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The strategy for FAST PTA Data sets simulation

Abstract In this work, we want to: 1) simulate PTA data sets. 2) limit for GWB versus time. 3) give an optimal strategy for FAST to detect GWB by using PTA.

To do list:

1. Define simulations
2. Finish simulations (plotmany)
3. Install NX01 on a slow computer (test simulated data sets can work in NX01)
4. Define final simulations (nreal:)
5. Install NX01 on a fast computer
6. Run NX01 on all simulations to get results
7. Finish the paper (RAA/MNRAS)

1 DEFINE SIMULATIONS WITH FAST

Most of the previous calculations to answer questions like "when will a given PTA discover GWs?" have assumed idealised data sets. It is common to assume that the data sets are regularly sampled, often the ToA uncertainties are all identical and that the noise processes take a simple form. Clearly, real data sets are more complex and in order to obtain a realistic estimate of the sensitivity of a particular PTA to GWs and to test the GW detection code it is necessary to create realistic simulations. We describe our simulations four parts as follows:
(1) the choice of pulsars
(2) the observing systems and observing cadence
(3) modelling the high frequency noise (jitter noise) processes and the ToA uncertainties (radiometer noise)
(4) modelling the low frequency noise (DM variations and timing noise) processes including the GW signal

For part (1), we note that there are 30 pulsars in the FAST sky that are part of the IPTA data release 1 (Verbiest et al. 2016). In Table 1, we use simple models for the expected radiometer noise with 19-beam receiver according to:

$$\sigma_{rad} \approx \frac{W}{S/N} \approx \frac{W T_{sys}}{GS\sqrt{2\Delta f t}}\sqrt{\frac{W}{P-W}} \tag{1}$$

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where S/N is the profile signal-to-noise ratio, Tsys is the system temperature, G is the telescope gain, S is the pulsar's flux density, Δf the usable bandwidth, t is the observing time, P is pulsar's period and W is the pulsar's effect pulse width (we used W50 in this paper).The radiometer noise is modelled assuming a gain of 16 K/Jy and a system temperature of 25 K.

The jitter noise levels from PPTA data sets (Shannon et al. 2014) or a simple analytic model provided by Equation 2 for pulsars that don't have measuring jitter noise leves in PPTA data sets.

$$\sigma_J \approx 0.2W\sqrt{\frac{P}{t}} \tag{2}$$

where all parameters are measured in seconds, W is the pulse width, P the pulse period and t is the integration time.

We then calculated the time required (in an ideal case) to reach a timing precision of 500ns and also 100ns. If the expectation is that the timing precision could reach 100ns or 500ns in 5-10 minutes of observing then we select an observing time (in graduations of 5 minutes) for these pulsars to achieve 100ns or 500ns. We also list those pulsars that we do not believe will provide sufficient timing precision for inclusion in the array in this table. In total we therefore assume that 21 of the existing IPTA pulsars will be including in the FAST PTA.

Numerous pulsar surveys are ongoing and already the current PTAs have added new pulsars into their sample. We therefore believe it likely that at least five other millisecond pulsars will provide high quality timing by the time FAST begins its long-term timing program. So, we selected these five pulsars from NANOGrav with known pulse width (W50) and period in FAST sky and listed those pulsars in the Table 1.We therefore start our simulations with 21 known IPTA pulsars along with five NANOGrav pulsars. The initial science projects with FAST are to discover new pulsars and so it is expected that a large number of new pulsars will be discovered in the first few years of FAST scientific operations. We model this by adding a further five millisecond pulsars into the array two years after the start of our simulations and then add a further two each year for the first 10 years. Although we don't know where these FAST new pulsars, but they provide a reasonable sky coverage for the pulsars according to the highest discover position area with FAST from Shi et al (2017) in Figure 1. We choose the galactic longitude (gl) in $20^\circ < gl < 40^\circ$, $80^\circ < gl < 110^\circ$ and $215^\circ < gl < 225^\circ$, the galactic latitude (gb) in $-5^\circ < gb < 5^\circ$ as the places to put the new pulsars which will be discovered by FAST. So, we assumed a bunch of these pulsars position in random way and also list in the Table 1. **(give Shi FAST new pulsars' position (gl, gb), then get these pulsars' W50, P, S1400, DM)**

