Part 2
Precision Measurements

Section A
Timing

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The Next Five Years of Pulsar Timing

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Abstract. Timing measurements of pulsars have yielded a number of important results over the years, and their value is generally a strong function of measurement accuracy. I briefly summarize the present state of affairs in pulsar timing, and then offer some judgments about what may help to produce the best results in coming years.

1. Introduction

Timing observations of pulsars have taught us much of what we know about these curious stars, and a great deal more besides. A spinning neutron star emitting tightly beamed radio noise can be modeled, as far as the observed timing of its pulses is concerned, with just a handful of parameters. The phase of the periodic waveform can be measured to within a milliperiod or so at a given epoch, whereas $10^7 - 10^{10}$ or more periods may elapse over a long series of timing measurements; consequently, the model parameters can often be determined with accuracies of many significant digits. Laboratory measurements of any quantity with accuracies of 6–12 digits are unusual, so it should not be surprising that pulsar timing results have proven useful for a wide range of physics and astrophysics applications.

Much of the recent attention has been focused on timing the shortest-period pulsars, whose stable profiles and narrow pulse widths can lead to time-of-arrival accuracies in the microsecond range or even better. Most of these "recycled" pulsars are found in binary systems; moreover, most have been found to be extremely stable and predictable in their spin-down behavior, so they provide excellent astrophysical test signals for many purposes. Having gazed into my crystal ball and considered its cloudy images, I shall attempt in this paper to identify avenues of pulsar timing work that may be especially ripe for progress in the near future.

2. The Present State of Affairs

Most of the known pulsars have been timed for at least a few months, and the timing behavior of a few has been followed for more than a quarter century. After fitting out the effects of the observer's motion and the pulsar's spin-down, one generally finds post-fit residuals consistent with the measurement uncertainties, at least for data spans up to a year or so. In this process one measures the

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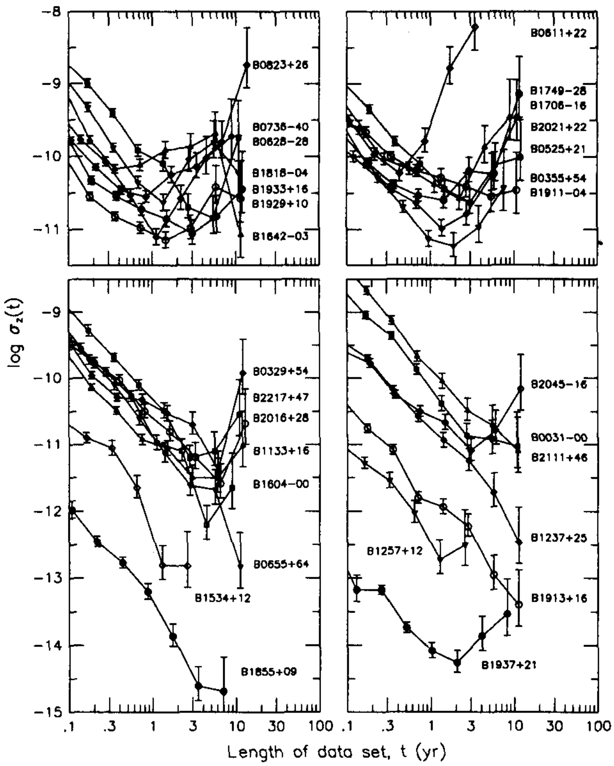

Figure 1. Fractional instabilities, $\sigma_z(t)$, of 29 pulsars. On short time scales the curves have slopes of $-3/2$, consistent with uncorrelated phase noise dominated by the measurement uncertainties. Over longer intervals most of the curves turn upward, indicating some intrinsic rotational instability.

pulsar's period, period derivative, and position with high accuracy. Such data are now available for about three quarters of the 700-plus known pulsars.

