Pulsar Timing Array

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- Ensemble pulsar time scale
- Detection of gravitational waves

Concept: Foster & Backer, 1990, polynomial approach.

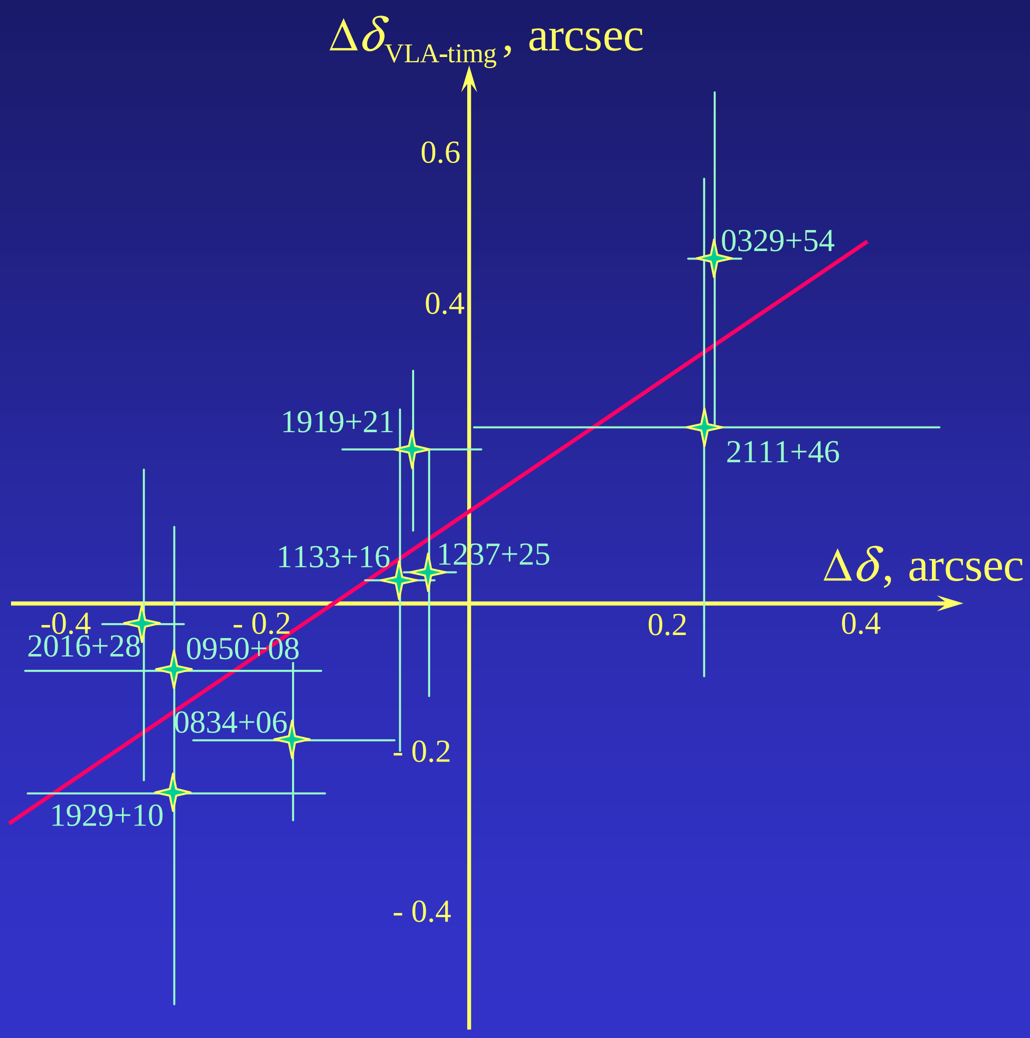
Link between celestial reference frames

Classical astrometric problem – link between celestial coordinate systems (e.g. DE200/405 and ICRF).

