PULSAR TIMING

D. C. Backer
Astronomy Department and
Radio Astronomy Laboratory
University of California
Berkeley, CA 94720
USA

ABSTRACT An introduction to the methods of measurement of radio pulse arrival times and some recent results.

1. INTRODUCTION

Following the discovery of pulsars in 1967 a number of extensive pulse timing programs were initiated. The first wave of timing included efforts at Arecibo Observatory, Jodrell Bank, Parkes, the University of Massachusetts, and the Jet Propulsion Laboratory.

In the past several years a number of new programs have been initiated. In these proceedings you will find reports about many of these programs. The excitement in the new efforts is divided between deeper investigations of the neutron star structure in young pulsars, and the use of old, yet short period pulsars as celestial clocks to conduct fundamental physics experiments.

My goal is to introduce the experimental methods of pulsar timing. I will conclude with a few results from recent work. Taylor's contribution in these proceedings continues this topic with particular attention on the celestial clock topic.

2. TIME OF ARRIVAL MEASUREMENT

2.1. Signal Averaging

The primary data recorded in most timing observations is a series of average pulse profiles with the averaging interval in the range between 1 and 20 minutes. Each profile is the result of folding the data samples modulo the apparent pulse period. Time resolutions range from 0.0002 (*e.g.,* Downs and Reichley 1983) to 0.015 (*e.g.,* Davis *et al.* 1985) periods. The data are often sampled synchronously with the apparent period so that folding is simply modulo a fixed number of samples, *e.g.,* 1024. In other cases hardware constrains the sampling interval to asynchronous values. Folding this data requires computation of the pulse phase with respect to the first sample, depositing the sample in the correct pulse phase averaging 'bin', and incrementing a counter that keeps track of the additions in each bin for subsequent normalization.

The apparent period is predicted from previous estimates of the pulsar parameters and an ephemeris of the earth's motion (see section 6). The precision required is such that the smearing of the pulse during the multi-minute averaging interval is significantly less than the arrival-time estimation error expected for each profile.

The reading of the observatory time standard at the time of the first sample of each profile is recorded. The estimation of the arrival time of the first pulse following this time is discussed in

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section 2.4. In some observations each profile is started at a fixed phase within the apparent pulse period. In other cases observations begin at a fixed time such as an even 10s, or even at a random time.

2.2. Differential Dispersion Removal

Dispersion of pulsar signals by thermal electrons in the interstellar, and interplanetary, media must be removed from the observed bandwidth of radio signals to obtain a desired resolution. Alternatively the bandwidth could be reduced to limit dispersion, but this reduces sensitivity as discussed in the next section. The time smearing that results from a given bandwidth b at a given radio frequency ν_o for a given column density of electrons, or dispersion measure DM, is

$$\Delta t = 8.3\ \mu s \frac{DM(\mathrm{pc\ cm^{-3}})b(\mathrm{MHz})}{\nu_o^3(\mathrm{GHz})}$$

For example, if $DM = 35$, $b = 1$, and $\nu_o = 1.4$, then $\delta t = 100\mu s$. If we want 128 bins per period, then these parameters would limit observations to periods in excess of 12.8 ms. Hankins and Rickett (1975) discuss signal processing techniques for improving resolution by dispersion removal.

An approach that allows high time resolution and wide total bandwidth uses a multi-bandwidth receiver. Many narrow channels defined by a bank of filters are sampled and synchronously averaged as described above. The relative dispersion between these channels is removed with respect to a fiducial channel in post-observing analysis. The center frequency of the fiducial channel becomes the effective frequency of the observation. The center of the band is recommended. Rawley (1986) constructed a bank of signal averagers that allow each filter bank output to be independently averaged for precise removal of dispersion.

At Berkeley we have developed an alternative approach which uses a digital correlator for the multichannel analyzer. The output of the correlator is synchronously averaged just as with the filter-bank approach. In post-processing we fourier transform the pulse-phase resolved correlation functions into the frequency domain before dispersion removal. The digital correlator has the advantages of bandwidth agility and stability. Figure 1 illustrates the steps involved in this approach to pulsar timing. The digital correlator technique has been implemented both in our digital signal processor which is devoted to pulsar research, and at Arecibo in their general purpose, 40-MHz correlator.

Alternatively the dispersion may be removed in real-time by a hardware device. Orsten (1970) and Boriakoff (1973) describe devices that operate on a bucket-brigade principle. These devices are limited by their individual filter response times; Δt cannot be reduced below $1/2b$. Further effort at reducing the effects of dispersion requires processing of pre-detection data. The differential dispersion can be treated as a filter, and the inverse filter can be applied to the data. This is regularly done in chirped radar systems for chirps that are considerably less than those imposed by the interstellar medium. The inverse filter approach has been implemented both in software (Hankins 1971) and more recently in hardware using a surface acoustic wave filter (Hall, Hamilton and McCulloch 1985) and using a integrated circuit transversal filter (Hankins, Stinebring and Rawley 1987).

