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G.S. Downs
P.E. Reichley

August 15, 1980

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
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ABSTRACT

Natural radio emissions from pulsating radio sources (pulsars) have been detected at Goldstone on a regular basis since 1968. Scientific analysis of these signals has stimulated ideas of traversing the interplanetary medium and beyond, to the "home" of comets, using these natural beacons as navigation aids. Therefore, the techniques used in the ground-based observations of pulsars are described here in the required detail, many of them being directly applicable in a navigation scheme. The arrival times of the pulses intercepting Earth are measured at time intervals varying from a few days to a few months. Low-noise, wide-band receivers, unique to the stations of NASA's Deep Space Network, amplify signals intercepted by the 26-m, and 34-m, and 64-m antennas at Goldstone and in Spain. Digital recordings of total received signal power versus time are cross correlated with the appropriate pulse template, thereby providing an estimate of the pulse arrival time relative to the station clock. Corrections are applied to the station clock to obtain arrival times relative to ephemeris time. Drifts in phase encountered during signal integration are removed. The arrival times are then referred to the barycenter of the solar system for scientific studies, and to the geocenter for export to other investigators.

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SECTION I
INTRODUCTION

Natural sources of pulsating radiation were first observed in 1967 (Refs. 1, 2) by radio astronomers at Cambridge University in England. These pulsating radio sources (pulsars) are exciting because they (1) are thought to represent a stage in stellar evolution known as neutron stars (Ref. 3), providing a probe of an extremely dense state of matter; (2) exhibit changing, often dramatically so, behavior in the pulse period, signifying changes in the spin rate of the neutron star driving the pulse generating mechanism; and (3) have large space velocities, implying violent origins.

A series of measurements is being established using the NASA-JPL Deep Space Network (DSN) which will allow a probing of the neutron star interior and a direct measurement of changes in spin rate and angular motion. The purpose of the measurements is to measure the phase of the pulse train at known epochs. It requires little imagination to realize that the simultaneous comparison of the phase of a pulse train at two different DSN stations represents either a measurement of the difference between the station clocks, or a measurement of the location of one station relative to the other. In navigation, one assumes the clocks are synchronized. Differences in pulse phase are then attributed to differences in location. We need only to replace one DSN station with a spacecraft to complete the illustration.

The purpose of this report is to describe in appropriate detail the techniques used currently in the DSN for measuring the arrival time

of a particular pulse (alternatively, the phase of the pulse train relative to a given epoch). Phase measurements were begun in September 1968 and continue to the present. The 24 pulsars included in this series are listed in Table 1 with appropriate dates on which measurements began. An example of the results of this long series of measurements is presented in Table 7.

Many characteristics of the pulsars have been or can be deduced from the measurement of pulse phase at a series of epochs if the epochs occur often enough (weekly to monthly) and over a sufficient time span (years). Usually a parameterized model of the pulsar is constructed which is used to predict the time-of-arrival of a given pulse (or the phase of the pulse train at a given epoch). The parameters are then adjusted to minimize the mean square difference between the predictions and the measurements. The final values of the model parameters are dependent on the planetary ephemeris used in the data reduction, since all observations are usually referred to the barycenter of the solar system. The importance of this is clear when one realizes that 2 milliseconds flight time in the displacement of the barycenter amounts to as much as 1 arc-second displacement in the position of the pulsar. Errors in the knowledge of the barycenter with time scales of tens of years are caused by inaccuracies in the values of the masses of the outer planets. These slow curvilinear errors affect the values of the higher-order derivatives of the pulse period. Hence, though all current ephemerides may produce similar pulsar model parameters, improved ephemerides available twenty years from now will produce significantly different results. Tables of geocentric arrival times, being important

Table 1. 24 Pulsars Monitored at JPL at Frequencies
of 2295 MHz and 2388 MHz

Entry	Pulsar	Start Date
1	0031-07	5 Mar 1970
2	0329+54	5 Sep 1968
3	0355+54	5 May 1973
4	0525+21	1 Jun 1969
5	0628-28	30 Dec 1969
6	0736-40	1 Oct 1970
7	0823+26	12 Feb 1969
8	0833-45	22 Nov 1968
9	0950+08	5 Sep 1968
10	1133+16	25 Oct 1968
11	1237+25	10 Aug 1969
12	1604-00	1 Oct 1970
13	1642-03	12 Jul 1969
14	1706-16	1 Oct 1970
15	1749-28	2 May 1969
16	1818-04	29 Dec 1969
17	1911-04	5 Mar 1970
18	1929+10	29 Jun 1969
19	1933+16	23 Dec 1968
20	2016+28	5 Sep 1968
21	2021+51	30 Dec 1969
22	2045-16	10 Dec 1968
23	2111+46	30 Dec 1969
24	2217+47	30 Dec 1969

archives of pulsar behavior, are independent of small changes in the ephemerides of the planets. They form the exported form of the observational results.

The measurements were performed earlier at a frequency of 2388 MHz on the 26-m antenna at Deep Space Station 13 (DSS 13) and the 64-m antenna at DSS 14. Current observations are at 2295 MHz, utilizing all facilities at Goldstone and in Spain. Detected pulsar signals are sampled, integrated and recorded on magnetic tape. Data collection and recording is discussed in Section II. The data are then edited and, for the early years, collated according to the pulsar, as described in Section III. The collated data, stored on magnetic tapes, was used to derive a template for each pulsar, representing the average power level across a pulse of radiation. The template is then cross correlated with each data record of the particular pulsar to obtain an estimate of the pulse arrival time. The procedures used in constructing the templates is described in Section IV and the cross correlation process is discussed in Section V. The correction of the arrival time estimates for various small effects is discussed in Section VI. A sample list of geocentric times-of-arrival is presented in Section VII.

SECTION II
DATA COLLECTION

A. RECEIVING, DETECTION, AND RECORDING

It was shown shortly after the discovery of pulsars that they could be detected at 2295 MHz (Ref. 4). Shortly thereafter, in August 1968, JPL observations at 2388 MHz were begun using the 26-m antenna of DSS 13 at the Goldstone complex. The wide bandwidths (about 12 MHz) and the low system temperatures (about 16 K) allowed detection of three of the first four pulsars discovered. Over the following months the observations have been expanded to include 24 objects, utilizing all antennas at Goldstone and Madrid.

The receiver consists of the antenna, a right circularly polarized feed horn (left circularly polarized at 2388 MHz), and a maser pre-amplifier followed by conversion to and amplification at intermediate frequencies (IF). Low-loss cabling then carries the signal to the receiver room for more IF amplification. The receiver bandwidth is limited to 12 MHz by either the IF portion of the receiver or by a filter inserted for that purpose. Square-law detection of the signal is then performed, followed by low-pass filtering. The output of the low-pass filter is amplified by a wideband DC amplifier to a 1- to 2-volt level. Subsequently, the signal is converted to digital form in a sampling process. The integration time (see Ref. 5 for a definition) of the post-detection filter is chosen to match the time interval between analog-to-digital (A/D) conversions.

The data processing, from sampling to the dumping onto magnetic tape, is under computer control. The detected signal is sampled at a

rate equal to 5000 times the apparent pulse period, corresponding to sample intervals of 50 μ sec up to 800 μ sec. Converted to a digital signal by an A/D converter, the samples are stored in the memory of an SDS 930 computer or a standard station Modcomp computer. Data samples are superimposed modulo the pulse period. Samples from 500 pulse periods are superimposed congruently. Then a 5000-word array representing the superposition of 500 pulses is dumped onto tape. This accumulation of pulses continues until (a) detection is ensured, or (b) it is clear the pulses are too weak at this time to be observed. Accumulations rarely run more than one hour.

The form of the recorded data is sketched in Figure 1. The pulse is sitting on top of a system noise power corresponding to a temperature T_s . The peak equivalent temperature of the pulse is T_p . The 5000 samples spanning one pulse period are plotted from left to right. The time of the first data sample, plotted at the left, corresponds to a particular epoch of Universal Time (UT) as recorded at the station. This start time is recorded in UT (station). The train of received pulses then has a particular phase relative to the start time. The pulse train is folded in upon itself to beat down the effects of receiver noise fluctuations. Rather than think in terms of the phase of the pulse train, we ask for the arrival time of the first pulse after the start time. Hence, the pulse delay is added to the UT (station) epoch corresponding to the start time to yield an epoch for the arrival time of the pulse.

The phase of the pulse train may not remain constant during the superposition of many pulses. The subsequent drift in phase requires that a correction be applied to the measured pulse delay. This

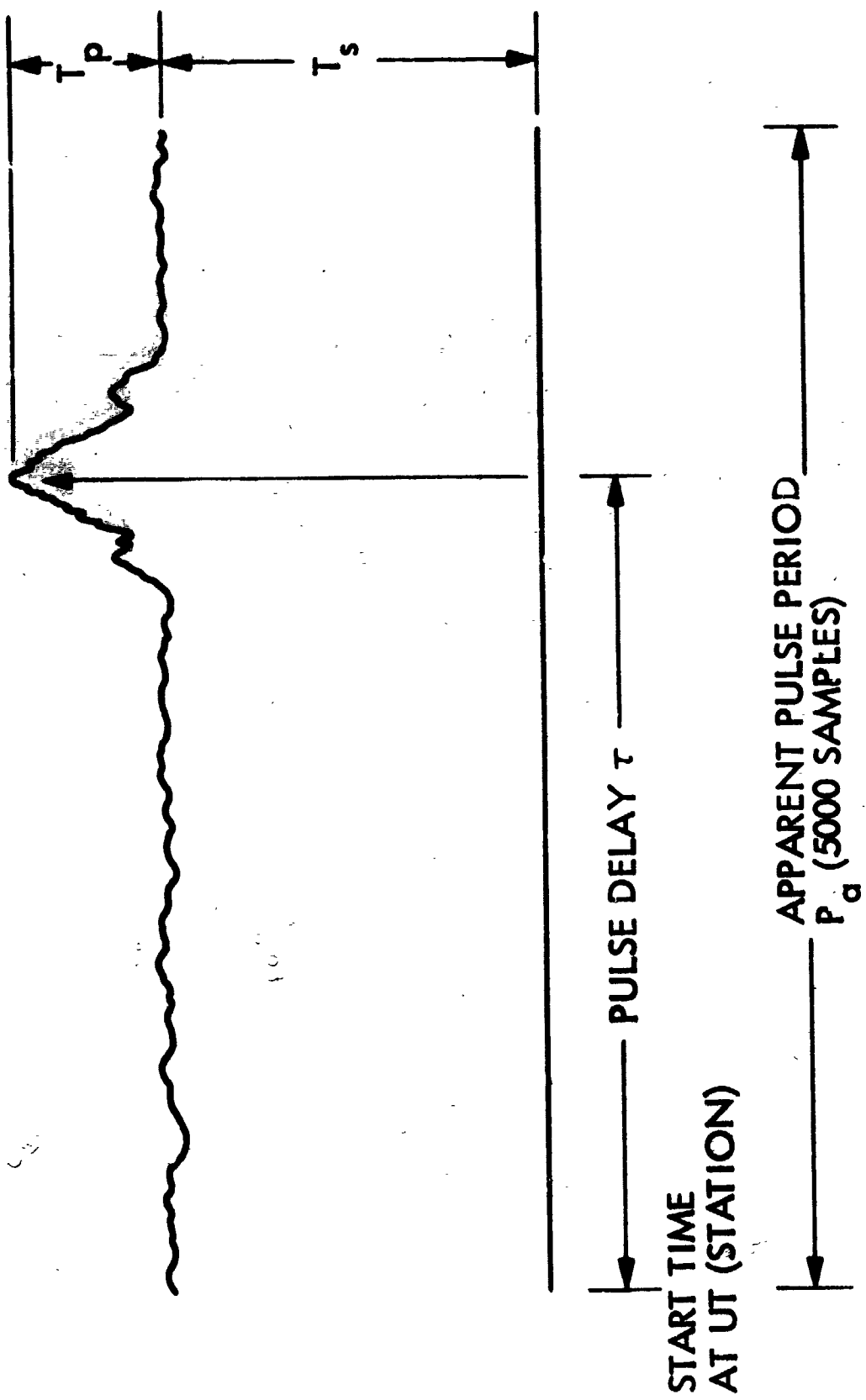


Figure 1. Nomenclature of the Pulsed Emission

correction is discussed in Section VI, D. Small corrections are required in the start time and in the UT (station) defined by a particular clock. These corrections are discussed in this section and in Section VI.

B. THE SYSTEM CONFIGURATION CODES

The measurement system is shown diagrammatically in Figure 2. The experimental hardware is grouped into units defined by the dashed boxes. Each subsystem so defined has been interchanged with other similar subsystems, causing significant changes in the measured phases. Hence, a system configuration code has been constructed to alert the analyst to changes in the system. The code varies from 0 to 21, representing 22 significantly distinct combinations of antenna, receiver, observing frequency, computer, data collection controller, and station clock. A summary of the basic configurations (0-5) and (17-21) appears in Table 2. Additional configuration codes (6-16) were created to denote the use of an observing frequency of 2295 MHz or 2328 MHz, and their relationship to the basic codes are shown in Table 3. Left circular polarization (LCP) is to be assumed unless specified as right circular polarization (RCP).

