SOME ASTROMETRIC DISCUSSIONS ON PULSAR PARAMETERS BY TIMING AND VLBI

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ABSTRACT. The errors in solar system ephemeris are one of the systematic errors for pulsar timing. We will discuss how the errors in the ephemeris affect the pulsar parameters. The quasi-long period variations in ephemeris errors can accurately be determined by simulations. MSPs are the powerful tools to link ICRF and dynamical planetary reference frame at mas-level, both with timing and VLBI observations with the same accuracy. The primary results we present show the limited link precision due to so few common MSPs by two methods. We also obtained the position parameter of MSP J1939+2134 based on the Chinese VLBI Network. And we plan to carry on the pulsar timing observations with Shanghai 65m radio antenna by the end of this year. It will contribute to establish the pulsar catalogue more precisely in China and to link the ICRF and dynamical planetary frames with better accuracy.

1. INTRODUCTION

The precision of pulsar timing of arrival (TOAs) can arrive at scores of nanosecond, and the timing models used in TEMPO2 package are accurate in its description of predictable systematic timing effects to better than 1 ns at present. Besides the pulsar timing measurement errors, the largest remaining sources of potential errors also include the interstellar scattering, solar system ephemeris errors, atomic clock instability and gravitational waves(Edwards, Hobbs & Manchester 2006). The latter 3 items are the systematic errors. We will discuss the relation between the ephemeris errors and the pulsar parameters in section 2.

The astrometric parameters of pulsars can be obtained both by timing and VLBI phase reference methods. The millisecond pulsars (MSPs) are more stable than canonical pulsars (CP) and the TOA precisions of MSPs are also much better. The MSPs timing gives the positions in the Earth reference frame at milli-arcsecond (mas) level. And the VLBI method also gets the positions close to mas level, which are described in ICRF frame. When we observe the MSPs both with two techniques, we can get the Earth (dynamical) reference frame tie to the ICRF frame. The primary frame tie results based on the published pulsar parameters are in section 3.

In addition, Shanghai 65 m telescope was successfully put into use in Chinese lunar project this year and the pulsar timing is one of the main projects. Besides, the Chinese VLBI Network (CVN) has been developed consisting of a correlation center in Shanghai and another four antennas, including two 25 m telescopes at Shanghai(SH) and Urumqi(UR), 40 m at Kunming(KM) and 50 m at Beijing(BJ)(Li, Guo & Zhang 2007). We observed MSP J1939+2134 with CVN, and the results are in section 4. At last section 5 concludes all of our results.

2. EPHEMERIS AND PULSAR PARAMETERS

The pulsar parameters are referenced to the solar system barycenter (SSB). In high-precision pulsar timing, TOAs of pulses at an observatory are converted to timing of barycenter (TOBs) based on the solar system ephemeris. Errors in the ephemeris could cause the systematic variations in observed TOAs residuals(Champion et al. 2010). The observed TOBs associate with the TOBs at reference time t_0 by pulsar period P_0 and period derivative P_1 if we neglect the variations caused by the second derivative of pulsar period, which is expressed by $T^c_{ob} = T_0 + nP_0 + \frac{1}{2}n^2P_1$. Where n is the n^{th} pulse accounted from the pulse at t_0.

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At the same time, compared with the real SSB, SSB in the ephemeris has different variations, shown by equation 1. where $\Delta\overrightarrow{r}_{ssb}(n)$ on the left side of the means the total differences between two SSBs, and $\delta\overrightarrow{r}_{ssb}(n)$, $\delta\dot{\overrightarrow{r}}_{ssb}(n)$, $\delta\ddot{\overrightarrow{r}}_{ssb}(n)$ respectively stand for the quasi-long period, time derivatives and second derivatives of the differences. Compared equation 1 with the above expression of T^c_{ob}, $\delta\dot{\overrightarrow{r}}_{ssb}(n)$ and $\delta\ddot{\overrightarrow{r}}_{ssb}(n)$ can't be separated from P_0 and P_1. However, the quasi-long period term in the form of $\delta = \frac{1}{c}(\overrightarrow{r}\cdot\delta\overrightarrow{r}_{ssb})+\sigma$, will remain in the residuals, which could lead to a predominantly sinusoidal variation with quasi-long period and phase associated with planet's orbital motion about the Sun. If we neglect physical errors in timing residuals and σ only consists of white noises, the period variations can be solved by quasi-simultaneously timing data of about more than 6 uniform distributed MSPs. It is simulated based on TEMPO2 package. In the simulation, SSB of DE421 ephemeris can be taken as the real SSB, while observed TOA data of the MSPs, including MSP J0437-4715, J0613-0200, J1022+1001, J1713+0437, J1744-1134, J1909-3744, J1939+2134, with interval of two weeks and 32 years time span are produced with ephemeris DE200. The TOAs errors are several μs based on the actual observation accuracy. The simulation result is shown by figure 1. The position offsets are respectively on X- Y- Z- axis from the top to the bottom. The red line is the real differences between these two ephemerides, while the blue one is the simulation results. Such quasi-long period term between two ephemerides is well determined. The annual differences between ephemerides are absorbed by pulsar positions, which should be one type of red noises in TOAs residuals at observation data reductions.