The dispersion can also be removed from a narrow band of signals by sweeping the local oscillator synchronously with pulse path in the frequency-time domain. This technique converts radio frequency into pulse phase. McCulloch, Taylor and Weisberg (1979) implemented this technique using a digital correlator. Biraud (1987 personal communication) in France is developing a similar system for millisecond pulsar timing.

2.3. Sensitivity

The sensitivity of a pulsar timing observation is dependent on both telescope and receiver parameters as well as pulsar parameters. The standard equation for the radiometer sensitivity is:

$$\Delta S(\mathrm{Jy}) = F \frac{(T_r + T_s + T_b)}{(N_p N_s b\tau)^{0.5}} \frac{k}{A_g \eta},$$

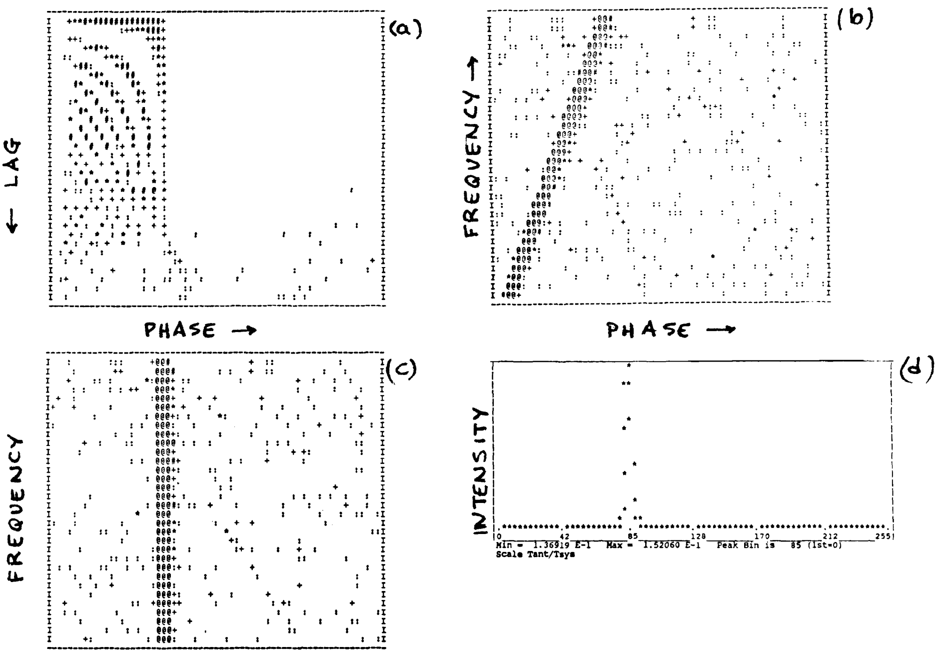

Figure 1 Data analysis for pulsar timing of PSR 1933+16 with the Berkeley correlator at NRAO Green Bank 300ft: (a) phase-resolved, time-averaged correlation function; (b) data after delay-radio frequency transform; (c) dispersion removed; (d) profile from average over radio frequency.

where F = clipping factor (1.2); T_r = receiver temperature (1-50K); T_s = spillover and scattering temperature(10-35K); T_b = background temperatures (1.7K sec(elev) + (1-10K) $\nu^{-2.7}$ + 2.7K); N_p = number of polarizations (2); N_s = number of spectral channels of width b (64); τ = integration time (250s); A_g = geometric area of telescope ($10^4 \mathrm{m}^2$); η = aperture efficiency (0.5). The parameters suggested above lead to values of ΔS in the range from 0.1 mJy to 1.0 mJy.

Pulsar flux densities are normally quoted in terms of the equivalent continuum flux density $< S >$. The arrival-time error is roughly equal to the pulse width W divided by the signal-to-noise ratio of the pulse peak detection when optimally sampled. The pulse peak is then $< S > P/W$, where P is the pulse period. The signal-to-noise ratio uses the radiometer equation above with the integration time reduced by W/P. The resulting arrival-time error is:

$$\Delta t = \frac{W^{1.5} \Delta S}{P^{0.5} < S >} \ .$$

The strong dependence of δt on W is reduced when the resolution of an observation is dispersion limited owing to the dependence of δS on the channel bandwidth which is determined by the resolution.

2.4. Time-of-Arrival Estimation

The next step in the analysis of timing data is estimation of the pulse arrival time within the averaged and dedispersed profile, typically an array of 64-1024 numbers. This step is usually accomplished by cross-correlation of the observed profile with a template profile. Estimation of the maximum of the cross-correlation function using a polynomial fitting algorithm gives the delay offset of the profile with respect to the template. This procedure is equivalent to a Chi-squared minimization between the template model and the observation, and is an example of the matched filter approach to signal estimation. The template is formed iteratively from the observations themselves. A delta function or triangle template can be used to make the initial period estimates; then the period estimate can be used to accurately phase individual observations to create a nearly noise-free template. Alternatively the pulse waveform can be modeled by a set of components; this is particularly useful for profiles that depend strongly on radio frequency owing to interstellar scattering (Rankin *et al.* 1970 and section 5.1 below).