Over time scales exceeding one to three years, most pulsars show some evidence of rotational instability. This stochastic behavior is conveniently measured in terms of a dimensionless quantity closely related to the Allan variance often used to characterize man-made clocks (Taylor 1991). Figure 1 illustrates values of this fractional instability, $\sigma_z(t)$, for 29 pulsars over time scales from a month to more than a decade. It shows that even the least stable pulsars keep time very well; for example, PSR B0611+22 (at the top right of the figure) typically gains or loses less than a second relative to atomic time over three years. The half-dozen pulsars nearest the bottom of the figure are many orders of magnitude more stable, most of them showing little or no timing irregularities attributable to the pulsar for as long as they have been observed.

The information content of pulsar timing observations increases rapidly with the measurement precision. As a result some of the most interesting results

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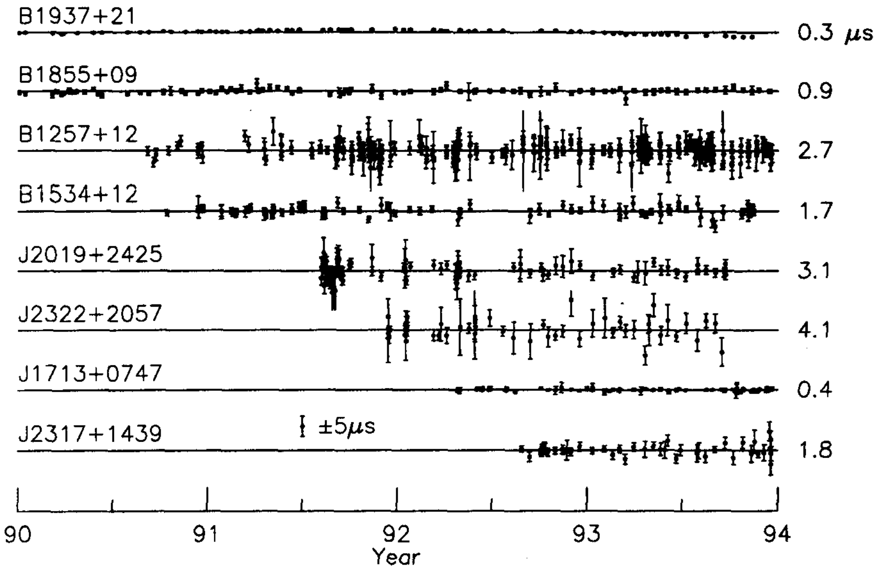

Figure 2. Timing residuals for 8 recycled pulsars observed at Arecibo. The vertical scale is the same for each pulsar and is given by the $\pm 5\,\mu$s error flag near the bottom. Median measurement uncertainties are indicated by numbers at the right. In addition to pulsar rotation and astrometric quantities, orbital elements have been fitted for all except the solitary pulsars B1937+21 and J2322+2057.

are provided by millisecond pulsars, with their proportionally smaller timing uncertainties. Most millisecond pulsars are found in binary systems; with timing uncertainties in the microsecond range and orbits a few light seconds across, their Keplerian orbital parameters can generally be determined to parts-per-million accuracies. Timing residuals from such solutions are usually consistent with the statistics of random measurement errors, as may be seen in the examples plotted in Figure 2. For each of these pulsars, as well as a number of others observed with the Arecibo, Green Bank, Jodrell Bank, Parkes, and other large radio telescopes, the data are sufficient to determine accurate spin-down parameters and celestial positions and proper motions at the milli-arcsecond and milli-arcsecond per year level, as well as orbital elements when applicable.

