The NANOGrav Glossary

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2D Autocorrelation Function
This typically refers to the autocorrelation of the dynamic spectrum with itself. That is, we shift the dynamic spectrum by some time lag and frequency lag and calculate the overlap between the two. This method allows us to find the characteristic size of the scintles in time and frequency because at very small time lags and frequency lags, we are averaging the structure in all of the scintles together.

Accretion
Accumulation of material onto an object. Old neutron stars begin to accrete from their expanding companions and then pull in material, increasing the mass but more importantly the angular momentum. The neutron star turns back "on" and the radio emission restarts. However, the increased angular momentum turns these once canonical pulsars into highly spin-stable millisecond pulsars.

Advisory Board
The group of external experts tasked with providing guidance on the directions the collaboration should take in the future.

Alternate Theories of Gravity
A theory of gravitation that deviates slightly from Einstein's General Theory of Relativity (GR). While we know that GR breaks down at small scales due to incompatibilities with quantum mechanics, large-scale astronomical tests of GR have consistently held. There are many different formulations for alternate theories of gravity that expand upon GR in some way. Pulsar timing is sensitive to a number of different of these tests.

Antenna Efficiency
The fraction of power lost in your receiving element due to electronic ("ohmic") losses in the element.

Antenna Pattern
For receiving antennas, a map or function describing the dependence of the sensitivity of a telescope on the angle of the incoming radiation.

Antenna Gain
Related to the system equivalent flux density, it is the K/Jy conversion. A higher gain is more sensitive. For example, the Green Bank Telescope has roughly a 2 K/Jy gain for our typical observing frequencies, which means that every Jansky received from a source will increase the

effective temperature of the antenna (compared to the system temperature noise) by 2 K.

Arecibo Observatory (AO)
A 305-meter radio telescope located outside Arecibo, Puerto Rico.

ASP/GASP
Arecibo Signal Processor / Green Bank Astronomical Signal Processor, used historically. See the GUPPI/PUPPI entry for more information. They were able to process 64 MHz of bandwidth.

Aperture Efficiency
The ratio of the effective area of a telescope to the geometric area. That is, there is an effective area that is illuminated on a dish of a certain size that is smaller than the actual size of the dish. Losses in the light can happen from imperfections in the surface of the dish, any support structures that are in the way (e.g., toward the receiver), the non-uniform illumination of light on the dish, etc. For example, at the Green Bank Telescope, this is roughly 75 to 80%.

Astrometry
Measurements of the position and motion of objects. For pulsars, we can measure these parameters from changes in the pulse arrival times and then predict these deviations via a timing model.

Astrophysics Source Code Library
An online registry of code meant for astronomy research. See `ascl.net`.

Astrophysics Working Group
The group in charge of drawing astrophysical inferences from our gravitational wave analyses. They are also in charge of combining information from electromagnetic counterparts to gravitational waves.

Backend
The data recording system that processes the radio signal. See GUPPI, PUPPI and VEGAS for descriptions of some of the backends currently used by NANOGrav.

Bandwidth
The size of the continuous range of frequencies over which our data are taken, calculated as the difference between the the highest and lowest frequencies.

Barycentric Coordinate Time (TCB)
From the French "Temps Coordonnée Barycentrique," this is a relativistic timescale defined as the proper time at the location of the Solar System Barycenter if the gravitational influence of the Sun, planets, and other Solar System objects were not present. That is, it can be viewed as a clock that moves with the Solar System but outside any gravitational well associated with the Solar System. TCB ticks faster than clocks found on the surface of the Earth, and thus there is a

linear transformation between it and TDB and TT.

Barycentric Dynamical Time (TDB)
From the French "Temps Dynamique Barycentrique," this is a relativistic timescale used to take into account time dilation in the reference frame of the Solar System Barycenter. It differs from TCB by a linear transformation. TDB remains close to Terrestrial Time.

Baseband Data
Nyquist-sampled, band-limited data, sometimes called "voltage data". The sample rate is twice the bandwidth of the signal, so this tends to be very voluminous data – data rate is twice the bandwidth times the bit depth (sample size) – but it allows for complete reconstruction/characterization of the original analogue signal. Our data are typically not baseband data, although it is used for some searches (typically checked in real-time and only kept if promising).

Bayes Factor
Comparison of the degree of belief in two hypotheses. When you have no a priori reason to favor one hypothesis over the other, it is equivalent to the odds. Calculated as the ratio of Bayesian Evidence for the two models. Because evidence is so hard to calculate, we often use approximations to the Bayes Factor, such as the "Savage-Dickey Ratio".

Bayes' Theorem
A result of probability theory. Posterior = Likelihood × Prior / Evidence

BayesEphem
Software used to statistically account for the uncertainties in the position of the Solar System Barycenter on our gravitational-wave analyses.

Binary Model
The component of the timing model that describes the orbit of the pulsar and its companion (e.g., a white dwarf). There are many types of models which can be used as approximations of a full description of the motion from General Relativity, for example for systems that are in extremely circular (but slightly offset from circular) orbits.

BIPM
See International Bureau of Weights and Measures (BIPM).

Burn-in
To be added

Burst With Memory (BWM)
Gravitational wave memory is a non-oscillatory, permanent change to spacetime caused by GWs. A burst of oscillatory GWs (for example from SMBHB merger) will produce GW memory. The louder (more energetic) the burst, the bigger the GW memory amplitude. PTAs can detect GW

memory even when the accompanying oscillatory burst is outside of their sensitive frequency range.

C Band
A frequency range covering 4–8 GHz. NANOGrav has started observing one pulsar, PSR J1903+0327, at this frequency band at the VLA.

Canadian Hydrogen Intensity Mapping Experiment (CHIME)
A Canadian interferometer array based on cylindrical telescopes; science carried out there include pulsar timing and Fast Radio Burst (FRB) detections.

Channel
A small frequency range in which you measure a signal. Often your total signal bandwidth is then broken into a number of smaller pieces. See also filterbank.

Chirp Mass
An effective-mass term commonly found in gravitational physics. For two bodies with masses m_1 and m_2, the chirp mass is $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$. For equal-mass binaries, i.e., when $m = m_1 = m_2$, then $\mathcal{M} = m/2^{1/5} \approx 0.87m$. The chirp mass can be related to the reduced mass μ and total mass $M = m_1 + m_2$ by $\mathcal{M} = \mu^{3/5} M^{2/5}$.
For a system of two inspiraling (spiraling towards merger) objects emitting gravitational waves, one can more easily measure the chirp mass of the system than the total mass. Measuring the frequency f of the gravitational wave and then the frequency derivative $\dot{f}$, or how quickly the frequency is increasing, then the chirp mass is related to the two by

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right)^{3/5}.$$

Clock Correction
A modification to be made to the recorded local time to get the "*true*" time.

Common Red Noise
A red-noise process that is common to every pulsar, with the same characteristic amplitude and spectrum.

Container
Akin to a Virtual Machine, this is a lightweight, packaged set of software which can include familiar tools such as Bash, gcc, Python as well as application code. Developed to allow a self-contained environment for running applications without the weight of a Virtual Machine; in particular, Operating System kernel functionality is provided by the Operating System of the host computer. Docker is a particularly popular containerization technology, but others exist such as

Singularity (Singularity can be deployed on conventional shared High Performance Computing resources, unlike Docker).

Continuous Wave source (CW)
A single SMBHB system that produces GWs. Called "continuous" because the system does not noticeably evolve over the 10–20 year timespan of a typical pulsar timing dataset.

Correlation
Qualitatively, how "related" certain quantities are. There are a number of types of correlation. Correlation in time refers to how some measurement is similar to the next measurement. Certain pulsar quantities are correlated in radio frequency. The GW signature in our pulsars will have some correlation in time and in angle on the sky.

Coordinated Universal Time (UTC)
This is the time standard used in civil situations (e.g., denoting time zones) worldwide, adjusted to Greenwich Mean Time (GMT) at the Royal Observatory in Greenwich, London. The abbreviation UTC derives from a compromise combination of "Coordinated Universal Time" (CUT) in English and the "Temps Universel Coordonné" (TUC) in French. It is related to the atomic clock time standard, TAI, by TAI = UTC + ΔT, where ΔT is the number of leap seconds. UTC is one version of Universal Time (UT).

Cosmic String
Cosmic strings are linear topological defects that can form in the early universe as a result of symmetry-breaking phase transitions.

Covariance
A measure of the joint variability of two variables, cf: variance. Whereas the variance of a single random variable is the expectation of the square of the deviations from the mean, the covariance of X and Y is the expectation of the product of their deviations from the mean:

$$\begin{aligned}\mathrm{Cov}(X,Y) &= E[(X-E[X])(Y-(E[Y]))] \\ &= E[XY]-E[X]E[Y]\end{aligned}$$

If the covariance is 0, X and Y are said to be *uncorrelated*. if X and Y are independent, the covariance will necessarily be zero, but the converse is not true. With multiple variables, their covariances may be expressed in a *covariance matrix*.

Cyber-Infrastructure ("Cyber-I")
A term used to describe infrastructure managing a distributed computing environment over the internet (which is a series of tubes). In many cases, it's used as a general-purpose term to describe computing resources and frameworks (which are often distributed).

Cyber-Infrastructure Working Group

The group in charge of implementing hardware and software solutions to various NANOGrav activities. They are also in charge of data handling from the telescope to backed-up storage, and making the data available for processing on a variety of platforms including the Jupyter Notebook environment.

Cyclic Spectroscopy
A method of analyzing random signals in data that contain periodicities, such as is true with pulses from a pulsar. The practical application of this technique is to remove the effect of pulse scattering due to the interstellar medium, thereby producing a narrower pulse that is not broadened. While this has been shown to not be useful except for a small number of pulsars, another practical application is to resolve scintles in dynamic spectra in the cases when they are smaller than the typical range of a frequency channel.

DE405
Jet Propulsion Laboratory (JPL) Developmental Ephemeris 405.

DE421
Jet Propulsion Laboratory (JPL) Developmental Ephemeris 421.

DE430
Jet Propulsion Laboratory (JPL) Developmental Ephemeris 430.

DE435
Jet Propulsion Laboratory (JPL) Developmental Ephemeris 435.

DE436
Jet Propulsion Laboratory (JPL) Developmental Ephemeris 436.

DE438
Jet Propulsion Laboratory (JPL) Developmental Ephemeris 438.

Declination (Dec)
See Equatorial Coordinates.