An equivalent approach is to work with phases of the fourier components of the pulse profile. The phases, when corrected for the structure phase by subtracting the corresponding template phase, can be weighted and averaged to estimate the arrival time. Although this approach is equivalent to the cross-correlation technique (Backer 1985), there are some operational advantages (Rawley 1986).

The time offset determined in the analysis discussed above is then added to the start time of the first sample to obtain the observatory, or topocentric, arrival time. The offset between the first sample and some fiducial mark on the template profile must be added for accuracy and specificity. It is advisable to add an offset of an integral number of periods equal to about half the integration time to refer the observation to the midpoint just as the frequency was referred to the middle of the band.

2.5. Pulse Profile Stability

The discussion in the preceeding sections ignores the fact that pulsar emission is very erratic from one pulse to the next. Many time scales of variations exist (see summary in Manchester and Taylor 1977). The average pulse profile reaches a stable, reproducible form when the average extends over hundreds of pulse periods. This stability is essential for measurement of the stellar rotation with precisions reaching 0.001 periods or less. The reproducibility of the pulse profile patterns in each pulsar require a stable system of currents that are responsible for the radio emission.

Several authors have investigated the how the individual pulses approach the stable profile that is used in timing stellar rotations (Helfand, Manchester and Taylor 1975, Downs and Krause-Polstorff 1986). Figure 2 demonstrates the rapid decrease with averaging time of the mean-square deviation of pulse averages from the ensemble average.

3. 'TIME' CORRECTION

3.1. Atomic Time and Terrestrial Time

Our observatory arrival time are ultimately referred to a terrestrial standard atomic time. The atomic time standard is defined by

'The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the Cesium-133 atom.' (13th CGPM 1967).

Guinot (1988) has recently summarized the development of International Atomic time (TAI). This standard is an ensemble average of the individual realizations of atomic time (AT) at standards laboratories around the globe. The weights given to each vary according to an assessment of their stabilities. Some laboratories operate a bank of commercial Cesium clocks and take the ensemble average to define their local AT scale. Adjustments are made based on comparison with TAI. Other laboratories have in addition to a cesium clock bank a primary standard so that they can realize the standard given in the above definition to within a measurable tolerance.

The comparison between the scales at various standards laboratories requires a correction for relativistic effects (Ashby and Allan 1979). The reduction is to mean sea level of the equipotential geoid. The proposed nomenclature for this scale is evolving from Terrestrial Dynamic Time (TDT) to simply Terrestrial Time (TT) (Guinot and Seidelman 1988).

3.2. Time Transfer

The comparison of atomic time scales between standards laboratories and the use of an atomic time at a remote site requires a system of time transfer. There are a number of systems for time transfer.

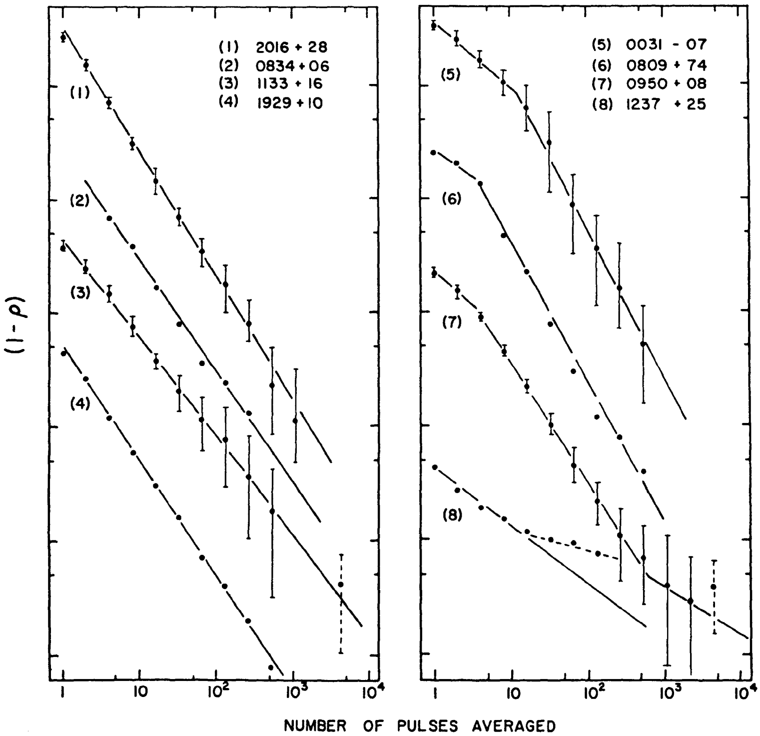

Figure 2 Stabilization of profile with increasing integration time (from Helfand *et al.* 1975).

Each has a different accuracy or other limitation. These systems are discussed in NBS Monograph 140 (1974).

In the US millisecond-level time transfer is done using HF transmissions of WWV from Ft. Collins, CO, and WWVH from Hawaii at 2.5, 5, 10, 15 and 25 MHz. Signals propagate by line of sight and by reflection off the ionosphere over distances of 1000's of kilometers.

