International Pulsar Timing Array Bench, a web-based application

ARCC Scholar thesis

Jose Guadalupe Martinez

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Abstract

There is currently an international effort to detect gravitational waves using radio pulsar timing techniques. The detection will involve the analysis of signals observed from a large number of radio pulsars by many different observatories. We have developed an on-line web tool known as the International Pulsar Timing Array Bench (IPTA Bench) that will allow researchers to determine the effectiveness of different lists of pulsars, observing strategies, and a simulator for the detection of gravitational wave signals. The observing strategies will enable the researcher to develop an optimal schedule depending on which radio telescopes and pulsars the researchers will use. This thesis describes the current and future capabilities of IPTA Bench.

Glossary of Abbreviations and Symbols

IPTA	International Pulsar Timing Array
NANOGrav	North American Nanohertz Observatory for Gravitational Waves
EPTA	European Pulsar Timing Array
PPTA	Parkes Pulsar Timing Array
PTA	Pulsar Timing Array
GWs	Gravitational Waves
MDA	Minimum Detectable Amplitude
SMBH	Super Massive Black-hole
RMS	Root Mean Square
TOA	Time of Arrival
CARA	Center for Advanced Radio Astronomy (at UTB)
PHP	Hypertext Preprocessor
MHz	MegaHertz
K	Kelvin
Jy	Jansky

Contents

1 Introduction

Radio pulsars are rapidly rotating, highly magnetized neutron stars, which are approximately 10 km in diameter but weigh more than our sun. These highly dense objects produce radio beams of radiation that sweep the sky similar to a lighthouse. These beams of radiation are detected by radio telescopes as pulses. Since the discovery of the first pulsar in 1967, by Jocelyn Bell and Antony Hewish, over 2000 pulsars have been discovered. Pulsars have provided an abundance of information about neutron star physics, general relativity, the Galactic gravitational potential and magnetic field, the interstellar medium, celestial mechanics, planetary physics and even cosmology [5].

Gravitational Waves (GWs) are "ripples in space-time," just like a boat sailing through the ocean produces waves in the water. Massive objects out in space produce gravitational waves that we can picture as ripples in the fabric of space-time. These GWs were predicted by Albert Einstein based on his theory of general relativity. Sources of GWs could possibly be binary star systems composed of neutron stars, white dwarfs, or black holes. Although GWs have not been directly detected, there is indirect evidence for their existence. For example, the 1993 Nobel Prize in Physics was awarded for measurements of the Hulse-Taylor binary system which emits gravitational radiation. By measuring the orbital decay of the binary system, through the change in epoch of periastron over time, they matched the theoretical expected change in epoch according to general relativity [2].

Pulsar timing is a process of regularly monitoring the rotation of a neutron star by tracking the times of arrival of the radio pulses. The very precise tracking of rotational phase allows pulsar astronomers to probe the interior physics of neutron stars, make extremely accurate astrometric measurements, and test gravitational theories in the strong-field regime in unique ways. The Pulsar Timing Array is a process of analyzing a set of bright, rapidly rotating pulsars to detect gravitational waves. The signals from a pulsar can be detected by a radio telescope as a series of regularly spaced pulses, like ticks from a clock. We are using pulsars as clocks, because gravitational waves affect the time it takes the pulses to travel from the pulsar to a telescope on Earth. We are searching for these disturbances due to gravitational waves in measurements of the times of arrival of pulses at a radio telescope. The Pulsar Timing Array searches for a correlation between signals from an array of different pulsars to search for gravitational waves.

Throughout history, all that we know from beyond our solar system has been discovered through electromagnetic waves, but hopefully in the future

Gravitational Wave Astronomy will give us an entirely new spectrum with which to observe the universe. This could lead to uncovering secrets about our mysterious universe. The “International Pulsar Timing Array Bench” (IPTA Bench), is an online web-tool that will help determine the best set of pulsars to be used in a project to detect gravitational waves by pulsar timing. The set of applications IPTA Bench currently has are the root mean square (RMS) Calculator which calculates the amount of noise in a pulsar signal, the Minimum Detectable Amplitude of a gravitational wave using a set of pulsars, the Hellings and Downs curve for a set of pulsars, and lastly the Optimal Observation Schedule, which calculates the most efficient observing schedule of a set of pulsars with one or more radio telescopes. IPTA Bench incorporates all these tools in one website to help in the process of detecting GWs by using pulsar timing.