Design Matrix
A matrix of independent quantities/variables describing the "design" of your model. In a general context, your data y_i (i representing each data point) is described by a model m_i plus noise ϵ_i, or $y_i = m_i + \epsilon_i$. The model has some number of parameters. We can decompose this into a matrix formalism to separate out the parameters of the model:

$$y_i = \sum_{j=1}^{k} X_{ij}\theta_j + \epsilon_i, \quad i = 1, \ldots, n.$$

There are n data points and k parameters, with the parameters labeled with the index j. In matrix notation, this is

$$\mathbf{y} = \mathbf{X}\boldsymbol{\theta} + \boldsymbol{\epsilon}.$$

The matrix $\mathbf{X}$ is the design matrix and $\boldsymbol{\theta}$ is the parameter vector.

As an example, imagine a timeseries of data y_i, taken at times t_i, that is modeled as a parabola, i.e.,

$$y_i = \left(\theta_1 + \theta_2 t_i + \theta_3 t_i^2\right) + \epsilon_i,$$

where the terms in the parentheses model the parabola. Note that even though the model is nonlinear in the independent variable of time t_i, is is linear in the parameters θ_j.

The design matrix is

$$\mathbf{X} = \begin{bmatrix} 1 & t_1 & t_1^2 \\ 1 & t_2 & t_2^2 \\ & \vdots & \\ 1 & t_n & t_n^2 \end{bmatrix}$$

while the parameter vector is

$$\boldsymbol{\theta} = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}.$$

De-dispersion
Removing the effect dispersion on our pulses. With some estimate of the dispersion measure and the amplitude of the time delays from it as a function of frequency, we apply the inverse time shift so that we obtain an estimate of the broadband pulse as it was emitted.

Detection Working Group
The group in charge of running the various gravitational-wave detection analyses.

Differential Galactic Rotation
The fact that the rotational velocity ω is not constant along a radial line drawn through the galactic disk.

Director's Discretionary Time (DDT)
An observing proposal that is submitted at any time rather than during a call for proposals. They are not reviewed by a TAC but rather by observatory staff. There are a number of possible reasons to submit a DDT, such as observations that need to be rapidly carried out because of their time-varying nature.

Dispersion Measure (DM)
The integral of the free electron density n_e along the line of sight, $\mathrm{DM} = \int_0^L n_e(l)\, dl$. The TOAs are delayed as a function of frequency as ν^{-2} (the "dispersive delay"), so lower frequency/longer wavelength emission arrives later. The higher the DM is, the more the TOAs are delayed. We

correct for the effect of DM by "referencing" TOAs to "infinite frequencies", in which the delay would be zero. The typical units are pc cm^{-3}.

DMX
A model for dispersion measure in which we assume that the DM is constant over very small times (e.g., a few days). Observations at different frequencies taken on different days are then assumed to have the same DM which can then be fit for.

Docker
A particular containerization technology (see Container). Docker software runs on Linux, Windows and Mac OS computers, and of particular convenience is that Linux Docker containers can now be run on Windows and Mac hosts. The NANOGrav container contains all of our software, and includes a Jupyter Notebook server.

Document Database
A document repository for NANOGrav, located at `http://docdb.nanograv.org` (NANOGrav login currently required). Includes posters, images, templates and other NANOGrav-related materials.

Dropout Analysis
A method of determining which pulsars contribute significantly to a GW search by removing individual pulsars one at a time.

DSPSR
A Digital Signal Processing package for pulsar astronomy. Amongst other features, allows for the folding of baseband or other time-series data. `https://sourceforge.net/projects/dspsr/`.

Dynamic Spectrum
The pulse intensity as a function of time and frequency. A number of parameters describing the interstellar medium along the line of sight can be obtained through analyses of a dynamic spectrum and of follow-up data products.

Ecliptic Coordinates
A coordinate system in the reference frame of the Ecliptic, which is the plane of the Solar System. The ecliptic longitude and latitude are often denoted as (λ, β), where $\beta = 0$ means that an object on the sky is in the same plane as the planets orbiting around the Sun. For pulsar observations, we now fit in these coordinates as there is less covariance between fitting these parameters in the timing model than when fitting in equatorial coordinates.

ECORR
An error added in quadature (adding the squares of values together) to the template-fitting error, similar to EQUAD, except that it is an error that is correlated between frequency channels. For a template-fitting error due to finite S/N, $\sigma_{\mathrm{S/N}}$, then the rescaled TOA uncertainty is then $(\sigma^2_{\mathrm{S/N}} +$

$J^2)^{1/2}$, where J is the ECORR, but again recall that there is a correlation among frequencies not shown here.

Education and Public Outreach Working Group
The group in charge of developing and executing outreach efforts, largely towards the public but also towards other scientists not affiliated with NANOGrav.

EFAC
An error that multiplies the template-fitting error. That is, for a template-fitting error due to finite S/N, $\sigma_{\mathrm{S/N}}$, then the rescaled TOA uncertainty is then $(F\sigma_{\mathrm{S/N}}$, where F is the EFAC. Note that in some instances in the literature, EFAC does not multiply the template-fitting error alone but multiplies the quadrature (adding the squares of values together) sum of the template-fitting error, the EQUAD, and the ECORR.

Electron-density Wavenumber Spectrum
This represents the power spectrum of electron density $P_{\delta n_e}(q)$, typically in angular wavenumber q. Wavenumbers are related to the inverse length scale by $q = 2\pi/l$. Over many orders of magnitude, the spectrum can be described as a power law, often parameterized as $P_{\delta n_e}(q) = C_n^2 q^{-\beta}$, where C_n^2 is the amplitude of the power law and β is the spectral index. For a Kolmogorov Medium, $\beta = -11/3$. This spectrum results in DM variations in time with a power spectrum with power-law $\beta - 1 = -8/3$.

Emission Measure (EM)
The integral of the free electron density squared along the line of sight, $\mathrm{EM} = \int_0^L n_e^2(l)\, dl$. Typically we measure this from Hα emission. Combined with measurements of DM, we can obtain information about the clumping of material along the line of sight. The typical units are pc cm^{-6}.

ENTERPRISE
Enhanced Numerical Toolkit Enabling Robust PulsaR Inference SuitE. A software package used in detection and some noise analyses. Enterprise is a toolkit providing the pieces needed to construct our models for GW and noise processes. Enterprise constructs likelihood and prior functions that can then be used in Bayesian (or other) data analysis. Get the code here: `https://github.com/nanograv/enterprise`.

Ephemeris
A generic term meaning the model for the orbit of an object. It is often used with respect to the model of the planet orbits but can also be used to describe the pulsar parameters in a par file.

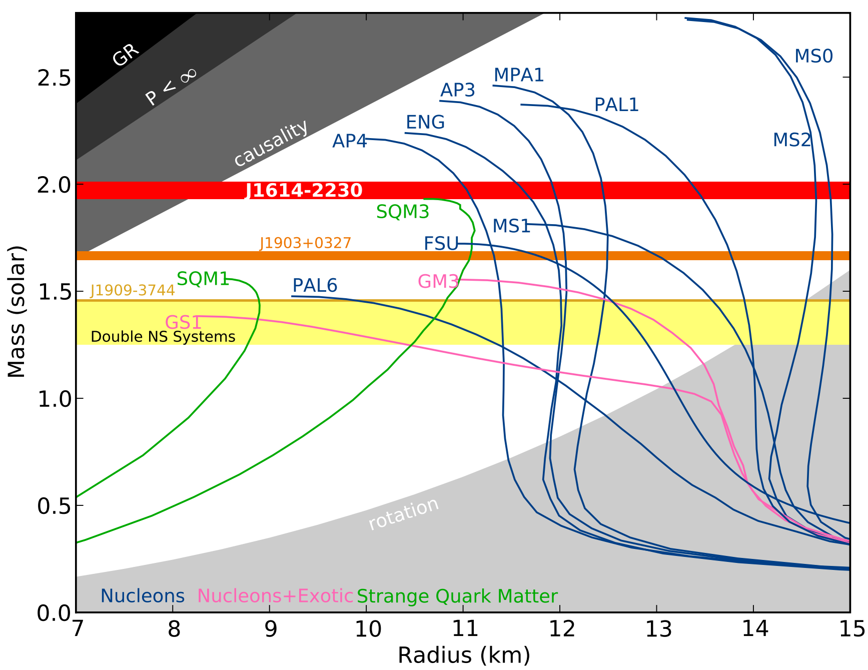
EPO
Education and Public Outreach, see more about the Education and Public Outreach Working

Group.

Epoch
One "observation". This is used interchangeably to mean one literal observation, or sometimes combining multifrequency data on separate days into one effective day.

EQUAD
An error added in quadature (adding the squares of values together) to the template-fitting error, that is, for a template-fitting error due to finite S/N, $\sigma_{\mathrm{S/N}}$, then the rescaled TOA uncertainty is then $(\sigma_{\mathrm{S/N}}^2 + Q^2)^{1/2}$, where Q is the EQUAD.

Equation of State
For astronomical bodies, this is typically expressed in terms of how the mass of an object is related to the radius of the object (more fundamentally, the pressure and density). Neutron stars are excellent laboratories for nuclear physics because we need extreme physics to explain how we observe very massive, very compact objects. Pulsar timing provides precision measurement of pulsar masses while instruments like NICER will be able to precisely measure the radii of neutron stars, thus telling us about the equation of state and the internal composition of neutron stars.



The mass-radius relation showing different classes of theories (lines) and the observations that rule them out. While another more massive pulsar is known currently (PSR J0348+0432) than what is shown on this plot (this plot displays the different classes of theories more succinctly), PSR J1614-2230 is a pulsar with a mass just under 2 solar masses and rules out neutron stars with either exotic matter (pink lines) or strange quark matter (green lines) in the cores since the physics suggests that they cannot "support" such a massive neutron star from collapsing in on itself due to the strength of gravity. Figure from Demorest et al. (2010).

Equatorial Coordinates

A coordinate system as a projection of the Earth's longitude and latitude onto the sky, where the "right ascension" (RA) is analogous to the longitude and the "declination" (dec) is analogous to the latitude. These symbols vary but often are represented by (α, δ). A declination of 0° is equivalent to the Celestial Equator, which is the circle in the sky found by taking the Earth's equator and expanding it out into space. A declination of $+90^\circ$ is the direction of the Celestial North Pole, which can be found if you take the Earth's North Pole and point it straight out into the sky. Similarly, a declination of -90° is the direction of the Celestial South Pole.

Right ascension is often measured in units of "hour angle", of which there are 24 hours (24 hours of angle covering a 360 degree circle means 1 hour of angle is 15 degrees). Declination is often measured in degrees between $\pm 90^\circ$. For a telescope on the ground, because the sky rotates overhead, all RAs are typically visible but the declination range is fixed. For Arecibo, for example, the declination coverage is between $-1^\circ < \delta < 37.5^\circ$ and so can only see sources within that range.