Rotation angles (mas) from DE200 to ICRF

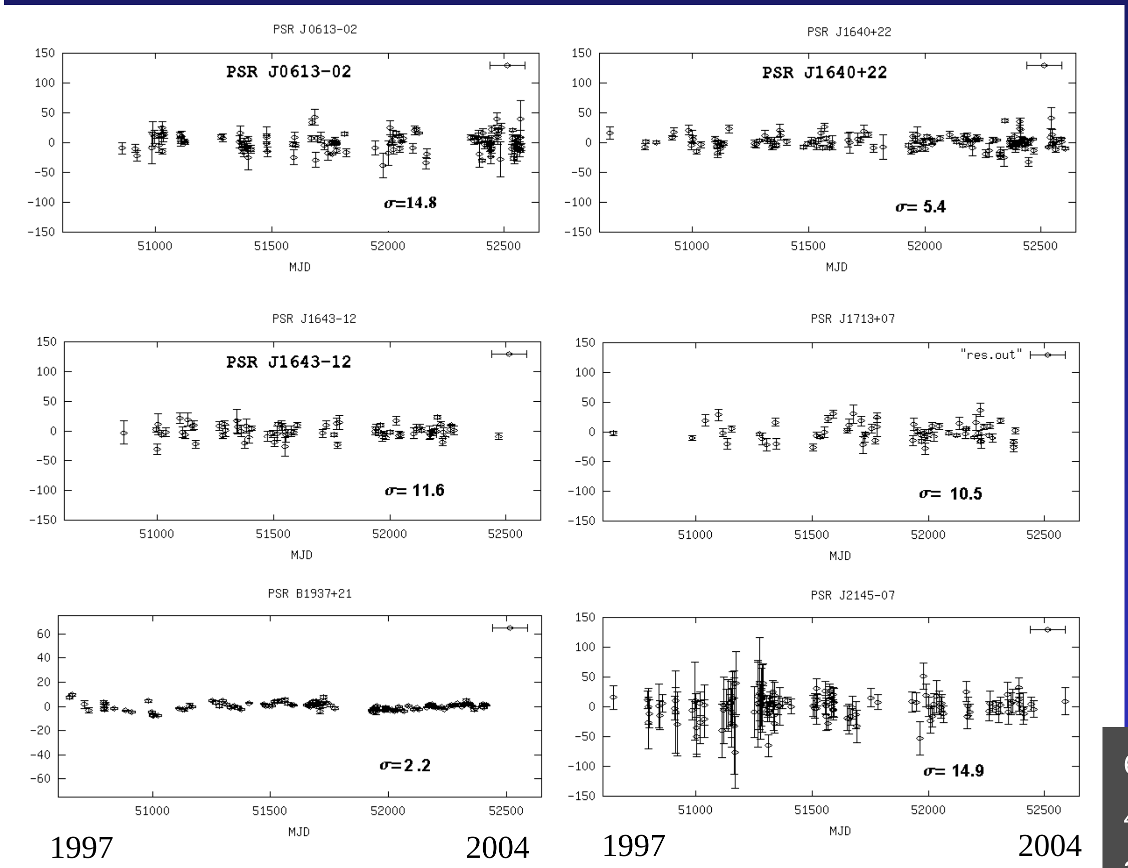
	Finger, Folkner, 1992	Folkner *et al.*, 1994	Rodin, Sekido, 2002
	LLR & VLBI	LLR & VLBI	Pulsar VLBI & timing
	(TDA Progr. Report 42–109, JPL, CA)	(A&A, 287, p. 279–289)	(Proc. Of 6th EVN Symp, MPIfR, Bonn, p.247)
A_x	1 ± 3	– 2 ± 2	– 4 ± 2
A_y	–10 ± 3	–12 ± 3	–13 ± 3
A_z	– 4 ± 5	– 6 ± 3	–17 ± 5

Link between celestial reference frames



Correction of the pulsar timing coordinates made on the basis of Fourier analysis of the post-fit residuals and their comparison with difference between VLBI and timing positions (Rodin, Ilyasov, Oreshko, Sekido, *Timing noise as a source of discrepancy between timing and VLBI positions*, in “Pulsar Astronomy – 2000 and beyond”, IAU Coll. 177, 2000).

Timing data

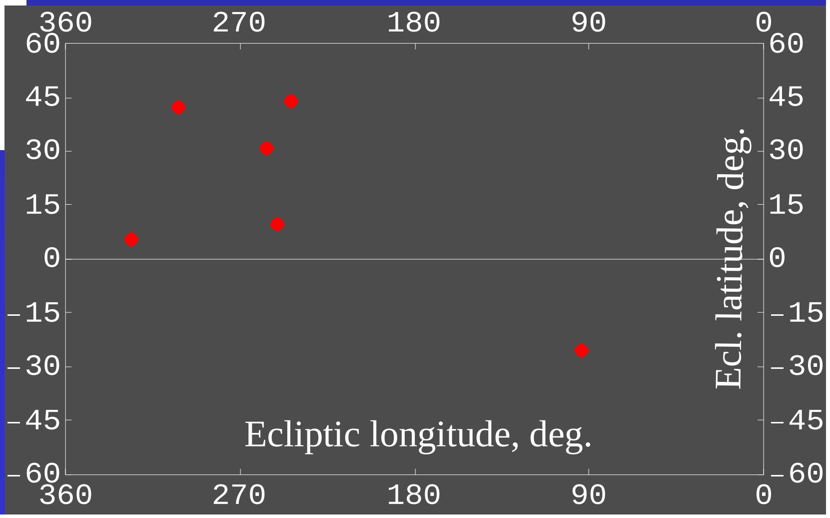


Post-fit timing residuals (in mcs) of 6 millisecond pulsars.

Pulsar timing data used for calculations were taken from the paper:

Ilyasov, Y. P.; Oreshko, V. V.; Potapov, V. A.; Rodin, A. E., *Timing of Binary Pulsars at Kalyazin, Russia*, 2004, IAUS, 218, 433.

Distribution of pulsars on the sky



Timing data

Table1. Pulsar parameters

Pulsar name	Spin period, ms	DM, $cm^{-3} \cdot pc$	Binary period, days	RMS, mcs
J0613-0200	3.062	38.78	1.2	14.8
J1640+2224	3.163	18.42	175.46	5.4
J1643-1224	4.622	62.41	147.02	11.6
J1713+0747	4.570	15.99	67.83	10.5
J1939+2134	1.558	71.04	-	2.2
J2145--750	16.052	9.00	6.84	14.9

Pulsar timing observations were carried out with 64 m radio telescope of Kalyazin radio astronomy observatory (KRAO) at frequency 610 MHz in bandwidth 3.2 MHz (Oreshko.V.V., *Pulsar timing instrumental errors. AC-600/1600 facility*. Proceedings of the Lebedev Physical Institute., Moscow, 2000, v. 229, p. 110 (*in Russian*).