$$\Delta\overrightarrow{r}_{ssb}(n) = \delta\overrightarrow{r}_{ssb}(n) + \Delta\dot{\overrightarrow{r}}_{ssb}(n)P_0 + \Delta\ddot{\overrightarrow{r}}_{ssb}(n)n^2P_1 \qquad (1)$$

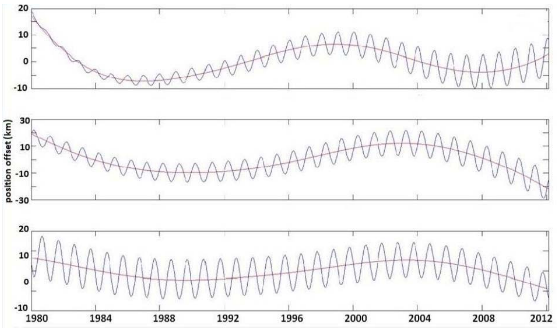

Figure 1: Comparison of the deduced differences by pulsar timing simulations and the real differences between the ephemerides DE421 and DE200

The ephemeris errors determined by observation timing data will be presented in our near future work. The evaluated parameters are usually determined after fitting a polynomial to 'whiten' the residuals of individual pulsar(Champion et al. 2010; Hobbs, Coles & Manchester 2012). Pulsar timing is the potential method to improve the precision of ephemeris SSB with the improvement of observation accuracy and longer observation span, while other spacecraft measurements are only sensitive to the individual planet.

3. REFERENCES FRAME TIE BASED ON MSPs

The link between the planet dynamical reference frame (DRF) and the radio source frame is usually derived from spacecraft delta VLBI observations. The pulsar parameters by timing are deduced referenced to SSB with the Earth ephemeris, which embodies the DRF, while the positions by VLBI is in the ICRF. By comparison with the pulsar positions deduced by VLBI observation, the Earth ephemeris is aligned to the radio frame (or ICRF), which is the unique method to directly link these two reference frames.

Considering timing accuracy of MSPs is far better than that of canonical pulsars, we select five MSPs, J0437-4715, J0737-3039, J1713+0747, J1939+2134, J2145-0750, both with timing and VLBI with the accuracy generally arrives at 1 mas. The astrometric parameters of the MSPs are listed by table 1. The 'T' and 'V' in the first column of table 1 means the positions by timing and VLBI. The right ascension and declination are briefly listed in second and arc-second. Firstly the pulsar positions by two methods are deduced to the identical epoch based on parallax and proper motion (Brisken 2001). The MSPs positions at the same epoch by two methods are respectively $\vec{X}_{DE405}$ and $\vec{X}_{ICRF}$. The relation between them is shown by $\vec{X}_{ICRF} = A^{ICRF}_{DE405}\vec{X}_{DE405}$, where A^{ICRF}_{DE405} is the transfer matrix from the Earth frame to

ICRF(Sekido 2001). In table 2, 5MSPs, 4MSPs and 3MPSs respectively means the transfer results from all five pulsars, without J1713+0747 and without J1713+0747 and J1939+2134. The position difference of J1713+0747 is larger than 20 mas in right ascension, which causes significant differences of results. The parameters of J1939+2134 were determined more earlier with limited precision. From the results shown by table 2, the frame tie results change a lot with the MSPs number due to so few common MSPs both observed by VLBI and timing. However, it is still prospective because a large VLBA pulsar astrometry program is under way. A sample of 60 pulsars will be observed this year as scheduled, and a program of 200 pulsars would be expanded for the next step(Deller et al. 2011), which will greatly expand the common MSPs sample and improve the reference frame link accuracy.

Table 1 MSPs astrometric parameters by timing and VLBI

MSP	MJD (days)	α (ss)	δ (ss)	μ_α (mas/yr)	μ_δ (mas/yr)	PX (mas)	Ref
T1	52005	15.8147635(3)	08.624170(3)	121.453(1)	-71.457(1)	6.65	[6]
V1	54100	15.883250(3)	09.031863(3.7)	121.679(5)	-71.820(9)	6.396(54)	[7]
T2	52870	51.24795(2)	40.7247(6)	-	-	-	[8]
V2	54100	51.2484119(26)	40.714310(99)	-3.82(62)	2.13(23)	0.87(14)	[7]
T3	54312	49.532628(2)	37.50165(6)	4.924(10)	-3.85(2)	0.94(10)	[8]
V3	52275	49.5306(1)	37.519(2)	4.75(10)	-3.67(15)	0.95(5)	[7]
V4	47892	38.56120(18)	59.1316(24)	1.4	-0.6	-	[9]
T4	52601	38.561286(7)	59.12913(15)	0.13(3)	-0.25(5)	0.4(4)	[10]
V5	54100	50.461901(98)	18.462388(558)	-15.43(207)	-7.67(81)	-	[8]
T5	53040	50.46412(3)	18.4399(14)	-9.66(15)	-8.9(4)	1.6(5)	[7]

