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Millisecond Pulsar Timing at Kalyazin Observatory

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Abstract Pulsar timing of millisecond pulsars are carried on at Kalyazin radio astronomical observatory (Russia) since 1995. Seven pulsars are observed at 0.6 GHz by full steerable 64-m dish radio telescope RT-64 and filter-bank receiver. The millisecond pulsar B1937+21 is being monitored at Kalyazin observatory (0.6 GHz) and Kashima space research centre of NICT (Japan) (2.3 GHz), simultaneously since 1996.

Key words: pulsar — timing — radio telescope — time scale

1 INTRODUCTION

Pulsar timing has begun at the Pushchino radio astronomical observatory (PRAO) of the Lebedev Physical Institute since 1975. At that time the Large Phased Array (LPA) of PRAO was the largest telescope in the world at meter wavelengths, and its sensitivity was excellent to detect signals of the weakest pulsars at 102.5 MHz after about 15 min of integration. The LPA is a transit instrument with the effective area about 40 000 sq. m. A special kind of local time service was constructed, at first based on a high quality Crystal oscillators, delivered by the State Time Metrology Center of the Soviet Union (the diurnal instabilities about 10^{-12}). After several years they were replaced by Rubidium standards. Time synchronization was made by TV - signals within accuracy about 0.001 ms with regard to UTC(SU) scale (Universal Time Coordinated (Soviet Union)).

Isolated pulsars B0809+74, B0834+06. B0950+08, B1133+16, B1919+21 were taken for timing first, making *a priori* an assumption about their rotational period stability in a long time interval. After relative short time of observations it was founded out that pulsars B0834+06, B0950+08, B1919+21 showed a high stable pulse repetition periods, indeed. It was proved to use them as a space clocks and to suggest a new astronomical time scale - Pulsar time scale based on them. Then later on, when the Backer's millisecond pulsar was detected (Backer et al. 1982), this proposal was followed by others. A serious study of the problem was made by Guinot B. and Petite G. (Guinot and Petite 1991; Petite and Tavella 1996). There was putted a question: could be or could not to be Pulsar time substitute Atomic time completely? In general, such consideration is not relevant, because it is not defined what it means absolute time scale? That people, who proposed to introduce Pulsar time, understood well that both time scales are supplement to each another, having each one some peculiar properties:

- Atomic time is indispensable to life in short interval, having incomparable fractional stability in time, rather less than year;
- Pulsar time has a privilege, being permanent in long time interval, rather more than year (except constant drift sometimes as small as 10^{-21} s·s^{-1});
- Pulsars as some clocks are common for all users both on the Earth and in space.

The same as the Atomic Time, Pulsar Time can be established by an ensembles of "clocks-pulsars", that significantly improve accuracy and stability of Pulsar time scale realization (Il'in et al. 1983, 1984; Ilyasov et al. 1998). It should be pointed out that reference pulsars could be considered as coordinate clocks in the

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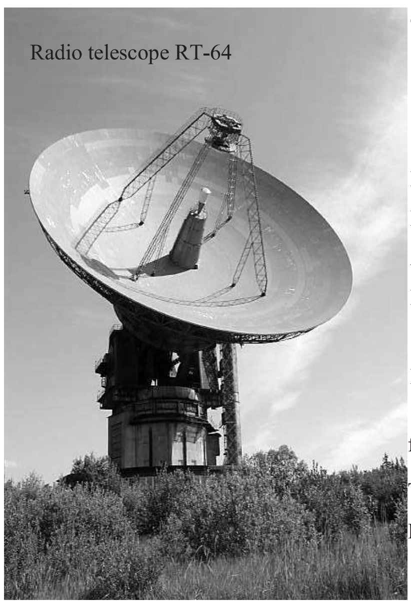
Solar system with referred to barycenter to be responsible for Barycenter Time scale - TB. At last, orbiting binary pulsars could be used for establishing Dynamic Pulsar Time (similar Ephemeris Time), which has to be well invariable based on orbital period of rotation, during very long interval (Ilyasov et al. 1998). By the way, binary pulsars could be relevant detectors of gravitational waves in super low frequency range, in particular, the stochastic Gravity Wave Background (GWB). These statements were reflected also by Dick Manchester in his excellent presentation at the Hanas Pulsar Symposium (China People Republic) in 2005, as well (Manchester 2005).