Binary pulsars provide important experimental constraints for evolutionary models of interacting binary star systems, as well as the best opportunities for measuring neutron star masses and for testing relativistic gravity. A wide range of orbital parameters have been observed, and some of their characteristics can be seen in Figure 3, a plot of mass function *vs.* orbital eccentricity. If a pulsar and its companion have masses m_1 and m_2, respectively, and the orbital inclination is i, the pulsar's mass function is defined by

$$f_1(m_1, m_2, \sin i) = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} = 1.07 \times 10^{-3} \left(\frac{x^3}{P_b^2} \right), \tag{1}$$

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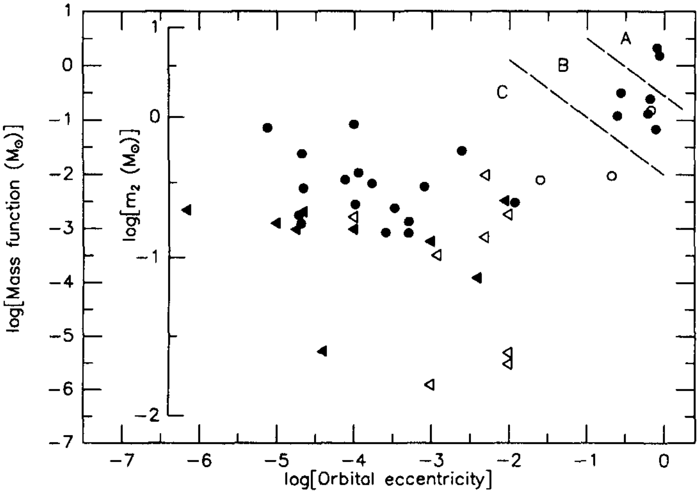

Figure 3. Mass functions and orbital eccentricities of 44 binary pulsar systems. Open symbols denote pulsars in globular clusters, and triangles represent upper limits to eccentricity. Approximate masses of companion stars, m_2, may be read from the interior scale at left.

where $x \equiv a_1 \sin i/c$ is the projected semi-major axis in seconds, P_b is the period of the binary orbit in days, and the masses are in solar units. In the region labeled "A" at the upper right of the figure are two pulsars with highly eccentric orbits and massive, upper-main-sequence companions. Slightly below them in region "B" are six pulsars with large orbital eccentricities and somewhat smaller mass functions consistent with their being double-neutron-star systems. Finally, region "C" contains 36 pulsars in nearly circular orbits and smaller mass functions consistent with degenerate dwarf companions, some of which have been observed optically.

Nine binary pulsar systems have yielded useful measurements of one or more relativistic orbital parameters. A summary of fractional uncertainties of these measurements is presented in Figure 4. Most commonly the relativistic orbital precession $\dot{\omega}$ is the easiest "post-Keplerian" (PK) parameter to measure; occasionally, as for PSRs J1713+0747 and B1855+09, a large inclination makes the Shapiro delay parameters r and s measurable even when the eccentricity is small and $\dot{\omega}$ is inaccessible. Any two measured PK parameters make a solution for the two component masses possible, and tests of relativity are possible when three or more PK parameters can be determined.

3. Near-Term Goals: Accuracy Counts!

The importance of high timing accuracy means that pulsar observers should ask themselves the following questions: Am I achieving time-of arrival uncertainties as small as the pulse width divided by the signal-to-noise ratio? Do the uncertainties integrate down as $T^{-1/2}$ for longer integrations? Do I understand the

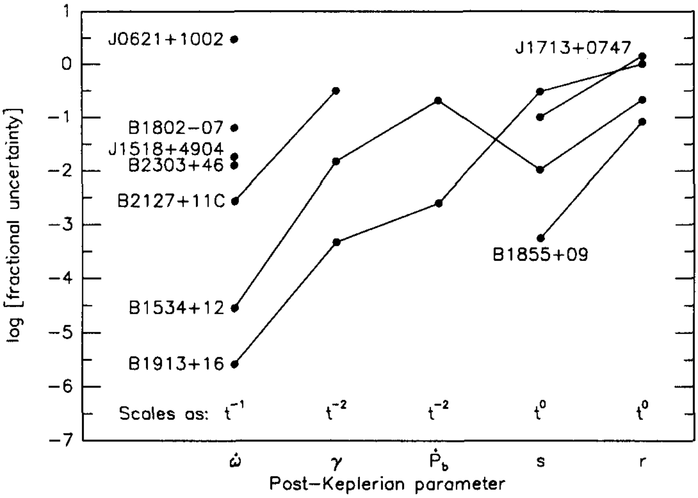

Figure 4. Fractional uncertainties of measured post-Keplerian parameters for binary pulsar systems.