Table 2 Rotation angles between the Earth frame and ICRF

	θ_x(mas)	θ_y(mas)	θ_z(mas)
DE405→ICRF(5MSPs)	-0.2±0.5	27.2±1.4	-23.3±1.6
DE405→ICRF(4MSPs)	-8.9±1.6	4.1±4.2	3.4±4.9
DE405→ICRF(3MSPs)	-8.4±0.5	5.4±0.3	1.9±0.2

4. MSP OBSERVATIONS WITH CVN

CVN has been put into work since Chang'E-1 lunar project in 2007(Li, Guo & Zhang 2007). The first successful CVN phase referencing observations of pulsar B0329+54 was in 2008(Guo et al. 2010). With the improvement of hardware and software of CVN, the network sensitivity has also been improved. We also pursue the observations of weaker MSPs. The MSP J1939+2134 is one of the best candidates of frame link and in deep space auto-navigation application, whose flux is 5 mJy at S band. And the parallax parameter by VLBI was published in 1995, whose precision was limited and its proper motion parameter is determined by timing. However, the red noise in the TOAresiduals reach scores of macro-second(Hobbs, Coles & Manchester 2012). Therefore it is the first MSP target with CVN.

The experiment of MSP J1939+2134 with CVN 3 antennas, SH 25 m, UR 25 m and KM 40 m, was on April 8, 2012. The calibrator in our observation is J1935+2031 with 1.5^o separation from the pulsar, whose position precision is 0.1 mas. The CVN observation mode is fast-switching between the pulsar and calibrator with a cycle time of 180 s on pulsar and 80 s on calibrator and the total record rate reaches 1024 Mbps. We used the Distributed FX (DiFX) software to correlate the data and AIPS to reduce the data (Deller et al. 2011; Deller, 2009). In the data reduction, we have considered updating the EOP parameters, correction of clock errors and clock rates, ionospheric errors by GPS data, the phase and delay corrections and so on. At last, we used the AIPS task 'JMFIT' to get the pulsar position shown by figure 2. Table 3 shows the best-fit position of the pulsar with CVN and the timing position reduced from parameters (Verbiest et al. 2009) at the observations epoch. From the comparison, the offsets between them are only 1.5 mas and 2.3 mas in right ascension and declination. And such little difference may be caused by the observation errors or link errors between ICRF and Earth ephemeris. To get further astrometric parameters of MSP J1939+2134, we will arrange another 4-5 observations with CVN next year. Besides J1939+2134, we will plan to observe more MSP at L, S and C band with 65 m antenna in the following year, which will contribute to improving the accuracy of the frame tie and the ephemeris, detecting the gravitational waves and so on.

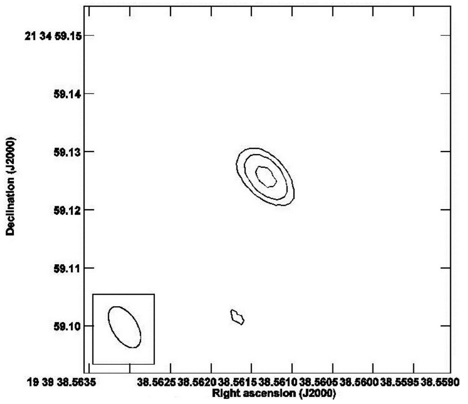

Figure 2: Image of MSP J1939+2134 observed with CVN at 2.2 GHz.

Table 3 The comparison of position parameters of MSP J1939+2134

	$\alpha(J2000.0)$	$\delta(J2000.0)$	$Obsfreq$
	h m s	^{o} ’ ”	GHz
1^a	19 39 38.5613	21 34 59.1267	2.2
2^b	19 39 38.5614	21 34 59.1244	1.4

^{ab} Results are respectively reduced from CVN in S band and timing observations by Pakes in L band.

5. CONCLUSION

The quasi-long period term of ephemeris errors can be deduced based on the simulations. But the annual errors of ephemeris are absorbed into pulsar position parameters. In addition, it is still difficult to get precise frame tie between ICRF and the earth ephemeris based on MSPs by timing and VLBI. The main cause is so few common MSP both by VLBI and timing. But it is promising in the near future with more results from the VLBA PI pulsar project and CVN observations.

At the same time, MSP J1939+2134 was successfully observed with CVN last year. To obtain the proper motion and parallax parameters more precisely, more observations will be carried on in 2014. Besides the CVN pulsar observation plan, Shanghai 65 m antenna will also concentrate on scores of MSPs timing topics. The results in the paper are primary, and they will be improved with more precise observations in the future.

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