Pulsar Timing Arrays: No longer a Blunt Instrument for Gravitational Wave Detection

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Pulsar Timing Arrays: No longer a Blunt Instrument for Gravitational Wave Detection

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Abstract. Pulsar timing now has a rich history in placing limits on the stochastic background of gravitational waves, and we plan soon to reach the sensitivity where we can detect, not just place limits on, the stochastic background. However, the capability of pulsar timing goes beyond the detection of a background. Herein I review efforts that include single source detection, localization, waveform recovery, a clever use of a “time-machine” effect, alternate theories of gravity, and finally studies of the noise in our “detector” that will allow us to tune and optimize the experiment. Pulsar timing arrays are no longer “blunt” instruments for gravitational-wave detection limited to only detecting an amplitude of the background. Rather they are shrewd and tunable detectors, capable of a rich and dynamic variety of astrophysical measurements.

1. Introduction
Pulsars are basically celestial clocks, and as such, can be used to construct a Galactic-scale gravitational wave detector using the same concept as ground-based interferometric detectors, i.e. one looks for phase changes in the arrival of the signal at the vertex station, in this case, earth. The length scales of our detector ‘arms’ (1000 light years) as compared to the length of ground-based arms (4km) allow us to probe a different gravitational-wave frequency regime (nHz), a complement to the ground-based kHz regime (Yardley et al. 2010). For almost 30 years pulsar timers have been putting limits on the energy density of the stochastic background using pulsar timing (Romani & Taylor 1983; Stinebring et al. 1990; Kaspi, Taylor, & Ryba 1994; Lommen 2001; Jenet et al. 2006; van Haasteren et al. 2011; Yardley et al. 2011). They point out that at some moment in the future, we will detect rather than limit the stochastic background. This moment is predicted to be sometime within this decade (Demorest et al. 2009; Verbiest et al. 2009).

In the last 10 years the field of gravitational-wave detection using pulsars has matured, and we are now considering much more than just the background of gravitational waves. We are demonstrating that very precise work on specific sources can be done, and that we need to ‘tune’ this detector in order to maximize our sensitivity to these sources. This manuscript briefly reviews these efforts, and is organized as follows. In §2 I give some more details about the concept and current thought behind using pulsar timing arrays (PTAs) to detect gravitational waves. In the subsequent sections I review the work that shows that PTAs can be (§3) directional detectors, (§4) used to recover the gravitational waveform, (§5) used to recover information about the source at some time in past, (§6) used to measure luminosity distance to gravitational-wave sources, (§7) used to test alternate theories of gravity, and (§8) characterized as a formal ‘detector’
using measurements of their noise. Finally, in §9 I summarize the ways in which a PTA is no longer a ‘blunt’ instrument for gravitational-wave detection, but rather a tunable, pointable, and adjustable detector that can be used to gain very specific astrophysical information about the gravitational-wave source being detected.

2. An overview of the concept of gravitational-wave detection using pulsars.

Assume a gravitational wave is propagating through space in direction $\mathbf{k}$ apparently due to some distant source such as a supermassive binary black hole (see figure 1). The gravitational wave changes the curvature of the space-time along which the electromagnetic wave is traveling, and as such induces a change in the time that the pulse arrives at earth. The size of the change at time $t$ for a pulse from pulsar $j$, $\tau_{GW}(\mathbf{k}, t)_j$, is given by

$$
\tau_{GW}(\mathbf{k}, t)_j = F^+(\mathbf{k}, \mathbf{n}_j) g_+(t, L_j, \mathbf{k} \cdot \mathbf{n}_j) + F^\times(\mathbf{k}, \mathbf{n}_j) g_\times(t, L_j, \mathbf{k} \cdot \mathbf{n}_j),
$$

for a TT-gauge gravitational-wave metric perturbation with form $h_+ e_+ + h_\times e_\times$. $\mathbf{n}_j$ is a unit vector pointing to pulsar $j$, $L_j$ is the distance to that pulsar. $F^+/\times$ are geometric functions of $\mathbf{k}$ and $\mathbf{n}$ which we omit here for brevity but can be found in Burt, Lommen, & Finn (2011). Functions $g_+$ and $g_\times$ are integrals of $h_+$ and $h_\times$ as follows (Finn & Lommen 2010):

$$
g_{(+/\times)}(t, L_j, \mathbf{k} \cdot \mathbf{n}_j) = \int_0^{L_j} h_{+/\times} \left( t - (1 + \mathbf{k} \cdot \mathbf{n}_j)(L_j - \lambda) \right) d\lambda.
$$