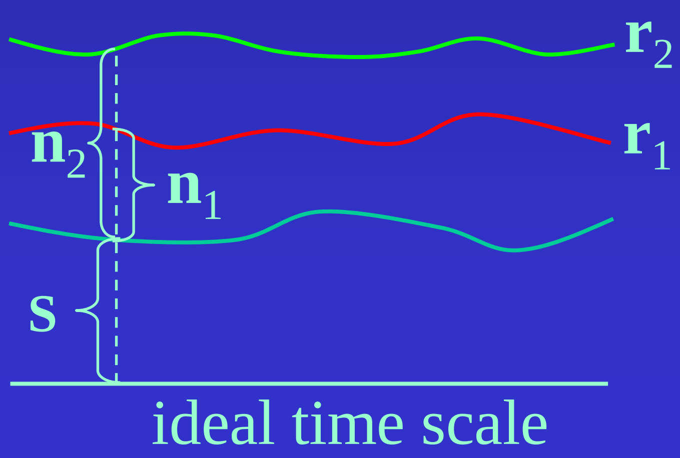
Radio telescope RT- 64 KRAO.

Ensemble Pulsar Time scale

The main idea is to use optimal Wiener filter before weighted average.

$$H = \frac{G_s}{G_s + G_n}$$ - Wiener filter, G_s, G_n – power spectrum of signal and noise

$$\mathbf{s} = \Phi^{-1}\left[H\left[\Phi(\mathbf{r})\right]\right]$$ - common signal (clock contribution) in pulsar TOA



Ensemble Pulsar Time scale

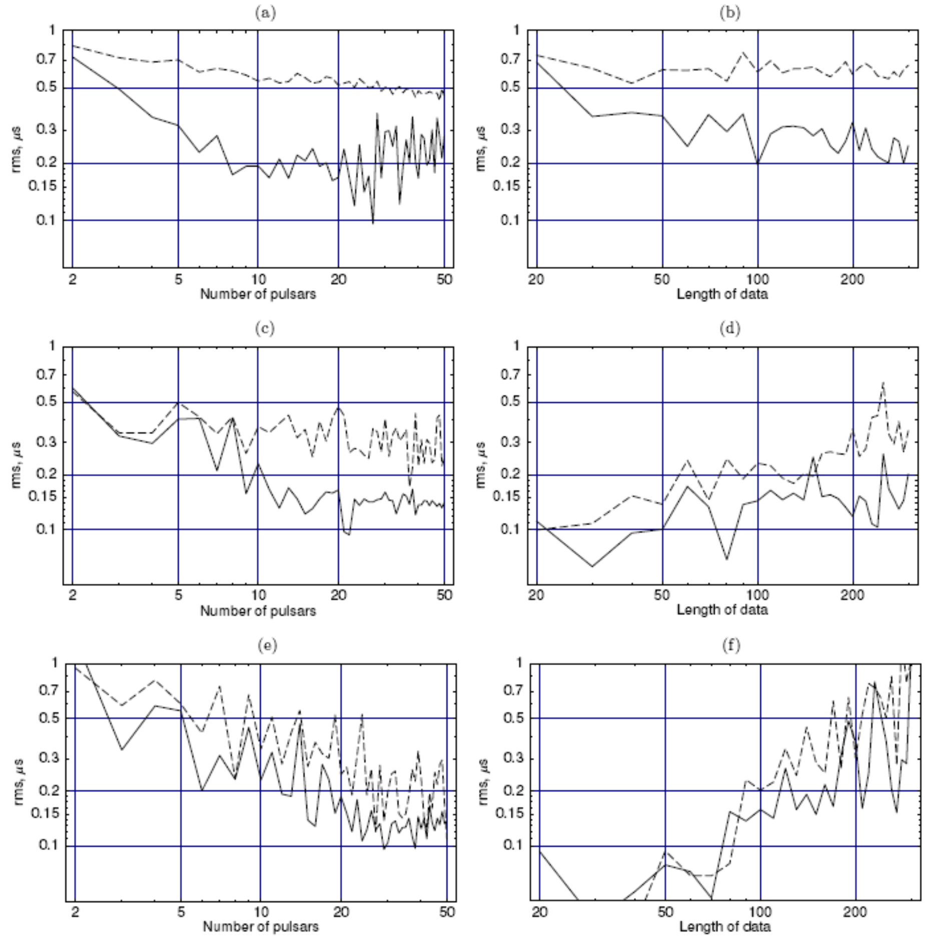


Figure 1. The accuracy of signal estimation based on the methods of weighted average (dashed line) and Wiener filter (solid line) as dependent on the number of pulsars (left panels) and length of the data (right panels). For the calculation shown in the left panels 256 points of data were taken, for calculations shown in the right panels five pulsars were used. Different types of noise were generated: (a), (b) - white phase noise, (c), (d) - white noise in frequency, (e), (f) - random walk noise in frequency. Data in the panels (d) and (f) were scaled accordingly for fitting within in all the panels.

Results of numerical simulations (Rodin, 2008).