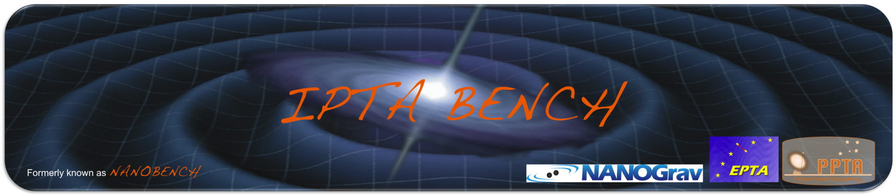
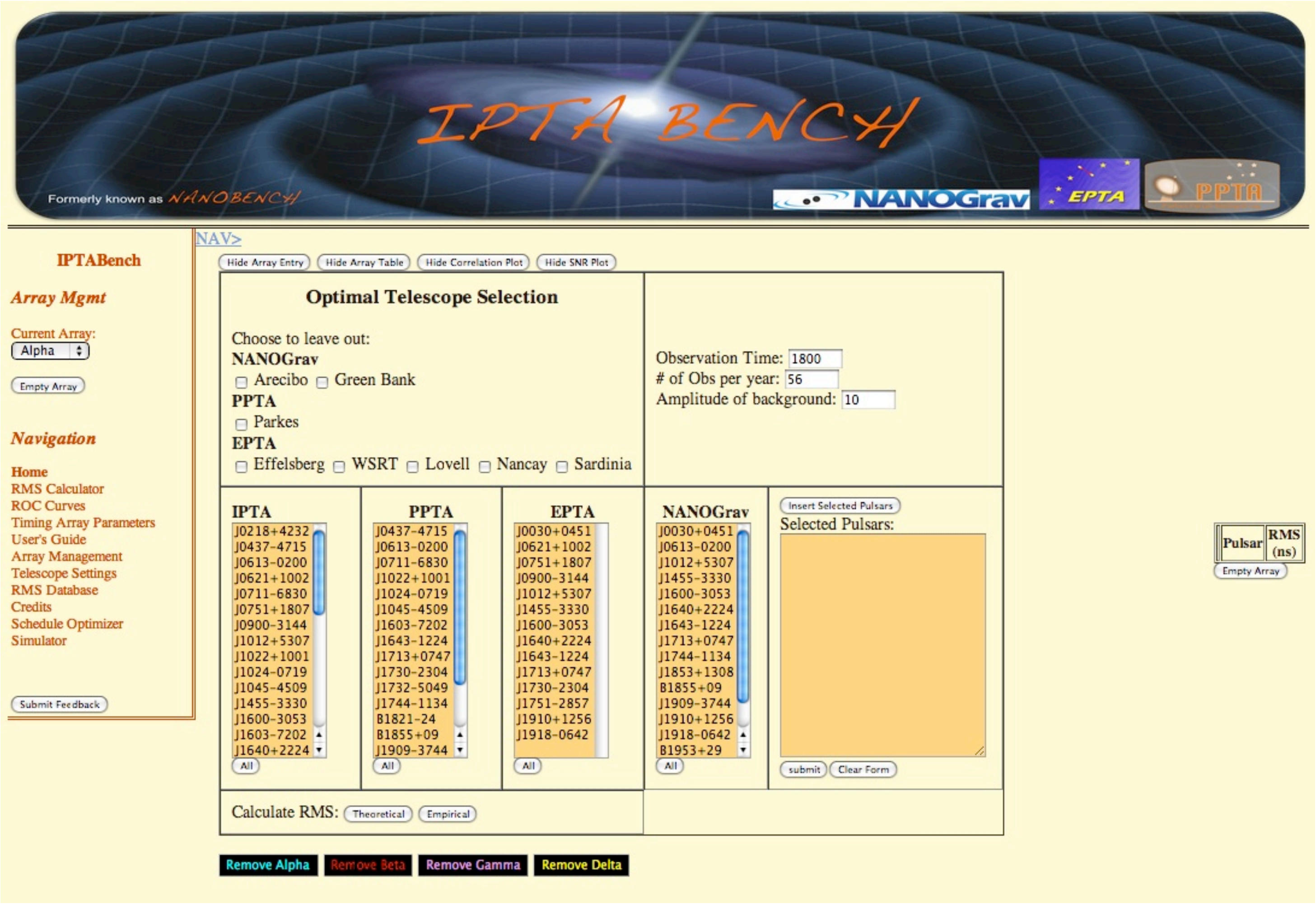


Figure 1: The logo of IPTA Bench, which represents the collaboration of all the pulsar timing array groups across the world: North American Nanohertz Observatory for Gravitational Waves (NANOGrav), European Pulsar Timing Array (EPTA), and Parkes Pulsar Timing Array (PPTA).



Current Array: Alpha

Optimal Telescope Selection

Choose to leave out:

NANOGrav

☐ Arecibo ☐ Green Bank

PPTA

☐ Parkes

EPTA

☐ Effelsberg ☐ WSRT ☐ Lovell ☐ Nancay ☐ Sardinia

Observation Time: 1800

\# of Obs per year: 56

Amplitude of background: 10

IPTA	PPTA	EPTA	NANOGrav
J0218+4232	J0437-4715	J0030+0451	J0030+0451
J0437-4715	J0613-0200	J0621+1002	J0613-0200
J0613-0200	J0711-6830	J0751+1807	J1012+5307
J0621+1002	J1022+1001	J0900-3144	J1455-3330
J0711-6830	J1024-0719	J1012+5307	J1600-3053
J0751+1807	J1045-4509	J1455-3330	J1640+2224
J0900-3144	J1603-7202	J1600-3053	J1643-1224
J1012+5307	J1643-1224	J1640+2224	J1713+0747
J1022+1001	J1713+0747	J1643-1224	J1744-1134
J1024-0719	J1730-2304	J1713+0747	J1853+1308
J1045-4509	J1732-5049	J1730-2304	B1855+09
J1455-3330	J1744-1134	J1751-2857	J1909-3744
J1600-3053	B1821-24	J1910+1256	J1910+1256
J1603-7202	B1855+09	J1918-0642	J1918-0642
J1640+2224	J1909-3744		B1953+29

Selected Pulsars:

Calculate RMS:

Figure 2: The Home page of IPTA Bench.

2 Face of IPTA Bench Site

The face of IPTA Bench is the homepage where the user will begin. The logo at the very top represents itself and the collaboration with the Pulsar Timing Array (PTA) groups from around the world. At the very far left is the Navigation and current array status. The Navigation system contains a set of links to various pages that are different aspects of IPTA Bench. The current array status is a tool, where the user can choose up to four different sets of pulsars. The set of pulsars that have been selected will be saved within a 24 hour PHP session. This feature allows the user to have the option of choosing another current array status, to select a different set of pulsars, and compare future results against one another.

2.1 Pulsar List and Optimal Telescope Selection

The first box next to the Navigation/current array status is the Array Entry box. In this area the user can choose either a pre-selected list of pulsars from the various PTA groups or type in a list of their choosing. The pre-selected lists available are the International Pulsar Timing Array (34 pulsars), the Parkes Pulsar Timing Array (19 pulsars), the European Pulsar Timing Array (14 pulsars), and the North American Nanohertz Observatory for Gravitational Waves (17 pulsars).

Above the pre-selected lists, the Optimal Telescope Selection system can be found. Here the user can choose which telescope they would like to leave out of their calculations on the set of pulsars. It will also automatically choose the most sensitive telescope with which each pulsar can be seen. Beside the Optimal Telescope Selection system are a few parameters that will be included in the list of pulsars selected and various calculations. The parameters consist of: the observation time, which is the amount of time a pulsar is observed during an observation; the number of observations per year (also known as the cadence) which is how many times a year the pulsar is observed; and lastly the amplitude of background, which estimates the amplitude of background noise. Note, each of these parameters will automatically fill in for all the pulsars selected; if the user does not want these default parameters on specific pulsars they can manually change each parameter in the "Selected Pulsar" box individually by pulsar name.

At the end, once the preferred parameters have been chosen and selection of a pre-selected list of pulsars has been made, the user must press the "Insert Selected Pulsars" button. Information of the pulsar's name and the parameters will appear in the "Selected Pulsars" text box. The following order of information will appear: pulsar name, observation time (seconds), and the first letter of the most sensitive telescope which can view the pulsar, example "J0030+0451,1800,A". Here the user can change any parameter on individual pulsars before submitting it. After pressing the "submit" button, a table will appear to the right of the page showing the pulsar's name and RMS of the pulsar (the calculated amount of noise in a pulsar signal). This is the first step needed to use IPTA Bench. Once this step has been completed the PHP session will save your progress on your browser. There is access to all the information in the Navigation links under "Array Management."

