International Telecommunication Union



Report ITU-R RA.2099-1 (09/2013)

## Radio observations of pulsars for precision timekeeping

RA Series Radio astronomy



Telecommunication

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## REPORT ITU-R RA.2099-1

## **Radio observations of pulsars for precision timekeeping**

(Question ITU-R 205/7)

(2007-2013)

### Scope

This Report examines the possibility of using high-precision timing radio observations of millisecond pulsars for constructing and maintaining new pulsar-based astronomical time-scales. No changes in the Radio Regulations (RR) are needed to enable this activity.

### 1 Introduction

Pulsars are identified with strongly magnetized, rapidly-rotating neutron stars. The presently known pulsars have masses of order 1.5 times the solar mass, diameters of about 20 km and spin rotation periods from 1.39 ms up to 11.7 s. Clearly pulsars have large moments of inertia and large stores of rotational energy, and so can be treated as space "flywheels" with stable rotation periods that can be used for precision astronomical timekeeping [Manchester and Taylor 1977]. In 1993, ITU recognized the potential use of pulsars for precision timekeeping, and adopted Question ITU-R 205/7, as well as Opinion ITU-R 99 "Time-scale based on pulsar timing" (2003).

Pulsars, as sources of regular radio pulses, have "life times" of a few millions to billions of years. There are two well-known groups of pulsars. The first of these are normally isolated objects, which usually have periods of 0.2 s to 8 s. The second class are very rapidly rotating pulsars, which are often in binary stellar systems, the so-called "millisecond" pulsars, with periods of 1.39 ms to 50 ms. At this time more than two hundreds such pulsars are known. Millisecond pulsars are believed to originate when mass is accreted from a companion onto a neutron star. They are thus recycled old pulsars that have magnetic fields of about  $10^4 \text{ T} (10^8 \text{ G})$ .

Pulsars in close binary systems have orbital periods that range from a few hours up to several months. Their orbital parameters can be determined by high-precision timing observations.

Some millisecond pulsars have spin-period instabilities as small as 0.12  $\mu$ s over five years, i.e. a relative frequency instability of 5 \* 10<sup>-16</sup>. Their radiation losses are negligible, so that the rotation period of some systems increases with as little as 10<sup>-21</sup> s/s (i.e. seconds per second), and usually linearly with time (ITU-R Handbook – Radio Astronomy, edition 2013). Better accuracy can be achieved by using of ensemble time-scale based on the observations of an ensemble of pulsars. At long-time intervals (a few years), this time-scale has a stability which is comparable with the stability of atomic time-scales (Joint Discussion JD6 "Time and Astronomy", XXVII IAU GA, Rio de Janeiro, August 2009).

Thus, pulsars are well suited to the role of providing mankind with highly regular space clocks, which permits the generation of new, pulsar-based, astronomical time-scales, both a Pulsar Time-scale (PT) and a Dynamic Pulsar Time-scale (DPT) – [Ilyasov *et al.*, 1998, Il'in *et al.*, 1984, Ilyasov, 2006, Manchester, 2011, Stappers *et al.*, 2006, Souchay, 2006].

The extreme rotational stability of pulsars allows the application of a unique technique to increase the S/N ratio of pulsar profiles – the "synchronous integration mode", in which the signal is summed synchronously with the pulsar period.

Precision pulsar timing programmes are being conducted at radio observatories in Australia, France, Germany, Japan, the Netherlands, the Russian Federation, the United Kingdom and the United

States of America (USA). Ensembles of millisecond pulsars (or Pulsar Timing Array – PTA) are observed regularly for forming of pulsar time-scale in these programmes.

# 2 Preferred frequency bands for high-precision timekeeping observations of radio pulsars

Observations of pulsars are currently made in a wide range of frequencies, from 10 MHz up to 40 GHz. The basic achievable noise level in radio astronomical observations is defined primarily in the metre wavelength range by Galactic background radiations, though at higher frequencies, the receiver noise dominates the total noise. The brightness temperature of the Galactic background decreases from several thousand kelvins (K) at frequencies around 100 MHz down to 1-10 K at 1 GHz, and is characterized by a flux-density:

$$S(f) \propto f^{-\alpha}$$

where *f* is radio frequency, and the spectral index  $\alpha$  is about 2.5.

On the other hand, the flux-density of pulsars decreases with frequency, following a spectral index of about 2 (on average). A low noise preamplifier in a pulsar receiver typically has a noise temperature of 10 K for receivers in the frequency range 1-10 GHz. The best S/N is achieved by observing in the 0.4-2.0 GHz range [Ilyasov *et al*, 1999].

The *S*/*N* ratio increases with receiver bandwidth: the gain in observing sensitivity for a bandwidth  $\Delta f$  is proportional to  $\sqrt{\Delta f}$ . It is well known that pulsar's pulses are dispersed as they propagate through the interstellar medium, such that the magnitude of the resulting delay in the pulse arrival time decreases as the square of the frequency. From this point of view, higher frequencies are preferable. The magnitude of the resulting delay depends on the electron density along the line of sight to the pulsar, and is characterized by the "dispersion measure" (DM). The effects of dispersion can be removed from the signal using techniques based on multichannel filter-bank receivers in the time domain or coherent de-dispersion in the frequency domain.

Multipath scattering in the interstellar medium causes a broadening of pulses of radio emission from pulsars, which decreases approximately as  $f^4$ . This is also an argument for using higher frequencies in pulsar timing, when possible.