2 KALYAZIN OBSERVATORY PULSAR TIMING COMPLEX

It is well known, that the best frequencies of pulsar timing are in decimeter wavelengths (range 0.4–3.0 GHz) from point of view of Signal to Noise ratio (S/N). In these frequencies an instrumental measurement accuracy of Time of Arrival (TOA) pulses of millisecond Backer's pulsar B1937+21 could be achieved as small as 10–20 ns, if integration would be made through 30 min by 64-meter dish telescope with 20–30 K the system noise temperature, and a receiver could be used with bandwidth of about $0.01f$ (Ilyasov et al. 1989).

There are two similar radio telescopes in Russia with reflector of 64 meter in diameter, which belong to the Special Research Bureau of the Moscow Power Engineering Institute (named as TNA-1500 SRB MPEI) and are located: one at Bear Lakes, 30 km apart to the North from Moscow, another - at Kalyazin, 150 km in the same direction in Tver' region. In Figure 1 such telescope RT-64 is shown. Its main parameters are given on the right side of Figure 1.



Cassegrain system:

main dish (homology)	64 m,
secondary dish	6 m
RMS	0.7 mm
Feed: wide range horn	5.2m x 2.1 m
Frequency range	0.5 -22.5 GHz
Antenna noise temp. T_{ant}	20 K
Pointing accuracy	5 arcsec
Slewing rate	1.5 deg/s
Kryo "close cycle 20K"	4 "loops"

RECEIVERS:

f GHz	0.6	1.4	2.2	8.3
T_{sys} K	70*	40	30	32
Effic.	0.60	0.55	0.55	0.43
Gain K/Jy	0.69	0.64	0.64	0.50

* uncooled

Fig. 1 The 64-m dish radio telescope of the Special Research Bureau of the Moscow Power Engineering Institute at Kalyazin.

The telescope can be used at the same time, at least for $4-5$ frequencies due to the fact, that special 5-m long horn has been constructed as a primary feed. Two orthogonal linear polarizations adapters are located along horn wall for different frequencies, and the highest frequency adapters are made closer to the horn neck. The Cassegrain system has 6 meter secondary mirror, illumination of which is a good quality with small spillover by the long horn feed with aperture 2.1 m in diameter. Total efficiency radio telescope is about $0.55-0.6$ in frequency range $0.4-6.0$ GHz.

PRAO has made pulsar receiving complex for the four frequencies: 0.6, 1.4, 2.2, and 8.3 GHz. The last two receivers are used mostly for pulsar VLBI observations.