The Array Management will provide information on everything that has been saved for each pulsar under a session.

The following sections describe additional tools of IPTA BENCH.

2.2 Minimum Detectable Amplitude (for a SMBH Binary Background)

Underneath the the Array Entry box is the Minimum Detectable Amplitude (MDA), which runs a series of calculations to estimate the minimum detectable GW amplitude for a supermassive black hole binary background using a set of pulsars. The series of scripts were written by Dr. Joseph Romano and Dr. Fredrick Jenet.

The MDA interface asks the user for the following information on each different pulsar list:

1. False Alarm Probability
2. Detection Probability
3. Cadence
4. Background Spectral Index
5. Max Amplitude
6. Statistic

These are the parameters that calculate the MDA of a gravitational wave background for a set of pulsars in IPTA Bench. After the parameters are input by the user (or the default values), it first calculates the false alarm probability versus threshold for a statistic for the chosen array of pulsars. Then it calculates the detection probability as a function of false alarm probability for different amplitude stochastic GW background signals for the chosen set of pulsars. After having all that information from previous calculations, it finally calculates the detection probability for a fixed threshold as a function of the stochastic GW amplitude for the chosen set of pulsars. It runs over 1000 times with two different types of simulations. One simulates time-series for the GW signal from the chosen set of pulsars having dimensionless characteristic strain. The other simulates white noise with zero mean and variance. This simulated data is then used as input to a statistic that Dr. Fredrick Jenet wrote.

After the MDA has finally finished calculating, it will display the result on the far right of the MDA interface, under Minimum Detectable Amplitude under the observation time you have chosen (the default values are 1, 5, and 10 years).

2.3 Correlation vs Angle Between Pulsar

At the bottom of the front page, after selecting a set of pulsars, the website will calculate the famous “Hellings and Downs” curve. This curve is used for the detection of a stochastic GW background, which depends on the correlated modulation of timing residuals for different pulsars as a GW passes over the Earth. GW are quadrupolar in nature so that modulations are opposite in sign for pulsars which are 90 degrees apart in the sky. For an isotropic stochastic GW background, the correlation between residuals in different pulsars depends only on the angular separation of the pulsars.

A pulsar and the Earth could be thought as end masses of a free mass gravitational wave antenna, in which the relative motion of the masses is monitored by observing the Doppler shift of the pulse arrival times. You can find a more detailed discussion of how to use timing residuals from pulsars to derive an upper limit to the spectrum of the isotropic gravitational radiation background in [1].

A stochastic GW background leaves angular dependent correlations in the timing residuals of widely separated pulsars. The correlation coefficient between timing residuals of a pulsar pair is a function of the angular distance between the two pulsars. Such a spatial correlation in pulsar timing signals makes it possible to directly detect GW using pulsar timing arrays. Previous analyses [3] have calculated PTA sensitivity to a stochastic GW background generated by super massive blackhole (SMBH) binaries at cosmological distances. They have shown that a positive detection of the GW background is feasible if one uses state of the art pulsar timing technologies. From the figure below the abscissa gives the angle subtended at the observer by a particular pulsar pair. The ordinate gives the expected correlation between the timing residuals of that pair. This signal is independent of the GW frequency and assumes that GWs behave as predicted by general relativity.

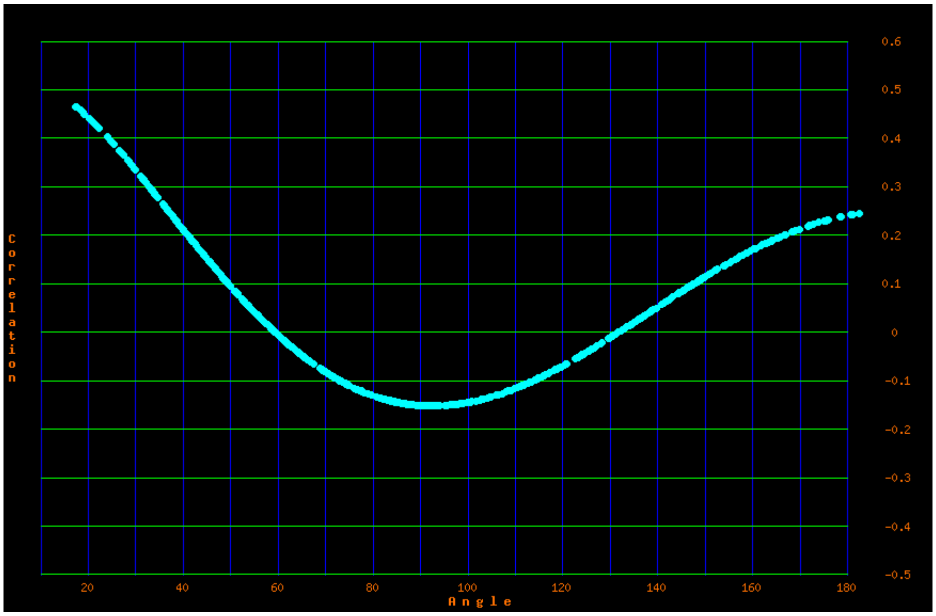
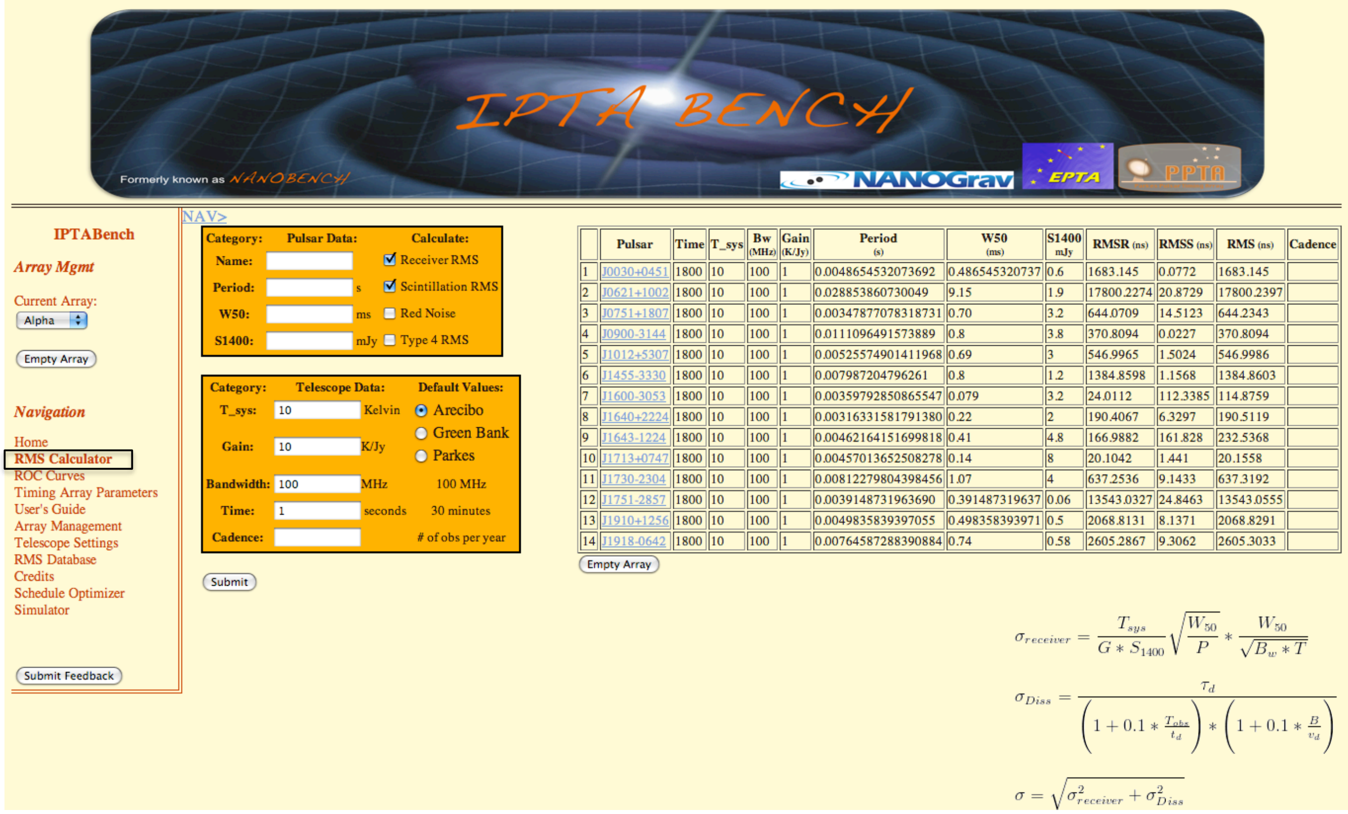