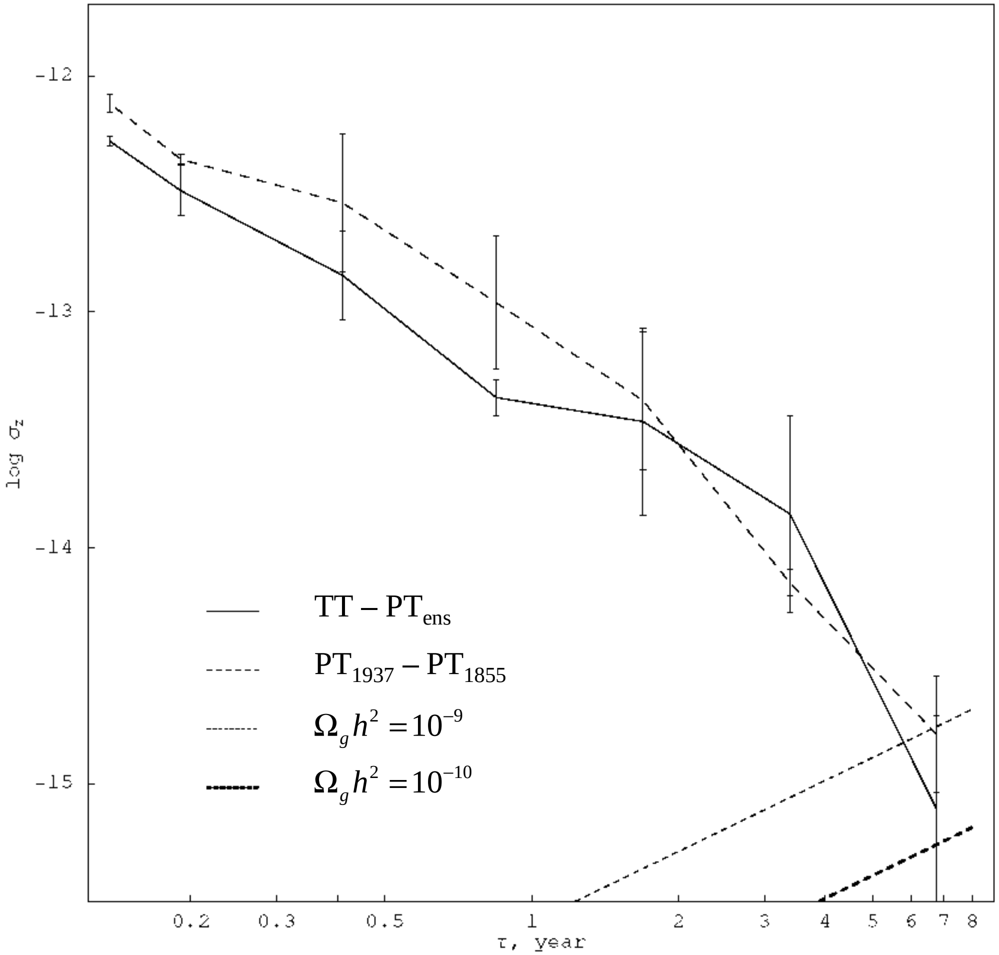
The accuracy of signal estimation based on the methods of weighted average (dashed line) and Wiener filter (solid line) as dependent on the number of pulsars (left panel) and length of data (right panels).

(a)-(b) white noise,

(c)-(d) white noise in frequency,

(e)-(f) random walk in frequency.

Ensemble Pulsar Time scale



Fractional instability σ_z of the difference TT(BIPM06) – PT (solid line) and PT_{1937}-PT_{1855}. Theoretical values of σ_z in the cases $\Omega_g h^2 = 10^{-9}$ and 10^{-10} are shown in the lower right-hand corner of the plot (Rodin, 2008) .

Detection of gravitational waves

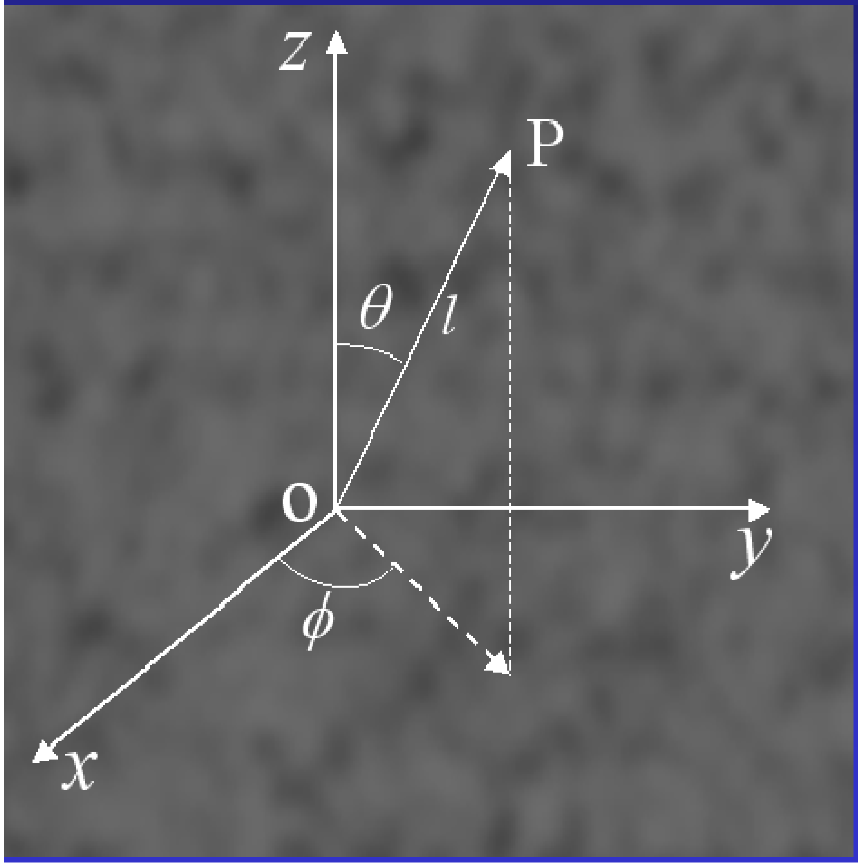
Fractional change of pulsar spin frequency due to propagation of GW:

$$\frac{\Delta\nu}{\nu} = \frac{1}{2}\cos 2\phi[1-\cos\theta]\times\left(h(t)-h(t-l-l\cos\theta)\right)$$

