Spectral Analysis of Timing Noise in NANOGrav pulsars

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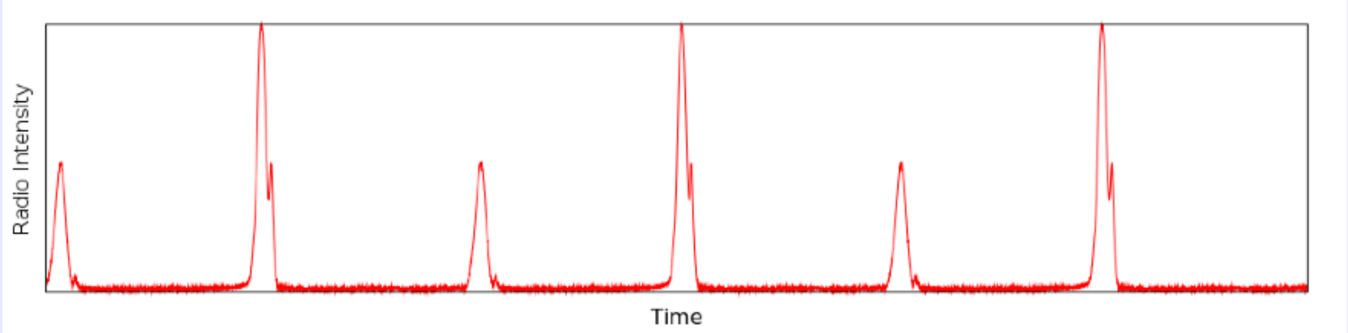
Outline

- Pulsar timing residuals
- Autocorrelation of timing residuals
- White noise vs Red noise
- Sources of timing noise
- Why study timing noise?
- Complications
- Cholesky method

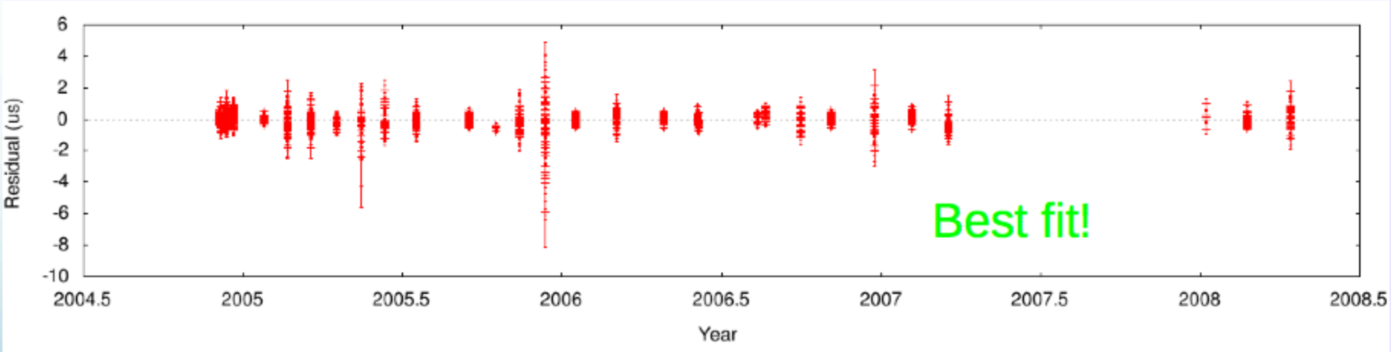
The International Pulsar Timing Array

Image source, clockwse from upper left: http://www.gb.nrao.edu/; http://www.astron.nl/; http://www.mpifr-bonn.mpg.de/english/index.html; http://gmrt.ncra.tifr.res.in/; http://www.flickr.com/photos/shami_chatterjee/455275921/; http://www.srt.inaf.it/; http://www.obs-nancay.fr/; http://www.jb.man.ac.uk/; http://www.naic.edu/

