Pulsar timing techniques

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Received 23 May 2013, in final form 5 August 2013
Published 4 November 2013
Online at stacks.iop.org/CQG/30/224001

Abstract
We describe the procedure, nuances, issues, and choices involved in creating times-of-arrival, residuals and error bars from a set of radio pulsar timing data. We discuss the issue of mis-matched templates, the problem that wide-bandwidth backends introduce, possible solutions to that problem, and correcting for offsets introduced by various observing systems.

PACS numbers: 95.30.Sf, 97.60.Gb, 95.55.Jz
(Some figures may appear in colour only in the online journal)

1. Introduction to pulsar timing arrays

A pulsar is essentially a clock. Pulsars pulse with stunning precision, e.g. in the best-timed radio millisecond pulsars we can predict the arrival time of the next pulse to within 100 ns over a five year period (Verbiest \textit{et al} 2008). A system of well-timed radio millisecond pulsars, therefore, is a system of clocks, and can be used to measure spacetime disturbances such as gravitational waves. Such as system has been termed a ‘pulsar timing array’ by Backer \textit{et al} (1983) and according to current models pulsar timing arrays will detect gravitational waves within the next decade Demorest \textit{et al} (2009).

2. Introduction to the problem

The idea of pulsar timing is simple: we time the arrival of a series of pulses, and fit a model to the measured arrival times. As more pulsar data becomes available we improve the accuracy of the model.

There is a fundamental chicken and egg problem in pulsar timing that goes as follows. The pulsed radio signal is buried in the noise for most pulsars, i.e. most single pulses are undetectable. Thus, in order to detect a pulse, one must add together many thousands of pulses over many thousands of turns of the pulsar. In order for this procedure to yield an accumulated pulse profile with a high signal-to-noise ratio (S/N), one must have a model that tells you how to ‘fold’ the pulsar data onto itself. In order to find this model, one must be able to detect
a pulse (Lorimer and Kramer 2012). The chicken and egg problem is therefore that in order to get a model you need accumulated pulses, and in order to accumulate pulses you need a model.

The chicken and egg problem is solved iteratively. When a pulsar is first discovered, the observer usually has a rough idea of its spin frequency by the location of the peak in the FFT in which it was discovered. This approximate spin frequency is used to accumulate pulses in small batches and acquire three or four times-of-arrival (TOAs) for the pulsar. A model is fit to the TOAs and the new model is used to fold the next set of data that comes in, and the process iterates. Depending on the pulsar ‘backend’ one may be able to go back to the original data and re-fold the data using the improved model. Employing this iterative process results in a good timing model within a year, i.e. one that predicts the arrival time of the next pulse to within a few milliperiods (0.001 times the pulse period) (Verbiest et al 2009, Demorest et al 2013).

The iterative process continues throughout the dataspan of the pulsar, but the model is updated much less frequently than at first, perhaps every couple of years. For example, it is only after a couple of years of data-taking that one is able to fit for proper motion and parallax, so at that moment those parameters are added to the model and the model improves.

3. What time do you say the pulse arrives?

In the previous section we evaded the question of how we measure the arrival time. When a pulsar signal is folded, as described above, over many thousands of turns, the resulting high signal-to-noise data representing the average shape of the pulse is called a ‘pulse profile’. The shift in rotational phase between this profile and a high signal-to-noise reference profile (usually called the ‘template’ or ‘standard’ profile) is then determined, typically using a Fourier-domain algorithm (Taylor 1992). We review the standard algorithm below.

The template profile represents a model for the expected profile shape in the absence of noise (see figure 1 for an example.) This may be created by summing a large amount of profile data together, and post-processing the result to remove remaining noise. As demonstrated by Hotan et al (2005), using a noisy template can produce biased results due to correlation between the noise in the template and the profiles from which it was generated. Noise in the template is often removed by a low-pass filter. Demorest et al (2013) used a wavelet-based noise removal process. Another common technique is to create a template by fitting a series of Gaussian functions to a high signal-to-noise profile (Kramer 1994).