Since the system configurations do not change in principle from one to the other, only configuration 0 is described in detail. Highlights of the other configurations are noted in the following paragraphs. Configuration 0 includes the 26-m antenna at DSS 13. The radio frequency bandpass is determined by the IF amplifiers. The final IF amplification, detection, and low-pass filtering is done by a receiver (labeled as receiver 1) built in 1968 by C. F. Foster. The timing control box was designed by G. A. Morris and is labeled timer 1.

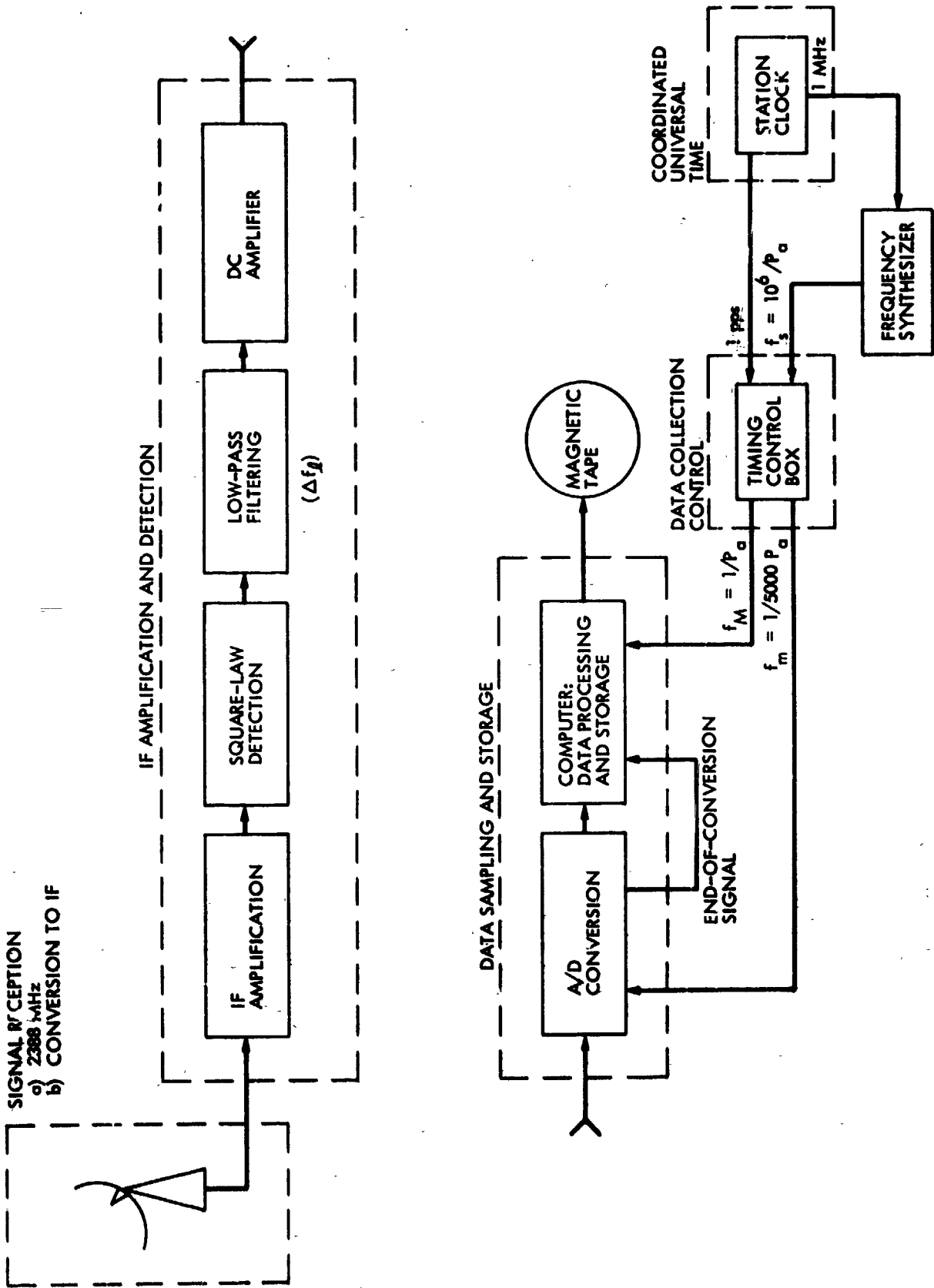


Figure 2. The Receiving, Detection, and Data Recording of Signals from Pulsars

Table 2. Chronology of the Major Experiment Configurations for Collecting Pulsar Timing Data

Configuration Code	Station	Dates In Effect (d/m/yr)	Description
0 (early)	DSS 13	05/09/68-10/01/74	26-m Antenna; Receiver 1; Timer 1; 1-sec Tick Derived From Ce Frequency Standard; Slow A/D Converter
0 (late)	DSS 13	10/01/74-01/04/76	Changed From Receiver 1 to 2
4	DSS 13	01/04/76-Present	Changed from Timer 1 to 3
1	DSS 14	05/09/68-14/04/73	Receiver 1 Plus 12-MHz IF Filter; Fast A/D Converter
2	DSS 14	14/04/73-01/11/74	Changed From Timer 1 to 2
3	DSS 14	01/11/74-01/04/76	1-sec Pulse Widened From 100 μ sec to 200 μ sec; -0.996550 Seconds Added to Start Epoch if Julian Date > 2442460.5
5	DSS 14	01/04/76-Present	Timer 2 Replaced With Timer 1
17	DSS 62	01/04/79-Present	2295 MHz, RCP, using station TPA with Modcomp
18	DSS 11	01/12/79-Present	2295 MHz, RCP, using station TPA with Modcomp
19	DSS 63	01/11/79-Present	2295 MHz, RCP, using station TPA with Modcomp
20	DSS 12	01/04/80-Present	2295 MHz, RCP, using station TPA with Modcomp
21	DSS 14	01/04/80-Present	2295 MHz, RCP, using station TPA with Modcomp

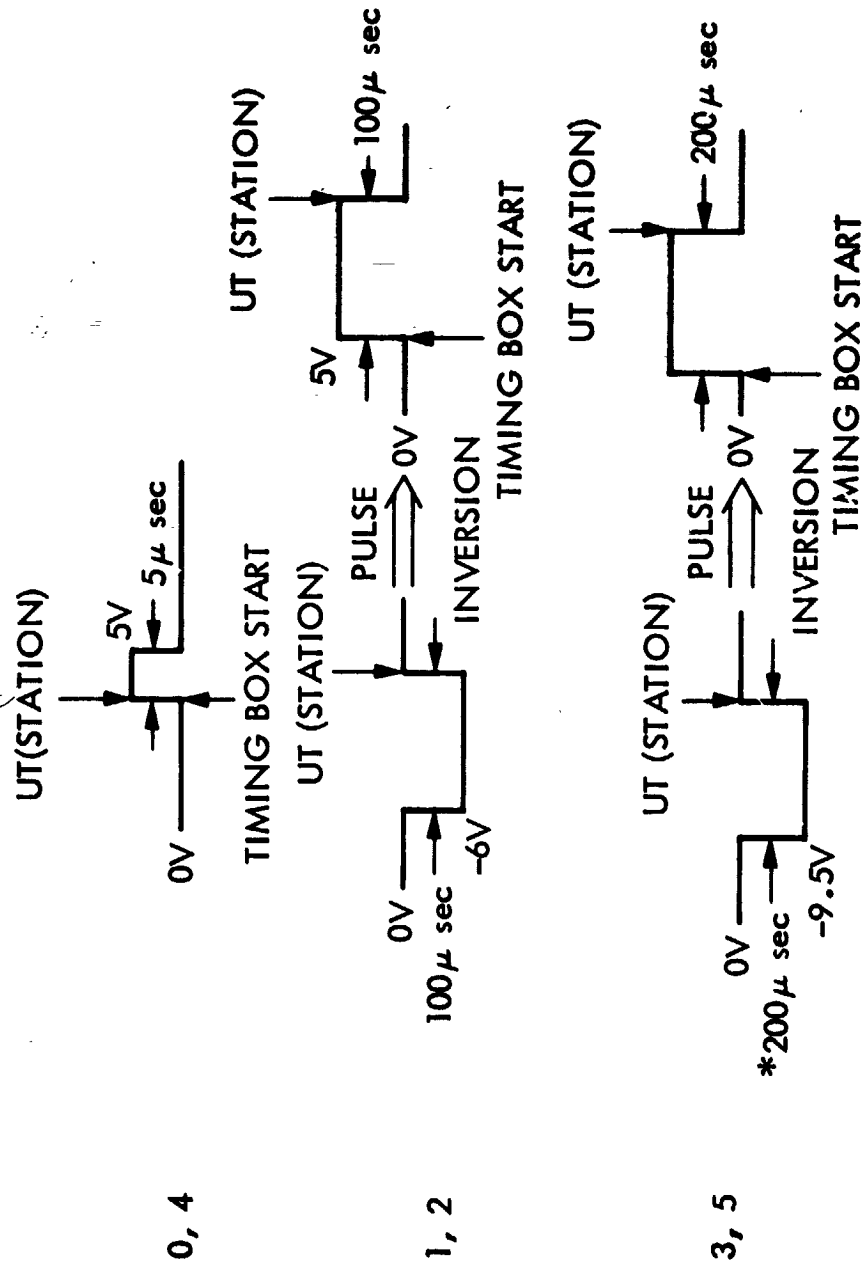
Table 3. The Configuration Codes Corresponding to Non-Standard Observing Frequencies

Configuration	Configuration	Observing Frequency (MHz)	Description
8 } 9 }	0	2328 2295	
10 } 11 }	1, 2, 3	2328 2295	
8 } 7 }	4	2328 2295	
6	5	2295	
12	Any		Denotes a correction w. s made to standard post-detection Δf_l
13	4	2295	RCP
14	5	2295	RCP
15	5	2295	DSS 13 via link to DSS 14
16	5	2295	DSS 12 via link to DSS 14

The relationship between the epoch-defining 1-second pulse and Universal Time as disseminated at the station, UT (station), is shown in Figure 3 along with the relationships for the other codes. Exact relations between UT (station) and Coordinated Universal Time (UTC) is discussed in Section VI. Data sampling in configuration codes less than 17 is performed by a 12-bit A/D converter with a 40 μ sec conversion time. The samples are stored in an SDS 930 computer having a 16,384-word memory. The station telemetry processor assembly (TPA) is used in codes 17 or larger.

CONFIGURATION CODE

CLOCK 1-SECOND PULSE



*(CHANGE IN WIDTH AS OF 1 NOV 1974)

Figure 3. The 1-Second Pulses from the Station Clocks at DSS-13 and DSS-14, Goldstone, and Their Relation to UT (station)

The final IF amplification and detection is performed in the steps shown in Figure 2. The first unit built was transported between DSS 13 and DSS 14 until 10 Jan. 1974, when it was permanently installed at DSS 14. This unit was replaced at DSS 13 by a programmable unit built by C. F. Foster (described in Ref. 6 and labeled receiver 2). This change is not noted by a configuration code change. Hence, code 0 consists of an early phase (pre-10 Jan. 1974, Julian date 2442057.5) and a late phase (post-10 Jan. 1974).

The timing control box used here is not described elsewhere, so a block diagram is presented here for tutorial purposes. Other control boxes used in other configurations operate on the same principle, but differ in complexity and detail. Careful study of Figure 4 shows that a string of fast and slow pulses are generated by the timing control box to control the data sampling. The pulses are derived by counting down pulses from a frequency synthesizer, starting at a well-defined time by gating the synthesizer output. The gate must be armed and then a 1-sec pulse must be received before counting begins. To assist the operator in determining on which second the counting started, the 1-sec pulses are counted down by 10 so that counting will start modulo 10 seconds.