Pulsar timing residuals



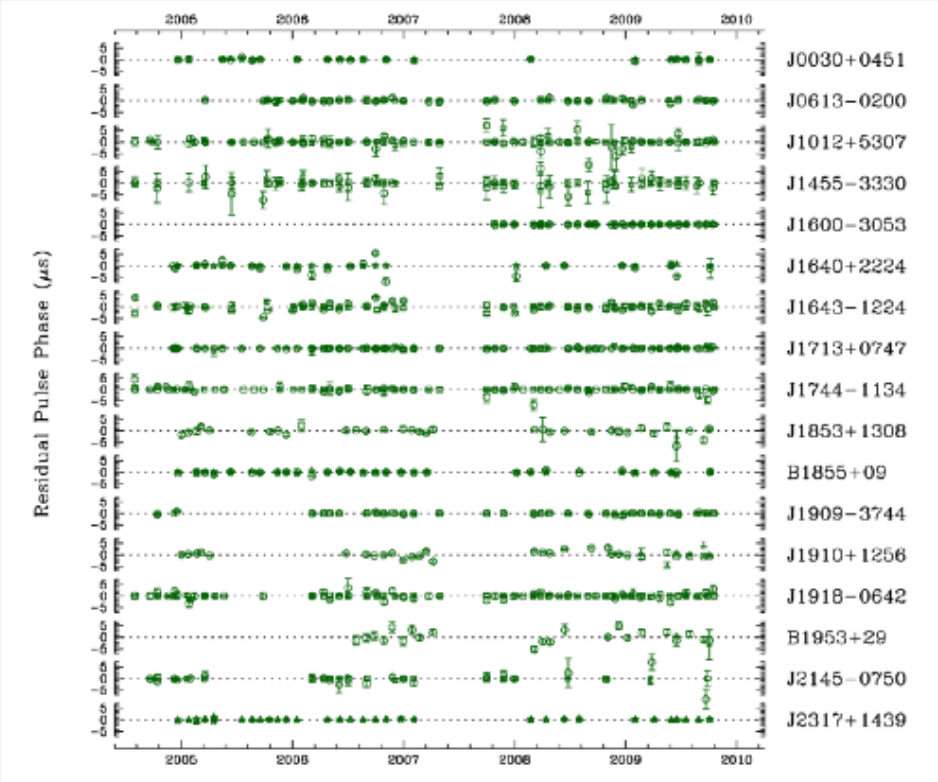
"Timing residuals" = Data – model pulse arrival times



Credit: Paul Demorest

NANOGrav residual data

NANOGrav 5-year timing results overview:



(plot: D. Nice)

NANOGrav residual data

Source	Per-channel RMS, μs	χ^2	Daily RMS, μs	Hi-freq RMS, μs
J1713+0747	0.106	1.48	0.030	0.041
J1909–3744	0.181	1.95	0.038	0.047
B1855+09	0.395	2.19	0.111	0.101
J0030+0451	0.604	1.44	0.148	0.328
J1600–3053	1.293	1.45	0.163	0.141
J0613–0200	0.781	1.21	0.178	0.519
J1744–1134	0.617	3.58	0.198	0.229
J2145–0750	1.252	1.97	0.202	0.494
J1918–0642	1.271	1.21	0.203	0.211
J2317+1439	0.496	3.03	0.251	0.155
J1853+1308	1.028	1.06	0.254	0.271
J1012+5307	1.327	1.40	0.276	0.345
J1640+2224	0.562	4.36	0.409	0.601
J1910+1256	1.394	2.09	0.708	0.710
J1455–3330	4.010	1.01	0.787	1.080
B1953+29	3.981	0.98	1.437	1.879
J1643–1224	2.892	2.78	1.467	1.887

Credit: Paul Demorest

Are the timing residuals correlated?