Figure 3: The expected correlation in pulsar timing residuals due to an isotropic stochastic GW background.



Category:	Pulsar Data:		Calculate:
Name:			☑ Receiver RMS
Period:		s	☑ Scintillation RMS
W50:		ms	☐ Red Noise
S1400:		mJy	☐ Type 4 RMS

Category:	Telescope Data:		Default Values:
T_sys:	10	Kelvin	● Arecibo
Gain:	10	K/Jy	○ Green Bank ○ Parkes
Bandwidth:	100	MHz	100 MHz
Time:	1	seconds	30 minutes
Cadence:			# of obs per year

	Pulsar	Time	T_sys	Bw (MHz)	Gain (K/Jy)	Period (s)	W50 (ms)	S1400 mJy	RMSR (ns)	RMSS (ns)	RMS (ns)	Cadence
1	J0030+0451	1800	10	100	1	0.0048654532073692	0.486545320737	0.6	1683.145	0.0772	1683.145	
2	J0621+1002	1800	10	100	1	0.028853860730049	9.15	1.9	17800.2274	20.8729	17800.2397	
3	J0751+1807	1800	10	100	1	0.0034787707831873l	0.70	3.2	644.0709	14.5123	644.2343	
4	J0900-3144	1800	10	100	1	0.0111096491573889	0.8	3.8	370.8094	0.0227	370.8094	
5	J1012+5307	1800	10	100	1	0.0052557490141l968	0.69	3	546.9965	1.5024	546.9986	
6	J1455-3330	1800	10	100	1	0.007987204796261	0.8	1.2	1384.8598	1.1568	1384.8603	
7	J1600-3053	1800	10	100	1	0.00359792850865547	0.079	3.2	24.0112	112.3385	114.8759	
8	J1640+2224	1800	10	100	1	0.0031633158179138O	0.22	2	190.4067	6.3297	190.5119	
9	J1643-1224	1800	10	100	1	0.0046216415169981 8	0.41	4.8	166.9882	161.828	232.5368	
10	J1713+0747	1800	10	100	1	0.0045701365250827 8	0.14	8	20.1042	1.441	20.1558	
11	J1730-2304	1800	10	100	1	0.0081227980439845 6	1.07	4	637.2536	9.1433	637.3192	
12	J1751-2857	1800	10	100	1	0.003914873196369O	0.391487319637	0.06	13543.0327	24.8463	13543.0555	
13	J1910+1256	1800	10	100	1	0.0049835839397055	0.498358393971	0.5	2068.8131	8.1371	2068.8291	
14	J1918-0642	1800	10	100	1	0.0076458728839088 4	0.74	0.58	2605.2867	9.3062	2605.3033	

$$\sigma_{receiver} = \frac{T_{sys}}{G * S_{1400}} \sqrt{\frac{W_{50}}{P}} * \frac{W_{50}}{\sqrt{B_w * T}}$$

$$\sigma_{Diss} = \frac{\tau_d}{\left(1 + 0.1 * \frac{T_{obs}}{t_d}\right) * \left(1 + 0.1 * \frac{B}{v_d}\right)}$$

$$\sigma = \sqrt{\sigma^2_{receiver} + \sigma^2_{Diss}}$$

Figure 4: The RMS Calculator page of IPTA Bench.

3 RMS Calculator

The RMS (root mean square) calculator computes a statisticial measure of the difference of the actual pulse arrival time of a pulsar from the model pulse arrival times of that pulsar. The smaller the difference, the better one is able to predict the arrival times of a pulsar. In essence, it determines how much noise is introduced to the signal from a pulsar from the point of emission to the point of reception:

$$\sigma \simeq \frac{T_{sys}}{G \times S_{1400}} \times \sqrt{\frac{W_{50}}{P}} \times \frac{W_{50}}{\sqrt{B \times T}}. \tag{1}$$

The formula above is used by the RMS calculator. The user has the option of individually inputting the parameters or using the defaults values listed in the IPTA Bench website. The RMS of a pulsar is labeled as σ.

The RMS of a pulsar depends on the following variables: T_{sys} is the system temperature of the radio telescope, G is the gain of the radio telescope, S_{1400} is the mean flux density of the pulsar measured at 1400 MHz, W_{50} is the pulsar's pulse width half maximum, P is the pulse period, B is the observing bandwidth, and T is the integration time. Optimal results therefore are obtained with sensitive, wide-band systems for bright, short-period pulsars with narrow pulses. The arrival times of individual pulses jitter within the pulse window, the timing of those would result in uncertainties scaling roughly with the pulse width. As each pulsar gives a profile stabilization timescale, a sufficient number of pulses, typically at least a few hundred, need to be added to achieve a stable profile that can be matched to the template. Some other effects not accounted for by the RMS calculator are the effect of the turbulent interstellar medium, where varying pulse scattering and scintillation can broaden the pulse differently for different times [5].

