PULSAR ASTROMETRY—AVAILABILITIES AND RELATIVISTIC ASPECTS OF A PULSAR REFERENCE FRAME

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ABSTRACT. We propose a quasi-inertial four-dimensional reference frame in the solar system asymptotically-flat spacetime on the basis of pulsar astrometry techniques. The Pulsar Reference Frame (PRF) consists of the Pulsar Time Scale (PT) and the the Pulsar Reference System (PRS) on the sky .

1. Pulsar Time Scale

It was shown after 10 years timing observations of pulsars in the USSR and the USA that some pulsars have a high rotational stability— especially millisecond pulsars (Il'in et al. 1984; Sazhin 1989; Rawley et al. 1987). They can be more stable than the best atomic clock. The Pulsar Time Scale (PT) based on such pulsars was proposed as an independent new realisation of barycentric time TB (Il'in *et al.* 1984; Il'in *et al.* 1982). The PT is defined as a continuous sequence of time intervals between radiopulses of the pulsar in the barycentre:

$$t_N = t_0 + P_0 N + \frac{1}{2} P_0 \dot{P} N^2 + O(N^3) \qquad (1)$$

where t_0 is the starting epoch of PT, P_0 is the pulsar period corrected for its radial velocity, $\dot{P}$ is the period derivative corrected for its radial acceleration and Shklovskii's term (Shklovskii 1969), and where N is the number of pulses.

A reduction from the topocentric arrivial time τ_N to the barycentric one t_N should be made by:

$$c\,\tau_N = c(t_N + \Delta t) - \mathbf{k}_0 \cdot \mathbf{x}_N - \dot{\mathbf{k}}_0 \cdot \mathbf{x}_N \Delta t_N + \frac{1}{2R_0}(\mathbf{k}_0 \times \mathbf{x}_N)^2 +$$
$$+ \sum_B \frac{2GM_B}{c^2} \ln\left(\frac{r_{NB} + \mathbf{r}_{NB} \cdot \mathbf{k}_0}{2R_0}\right) + 10^{-2}\left(\frac{1}{f^2} - \frac{1}{f_0^2}\right)\frac{DM}{2.41} c \qquad (2)$$

where

$$\mathbf{x}_N = \mathbf{x}_E + \mathbf{w}_N + O(c^{-2}) \qquad\qquad \mathbf{w}_N = \mathrm{P}^{-1}\mathrm{N}^{-1}\mathrm{S}^{-1}\mathbf{y}_N \qquad (3)$$

J. H. Lieske and V. K. Abalakin (eds.), Inertial Coordinate System on the Sky, 213–216.

where Δt_r is the relativistic time correction from terrestrial time TT (TAI) to barycentric time TB; $\mathbf{k}_o$ is the unit vector from the barycentre to the pulsar; $\dot{\mathbf{k}}_o$ is the proper motion vector; R_o is the barycentre-pulsar distance; $\mathbf{x}_E$ is the barycentric vector to the Earth's centre-of-mass; $\mathbf{y}_N$ is the geographical vector to an observer; P, N, and S are matrices of precession, nutation and diurnal rotation of the Earth; DM is the dispersion measure; and

$$r_{NA} = \left[\mathbf{r}^i_{NA} \cdot \mathbf{r}^i_{NA}\right]^{\frac{1}{2}}$$

$$\mathbf{r}^i_{NA} = \mathbf{x}_N^i(t_N) - \mathbf{x}_A^i(t_A)$$

where $\mathbf{x}^i_A(t_A)$ represents the solar (or planet) coordinates at t_A, the moment of closest approach of radio pulse to the Sun (or planet) and f and f_o are the local-received and barycentric-received frequencies respectively.

2. Pulsar Reference System—PRS

The practical realisation of the Pulsar Reference System (PRS) is achieved by VLBI measurement of the pulsar coordinates (Fomalont *et al.* 1984). A reduction of the observations should be made with an equation which has a precision on the order of some picoseconds (Kopejkin 1990):

$$\begin{aligned}
\tau_2 - \tau_1 = {} & \frac{1}{c}\mathbf{k}_o \cdot \mathbf{b} + \frac{1}{c}(\dot{\mathbf{k}}_o \cdot \mathbf{b})\Delta t + \Delta\tau_r + \frac{1}{c^2}\left[\mathbf{v}_E \cdot \mathbf{b} - (\mathbf{k}_o \cdot \mathbf{b})(\mathbf{v}_E \cdot \mathbf{k}_o) - (\mathbf{k}_o \cdot \mathbf{b})(\dot{\mathbf{w}}_2 \cdot \mathbf{k}_o)\right] \\
& - \frac{1}{c^3}(\mathbf{k}_o \cdot \mathbf{b})\left[\frac{1}{2}\mathbf{v}_E^2 + \mathbf{v}_E \cdot \dot{\mathbf{w}}_2 + \frac{1}{2}\dot{\mathbf{w}}_2^2 + 2\bar{U}(\mathbf{x}_E) + U_E(\mathbf{w}_2) - (\mathbf{v}_E \cdot \mathbf{k}_o)^2 - 2(\mathbf{v}_E \cdot \mathbf{k}_o)(\dot{\mathbf{w}}_2 \cdot \mathbf{k}_o) - (\dot{\mathbf{w}}_2 \cdot \mathbf{k}_o)^2\right] \\
& - \frac{1}{c^3}\left[\frac{1}{2}(\mathbf{v}_E \cdot \mathbf{b})(\mathbf{v}_E \cdot \mathbf{k}_o) + (\mathbf{v}_E \cdot \mathbf{b})(\dot{\mathbf{w}}_2 \cdot \mathbf{k}_o)\right] \\
& + \frac{2GM_E}{c^3}\ln\frac{r_1 + (\mathbf{k}_o \cdot \mathbf{w}_1)}{r_2 + (\mathbf{k}_o \cdot \mathbf{w}_2)} + \sum_{A \neq E}\frac{2GM_A}{c^3}\frac{\mathbf{k}_o \cdot \mathbf{b} + \mathbf{N}_{EA} \cdot \mathbf{b}}{R_{EA}(1 + \mathbf{k}_o \cdot \mathbf{N}_{EA})}
\end{aligned} \qquad (4)$$