The fast pulses, occurring every $P_a/5000$ seconds, where P_a is the apparent pulse period, are used to strobe the A/D converter. The slower pulses, occurring every P_a seconds, are used to control the data transfer into core memory. On the first slow pulse, a computer interrupt is coincident with the slow pulse commands the A/D converter to begin operation. About 20 μ sec later the end-of-conversion (EOC) interrupt forces the computer to accept the new word, and about 20 μ sec after

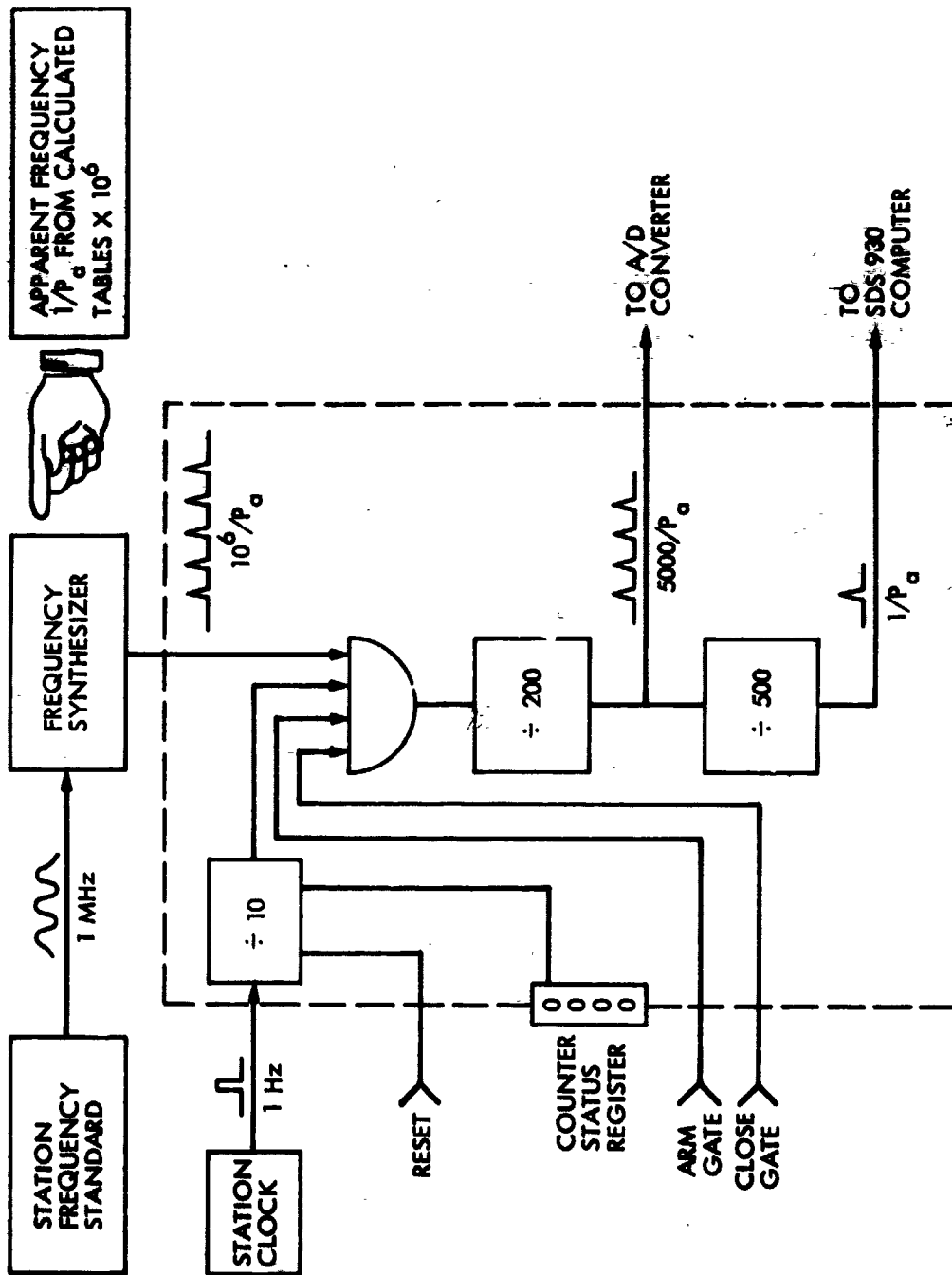


Figure 4. The Timing Control Box for Pulsar Data Collection

interruption, the word has been added to the proper memory location. Note that although it takes time to set up the computer to accept data, the EOC pulse arrives after the setup, so the first sample accepted is, in fact, coincident in time with the 1-sec pulse modulo one pulse period. However, a configuration exists in which the first sample is not coincident, and a correction must be applied.

The data sampling and superposition is under the control of a program written by G. A. Morris. The program also controlled the writing of the results onto magnetic tape for further reduction.

The apparent period P_a is the result of the Doppler effect caused by Earth's motion about the barycenter of the solar system. Tables of P_a are computed using a barycentric ephemeris of Earth and a crude but adequate model of the pulsar. The model includes the celestial coordinates of the object as well as the barycentric model of the pulse period (usually a period P_0 at some epoch t_0 , and the first derivative \dot{P}_0). The values of P_a are tabulated at 15-minute intervals between rise and set for any given day. The operator then chooses the value corresponding to the middle of the intended interval of pulse integration.

Configuration 1 consists of the 64-m antenna at DSS 14, the same IF amplification and detection unit, and the same timing box used in the early configuration 0. A 12-MHz IF filter is added to the chain to limit the IF bandwidth. The computer is again the SDS 930. The A/D converter, however, responds within 5 μ sec of being strobed with a convert command. The computer, requiring about 20 μ sec to arm the interrupt and start the data flow, misses the first data sample. The data stream is then shifted $P_a/5000$ seconds later in time. This shift is as large as 0.8 msec and is added to the UT (station) recorded by the operator.

Timer 1 was designed to accept the rising edge of a positive 1-sec pulse as the definition of UT (station). The 1-sec pulse distributed at DSS 14 is negative-going, the rising edge being coincident with UT (station). The necessary pulse inversion then causes the timing box to begin counting earlier than intended by a time equal to the width of the 1-sec pulse. This amounts to 100 μ sec in configuration 1 and 200 μ sec in configurations 3 and 5.

A programmable timing box, designed, built, and programmed by A. G. Sleky (Ref. 7) replaced the original timing box at DSS 14. This timer is labeled timer 2, and pertains to codes 2 and 3. A failure occurred in timer 2 which caused the start times of code 3 recorded between Julian dates 2442460.5 and 2443105.5 (17 Feb. 1975 and 23 Nov. 1976) to be earlier than intended. The correction is a subtraction of nearly 1 second. The exact correction was determined from a preliminary fit of a model of the pulsar emission times to the data. A correction of -0.996550 seconds to the start time aligned the affected arrival times with the times measured at DSS 13 (code 0 and 4) and with those unaffected from DSS 14.

Timer 1 was replaced at DSS 13 on 1 April 1976 by a programmable data collector/timer designed by S. S. Brokl (Ref. 8) and programmed by K. I. Moyd. This timer is labeled timer 3, and pertains to configuration code 4.

Occasionally a non-standard value is used for Δf_0 in the post-detection filtering. If a correction is applied, the configuration code is 12, corresponding to a correction to code 0 for dates prior to 1970 and to code 5 after 1976. (None occur in the intervening years.)

During the first half of 1979, the SDS 930 computer was phased out of service and removed in June 1979. This created the need to transmit IF signals over the microwave communication links to DSS 14 for data recording. The required 12 MHz bandwidth was obtained from the 6 MHz bandwidth of the link by folding the IF spectrum about the midpoint during base-banding. This technique was also used in obtaining signals from DSS 12. The configuration codes 15 and 16, then, indicate the recording at DSS 14 of signals from DSS 13 and DSS 12, respectively.

The most recent configuration for collecting pulsar data requires the use of the telemetry processor assembly (TPA) found in all DSN stations except DSS 13. The scheme was constructed by J. and M. Urech at DSS 62. Many of the hardware functions of Figure 2 are duplicated by their software. The data output is still in the form of 5000-word records on magnetic tape. The configuration code of this scheme for each station is listed in Table 2.

C. EFFECTS OF RECEIVER PARAMETERS ON THE ARRIVAL TIME

Pulsar signals are dispersive since the interstellar plasma introduces a frequency-dependent group velocity. A broadband pulse, covering the radio spectrum from 30 MHz to 10 GHz, will arrive at the receiving antenna and sweep through the receiver passband at a rate given by

$$\frac{B}{\Delta t} = KF^3/DM \text{ (MHz/sec)} \quad (1)$$

where the bandwidth B is in MHz, the observing frequency F is in MHz, Δt is in seconds, DM is the dispersion measure in parsecs $(pc) \text{ cm}^{-3}$, and $K = 1.205043 \times 10^{-4}$. Let Eq. (1) define the amount of smear Δt in the received pulse shape when all the other parameters are known. At $F = 2388 \text{ MHz}$, a dispersion measure of 10 pc cm^{-3} causes the pulse to

smear 75 μ sec when the receiver passband is 12-MHz wide. The smear is 750 μ sec when the dispersion measure is 100.

Computed values of smear are presented in Table 4. As long as the bandpass parameters remain fixed over the years, the dispersive effect should not affect the measured arrival times. However, changes in a filter element or the slight alteration in the tuning of the maser amplifier will change the frequency centroid of the passband. This, in turn, will change the time centroid of the detected pulse. The magnitude of this effect must be determined experimentally and has not been done. The effect is expected to be small since it is not the limits of the passband that change, but only the shape.

The response of the post-detection filter is chosen such that the integration time τ is close to the time interval $P_a/5000$. In the case of these simple RC filters, $\tau = 2RC$ (Ref. 5), where R and C are the filter resistance and capacitance, respectively. Considerable care is exercised in using the appropriate filter combination for each pulsar throughout the observations. Use of non-standard values of τ could cause up to 200 μ sec of time shift in the arrival time. The values are listed in Table 4. Note that the change from pre-10 Jan. 1974 (Code 0) to post-10 Jan. 1974 (Code 0) is principally a change in the post-detection filters, and much care was taken to duplicate the previous values of τ in the new filters.

A quantitative measure of the system performance is given by the ratio of σ , the root-mean-square (rms) value of the noise fluctuations about the mean, divided by ζ , the mean. Letting N represent the number of pulses superimposed,

$$\frac{\sigma}{\zeta} = \frac{1}{\sqrt{N\tau B}}$$

Table 4. Pulse Smearing Due to Dispersion
and Post-Detection Filtering

Pulsar	Dispersion Measure* (pc cm ⁻³)	Smear for B = 12 MHz (μsec)	Integration Time (μsec)
PSR 0031-07	10.89	79	200
0329+54	26.776	195	50
0355+54	57.03	416	50
0525+21	50.955	372	400
0628-28	34.36	251	200
0736-40	161.0	1174	100
0823+26	19.4634	142	400
0833-45	69.08	504	50
0950+08	2.969	22	50
1133+16	4.8479	35	50
1237+25	9.296	68	200
1604-00	10.72	78	100
1642-03	35.71	261	100
1706-16	24.88	182	150
1749-28	50.88	371	400
1818-04	84.38	616	150
1911-04	89.43	653	150
1929+10	3.176	23	50
1933+16	158.53	1157	50
2016+28	14.176	103	50
2021+51	22.580	165	100
2045-16	11.51	84	200
2111+46	141.50	1033	200
2217+47	43.54	318	100

*Values From Ref. 22

One expects for $N = 500$, $\tau = 50 \mu\text{sec}$ and $B = 12 \text{ MHz}$, that $\sigma/\zeta \sim 0.0018$. Throughout the years of data collection this parameter has varied between 0.0013 and 0.0025, corresponding to $42 \mu\text{sec} < \tau < 59 \mu\text{sec}$. Hence, the values of integration time listed in Table 2 were stable to within 16 percent of the tabulated value.

SECTION III
EDITING AND COLLATING

A. EDITING THE DATA

Successfully measuring the time-of-arrival of a pulse near a given epoch does not ensure that the result is free of biases. The editing process involves detecting the biases, correcting the measurement if the reason for the bias is known, or omitting the measurement if the reason for the bias is known but does not allow correction. A good example of a correctable situation is the use of a receiver frequency other than the 2388 MHz frequency used in most of the measurements.

A preliminary model (position and pulse period) is devised for each pulsar. These models are used in a computer program of adequate accuracy to predict pulse arrival times at the barycenter of the solar system. A barycentric ephemeris of the Earth is used to refer the measured arrival times to the barycenter and a residual (measured minus predicted) arrival time is computed. The occurrence of a residual that is large compared to the average fluctuation is cause for further investigation.

Several properties of the pulsar or the system are directly responsible for the need to correct or omit the arrival time measurement. They are:

(1) Scintillations

Interstellar clouds of ionized hydrogen impose variations on the received pulse power. The time scale of the fluctuations is on the order of tens of minutes. If the pulsar is far enough away, and several are, large fluctuations in the pulse power force the signal down into the receiver

noise for many minutes, causing a spurious estimate of the pulse arrival time.

(2) Start Times

The early timing box divides the incoming 1-sec pulse by 10 (see Fig. 4), allowing the counting to be started at well-defined 10-sec intervals. It is imperative that the counter status register be synchronized with the station clock, modulo 10 seconds; i.e., on the even 10-second mark, the counter should read 0. Occasionally synchronization is lost. In these cases it is easy to deduce how many integral seconds (never more than 10) the start time has to be retarded or advanced to obtain the true start time.

(3) Receiver Frequency

Dispersion caused by the interstellar plasma causes the arrival time to be a function of observing frequency. Using a non-standard receiver frequency produces a correctable error (see Section VI, F).

(4) Post-Detection Filter

Occasionally a non-standard filter width was used, resulting in unusual time delay through the filter. A correction is readily applied.

During the summer months of 1969 a bad detector connection caused unusually large (~1 ms) time delays. The corrections for this effect were derived by computing the autocorrelation function of the system noise, the width of which then gave the effective time constant of the filter. Both situations are labeled as system code 12 (see Section II, A).