Note that we are using geometrized units where $c = G = 1$. Following Finn & Lommen (2010) we assume that a function $f$ exists for which

$$
df_{+/\times}(u)/du = h_{+/\times}(u).
$$

Figure 1. (Adapted from NASA) Schematic of a gravitational wave from a black hole binary impinging on a 2-pulsar pulsar timing array. When proper length scales are used the gravitational waves are nearly planar on the scale of the earth-pulsar systems, but §6 discusses the possibility of measuring their curvature.
For a plane wave we can then do the integral as follows:

\[ g_{(+/\times)}(t, L_j, \hat{k}_j \cdot \hat{n}_j) = \frac{f_{+\times}(t)}{1 + k \cdot \hat{n}_j} - \frac{f_{+\times}(t - (1 + \hat{k} \cdot \hat{n}_j)L_j)}{1 + \hat{k} \cdot \hat{n}_j}. \]  

(4)

The first term is the so-called ‘earth term’, and the second the ‘pulsar term’(Jenet et al. 2004). The pulsar term is delayed from the earth term by \((1 + \hat{k} \cdot \hat{n}_j)L_j\) which amounts to thousands of years in most cases.

Pulsar timers attempt to measure \(\tau_{GW}\) by measuring the difference between the expected arrival time of the pulse and the measured arrival time of the pulse. This difference is called a ‘residual.’ The residuals that we measure are certainly not entirely due to passing gravitational waves, but to a variety of effects including the interstellar medium (van Straten 2006; You et al. 2007; Hemberger & Stonebring 2008), measurement noise, and calibration errors (Verbiest et al. 2009). The gravitational-wave signature, however, has a distinct feature that none of the other sources of noise can produce: part of the gravitational-wave signal, the earth term, is correlated among all the pulsars. In other words, the earth term describes a response that all pulsar timing residuals will exhibit at the same moment, independent of their distances. This characteristic can be used to distinguish gravitational waves from other sources of residual (Jenet et al. 2005).

The pulsar term, however, is not correlated among the pulsars. For each pulsar, the amplitudes of both terms will be modulated by the direction of the pulsar with respect to the gravitational-wave source. In addition, the temporal signature in the pulsar term is delayed by an amount which depends upon the distance to that pulsar. The distance is generally not known to better than 10% which corresponds to hundreds of gravitational wavelengths, and as such, it is basically a randomizer of the phase. One must confront this fact when attempting to recover the original waveform and direction of the gravitational waves, as I discuss in the following section.

However, before discussing PTAs as single source directional detectors, let us first consider the combined effect of many sources. This is actually the situation we expect in the universe at large - hundreds of thousands of galaxy pairs merging, with their central black holes eventually coming together to form black hole binaries. Those black hole binaries create a stochastic background of gravitational waves that we expect to be able to detect in pulsar timing.

Though no stochastic background has been detected thus far, many authors have used pulsar timing to limit the energy density of gravitational waves in the universe (Stonebring et al. 1990; Kaspi, Taylor, & Ryba 1994; Lommen & Backer 2001; Jenet, Creighton, & Lommen 2005; van Haasteren et al. 2011). The most strict limit, that placed by van Haasteren et al. (2011) places an upper limit on \(A\) equal to \(6 \times 10^{-15}\) where \(h_c = A \left( \frac{f}{10^{-19}} \right)^{\alpha} \) and \(\alpha = -2/3\), which is at the boundary of existing models of galaxy merger rates (see Jaffe & Backer 2003; Sesana, Vecchio, & Colacino 2008, and references therein). Wen et al. (2011) use this to constrain the coalescence rate of supermassive black-hole binaries. Van Haasteren et al. (2011) demonstrate that their analysis will eventually yield not just the amplitude, but also the slope and perhaps even the shape of the spectrum.

Thus, limiting the stochastic background has been a necessary first step for the field, but there is much to do beyond that. PTAs can do much more than detect a single number such as the amplitude of the stochastic background. They can be fashioned into a multi-faceted precision instrument for gravitational-wave detection.

Armed with an understanding of the earth and pulsar terms, we can now proceed to discuss the challenges of the analysis using PTAs for gravitational-wave detection. Basically, most methods of detection seek to capitalize on the coherence of the earth term without being unduly hindered by the incoherence of the pulsar term. In the next section I review ways in which analyses of single sources go about seeking the same advantage.
3. PTAs as directional detectors

As shown above, there are two terms in the response of a PTA: the earth term and pulsar term. Given the location and waveform of a gravitational-wave source, the earth term in the equation above is completely known. We can turn that statement around and say that if we could somehow distinguish the earth term separately from the pulsar term, and could then measure the amplitudes of the earth term in all our pulsars, we could determine the location and waveform of the gravitational-wave source. In most cases, we cannot separate those two terms. However, it turns out to be possible to determine the direction of the source using various means described below. The methods below all differ in the ways they have treated the pulsar term.