where $\mathbf{b}$ is the baseline vector in the Geocentric nonrotating reference system (GRS), $\mathbf{w}_1$ and $\mathbf{w}_2$ are the first and the second antennae coordinates in the GRS, τ_1 and τ_2 are topocentric times of arrivial of the same radio pulse to the first and the second antennae, $\Delta\tau_r$ is a relativistic correction for different time rates between observer clocks caused by distinct geographical positions of the radiotelescopes, $\mathbf{v}_E$ is the barycentric velocity of the Earth, $\mathbf{w}_2$ is the velocity of the second radio telescope, U_E is the geopotential, and where $\bar{U}$ is the solar system gravitational potential excluding the Earth, $\mathbf{N}^i_{EA} = \mathbf{r}^i_{EA}/r_{EA}$.

3. Reference Pulsars

The parameters of 17 reference pulsars are compiled in a catalogue from Lyne *et al.* (1989). The pulsars of small $\dot{P}$ are chosen so as to obtain objects with a weak "activity" A (Cordes and Downes 1985). An error of measurement of pulse arrivial times σ_{TN} depends on the signal/noise ratio. It was calculated under the conditions that the radiotelescope had 1000 m² effective area, 10 MHz bandwidth at 400 MHz, 100 K system noise temperature for 1 hour observations with a time-constant 0.1 of equivalent width of pulse. The RMS of timing errors in pulsar noise σ_N which depend on pulsar rotation fluctuations are taken from Lyne *et al.* (1989). The distribution of reference pulsars over the sky is good enough.

PSR	$\alpha(2000)$ h m s	$\delta(2000)$ ° ' "	P s.	$\dot{P}$ 10^{-15}s/s	σ_{TN} mks	σ_N mks	A	μ_α mas/yr	μ_δ mas/yr
0031–07	00 34 08.890	–07 22 01.	0.9429	0.4083	436.0	960.	–1.68	–	–
0355+54	03 58 53.62	+54 13 44.5	0.1564	4.3912	25.9	1111.	–1.38	5.3	6.2
0834+06	08 37 05.524	+06 10 13.70	1.2738	6.79918	37.2	500.	(–0.01)	1.9	51.1
0950+08	09 53 09.206	+07 55 35.81	0.2531	0.22915	3.8	770.	–1.85	14.9	30.6
1133+16	11 33 03.200	+15 51 00.85	1.1879	3.73273	8.2	450.	–2.07	–101.5	356.7
1237+25	12 39 40.450	+24 53 49.13	1.3824	0.95954	25.8	230.	–2.33	–106.0	42.1
1449–64	14 53 32.77	–64 13 15.0	0.1795	2.74754	4.5	–	(–0.65)	–	–
1556–44	15 59 41.497	–44 38 45.9	0.2570	1.01955	12.9	–	(–1.35)	–	–
1604+00	16 07 12.045	+00 32 40.13	0.4218	0.30607	51.9	290.	–2.07	–0.7	–.72
1821–24	18 24 31.948	–24 52 10.56	0.0031	0.00155	5.3	–	(–5.96)	–	–
1913+16	19 15 27.922	+16 06 27.41	0.0590	0.00864	89.7	–	(–4.74)	–	–
1919+21	19 21 44.710	+21 53 01.82	1.3373	1.34809	17.5	500.	(–1.16)	–	–
1933+16	19 35 47.739	+16 16 40.58	0.3587	6.00354	4.1	1730.	–1.49	–	–
1937+21	19 39 38.471	+21 34 59.25	0.0016	0.00001	0.2	–	(–6.77)	–0.3	–0.5
1957+20	19 57 22	+20 49	0.0016	<0.00003	1.0	–	–	–	–
2016+28	20 18 03.750	+28 39 54.25	0.5580	0.14936	18.1	1.5	–1.60	–	–
2217+47	22 19 48.068	+47 54 53.96	0.5385	2.76421	20.9	1.6	–1.46	–	–

4. Practical Applications

The construction of the PRF produces a possibility to define more precisely (up to 1 mas) the mutual orientation of the ecliptic and the equatorial reference frames, to measure the accurate position of the solar system barycentre, and to obtain corrections to the ephemerides of the Earth and planets.

One additional consequence of the PRF can be its application for investigation of the stochastic gravitational wave background (Sazhin 1978). The amplitude of gravitational waves which can be generated by some cosmological sources for instance, the domain stage of the early universe or cosmic strings, can reach 10^{-14} in the frequency band 10^{-7} to 10^{-8} Hz.

Thus, pulsar astrometry comparing timing and VLBI parameters of pulsars can essentially improve the inertial reference frame on the sky and can extend our knowledge in fundamental astrometry and astrophysics.

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Discussion

BASTIAN: Are the presently known millisecond pulsars bright enough to be observed by VLBI with the full precision nowadays attainable with this technique?

KOPEJKIN: Yes, some are. The pulsar PSR1937+21 was observed by VLBI.

https://doi.org/10.1017/S0074180900086861 Published online by Cambridge University Press