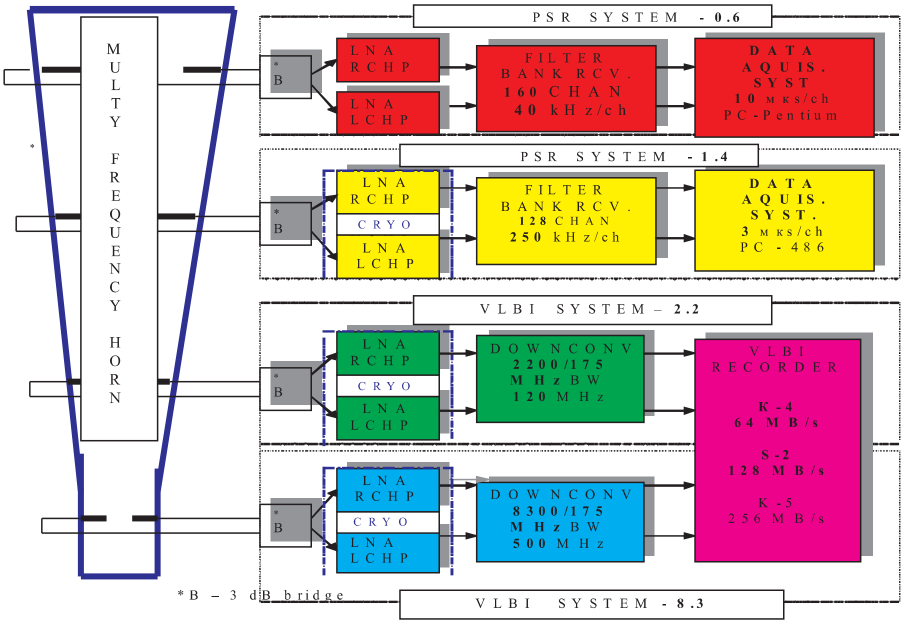


Fig. 2 Multi frequency pulsar complex of PRAO of Lebedev Physical Inst at Kalyazin radio telescope RT-64 of the SRB MPEI.

In Figure 2 block-diagram of the PRAO complex is presented. The pulsar receiver at 0.6 GHz was constructed in collaboration with the well-known institute - NIRFI (the Nizhnii Novgorod Radio Physical Institute). Spectral analyzer part of receiver includes 160 channels (40 kHz bandwidth each) distributed by 80 channels for the right hand and for the left hand circular polarizations, correspondingly. The highest time resolution in each channel is 0.01 ms. Synchronous integration and de-dispersion removing is controlled by computer, and data are collected by hard disc. Usually 3 min integration is made with constant pre-calculated pulsar period. Apparent period, which is defined by the Earth motion, calculated for each short time interval (1−5 min) and taken into account, that to avoid integrated pulsar broadening (Ilyasov et al. 2000).

This receiving complex has been tested in 1993−1994 on telescope RT-64 of SRB MPEI at Bear Lakes and then was moved to Kalyazin on similar radio telescope RT-64 after small correction in complex construction. Regular precise pulsar timing was begun at Kalyazin from 1995 at 0.6 GHz, first of all for PSR B1937+21.

Every integration cycle (usually 3 min) information on each channel is seen on monitor controlled by computer in two dimensional time-frequency plot (part of pulsar period -“window” - (x-coordinate) and channels numbers (y-coordinate, the lowest frequency in upper line). Integrated profile is seen above plot, in the left part for all integrated time and dispersion delay correction.

In Figure 3 an example data observation of the millisecond pulsar J2145−0750 is demonstrated as a plot-diagram. It is clear seen dispersion delays through channels and difference intensity for left and right hand circular polarizations, in particular for pulse components. (Wrong channels and interferences are seen on plot, as well).

Integrated pulse profile of all set of millisecond pulsars, which are monitored at Kalyazin from 1995, are shown in Figure 4. They are obtained at 0.6 GHz. By the way, it is necessary to say, that interference level at Kalyazin is lower on average about - 20 dB in comparison with the Bear Lakes site.