Given a data profile \(d(\phi)\) and a template profile \(p(\phi)\) where \(\phi\) runs from 0 to 1, the relative phase shift between the two, \(\Delta \phi\), is usually determined via a \(\chi^2\) minimization in the Fourier domain:

\[
\chi^2(a, \Delta \phi) = \sum_{k=1}^{k_{\text{max}}} \frac{|d_k - a p_k e^{-2\pi i k \Delta \phi}|^2}{\sigma^2}.
\]

(1)

Here, \(d_k\) and \(p_k\) are the discrete Fourier transforms of the profiles and \(\sigma^2\) is the noise power in each harmonic component, assumed to be constant. The fit parameter \(\Delta \phi\) is the phase shift of interest, and the nuisance parameter \(a\) is a scale factor between the two profiles (related to the pulse flux). It is possible to expand the sum in the above equation into three terms:

\[
\chi^2(a, \Delta \phi) = \sigma^{-2}(D^2 + a^2 P^2 - 2a C_{\Delta \phi} \langle \Delta \phi \rangle).
\]

(2)

3 ‘Backend’ refers to the equipment at the telescope that is used to process the voltages that come in from the ‘front end’ or telescope. Descriptions of backends can be found in Kramer et al (1999a), Volle et al (2002), DuPlain et al (2008), Cognard et al (2009), Karuppusamy et al (2008), Karuppusamy (2011) and Sarkissian et al (2011).

4 An additional nuisance factor—the dc offset between the two profiles—has been avoided by starting the sum at \(k = 1\).
Figure 1. Illustration of the template matching process. The upper panels show a template profile for the 4.6 ms pulsar J1713+0747 determined from 1600 MHz data taken with the Green Bank Telescope (note the same profile is shown in both upper panels). The fiducial point is at phase zero, and was determined via the phase of the first Fourier component. In the middle left-hand panel, this template profile is fit to a 1600 MHz ‘data’ profile using the method described in the text. The measured phase shift is $0.4158 \pm 0.00013$ turns. The bottom-left panel shows the noise-like profile residuals from this fit. The middle-right panel shows a fit of the same template to data taken at 750 MHz. In this case, the template is a poor match to the data and there is highly significant structure left over in the residuals (bottom right). The phase shift in this case is $0.19036 \pm 0.00016$ turns. Using the correct template for the 750 MHz data results in a factor of $\sim 3$ smaller phase shift uncertainty.

Here, $D^2$ and $P^2$ are the sum of squares of the Fourier amplitudes of the data and template profiles respectively. The final term, $C_{dp}(\Delta \phi) = \text{Re} \sum_k d_k p_k^* e^{2\pi i k \phi}$, can be interpreted as the cross-correlation between the two profiles. This term contains all the phase shift information, and it is straightforward to show that the $\chi^2$ minimum always occurs at the phase shift that maximizes $C_{dp}$. We call this phase shift where $C_{dp}$ is a maximum $\hat{\Delta} \phi$.

This phase shift represents the difference between the observed and model-predicted pulse phases, averaged over the timespan of the observation. This is converted to a TOA as follows: first, the model-predicted phase at the midpoint of the observation is subtracted from the measured phase shift. The result is multiplied by the model-predicted pulse period and added to the midpoint time, giving the final time of arrival. TOAs calculated in this manner are independent of the timing model used to fold the data, and can then be used as input for future model fits without needing to retain full details of the original folding. Referring the TOA to the midpoint of the observation (rather than the start) avoids biases that can be introduced due to an inaccurate initial model. TOAs are however not independent of the template profile used to measure them and care must be taken when combining sets of TOAs determined using different templates (see section 6 for additional discussion).
Relating the time-stamp to UTC is also a non-trivial endeavor. The original time-stamp from the observatory is generally from time kept by a hydrogen maser local to the observatory. The comparison between this ‘observatory time’ and GPS ‘common view’ time is kept on an hourly basis and is generally smaller than 100 ns. The comparison between GPS time and Bureau International des Poids et Mesures (BIPM) time is published by BIPM monthly. These three ingredients are added together to yield time stamps that are within a few nanoseconds of UTC. Various telescopes have slight variations on this scheme but the general idea is usually the same. For a more complete description of this process see Edwards et al (2006).