TIME (MJD)	Residual (ms)
54044.089435873136551	-0.0018164628493641641436
54044.090130776945745	-0.0018199607840530716779
54044.090825680814575	-0.0018183061811999605721
54044.091520528383526	-0.0018155078738482632365
54044.092215432230436	-0.0018157471801402454965
54044.092910336108684	-0.0018132788409635254637
54044.093605183643156	-0.0018134595268065353304
54044.094300087480185	-0.001814552473309981613
54044.094994991339053	-0.0018137585708685278125
54044.095687642665851	-0.0018136071309974953137
54044.096382546533118	-0.0018120875881923725662
54044.09707745041473	-0.001809328563231535 8352
54044.097772354259284	-0.0018097713802649205304
54092.92233343031689	0.00035644731039197293804
54092.92302827777306	0.00034950081873088501217
54092.92372312527203	0.00034625220756559240447
54092.924418029180064	0.00035129352320060902988
54092.925112876770228	0.00035592412603733835473
54092.925807724170209	0.00034412284260613678193
54092.926502571801255	0.00035228557046705851313
54092.927197419369701	0.00035503976059475 98151
54092.927892323351383	0.00036644424233834594414
54092.928587170740517	0.00035370582682625731469
54092.929282018401906	0.00036449025267239360587
54092.929976865708504	0.00034462067118614673143

Autocorrelation:

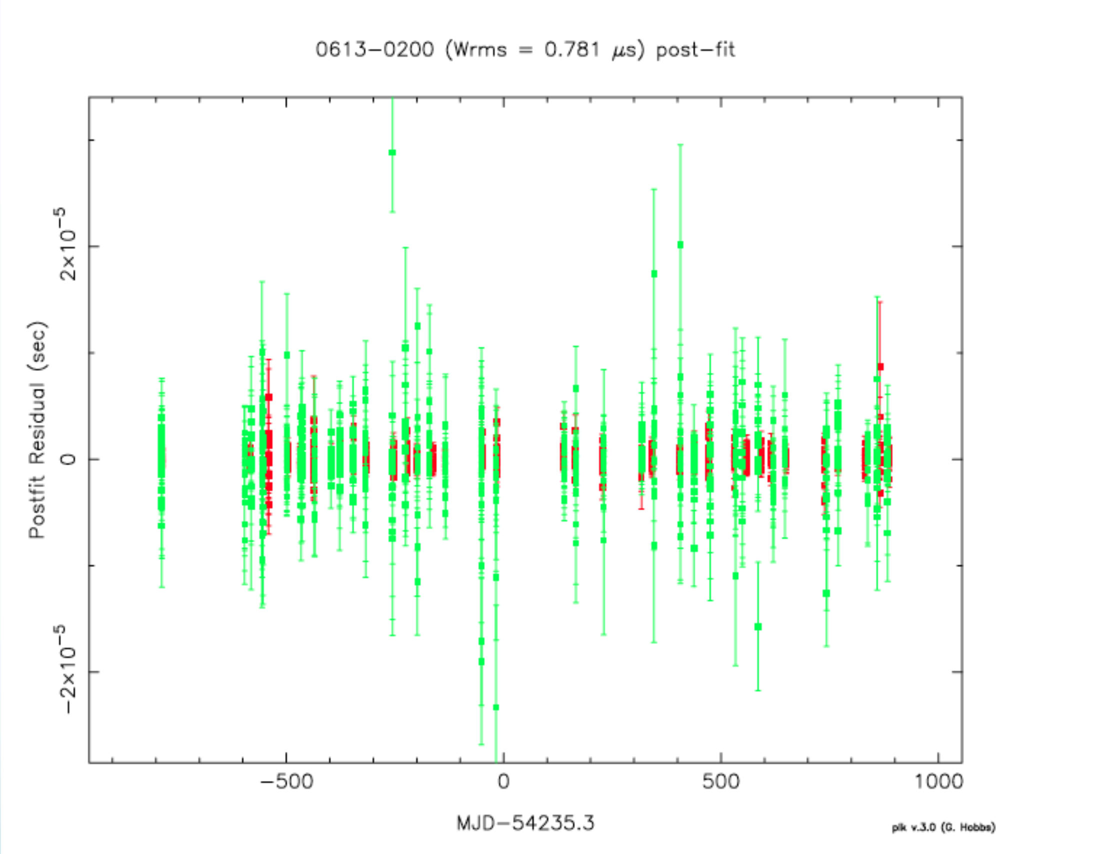
$$\hat{R}(k) = \frac{1}{(n-k)\sigma^2} \sum_{t=1}^{n-k} (X_t - \mu)(X_{t+k} - \mu)$$