Equity and Inclusion Committee

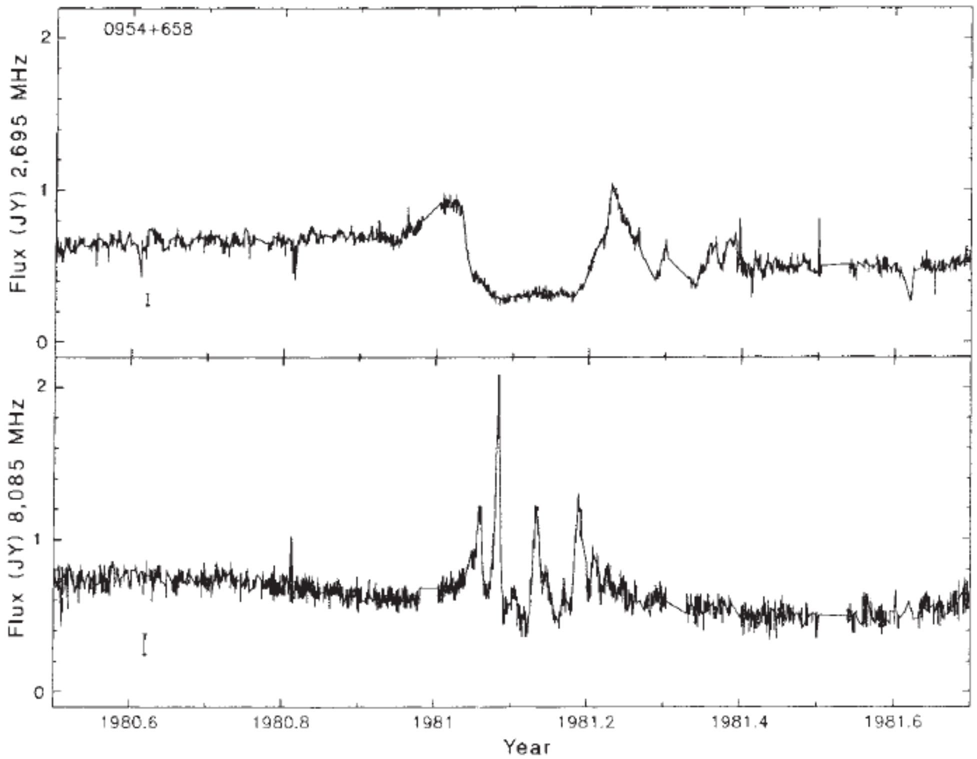
The group in charge of developing new strategies to advancing equity, diversity, and inclusion within the collaboration.

Evidence

Sometimes called Bayesian Evidence or Marginal Likelihood. The normalization factor for the Posterior. Very difficult to calculate in parameter spaces with more than a few dimensions.

Extreme Scattering Events

Events seen in timeseries of fluxes, arrival times, scintillation parameters (e.g., scintillation bandwidth/scintillation timescale), etc. They are likely due to some refraction in the interstellar medium due to a "lensing" structure crossing the line of sight.



The original extreme scattering event from Fiedler et al. (1987), seen in the changing flux density of a quasar.

$\mathcal{F}_e$ Statistic
To be added

$\mathcal{F}_p$ Statistic
To be added

False Alarm Probability (FAP)
To be added

False Negative
To be added

False Positive
To be added

Fast Radio Bursts (FRBs)
A short duration (∼milliseconds), very energetic flash of radio emission. These were originally detected in pulsar surveys and were found to be of extragalactic origin. Since then we have found some which have repeated and one which has been localized to a dwarf galaxy (FRB 121102). While official NANOGrav activities does not specifically support FRB research, because of the

long connection with pulsar timing personnel, many members of NANOGrav also work on FRBs. They may be useful analogues to understanding the pulsar emission mechanism and their propagation through the intergalactic medium parallels the processes of propagation through the interstellar medium.

FD Parameters
A model of time delays that are supposed to account for the fact that pulse profiles change shape (evolve) as a function of frequency. They are defined so that the time delay as a function of frequency ν is a polynomial in log-frequency, i.e., $\Delta t(\nu) = \sum_i \mathrm{FD}_i \log(\nu)^i$, where $\log$ is the natural log.

Feed
The part of instrumentation which channels incoming radio waves to the rest of the instrument, terminating at the frontend.

Final Parsec Problem
The problem of how SMBHB's separation gets smaller than about a parsec, into the separation regime of about a tenth of a parsec or smaller, where gravitational waves can drive the eventual coalescence of the binary. Various proposed solutions exist, primarily involving interactions with the contents of the host galaxy.

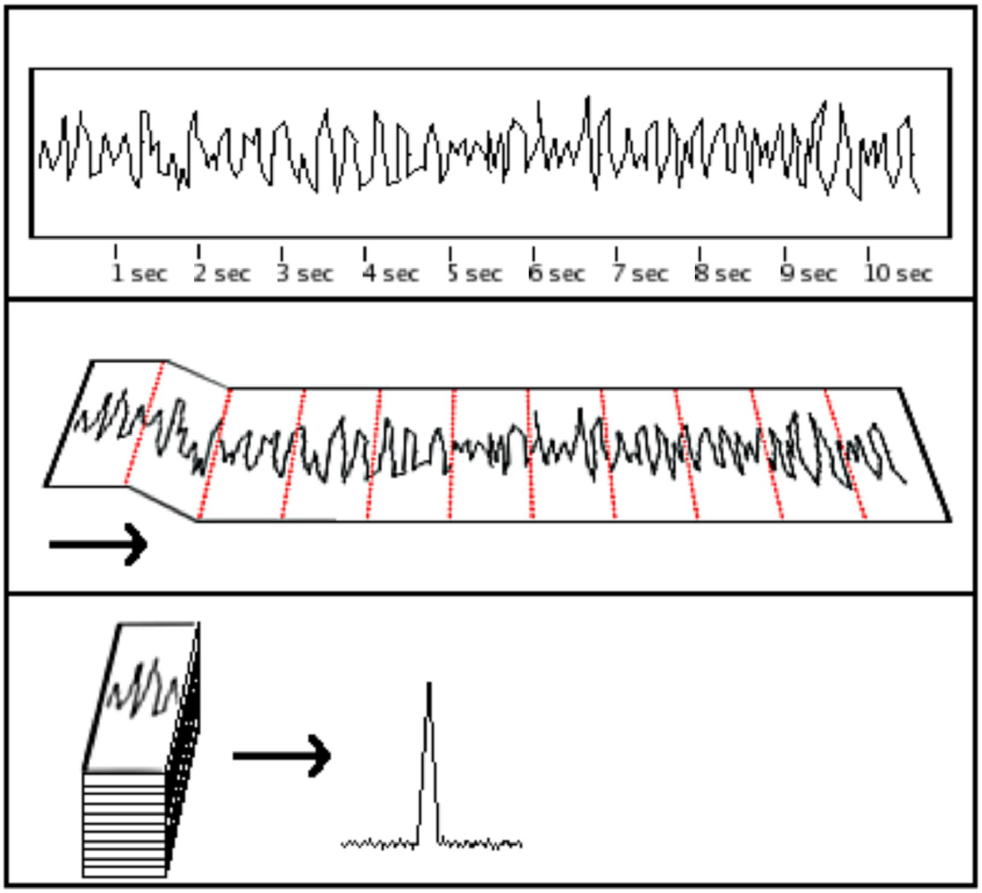
Fermi Gamma-ray Space Telescope
A space-based telescope which observes in the gamma ray portion of the electromagnetic spectrum. For NANOGrav, Fermi sees point sources of gamma rays on the sky, which provides a "treasure map" to finding potential pulsars to add to our array. Put another way, instead of surveying the sky blindly, we can point our radio telescopes more directly to these sources to find pulsars.

Filterbank
A filter array which produces channelized data made up of frequency subbands, often called *filterbank data*.

Flux Density
Most fundamentally, the amount of flux through some area. In astronomy generally, we often take this to mean the amount of power output over some area (for example, the average solar energy reaching the top of Earth's atmosphere is 1360 watts per square meter, or W m^{-2}). In radio astronomy, we use this term to mean the "spectral flux density", which then is the power output over some area and in some frequency range, so for example in units of watts per square meter per hertz (W m^{-2} Hz^{-1}). The typical unit we use is called the Jansky. Sometimes we shorten this term simply to "flux" although this is not technically correct.

Folding

Dividing up a time series into fixed time periods (say, the period of a pulsar) and then aligning them all and adding all the signals (so that the nth sample in each period is added together. This will increase the signal-to-noise of a signal which reoccurs at the time period chosen (or, to a lesser extent, at a multiple of that time period. With many folds, the pulse profile is stable despite highly variable appearance in individual pulse periods).



Conceptual illustration of folding on a pulsar period of 1s. Note how individual second's worth of data are dominated by noise, which is beaten down by the folding while the pulse becomes more prominent

Free-spectral Model
A red noise model that makes no assumption about the shape of the red noise power spectral density. This is the most agnostic noise model we use.

Frequency Allocation
The International Telecommunications Union helps decide which radio frequency ranges are used for what purposes. Only several small ranges are protected for radio astronomy, which means that radio frequency interference can affect a whole radio band if not properly taken care of. Other

allocations include wifi, radio stations, television, airplane communications, etc.

Frontend
The instrument that receives (the "receiver") the radio signal, and includes filters and mixer.

Fuzzy Dark Matter
To be added

Gain
See Antenna Gain.

Galactic Coordinates
A coordinate system in the reference frame of the Galactic plane. The Galactic longitude and latitude are often denoted as (l, b), where $l = 0$ points in the direction of the Galactic center and $b = 0$ means that an object on the sky is in the same plane as the Milky Way/Galactic plane. In the context of pulsars, we often convert to Galactic coordinates in order to place where our objects are in relationship to other pulsars or material in the Galaxy.

Gaussian Process
A method of smoothly modeling a series of data. More formally, it is a collection of random variables where any finite set of them have a joint Gaussian distribution.

General Relativity
Einstein's geometrical description of gravity. This describes the curvature of spacetime due to masses and then how those masses move because of the curvature of that spacetime.

Ghost Image
An artifact in data from pulsar backends due to interleaved samplers (analog-to-digital converters, or ADCs) that are not perfectly synced and have different gains. The "image" appears as the recorded signal (multiplied by a small system-dependent factor) that has been reflected around the center observing frequency prior to dedispersion/folding, etc. The artifact is worst for very strong, low-DM pulsars. First removed from GUPPI/PUPPI data in the 12.5 year dataset.