An estimate of the uncertainty of the best-fit $\Delta\phi$ (and $a$ if desired) is then found via second derivatives of $\chi^2$ following standard procedures (e.g. Press et al 1992):

$$\sigma_{\Delta\phi}^2 = \frac{1}{2} \left( \frac{\partial^2 \chi^2}{\partial \phi^2} \right)^{-1} = \frac{\sigma^2 P^2}{-2C_{dp}(\Delta\phi)C'_{dp}(\Delta\phi)}.$$  

(3)

This uncertainty estimate implicitly assumes that the parameter likelihood function (proportional to $e^{-\chi^2/2}$) has a Gaussian shape. In the high-S/N limit this is an extremely good approximation. However, at lower S/N values, this approximation becomes worse, and the TOA error distribution becomes non-Gaussian, and highly dependent on the profile shape. This is most often dealt with by employing a signal-to-noise ratio cutoff, below which profile data is not used for TOA generation.

The uncertainty in a TOA is roughly the pulse width $W$ divided by the signal-to-noise of the profile $S/N$ and scales as follows (Lorimer and Kramer 2012)

$$\sigma_{\phi} \approx \frac{W}{S/N} \propto \frac{S_{\text{sys}}}{\sqrt{t_{\text{obs}}/\Delta f}} \times \frac{P^{3/2}}{S_{\text{mean}}}$$  

(4)

where $S_{\text{sys}}$ is the flux density of the pulsar, $\Delta f$ is the observing bandwidth, $t_{\text{obs}}$ is the integration time, $P$ is the pulse period, and $W$ is the width of the pulse, and $S_{\text{mean}}$ is the mean flux density of the pulsar. Bright, short-period, narrow pulsars yield smaller uncertainties as do sensitive wide-band detecting systems.

The uncertainty in the TOA is determined via the $\chi^2$ procedure described above, and depends only on the shape of the template data profiles, and the noise level in the data ($\sigma$). The noise level is primarily due to radiometer noise, and the standard TOA uncertainty does not explicitly include additional sources of TOA systematic bias, for example from the interstellar medium (ISM) or clock errors. However, both ISM errors and polarization calibration errors can produce a mis-match between the shape of the template and the shape of the profile (as shown in figure 1) and as such will bias TOAs by some amount, possibly in excess of their formal $\chi^2$-estimated uncertainties.

Many pulsars exhibit evidence for additional sources of noise beyond the simple radiometer-noise-dominated measurement errors (Hobbs et al 2006, also see articles by Stinebring and Cordes in this volume) and it is less clear how to account for these in the estimate of uncertainty in the TOAs. First, the pulsar is likely to have intrinsic phase or frequency noise (see article by Cordes in this volume and also Shannon and Cordes (2010)) but it is unclear at what level this enters. In either case this intrinsic noise is not easy to estimate, and is not generally reflected in the formally calculated uncertainties. Similarly, the ISM adds noise both by changing the index of refraction along the line-of-sight to the pulsar, and by scattering the pulse (see article by Stinebring in this issue). Both effects cause delays. The standard way of accounting for the former is to take data at two radio frequencies separated substantially in frequency (such as 1400 and 2400 MHz, see e.g. Kaspi et al 1994). The difference in arrival time between the two frequencies allows one to calculate the ‘dispersion