Consistent with zero: White noise

Positive correlation: Red noise

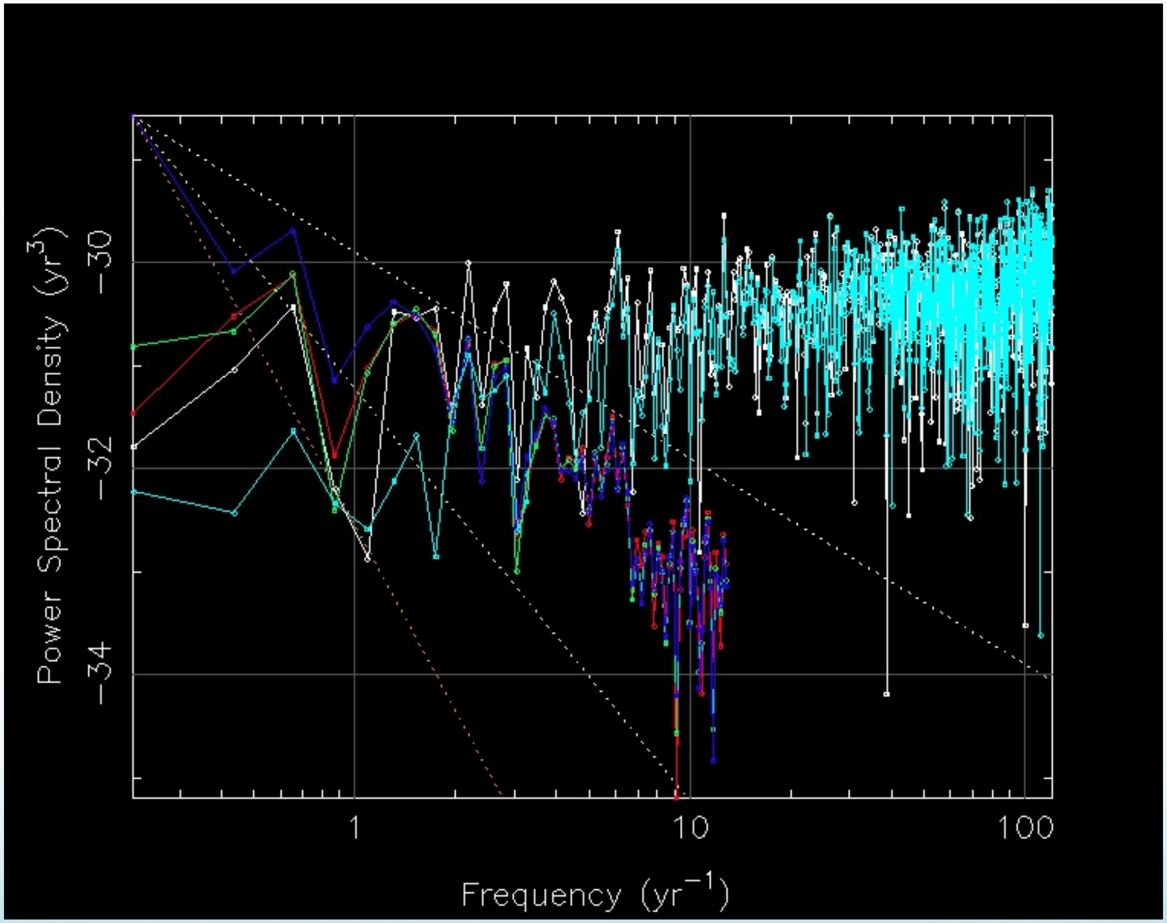
