is to acquire the radio data necessary to support and complement pulsar observations with the *Fermi* Large Area Telescope (*Fermi* LAT) to improve the Galactic neutron star census. A first aspect is about constrains put on pulsar emission models through detailed studies of individual objects. In the second part, we try to obtain the least-biased population sample possible through varied pulsar searches across different parts of parameter space. All this implies long-term radio pulsar monitoring of gamma-ray pulsar candidates throughout the *Fermi* mission and long search in *Fermi* unidentified sources likely to be hiding yet unknown pulsars. This program is part of an international joint effort between several large radio telescopes as well as X-ray telescopes. For a subset of pulsars being monitored for *Fermi*, the data are also used for accompanying XMM-Newton, AGILE, INTEGRAL, and HESS observations.

A large number of pulsars was detected at high energy with the *Fermi* LAT using radio ephemerides, e.g. Abdo et al. (2009) and Abdo et al. (2013) including a major contribution from Nançay data. Targeted searches for pulsars were conducted in *Fermi* unidentified sources having all the characteristics of a high energy pulsar (no variations and cutoff around a few GeV). More than 50 new MSPs were discovered including 3 from Nançay observations (Cognard et al. 2011; Guillemot et al. 2012), which is already ∼1/4th of all the Galactic Plane MSPs (excluding the MSPs in globular clusters).

3.2 Timing of an array of millisecond pulsars to detect GWs

This program involved a long term high-precision timing campaign on a set of ultra-stable pulsars to search for the signature of gravitational waves. The main target is the Gravitational Wave Background (GWB) coming from the super-massive binary black holes nested in nearby merging galaxies. The up-to-date coherent dedispersion pulsar instrumentation (Fig.1) installed at Nançay is used to time a few dozens of ultra-stable recycled millisecond pulsars. The almost 10 years of Times Of Arrival measurements (ToAs) made on pulsar J1909-3744 at Nançay gives a overview of the stability of the pulsar and of the quality of the instrumentation. ToA uncertainties as low as 10-20ns can be reached as well as an overall rms of ToAs residuals of only $\sim$90ns rms (Fig.2).

A multi-national european collaboration gathers pulsar astronomers from the five large decimetric European radio telescopes (Jodrell Bank, UK ; Westerbork, NL ; Effelsberg, G ; Cagliari, IT and Nançay, F). This collaboration, called the European Pulsar Timing Array (EPTA, `http://www.epta.eu.org/`), is mainly about coordinating observations, sharing data, common analyses. Two meetings are organized every year since 2006. An even larger organisation exists at the world wide level, the International Pulsar Timing Array (IPTA), gathering the different continental efforts (EPTA for Europe, NanoGrav for North-America and PPTA for Parkes Pulsar Timing Array in Australia).

Characterized by high precision uncertainties (on J1909-3744 for example) together with a high cadence of observations, the Nançay ToAs are dominant in the Gravitational Wave Background limit published two years ago (van Haasteren et al. 2011). Based on 7 datasets for 5 MSPs, among which 4 datasets coming from Nançay, this limit with an amplitude for the characteristic strain of $A=6 \times 10^{-15}$ is still the best published ever. A recent work (see Fig.3 to be put in perspective with Fig.2) confirmed the existence of a non negligible chance of detection in the next few years (Sesana 2013). Finishing his PhD at the LPC2E, Orléans, A.Lassus made an strong contribution for the detection of individuals sources using a bayesian approach.

The Large European Array for Pulsars (LEAP) project is a joint development within the European Pulsar Timing Array (EPTA) collaboration to tie together the five 100 m class telescopes in Europe to make a phased array telescope for high precision pulsar timing. Using specialized software, the simultaneous observations are combined into a telescope with a diameter equivalent to that of a 194 m dish. The increased sensitivity of the phased array telescope allows us to improve pulsar timing accuracy and observe more and fainter pulsars than was presently possible with the telescopes in Europe. A recent observation conducted on pulsar J1713+0747 simultaneously at Effelsberg and Nançay, each characterized by SNR of 1375 et 1450 respectively, ended up with a combined SNR of 2635, almost exactly the sum of the SNRs from individual observations, as expected. Similarly, ToAs uncertainties of 101 and 90ns became 56ns after the combination of the data from the two instruments.

4 Conclusions

Nançay pulsar studies cover a large variety of aspects, from the modelling of radio and gamma-ray emission properties of pulsars to the search for gravitational wave signatures imprinted in the times of arrival of the most stable millisecond pulsars.