(5) Miscellaneous

In a very few cases the reasons for a large residual are unknown. Common experimental situations in such cases are receiver tuning problems, repeated power failures, and radio frequency interference (RFI). The measurement results are usually omitted.

B. COLLATING THE DATA

A data tape produced at Goldstone contains data files corresponding to the pulsars observed during a particular observing session. This format is inconvenient for producing average pulse profiles. (These profiles, discussed in Section IV, are a necessary part of optimally estimating the pulse arrival time). Therefore, the early data files of a particular pulsar were gathered onto one or more magnetic tapes in the order they were collected at Goldstone. Preliminary editing took place during this process, to delete obviously faulty data. The main cause for omission at this stage is RFI. These data were used to compute the mean pulse profile presented in Section IV.

Data collected after August of 1972 is not collated according to pulsar. Data files are merely written onto magnetic tapes in the order they were collected without regard to the particular pulsar. The files were condensed by editing the data and filling each tape completely. Estimates of arrival times are obtained after each tape is filled (every 2 to 3 months).

SECTION IV
PULSE-SHAPE TEMPLATES

In the presence of white noise the maximum signal-to-noise (S/N) ratio for the output of a particular filter can be obtained when the filter response has the same form as the input signal (a matched filter). The required matched filter is realized by cross correlating a received pulse with an estimate of the noise-free shape of the pulse. The estimates of the noise-free pulse shapes are obtained by superimposing many thousands of pulses to average down the effects of noise. The result is referred to herein as a template.

The proper registration or alignment of the pulses needs to be obtained to build a template with a minimum of smearing. Two passes, each described below, are used to optimize the registration. Correlation with a triangular function is first performed to obtain first-order estimates of pulse position within the data records. The template position in the data array corresponding to the maximum cross correlation coefficient is defined to be the pulse position. The numbers in each data record are then shifted circularly by the amount required for proper registration with all the other data records. Adding all the records produces a preliminary template. This template is cross-correlated with the original data to provide new estimates of pulse positions within the data arrays. The second result of the addition of all the properly registered data is taken as the correct average pulse shape. Finally, the central 4096 words of the 5000 word array are used to form the template. See Section V regarding the choice of the 4096 words.

A. CORRELATION WITH A TRIANGLE

In the early analyses of pulsar data (Ref. 9), the data were cross correlated with a triangular function closely matched in width to the pulsar signal. The pulses resemble the triangular function so the correlation function provides an adequate estimate of the pulse position within the data array.

The shape of the triangular function lends itself to a particularly fast algorithm for computing the cross correlation coefficients. Let the data record be presented by f_n , $1 \leq n \leq 5000$. Then correlate with the function

$$T_r(n, n_0, W) = \begin{cases} 1 - \frac{|n-n_0|}{W} & ; \frac{|n-n_0|}{W} \leq 1 \\ 0 & ; \text{otherwise} \end{cases} \quad (2)$$

W is the half-width of the base of the triangle and n_0 is the position of the peak in the data array. This function is shown in Fig. 5

for $n_0 = W, W+1$, and $W+2$. Inspecting Fig. 5, the correlation coefficients C_0 and C_1 can be written as

$$C_0 = \sum_{n=1}^{2N-1} T_r(n, W, W) f_n = f_W + \sum_{n=1}^{W-1} \frac{n}{W} f_n + \sum_{n=W+1}^{2W-1} \frac{2W-n}{W} f_n$$

and

$$C_1 = \sum_{n=2}^{2N} T_r(n, W+1, W) f_n = f_{W+1} + \sum_{n=2}^W \frac{n-1}{W} f_n + \sum_{n=W+2}^{2W} \frac{2W+1-n}{W} f_n$$

The difference between the coefficients becomes

$$C_1 - C_0 = -\frac{1}{W} \sum_{n=1}^W (f_n - f_{W+n}) \quad (3)$$

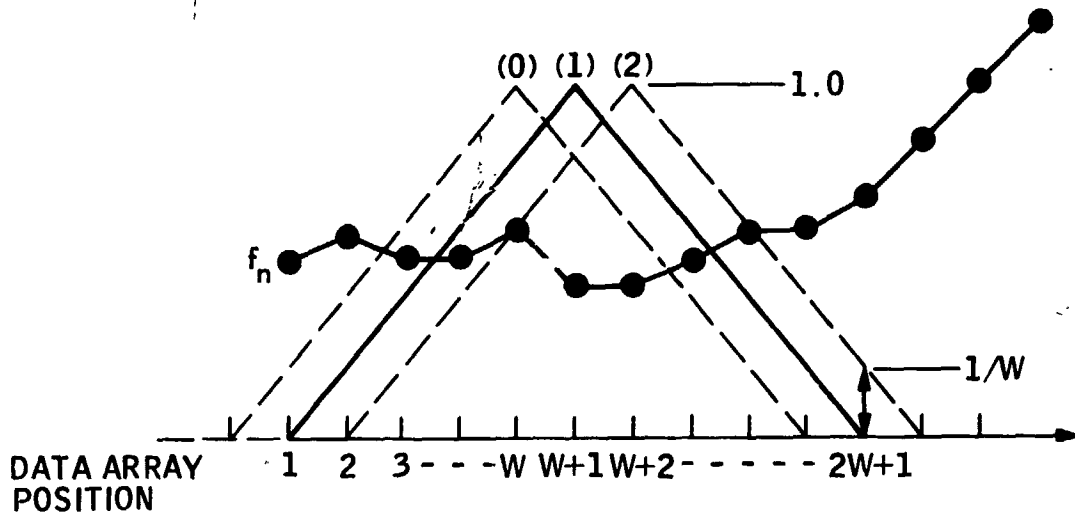


Figure 5. Three Triangular Functions Overlying a Data Array

This is the first quantity computed.

In a similar manner the difference between coefficients C_2 and C_1 is

$$C_2 - C_1 = -\frac{1}{W} \sum_{n=2}^{W+1} (f_n - f_{W+n}) \quad (4)$$

This is the second quantity computed, but in the following manner. This new quantity is obtained from Eq. (3) by adding the term

$$\frac{f_1}{W} - \frac{2f_{W+1}}{W} + \frac{f_{2W+1}}{W}$$

In general the new difference in adjacent coefficients is computed from the previous difference by

$$C_\ell - C_{\ell-1} = C_{\ell-1} - C_{\ell-2} + \frac{1}{W} (f_{\ell-1} - 2f_{W+\ell-1} + f_{2W+\ell-1}) \quad (5)$$

The value of C_ℓ relative to the coefficient C_1 is calculated by accumulating the sums $C_\ell - C_{\ell-1} + C_{\ell-1} - C_{\ell-2}$ from Eq. (4) through the many steps suggested by Eq. (5):

$$C_3 - C_2 + C_2 - C_1 = C_3 - C_1$$

$$C_4 - C_3 + C_3 - C_1 = C_4 - C_1$$

⋮

$$C_\ell - C_{\ell-1} + C_{\ell-1} - C_1 = C_\ell - C_1$$

The position of the peak of the triangular function corresponding to the largest value of $C_\ell - C_1$ denotes the position of the pulse in the data array.

B. CORRELATION WITH THE TRUE TEMPLATE

The cross correlation function $C(\tau)$ of two continuous functions is written as

$$c(\tau) = \int p(t)e(t - \tau) dt \quad (6)$$

where $p(t)$ is the pulse power as a function of time t , $e(t)$ is the expected pulse shape (the pulse template) and τ is the displacement in time of the two functions relative to some well-defined reference time. In the discrete case encountered here, the correlation coefficients can be evaluated by directly performing the operation suggested in Eq. (6). However, it is much faster to use Fourier analysis techniques. Direct evaluation of Eq. (6) requires 2.5×10^7 multiplications, while using the fast Fourier transform (FFT) algorithm requires only about 1.4×10^5 multiplications.

Consider the Fourier transforms of the functions involved. The transform of the correlation function $c(\tau)$ becomes

$$C(s) = \iint p(t) e(t - \tau) dt e^{-i2\pi s\tau} d\tau$$

where s is the transform variable. Interchanging the order of integration,

$$C(s) = \int p(t) e^{-i2\pi s\tau} \int e(u) e^{i2\pi su} du d\tau$$

or

$$C(s) = P(s) E(-s) \tag{7}$$

where $P(s)$ and $E(s)$ are the transforms of $p(t)$ and $e(t)$, respectively.

Hence, the procedure is to calculate $E(-s)$ for each template (calculated only once), $P(s)$ for the data record, and then the complex function $C(s)$. Inverse transformation of $C(s)$ yields $c(\tau)$.

The FFT algorithm is used in a form that takes advantage of the fact that a Fourier transform of a real function is the sum of a real even function and an imaginary odd function. Hence, if the data array is L samples long, only $L/2$ values need be calculated in the transform. See Ref. 10 for the original work on this form of the algorithm or the detailed discussion of its use by Brigham (Ref. 11). Briefly, the data is placed in an array L samples long, where L is a multiple of 2. Pretending that the array is complex of dimension $L/2$, an FFT is performed on the complex array. A final step is needed to unscramble the result into $(L/2) - 1$ complex pairs, one 0-frequency value, and one Nyquist-rate value. Alternatively, putting complex data such as the quantities $P(s)E(-s)$ in this form, the inverse of the above process can be formed. Software to perform the calculations was written for this project by G. A. Morris.

The central 4096 data points of the integrated pulse profiles were selected for the templates since the correlation process involves using the FFT algorithm for 2^{12} data points. The correlation is done twice to cover all 5000 data points. The details are presented in Section V. The value of τ corresponding to the maximum value of $c(\tau)$ denotes the position of the pulse in the data array.

C. SUBTRACTION OF THE BACKGROUND

Once an estimate of the pulse phase has been made, the pulsed power must be separated from the steady component contributed by the system. Let the signal be represented by a pulse template $U(t - \tau)$ of unity maximum height. The pulse is superimposed on a constant term N_s due to system noise. Associated with N_s are small noise variations $n(t)$ caused by a non-zero post-detection bandwidth. Hence, the total signal $S(t)$ becomes

$$S(t) = gU(t - \tau) + n(t) + N_s \quad (8)$$

where g scales the template to the data. The expected value of n , denoted by $E\{n\}$, is zero. The objective is to minimize the quantity

$$I_1 = \int \left[S(t) - gU(t - \tau) - N_s \right]^2 dt \quad (9)$$

All terms in I_1 are constant except the term

$$2g \int S(t) U(t - \tau) dt$$

which must be maximized to minimize I_1 . But this is merely the cross correlation performed above.

Estimates of g and N_s are needed to separate the pulse from receiver noise. The estimates should minimize I_1 :

$$\frac{\partial I_1}{\partial g} = 0 = - \int S(t) U(t - \hat{\tau}) dt + g \int U^2(t - \hat{\tau}) dt + N_s \int U(t - \hat{\tau}) dt$$

$$\frac{\partial I_1}{\partial N_s} = 0 = - \int S(t) dt + g \int U(t - \hat{\tau}) dt + N_s \int dt$$

where $\hat{\tau}$ is the estimate of τ from the correlation procedures. Solving for the estimates \hat{g} and \hat{N}_s of g and N_s , respectively.

$$\hat{g} = \left[\int dt \int S(t) U(t - \hat{\tau}) dt - \int S(t) dt \int U(t - \hat{\tau}) dt \right] / D$$

$$\hat{N}_s = \left[\int S(t) dt \int U^2(t - \hat{\tau}) dt - \int S(t) U(T - \hat{\tau}) dt \int U(t - \hat{\tau}) dt \right] / D$$

(10)

where

$$D = \int dt \int U^2(t - \hat{\tau}) dt - \left[\int U(t - \hat{\tau}) dt \right]^2$$

Note that only the quantities involving $S(t)$ need to be calculated for each data record. All other terms are calculated once for each template.

The discrete version of Eq. (10) is used in the data reduction. The value \hat{N}_s is subtracted from each data record before adding the record to the evolving template.

D. THE TEMPLATES

Several hundred thousand pulses were superimposed as described above to form the final estimates of the average pulse shapes of 24 pulsars. The results appear in Figures 6 through 29. Part (a) of each figure represents the template used in the data reduction. The abscissa presents time in terms of the pulse period P , while the ordinate is in arbitrary units of power. The vertical marks above and below the main pulse define the time origin. Some templates were smoothed beyond the

amount inherent in the receiver. The smoothing was obtained by convolving a $\text{sinc}(\tau)$ function of the appropriate width with the original data. The amount of smoothing noted in the figure caption represents the interval from the peak to the first zero of $\text{sinc}(\tau)$. A quantitative discussion of the choice of smoothing is presented in the next section.

Part (b) of each figure presents the details of the pulse on an expanded time scale. If the data has been smoothed more than in part (a) of the figure, the amount of smoothing is noted. The position of the pulse relative to the vertical marks above and below the main pulse defines, for that pulsar, the "zero phase" condition relative to a given epoch; i.e., to obtain a zero time-of-arrival residual relative to a given epoch, the vertical marks must be coincident with that epoch.