The US Navy maintains cesium standards at the transmission sites of the LOng RAnge Navigation C system (LORAN C) around the globe. These signals at 100 kHz propagate up to 1500 km as surface waves and provide microsecond level time transfer.

The most recent development in time transfer is the Global Positioning Satellite system (Allan *et al.* 1985). These US DoD navigation satellites have cesium clocks on board. The orbital period of the satellites is about 24 hours, and the plan is for a web of 18 satellites circling the globe. The time information from these clocks is transmitted at frequencies near 1.5 GHz. The epochs and rates of the individual cesium clocks are monitored at the standards laboratories so that a extrapolated correction can be sent up to the satellites for transmission. Time is transferred at the level of 100 ns by this means. If a given satellite is observed by two parties simultaneously, then time can be transferred from one site to the other at the level of 10 ns. This 'common-view' technique requires precise application of relativistic principles (Allan, Weiss and Ashby 1985).

3.3. Barycentric Time

The time scale kept by an earth-based clock does not flow uniformly with respect to an external observer owing to the combined effects of gravitational redshift and time dilation. The elliptical orbit of the earth leads to a variation of the epoch of an earth clock with respect to an external observer with an amplitude of 1.6 ms and a period of one year. The corresponding variation that results from the moon pulling the earth in and out of the solar potential has an amplitude of 0.5 μs and a period of about 29 days.

Barycentric Dynamical Time (TDB) is defined to remove these periodic variations that result from relativity (USNO 1984, Chandler 1985, Backer and Hellings 1986). The time scale that results is that of a clock in a circular orbit about the sun at one astronomical unit. This definition is chosen so that TDB runs at nearly the same rate as TDT, and has only small deviations in epoch, *i.e.,* much less than 1.6 ms. For the pulsar timing analysis a cleaner definition would be to define a time scale that removes the solar system effects completely (Backer and Hellings 1986). TDB effectively does this since the difference between TDB and a true clock at rest in the barycenter of the solar system is a uniform rate which can be absorbed into the definition of the second.

Operationally the conversion from TDT to TDB is done by an ephemeris for time similar to the ephemeris for position that will be discussed in the next section. There is no conceptual difficulty is this process – it is a straightforward application of the equivalence principle and special relativity that can be performed with adequate precision for pulsar observations. The differential rate that includes the effects of all solar system masses and motions is first integrated to give the difference between the true barycentric clock and TDT. Then a linear term that represents the mean rate is removed to leave the periodic terms. The interval over which the linear term is removed is presently a matter of choice: 100 years (Hellings 1985) or 59 years which is near twice Saturn's period and five times Jupiter's (Chandler 1985). Fairhead (1987) has developed an analytic approach applicable over a few thousand years.

3.4. Stability

Observations of PSR 1937+21 now rival the stability of atomic clocks over intervals of a year or more - 10^{-14} or 0.3μs over one year (Allan, Ashby and backer 1985; Rawley *et al.* 1987). This topic will be discussed at further length in the lecture by Taylor. The stability of atomic time scales will not limit the timing of an array of millisecond pulsars since they can be compared to each other. This is discussed below in section 8.

4. 'SPACE' CORRECTION

4.1. Earth Ephemerides

After correcting the pulse arrival time to TDB we next want to correct it to an inertial frame, the solar system barycenter. Two ingredients are required – the celestial coordinates of the source and the instantaneous location of the telescope. The dot product between the unit vector to the source and the telescope position is then added to the arrival time to obtain the barycentric arrival time. Two groups, one at the Harvard-Smithsonian Center for Astrophysics and one at the Jet Propulsion Laboratory, provide ephemerides of the earth's position, and velocity that can be used for this correction.

The correction from the earth's center to the telescope requires the telescope's geocentric coordinates and a simple model of the earth's motion. This correction is identical to the delay calculated in VLBI observations although orders of magnitude less precision is required. If observations from different observatories are to be compared at the microsecond level, then one must specify both the fiducial point on the pulse and the reference point at the telescope. The telescope reference point used in VLBI is the intersection of the axes (Thompson *et al.* 1986; p. 95).

4.2. Radio Astrometry

The space correction requires precise coordinates of the pulsar. These are derived in the parameter fitting process discussed below. The coordinate frame is inertial since the ephemeris of the earth's motion is given in an inertial reference frame. The common reference frame of radio interferometry, B1950.0–B for Besselian, is not inertial. The terms of elliptical aberration (USNO 1984) are required