(Eastabrook & Wahlquist 1975; Hellings & Downs 1983)

$h(t)$ – amplitude of the gravitational wave,

l – distance to pulsar P,



ϕ – angle between a principle polarization vector of the wave and projection of the pulsar position l on the transverse plane $x0y$,

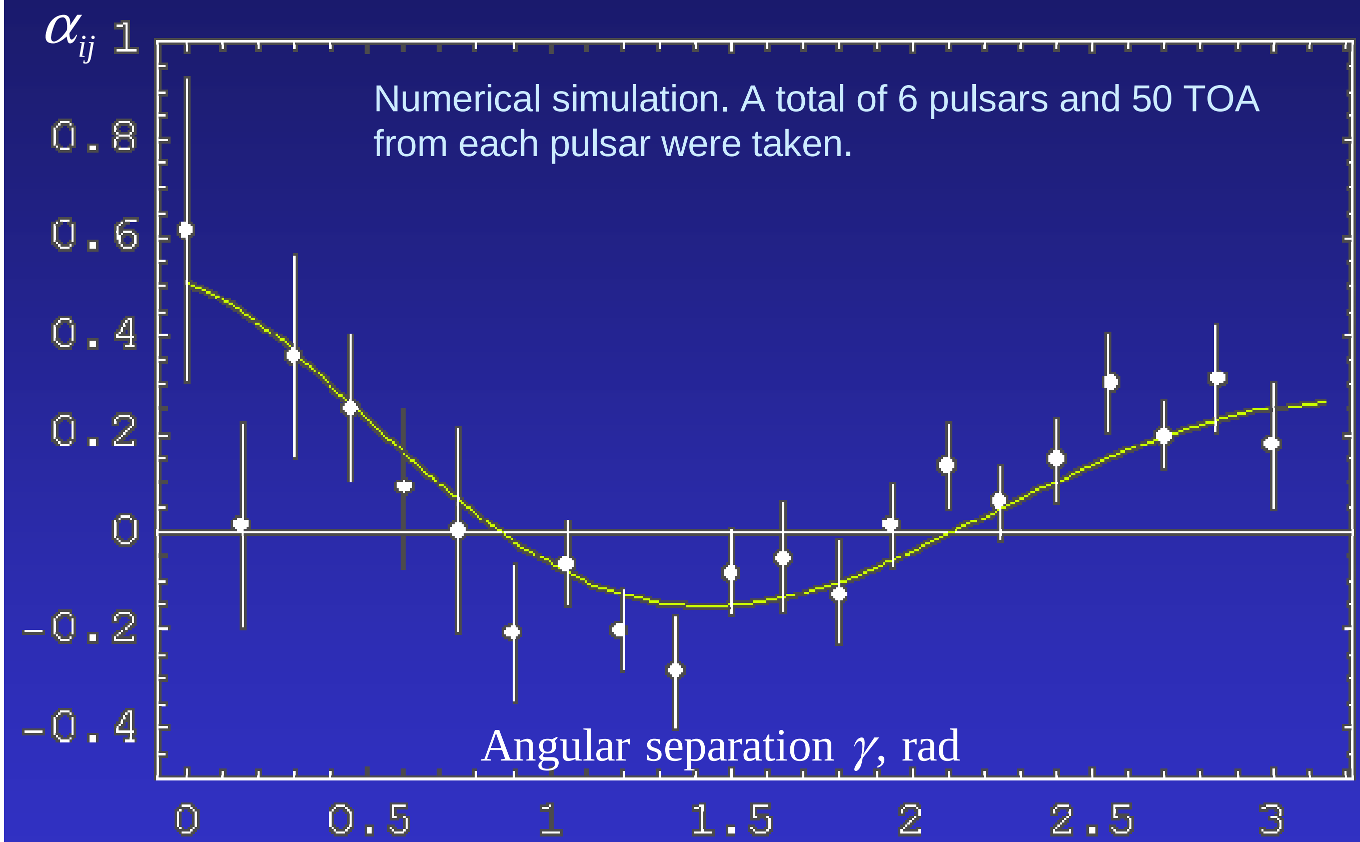
θ – angle between Earth-pulsar distance and the wave propagation direction (z-axis).

$$C_{ij} = \alpha_{ij}\left\langle h^2 \right\rangle + \delta C_{ij},$$ – two-point correlation

$$\alpha_{ij} \equiv \frac{1}{4}\int \alpha_i \alpha_j d\Omega = x\ln x - \frac{x}{6} + \frac{1+\delta(x)}{3}, \; x = \frac{1-\cos\gamma}{2}.$$

(Hellings, Downs, 1983); (Zhao, Zhang, 2003); (Jenet, Hobbs, Lee and Manchester, 2005).

Detection of gravitational waves



This plot shows results of numerical simulation, α_{ij} vs. angular separation γ. Post-fit timing residuals (length is 50 points) of 6 pulsars were used to plot $\alpha_{ij}(\gamma)$.