systematic errors of the experiment? Can I reduce them? Experience shows that it is very difficult to achieve timing accuracies much less than the width of one bin in the folded profile, the dispersion smearing across a single channel of the receiver bandpass, or the interstellar scattering time scale. For these and other reasons, my colleagues and I at Princeton have concluded that in future the very best pulsar timing measurements will probably make use of coherent dispersion removal techniques. We've built and tested two trial versions of a data acquisition system for this purpose, first with 0.5 MHz and then with 5.0 MHz bandwidth. Some details of our implementation are outlined in a poster paper by Shrauner *et al.*, elsewhere in this volume. A 10 MHz bandwidth version is presently nearing completion and will soon be installed at Arecibo.

Some early results with the $B = 0.5$ MHz system used at Arecibo are summarized in Figures 5 and 6. The former shows the integrated profile of PSR B1534+12, followed by plots of the amplitudes and phases of its Fourier coefficients. I show these to illustrate that even with this narrow-bandwidth observation the coefficients contain significant information up to harmonic numbers well beyond 100. It is important to use observing systems that preserve such information, keeping the instrumental resolution well below, say, a milliperiod. This is easy to achieve with a coherent signal-processing system, for which the time resolution equals the inverse bandwidth.

Figure 6 provides some hints of the timing accuracies that a coherent observing system should provide at Arecibo. It shows short sequences of timing measurements for six millisecond pulsars that together illustrate some of the most important phenomena. Above each panel is a curve showing scintillation-induced changes in signal strength during the 35- to 120-minute-long observations. The pulsar names and integration times T (in seconds) are listed along the right border, together with the number N of times of arrival (TOAs) with

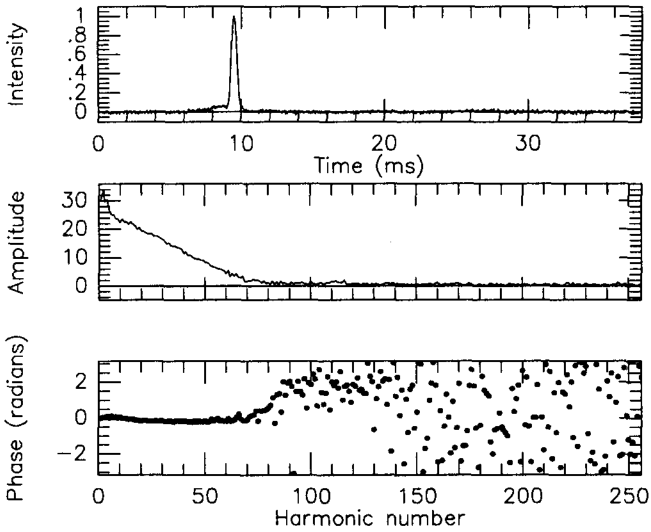

Figure 5. Integrated profile of PSR B1534+12 at 430 MHz, obtained in a 20 min observation with coherently de-dispersed bandwidth B = 0.5 MHz. Lower panels show the profile's Fourier coefficients up to harmonic number 256.

estimated uncertainties less than a stated value σ (in μs). For most pulsars the data obtained over an hour or so will usually be combined to yield an "average daily TOA" with much smaller uncertainty. It should be clear that a suitable algorithm for combining the data must allow for the large variations in signal strength. The data plotted for PSR B1937+21 show that 430 MHz is too low a frequency for accurate timing measurements of this pulsar: the timing deviations are dominated by changes in the interstellar scintillation features, and the resulting scattering profiles, over time scales of a few minutes. But in general our results show that for pulsars such as these, sub-microsecond timing accuracies should be possible with a coherently processed system with B = 10 MHz bandwidth.