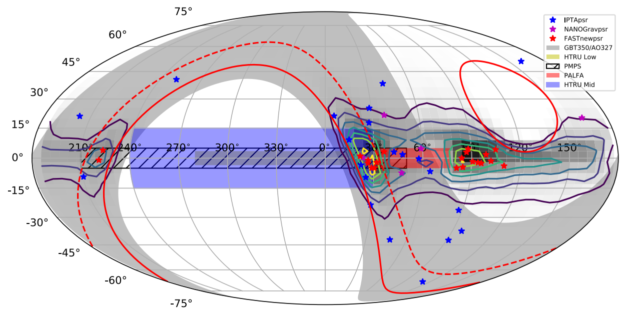

Fig. 1 The discovering potential for pulsars with FAST and all pulsars (IPTA, NANOGrav, FASTnew pulsars) that used in simulation.

Table 1 There listed 30 IPTA pulsars, 5 NANOGrav pulsars in FAST sky ($-14° \leq$ Dec $\leq +66°$) and 21 FAST new pulsars in this table. The columns of (2), (3), (4), (12), (13) and (14) are the FWHM pulse width, period, flux in 1400MHz, galactic longitude, galactic latitude and DM for each pulsar from PSRCAT. We gave jitter noise level from PPTA measured value (mark with *) or calculation result and radiometer noise level for each pulsar with FAST receiver ($G = 16.5K/Jy, T_{sys} = 20K, \Delta f = 800MHz$) using 1houre observation time using in column (5) and (6). Column (7) tells us whether jitter noise dominated. Column (8) and (9) gives the integration time for each pulsar, which is jitter noise or radiometer noise dominated, to reach the noise level of 100ns and 500ns with 19-beam receiver. We give the expected ToA uncertainty level and the observation time for simulations in column (10) and (11). Column (15) is the value of the structure function at 1000d if the number come from PPTA real data marked with *. The last three columns gave the timing noise model parameters which we used in simulations if the number come from real data marked with *.