Giant Pulses
In some pulsars, we see very bright, very sharp emission that is not necessarily at the usual rotational phase of the pulses we typically see. They happen infrequently and the brighter giant pulses usually happen even more infrequently.

Globular Cluster
A gravitationally-bound star cluster orbits a galaxy's center. Typically consisting of old stars in a relatively dense configuration, stars within the cluster often undergo partner- and satellite-exchange. Because of their age, several globular clusters are known to host many millisecond

pulsars.

Green Bank North Celestial Cap (GBNCC) Survey
One of the main pulsar surveys performed at the Green Bank Observatory. Originally it started looking for pulsars not in the Galactic plane but at the North Celestial Pole but has since moved down to lower declinations.

Green Bank Observatory (GBO)
A 100-meter fully-steerable radio telescope located in Green Bank, West Virginia. It is located in the United States National Radio Quiet Zone.

Gravitational Wave (GW)
The stretching and compressing of spacetime, which propagates as a wave and are caused by accelerations of very compact, massive objects (including SMBHs orbiting each other).

GUPPI/PUPPI
Green Bank Ultimate Pulsar Processing Instrument / Puerto Rican Ultimate Pulsar Processing Instrument. These are the current (started recording in 2014/2015 for GUPPI/PUPPI) data recording (backend) instruments at Arecibo and Green Bank, respectively. They are made up of analog to digital converters (ADCs, also known as samplers), field programmable gate arrays (FPGAs), and computer servers with graphical processing units (GPUs). GUPPI/PUPPI are capable of recording data in multiple modes, but for NANOGrav observations they sample, coherently dedisperse, and fold the incoming data using the observed pulsar's par file across up to 800 MHz of bandwidth.

GW Memory
Non-oscillatory GWs that cause a permanent change to spacetime as they pass by. GW memory is non-linear effect. It can be thought of as the GWs produced by the usual oscillatory GWs. The amplitude of GW memory is related to the energy of oscillatory GWs that produces it.

Hellings and Downs Curve
As a gravitational wave passes by the Earth, pulses will arrive early or late depending on whether space has compressed or stretched. If there are several pulsars in exactly the same direction in the sky, then all of the pulses from those pulsars will arrive early or late, and thus the arrival times are correlated. If the pulsars are not exactly in the same direction in the sky, but are separated by some angle, then the Hellings and Downs curve describes how correlated we expect the arrival times to be as a function of that angle.

Hertz
The standard unit of frequency. One hertz (Hz) is equal to one cycle per second. NANOGrav observes gravitational waves in the nanohertz to microhertz range, or with periods of about months to decades. A wave with a frequency of one nanohertz has a period of about 31 years.

Note that as with the standard unit, "nanohertz" is written without a capital H. The N is only capitalized at the start of a sentence or in an acronym as with "NANOGrav." As with other metric units, a lowercase n is attached to the symbol so that it is written as “nHz.”

Hyperparameters
To be added

International Atomic Time (TAI)
From the French “Temps Atomique International,” this time standard is derived from measurements of over 400 atomic clocks worldwide. The clocks are compared with GPS signals and a weighted average is taken so that the time standard is more accurate than any one atomic clock. It is related to Terrestrial Time by TT = TAI + 32.184 seconds. It is related to Coordinated Universal Time by TAI = UTC + ΔT, where ΔT is the number of leap seconds.

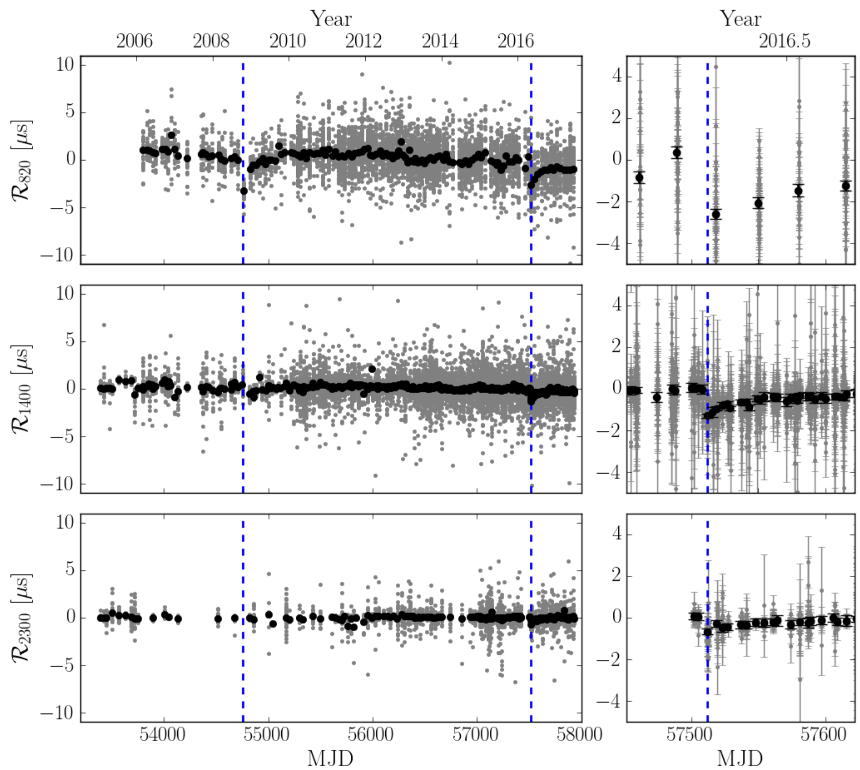
International Bureau of Weights and Measures (BIPM)
From the French “Bureau International des Poids et Mesures,” this is an organization that coordinates the system of measurements throughout the world. In our context, we use Terrestrial Time clock standards as realized by BIPM. For example, in NANOGrav’s 12.5-year data release with a cutoff of mid-2017, we use TT(BIPM2017).

International Pulsar Timing Array (IPTA)
The international consortium of other pulsar timing array consortia. Currently it is composed of the European Pulsar Timing Array (EPTA), the Parkes Pulsar Timing Array (PPTA), and NANOGrav. We are working towards a new framework to include the Chinese Pulsar Timing Array (CPTA), the Indian Pulsar Timing Array (InPTA), and a South African Pulsar Timing Array via MeerKAT.

Interstellar Medium (ISM)
The material of particles, gas, and dust, between stars. The portion of the ISM we care about are the free electrons because of the dispersive delay (see dispersion measure) along with other effects due to radio propagation through the medium.

International Research Experiences for Students (IRES)
A National-Science-Foundation-funded grant to support international research opportunities for students. Currently through IRES, NANOGrav sends students to China, India, and South Africa as part of IPTA development activities.

“ISM Events”
Seen in the arrival times for PSR J1713+0747, we have detected two rapid changes in the TOAs due to some structure in the interstellar medium. They are consistent with a plasma lens.



The residual timeseries for PSR J1713+0747 as a function of frequency band. Besides the frequency-independent timing model, only a mean DM has been removed. The rapid variations are denoted by the blue dashed lines and are more easily seen in the 820 MHz band though can be seen in all three bands in the zoomed-in panels at right. Black points denote the residuals averaged over a single epoch.

Jansky (Unit)
A unit of flux density equal to 10^{-26} W m^{-2} Hz^{-1}. Many of our pulsars have millijansky (mJy) flux densities.

Jitter
While the average pulse shape of a pulsar is very stable, each single pulse varies; this is jitter. We have to account for this as an additional error when calculating our TOAs.

Jump
A time (or phase) offset between TOAs, for example between two backend recording devices or between two telescopes where the absolute time difference is not known.

Jupyter Notebook

See Notebook.

Keplerian Parameters
The components of the binary model that describe the first-order motion of a pulsar and companion (e.g., a white dwarf) orbiting around each other.

Kolmogorov Medium
A description of the type of turbulence seen. In our work, we use this as a descriptor of the ISM.

L Band
A frequency range covering 1400 MHz, or more notable, 1420 MHz where atomic hydrogen is seen.

Leap Second
A one-second adjustment to UTC which tries to keep the time measured by atomic clocks (TAI) in sync with solar time as measured by UT1. Otherwise, the slowdown of Earth's rotation would cause noon to drift with respect to seconds as derived from atomic clocks.

Likelihood
The probability that you would observe the data you did, assuming your hypothesis is true. This sounds backwards, but in practice it is easier to calculate the likelihood than directly calculating the posterior. The likelihood is used in both Bayesian and Frequentist data analysis.

Management Team (MT)
The group of senior personnel within NANOGrav whose task is to lead collaboration members, plan future activities for the collaboration, and more. Consists of PFC Director and co-Director, any other PIs (principal investigators) of significant NANOGrav grants, a Chair and four other members elected for two-year terms by vote of all of the full members of NANOGrav. Each year two MT positions come up for election.

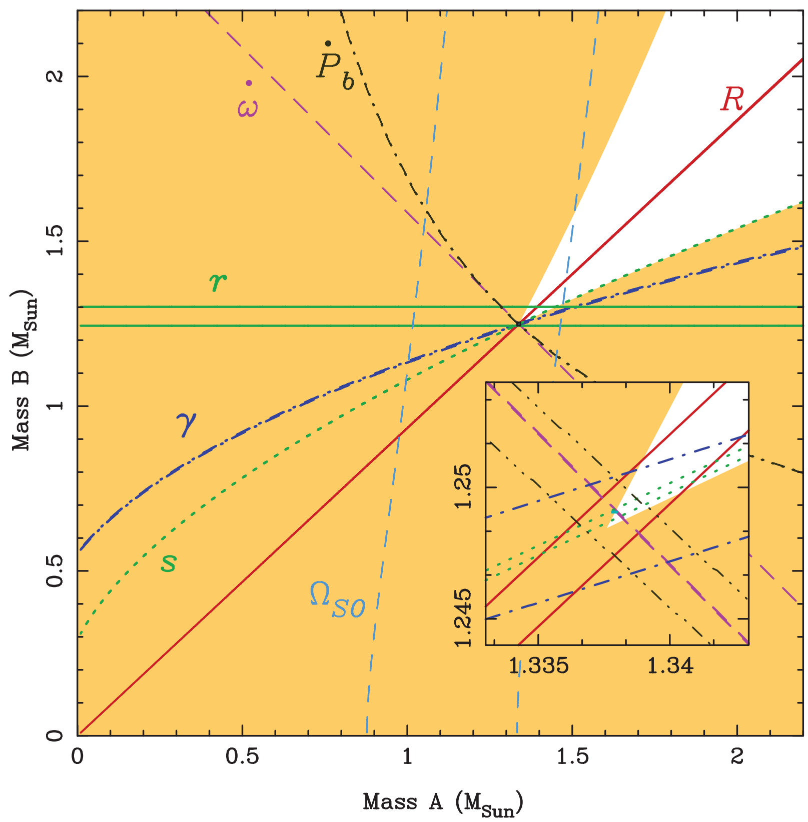
Markov Chain Monte Carlo (MCMC)
A type of sampler. Calculates samples from the posterior distribution in a way that only uses the likelihood and prior functions. Useful because the hard to calculate evidence is not needed.