5 www.bipm.org
measure’ or DM along the line-of-sight and allows the subtraction of the delay caused by the ISM as follows:

\[ t_2 - t_1 = (1/0.241) \text{ ms DM } [(v_1/\text{GHz})^{-2} - (v_2/\text{GHz})^{-2}] \]  

where \( t_1 \) and \( t_2 \) are the arrival times at the two frequencies \( v_1 \) and \( v_2 \) and DM is proportional to the column density of electrons along the line of site (Lorimer and Kramer 2012). With current instruments, variation of DM over time is detectable in the timing of most bright MSPs, and correcting them via a technique such as this is necessary to achieve \( \sim 100 \text{ ns} \) level timing (Demorest et al. 2013, Keith et al. 2013). Recent work by Shannon and Cordes (2010) suggests that three- or four-frequency data and more advance corrections schemes may be necessary to achieve sub-100 ns results for many pulsars. However, the newest pulsar machines (see articles by McLaughlin, Kramer and Hobbs in this volume) have such wide bandwidths (\( \sim 1 \text{ GHz} \)) that it may be possible to leverage the bandwidth to accomplish the same thing. This is a bit tricky, as we will describe in the next section. Keith et al. (2013) found success using the same equation above in conjunction with a ‘common mode’ TOA and an iterative process to find DM(t).

In addition, pulsar backends must deal with dispersion within (not just between) observing bands. For a full treatment of this issue please see Lorimer and Kramer (2012).

One common software package used for measuring TOAs (as well as calibration and a large number of other standard data processing steps) is called PSRCHIVE6 (Hotan et al. 2004, van Straten et al. 2012). PSRCHIVE is developed collaboratively by members of the pulsar research community worldwide, and is freely available, open-source software.

4. Fitting to a model

The basic ingredients of a pulsar timing model are the spin period and period derivative, right ascension (RA) and declination (DEC) of a pulsar. With these ingredients one can usually construct a phase-connected solution that spans several months, or perhaps even a year. If the pulsar is in a binary system, one needs five additional Keplerian orbital parameters: the projected semi-major axis of the orbit, the orbital period, the position of peri-astron, the eccentricity, and the mass function. Other circumstances and additional refinements can warrant additional parameters: relativistic orbits, glitches, proper motion, parallax, etc (Lorimer and Kramer 2012). The criterion of ‘phase-connection’ refers to the necessity for the model to keep track of which turn the pulsar is on. For example a particular model may do well to predict the arrival time of several pulses separated by a couple days, but when another data point is added a month later, the model may not be good enough to predict the fourth point and connect its phase. In fact if the model is off by more than a pulse period, the model will not even be able to correctly calculate which turn the pulsar is on (much less its phase), and therefore the fit to such a model produces erratic results. A phase-connected model will correctly predict the arrival time of every pulse corresponding to a TOA to within a half of a pulse period. For more information on the details of timing model fits, see Edwards et al. (2006).

The output of the model-fitting is a list of the fitted parameters and their uncertainties, but also the so-called residuals, i.e. the difference between the model and the measured TOAs. For high signal-to-noise data a good model generally yields residuals that are in the vicinity of or better than a milliperiod. Two example plots of residuals are shown in figure 2.

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6 http://psrchive.sourceforge.net
The fit of a model to the TOAs is done using the more traditional TEMPO\(^7\) or the newer TEMPO\(^8\). Both are freely available for download, contain most of the same features, and for the remainder of this paper both will be implied when we say ‘TEMPO’. In both cases the input to the program is a list of TOAs (produced as described above) plus a timing model that fits the data well enough for phase connection as described above. If the data are indeed phase connected then the least-squares fitting algorithm performed in TEMPO will improve the fit (as judged by its \(\chi^2\) or by its RMS residual) and refine the fitted parameters. If the model is not sufficiently good to phase connect the timing solution then the fitting procedure will not achieve anything worthwhile, and is likely to find a solution in local minimum that is even worse than the original input model.

Fits often yield large \(\chi^2\) values indicating that the error bars on the timing points have been underestimated or there is unmodeled noise, perhaps due to some of the issues discussed in the previous section. Pulsar timers commonly multiply the errors acquired from the comparison of the template to the profile (using the parameter EFAC in TEMPO, software described in section 4) or add in a quadrature another component (using the parameter EQUAD). This is a practice that is empirical, based on noticing that the scatter of residuals exceeds what you would expect from the size of the error bars (such as in the left-hand panel of figure 2).

