Searching for Gravitational Waves via Pulsar Timing

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The NANOGrav collaboration is using millisecond pulsar timing observations at Arecibo and the Green Bank Telescope in a program designed to directly detect gravitational waves.

The first millisecond pulsar was discovered at the Arecibo Observatory in 1982 (Backer et al. 1982). In the years following that discovery, measurements made at Arecibo of the arrival times of pulses from this and other millisecond pulsars showed these objects to be superb astrophysical clocks. In the best cases, pulse arrival times can be measured and predicted with accuracy of order 100 ns on time scales of years.

Arrival times of pulses measured at a telescope are perturbed by anything that changes the distance between the pulsar and the telescope. Gravitational waves, a key prediction of Einstein's theory of general relativity, are a tantalizing source of such perturbations. As a gravitational wave passes, it changes the space-time metric along the line of sight from pulsar to observatory, causing pulses to arrive at the observatory slightly earlier or later than they otherwise would. Our millisecond pulsar timing observations are designed to detect these perturbations over time scales of several years. Periods of several years correspond to frequencies of nanohertz, hence our collaboration name, NANOGrav, which stands for North American Nanohertz Observatory for Gravitational Waves.

Gravitational waves are quantified by their strain, h, the fractional change in proper distance as a gravitational wave passes. Thus a $h = 10^{-15}$ gravitational wave would perturb the proper length of a 1 m long rod by 10^{-15} m, roughly the size of an atomic nucleus. A gravitational wave with period of ten years and a strain amplitude of 10^{-15} would perturb measured pulse arrival times by ~ $(10^{-15})(10\ \mathrm{yr})/2\pi = 50$ ns. This would be observed as gradual increases and decreases in pulse arrival times of this magnitude.

The most likely sources of gravitational waves detectable by pulsar timing are merging massive black hole binary systems. Black holes with masses 10^6 to 10^9 solar masses can be found at the centers of galaxies. Galaxies are known to undergo mergers. Following a merger of two host galaxies, dynamical friction causes the central black holes to sink toward each other, forming a binary system. This binary decays over time, eventually coalescing into a single, larger black hole. The strongest expected gravitational wave signal in the nanohertz band is the stochastic background created by the sum of all such binary systems with orbital periods greater than 1 year. If we are lucky, and there is such a black hole binary sufficiently close to us, it may be possible to resolve individual black hole binary systems in addition to detecting the background signal (Sesana et al. 2009).

Strong indirect evidence for gravitational waves comes from the discovery of the first binary pulsar at Arecibo (Hulse & Taylor 1975). Observations over more than three decades have shown the pulsar orbit to be decaying at the rate predicted due to loss of energy and angular momentum from gravitational radiation emission, with measurement precision of 0.2% (Weisberg et al. 2010). Similar results from more recently discovered pulsars, including the double