Detection of gravitational waves

A new approach is proposed:

• pulsar TOAs contain noise signals of different kind (red noise with different spectral index);

• each kind of red noise has a distinct features. Human eye recognizes easily what type of noise is presented in time series;

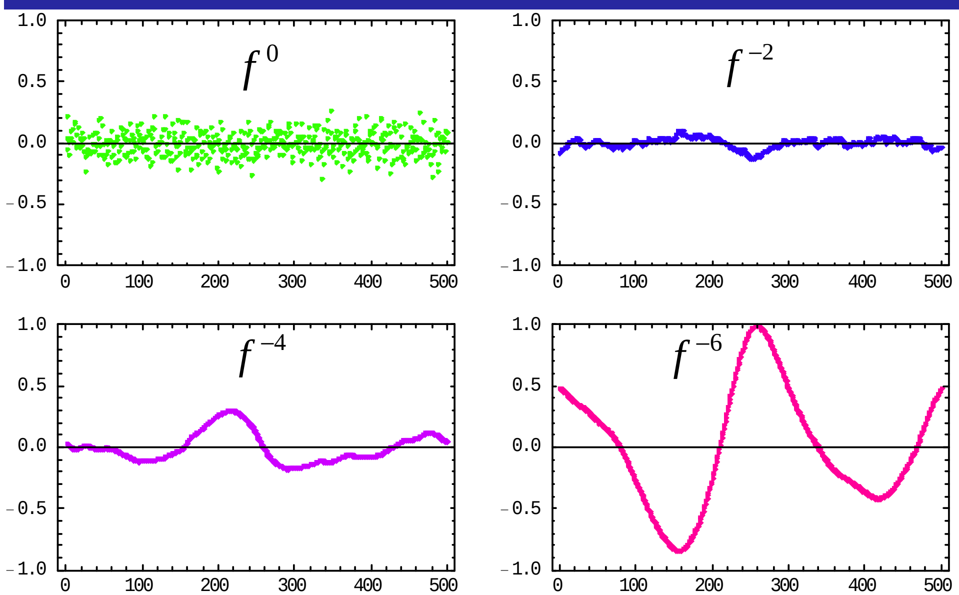
• as a rule, for any physical object (e.g. frequency standard, pulsar) each type of the noise begins to dominate and reveals itself at the different time intervals;

• it is proposed to expand pulsar signal (TOA residuals) into components of different type and calculate the angular correlation separately for each component;

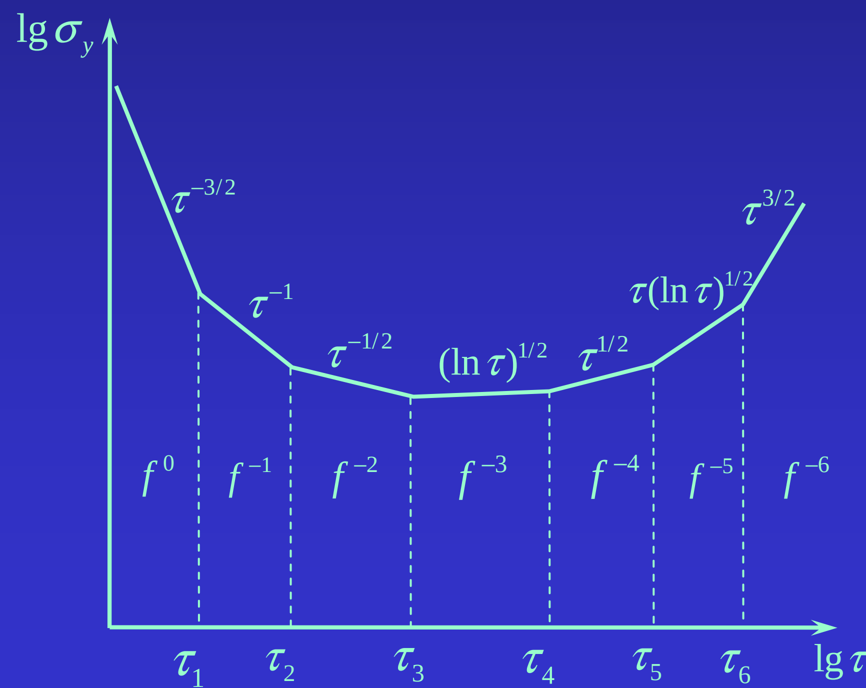
• Caterpillar-SSA (singular spectrum analysis) was selected as the most general method of signal expansion into components.