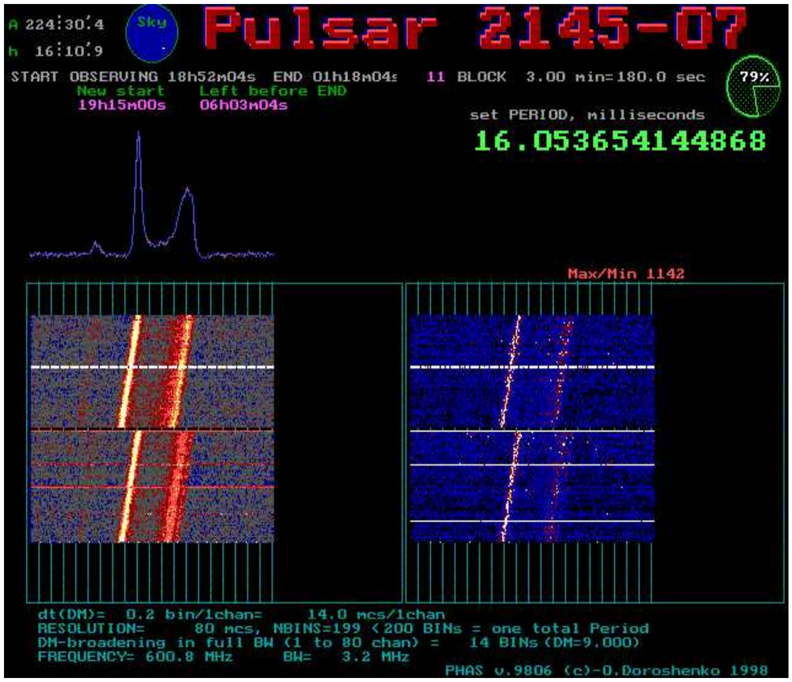


Fig. 3 Integrated profile of PSR J2145 − 0750 after 30 min time integration by 0.6 GHz PRAO complex.

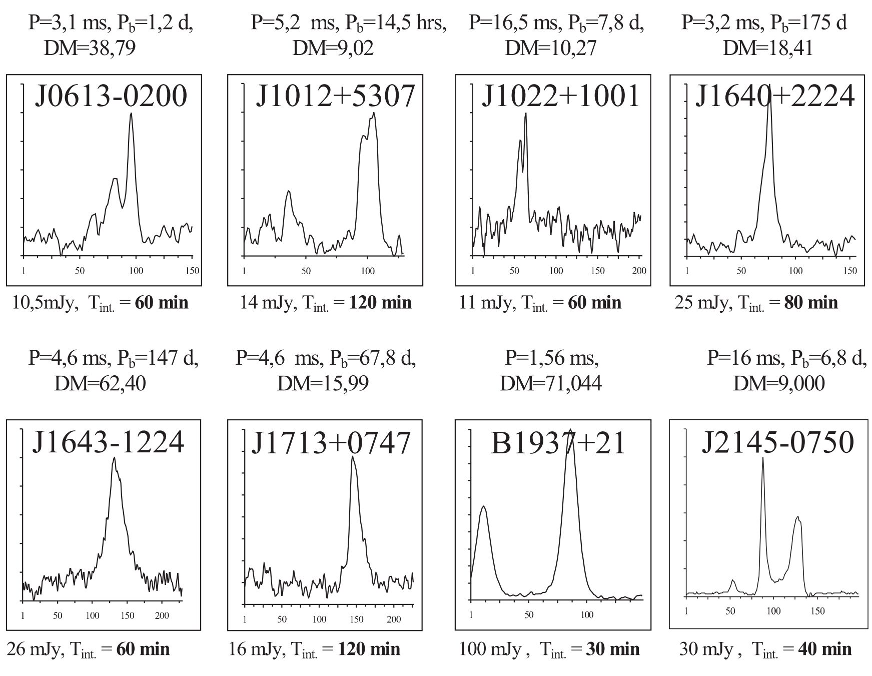


Fig. 4 Integrated pulse profiles of millisecond pulsars set at 0.6 GHz (RT-64, Kalyazin).

3 MAIN RESULTS OF MILLISECOND PULSAR TIMING AT KALYAZIN

Once per week on average, each millisecond pulsar of set was observed by Kalyazin pulsar complex at 0.6 GHz. One cycle of precise timing of each pulsar was continued at least about one hour or more to obtain good S/N, in spite of severe scintillation due to Inhomogeneous Interstellar Medium (ISM) at 0.6 GHz. Local Time Service (LTS) of the Kalyazin observatory is based on Rubidium standards and H-masers. Time synchronization is made by GPS (or TV-channels) within total RMS about 20−50 ns. It is clear seen from Figure 4, that about two hours observation were quite enough to achieve S/N about 40−50 just for the weakest pulsars, which flux was about 10−20 mJy. Data reduction was made by using own software package TIMAPR (Doroshenko et al. 1990) and ephemeris DE-200/LE 200. (Later on this ephemeris was replaced by DE-405, and all previous results were updated).