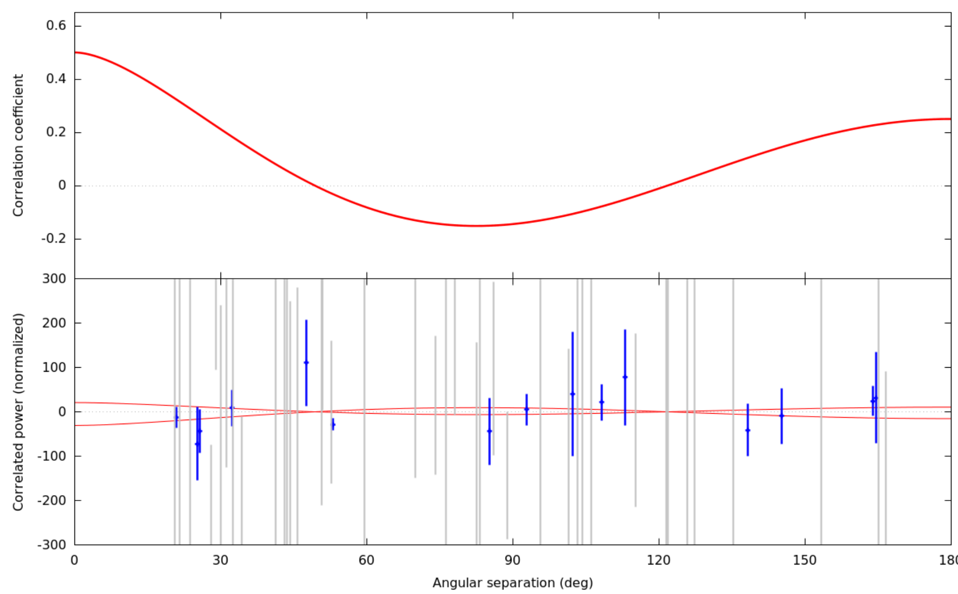


Figure 1. — Top panel: Expected correlation and anti-correlation of perturbations in arrival times between the pulsars on the sky expected from a background of gravitational waves. This is the characteristic signature of gravitational waves we hope to detect. Bottom panel: Timing correlations between pulsar pairs measured in 5 years of NANOGrav Arecibo and Green Bank Telescope data (Demorest et al. 2013). The blue points are the 15 smallest-uncertainty correlation points, while those with larger uncertainties are shown in gray. The red lines show a ±2-σ fit to the expected correlation function, the results of which are consistent with no detectable gravitational wave signal, and imply $h_c < 7 \times 10^{-15}$ on a time scale of 1 year.

pulsar system, have confirmed and extended this result. These experiments, compelling as they are, do not directly measure the metric perturbations, as we expect to do with the NANOGrav millisecond pulsar timing observations.

A challenge in the detection of gravitational waves by pulsar timing is that some other physical phenomenon might influence the measured pulse arrival times in a way that mimics the expected signature of gravitational waves. Indeed, young (non-millisecond) pulsars are known to exhibit "timing noise," irregularities in rotation which, although small, swamp any gravitational signal. The level of timing noise in millisecond pulsars is small, but it may be present at some level in some or all such sources. Thus, a secure measurement of gravitational waves will likely require detection of the same gravitational wave signal in many pulsars observed quasi-simultaneously. Such a set of observations is called a pulsar timing array.

Hellings and Downs (1983) showed that an isotropic gravitational wave background generated by the combination of many sources, such as massive black hole binary systems, produces a distinct pattern of correlation and anticorrelation between signals from pairs of pulsars depending on the angle between the pulsars on the sky (Figure 1). In Demorest et al. (2013), we used NANOGrav pulsar timing data collected at Arecibo and Green Bank over 5 years to seek out the correlation predicted by Hellings and Downs. We also analyzed individual pulsar time series to seek out long-period perturbations characteristic of gravitational waves. We have not yet detected gravitational waves, but we put an upper limit on the massive black hole strain amplitude spectrum of $h_c < 7 \times 10^{-15}$ on a time scale of 1 year.

Pulsar timing arrays are complementary to other techniques attempting to directly detect gravitational waves. The gravitational wave frequencies to which pulsar timing arrays are sensitive (around 10^{-9} Hz) are orders of magnitude away from the frequencies probed by proposed space-based detectors such as eLISA (around 10^{-2} Hz) and by ground-based detectors such as LIGO (around 10^{2} Hz) — see Figure 2. Using these three separate techniques to explore the gravitational wave spectrum is analogous to