Detection of gravitational waves

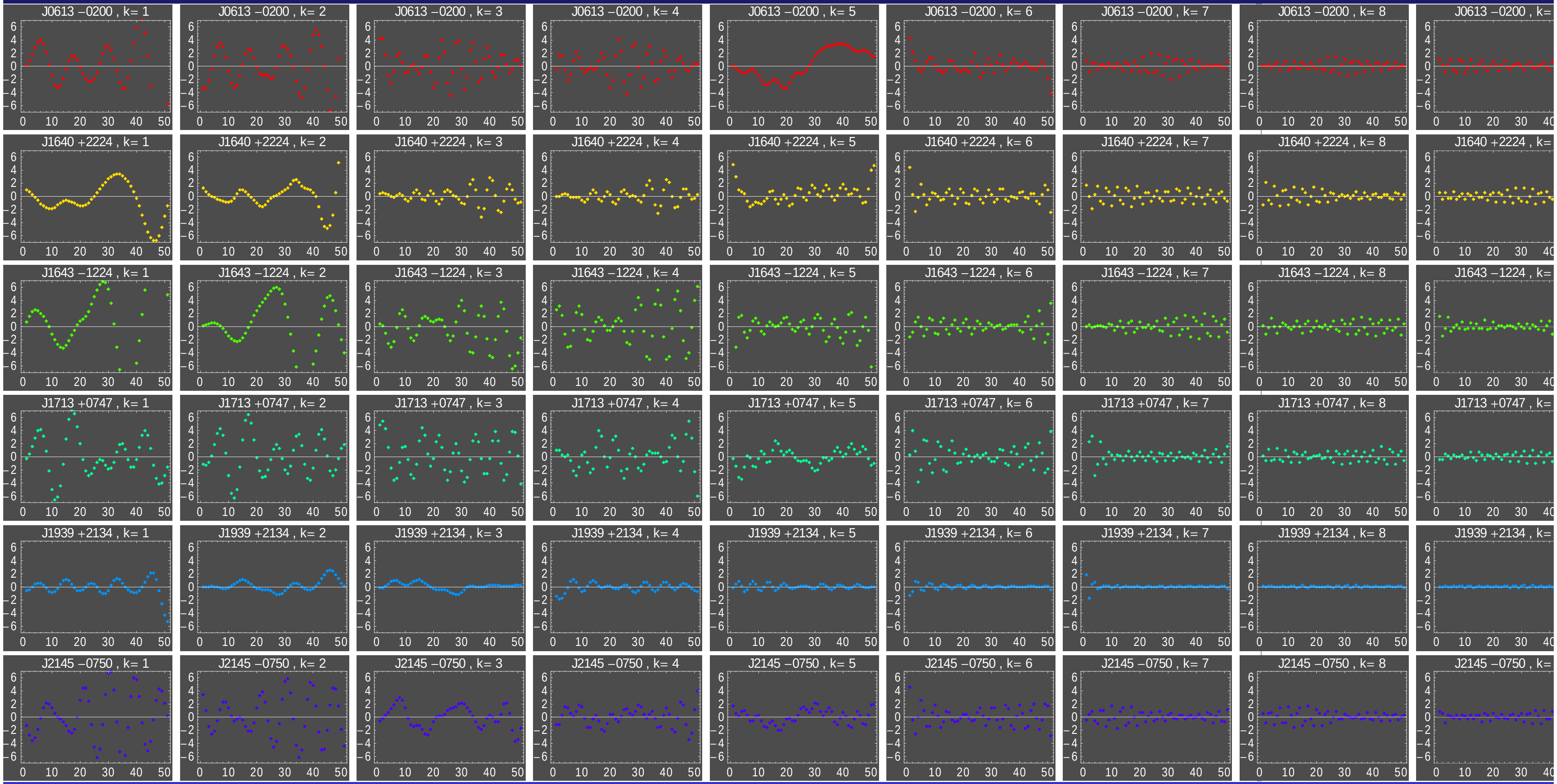
The white and red noise of different type.



Behavior of the fractional instability σ_y in dependence on observation interval τ and kind of noise (Ilyasov, Kopeikin, Rodin, *The astronomical timescale based on the orbital motion of a pulsar in a binary system*, 1998, AstL, 24, 228).



Detection of gravitational waves



Pulsar timing data expanded into components by caterpillar-SSA method.