E. TEMPLATE SMOOTHING

The accuracy with which one can estimate the arrival time of a pulse increases as the random fluctuations in the signal decrease and as the sharpness of the pulse increases. However, attempts to smooth the signal to lower the effects of receiver noise also tend to destroy the sharpness of the pulse. A compromise must then be reached. This is done by estimating the uncertainty in the arrival time measurement when the signal-to-noise ratio is large.

Imagine that having performed the correlation process to measure the arrival time of the pulse, an estimate $\hat{\tau}$ has been obtained. The scaling of the template, \hat{g} , and the constant component, \hat{N}_s , have also been estimated. Allowing for small errors in the estimates, the model of Eq. (8) can be rewritten as a Taylor expansion:

$$S(\tau) = \hat{g}U(\Delta\tau) + \Delta gU(\Delta\tau) - \hat{g}\Delta\tau U'(\Delta\tau) + \hat{N}_s + \Delta N_s + n(\Delta\tau) \quad (11)$$

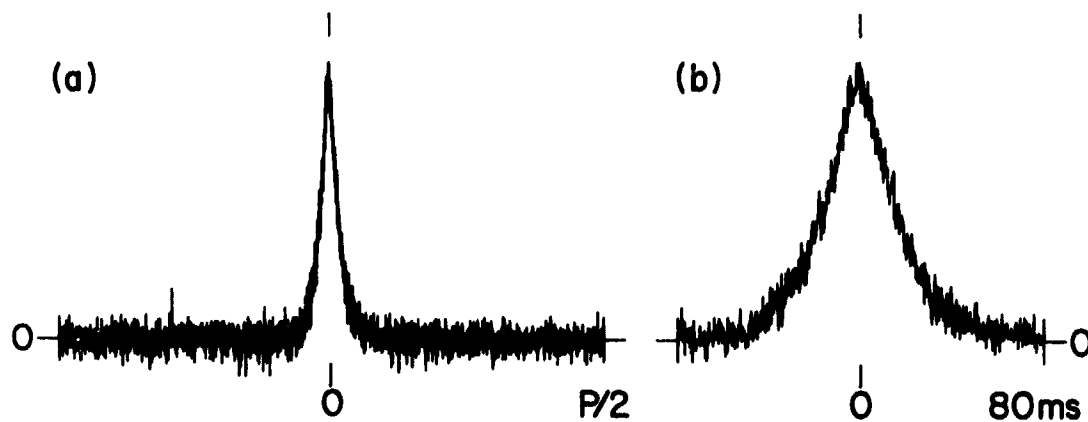


Figure 6. The template of PSR 0031-07: (a) $P = 0.943$ sec;
 (b) Expanded time scale

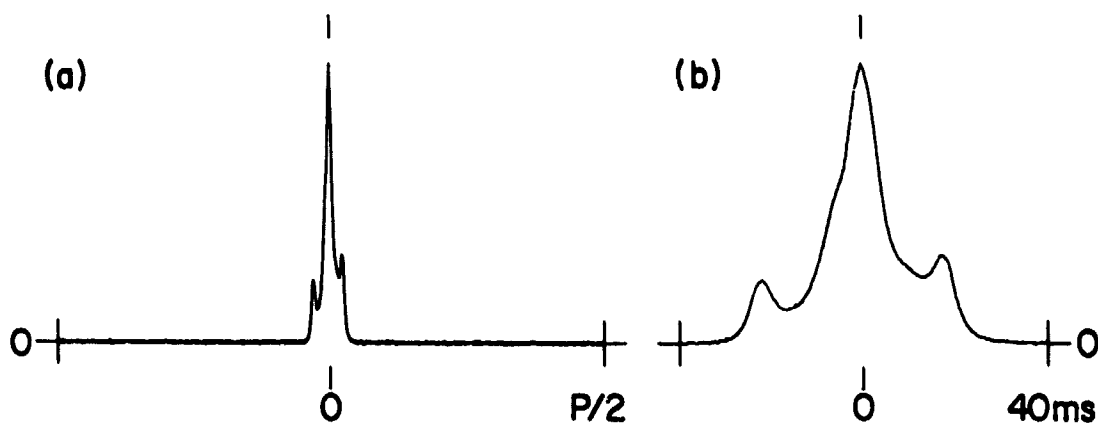


Figure 7. The template of PSR 0329+54: (a) $P = 0.715$ sec;
 (b) Expanded time scale

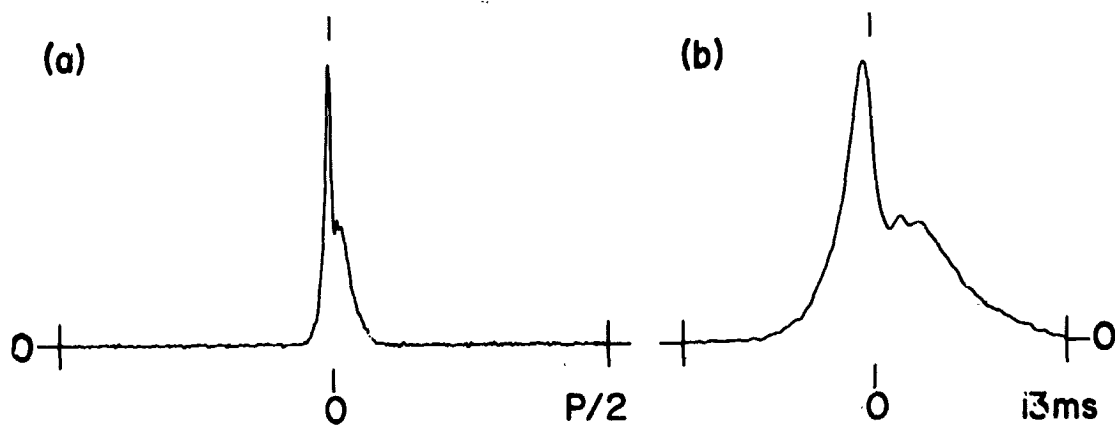


Figure 8. The template of PSR 0255+54: (a) $P = 0.156$ sec. The pulse has been smoothed by a window $160 \mu\text{sec}$ wide. (b) Expanded time scale

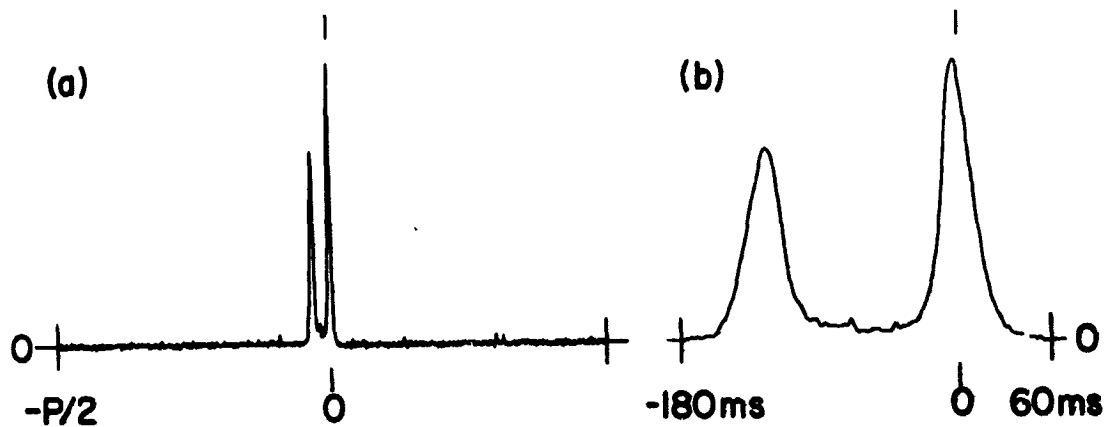


Figure 9. The template of PSR 0525+21. (a) $P = 3.745$ sec. The pulse has been smoothed by a window 2.2 ms wide. (b) Expanded time scale

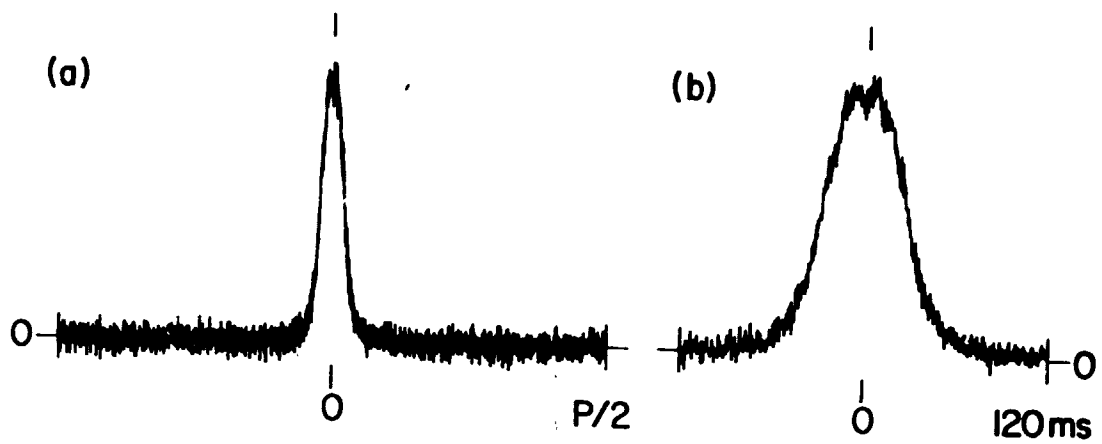


Figure 10. The template of PSR 0628-28: (a) $P = 1.244$ sec;
 (b) Expanded time scale

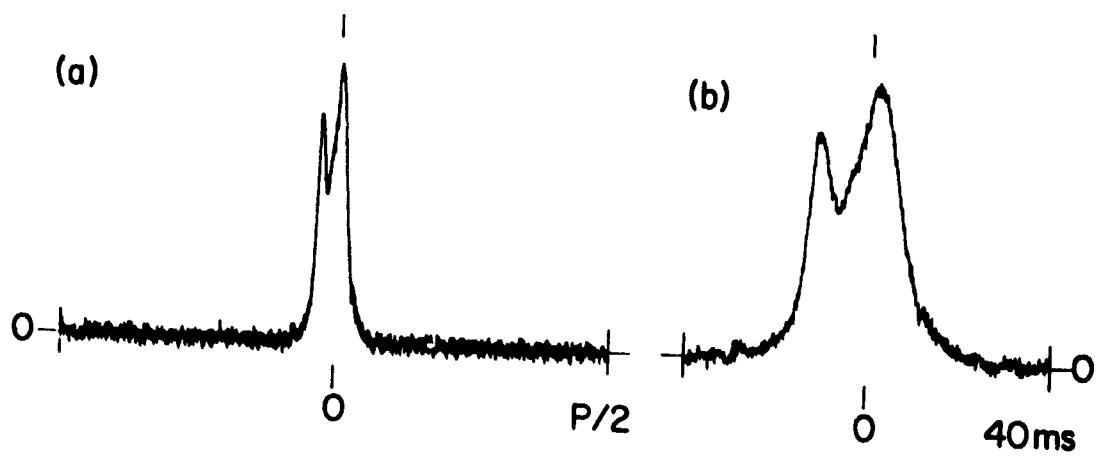


Figure 11. The template of PSR 0736-40: (a) $P = 0.374$ sec;
 (b) Expanded time scale

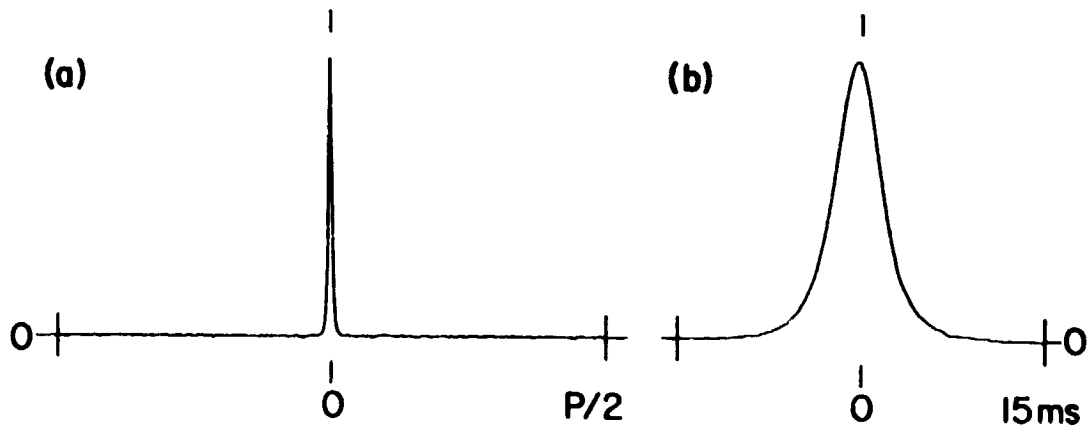


Figure 12. The template of PSR 0823+26: (a) $P = 0.531$ sec;
 (b) Expanded time scale