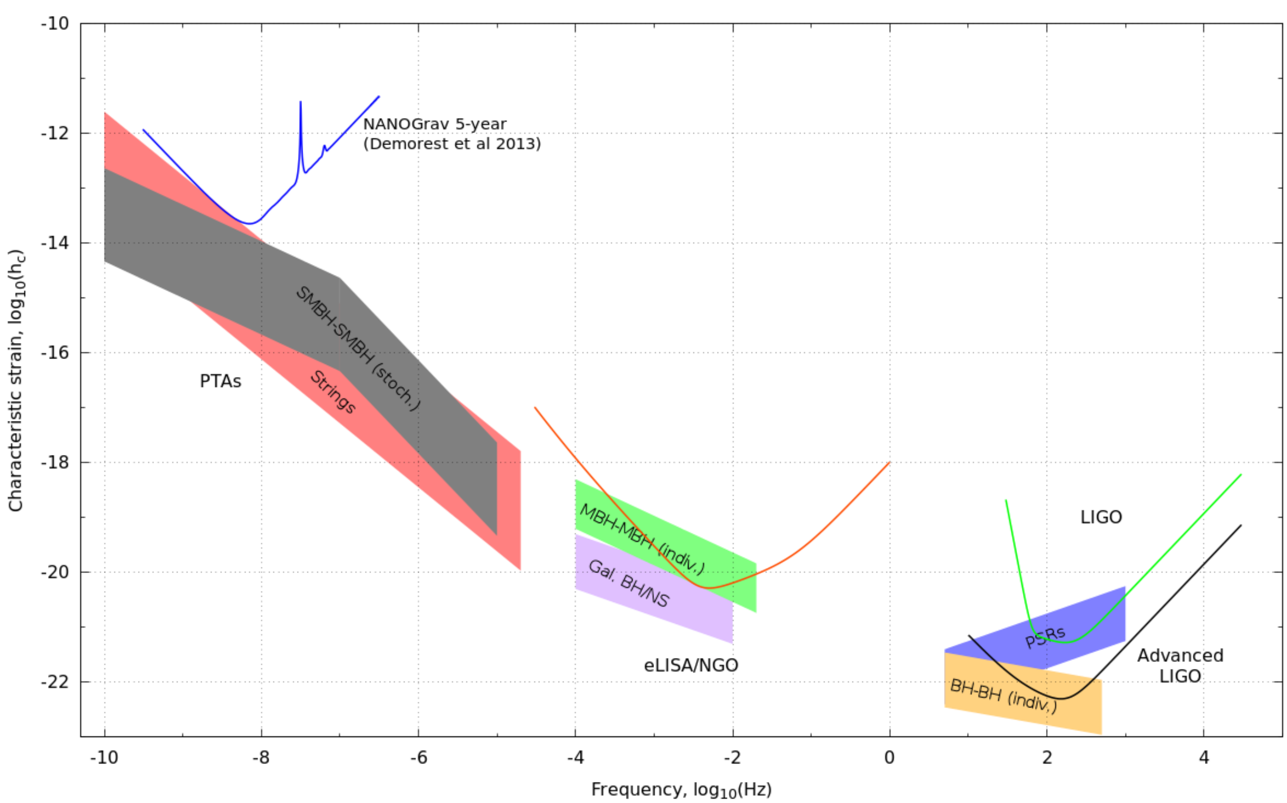
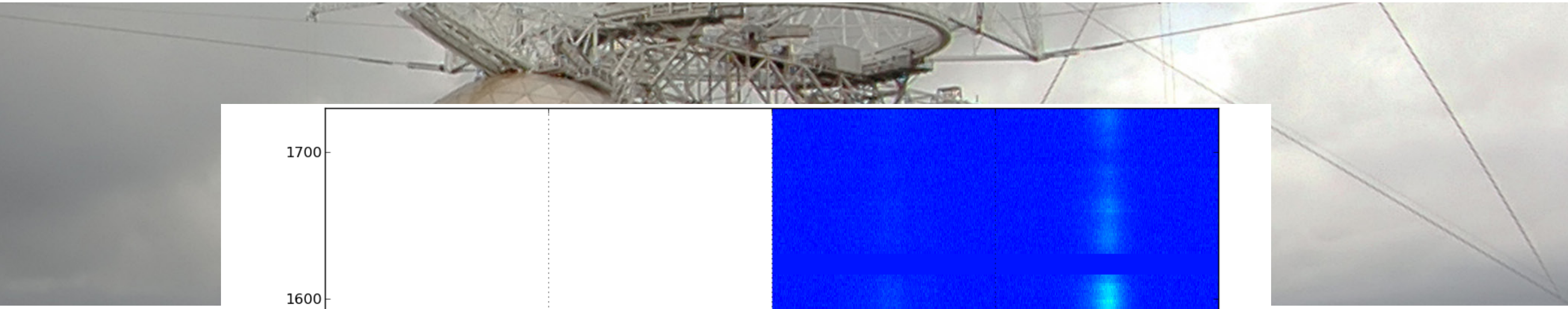


