Tying the dynamical and extragalactic reference frames via millisecond pulsars

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Abstract. This chapter recalls the basic principles of the method for tying the solar system dynamical reference frame to the extragalactic ICRF. It summarizes the set of fiducial objects currently available for implementing the method. Its expected precision makes it a prospective competitor to the classical LLR-based tie, which accuracy was recently brought to the sub-milliarcsecond level.

1 Introduction

The co-existence of high precision celestial frames based on either the kinematics of extragalactic objects observed with VLBI, e.g. the International Celestial Reference Frame (ICRF), or the dynamics of the solar system, e.g. ephemerides of the Earth-Moon-planetary system, makes it necessary to maintain the tie between these frames, using some celestial bodies as transfer objects.

The current way of tying the dynamical and extragalactic reference frames is the well established method that uses the planet Earth has the transfer fiducial object: Lunar Laser Ranging (LLR) Earth orientation measurements, that are relative to a reference frame tied to the solar system, are compared with the VLBI ones, that are related to the ICRF. Folkner et al. (1994) estimated the tie with a 3 milliarcseconds (mas) precision. Progress in LLR observing precision and refinement in the modelling of the Earth-Moon system recently improved the precision by an order of magnitude (Chapront et al. (2002, 2003).

Other candidate fiducial bodies are fast rotating pulsars. The timing observation of their pulses allow to relate their motion in the Galaxy to the Earth's orbit in the solar system, while this same motion relative to background ICRF objects can be measured with VLBI differential observation. The method has been shown to be precise at the sub-milliarcsecond level.

2 Millisecond pulsars

A pulsar is an extremely dense and small neutron star believed to have been born as a result of a supernova, or explosion of a large star from a class ten or more times the mass of the sun. Pulsars emit beams of radio waves that have been focused by the stars' extremely strong, approximately dipolar magnetic fields. These signals are analogous to rotating lighthouse beams periodically sweeping across the universe.

All pulsars are slowing down their rotation rates as part of their aging process. After a few million year, old pulsars turn off; but if they are part of a binary (two-star) system, they may be reborn as millisecond pulsars. Absorbing energy and momentum relinquished by their dying partner, they spin up to rates as fast or faster than newborns. In general, they rotate hundreds of times more rapidly than their younger relatives and slow down at a much lower rate. This combination of characteristics sets millisecond pulsars apart as a distinct class whose emissions are so regular that their pulses can be averaged to create a most accurate clock, used by researchers studying a variety of problems including general relativity theory.

As the name suggests, millisecond pulsars have pulse periods that are in the range from one to ten milliseconds. The first millisecond pulsar, designated PSR 1937+21, was discovered by Backer et al. (1982) using the Arecibo telescope. Its pulse period of 1.6 milliseconds; its mass is about 1.4 solar masses.

3 Frame tie using millisecond pulsars

Millisecond pulsars, by virtue of their relatively stable rotations and sharp pulses of nearly point-source radio emission, can be used to tie Earth-orbit-oriented reference frames to Earth-spin-oriented reference frames with unprecedented accuracy through a combination of timing and VLBI measurements.

We quote Bartel et al. (1986), who " determined the coordinates of PSR B1937+21 relative to those of the extragalactic source 1923+210, whose coordinates in a quasi-inertial extragalactic reference frame have a standard error of about 0.1 mas. They agree within the root-sum-square standard errors with those determined via VLBI by Petit (1994) and Dewey et al. (1996) and with those yielded by the application of the rotation of an indirect frame tie of Folkner et al. (1994) to the pulse-timing positions obtained by Kaspi et al. (1994) with JPL's DE200 ephemeris."

When applied on a set of well distributed pulsars, this method is expected to provide a frame tie at the level of tens of microarcseconds (μas). A few pulsar VLBI observing programs are run, see, e.g., Campbell (2001), Sekido et al. (1999).

4 Millisecond pulsars timing campaigns

Timing campaigns are run by several groups or consortia at a set of observatories. They are listed hereafter in approximate order of record length.