Mass Function
Related to Newton's formulation of Kepler's Third Law, the mass function describes the minimum mass of a binary companion through measurements of basic Keplerian orbital parameters and an assumption about the mass of the neutron star. For a circular orbit, the mass function is

$$f(m_1, m_2) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_b^2}.$$

Therefore, given a measure of the orbital period P_b and the projected line-of-sight semi-major axis $a \sin i$, and assuming a standard pulsar mass m_1 of 1.4 solar masses, we can estimate the minimum mass (assuming an inclination of $i = 90°$, or an edge-on orbit) of the binary companion, m_2.

Mass-Mass Diagram
A plot of the primary mass versus companion mass. While two post-Keplerian parameters can constrain the masses, three or more can offer tests of the consistency of General Relativity and of alternate theories of gravity.



Mass-mass diagram for the Double Pulsar, PSR J0737–3039 A/B. Post-Keplerian parameters (and derived parameters) are shown and any theory of gravity must lie within the small teal region shown in the inset where all curves overlap. Figure from Berti et al. (2015), courtesy M. Kramer.

Mass Ratio
For two masses m_1 and m_2, the mass ratio is defined as $q = m_1/m_2$. We typically define $q \leq 1$.

Maximum Likelihood Estimator (MLE)
To obtain the best estimate of the parameters that describe a model, we calculate the likelihood and for whatever values of the parameters that maximize the likelihood, we say that those are the best estimates.

Metaparameters

To be added

Mid-Scale Innovations Program in Astronomical Sciences (MSIP)
A National-Science-Foundation-funded program to support "mid-scale" programs in astronomy within a cost range of up to tens of millions of dollars.

Millisecond Pulsar (MSP)
A pulsar which has been "spun up" by accumulating material from a companion star; this process is sometimes called "recycling". Rotation period is typically a few milliseconds and is more stable than that of a non-recycled pulsar (which are sometimes called "canonical pulsars").

Model 2A
A model for testing red-noise in our data, introduced in our 11-year stochastic background paper (Arzoumanian et al. 2018). It assumes that there is intrinsic red noise per pulsar and an uncorrelated common red-noise process per pulsar.

Model 3A
A model for testing red-noise in our data, introduced in our 11-year stochastic background paper (Arzoumanian et al. 2018). It assumes that there is intrinsic red noise per pulsar and a quadrupolar Hellings-Downs correlation indicative of a gravitational wave signal. When compared against Model 2A, this is a measure of the signal-to-noise ratio.

Mueller Matrix
A representation of how the receiver alters the intrinsic Stokes parameters and thus must be corrected for. If the Mueller Matrix is known, polarization calibration can be performed by multiplying the Stokes parameters as measured by the telescope by the inverse of the Mueller Matrix.

Multi-Messenger Astronomy
Astronomy conducted using more than one *messenger* carrying information from astrophysical sources, where messengers include photons, gravitational waves and particles such as neutrinos.

nanopipe
A pipeline script for taking raw pulse profiles, applying calibrations, cross-correlating with templates, then outputting TOAs. Post-nanopipe, further processes are applied, such as discarding TOAs with signal-to-noise below a threshold.

Neutron Star
A stellar remnant left behind by higher-mass stars. Rapidly spinning ones with radiation beams are known as pulsars.

Neutron Star Interior Composition Explorer (NICER)
An X-ray observatory attached to the International Space Station. Its primary mission to measure the radii of neutron stars. In combination with mass measurements that NANOGrav and other

groups can make, we can constrain the Equation of State of neutron stars, thereby understanding their internal composition.

nmodel
To be added

Noise Budget Working Group
The group in charge for characterizing the noise properties of each pulsar line of sight. From there, they use that information to try to predict future pulsar performance, including those being added to the array, and to optimize the array. They are also in charge of understanding how to mitigate the effects of the interstellar medium.

Noise Dictionary
To be added

Noise Model
In addition to the timing model, we incorporate a description of all of our sources on uncertainty into our modeling.

Noise Temperature
The temperature of a hypothetical resistor that would cause an equivalent amount of noise to that which is observed. Commonly used in radio astronomy to compare noise contributions from various sources. Noise temperatures from components can be *summed* to create a system temperature.

Notebook
A web-accessible interface which allows code to be written in the web page and then run though an interpreter, with the subsequent output displayed; for NANOGrav, the Notebooks are set up for Python 3 and also Python 2, and have accessible to a variety of compiled code via Python bindings. This technology is sometimes referred to as "iPython Notebooks" but is now subsumed into the more general Jupyter project. Available at `https://notebook.nanograv.org`.

Optimal Statistic
To be added

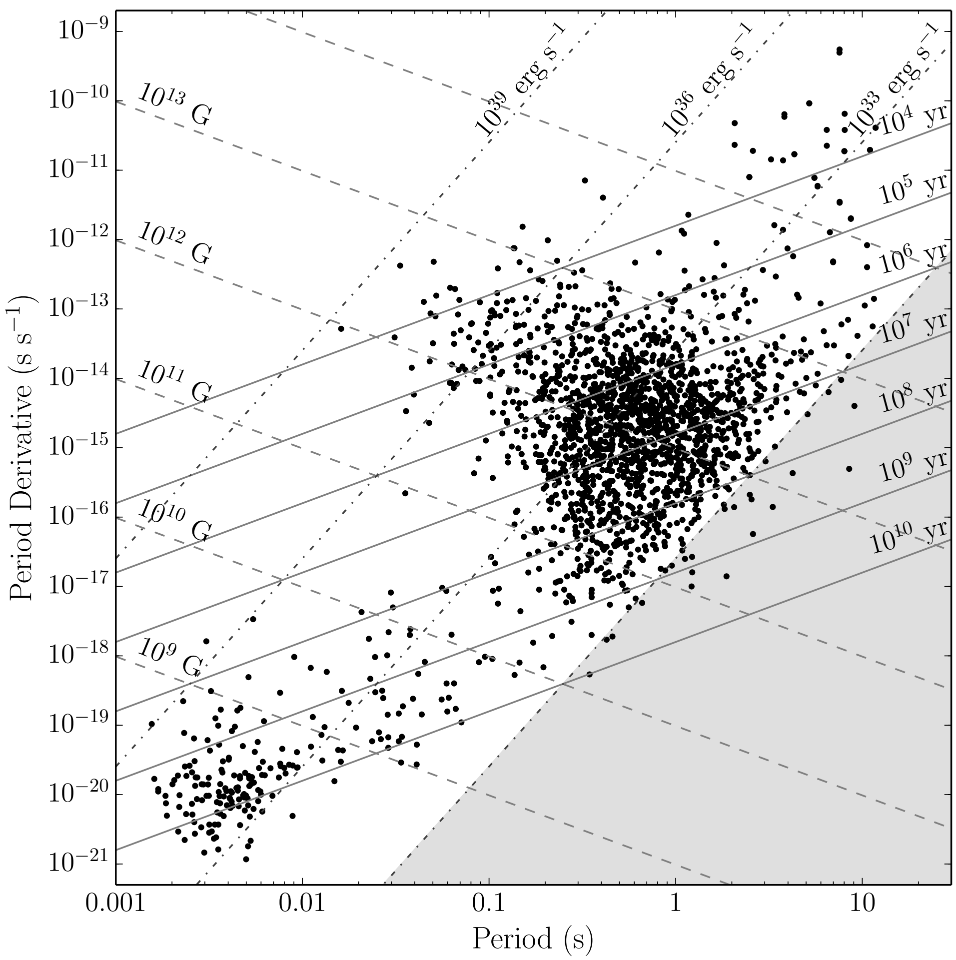
Outlier Analysis
Generically, this is any analysis (systematic or otherwise) in which one looks for discrepant data points. In the context of NANOGrav, we use this to describe automated methods for TOA rejection. The primary algorithm used is described in Vallisneri & van Haasteren (2017).

P Band
A frequency range covering the 300–400 MHz range. We had observed one pulsar, PSR J2317+1439,

at 327 MHz at Arecibo for many years.

P-Pdot Diagram

The spin period vs spin period derivative (how quickly the pulsars spin rate is slowing due to loss of luminous energy) diagram shows the different classes of neutron stars. From it, we have understood different properties of the neutrons stars, how they change over time, etc.



The $P - \dot{P}$ diagram. In the middle are canonical (slow period) pulsars, the majority of known neutron stars. The top right shows magnetars and the bottom left shows millisecond pulsars. Derived from spin-period P and spin-period-derivative $\dot{P}$ are the characteristic age (solid lines), surface magnetic field (dashed lines), and spin-down luminosities (the loss rate of rotational energy assuming the complete conversion of rotational energy into luminous radiation; dashed-dotted lines). The gray region in the bottom right is the pulsar graveyard, with the boundary known as the "death line". Data are taken from PSRCAT and the McGill Online Magnetar Catalog (Olausen & Kaspi 2014). Figure from Lam (2016).

Par File
A text file that contains all of the relevant parameters/values describing the pulsar's spin, spin-down, position, motion on the sky (proper motion), distance/parallax, binary Keplerian and post-Keplerian elements if relevant, etc.

Parallactic Angle
The angle of the receiver feed with respect to the plane of polarization.

Phase Transitions
Typically, one discusses phase transitions in what happens when different states of matter change to other states of matter, e.g., liquid to solid. As this happens when water freezes into ice, cracks form in the ice. It is theorized that when the Universe cooled, similar cracks or "defects" would have happened in spacetime that should be detectable through their gravitational radiation.

Physics Frontiers Center (PFC)
A National-Science-Foundation-funded organization designated to explore hard problems at the frontiers of physics. NANOGrav's current primary funding is from a PFC grant.

Plasma Lens
A region of plasma which causes bulk refractive deflection of radiation propagating through it.

PINT
PINT Is Not Tempo. An all-Python package with the functionality of Tempo and Tempo2, produced by the NANOGrav PFC, with the routines independently implemented based on the original scientific sources.

Partnerships for International Research and Education (PIRE)
A National-Science-Foundation-funded grant to support international activities and partnerships. NANOGrav's first five-year grant was an NSF PIRE award which helped in the organization of IPTA conferences as well as sent many students to radio astronomy facilities around the world.