Negative correlation: Blue noise

White noise



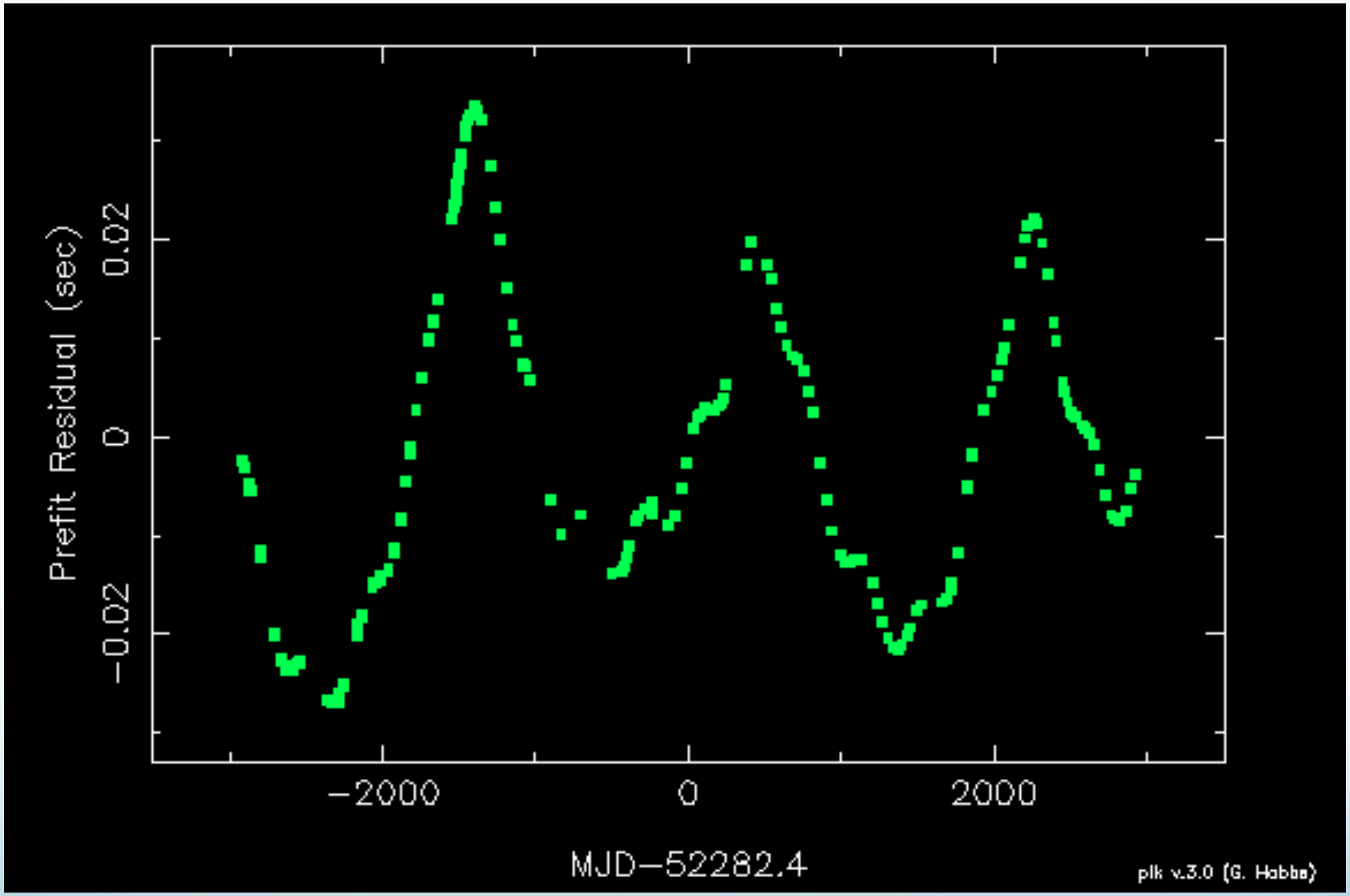
Timing residual for J0613-0200 (NANOGrav data)