References

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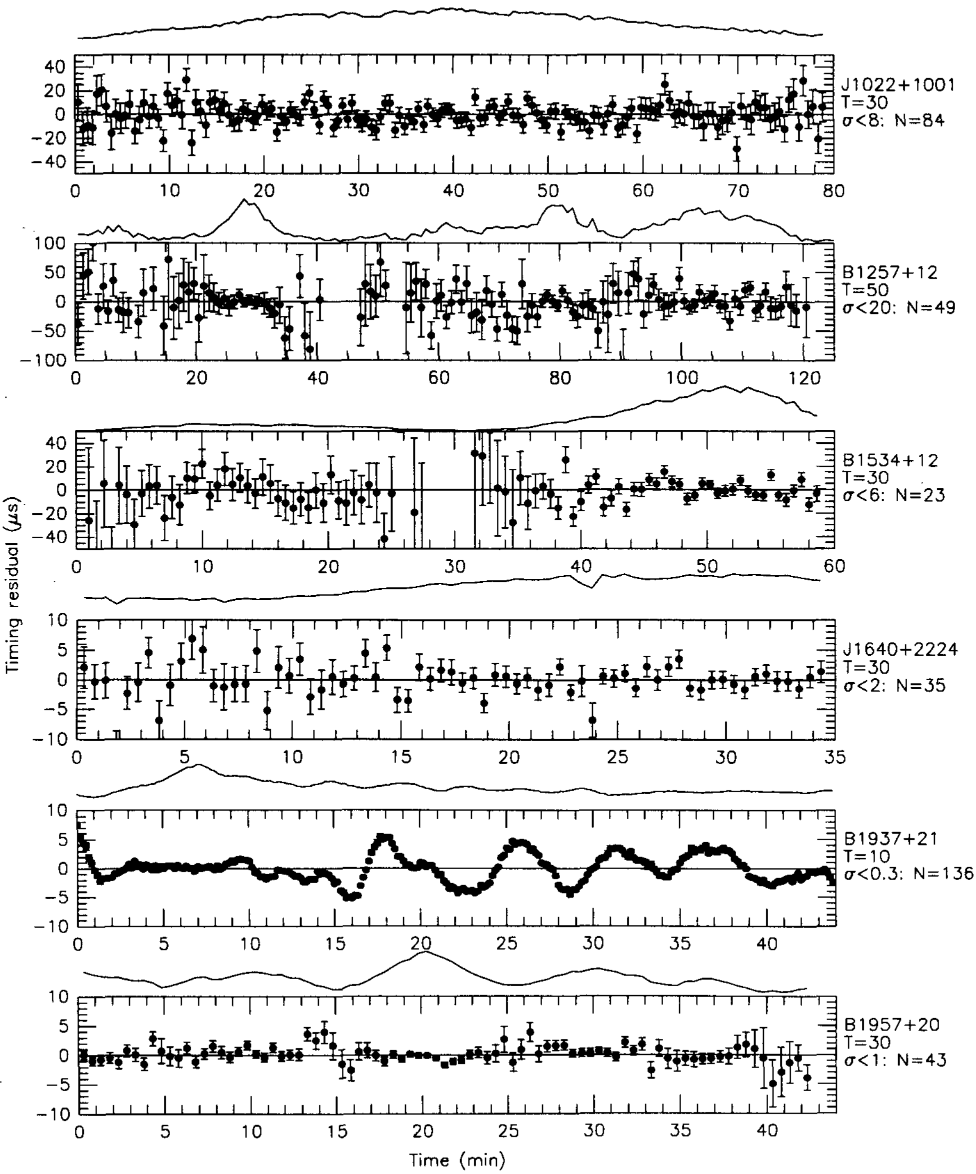

Figure 6. Timing residuals for sequences of short integrations (T = 10 to 50 s) of six millisecond pulsars at Arecibo Observatory, using coherent dispersion removal and a bandwidth 0.5 MHz at 430 MHz.

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