Finn & Lommen (2010) looked at bursts of gravitational waves, sources whose duration is shorter than the data span. Pulsar timing data spans are tens of years, so a burst could be a month-long source. They put forth that by looking at bursts, one can ignore the pulsar term because it is unlikely to enter the dataset in a human lifetime. Note that because the distance between the earth and the pulsar is hundreds or thousands of light years, the delay between the earth term and the pulsar term is hundreds or thousands of years. Thus, any source that produces a burst of coherent response in all the pulsars (i.e. the earth term) will inflict its pulsar term on the same pulsars many hundreds of years later. Finn & Lommen (2010) were able to localize a strong source to less than 1 square degree. For a moderate source it was hundreds of square degrees. For a weak source it was thousands of square degrees.

Sesana and Vecchio (2010) looked at continuous gravitational-wave sources such as binary black holes, where one must include the pulsar term, and they are able to localize the gravitational-wave source to within 40 square degrees for a 100-pulsar array and a signal to noise ratio (S/N) of 10. That number is big because they assumed they could not know the distances to the pulsars, so the 100% variation of the pulsar term makes it very hard to pin down the direction as described at the beginning of this section. Ellis, Jenet, & McLaughlin (2012) has achieved similar results working on a continuous wave pipeline.

Corbin & Cornish (2010) claim they can actually search over and recover the pulsar distances from the chirp signal. They have assumed Gaussian noise for the timing residuals which we may in fact have (see section on detector characterization below), but their technique has not been studied in the presence of red noise. They are able to localize the source to less than 3 square degrees for strong sources. Lee et al. (2011) point out that if the timing parallax (a distance measurement independent of the chirped signal) is estimated at the same time as the GW parameters are estimated then the pulsar term can be used as a great asset in increasing signal strength in single source cases. They carefully predict the statistical uncertainty that PTAs can expect to achieve in determining characteristics of gravitational-wave sources such as orbital inclination angle, source position, frequency, and amplitude. They predict that PTA source localization ability will range from a radian down to several microradians depending on the strength of the source.

Before I summarize these localization results, let me point out that all the above work was done on simulated data in preparation for using real data. However, work has been done on single gravitational-wave sources using real data. Yardley et al. (2010) has used pulsar timing data to limit the number of coalescing binary systems of a given chirp mass as a function of redshift.

My summary for single source localization is as follows. We can localize well for strong burst sources, i.e. less than 1 square degree. For continuous wave sources it is more difficult because one cannot ignore the pulsar term. Without knowing the pulsar distances, it is not clear that one can do better than 40 square degrees, but there is hope for getting the pulsar distances either by mitigating the red noise in pulsars (see section on detector characterization below) so that the distance can be found from the chirp signal (Corbin & Cornish 2010), or by getting the
distances from other means such as timing or VLBI parallax (Lee et al. 2011). One interesting
thing to note is that if one had an eccentric black-hole-binary instead of a circular one, it would
be a repetitive burst source, and the localization would be much easier.

4. PTAs as waveform recoverers
PTAs are potentially able to do much more than detect and localize a gravitational-wave source.
They may be able to actually recover the gravitational waveform. This means that we would
not just be able to pinpoint a source, but also actually decode the structure of the object that
created it. Things like masses, spins, and orientations are encoded in these waveforms. Direct
observations would enable us to learn about the underlying structure of the black holes.

Finn & Lommen (2010) demonstrate that one can recover the waveform of the gravitational-
wave source provided the signal to noise ratio of the source in the data is above about 1/10 in
each of about 30 pulsars. They employ a likelihood method that does not rely on any input
template ‘bank.’ This could be used to recover astrophysical parameters of the source such as
inclination and polarization angles (Sesana & Vecchio 2010).

5. PTAs as time machines
Mingarelli et al. (2011) show that when detecting a binary gravitational-wave source using
pulsar timing, one can detect the source at two different moments in its orbit, because the
earth and pulsar terms represent two different moments in its evolution. If the black holes are
spinning, for example, and there is spin-orbit precession in the system, the PTA will measure
two moments in its spin-orbit evolution at the same time. They can therefore probe higher order
relativistic corrections in \((v/c)\), including the effect of spin-orbit coupling beyond the Newtonian
approximation to the dynamics.