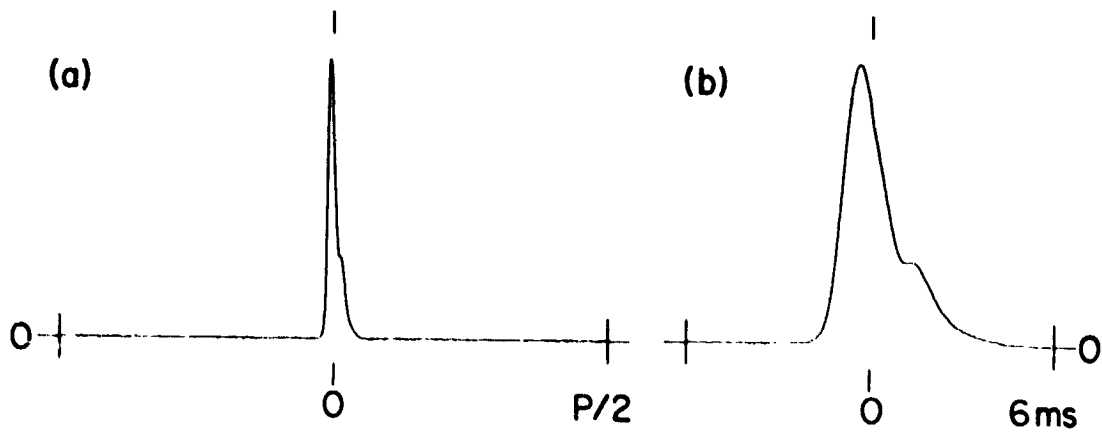


Figure 13. The template of PSR 0833-45: (a) $P = 0.089$ sec;
 (b) Expanded time scale

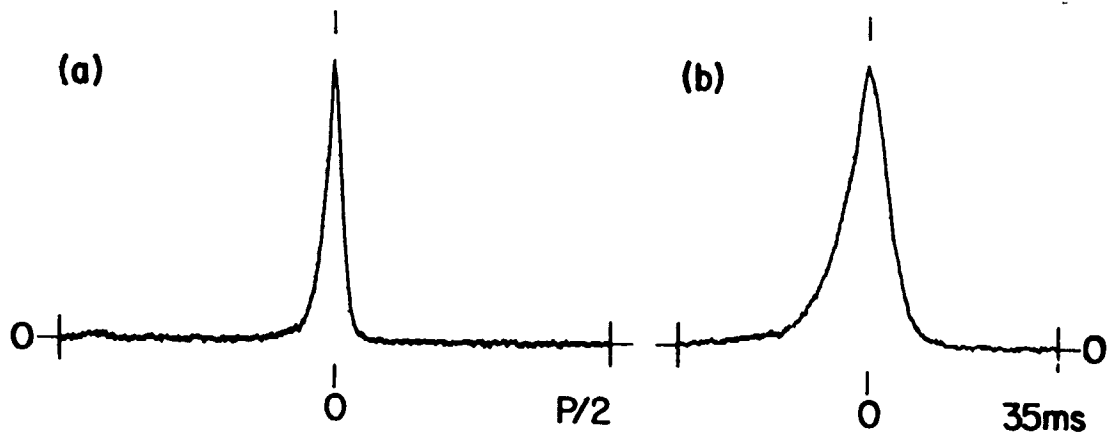


Figure 14. The template of PSR 0950+08: (a) $P = 0.253$ sec;
 (b) Expanded time scale

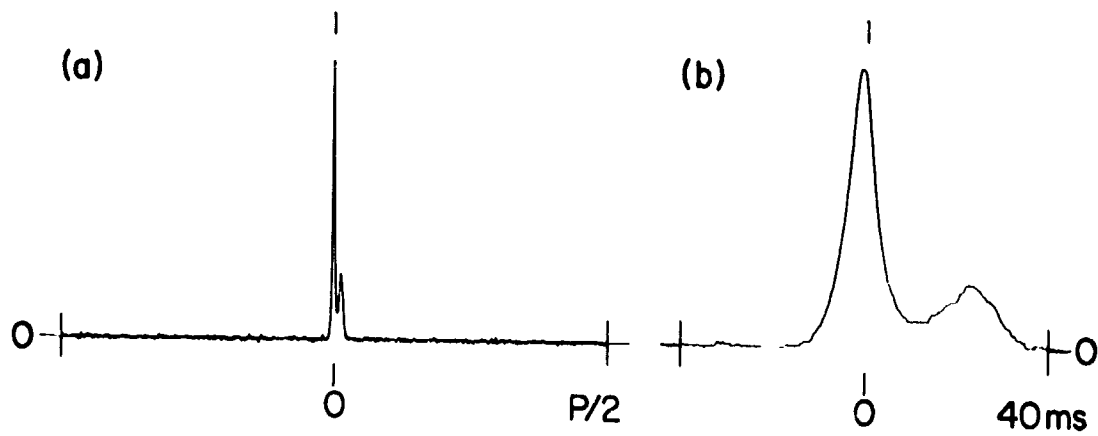


Figure 15. The template of PSR 1133+16: (a) $P = 1.188$ sec;
 (b) Expanded time scale

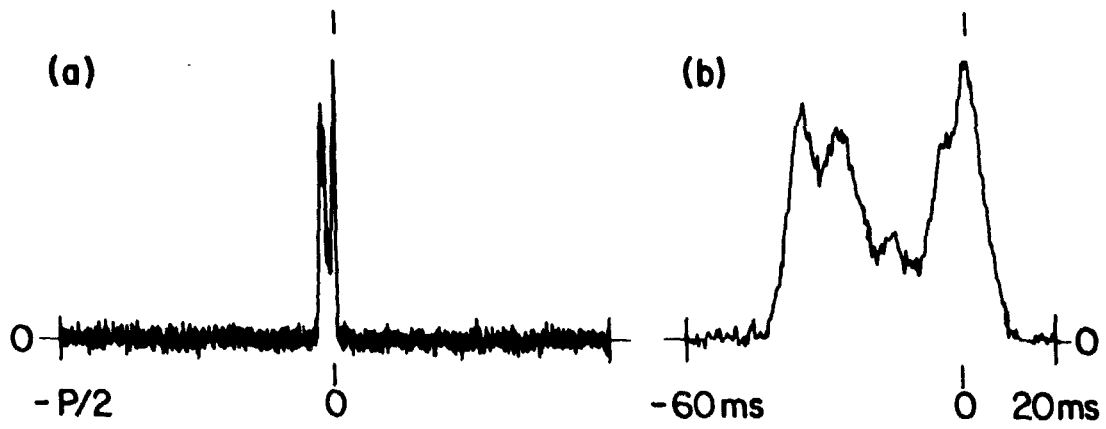


Figure 16. The template of PSR 1237+25: (a) $P = 1.382$ sec;
 (b) Expanded time scale

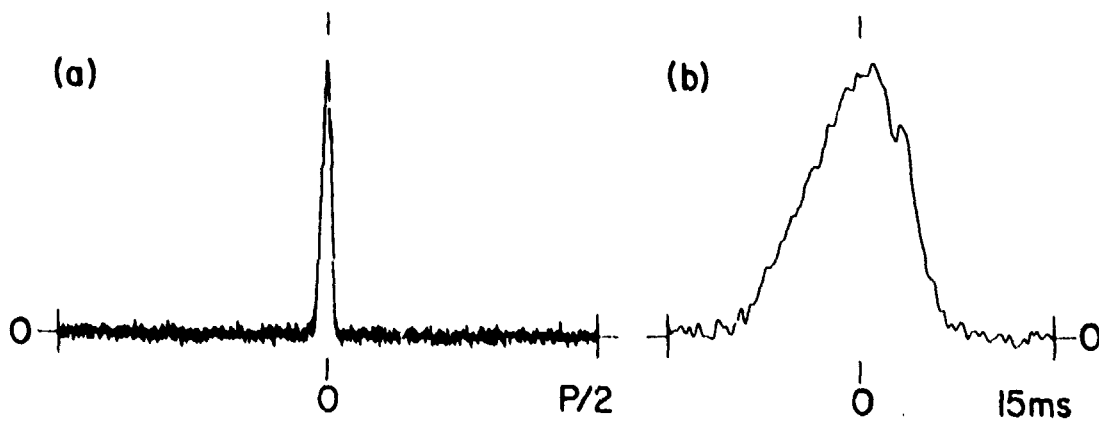


Figure 17. The template of PSR 1604-00: (a) $P = 0.422$ sec;
 (b) Expanded time scale

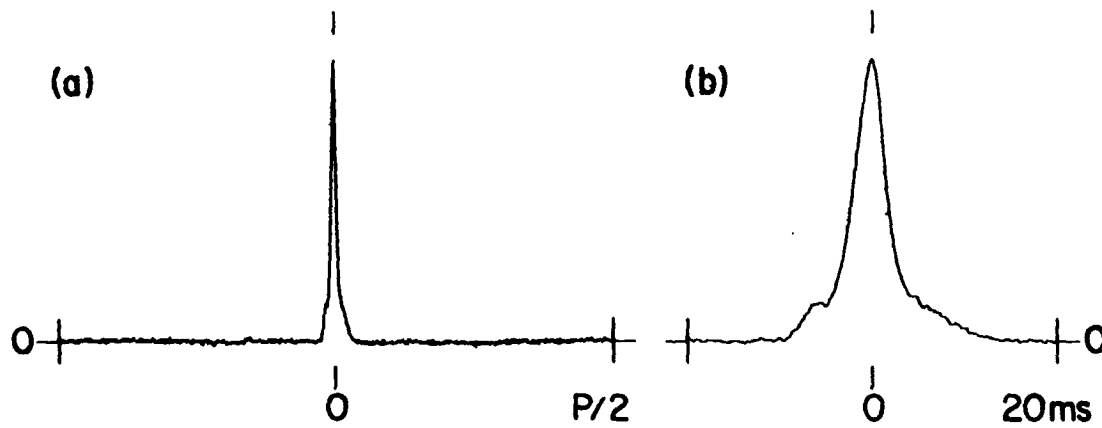


Figure 18. The template of PSR 1642-03: (a) $P = 0.388$ sec; The data has been smoothed by a window $230 \mu\text{sec}$ wide. (b) Expanded time scale

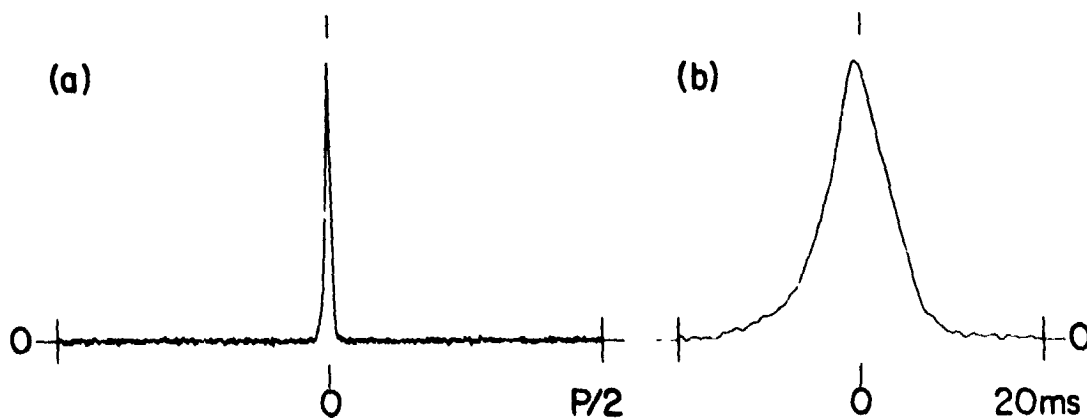


Figure 19. The template of PSR 1706-16: (a) $P = 0.653$ sec; The data has been smoothed by a window $390 \mu\text{sec}$ wide. (b) Expanded time scale

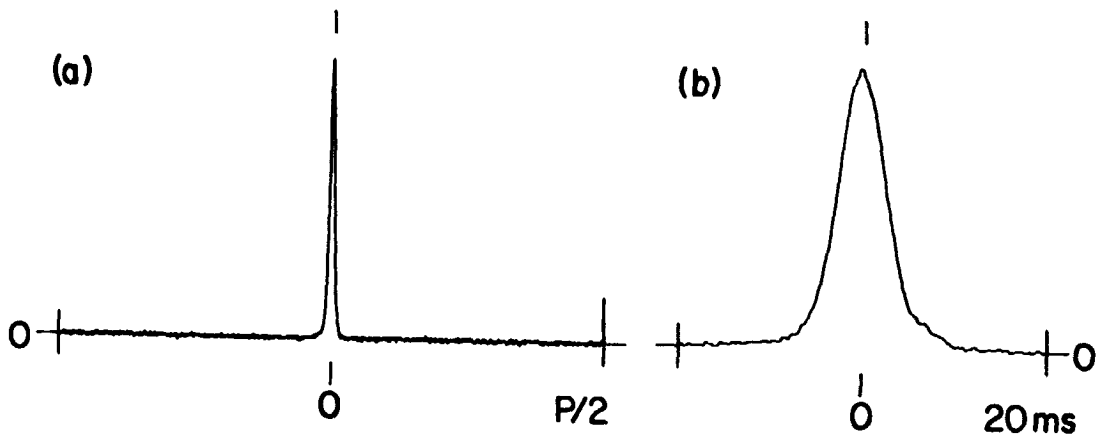


Figure 20. The template of PSR 1749-28: (a) $P = 0.563$ sec;
 (b) Expanded time scale