Polarization Angle
The angle of the electric field of an electromagnetic wave with respect to the incidence angle.

Polarization Calibration
Some part of the pulse emission is polarized, that is, the electric field part of the electromagnetic waves are all aligned with respect to one another. As the radiation is measured at the telescope, this polarization is altered as it passes through the signal path that measures it, and so we must correct for these alterations ("calibrate") so that we know what the intrinsic emission at the pulsar looks like for the best possible arrival-time precision.

Position Angle

The angle measured clockwise from the North Celestial Pole (see Equatorial Coordinates).

Posterior
The probability that a hypothesis is true AFTER you have made a measurement. This is the output of Bayesian data analysis and the result of your experiment. Calculated using Bayes' Theorem.

Post-Keplerian Parameters
The components of the binary model that describe the second-order motion of a pulsar and companion (e.g., a white dwarf) orbiting around each other, due not from simple Newtonian gravity but from Einstein's General Relativity.

Power Spectrum
The power in a data series as a function of frequency. This is a quantity that describes the amplitude of sinusoidal structure in our data. It is a function of "fluctuation frequency", or inverse time. That is, if you have a sinusoid with a certain period/frequency, each value of the power spectrum describes the amplitudes of sinusoids in the data with that exact period/frequency. As usual, one can talk about a power spectrum in other quantities, such as inverse length (see Electron-density Wavenumber Spectrum).

PRESTO
A suite of software for pulsar-searching. Includes routines for searching for pulsars in binaries with periods sufficiently short, compared to the observation length, that acceleration must be taken into account. Developed by Scott Ransom, it is available at `https://github.com/scottransom/presto`

Pre-whitening
A method of analyzing signals with very steep power spectra. For us, it helps to minimize the effect on the spectra that we do not have an infinite amount of data with time but only a finite length of observation over years and decades.

Prior
The probability that a hypothesis is true before you make a measurement. This can be used to include knowledge from previous experiments or theoretical models in Bayesian data analysis, or may be set to encode maximal ignorance.

Profile Evolution
There are two definitions by which this can be used. Typically in NANOGrav we talk about how the pulse profile changes slightly as a function of frequency. That is, the pulse shape looks different from one frequency to the next and thus we have to make sure to account for this when creating TOAs, and we now parameterize them with FD parameters. However, we are also concerned that there is no evolution of the profile in time since we want our pulses to be very stable.

This stability has been tested.

PSRCAT
The ATNF (Australia Telescope National Facility) Pulsar Catalogue. This contains a list of all known pulsars and a variety of observational parameters. It can be accessed from the web interface or the command line. See Manchester et al. (2005) for more information.

PSRCHIVE
A set of powerful tools, written in C++, for pulsar data analysis. `http://psrchive.sourceforge.net/`.

PSRFITS
Data files that contain our pulse profiles as a function of time, polarization, frequency, and phase (search data are also contained within PSRFITS files). These are built on standard FITS (Flexible Image Transport System), which allows for data to be stored in binary formats and metadata, e.g., about the observation, to all be stored internal. The standard package to handle these files is PSRCHIVE, but NANOGrav has an all-Python package called PyPulse which has much of the PSRCHIVE functionality.

Pulsar
A rapidly rotating neutron star emitting electromagnetic radiation in a beam which rotates with the neutron star, causing pulsed energy received at the earth at the rotation period of the neutron star.

PTMCMC
To be added

Pulsar ALFA (PALFA) Survey
A survey conducted with the seven-beam Arecibo L-Band Feed Array (ALFA) at the Arecibo Observatory, at frequencies near 1.4 GHz. Primarily concentrated in those areas of the plane which can be seen from Arecibo, this survey is ongoing, having started in 2004. Originally using the WAPP autocorrelators as backend and now using the Mock spectrometers, which allows about 300 MHz of bandwidth. Website: `http://www2.naic.edu/alfa/pulsar/`.

Pulsar Search Collaboratory (PSC)
A program to involve high school students in looking at plots of pulsar candidates. We teach them about pulsars, pulsar searching, and get them involved in various aspects of our science.

Pulsar Signal Simulator (PSS or PsrSigSim)
A software package that does an end-to-end simulation of the pulse emission, the propagation of the pulses through the interstellar medium, and the reception of the emission at the telescope.

Pulse Portrait

The 2D pulse template used in wideband timing, which accounts for profile evolution across the entire band.

Pulse Profile
The pulse shape, or alternatively the intensity of the pulse as a function of phase.

Pulse Template
A canonical pulse profile for a given pulsar in a given frequency band; this is constructed from the averaging of many recorded pulse profiles and represents the stable profile against which observations are correlated to calculate the TOA for an epoch.

PyPulse
A software package written entirely in the Python programming language, using only basic packages, with overlapping functionality with PSRCHIVE so that for many applications it can be used as an alternative to, or a check against, PSRCHIVE. To install, go to `https://github.com/mtlam/PyPulse`, and do not use `pip install pypulse` as that is a different package with the same name.

Quadrupole
The third term in a "multipole" expansion, which describes some spherical pattern as the sum of components with different angular features. This is similar to a Taylor expansion but over a sphere. The first term, called the "monopole", is a constant that does not depend on the orientation on the sphere. The second term, called the "dipole", splits the sphere up into two sides. One way to think about these two is as follows. Usually when you think of Newtonian gravity of a sphere, the gravitational field points equally down in all directions and does not depend on angle, and thus is a monopole. A bar magnet, with a north and south pole, has a magnetic field that is a dipole because it is broken up into two halves. The third term in the multipole expansion is the quadrupole, which breaks up the sphere into four possible parts, though there are different ways that these parts can be oriented. A gravitational wave passing by the Earth produces a quadrupolar pattern in the shifts of pulsar arrival times.

Quicklook
A software package built upon PyPulse that allows for a rapid look at a single PSRFITS file observation and provide some useful diagnostics to visualize. Not to be confused with the PALFA Quicklook program. It is written entirely in the Python programming language. To install, go to `https://github.com/mtlam/Quicklook`. PyPulse is a requirement. It is not available on pip.

Radio Frequency Interference (RFI)
Radio signals of terrestrial origin, which have the effect of lowering the significance of astrophysical radio frequency signals of interest. Caused by cellphone towers, microwave ovens, over-the-air television transmissions, GPS satellites, airplane radar, lightning, wifi, etc.

Radio Quiet Zone

An area in West Virginia and the west of Virginia where there are strict limits on radio emissions. The limits vary with distance, but at or near the Green Bank Observatory (GBO) they are very strict.

Radiometer Equation

There are a number of ways to write this but most succinctly is that the errors in your system temperature is just equal to your system temperature divided by the number of independent measurements you make, which is true of many statistical quantities anyway. In equation form for radio astronomy, this is roughly

$$T_{\rm rms} = \frac{T_{\rm sys}}{\sqrt{p\tau\Delta\nu}} \quad (1)$$

where $T_{\rm rms}$ is your root-mean-square error (the square root of the variance), $T_{\rm sys}$ is your system temperature, p is the number of polarizations (typically two), τ is your integration time (time of observation on source), and $\Delta\nu$ is the bandwidth.

Radiometer Noise

Fluctuations that add to the pulse profile due to electronic noise.

Receiver

One component of a frontend, the actual component that receives the radiation.

Red Noise

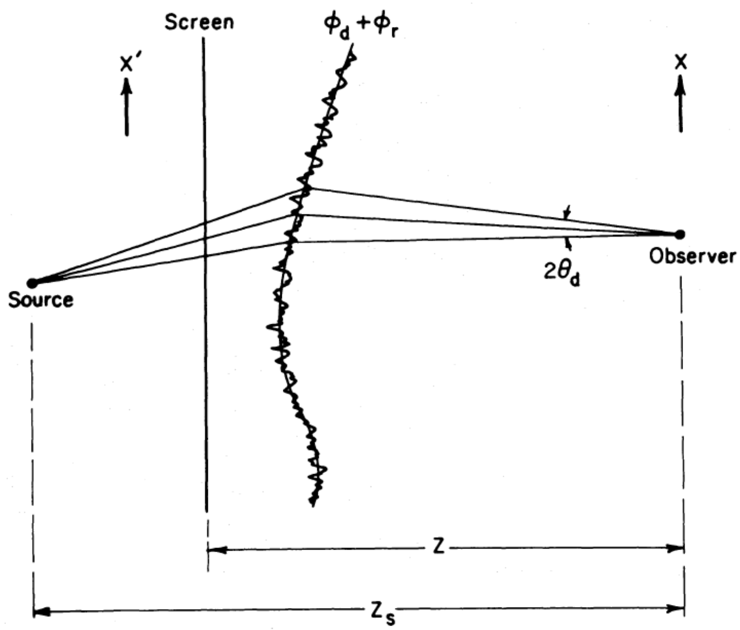
Noise that is correlated in time. There are larger scale amplitude variations on longer timescales, or lower "fluctuation" frequencies, and so there is more "power" at low frequencies, which is why we call the noise red (the color red has more intensity at low frequencies). Often we model red noise with a power law power spectrum but that functional form need not be the case.

Reduced Mass

The effective mass when a two-body problem is mapped to a one-body problem. For masses m_1 and m_2, the reduced mass is $\mu = \dfrac{m_1 m_2}{m_1 + m_2}$. When both masses are equal, i.e., $m = m_1 = m_2$, then $\mu = m$. In the case where $m_1 \gg m_2$, then $\mu \approx m_2$.

Refraction

The bulk deflection (scattering) of pulse emission through the interstellar medium. Somewhat interchangeable with scattering, usually we think about scattering as slight deflections of the light rays.



We see that light rays due to a thin screen in the interstellar medium can be deflected such that the source does not appear in its true position on the sky with respect to the observer. Figure from Cordes et al. (1986).

By "bulk" deflection, we are referring to all of the ray paths being deflected, as if light passing by a lens.

Relic/Primordial GWs
GWs generated in the early universe, shortly after the Big Bang.

Residual
The observed TOA minus the expected model TOA. If we predicted it exactly, the residual is zero. If the observed TOA arrives early, the residual is negative, if it arrives late, the residual is positive. We often describe our precision of the timing of an individual pulsar in terms of the root-mean-square (rms) of the residuals.

Right Ascension (RA)
See Equatorial Coordinates.

Rotation Measure (RM)
A quantity related to how the polarization angle of a pulse profile changes as a function of frequency. It is proportional to the integral of the free electron density times the parallel magnetic field along the line of sight, or $\mathrm{RM} \propto \int_0^L n_e(l) B_{\parallel}(l)\, dl$. Therefore, combined with the DM, we

can make estimates of magnetic fields. The typical units are rad m^{-2}.