- Jodrell Bank: about 500 pulsars are monitored.[1]
- Parkes: several hundred pulsars are monitored.[2]
- Arecibo: many groups are using this telescope but telescope time is expensive and not so many pulsars are regularly observed.[3]
  - Princeton: for binary Nobel pulsar PSR B1913+16 and a handful of millisecond ones.[4]
  - Penn State University.
  - UC Berkeley
  - Caltech

[1] See http://www.jb.man.ac.uk/~pulsar/
[2] See http://www.atnf.csiro.au/research/pulsar/
[3] See http://www.jb.man.ac.uk/~drl/ao2002/
[4] See http://pulsar.princeton.edu/

- Paris Observatory's Nançay station. As an example, table 1 summarizes the existing pulsar timing series at Nançay. See Lestrade et al. (1999).
- Effelsberg: about 10 pulsars are monitored (Lang et al., 2000; Wolcsczan et al., 2000).
- Torun: 88 slow pulsars are monitored once a week (Lewandowski et al., 2000).
- Urumqi: about 100 pulsars are monitored (Wang et al., 2000).
- Kalyazin: 8 pulsars are monitored 2-3 days per month (Doroshenko et al., 2000; Potapov et al., 2003).
- Kashima: see Hanado et al. (2002).

Table 1. Current Nançay pulsar timing series. Another group of pulsars is also observed, but their timing results are not finalized. Those are 0030+04, 1257+12, 1516+02A, 1518+49, 1534+12, 1802-07, 1804-27, 1820-30, 1951+32, 2127+11A.

Pulsar		Period (ms)	Start date
B0244+60		217.093	Jul 1998
B0613-02		3.061	Dec 1998
B0751+18		3.478	May 1999
B1012+53		5.255	Feb 1999
B1022+10		16.452	Avr 1999
B1620-26	J1623-2631	11.075	Dec 1996
B1640+22	J1640+2224	3.163	Feb 1999
B1643-12		4.621	Mar 1996
B1713+07		4.570	Feb 1996
B1730-23		8.122	Dec 1998
B1744-11		4.074	Feb 1999
B1821-24	J1824-2452	3.050	Mar 1989
B1937+21	J1939+2134	1.557	Dec 1988
B2043+27		96.130	Dec 1998
B2051-08		4.508	Avr 1999
B2124-33		4.931	Feb 1999
B2145-07		16.052	Jul 1999
B2238+58		139.935	Dec 1998

5 Reference ICRF radio sources

Table 2 gives a preliminary list of ICRF objects close enough to pulsars with rotation periods shorter than 0.5 second, to can be used as reference objects for differential VLBI observation of these pulsars.

Table 3 gives statistics on 24 out of the 34 ICRF reference sources of table 2, based on all VLBI observations over 1989.5-2002.4: standard deviation of the source coordinates based on one session and estimated linear drift. The remaining 10 sources (0459-753, 1129-580, 1329-665, 1334-649, 1352-632, 1600-445, 1729-373, 1748-253, 1932+106, 1955+343) were observed in only one or two sessions over this time span. Their stability cannot be qualified with the currently available data.

Table 2. ICRF extragalactic radio sources closer than 1.5 degrees from pulsars with rotation periods shorter than 0.5 second. The pulsar names are J2000 IAU names.