The practice of adding arbitrarily to the error bars is admittedly unappealing; there are other solutions. One method involves using the scatter of the residuals on a particular day, typically the standard deviation of them, as an estimate of the uncertainty from these unknown sources. This accounts for noise on shorter timescales (typically data are taken over a half-hour period) but does not account for noise on longer timescales (many of the timescales in the ISM are multiple days.)

Large \(\chi^2\) values in the timing fit also can be indicative of red noise in the residuals. Both Coles \textit{et al} (2011) and van Haasteren and Levin (2013) have developed advanced techniques for dealing with correlated noise in pulsar timing residuals. Coles \textit{et al} (2011) employs a whitening procedure before fitting, and van Haasteren and Levin (2013) develops a Bayesian technique for parameter estimation in the presence of red noise.

\footnotesize
\textsuperscript{7} http://tempo.sourceforge.net
\textsuperscript{8} www.sf.net/projects/tempo2/
One way to improve this procedure is to find values of fitted parameters in ways other than performing timing fits, such as finding the RA and DEC and proper motion of the pulsar using very-long baseline interferometry (VLBI). This has advantages. First, it can allow one to find a phase-connected solution earlier. Second, it will reduce the uncertainties in parameters that covary with the astrometric parameters (especially in shorter data sets (<1 year), the pulsar parameters (e.g. period derivative) covary with the astrometric parameters (e.g. RA). This elimination of covariance has favorable consequences such as allowing pulsars to be assessed for the presence of red noise more accurately earlier than without (Madison et al 2012). Madison et al (2012) also showed that a sub-milliarcsec determination of a pulsar’s position and proper motion using VLBI would allow some gravitational wave signatures to be found more easily.

5. Daily averaging of TOAs

Commonly, the data from the telescope arrives in one-minute ‘scans’ and a typical pulsar timing array (PTA) observing run will acquire 30 scans on each pulsar at each frequency. Each scan yields a single TOA, so one begins with 30 TOAs per frequency per day. For two reasons, one typically compiles these 30 successive scans into a single ‘daily averaged’ TOA. First, the averaging improves the S/N of the TOAs by roughly a factor of $\sqrt{30}$. Second, PTAs are not as sensitive to gravitational waves from either massive black-hole binaries or relic sources of gravitational waves sources in the vicinity of frequencies near 1/min as they are to sources near 1/year because of the expected spectrum of those sources (see articles in this volume by Sesana, Cornish, Siemens, Cordes and Ellis), so there is little need to maintain the time resolution of the array near the minute-long timescales.

There are two ways to accomplish this daily averaging, and both depend on having a good timing model for the pulsar. First, one can average the profiles together into a single profile and compute a single TOA. Alternatively one can average the TOAs together. Averaging TOAs together is non-trivial, but straightforward. First, the timing model is used to create residuals from each of the TOAs. One then performs a weighted average of the residuals, yielding a single residual and a single uncertainty. This residual is then added to the model prediction of an arrival time in the center of the time-range represented by the original TOAs.

The result is a new set of TOAs, one for each day for each frequency at which the pulsar was observed. This resulting set of TOAs is generally what is used for the remainder of the analysis.

This procedure could in principle be carried even farther in order to combine the TOAs at widely different frequencies into a single TOA representing an ‘infinite frequency’ (non-ISM-disturbed) TOA (Keith et al 2013). The procedure would be similar to that described above. (See section 6.2 for another way to average timing data over large ranges in frequency.) In practice, this is not common yet. Typically pulsar astronomers like to look at the nuances in the residuals at different frequencies, and some frequencies may be missing on some days. All these caveats make astronomers reluctant to absorb all that detailed information into a single TOA.