The RMS calculator saves each individual parameter for the list of pulsars the user has chosen. It runs in the background and is calculated in a class where it gathers and saves each individual pulsar parameter. It then runs through the equation stated above. The user can choose individual pulsars by clicking the link of the pulsar's name. At the left in the orange boxes, the pulsar and its parameters will appear, allowing the user to change whatever is needed. At the moment, it only uses default values of three telescopes: Arecibo, Green Bank, and Parkes radio telescope. The user is able to change the telescope parameters to whatever radio telescope they need. Once the user has adjusted the parameters for the specific pulsar chosen, it can be submitted. From there it will re-run the RMS Calculator with the new values and refresh the table to the right.

Telescope Settings

Arecibo	**Obs Frequency:**	1400	MHz	**Bandwidth:**	100	MHz
	Obs Time:	1	seconds	**Gain:**	1	K/Jy
	System Temp:	10	Kelvin	**Cadence:**	56	#Obs per year
Green Bank	**Obs Frequency:**	1400	MHz	**Bandwidth:**	100	MHz
	Obs Time:	1	seconds	**Gain:**	1	K/Jy
	System Temp:	30	Kelvin	**Cadence:**	56	#Obs per year
Parkes	**Obs Frequency:**	1400	MHz	**Bandwidth:**	100	MHz
	Obs Time:	1800	seconds	**Gain:**	0.08	K/Jy
	System Temp:	30	Kelvin	**Cadence:**	56	#Obs per year
Effelsberg	**Obs Frequency:**	1400	MHz	**Bandwidth:**	100	MHz
	Obs Time:	1	seconds	**Gain:**	1	K/Jy
	System Temp:	30	Kelvin	**Cadence:**	56	#Obs per year
Jodrell Bank	**Obs Frequency:**	1400	MHz	**Bandwidth:**	100	MHz
	Obs Time:	1	seconds	**Gain:**	1	K/Jy
	System Temp:	30	Kelvin	**Cadence:**	56	#Obs per year
Nancay	**Obs Frequency:**	1400	MHz	**Bandwidth:**	100	MHz
	Obs Time:	1	seconds	**Gain:**	1	K/Jy
	System Temp:	35	Kelvin	**Cadence:**	56	#Obs per year

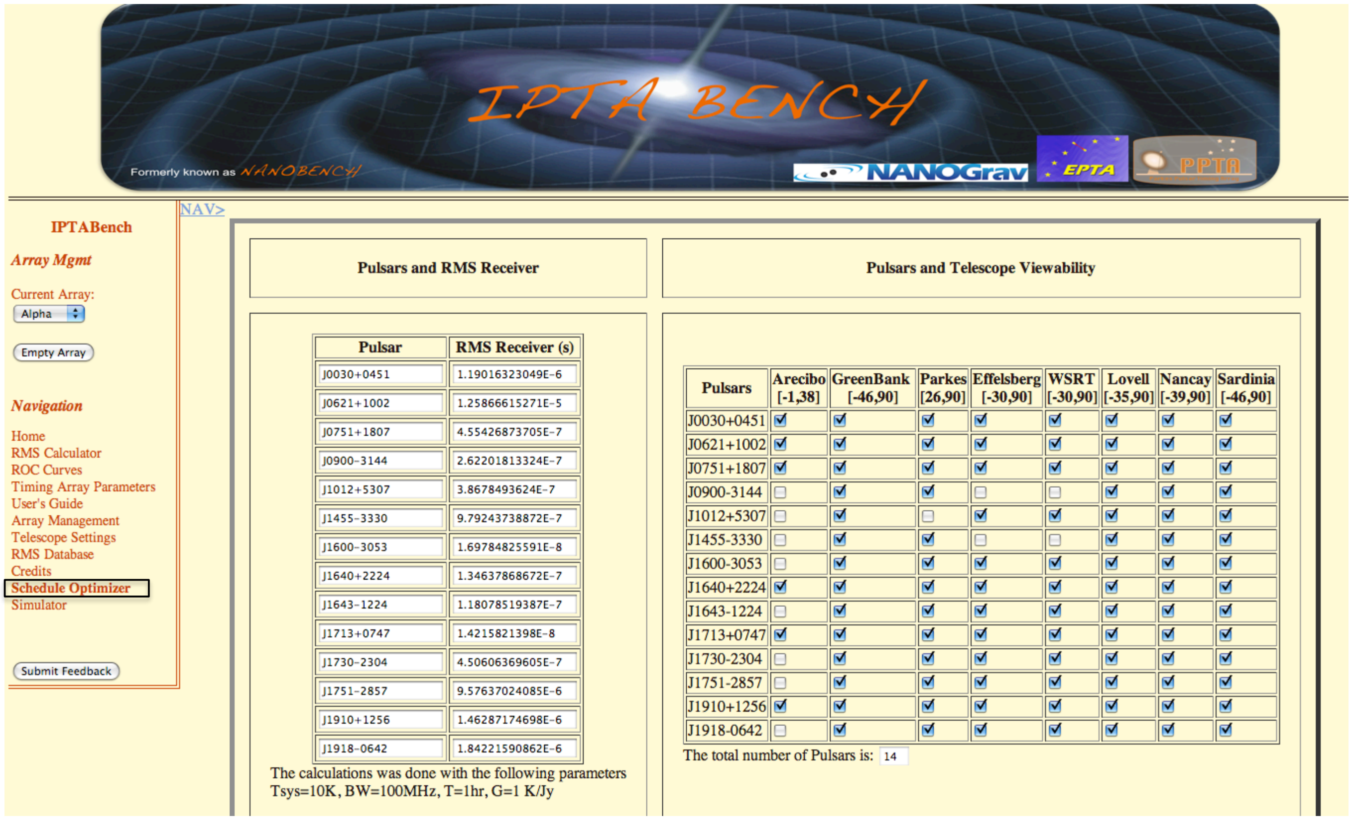
Figure 5: The Telescope Settings page of IPTA Bench.