Name (1)	W_{50} (ms) (2)	P_0 (s) (3)	S_{1400} (mJy) (4)	N_{J1h} (ns) (5)	N_{R1h} (ns) (6)	J_{Dom} (7)	T_{int_100ns} (min) (8)	T_{int_500ns} (min) (9)	ToAerr (ns) (10)	tobs (min) (11)	gl (deg) (12)	gb (deg) (13)	DM (cm^3pc) (14)	D_{1000} (us^2) (15)	α (16)	fc (17)	amp (p0) (18)
							IPTA	FAST	Pulsars								
J1713+0747	0.11	0.00457	10.2	*35.0	1.6	Y	7.4	0.3	100	10	28.751	25.223	15.97	0.31	2.77167	0.047136	4.9861e-27
J1744-1134	0.137	0.004075	3.1	*37.8	7.6	Y	8.6	0.3	100	10	14.794	9.18	3.14	1.3	4.09572	0.058945	4.55463e-27
J1911-1114	0.16	0.004626	0.08	36.3	348.5	N	10	0.4	100	10	25.137	-9.579	30.98	J2129-5721		J1802-2124	
J1939+2134	0.038	0.001558	13.2	5	0.4	Y	0.2	0	100	5	57.509	-0.29	71.02	8.9	6.46562	0.036896	4.07841e-22
J2229+2643	0.07	0.002978	0.9	12.7	11.1	Y	1	0	100	5	87.693	-26.284	23.02	J0711-6830		J1744-1134	
J0034-0534	0.8	0.001877	0.61	115.5	1040.7	N	86.3	3.5	500	5	111.492	-68.069	13.77	J1857+0943		J0437-4715	
J0613-0200	0.462	0.003062	2.3	85.2	78	Y	44	1.8	500	5	210.413	-9.305	38.78	0.3	5.71917	0.073121	4.05031e-26
J0751+1807	0.7	0.003479	3.2	137.6	101.1	Y	114.3	4.6	500	5	202.73	21.086	30.25	J2129-5721	1.92753	0.065402	2.64439e-26
J1012+5307	0.69	0.005256	3	166.7	82.3	Y	167.3	6.7	500	10	160.347	50.858	9.02	J2145-0750	1.70055	0.069214	1.88042e-27
J1024-0719	0.521	0.005162	1.5	124.8	107.1	Y	94.1	3.8	500	5	251.702	40.516	6.49	6.2	5.9462	0.062925	8.77794e-24
J1640+2224	0.22	0.003163	2	41.2	27.7	Y	10.4	0.4	500	5	41.051	38.271	18.43	J0711-6830		J1744-1134	
J1643-1224	0.314	0.004622	4.8	71.2	16.3	Y	30.5	1.2	500	5	5.669	21.218	62.41	65	2	0.056215	2.67207e-40
J1738+0333	0.43	0.00585		109.6		Y	72.1	2.9	500	5	27.721	17.742	33.77	J2129-5721		J1801-1417	
J1843-1113	0.25	0.001846	0.1	35.8	911	N	13.2	0.5	500	5	22.055	-3.397	59.96	J1045-4509	1.67934	0.115035	1.13013e-26
J1857+0943	0.518	0.005362	5	126.4	31.2	Y	96.1	3.8	500	5	42.29	3.06	13.3	0.9		J2145-0750	
J1911+1347	0.35	0.003626	0.5	70.3	210.7	N	30.9	1.2	500	5	47.518	1.809	30.99	J2129-5721		J1600-3053	
J2010-1323	0.28	0.005223	1.6	67.5	38.3	Y	27.5	1.1	500	5	29.446	-23.54	22.16	J0711-6830		J1643-1224	
J2019+2425	0.3	0.003935		62.7		Y	23.6	0.9	500	5	64.746	-6.624	17.2	J0711-6830		J1730-2304	
J2145-0750	0.337	0.016052	8.9	*192.0	5.1	Y	221.2	8.8	500	10	47.777	-42.084	9	J2145-0750	0.450459	0.057029	2.62466e-28
J2317+1439	0.46	0.003445	4	90	41.6	Y	48.6	2	500	5	91.361	-42.36	21.91	J0711-6830		J1910+1256	
J2322+2057	0.3	0.004808		69.3		Y	28.8	1.2	500	5	96.515	-37.31	13.37	J1857+0943		J1643-1224	
J0030+0451		0.004865	0.6														
J0218+4232		0.002323	0.9														
J0621+1002	9.15	0.028854	1.9	5180.9	3021.5	Y	161066.7	6442.7									
J1022+1001	0.972	0.016453	6.1	*290.0	36.8	Y	504.8	20.2									
J1853+1303		0.004092	0.4														
J1910+1256		0.004984	0.5														
J1918-0642	0.74	0.007646	0.58	215.7	384.5	N	281.4	11.3									
J1955+2908	1.8	0.006133	1.1	469.9	971.1	N	1330.6	53.2									
J2033+1734		0.005949															
							NANOGrav	FAST	Pulsars								
J0645+5158	0.086	0.008853		27.0		Y	4.4	0.2	100	5	163.963	20.251	18.25	J0711-6830		J1024-0719	
J1741+1351	0.160	0.003747	0.93	32.6	33.5	N	6.6	0.98	100	10	37.885	21.641	24.20	J0711-6830		J1600-3053	
J1832-0836	0.058	0.002719	1.10	10.1	7.2	Y	0.7	1.41	100	5	23.109	0.257	28.18	J2129-5721		J1939+2134	
J1923+2515	0.540	0.003788		110.8		Y	73.6	2.9	500	5	58.946	4.749	18.86	J0711-6830		J0437-4715	
J1944+0907	0.500	0.005185		120.0		Y	86.4	3.5	500	5	47.160	-7.357	24.34	J0711-6830		J1012+5307	