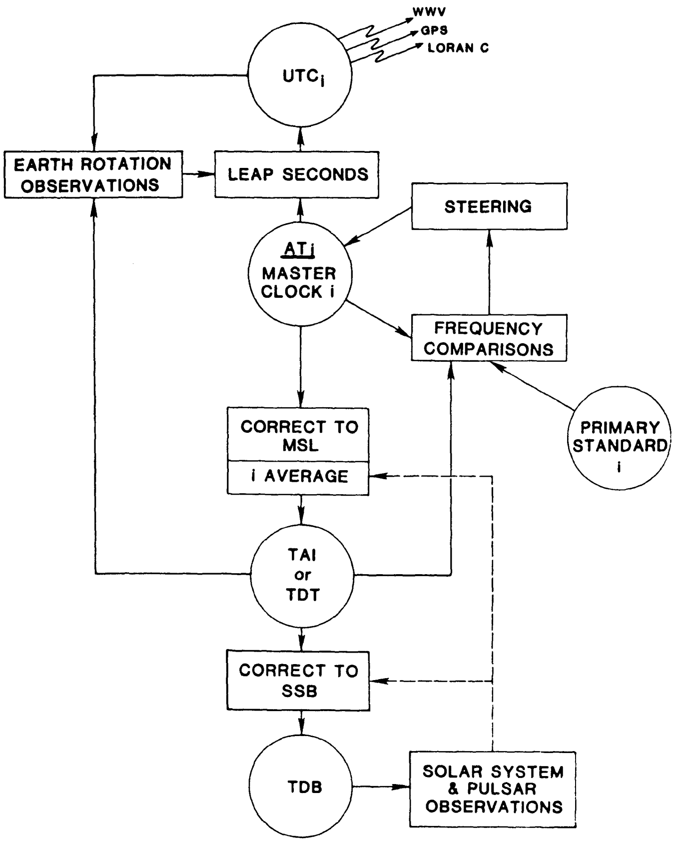

Figure 3 Connection between time scales (from Backer and Hellings 1986).

to transform between the two systems. The choice for future precision efforts is to work in the J2000 system, J for Julian, which is allows a unified approach with both pulsar timing and radio interferometry.

4.3. Stability

The accuracy of the earth ephemeris is difficult to estimate since one is interested in the extrapolation of a many parameter fit to the earth's motion. The Earth-Mars distance was measured with a precision of 25 ns during the lifetime of the Viking mission. This data is fundamental to the development of the Earth ephemeris, and residuals to fits to the data provide an estimate of the accuracy of ephemeris. Reasenberg *et al.* (1979) show residuals that have a rms of about 75 ns over a 14-month interval. The ephemeris correction stability is discussed by Hellings and by Chandler in Allan, Ashby and Backer (1985).

5. 'PROPAGATION' CORRECTION

5.1. Plasma Dispersion and Turbulence

Pulsar signals are dispersed by the column density of electrons between the pulsar and the earth.

$$t_d = 0.00415\text{s}\ \nu(\text{GHz})^{-2} DM(\text{pc cm}^{-3})$$

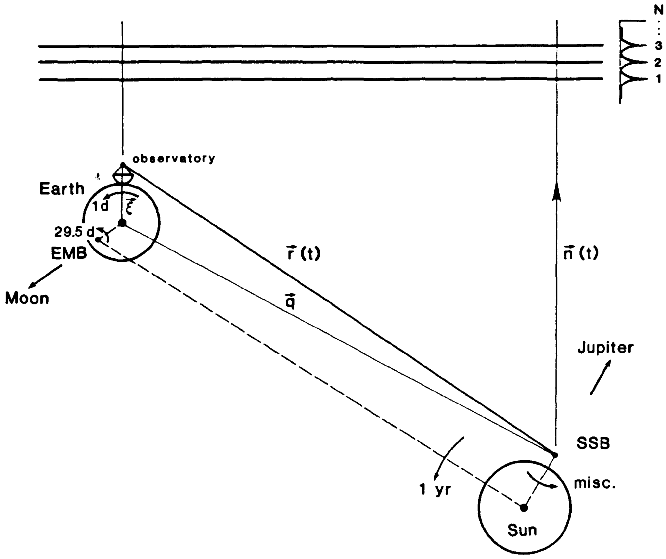

Figure 4 Space correction of telescope arrival time to the solar system barycenter (from Backer and Hellings 1986).

Furthermore turbulence in this plasma leads to diffractive and refractive propagation effects. Measurements over multiple radio frequencies, *e.g.*, 400 MHz, 700 MHz and 1400 MHz, can be used to determine the instantaneous column density of electrons so that the pulse arrival time can be extrapolated to infinite frequency. The observing frequency is the observatory value corrected by the doppler shift of the moving earth. Propagation delays in the solar wind can be significant; the column density from 1 e cm^{-3} over 1 AU leads to a delay of 0.5 μs at 1.4 GHz. Foster and Cordes discuss the removal of the effects of propagation in a turbulent medium later in this proceedings.

5.2. Relativistic Delay

The photons from a pulsar also suffer a relativistic delay as they traverse the solar potential. The additional delay is 135 μs when the signal passes by the limb of the sun compared to an observation six months later. The delay falls logarithmically with

$$c\Delta t = \frac{GM}{c^2}\ln(1+\cos\theta)^{-1}$$

where θ is the heliocentric angle between the pulsar and the earth. In a globular cluster there are sizeable delays from passing the nearest stars, but the effects are small and monotonic, and cannot be distinguished from a period derivative.