IERS name	Nearby pulsar(s)	Per. (sec)	Dist. (kPc)	Flux (mJy) 1.4GHz	.4GHz
0219+428	0218+4232	.002	5.85		
0252-549	0255-5304	.448	1.15	17.0	3.0
0355+508	0357+5236	.197	4.72	12.0	1.9
0426+273	0435+27	.326	3.43		
0430+289	0435+27	.326	3.43		
0437-454	0437-4715	.006	.14	600.0	90.0
0451-282	0448-2757	.450	1.55	2.7	1.2
0459-753	0455-6947	.320	49.40	.6	
0831-445	0835-4510	.089	.50	5000.0	1100.0
1048-313	1045-3033	.330	4.17	13.0	
1101-536	1057-5226	.197	1.53	80.0	
1105-680	1112-6613	.334	19.29	19.0	
1129-580	1126-6054	.203	8.05		1.2
1252+119	1300+1240	.006	.62	20.0	1.0
1313-333	1321-3509	.458	1.25	7.0	
1329-665	1327-6301	.196	6.50		3.4
1334-649	1340-6456	.379	1.93	9.0	1.1
	1341-6220	.193	8.66		2.0
1352-632	1357-6228	.456	6.90		6.0
	1359-6038	.128	5.91	105.0	7.0
1600-445	1559-4438	.257	1.63	110.0	40.0
1622-253	1623-2631	.011	1.80	15.0	1.1
1639+230	1635+2418	.491	2.09	9.1	.4
	1640+2224	.003	1.18		
1729-373	1733-3716	.338	3.45		2.6
	1737-3555	.398	2.25		.5
1741-038	1743-0337	.445	1.79	3.1	.5
1748-253	1748-2446A	.012	7.10		2.5
	1748-2446B	.443	3.91		.3
	1757-2421	.234	3.50	20.0	7.1
1817-254	1824-2452	.003	5.50	40.0	1.8
1901+319	1900+30	.602	4.56		
1923+210	1924+2040	.238	10.74	4.0	
1926+087	1933+07	.437	8.94		
1929+226	1932+2220	.144	9.80	7.8	1.2
1932+106	1932+1059	.227	.17	303.0	41.0
1932+204	1932+2020	.268	9.14	29.0	1.2
	1939+2134	.002	3.60	240.0	16.0
1955+335	1952+3252	.040	2.50	7.0	1.0
1955+343	1952+3252	.040	2.50	7.0	1.0
2005+403	2013+3845	.230	13.09	26.0	6.4
2134+004	2139+00	.312	2.97		

Table 3. Stability statistics of the reference ICRF extragalactic radio sources. Quality column: sources marked ** are well observed and stable, those marked @@ are well observed and unstable (Feissel-Vernier, 2003). Sources marked * are considered stable and those marked @ are considered stable although they were not frequently observed over the same time span.

IERS name	Quality	IVS alias	Standard error $\alpha\cos\delta$ (mas)	δ (mas)	Apparent linear drift $\alpha\cos\delta$ mas/year		δ mas/year	
0219+428	*		.076	.090	.014	± .057	.000	± .055
0252-549	@	4C67.05	.207	.310	.174	± .095	-.024	± .107
0355+508	**	3C84	.064	.060	.017	± .017	-.012	± .017
0426+273	*	NRAO150	.045	.099	.058	± .041	.010	± .099
0430+289	**		.023	.027	.009	± .016	.019	± .020
0437-454	*		.143	.237	.187	± .174	.203	± .117
0451-282	@@		.085	.225	.004	± .052	.055	± .074
0831-445	@		7.672	4.202	2.883	± 4.621	-.560	± 2.192
1048-313	@		.639	1.317	-.522	± .517	-.400	± 1.146
1101-536	@@		.058	.119	.100	± .035	.140	± .079
1105-680	@		1.781	1.017	.640	± .455	.398	± .313
1252+119	@@		.100	.130	.073	± .024	.059	± .028
1313-333	**		.035	.097	-.017	± .023	-.073	± .052
1622-253	**		.013	.020	-.002	± .005	-.005	± .006
1639+230	*		.060	.085	-.017	± .042	.018	± .051
1741-038	@@		.005	.007	-.020	± .001	.019	± .002
1817-254	@		.279	.376	.286	± .154	.051	± .249
1901+319	@@		.057	.048	-.003	± .035	-.008	± .030
1923+210	**	3C395	.033	.047	-.024	± .009	-.017	± .013
1926+087	*		.144	.172	-.034	± .098	.123	± .084
1932+204	*		.063	.145	.022	± .050	.109	± .107
1955+335	@		.140	.278	.044	± .068	-.156	± .110
2005+403	@		.496	.524	-.157	± .291	.140	± .314
2134+004	**		.034	.060	-.024	± .014	-.032	± .019

Acknowledgements. The general physical description of pulsars was collected from the scientific information websites mentioned in the text. The bibliographic survey made use of the NASA ADS Astronomy Abstract Service.

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