6. PTAs as measurers of luminosity distance
Deng & Finn (2011) demonstrate that the curvature of the waveform (seen in Figure 1) can
be used to measure a gravitational-wave parallax, and thereby obtain the luminosity distance
to sources approaching or exceeding 100 Mpc. This would serve as an important independent
measurement of distance to black hole binaries and other gravitational-wave sources.

7. PTAs as detectors of alternate theories of Gravity
In General Relativity, there are two transverse gravitational-wave polarization modes. However,
alternate theories of gravity can include up to 6 gravitational-wave polarization modes. Lee,
Jenet, & Price (2008) find that if these extra polarizations exist, they could be detected in 5 years
given 40-60 pulsars. Chamberlin & Siemens (2012) show that sensitivity to the vector and scalar-
longitudinal modes can increase dramatically for pulsar pairs with small angular separations.
For example, the J1853+1303/J1857+0943 pulsar pair, with an angular separation of about 3°,
is about 10,000 times more sensitive to a longitudinal component of the stochastic background
than to the transverse components. Detecting an extra gravitational-wave polarization would
provide the first evidence for the violation of General Relativity.

Also in General Relativity, gravitational waves travel at the speed of light, and the graviton is
therefore massless. However, in some alternate theories of gravity the graviton has mass, and the
gravitational wave is therefore dispersive. Lee et al. (2010) estimate that it should be possible
to detect this dispersion using PTAs. In particular they conclude that massless gravitons can be
distinguished from gravitons heavier than \(3 \times 10^{-22}\) eV with 5 years of bi-weekly observations
of 60 pulsars with a pulsar rms timing accuracy of 100 ns. This is not as good as limits placed
currently by Goldhaber & Nieto (1974) using galaxy cluster observations but the two methods
are independent and pulsar timing would represent an important substantiation of the cluster
results.
8. Characterizing the Detector Noise

As we make this transition to thinking about PTAs as shrewd and tunable detectors, one of the things we have had to confront is that we must characterize the noise in the detector just as any other experiment would (See for example Cuocco et al. 2001). In our case the “detector” is the collection of pulsars. Shannon & Cordes (2010), Osłowski et al. (2011), Jenet, Armstrong, & Tinto (2011), Perrodin et al. (2012), and Finn (2012) have all sought to characterize the noise in the pulsars. Shannon & Cordes (2010), and Osłowski et al. (2011) concentrate on determining what the ultimate sensitivity limit will be due to intrinsic variability in the pulsars. Perrodin et al. (2012) using the Cholesky transform as put forth by Coles et al. (2011) concentrates on characterizing the current noise spectrum, while Finn (2012) uses a Bayesian analysis to identify the parameters of a noise model that best describe the timing noise statistics. Jenet, Armstrong, & Tinto (2011) give a full error budget for pulsar timing considering various instrumental, propagation, and other fundamental sources of noise. The effort in all cases is complicated by the fitting of the pulsar model to the time-of-arrival (TOA) data and by the fact that the pulsars are sampled at irregular intervals. The former renders stationary noise un-stationary, and the latter precludes the use of simple FFTs for finding the spectrum.

Once the noise in the detector is characterized, we can optimize the detector. Lee et al. (2012) demonstrated the advantage of optimization which in our case primarily consists of adjusting the amount of time spent on each pulsar, and showed that it only helps appreciably in the case of white noise. Red noise has been identified in many pulsar data sets (Verbiest et al. 2009; van Haasteren et al. 2011), but recent techniques such as those by Demorest et al. (2012) which remove interstellar medium effects seem to significantly reduce the “redness” of the data. In any case the possibility of “tuning” the detector seems very promising.

9. Summary

PTAs have been long regarded as our hope for detecting gravitational waves in the nanoHertz band, but up until recently people have thought that the best one could hope for would be a detection plus one or two numbers parameterizing the stochastic background in gravitational waves in that regime (e.g., the spectral index and overall amplitude). We have started to be able to think about PTAs as detectors, with noise budgets, and various modes that we can tune to suit the source in which we are most interested. I have pointed to work here that is being done not only to detect gravitational waves, but to use them for very particular goals including gravitational-waveform recovery, parameter estimation for individual gravitational-wave sources, locating a source on the sky, distinguishing between theories of gravity, measuring luminosity distance to gravitational-wave sources, and also using the delayed pulsar term as something of a time machine, where we get a glimpse of the source as it existed in the past, and the present, all at once.

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