REPORT ITU-R RA.2099

Radio observations of pulsars for precision timekeeping

(Question ITU-R 205/7)

(2007)

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 1.34 ms up to 8 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 an Opinion ITU-R 99 "Time-scale based on pulsar timing" (2003).

Pulsars, as sources of regular radio pulses, have "life times" of 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 1.34 ms to 50 ms. At this time more than a hundred of these systems 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 T (10^8 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 radio-timing observations.

Some millisecond pulsars have spin-period instabilities as small as 0.2 μs over five years, i.e. a fractional instability of 10^{-15} . Their radiation losses are negligible, so that the rotation period of some systems increases with as little as 10^{-21} s/s (ie seconds per second), and usually linearly with time (ITU-R Handbook – Radio Astronomy, 2nd edition 2003).

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, Kopeikin and Rodin, 1998].

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.

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 radiation, though at higher frequencies 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 the spectral index α 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. So for using pulsars for high-precision timekeeping the optimal *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 Δf is proportional to $\sqrt{\Delta f}$. It is well known that a 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 the fourth power of the frequency. This is also an argument for using higher frequencies in pulsar timing, when possible.

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 MHz radio astronomy service (RAS) band, in conjunction with either the 608-614 MHz band or the 406.1-410 MHz radio astronomy band, and/or in a few cases, the 2 690 to 2 700 MHz band.

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 1400-1427 MHz and the 2690-2700 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.

TABLE 1

PSR	**Right ascen-sion 2000**	**Decli-nation 2000**	**Pulsar period (ms)**	**Pdot 10^{-15} (s/s)**	**P_b (days)**	**DM (pc cm^{-3})**	**S_{400} mJy**	**S_{600} mJy**	**S_{1400} mJy**	**S_{3000} mJy**	**α**
1	2	3	4	5	6	7	8	9	10	11	12
B1855+09	18:57: 36.393	09:43: 17.323	5.36210 045	1.78 10^{-5}	12.32	13.309	31	(16.3)	4.3	1.5	–1.6
B1937+21	19:39: 38.558	21:34: 59.137	1.55780 647	1.05 10^{-4}	-----	71.040	240	(100)	16	4.0	–2.17
J1640+2224	16:40: 16.742	22:24: 08.941	3.16331 582	2.8 10^{-6}	175.4	18.426	37	(16)	3	0.7	–2.1
J1713+0750	17:13: 49.530	07:47: 37.526	4.57013 652	8.53 10^{-6}	67.82	15.989	36	(16)	3	0.8	–2.0
J0437-4715	04:37: 15.786	–47:15: 08.462	05.7574 518	5.73 10^{-5}	5.741	2.6469	550	300	142	(61.4)	–1.1
J0613-0200	06:13: 43.973	–02:00: 47.097	3.06184 404	9.572 10^{-6}	1.198	38.779	21	7.3	1.4	(0.45)	–1.5
J1024-0719	10:24: 38.700	–07:19: 18.915	5.16220 455	1.8529 10^{-5}	-----	6.491	4.6	4.2	0.66	(0.18)	–1.7
J1744-1134	17:44: 29.391	–11:34: 54.575	4.07454 588	8.9405 10^{-6}	-----	3.1388	18	16	3	(0.76)	–1.8
J1909-3744	19:09: 47.438	–37:44: 14.318	2.94710 802	1.4026 10^{-5}	1.5334	10.3939	-----	-----	-----	-----	-----

Notes to Table 1:

Column 1 Pulsar name (B-name refers to the B(1950.0) epoch, J-name to the J(2000.0) epoch)

Columns 2, 3 Pulsar coordinates (Right Ascension, Declination)

Column 5 Pulsar period derivative (s/s)

Column 6 Period of binary system (days)

Column 7 Dispersion measure (pc cm^{-3}) , where pc = parsec = 3.087 10^{13} km.

Columns 8, 9, 10, 11 Average spectral power flux-density (10^{-29} $W/m^2 \cdot Hz$) at, respectively, 400, 600, 1 400 and 3 000 MHz. Values in brackets are calculated via spectral index α, where the flux density:

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

Column 12 Spectral index α

NOTE 1 – The differential dispersive delay across a bandwidth (BW) is calculated at any frequency *f* from the DM via:

$$t_s \approx 8.3\,DM \left(\frac{BW}{\text{MHz}}\right)\left(\frac{f}{\text{GHz}}\right)^{-3} \mu s$$

so that for a *BW* of 1 MHz and a *DM* of 10, the differential dispersive delay between the two edges of a 1 MHz band at 1.4 GHz is 30.25 μs.

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 MHz, and either 406.1-410 MHz or 608-614 MHz, and/or the 2 690 to 2 700 MHz band.

– 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 as reference clocks is by making precision timing observations of the pulsars B1855+09, B1937+21, J1640+2224, J1713+0750, J0437-4715, J0613-0200, J1024-0719, J1744-1134 and J1907-3744. 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. This list of objects will undoubtedly be augmented in time.

References

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