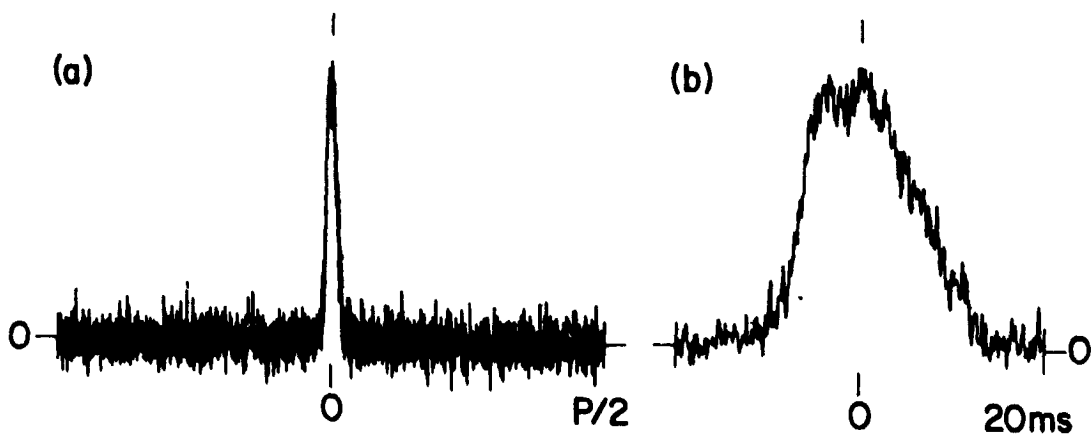


Figure 21. The template of PSR 1818-04: (a) $P = 0.598$ sec;
 (b) Expanded time scale

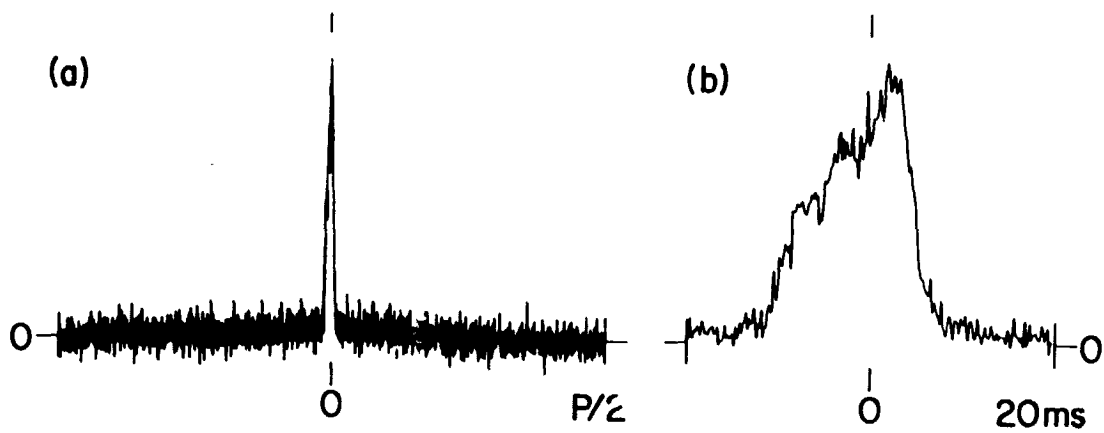


Figure 22. The template of PSR 1911-04: (a) $P = 0.826$ sec;
 (b) Expanded time scale

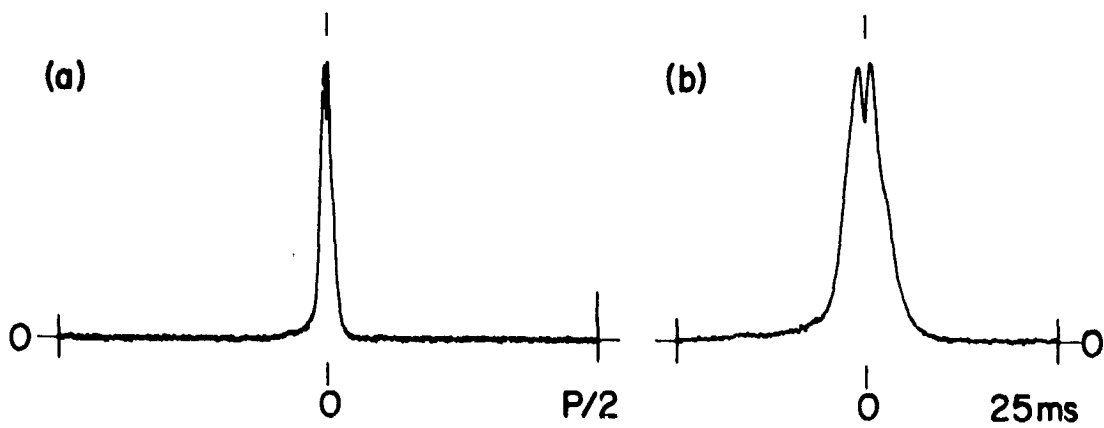


Figure 23. The template of PSR 1929+10: (a) $P = 0.227$ sec;
 (b) Expanded time scale

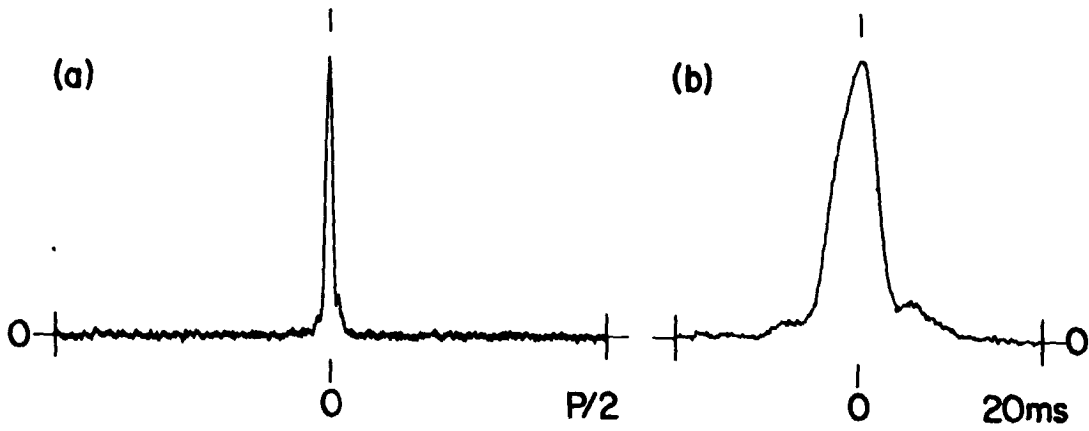


Figure 24. The template of PSR 1933+16: (a) $P = 0.359$ sec; (b) Expanded time scale

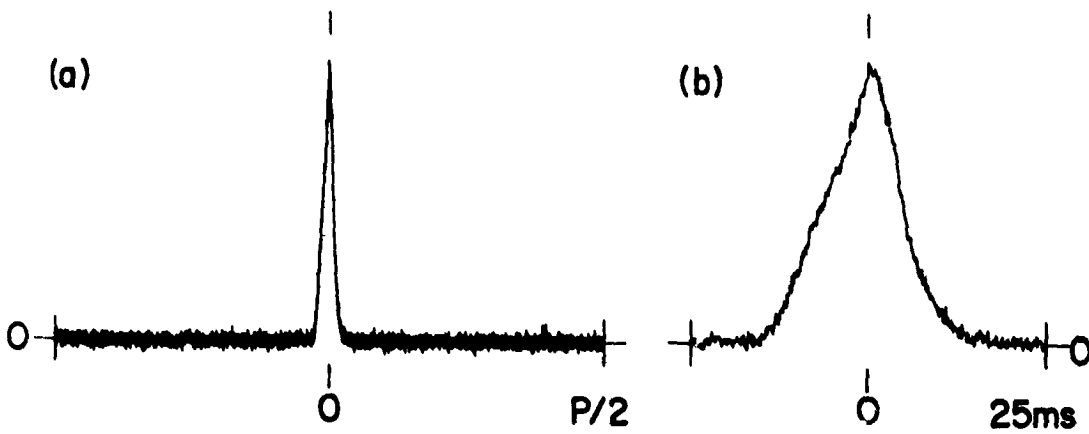


Figure 25. The template of PSR 2016+28: (a) $P = 0.559$ sec; (b) Expanded time scale

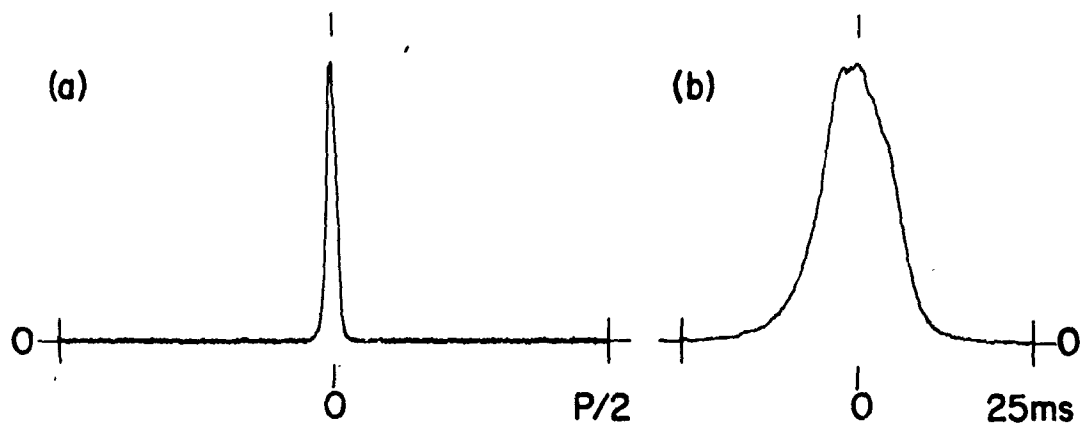


Figure 26. The template of PSR 2021+51: (a) $P = 0.529$ sec;
 (b) Expanded time scale

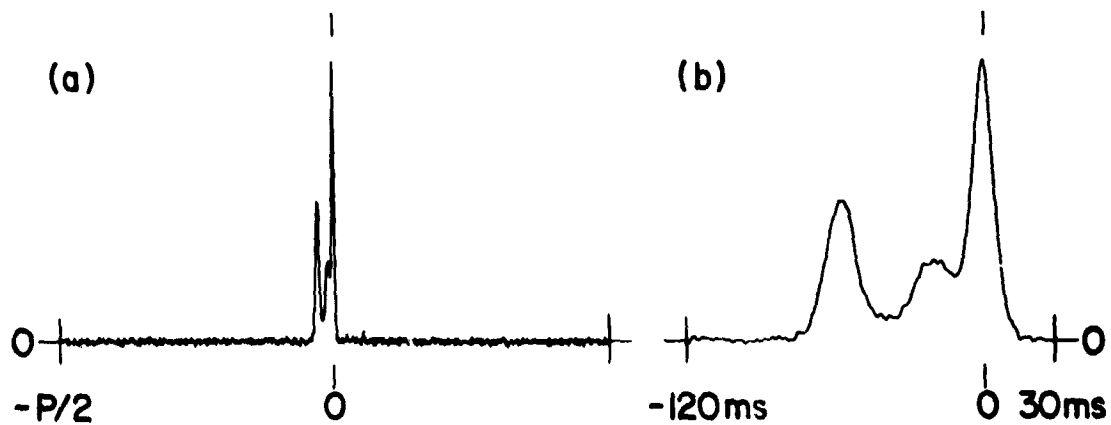


Figure 27. The template of PSR 2045-16: (a) $P = 1.96$ sec.
 The data has been smoothed by a window 1.2 ms wide.
 (b) Expanded time scale