Residuals of binary millisecond pulsars: J0613−0200, J1640+2224, J1643−1224, J1713+0747, J2145−0750 and isolated millisecond pulsar B1937+21 are shown in Figure 5. The catalogue parameters of the observed pulsars are improved just a little bit, but not so significant. More interest was paid to timing noise in long time interval to study pulsar spin rotation stability from point of view "pulsar clocks".

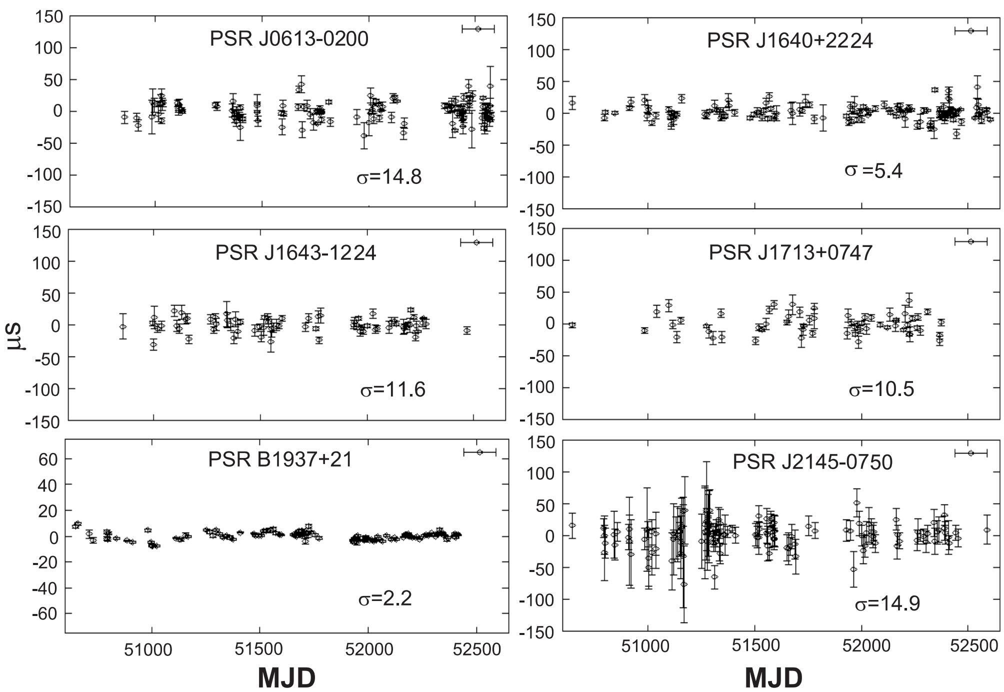


Fig. 5 Residuals of millisecond and binary pulsars PSR: J0613–0200, J1640+2224, J1643–1224, J1713+0747, B1937+21, J2145–0750 after timing at Kalyazin in 7 years.

All residuals of these pulsars (Figure 5) are looking as "a white phase noise" yet with different RMS from about 0.002 to 0.015 ms (fractional instabilities in 7 years: 9×10^{-15} to 7×10^{-14}, correspondingly). The value of RMS is correlated well with S/N of each pulsar (mainly due to small pulsar flux) and then because of scintillation over ISM. What should it be pointed out, that there is not seen significant "red noise" ("flicker" or "random walk" in phase/frequency spin pulsar rotation). It can give a hope that ensemble time scale (Il'in et al. 1983, 1984; Petite et al. 1996), based upon this reference pulsar set could be expected as 10^{-15} fractional instabilities through about 10 years, what is better comparing with Terrestrial Time - TT or International Atomic Time - TAI. Thus, precise pulsar timing of the pulsar set has to be continued at Kalyazin at least next 5 years or more.