White noise



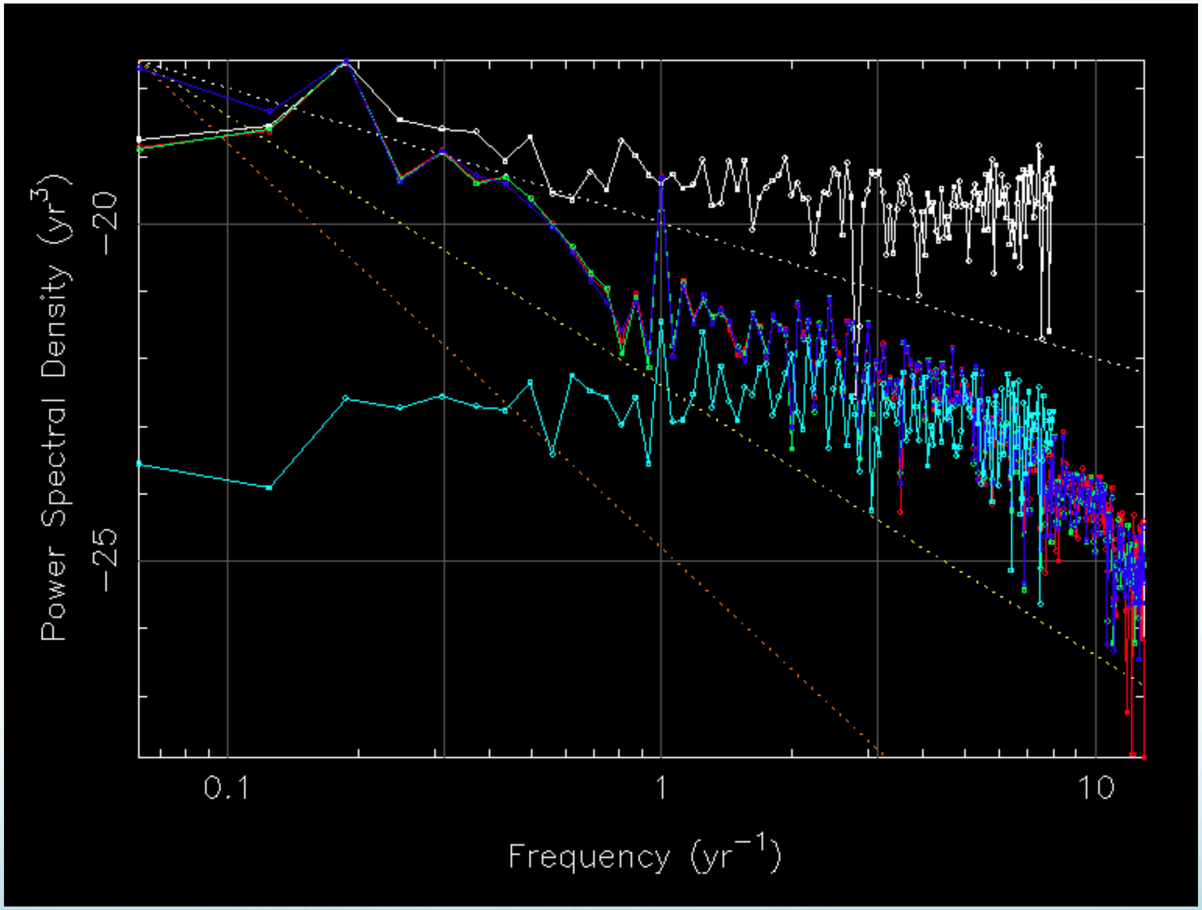
Power spectrum of residuals for J0613-0200 (NANOGrav data)
Use of TEMPO2 SpectralModel plugin

Red noise



Timing residual for J1539-5626, credit: Meng Yu and PPTA

Red noise



Power spectrum of residual for J1539-5626, credit: Meng Yu and PPTA

Sources of timing noise

Intrinsic to pulsar

- Superfluid interior affecting rotation and spin period
- Free precession
- Variations in outside magnetosphere affecting torque --> random walk in pulse frequency or phase, or discrete jumps
- Pulse shape variations
- Unknown orbital companions

Extrinsic

- Clock errors
- Uncorrected DM variations
- Gravitational waves!

Source: Hobbs et al.

Why care about timing noise?