6. PULSAR PARAMETER ESTIMATION

6.1. Least-Squares Analysis of Residuals

A set of observations must be treated in stages of slowly increasing data length to determine the pulse parameters. At each stage one uses the minimum number of parameters to model the arrival times without period ambiguity and within the experimental errors. Fractional period phase residuals from the model are analyzed in a least-squares fitting procedure to determine improved model parameters. In some cases one must start with estimates of the period from separate observations.

6.2. Rotation Model

The simplest model for a rotating neutron star consists of an initial phase, a period and a period derivative. In a few cases a second derivative can be determined. The model for the phase residuals is a simple power series:

$$\phi(t) = \phi_o + \Omega\, t + \dot{\Omega}\, t^2/2 + \ddot{\Omega}\, t^3/6,$$

where Ω is the rotation frequency. The detection of a second derivative allows an estimate of the 'braking index' n, $\dot{\Omega}^2/\Omega\ddot{\Omega}$. The braking index is 2.5-2.8 for the three pulsar with measured values of $\ddot{\Omega}$; the most recent determination is by Manchester, Durdin and Newton (1985). An index of 3.0 obtains if the decelaration torque is pure magnetic dipole radiation.

6.3. Astrometric Parameters

The celestial coordinates of a pulsar are required to do the space correction. The 'lever arm' of the space correction is 1 AU, or 500 s. If microsecond precision is required, then the celestial coordinates must be known or determined with a precision of 2 nanoradians, or 0.4 milliarcsec. This is sufficient to measure a proper motion of 2 km s^{-1} at a distance of 1 kpc in one year. Four parameters are then required to specify the pulsar's celestial position: an initial right ascension and declination, and a proper motion in right ascension and declination.

The precision that is possible with millisecond pulsars can only be matched by the precision in the solar system ephemerides that incorporate modern radar measurements of planetary orbits (Rawley, Taylor and Davis 1988). Radio interferometry has only reached a precision of around 5 nanoradians, for a limited number of strong, compact quasars, although recently the resolution has been pushed to 0.3 nanoradians with VLBI measurements at 100 GHz.

The comparison between positions derived from timing and interferometer measurements has led to some puzzles (Fomalont *et al.* 1984; Backer *et al.* 1985; Bartel *et al.* 1985). Part of the problem is that the pulsar positions are corrupted by low-frequency timing noise. Part of the problem may result from the use of the out-of-date B1950.0 conventions in radio interferometry that include old constants for precession and nutation. Rawley, Taylor and Davis (1988) question the inertial character of the CfA ephemeris. More work needs to be done within the modern J2000 system and using the most stable pulsars to clear up this issue.

6.4. Dispersion Measure

Observations with multiple frequencies allow a solution for the dispersion measure by fitting for a quadratic arrival time with radio frequency. Care must be taken in obtaining the true dispersion when the pulse shape changes with radio frequency.

7. ROTATION NOISE

7.1. Spectral Decomposition

The phase residuals after a model fit for the parameters discussed above are not always consistent with white noise from measurement errors. In many cases the pulsar's spin displays instabilities. The deviations of phase from the model are often no more than 0.1 rotation periods. The spectrum of these instabilities, $\delta t/t$, can be characterized by a power-law index (Thompson *et al.* 1986, section 9.4). If the torque on the star varied randomly on a short time scale, then the phase residual spectrum would have a slope of -2. Other processes have been discussed with flatter slopes. Figure 5 displays timing residuals from Cordes and Downs (1985) for PSRs 1237+25 and 1929+10 that are characterized by power spectrum indices of 2 (white phase noise) and 0 (white frequency noise), respectively.

7.2. Activity Parameter

In cases such as PSR 1929+10 mentioned above there is insufficient data to determine a reliable spectrum. Cordes and Downs (1985) have introduced the concept of an activity parameter–a single

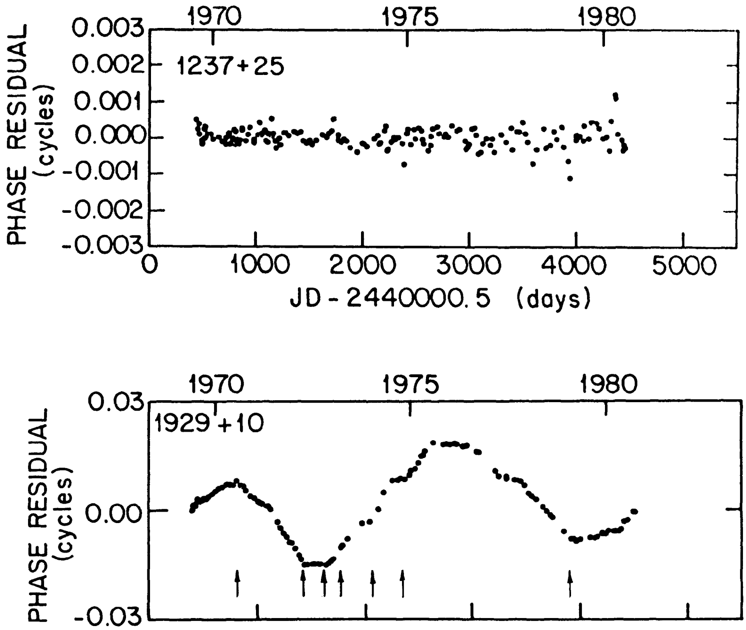

Figure 5 Timing residuals for two pulsars (from Cordes and Downs 1985).