Figure 2. — Comparison of current and planned gravitational wave detectors, showing characteristic strain (h_c) versus gravitational wave frequency. Pulsar timing observations probe a region of the gravitational spectrum space complementary to other existing and proposed detectors.



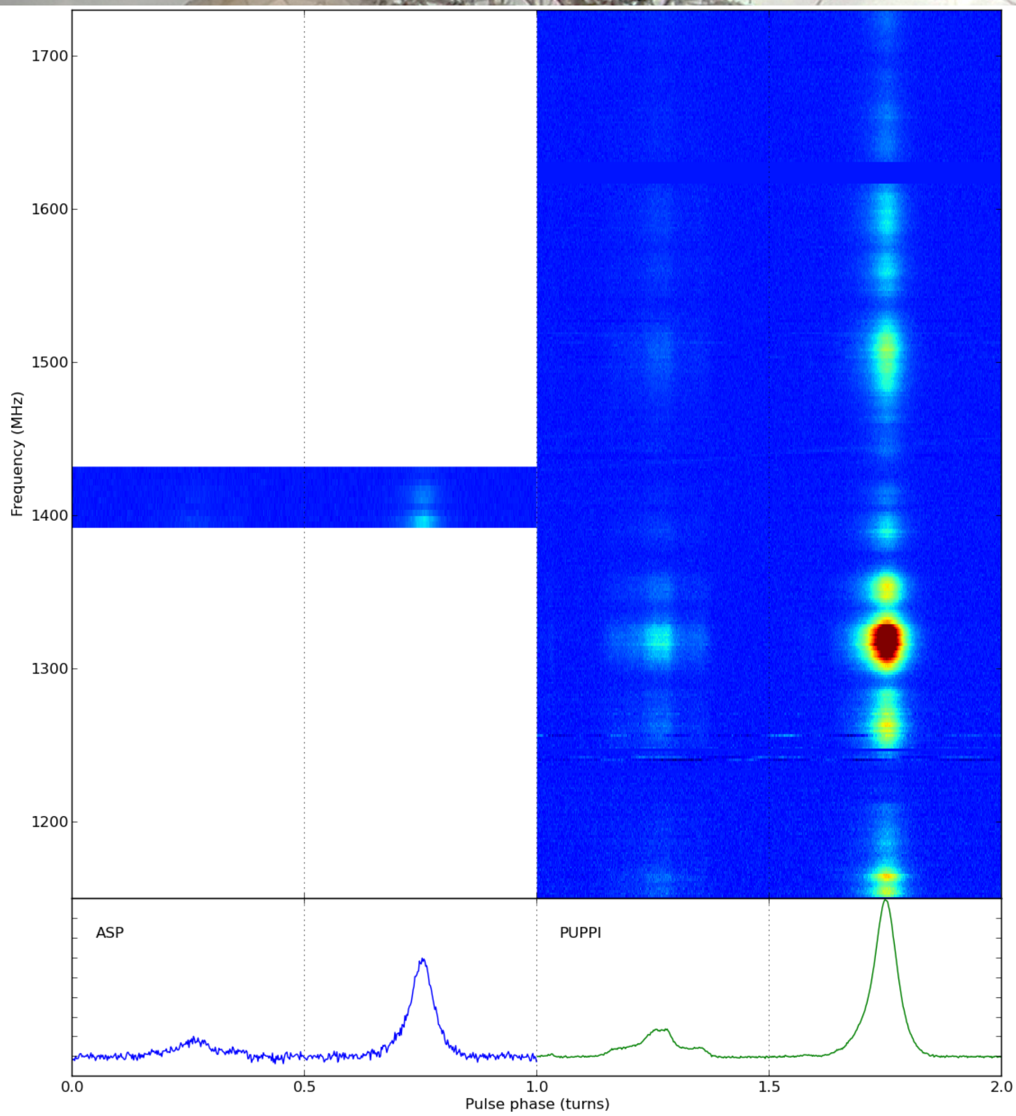


Figure 3. — Simultaneous multi-instrument data taken during a NANOGrav Arecibo observation of PSR J2214+3000 in March 2012 shows the amazing difference in bandwidth between the new PUPPI instrument now used for observations (right) and the previous best instrument, ASP (left). Each plot shows pulse phase on the horizontal axis and radio frequency on the vertical axis. The pulsar strength varies across the band due to interstellar scintillation. Because ASP missed the bright "scintle" near 1300 MHz, the resulting signal-to-noise ratio of the frequency-averaged pulse profiles (bottom panels) is about an order of magnitude larger for PUPPI.

using three separate bands, radio, optical, and X-ray, to explore the electromagnetic spectrum. Indeed, the ratio of the gravitational wave instrument frequencies, $10^{-9} : 10^{-2} : 10^{2}$, is the same as the ratios of the frequencies of radio, optical, and hard X-ray electromagnetic radiation, $10^{8} : 10^{15} : 10^{19}$. Each band of the gravitational spectrum offers its own unique, exciting science.

We are presently observing an array of 19 millisecond pulsars at Arecibo and a similar number of sources, primarily those outside the Arecibo declination range, with the Green Bank Telescope. Further, we have joined with astronomers worldwide to form the International Pulsar Timing Array (IPTA) consortium, which facilitates collaboration and exchanges of pulsar timing data. Pooling millisecond pulsar timing data from radio telescopes worldwide gives access to sources throughout the northern and southern skies, increases observing time and radio frequency coverage, and allows verification of data integrity by comparison of data collected using completely independent observing systems.