6. When things go wrong with determining TOAs

6.1. Polarization

As described above, when the data profile shape does not match the template profile shape, biases are introduced in the TOAs. While a constant error of this sort is unimportant, profile
shape errors that vary as a function of time and/or radio frequency can corrupt timing solutions. One important source of such errors is the polarization properties of the pulsar signal. Pulsar radiation is generally highly polarized, and the polarization state changes across the pulse profile (e.g. Stairs 2001). The response of the radio telescope receiver and backend systems can be represented by a matrix transformation (the Mueller matrix) that connects the ‘true’ astronomical source parameters with the observed values. In order to calibrate out the instrumental response this matrix typically must be determined empirically from observations of astronomical calibration sources (e.g., van Straten 2004). Errors or uncertainties in this process alter the profile shapes and affect timing results. One proposed solution to this problem is to determine TOAs using the ‘invariant interval’—this quantity, related to the unpolarized portion of the signal, is insensitive to calibration errors (Britton 2000). However this method has only proved useful for a small number of pulsars. A second approach, called matrix template matching, uses the full polarization content of the signal while simultaneously determining TOAs (van Straten 2006). This also reduces sensitivity to calibration errors and in some cases also improves TOA accuracy. Recent work has shown how pulsars can themselves be used as polarization calibrators (van Straten 2013), allowing calibration solutions to be determined from the brightest sources in a data set, then applied to the rest.

6.2. The large-bandwidth problem and its possible solutions

6.2.1. The problem. The large-bandwidth problem stems from our inability to identify a fiducial point in the pulse profile. A TOA is not so much the arrival time of a pulse as it is the arrival time of a particular template. One can use the leading edge of a particular template as the fiducial point, the tallest bin in the template, or the phase of the first Fourier component of the template. As long as one is consistent about the choice, and uses the same template for the whole data set then generally the choice does not matter.

However, pulse profiles evolve over frequency, i.e. they have a different shape at low frequency than they do at high frequency, and they change continuously in between. So first consider the problem of using just two frequencies, e.g. 1400 and 2400 MHz. The pulse profile looks slightly different at each, perhaps the profile is double-peaked and the relative height ratio between the two peaks is different at the two frequencies. Figure 3 shows how a pulsar might evolve over frequency. A close match between the shape of the template and the shape of the profile is crucial for reliable timing, so it would be ill advised to use the same template for both frequencies, and one must use one template for 1400 and a different one for 2400.

But now the choice of fiducial point is problematic. One has insufficient information to choose a fiducial point that represents a physical location on the star. In the case of a
single-sharp-peaked profile the choice would be likely be the peak, but what part of the peak would be chosen? The peak bin? The leading half-max point? Most profiles are much more complicated than a single sharp peak, and the choices are infinite. In the case of two-frequency data any mistake is absorbed by the fit to the column density of electrons described above. In other words, a bad choice of fiducial point will amount to a constant offset between the 1400 and 2400 MHz data. The constant offset will be absorbed by the fit to electron column density (usually called DM) by slightly changing the fitted DM. As a matter of nuance, we should also say that often, especially in precision timing work, the DM is allowed to change over the span of the data set. Physically this corresponds to changes in the electron content along the pulsar-observatory line-of-sight due to the motion of the pulsar, Earth, and ISM. The basic idea, however, of a single offset DM absorbing any error in fiducial point designation holds true.

Now imagine that instead of 2 frequencies there are 16. This was the case for early North American Nanohertz Observatory of Gravitational Waves (NANOGrav) data which consisted of 16 4-MHz channels (64 MHz total bandwidth). Now with the use of more recent backends (e.g. GUPPI, PUPPI, see DuPlain et al 2008) NANOGrav data is typically 512 1.5-MHz channels (800 MHz total). Each of the 16 templates looks slightly different, and the choice of fiducial point is not obvious. Because there are 16 frequencies instead of just 2, the DM fit no longer absolves one of confronting the issue. What should one do? This is the large-bandwidth problem. Following are descriptions of solutions to this problem.