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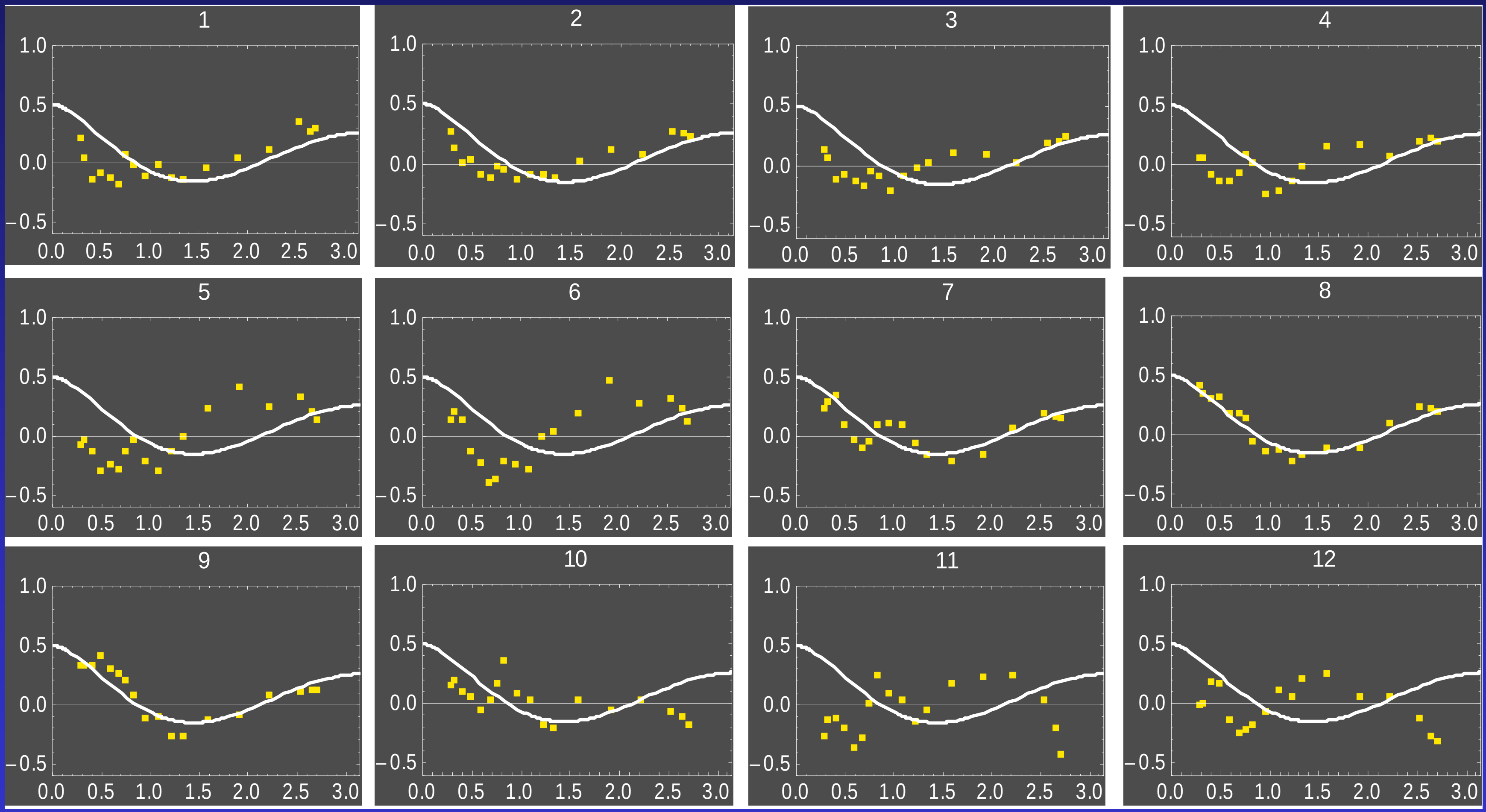
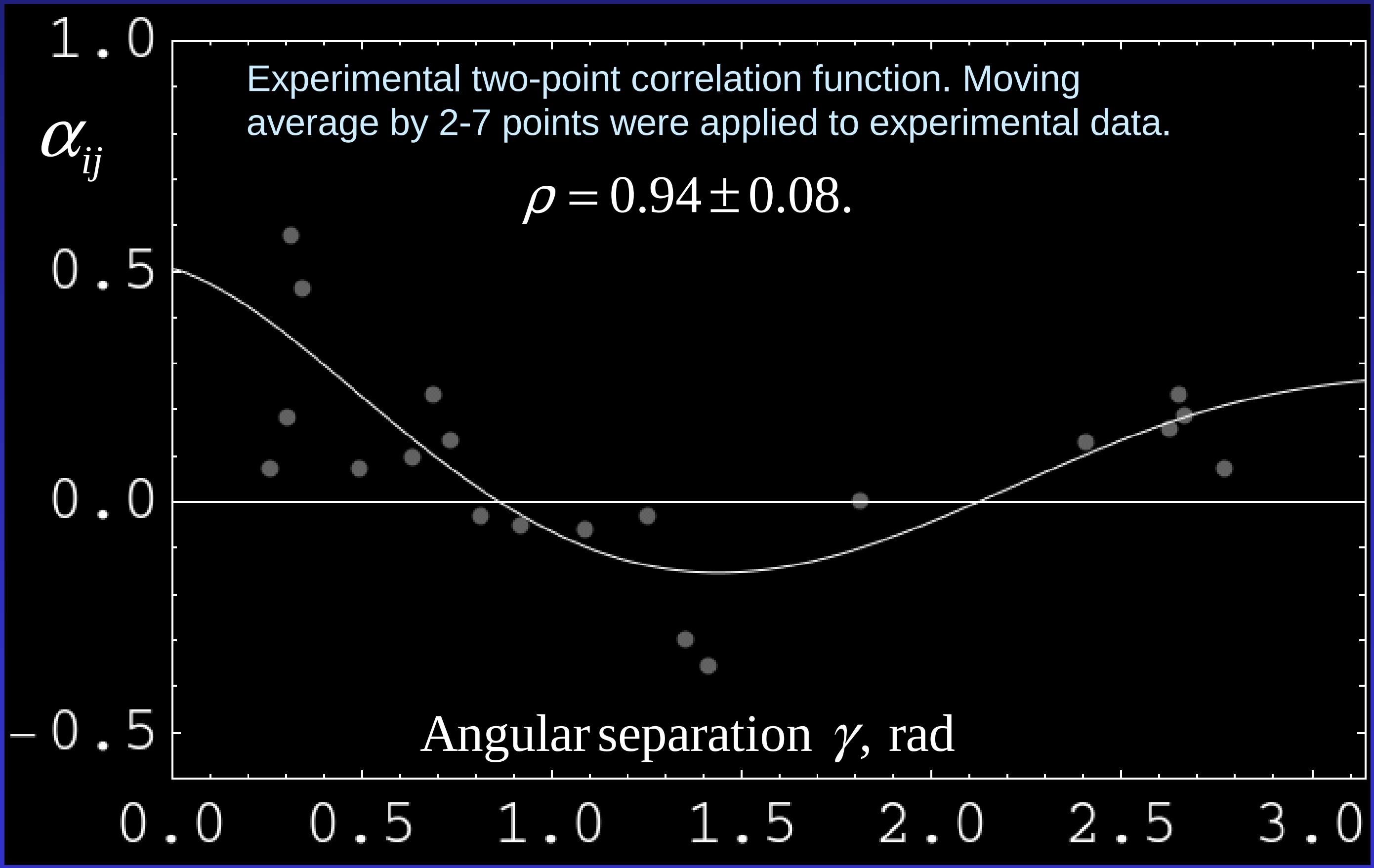
Detection of gravitational waves



Angular correlation for different SSA-components.

Detection of gravitational waves

This plot shows experimental angular correlation. Procedure of moving average by 2-7 points was applied for clarity. Averaged points are displayed by different gray level. Correlation coefficient ρ were calculated between theoretical line and averaged points.



Conclusion

A number of millisecond pulsars distributed over the sky (Pulsar Timing Array) gives possibility to solve different problems of astrometry, astrophysics, metrology and cosmology.

Ensemble Pulsar Time scale comparing with TT scale has stability 10^{-15} at 7 years time interval.

A new modified method of detection of GW was proposed. This method allowed to detect the unique signature similar to that derived for GW (Hellings, Downs, 1983). Additional calculations are required.

Acknowledgements

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