Sensitivity to the gravitational wave background is directly proportional to the number of high-precision sources under observation. Pulsar search programs such as the PALFA survey underway at Arecibo (Lazarus et al. 2013) are finding millisecond pulsars at an unprecedented rate. As new, high-precision millisecond pulsars are discovered in surveys, they are added to the NANOGrav long-term timing program.

In 2012, we began using a new data acquisition system, PUPPI (Puertorican Ultimate Pulsar Processing Instrument), for pulsar observations at Arecibo. Developed at NRAO and based on the open-source CASPER FPGA hardware/software suite, PUPPI digitizes the telescope voltages with 8-bit precision and uses a cluster of GPU-

enabled computers for real-time coherent dedispersion of pulsar signals, a necessary step in high precision timing. PUPPI can process bandwidths up to 800 MHz, an order of magnitude more than previous-generation instruments. This gives a large increase in signal-to-noise ratio and hence improvement in timing measurement precision. Further, as shown in Figure 3, pulsar signals observed at Earth show scintillation, random patterns of constructive and destructive interference resulting in regions of stronger and weaker pulsar signals across the observing band; PUPPI's wide bandwidth makes it much more likely that strong signals will be present in the observing band, increasing the reliability of pulsar detection in any given observation. As measurement precision is improved, the prospect of detecting gravitational waves is good, possibly within the next couple of years (Siemens et al. 2013).

For more about NANOGrav and the IPTA, see http://www.nanograv.org/ and www.ipta4gw.org. A repository for public distribution of our NANOGrav data products is under development at http://data.nanograv.org.

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