S Band
A frequency range covering 2–4 GHz. This is true at the VLA though for our observations at Arecibo, these typically cover just below 2 GHz to about 2.5 GHz.

Sampler
Method for generating samples from a probability distribution, especially if you don't know the form of the distribution a priori. The samples can then be used to reconstruct the distribution and calculate things like the mean, median, mode, and width of the distribution.

Scattering
As pulses travel through the interstellar medium, the ray paths are deflected ever so slightly by the free electrons in the interstellar medium. At a single frequency, this causes some of the pulse emission to arrive at slightly later times, such that the pulse shape is broadened since part of the radiation arrives later. The strength of this effect is heavily dependent on frequency though, with the largest broadening happening at the lowest frequencies.

Scattering Measure (SM)
The integral of the electron-density wavenumber spectrum amplitude along the line of sight, or $\mathrm{SM} = \int_0^L C_n^2(l)\,dl$. This tells us about the strength of the scattering. The typical units are kpc $\mathrm{m}^{-20/3}$.

Scattering Timescale
The timescale over which pulse broadening due to scattering happens, roughly related to how much the width of the pulse is increased by.

Scintillation
An optical effect caused by light rays constructively and destructively interfering. This is the same effect as why stars twinkle in the night sky, except that instead of optical light traveling through the Earth's atmosphere, we observe radio waves traveling through the interstellar medium. This causes the pulsar to appear brighter at some times (and frequencies) and dimmer at other times, thus the pulse signal-to-noise ratio will vary. Scintillation occurs on different timescales, short timescales of order the length of our observations typically, and then long timescales of order days to years, from two separate regimes.

Scintillation Arc
A "structure" observed in a secondary spectrum that is indicative of scattering material along the line of sight.

Scintillation Bandwidth

The characteristic size scale of scintles in frequency.

Scintillation Timescale
The characteristic size scale of scintles in time.

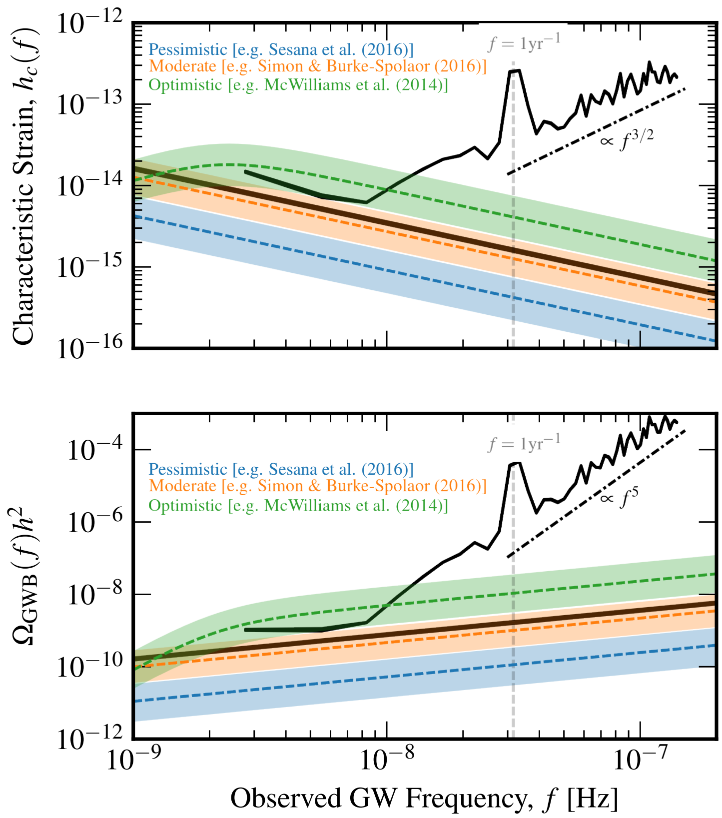
Scintles
Bright patches in a dynamic spectrum where the pulsar emission is brighter due to scintillation.

Scrunching
A colloquial term for the act of averaging a pulse profile in time, frequency, polarization, or even phase.

Searching Working Group
The group in charge of finding new pulsars and suggesting they be added to the array. They are also responsible for working on new algorithms for searches.

Secondary Spectrum
The 2D Fourier transform of the dynamic spectrum, which is useful for detecting certain periodic yet correlated (in time and frequency) structures among the scintles.

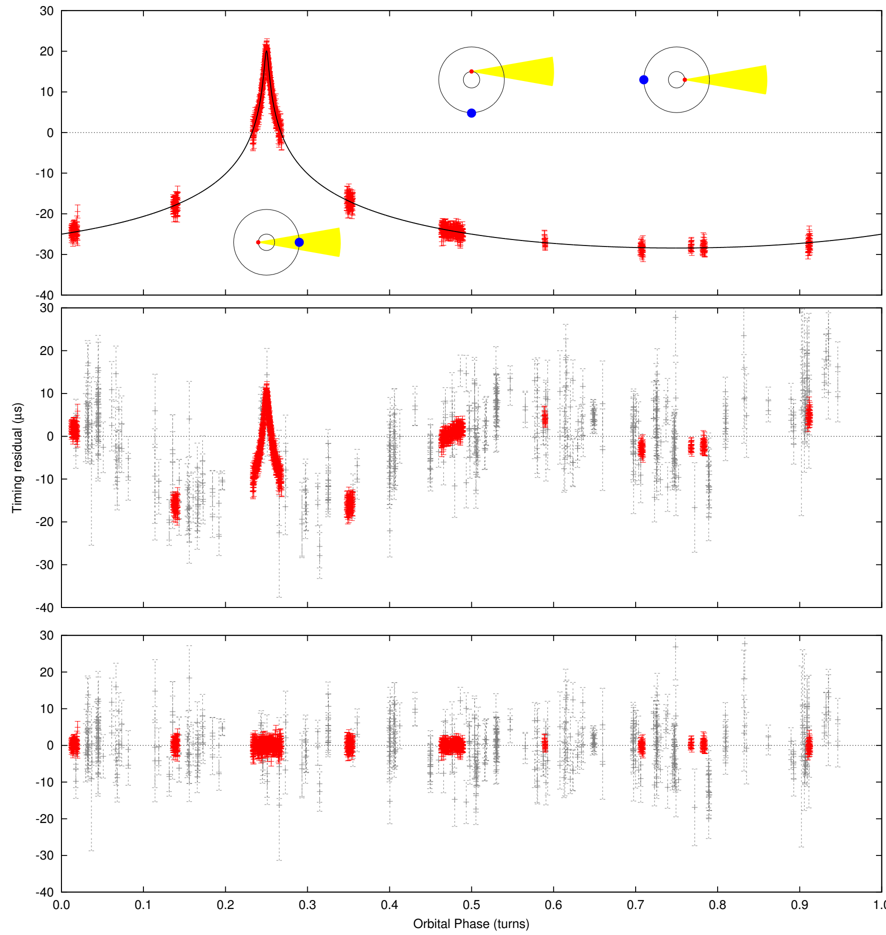
Sensitivity Curve
How sensitive we are to graivtational waves as a function of GW frequency. Usually these are plotted such that the lower the curve is, the more sensitive we are, as that represents the lowest amplitude of a signal that we can detect.



Sensitivity curve from NANOGrav's 11-Year data set constraints on the gravitational wave stochastic background Arzoumanian et et al. (2018b).

Shapiro Delay

A general relativistic effect where light takes slightly longer to travel through the local spacetime of a massive object. It was originally detected by bouncing radar signals off Venus and measuring the return time when the Sun was close to the line of sight in between Venus and the Earth. In pulsar timing, we measure the Shapiro delay from the pulses traveling close by the massive, compact companion. It is most easily measured for systems which are nearly edge-on as viewed by us.



The residuals as a function of orbital phase for PSR J1614–2230. The full Shapiro delay signal is shown at top, where the peak represents when the pulses are traveling right in the direction of its white-dwarf companion. Without fitting for the Shapiro delay term, the residuals appear as in the second panel, whereas adding the parameters produces a good fit in the bottom panel. Figure from Demorest et al. (2010).

Signal-to-noise (S/N)
A generic term used to define the ratio of the strength/amplitude of your "signal" (what you are looking for) to the strength/amplitude of the uncertainties in your measurement.

Site Visit
When members of the collaboration meet with program officers either at the National Science Foundation (called a "Reverse Site Visit"), or at a NANOGrav institution, to discuss the progress of large collaboration grants, such as the PFC.

Solar System Barycenter (SSB)
The center of mass of our solar system. We need to transform all of our pulsar measurements to the frame of the SSB because it is roughly an "inertial reference frame", meaning that it is not

accelerating with respect to the pulsar reference frame.

Solar Wind
The wind of particle blown off from the Sun. This affects the DM that we measure, and when a pulsar is observed very close to the Sun, we are careful in how we model the DM because of the rapid changes that we see as the line of sight changes through the denser medium.

Space Public Outreach Team (SPOT)
Network of undergrad/grad students across NANOGrav institutions giving the EPO presentation "Tuning Into Einstein's Universe" as well as hands-on activities to K-12 students in their local areas. Great for presentation skills development/EPO experience.

Spectral Index
If we model a power spectrum as a power law of the form $P(f) = Af^{-\gamma}$, then A is the amplitude of that power spectrum and γ is what's called the spectral index. Note that often the convention is to have Af^{γ} with γ negative.

Spillover Temperature
The component of the system temperature due to radiation from the ground and immediate surroundings.

Stochastic Background
The collection of gravitational waves produced from a variety of sources that we cannot individually resolve/detect. For our work, two contributions come from an ensemble of SMBHBs throughout the Universe, and from the random fluctuations in spacetime at the beginning of the Universe. For a background from an ensemble SMBHBs in perfectly circular orbits, we expect the background to have a power-law power spectrum, $h_c = A_{\rm SB}\,(f/f_0)^{\alpha}$. Primordial gravitational waves from the early Universe will also have a power-law spectrum, though with a different spectral index. We usually reference the amplitude in terms of a characteristic strain at a frequency of $f_0 = 1\ \mathrm{yr}^{-1}$.