Table 1 – *continued*

Name	W_{50} (ms)	P_0 (s)	S_{1400} (mJy)	$N_{\rm J1h}$ (ns)	$N_{\rm R1h}$ (ns)	$J_{\rm Dom}$	$T_{\rm int\_100ns}$ (min)	$T_{\rm int\_500ns}$ (min)	ToAerr (ns)	tobs (min)	gl (deg)	gb (deg)	DM ($cm^3 pc$)	D_{1000} (us^2)	α	fc	amp (p0)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
J2315+5634sim	0.196	0.004702	0.12	44.8	313.6	N	13.9	0.6	500	5	109.959	-3.86	23.69	J0711-6830		J1802-2124	
J1848-0700sim	0.263	0.002698	0.39	45.5	204.1	N	13.7	0.5	500	5	26.324	-2.47	83.27	J1939+2134		J1843-1113	
J1900-0607sim	0.416	0.006513	0.51	111.9	196.2	N	76.3	3.1	500	5	28.536	-4.886	131.9	J1824-2452A		J1824-2452A	
J2210-6119sim	0.013	0.000811	10.63	1.2	0.1	Y	0	0	100	5	104.826	4.253	51.58	J1600-3053		J1801-1417	
J1903-0434sim	0.173	0.004456	0.14	38.5	228.7	N	10.3	0.4	500	5	30.268	-4.853	43.09	J0613-0200		J1603-7202	
							3rdY	FAST	Pulsars								
J2216+5459sim	0.249	0.003778	0.27	51	225.5	N	17	0.7	500	5	101.839	-1.391	20.75	J0711-6830		J0751+1807	
J2046+4756sim	0.086	0.003482	0.51	16.9	24.7	N	1.9	0.1	100	5	86.877	3.01	57.37	J1732-5049		J1730-2304	
							4thY	FAST	Pulsars								
J2145+5541sim	0.116	0.002875	0.56	20.7	39.1	N	2.8	0.1	100	5	98.792	1.799	86.06	J1939+2134		J0751+1807	
J2109+4121sim	0.067	0.003155	0.47	12.5	19.3	N	1.1	0	100	5	84.643	-4.482	28.02	J2129-5721		J1603-7202	
							5thY	FAST	Pulsars								
J2149+5031sim	0.071	0.00506	1.53	16.8	5.1	Y	1.7	0.1	100	5	95.932	-2.556	149.02	J1824-2452A		J1744-1134	
J2058+3813sim	0.053	0.002082	0.13	8.1	60.7	N	0.8	0	100	5	80.834	-4.924	23.96	J0711-6830		J1024-0719	
							6thY	FAST	Pulsars								
J2137+4928sim	0.282	0.00682	0.69	77.6	78.1	N	36.6	1.5	500	5	93.846	-2.155	34.28	J2129-5721		J1600-3053	
J2121+4734sim	0.253	0.00362	1.49	50.7	42.9	Y	15.7	0.6	500	5	90.618	-1.718	98.43	J1824-2452A		J1730-2304	
							7thY	FAST	Pulsars								
J2042+4944sim	0.093	0.00229	0.54	14.8	32.6	N	1.5	0.1	100	5	87.95	4.571	20.6	J0711-6830		J1022+1001	
J2048+4343sim	0.183	0.00331	0.22	35.1	185.3	N	8.5	0.3	100	10	83.867	0.01	14.81	J1713+0747		J1801-1417	
							8thY	FAST	Pulsars								
J1845+0419sim	0.103	0.0021	1.11	15.7	19.4	N	1.6	0.1	100	5	36.158	3.19	166.87	J1824-2452A		J1730-2304	
J1856-0206sim	0.054	0.00278	1.21	9.5	5.8	Y	0.6	0	100	5	31.657	-2.144	119.28	J1824-2452A		J1603-7202	
							9thY	FAST	Pulsars								
J1843-0618sim	0.155	0.00716	0.22	43.7	96.5	N	12	0.5	500	5	26.383	-1.063	112.01	J1824-2452A		J1600-3053	
J1826-0941sim	0.476	0.00825	0.14	144.1	774.6	N	129.3	5.2	500	10	21.48	1.044	30.86	J2129-5721		J0621+1002	
							10thY	FAST	Pulsars								
J0720-0714sim	0.145	0.00467	0.15	33	159.3	N	7.5	0.3	100	10	223.357	3.961	31.63	J2129-5721		J1455-3330	
J0658-0730sim	0.101	0.00595	4.65	26	2.6	Y	4.1	0.2	100	5	221.056	-0.93	165.97	J1824-2452A		J0437-4715	