6.2.2. The solutions. The solution in Demorest et al (2013) is inspired by an extrapolation of the two-frequency method described above. One chooses a fiducial point in each of the 32 templates, and as above, the choice does not matter. One generates TOAs for each profile, and applies TEMPO to the TOAs with the following addition: an additional fittable arbitrary offset (known in TEMPO as a ‘jump’) is added for 31 of the 32 frequencies. In other words, one is pleading ignorance as to the alignment of the 32 templates, and allows TEMPO to find the alignment that best reduces the RMS. The 31 jumps are tantamount to the DM fit in the two-frequency case. In both cases, the fit allows adjustment for any fiducial-point errors made in the use of the templates. The analysis is concluded by averaging the residuals results together on any given day. Demorest et al (2013) demonstrated that this successfully removes the ISM contribution from the data. Criticisms include a concern that the extra free parameters may absorb some of the signal of interest.

Another solution that shows promise, but has not yet been placed into practice is to create a single two-dimensional template (intensity versus pulse phase versus frequency) rather than creating a one-dimensional template (intensity versus pulse phase) at a number of different frequencies. The phase of the template is adjustable smoothly as a function of frequency, but only adjustable perhaps according to the cold-plasma dispersion relation that governs the arrival time of pulses as a function of frequency. A model like this has been demonstrated to work on simulated data using Bayesian analysis by Messenger et al (2011) and is also being developed by both Pennucci et al (2013) and Liu et al (2013) using χ^2 minimization to optimize the solution. This scheme has the advantage of elegance, i.e. one only needs a single template for a single data scan no matter how wide the bandwidth of the scan.

6.3. Pulse-shape variations

There remain issues of pulse-shape changes even in single frequency data (i.e. apart from the wide bandwidth issues we discuss above). Some observed changed are thought to be intrinsic to the pulsar (Kramer et al 1999b) and some are calibration errors (Britton 2000). It is possible
to develop a completely general approach to the problem of pulse shape variation and timing errors. Rather than trying to anticipate the various causes of profile shape variations, these can be characterized empirically in the data using principal components analysis (PCA; Demorest 2007, Osłowski et al 2011). In this approach the observed profile variations in the residual (post template matching) profiles are measured via PCA. Correlations between the profile variations and timing residuals are then measured and used to correct the TOAs. A recent extension of this procedure that uses full polarization profiles has shown an 40% improvement in the timing of J0437−4715 (Osłowski et al 2013).

7. Calibrating telescope offsets using pulsars

Finally, the difference in telescope hardware and software causes observing-system-dependent delays in TOAs from any particular machine. If only one observing system is used to create a set of TOAs this delay is irrelevant. However, in this era of multi-telescope multi-backend observing the offsets between machines are important. The most common practice is to fit an arbitrary offset in phase between TOAs from different observing systems. For example, in a set of TOAs employing two different backends, an offset would be required between the two systems for each pulsar at each frequency (Verbiest et al 2008). These extra fitted parameters can serve to absorb gravitational wave signal. Rather than having to determine these instrumental offsets from pulsar data, Manchester et al (2013) developed a system to calibrate out the offsets by injecting a locally generated pulsed signal into the signal path.

8. Not included in this paper

Readers may be interested in some of the following ideas not discussed in this paper. First, Dan Stinebring and the Interstellar Medium Mitigation group of NANOGrav are mounting an effort to solve for the ISM scattering function using cyclic spectroscopy, a technique brought to pulsar timing by Demorest (2011). This work shows great promise and is the subject of an article by Stinebring in this volume. Second, a number of mode-changing regular (not millisecond) pulsars have been identified in which the pulsar switches between two different period derivatives (Lyne et al 2010). In the absence of the identification of such a mode, an observer might think that the pulsar was exhibiting simple stochastic timing noise. In fact, synchronously with the mode switching, the pulsar’s profile actually changes shape, so there is some promise that the analysis could properly and prescriptively account for the two modes. This mode-switching behavior has not been shown to exist in MSPs, but it has not been ruled out.

Acknowledgments

Thank you to Brian Christy, David Nice, and an anonymous referee for useful comments. ANL gratefully acknowledges the support of National Science Foundation grants PIRE OIP 09-68296 and AST CAREER 07-48580. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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