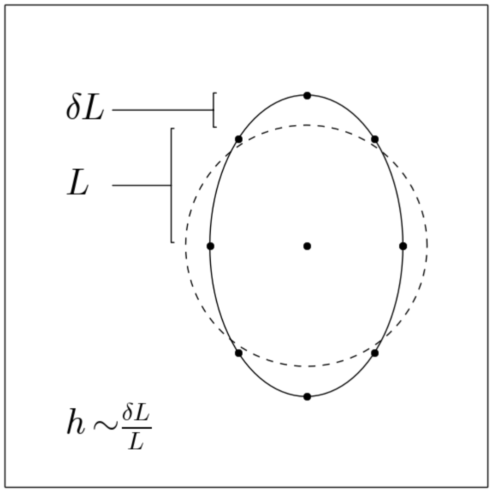
Stokes Parameters
A representation of electromagnetic radiation in terms of the polarization properties. Usually we represent these by the Stokes vector

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}, \tag{2}$$

where I is the total intensity, Q and U represent the linear polarization, and V is the circular polarization.

Strain
The fractional change in the separation between objects caused by the passage of the gravitational

wave as it stretches and squeezes spacetime. For a separation L and a change δL, then $h \sim \delta L/L$.



For a gravitational wave passing through the page, a ring of test particles gets stretched along one axis and compressed in the other. The strain is given by $h \sim \delta L/L$.

Structure Function
A statistical analysis tool similar to a power spectrum. Instead of describing the amplitude of variations in terms of fluctuation frequency, this describes it in terms of the differences in time (for a timeseries, one can also do the differences in space or any other quantity too). Formally, for a time series $x(t)$, it is defined as $D_x(\tau) = \langle [x(t+\tau) - x(t)]^2 \rangle$, where τ is the time lag and the brackets denote the (ensemble) average. One can see that this is the average of the squares of the differences ("increments") in the timeseries at some lag τ.

Student Team of Astrophysics ResearcherS (STARS)
The coordinated team of undergraduate students distributed across NANOGrav, with an emphasis on bringing students to learn about the science together.

Supermassive Black Hole (SMBH)
Large (10^6 – 10^{10} solar mass) black holes. They are thought to reside in the centers of every galaxy.

Supermassive Black Hole Binary (SMBHB)
A binary system of two SMBHs that forms after their host galaxies merge.

System Equivalent Flux Density (SEFD)
The conversion of the system temperature into units of flux density, so from Kelvin to Jansky. A lower SEFD is a more sensitive system.

System Temperature
The noise temperature resulting from all in the system contributions. This is the sum of all the

individual noise temperatures.

T-process model
A red noise model consisting of a typical power-law relation between noise spectral density and frequency but with deviation parameters included for every red noise frequency bin. A more flexible power-law model.

TAI
See International Atomic Time (TAI).

Target of Opportunity (TOO)
To be added

TCB
See Barycentric Coordinate Time (TCB).

TDB
See Barycentric Dynamical Time (TDB).

Telescope Allocation Committee (TAC)
Also known as a Time Allocation Committee, this is a group who reviews observing proposals for a given observatory.

Template Fitting
To calculate TOAs, we shift an idealized pulse profile shape and maximize the correlation (area overlap) between it and a noisy data profile. The best fit determines when the arrival time occurs and what the error is on that arrival time due to a finite signal-to-noise ratio. Note that this error is often just call "the TOA error" but formally this is incorrect.

TEMPO
Pulsar timing software written in fortran by many people over decades. The primary mode of use for TEMPO takes a par file which specifies a model for a given pulsar and a tim file that contains actual times of arrival for the pulsar, then calculates pre-fit residuals (actual TOA – predicted TOA), fits for selected parameters, and calculates post-fit residuals.

TEMPO2
Pulsar timing software written in TEMPO in C++; contains a fair amount of refactored TEMPO code.

Terrestrial Time (TT)
The time standard used for measurements on the Earth's surface. It is a theoretically idealized time that would be kept from a perfect atomic clock on the geoid (the Earth's surface at at mean sea level). As such, it is measured via International Atomic Time, but is offset slightly such that

TT = TAI + 32.184 seconds; the offset is historical.

The "Anomaly"
An erroneous noise feature in the 9-year data set that resembles a burst with memory originating in the direction of PSR J0030+0451. A search conducted on the 11-year data set and the IPTA DR2-lite set turned up no such feature; this led to the conclusion that incomplete sky coverage by 9-year NANOGrav pulsars provided a location in the MCMC parameter space to tuck in a such a signal.

The "Bump"
Noise feature uncovered in the 9-year continuous wave search. A decrease in sensitivity in the range of 10–20 nHz led to a bump in the typical sensitivity curve. It was isolated to PSR J0613–0200, and resolved with a free-spectral noise model for this pulsar.

The "Gremlin"
Revealed when calculating the Bayes factors for continuous wave signals with various spatial correlations. It is constrained to around 109 nHz with a Bayes factor of 20 and favors quadropole spatial correlations. It is likely an echo of some unmodeled noise in PSR J1713+0747. Dropout analysis will help determine exactly the cause.

The "Kink"
A uptick in stochastic background upper limits around 2012 uncovered during the time slice analyses which is thought to be some form of DM anomaly. Previous runs show removing certain pulsars diminishes it.

The Odds
Comparison of the degree of belief in two hypotheses. Literally a betting odds.

Thin Screen
We often approximate the material in the interstellar medium as being condensed from fully filling the line of sight to existing in a two-dimensional "screen". This approximation simplifies scattering/scintillation calculations while still remaining fairly robust; conversion to a thick medium or a uniform medium usually involves geometric terms that only slightly change coefficients in resulting expressions.

Tim File
A text file that contains each arrival time, the frequencies observed, the template fitting errors, and a lot of metadata such as which observation it came from, what integration number, what the flux of the pulse was, etc. Several different formats exist: NANOGrav has moved to the IPTA format.

Time Allocation Committee (TAC)

See Telescope Allocation Committee (TAC).

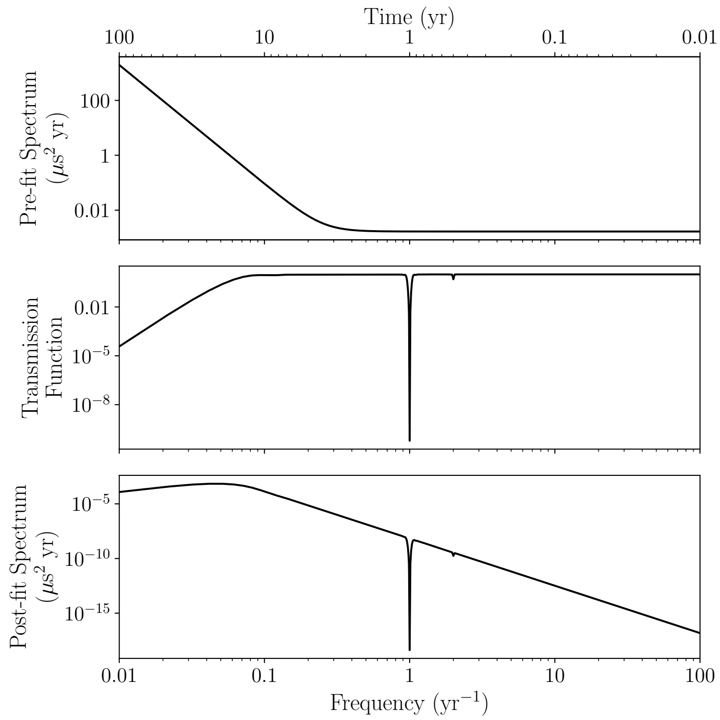
Time of Arrival (TOA)
A measurement of when a pulse (or an average of pulses) arrives at our telescope. We end up correcting these from a topocentric measurement at the observatory to a barycentric measurement at the center of mass of the solar system.

Timeseries
Some data as a function of time.

Timing Model
A description of when we expect pulses to arrive at our telescopes. It involves terms that describe the pulsar's spin, astrometric terms (how it appears to move on the sky), binary terms, interstellar medium delays, and more.

Timing Working Group
The group in charge of pulsar timing analyses and preparing the data sets, from the calibration of profiles to the calculation of TOAs to the fitting of individual pulsar timing models. Subsequent analyses of interesting systems, or of bulk pulsar properties as a whole, are done in this working group.

Transmission Function
Very generally, how much power (see Power Spectrum) is transmitted through some system. For example, perturbations on the TOAs away from the "true" arrival times due to noise in the pulsar or from graivtational waves will partially be absorbed by the timing model fit, and this absorption is described by the transmission function.



Top: The spectrum of TOA perturbations due to pulsar noise and gravitational waves. There is significant power in the GW component at low frequencies. Middle: Transmission function for a timing model consisting of spin and astrometric parameters and 20 years of observing. Bottom: The remaining power in the residuals. We see that the power due to our GW signal is significantly reduced due to the timing model fit for the unknown pulsar spin period and spin period derivative.

TT
See Terrestrial Time (TT).

Ultra-wideband (UWB) Receiver
While the VEGAS backend can process a significantly larger bandwidth than GUPPI, the frontend receivers are unable to collect more than a certain amount of bandwidth. This next-generation frontend will be able to receive 0.7–4.0 GHz simultaneously.

Universal Time (UT)
A general class of time standards based on Earth's rotation. Two common ones used in pulsar astronomy are UTC and UT1, which is conceptually related to the mean solar time at Greenwich, London but is instead made from astronomical measurements such as quasars, lunar laser ranging, etc.

UT

See Universal Time (UT).

UTC
See Coordinated Universal Time (UTC).

Variance
A common measure of the variability of a data set. Defined as the expectation of the square of the difference between a random variable X and X's mean, μ. Using E to denote the expectation:

$$\mathrm{Var}(X) = E((X - \mu)^2)$$

Identifying $E(X)$ as μ, it can simply be shown that $\mathrm{Var}(X) = E(X^2) - (E(X))^2$.

VEGAS
Versatile GBT Astronomical Spectrometer. This is the latest generation of backend at Green Bank, which will be able to process a significant bandwidth.

Very Large Array (VLA)
An array of 27 25-meter antennas located outside of Socorro, New Mexico.

White Dwarf
A stellar remnant left behind by lower-mass stars. Many millisecond pulsars are in a binary orbit with white dwarf companions.

White Noise
Noise that is entirely uncorrelated, meaning that every measurement is independent from every other measurement. Usually we talk about this as uncorrelated in time but also radio frequency, but you can have noise processes that are uncorrelated in time but correlated in frequency (jitter).

Wideband Timing
In "conventional" timing, we break up the pulse into many frequency bands ("channels") so that we can calculate TOAs separately and then model profile evolution. Wideband timing takes into account the shape of the pulse changes themselves across the band and produces a single arrival time and estimate of the DM.

Zapping
A colloquial term for the act of excising (removing) RFI. May involve blanking subbands (setting "weights" in the data to zero), or sections thereof, or replacing with an average signal or else all zeroes.

Zenith Angle
The angle between a point or line, and a line pointing directly "overhead".