The Nançay Radio Observatory is operated by the Paris Observatory, associated with the French Centre National de la Recherche Scientifique (CNRS).

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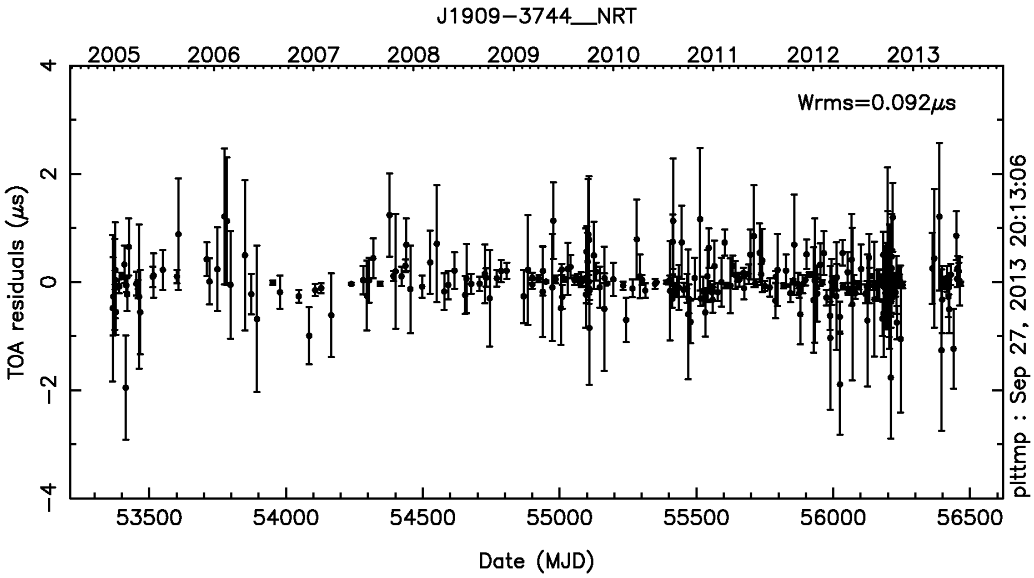

Fig. 2. Times of Arrival residuals obtained for the ultra-stable pulsar J1909-3744 with the Nançay radio telescope. The residuals obtained after substration of all the known propagation and rotational effects are characterized by a weighted rms of only ~90ns over almost 10 years.

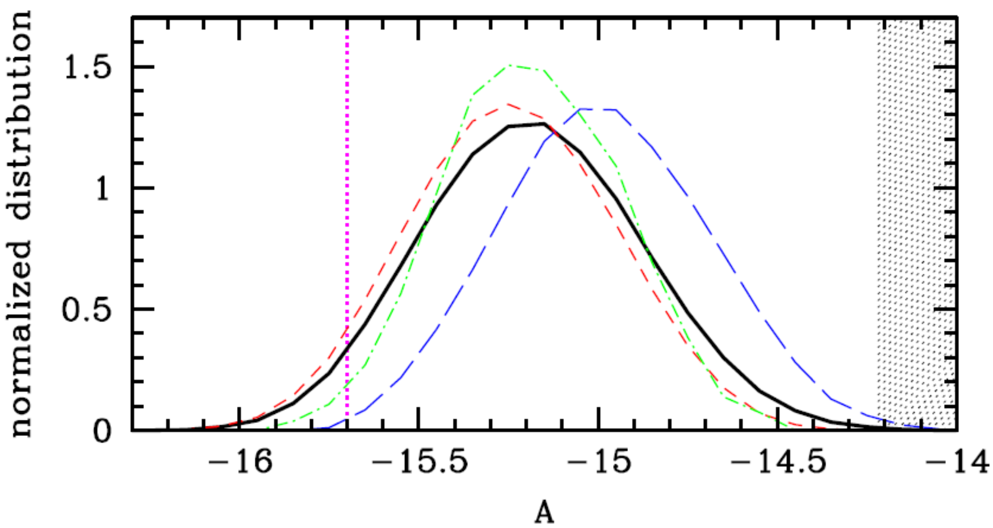

Fig. 3. Normalized distributions of the expected GW amplitude A at a frequency f=1yr^{-1} proposed by Sesana (2013) where the different lines represent different models. The shaded area marks the region excluded by current PTA limits, whereas the vertical solid dotted line represent what can be achieved by timing 20 pulsars at 100ns rms precision for 10 years