variance statistic that takes the logarithm of the ratio between the intrinsic timing noise residual (σ, in seconds) for any object and the corresponding statistic, determined over the same time interval, for the Crab pulsar.

$$\text{Activity } A = \log_{10}\left[\frac{\sigma_{TN}(\text{star}, t)}{\sigma_{TN}(\text{Crab}, t)}\right],$$

$$\sigma_{TN}(\text{Crab}, t) = 6.8\text{ms}\left(\frac{t}{1000\text{ d}}\right)$$

Cordes and Downs demonstrate a correlation between A and the period derivative $\dot{P}$.

7.3. Glitches

The most dramatic discrepancies between the model and the observations occur when suden changes in the period and period derivative–glitches–occur. These are now seen in 5 pulsars: 0355+54 (Lyne 1987; 0531+21, the Crab; 0833-45, Vela; 0525+21; 1951+32, CTB80 (below). McKenna also reports several new pulsars with glitches in this proceedings. The magnitude of the changes range are $10^{-6 \text{ to } -9}$ in $\delta P/P$ and $10^{-1 \text{ to } -3}$ in $\delta\dot{P}/\dot{P}$. Smaller less dramatic glitches also occur (see Fig. 5: arrows in PSR 1929+10 data indicate small discontinuities in phase). The analysis and interpretation of these events in the life of some neutron stars is beyond the scope of this introductory lecture, but is discussed elsewhere in these proceedings.

8. RECENT RESULTS

8.1. PSR 1951+32 in CTB80

We began timing the pulsar found in the radio nebula CTB80 shortly after its discovery, or uncovery, in July 1987 (Kulkarni *et al.* 1988; Fruchter *et al.* 1988). Observations are continuing at the Arecibo

Observatory with the time shared between 430 MHz and 1400 MHz. A new timing system with the 40-MHz correlator was developed. The data were sparsely sampled in 1987 and more frequently sampled in 1988. At the time of the NATO ASI we knew that the rotation of the CTB80 star was not stable. Either it had one of the highest activity parameters of all pulsars, or it had undergone a glitch. Figure 6 demonstrates now that there was a glitch with a magnitude of 4×10^{-9} in $\delta P/P$. A full account of this event and the recovery of the star will be presented elsewhere by Foster, Backer and Wolszczan. The hopes that the star would be sufficiently stable to determine a proper motion from timing have been dropped.

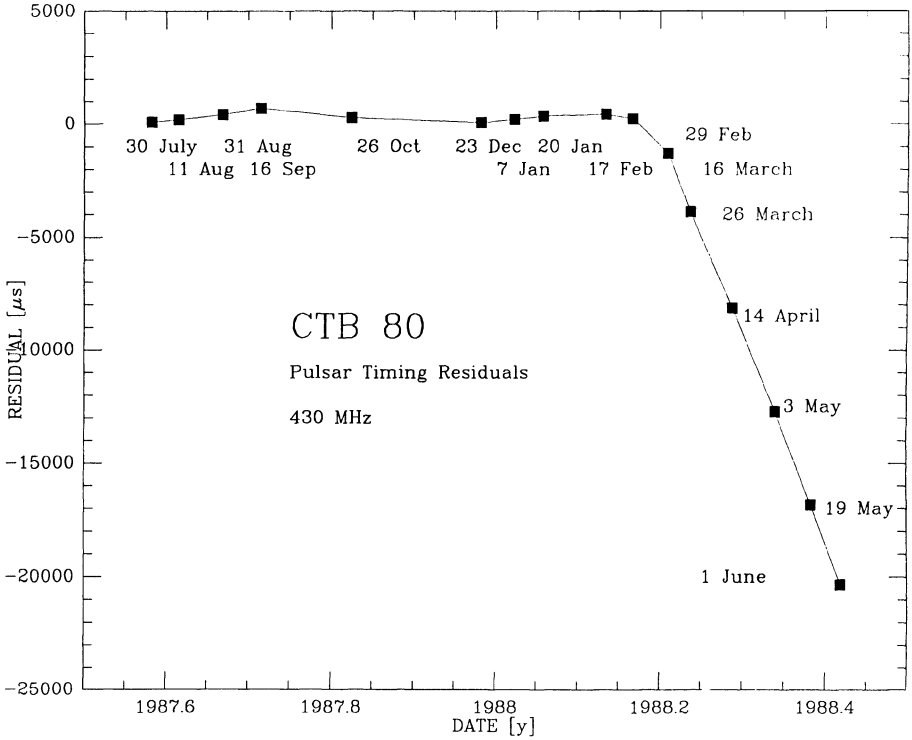

Figure 6 Residuals from timing PSR 1951+32 at Arecibo by Foster, Backer and Wolszczan. Fit was performed on data up to 17 February 1988.