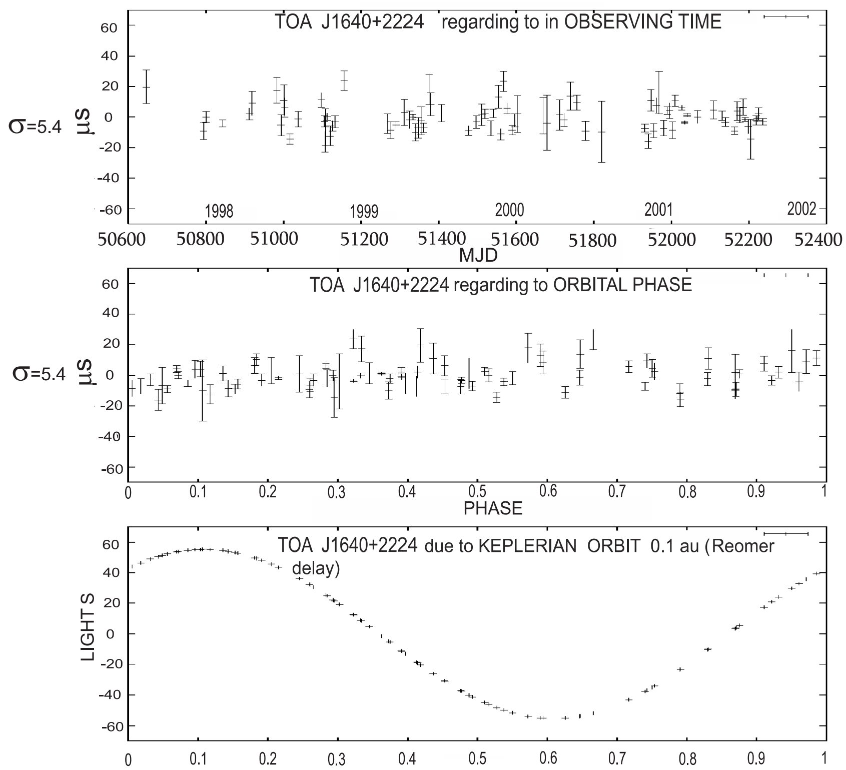


Fig. 6 Millisecond binary pulsar J1640+2224 timing data by Kalyazin complex.

Residuals of binary pulsar J1640+2224 are presented in Figure 6 to demonstrate, at first, its well homogeneity in 7 years versus time and regarding to orbital phase. This pulsar, having relatively large orbits with orbital period $P_b = 178$ days with eccentricity close to zero, is appropriate as GWB detector, which upper limit density was estimated on level $\Omega_g h^2 \leq 10^{-4}$ in (Potapov et al. 2003).

4 PULSAR B1937+21 TIMING AT KALYAZIN

The most appropriate pulsar as reference clock of Pulsar Time and a detector of Gravity waves is the fastest, Backer's, pulsar B1937+21 (Backer et al. 1982), which spin period is about 1.56 ms. Timing of B1937+21 was begun at PRAO from 1993 when pulsar receiver at 0.6 GHz was tested at Bear Lakes 64-m dish radio telescope. Then its timing was continued at Kalyazin from 1995. Their residuals are shown in Figure 5 (RMS close to 0.002 ms). Timing of B1937+21 was made from 1996 at two frequencies: 0.6 GHz at Kalyazin (Russia) by RT-64 telescope and 2.3 GHz at Kashima space research center (KSRC NICT, Japan) by RT-34, in the same time due to collaboration within agreement between Lebedev Physical Inst. (Russia) and the CRL (now NICT of Japan).