4 Telescope Settings

The Telescope Settings page is where the parameters of all the current radio telescopes can be set for the calculations run by IPTA Bench. The parameters of each telescope are the following: Observation Frequency (MHz), Observation time (seconds), System Temperature (Kelvin), Bandwidth (MHz), Gain (K/Jy), Cadence (number of observation per year). The radio telescopes listed are: Arecibo, Green Bank, Parkes, Effelsberg, Jodrell Bank, Nancay, Westerbork Synthesis, Sardinia, and Other. In the "Other" section the user can input any specific radio telescope not listed above.

This page is the source of information of all the radio telescopes IPTA Bench uses in its calculations. On this page the user can change any of the listed radio telescope parameters. Once changed, it will save the information during the PHP session for about 24 hours. The user can freely move to other pages of IPTA Bench knowing the parameters they changed in the Telescope Setting page are saved for use in other calculations.

This page is very important for many calculations throughout the entire IPTA Bench website. The user must note that the default values of the radio telescope parameters are generally not true for the user's specific project. This page allows the user to set the parameters for their own project or desire. After making the necessary changes the user can submit their work and be ensured it will be saved during its PHP session. The user should remember that the PHP session is limited to a 24hr time period in the IPTA Bench, and will be cleared once the time expires. Also note that having all these radio telescopes does not mean that every calculation you make throughout IPTA Bench will use all the radio telescopes listed. In all of the other calculations in IPTA Bench the user may leave out or choose specific radio telescopes for their calculations. The long list of radio telescopes in Telescope Settings is just showing all the major radio telescopes it has saved in IPTA Bench.



Current Array: Alpha

Pulsars and RMS Receiver

Pulsar	RMS Receiver (s)
J0030+0451	1.19016323049E-6
J0621+1002	1.25866615271E-5
J0751+1807	4.55426873705E-7
J0900-3144	2.62201813324E-7
J1012+5307	3.8678493624E-7
J1455-3330	9.79243738872E-7
J1600-3053	1.69784825591E-8
J1640+2224	1.34637868672E-7
J1643-1224	1.18078519387E-7
J1713+0747	1.4215821398E-8
J1730-2304	4.50606369605E-7
J1751-2857	9.57637024085E-6
J1910+1256	1.46287174698E-6
J1918-0642	1.84221590862E-6

The calculations was done with the following parameters Tsys=10K, BW=100MHz, T=1hr, G=1 K/Jy

Pulsars and Telescope Viewability

Pulsars	Arecibo [-1,38]	GreenBank [-46,90]	Parkes [26,90]	Effelsberg [-30,90]	WSRT [-30,90]	Lovell [-35,90]	Nancay [-39,90]	Sardinia [-46,90]
J0030+0451	☑	☑	☑	☑	☑	☑	☑	☑
J0621+1002	☑	☑	☑	☑	☑	☑	☑	☑
J0751+1807	☑	☑	☑	☑	☑	☑	☑	☑
J0900-3144	☐	☑	☑	☐	☐	☑	☑	☑
J1012+5307	☐	☑	☐	☑	☑	☑	☑	☑
J1455-3330	☐	☑	☑	☐	☐	☑	☑	☑
J1600-3053	☐	☑	☑	☑	☑	☑	☑	☑
J1640+2224	☑	☑	☑	☑	☑	☑	☑	☑
J1643-1224	☐	☑	☑	☑	☑	☑	☑	☑
J1713+0747	☑	☑	☑	☑	☑	☑	☑	☑
J1730-2304	☐	☑	☑	☑	☑	☑	☑	☑
J1751-2857	☐	☑	☑	☑	☑	☑	☑	☑
J1910+1256	☑	☑	☑	☑	☑	☑	☑	☑
J1918-0642	☐	☑	☑	☑	☑	☑	☑	☑

The total number of Pulsars is: 14

Figure 6: The Schedule Optimizer page of IPTA Bench.

5 Schedule Optimizer

The Schedule Optimizer helps maximize the sensitivity of a pulsar timing array to a stochastic gravitational wave background. It is a series of computational techniques to optimize the observing schedules of a set of pulsars that can be used for single or multiple radio telescopes. The observing schedule is optimized for each telescope by adjusting the observing time allocated to each pulsar while keeping the total amount of observing time constant. The optimized schedule depends on the timing noise characteristics of each individual pulsar as well as the performance of each instrument.

The usage of radio telescope observations will be of importance to the detection of GWs using pulsar timing. Many of the major pulsar timing array groups from around the world ask the question: “how should the observing schedule be arranged to maximize the opportunity to detect GW signals?” The Schedule Optimizer answers this question and allows the user to create an observation schedule for any set of pulsars with any set of single or multiple radio telescopes.

To appropriately use this Schedule Optimizer the user must first choose a set of pulsars at the beginning in the home page of IPTA Bench. Once the user has chosen their list of pulsars they can click the tab called “Schedule Optimizer”. This will display a series of tables. The first two top ones are:

1. Pulsars and RMS Receiver
2. Pulsars and Telescope Viewability

The Pulsars and RMS Receiver displays the pulsar’s name and the pulsar’s white noise RMS level calculated by the parameters in the bottom of the table. The Pulsars and Telescope Viewability table shows all the major radio telescopes and a series of boxes either checked or not checked. If the specific pulsar is checked under a radio telescope it means that the radio telescope can view the pulsar. If not checked it means that the radio telescope cannot view that specific pulsar due to its declination ranges. The user has the option to select a set of radio telescopes or a single radio telescope. This can be done by deselecting the checkboxes of the specific radio telescope the user would like to exclude from their optimized schedule. This is done as soon as you have clicked on the Schedule Optimizer tab and have already chosen a list of pulsars. At the very bottom it has a counter of the total number of pulsars that have been chosen originally.

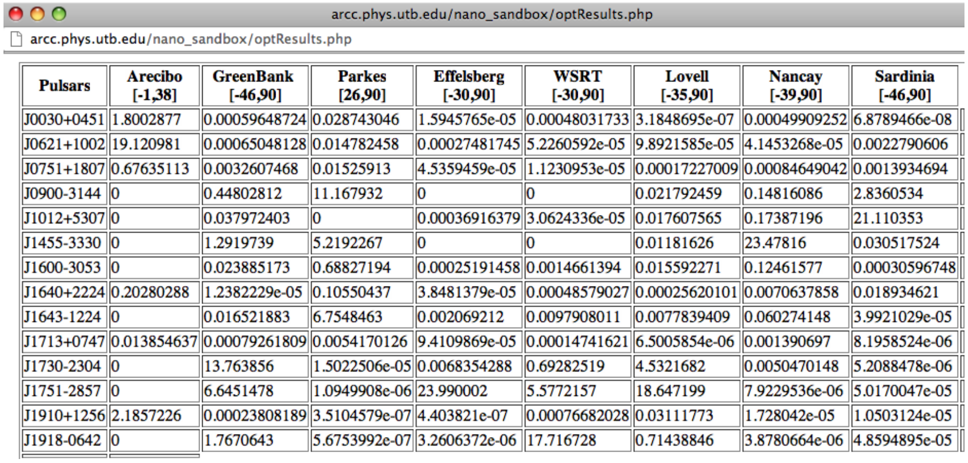
The lower two tables of information in the Schedule Optimizer page are:

1. Observations Interval
2. Telescope and Information

The Observations Interval asks the user what interval (in days) will be used to observe the list of pulsars. The interval can be a fraction in the form of days/week but must be entered as a decimal number on the website. Duration asks how long the observer will be observing the set of pulsars in number of weeks. Lastly it asks what type of GW characteristic strain the user would like to be doing their optimization, the default is 10^{-12} but can be changed.