8.2. The Globular Cluster Pulsars

In late 1986 we learned about the strong polarization of the point source in the globular cluster M28 (Erickson *et al.* 1987). This set in motion an effort to combine data from one of the largest radio telescopes, at Jodrell Bank, with the largest capacity data analysis procedure, that of Middleditch at Los Alamos. A 3.1-ms second pulsar was found (Middleditch *et al.* 1987). In the year following this uncovery, many globular cluster pulsar searches have been conducted. There are now a total of 5 pulsars in 4 globular clusters. These are: 0021-72A in 47TUC (P=4.479 ms)–Ables *et al.* 1988; 0021-72B in 47TUC (P=6.127 ms)–Ables *et al.* 1988; 1620-26 in M4 (P=11.076 ms)–Lyne *et al.* 1988; 1821-24 in M28 (P=3.054 ms)–Lyne *et al.* 1987; and 2127+11 in M15 (P=110.665)–Wolszczan *et al.* 1988. These neutron stars are concentrated within one core radius of the cluster centers, which is similar to the Xray objects (Grindlay *et al.* 1983). Verbunt discusses these pulsars in more detail in these proceedings.

The first period derivative of a globular cluster pulsar has been determined by Foster *et al.* (1988). The value for PSR 1821-24 leads to a spindown age of only 30 My. This is surprisingly short given the nominal age of clusters, and the likely age of the millisecond pulsars. The authors dismiss the influence of a gravitational encounter as the dominant source of the period derivative; an acceleration leads to a period derivative of aP/c.

8.3. The Pulsar Timing Array

The globular cluster millisecond pulsars have provided us with objects distributed across the sky. The timing observations of this array of pulsars can be used to solve for the uncertainties in both atomic time and in the location of the earth. The time term has a monopole signature on the sky–all timing residuals are affected by a constant. The space term has a dipole signature–there is an instantaneous vector error in the assumed earth position and therefore a dipole-like correlation in the barycentric correction. Pulsar timing array data can be used to look for a stochastic background of gravitational wave radiation (Detweiler 1979). This background will have a quadrupole correlation that can be detected in the timing array data without the limitation of the time and space uncertainties. Romani discusses this measurement further in these proceedings. We have started a Pulsar Timing Array experiment using the fully steerable 140-ft telescope at NRAO Green Bank. The first results from this are displayed in Figure 6. With improved hardware and longer time spans we expect the Pulsar Timing Array data to reach a level of 10^{-8} in the energy density of gravitational radiation relative to the closure density.

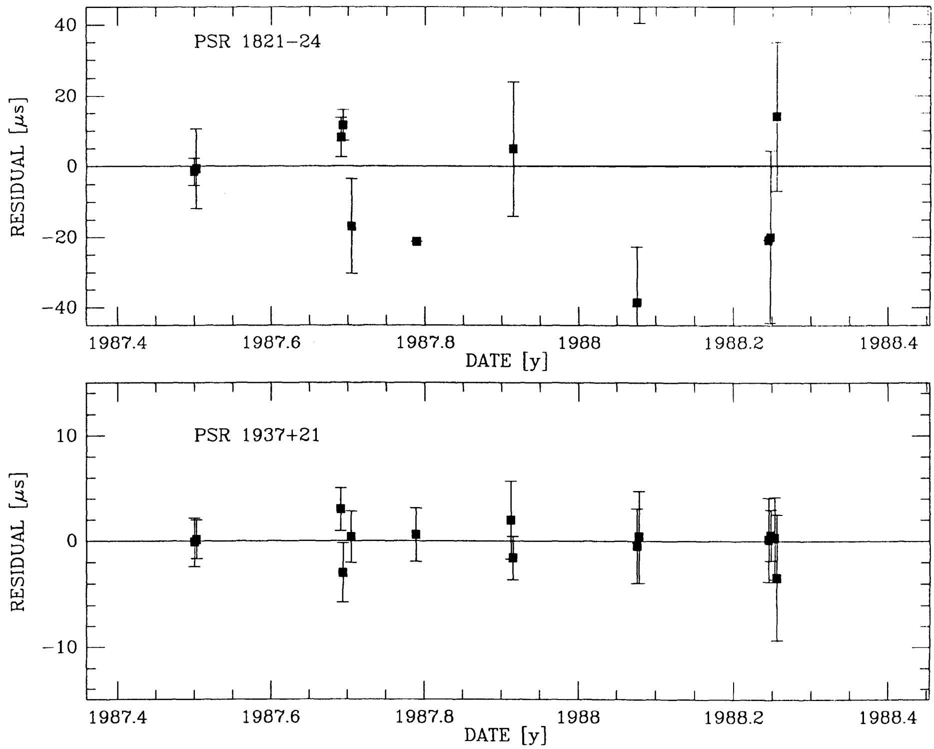

Figure 7 Residuals for two pulsars in Pulsar Timing Array experiment at the NRAO 140ft telescope.

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