Therefore, the dispersion measure is usually not entirely stable, so precise pulsar timing at about the microsecond level requires observations, preferably simultaneously, in *at least* two frequency bands that are separated by an octave, to measure the changes in dispersion measure.

The preferred frequency bands for high-precision timing observations of pulsars *for precision timekeeping* are the 1 400-1 427, 2 690-2 700, 4 990-5 000 MHz radio astronomy service (RAS) bands, in conjunction with either the 608-614 MHz band or the 406.1-410 MHz radio astronomy band for monitoring variations of dispersion measure.

## **3** Threshold levels of interference

Pulsars are generally weak radio sources. Clearly, it is necessary to achieve a significant S/N to get a precise measurement of the time of arrival (TOA) of the pulse of a pulsar. High-precision pulsar timekeeping observations therefore need to be protected from harmful interference. The threshold levels for interference detrimental to high-precision pulsar timing are those given in Table 2 of Recommendation ITU-R RA.769 for single-dish continuum observations.

## 4 The feasibility of frequency sharing with other services

High-precision timing observations of pulsars intended for maintaining a pulsar-based time-scale can usually be conducted using the frequency bands allocated to the RAS. Radio astronomy does not share the 1 400-1 427, 2 690-2 700 or 4 990-5 000 MHz bands with any active service. In the 406.1-410 MHz band sharing is possible with the fixed and mobile except aeronautical mobile services and in the 608-614 MHz band sharing is possible with the terrestrial broadcasting service (Region 1), the mobile-satellite except aeronautical-mobile satellite (Region 2) and the fixed, mobile, radionavigation and broadcasting services (Region 3) as RAS stations are located at remote sites, and mobile-satellite service links are Earth-to-space.

## 5 The most appropriate pulsars for use in high-precision timekeeping

For the purpose of high-precision timekeeping, the most appropriate pulsars are those which have the highest radio power flux-densities and the most stable periods, and which are observable from both the northern and southern hemispheres. New pulsars are constantly being discovered, and some of these are in systems that can be used to advantage for precision timekeeping: ongoing pulsar surveys make any list of preferred pulsars dynamic. Currently, the ensemble of pulsars that fulfils these constraints is listed in Table 1.

Pulsar (J2000) 1	Australia (PPTA) 2	Europe (EPTA) 3	Russian Federation (KPTA) 4	USA (NANOGrav) 5	σ <sub>residual</sub> TOA (μs) 6
0030+0451				+	
0034-0534		+			
0218+4232		+			
0437-4715	+				0.12
0613-0200	+	+		+	0.83
0621+1002		+			
0711-6830	+				1.56
1012+5307		+	+	+	
1022+1001	+	+	+		1.11
1024-0719	+				1.2
1045-4509	+				1.44
1455-3330				+	
1600-3053	+	+		+	0.35

TABLE 1

### The list of pulsars included in different programmes

Pulsar (J2000) 1	Australia (PPTA) 2	Europe (EPTA) 3	Russian Federation (KPTA) 4	USA (NANOGrav) 5	σ <sub>residual</sub> TOA (μs) 6
1603-7202	+				1.34
1640+2224		+	+	+	
1643-1224	+		+	+	2.1
1713+0747	+	+	+	+	0.19
1730-2304	+				1.82
1732-5049	+				2.4
1744-1134	+	+		+	0.65
1824-2452	+	+			0.88
1853+1308				+	
1857+0943	+	+		+	2.09
1909-3744	+	+		+	0.22
1910+1256				+	
1918-0642				+	
1939+2134	+	+	+		0.17
1955+2908				+	
2124-3358	+				2
2129-5721	+				0.91
2145-0750	+	+	+	+	1.44
2317+1439				+	

TABLE 1 (end)

Notes to Table 1:

Column 1 Pulsar name (J2000 convention).

Columns 2-5 Observations of the pulsars in Australia, Europe, the Russian Federation, USA respectively (PPTA – Parkes PTA, EPTA – Europe PTA, KPTA – Kalyasin PTA, NANOGrav – the North American Nanohertz Observatory for Gravitational Waves).

Column 6 rms of residuals of TOA (time of arrival). This is one of the parameters that indicate the expected accuracy of the pulsar's time-scale after one year's observation.

## 6 Conclusions

This Report answers Question ITU-R 205/7, which was formulated for exploring the use of high-precision timing observations of millisecond pulsars for constructing and maintaining new pulsar-based astronomical time-scales PT and DPT.

- The preferred frequency bands for high-precision timing observations of radio pulsars for the purpose of *precision timekeeping* are the RAS bands 1 400-1 427, 2 690-2 700, 4 990-5 000 MHz, and either 406.1-410 MHz or 608-614 MHz bands.
- The threshold levels for interference detrimental to high-precision pulsar timing are those given in Table 2 of Recommendation ITU-R RA.769 for single-dish continuum observations.
- The aforementioned, preferred, RAS bands do not require any change in frequency allocations or in sharing arrangements with any of the active services sharing the bands with the RAS.
- The final goal of providing a new, long-term, stable time-scale by using the most appropriate pulsars (see Table 1) as reference clocks is making precision timing observations. New pulsars are constantly being discovered, and can be used to advantage for precision timekeeping. Therefore, the list of pulsars used for timekeeping will increase in the future.

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