Want more information about timing residuals:
timing noise (uncorrelated + correlated) in order to:

- Accurately estimate pulsar parameters. If red pulsar, parameter errors can be underestimated.
- Useful when trying to make sense of (and combine) observations at different frequencies and different observatories
- Identify/understand the sources of timing noise
- Quantify amount of red noise and use as input in gravitational wave detection pipelines, want to distinguish timing noise from gravitational wave signature
- Construct optimal filter: when adding various pulsar signals together, need to know how much to weigh them in sum – depends on noise each pulsar has.

Complications

- Issues with non-uniform time sampling when computing power spectrum

→ Use of the (Cholesky) Generalized Least-Squares method to compute power spectrum

→ Cholesky method takes covariance matrix into account

- Timing noise is different at different frequencies and at different observatories. Why?

Cholesky method

- Study of timing noise in pulsar residuals: how to quantify the amount of red noise?
- Pulsar data non-uniformally sampled, cannot simply do Fourier analysis.
- Lomb-Scargle not adequate for steep spectra and not good for irregular spacing.
- Use Cholesky transformation with the TEMPO2 “spectralModel” plugin (W. Coles & G. Hobbs)
- Cholesky method separates out low-frequency (red noise) from high-frequency (white noise) components of spectrum. Unlike ordinary least-squares, Cholesky uses the covariance matrix during least-squares minimizing.

Sample fit for autocorrelation function

Example of what fits look like:

$$C(d) = Ce^{-d/\tau}$$

$$C = 1.96 \times 10^{-12} yr^2$$

$$\tau = 35 days$$

But in a lot of cases C1 is a small negative number.
Should be consistent with white noise (i.e. C1=0) within error bars.

Negative number possibly due to overshoot by quadratic removal.

Results

Pulsar	Freq (MHz)	Obs	τ (days)	C (yr^2)	δC (yr^2)	corr	Prob (%)
J0030+0451	400	AO	170	0		-0.105	20.3
J0030+0451	1400	AO	26	-2.39E-13		0.079	10.9
J0613-0200	800	GBT	–	–		-0.009	84.4
J0613-0200	1400	GBT	55	1.22E-13		-0.204	0.04
J1012+5307	800	GBT	80	1E-12		0.024	51.2
J1012+5307	1400	GBT	12	-6.07E-13		-0.020	51.4
J1455-3330	800	GBT	4	-1.08E-12		0.093	3.7
J1455-3330	1400	GBT	16	5.22E-11		0.103	0.53
J1600-3053	800	GBT	160	-3.07E-14		-0.076	24.1
J1600-3053	1400	GBT	17	7E-13		0.0006	99.2
J1640+2224	400	AO	29	-2.82E-14		-0.034	55.8
J1640+2224	1400	AO	18	-3.60E-12		0.126	1.58
J1744-1134	800	GBT	27	3.3E-13		0.022	52.3
J1744-1134	1400	GBT	26	-1.75E-13		0.030	33.7
J1853+1308	1400	AO	48	-1.47E-12		-0.151	0.06
B1953+29	1400	AO	60	1.11E-12		0.110	12.2
B1855+09	400	AO	–	–		-0.114	9.5
B1855+09	1400	AO	73	-1.34E-13		0.145	0.27
J1909-3744	800	GBT	–	–		-0.170	2.66
J1909-3744	1400	GBT	153	-3.40E-14		-0.354	0.02
J1918-0642	800	GBT	–	–		0.045	28.1
J1918-0642	1400	GBT	8	5.79E-12		0.020	58.1
J2145-0750	800	GBT	–	–		-0.055	32.3
J2145-0750	1400	GBT	175	-4E-13		-0.038	45.9
J1713+0747	1400	GBT	23	3.25E-14		0.011	1.45
J1713+0747	1400	AO	450	-1E-15		-0.047	7.1
J1713+0747	800	GBT	–	–		-0.169	0.06
J1713+0747	2300	AO	35	7.97E-14		0.00036	48.9

Summary

- Millisecond pulsars used in PTA for GW detection exhibit white noise and red noise
- Need to quantify red noise when fitting for pulsar parameters + looking for GW
- Dependence on radio frequency and observatory. Need to better understand source of red noise in our observations