The Telescope and Information section provides a chance for the user to change specific parameters of a given radio telescope. The parameters that can be changed are Bandwidth (MHz), System Temperature (Kelvin), Gain (K/Jy), Telescope Time (hrs). If the user has deselected a radio telescope in the “Pulsars and Telescope Viewability” they do not have to worry about those telescopes being carried over into the Telescope and Information section. They will not be accounted for in the calculation of the optimization of a schedule.

After all the parameters have been set and the user feels ready to produce an optimized schedule, it can be submitted at the bottom of the page. Depending on the number of pulsars that the user has sent, the website will display a pop-up of an optimized schedule. The numbers give a certain percentage of how much time you should observe a specific pulsar on a specific radio telescope. If the number is about 10^{-4} the user can assume that it would be zero time for the telescope on that certain pulsar. If the number is zero it means that that radio telescope cannot see that pulsar due to its declination range or a radio telescope has been deselected. The figure below shows an example of how the optimize schedule looks.



Pulsars	Arecibo [-1,38]	GreenBank [-46,90]	Parkes [26,90]	Effelsberg [-30,90]	WSRT [-30,90]	Lovell [-35,90]	Nancay [-39,90]	Sardinia [-46,90]
J0030+0451	1.8002877	0.00059648724	0.028743046	1.5945765e-05	0.00048031733	3.1848695e-07	0.00049909252	6.8789466e-08
J0621+1002	19.120981	0.00065048128	0.014782458	0.00027481745	5.2260592e-05	9.8921585e-05	4.1453268e-05	0.0022790606
J0751+1807	0.67635113	0.0032607468	0.01525913	4.5359459e-05	1.1230953e-05	0.00017227009	0.00084649042	0.0013934694
J0900-3144	0	0.44802812	11.167932	0	0	0.021792459	0.14816086	2.8360534
J1012+5307	0	0.037972403	0	0.00036916379	3.0624336e-05	0.017607565	0.17387196	21.110353
J1455-3330	0	1.2919739	5.2192267	0	0	0.01181626	23.47816	0.030517524
J1600-3053	0	0.023885173	0.68827194	0.00025191458	0.0014661394	0.015592271	0.12461577	0.00030596748
J1640+2224	0.20280288	1.2382229e-05	0.10550437	3.8481379e-05	0.00048579027	0.00025620101	0.0070637858	0.018934621
J1643-1224	0	0.016521883	6.7548463	0.002069212	0.0097908011	0.0077839409	0.060274148	3.9921029e-05
J1713+0747	0.013854637	0.00079261809	0.0054170126	9.4109869e-05	0.00014741621	6.5005854e-06	0.001390697	8.1958524e-06
J1730-2304	0	13.763856	1.5022506e-05	0.0068354288	0.69282519	4.5321682	0.0050470148	5.2088478e-06
J1751-2857	0	6.6451478	1.0949908e-06	23.990002	5.5772157	18.647199	7.9229536e-06	5.0170047e-05
J1910+1256	2.1857226	0.00023808189	3.5104579e-07	4.403821e-07	0.00076682028	0.03111773	1.728042e-05	1.0503124e-05
J1918-0642	0	1.7670643	5.6753992e-07	3.2606372e-06	17.716728	0.71438846	3.8780664e-06	4.8594895e-05

Figure 7: An example of what an optimize schedule results looks like.

6 Organization of Code

6.1 Header Files

The header files of IPTA Bench are shown in Fig. 8. The Home Page (index.php) is the starting page of IPTA Bench, the user must start here in order to chose or create a list of pulsars that they will use for all the other applications in IPTA Bench. The files (nanoHeader.php, nav.php, header.php, and nanojava.js) are header files and are connected to all the files below them. The scripts described in the following subsections run underneath all the header files.

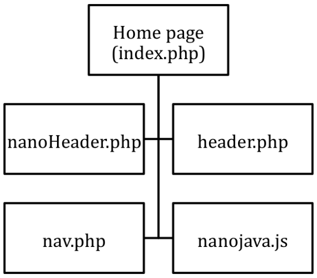


Figure 8: Header files.

6.2 Minimum Detectable Amplitude Files

The scripts for Minimum Detectable Amplitude are shown below in Fig. 9. The main script is minimumDetectableAmplitude.m. It calculates the minimum detectable amplitude for a stochastic GW background with parameters specified in the parameter file, with the help of the following scripts. The routine readParamsFromFile.m reads in parameters from a file, returning them in a structure that is made available to all the other routines. The routine alphaVSthreshold.m calculates the false alarm probability versus threshold for a statistic for an array of pulsars, and the routine gammaVSalpha.m calculates the detection probability as a function of false alarm probability for different amplitudes of a stochastic GW background for an array of pulsars. Another script called gammaVSamplitude.m calculates the detection probability for fixed threshold as a function of the stochastic GW amplitude for an array of pulsars with the help of simulateSB.m which simulates time-series for the GW signal from an array of pulsars having dimensionless characteristic strain. The file simulateSB.m uses scripts: readPulsars.m, which reads and extracts pulsars parameters and radec2HellingDown.m, which calculates the Hellings-Down factors for a set of pulsars. Another routine is simulateWhiteNoise.m, which simulates white noise with zero mean and variance σ_N^2. Both simulations use the routine jenet.m, which calculates value of the statistic in Jenet et. al [4].