Reduction of timing data was made when both long time span was fitted together by TIMAPR package. These results are shown in Figure 7. The residuals at 0.6 GHz (Kalyazin) are inclined with refer to residuals at 2.3 GHz (Kashima) permanently. It could be explained if to suppose that DM is decreased continually in direction to PSR B1937+21. After a new data reduction when time variability of DM was taken into account in a polynomial form, both timing results are agreed satisfactory. Found out a secular DM slope is shown in Figure 8 together with earlier published data. It's not so easy to explain this fact by of an electron density reduction but relative motion pulsar-observer - large scale plasma clouds could be considered, as version.

The long time variations of DM of PSR B1937+21 are shown in Figure 8.

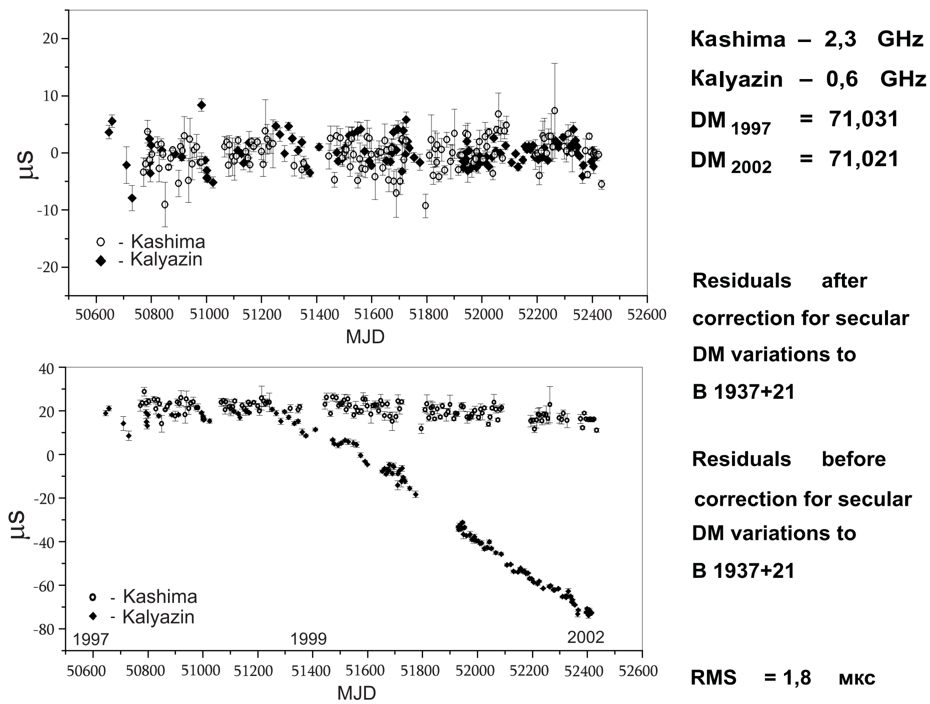


Fig. 7 Russian-Japanese Timing of PSR B1937+21 in 1997–2003.

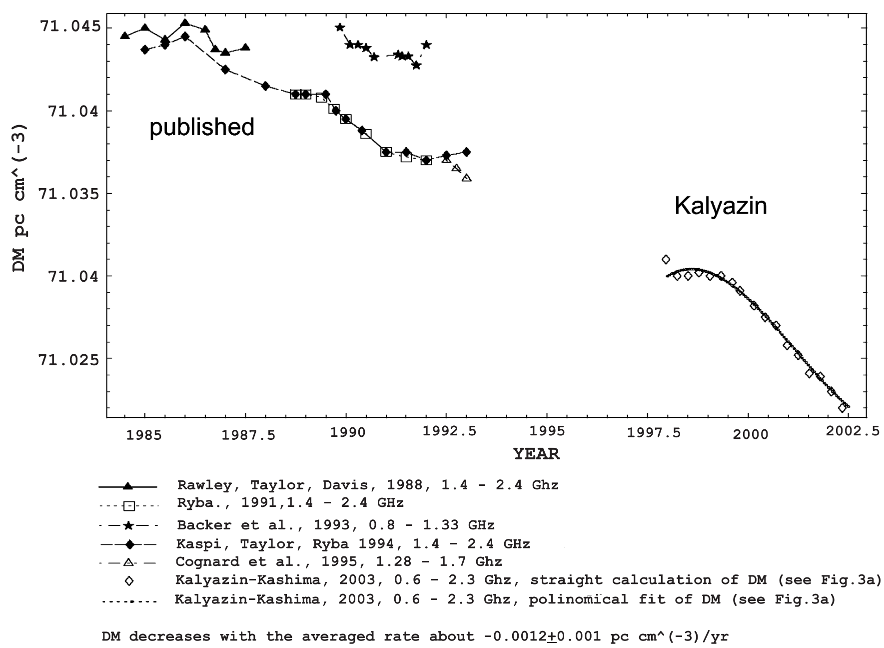


Fig. 8 Secular changes of DM toward millisecond pulsar B1937+21.

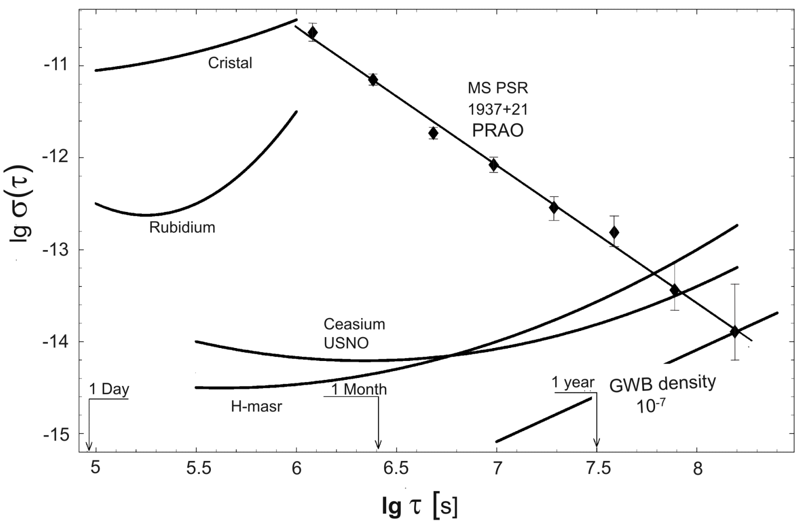


Fig. 9 Allan variance of different Time standards and millisecond pulsar PSR B1937+21.

From point of view of precise time keeping it is shown fractional instabilities different standards with compare to properties of PSR B1937+21. In Figure 9 there is fractional frequency stability in time (Allan variance) (Allan 1966; Allan & Winkler 1983) of the standards and millisecond isolated pulsar B1937+21. By the way, it is seen that "gravitational natural GWB upper limit", which has to be influenced as f^{-5}, should be reduced till to less than $\Omega_g h^2 \leq 10^{-7}$ after these data.

5 CONCLUSIONS

As a main results of the long time millisecond pulsar timing at Kalyazin it should be mentioned:

1. Pulsar timing complex at Kalyazin was constructed to 1993 by PRAO Lebedev Institute based upon the unique radio telescope R-64 (TNA-1500 SRB MPEI, Kalyazin). Timing observations of PSR B1937+21 are in progress more then 10 years steadily (Bear Lakes and Kalyazin).
2. Fractional instabilities of TOA residuals of reference millisecond pulsars of "the Kalyazin set" (Allan variances) are in range. $10^{-13} \div 10^{-14}$ more then 5 years span.
3. Pulsar time scale was contrived by experts of the PRAO Lebedev Phys. Inst. and Soviet State Standard Committee in 1979.
4. Time scale based on ensemble of millisecond pulsars is very actual - $\mathrm{PT}_{\mathrm{ensemb.}}$, as well Dynamic Time scale based upon orbital motion of binary pulsars.
5. International community (IAU, ITU-R, BIPM) approved and encouraged pulsar time explorations.
6. Pulsar timing technique was awarded by diplomas at International exhibitions in 2004–2005.
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