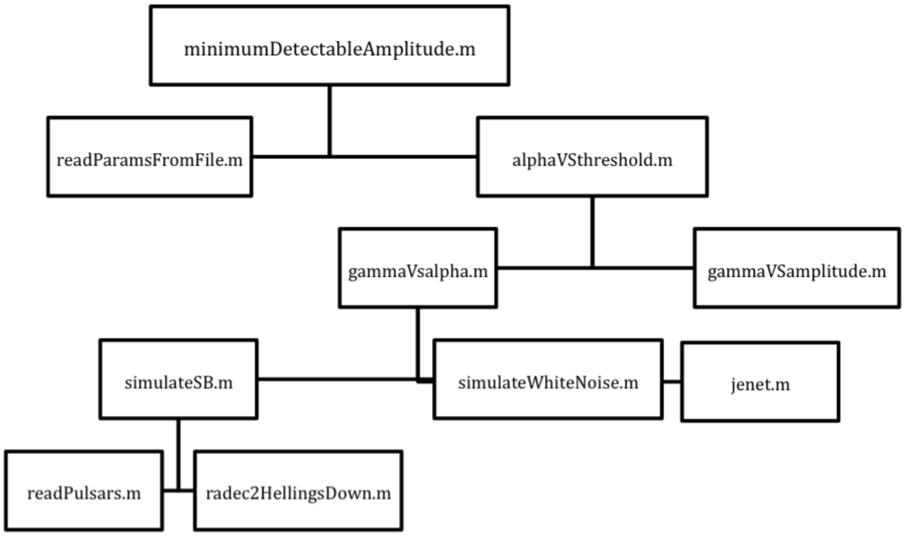


Figure 9: Minimum Detectable Amplitude scripts.

6.3 RMS Calculator Files

The following scripts are for the RMS calculator in Fig. 10. It first starts off with rmsT.php, which shows the front interface page of RMS calculator and lets the user set different values for any specific pulsar. The rmshead.php stores all the pulsar parameters in a php session and the rmsEntry.php takes in any new changes made by the user for changing pulsar parameters. The script tel.php holds the radio telescope parameters and takes them into account when calculating the pulsars' RMS values.

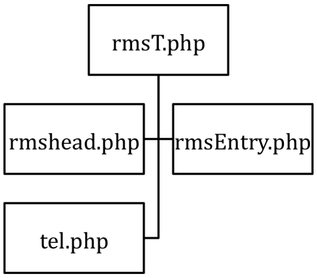


Figure 10: RMS calculator scripts.

6.4 Schedule Optimizer Files

The Schedule Optimizer scripts are shown in Fig 11. It starts with optimizer.php, which displays the front interface for the user to input information for scheduling an optimal observing schedule. Then at the back-end of the page we have OptimizerFileCreator.php, which generates files of the pulsar parameters and telescope view-ability for each pulsar to send to the schedule optimizer generator. The generator is optincoh.exe, which creates the optimized schedule using the files passed to it. This script was written by Dr. K.J. Lee. Lastly there is OptResults.php, which displays the optimized schedule to the user from the optincoh.exe.

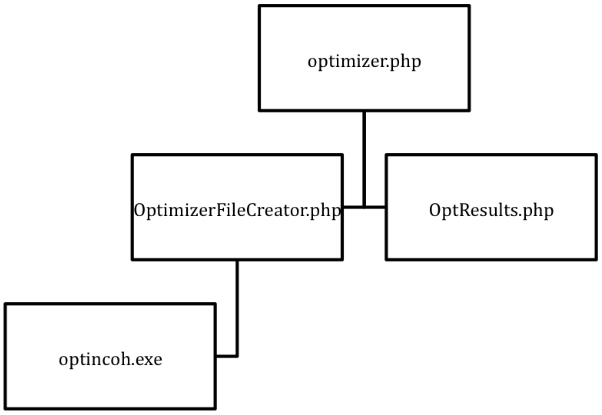


Figure 11: Optimizing Schedule scripts.

6.5 TOA Simulator Files

IPTA Bench already has the environment for the TOA simulator. The TOA simulator in the future will generate simulated times of arrivals of pulsars given by the pulsars parameter files (or par files) of each pulsars. Some of the par files are stored in the IPTA Bench database and are displayed in the front interface of the simulator.php; it allows the user to input information for simulating pulsar TOAs. The routine SimulatorFileCreator.php generates files that are ready to send to a TOA simulator.

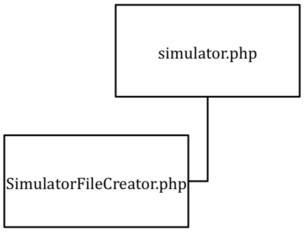


Figure 12: TOA Simulator environment.

6.6 Other Files

These files are separate. Correlation.php calculates and plots the "Hellings and Down Curve" storing the results in the plotdata directory. The routine psrparams.php displays all the information for the set of pulsars. The routine usrguide.php is where a thesis is stored for people to read on how to use IPTA Bench site. The tableMgmt.php creates a table of all the pulsars parameters. There is another environment set-up called RMScal.php, which is left for future workspace for the red noise RMS calculator. Lastly we have the Credits.php, which displays credits of the people involved in the IPTA Bench team.

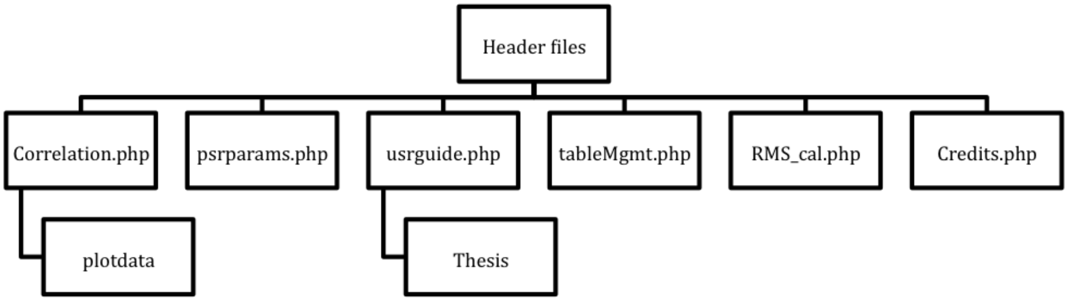


Figure 13: Other files.

7 Conclusions

The IPTA Bench website has many tools for a pulsar astronomer that can be implemented in their research work. The website is available at: `arcc.phys.utb.edu/nano_sandbox/index.php` for anyone to access at anytime. In working on this research project I have learned the amount of effort it takes to detect gravitational waves using pulsar timing techniques. This website resembles others as it is never truly completed. In the future I hope to implement more tools such as a TOA simulator, which will simulate TOAs of specific pulsars selected, and an RMS calculator, for red noise pulsars. I welcome more people to use the site and provide feedback as there is always room for improvement and new developments.

8 Acknowledgment

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