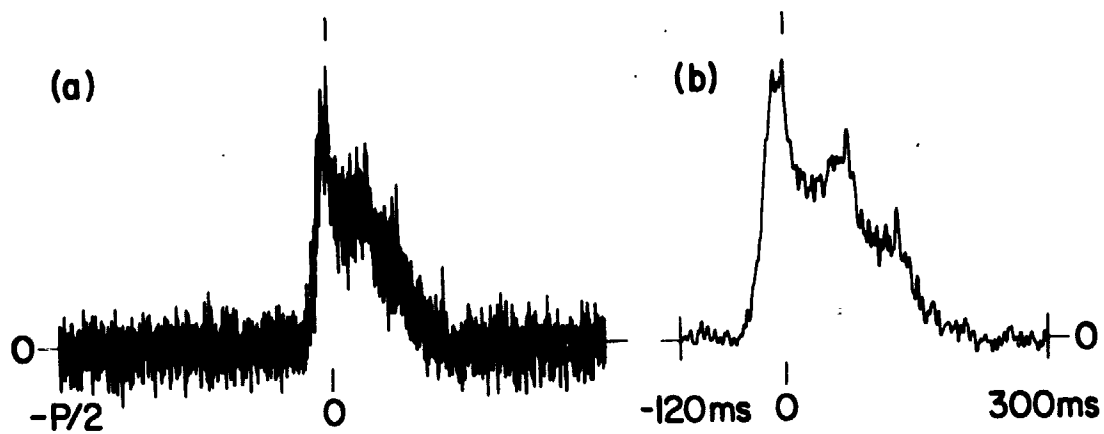


Figure 28. The template of PSR 2111+46: (a) $P = 1.015$ sec;
 (b) Expanded time scale, with the data smoothed
 for display by a window 2.0 ms wide

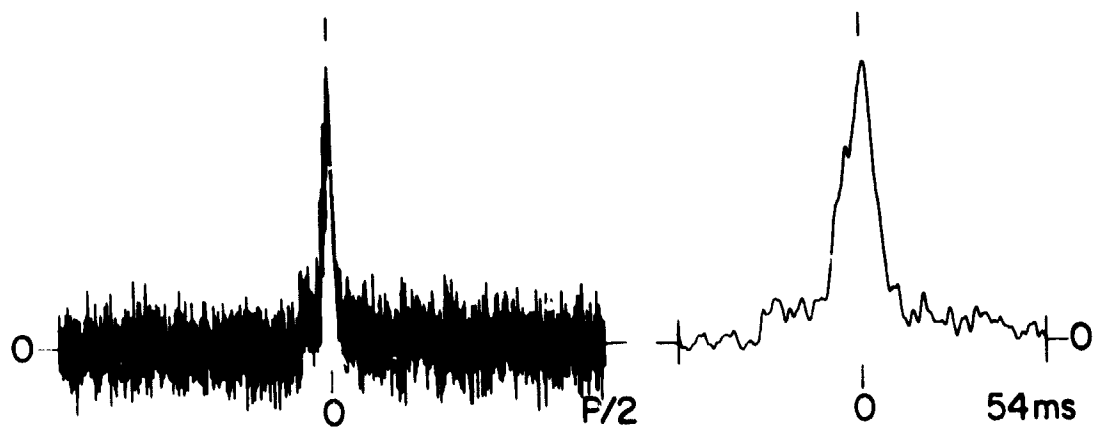


Figure 29. The template of PSR 2217+47: (a) $P = 0.538$ sec;
 (b) Expanded time scale, with the data smoothed
 for display by a window 1 ms wide

where the prime denotes a derivative, and

$$\Delta g = g - \hat{g}, \Delta \hat{N}_s = N_s - \hat{N}_s \text{ and } \Delta \tau = \tau - \hat{\tau}$$

Substituting Eq. (11) into Eq. (9) yields the mean square error in using estimates \hat{g} , \hat{N}_s and $\hat{\tau}$ instead of the mean values g , N_s and τ .

Minimize the mean square error with respect to $\Delta \tau$ to obtain

$$\begin{aligned} \frac{\partial I_1}{\partial \Delta \tau} = 2 \int_0^P \left[\Delta g U(\Delta \tau) - \hat{g} \Delta \tau U'(\Delta \tau) + \Delta N_s + n(\Delta \tau) \right] \\ \times \left[\Delta g U'(\Delta \tau) - \hat{g} U'(\Delta \tau) - \hat{g} \Delta \tau U''(\Delta \tau) + n'(\Delta \tau) \right] d\tau = 0 \end{aligned}$$

where

$U' = dU/dt$, $U'' = d^2U/dt^2$, etc. The integration is over one full pulse period. Collecting terms, we make use of the following facts:

- (1) $U(0) = U(P) = 0$
- (2) $U'(0) = U'(P) = 0$
- (3) $\int n' d\tau = n(0) - n(P) \approx 0$

and

$$(4) \int n n' d\tau \approx 0$$

Then

$$\Delta \tau \approx \frac{\int U' n d\tau}{\hat{g} \int (U')^2 d\tau} \quad (12)$$

where terms of the order $\Delta g/\hat{g}$ have been omitted.

Since

$$E\{\Delta \tau\} = \int U' E\{n\} d\tau / \hat{g} \int (U')^2 d\tau = 0,$$

then

$$\sigma_{\tau}^2 = E\{\Delta\tau^2\} = \frac{E \left\{ \int U'(s) n(s) ds \cdot \int U'(q) n(q) dq \right\}}{\hat{g}^2 \left[\int (U')^2 d\tau \right]^2}$$

or

$$\sigma_{\tau}^2 = \frac{\iint U'(s) U'(q) R_n(s-q) ds dq}{\hat{g}^2 \left[\int (U')^2 d\tau \right]^2}$$

where $R_n(\Delta\tau)$ is the auto-correlation function of the random fluctuation $n(t)$. $R_n(0) = \sigma_n^2$. If R_n always decreases significantly before U' can change significantly, then this result remains independent of the post-detection bandwidth. Measuring the variance of the fluctuations in a region not containing the pulse, we can write

$$\sigma_{\tau} \approx \frac{\sigma_n / \hat{g}}{\left[\int_0^P (U')^2 d\tau \right]^{1/2}} \quad (13)$$

The denominator is corrected for contributions to U' from random fluctuations. The expected standard deviation associated with $\hat{\tau}$ is then σ_{τ} .

The expression for σ_{τ} satisfies our intuition with respect to how well τ can be measured for a given signal-to-noise ratio (\hat{g}/σ_n) and a given pulse sharpness (measured by $\int (U')^2 d\tau$). A test of Eq. (13) was performed which did not rely on intuition. The extremely noise-free template for PSR 0833-45 was used as the basis for producing 100 records of simulated data. A random number generator was used to superimpose uncorrelated fluctuations onto the original template. Equation (13) was

used to choose the variance σ_n^2 given that $\sigma_\tau = 5 \mu\text{sec}$. The sharpness $\int (U')^2 d\tau$ is known from the template, and $g = 1$ in this case.

Would the correlation method define a random process $\hat{\tau}$ from the 100 simulated data records with the correct standard deviation? It did. The true value of τ was known in this test, and the standard deviation of the estimates $\hat{\tau}$ about the expected value τ was $5.2 \mu\text{sec}$.

The templates were smoothed to the resolution where σ_τ stopped decreasing due to a lower σ_n and began increasing due to loss in sharpness of the pulse.

F. CENTRAL SPIKES

Occasionally, the pulse strength in some of the weaker pulsars ebbs to the point of invisibility (a S/N ratio of 1 or less), even after an hour of integration. In these data records the template seeks out the stronger, sharper random fluctuations. The resulting estimate of τ represents the position in the data array of one of the larger noise spikes. In superimposing data records to produce a template, a narrow central spike was formed.

The central spike phenomenon was observed in the templates for PSR 1818-04 and PSR 2111+46. The spike was removed by placing in the central nine array locations a random process with a mean computed from the eight neighboring values. The variance was set equal to that of the pulse-free portion of the array.

G. DEFINING THE ZERO-LEVEL

Defining the zero-level of the pulsed radiation is straightforward in the cases where the pulses are narrow and confined to one window. This is not to say that the radiation between the pulses is not in part pulsed and associated with the pulsar. In most cases, however, the

emission is featureless. If a portion of the flat interpulse region is also pulsed, measurements of a different nature are required to detect this possible situation. In general, the mean value of the interpulse emission is used to define the zero-level.

In several cases, such as PSR 0950+08, the presence of sharp or broad features requires a careful definition of the interpulse region. In these carefully defined regions the mean value is then taken to be the zero-level of pulsed emission.

SECTION V

ESTIMATING THE PULSE ARRIVAL TIME

Each data record on magnetic tape presents an opportunity to measure the arrival time of a received pulse relative to a given epoch. The measurement is completed by correlating the appropriate template (Figures 6 through 29) with data records represented by Figure 1. The correlation process leads to an estimate of the maximum cross-correlation coefficient. However, the coefficients occur only every $P_a/5000$ seconds of delay, so interpolation in the neighborhood of the largest coefficient is required to obtain the best estimate of the delay corresponding to the true maximum of the coefficients. The value of the largest correlation coefficient and an estimate of the random fluctuations due to receiver noise are used to estimate the uncertainty in the time delay.

A. THE CORRELATION PROCESS

The data records are 5000 words long. Two arrays of 4096 words each are constructed to allow easy use of the FFT algorithm. The two separate results, each 4096 words, are combined to yield one 5000-word array of cross-correlation coefficients.

The template is shifted in position before transformation, as shown in Figure 30. The time within each pulse corresponding to the arrival time of the pulse is, in practice, the time marked "0" in Figures 6 through 29. Each template is shifted circularly until this time occurs in the first word of each array. Hence, the position of the largest correlation coefficient will be the estimate of the arrival time of that particular pulse. In addition, this shift keeps the size of the imaginary component of the transformed template to a minimum.

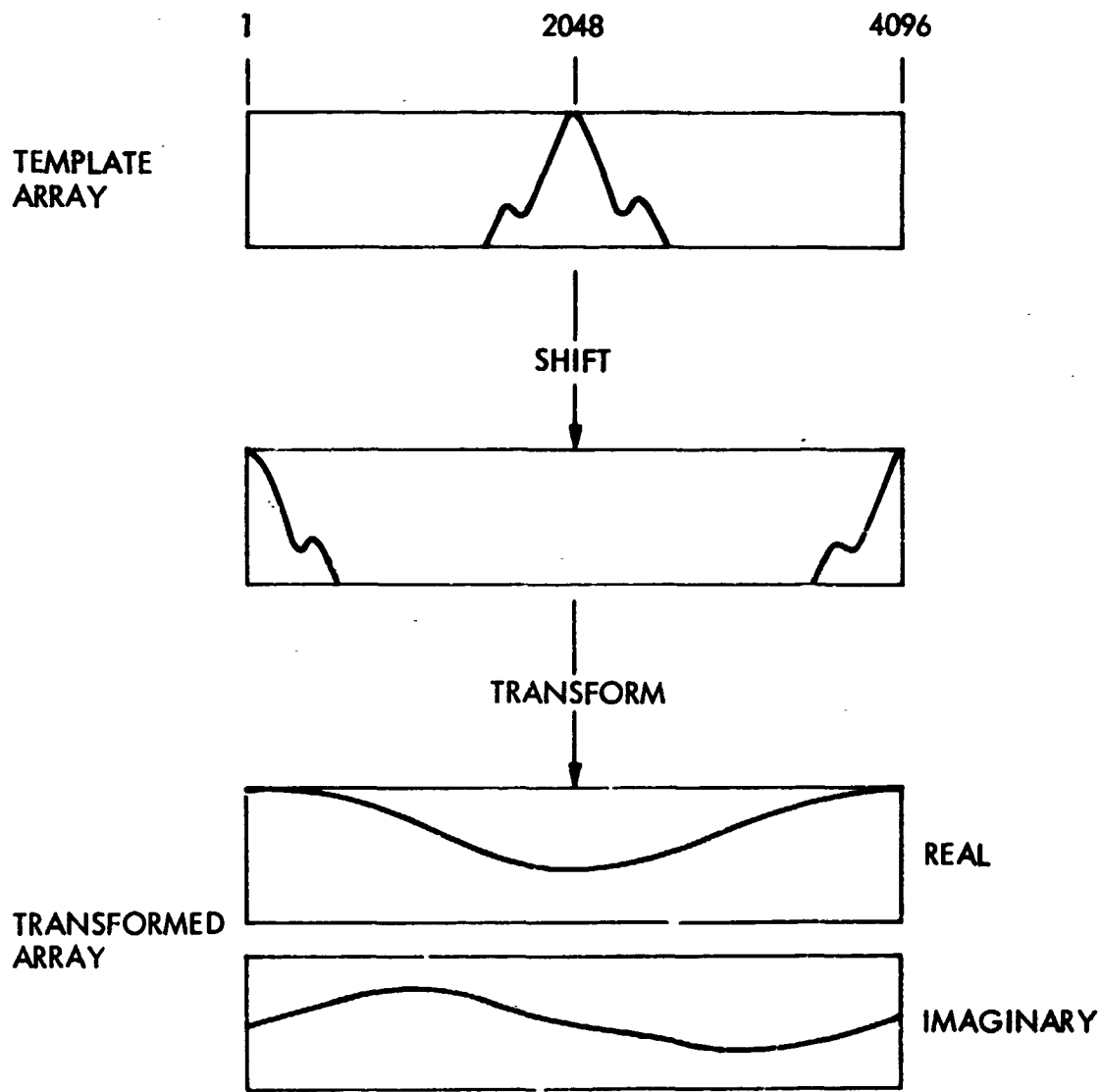


Figure 30. Shifting and Transforming the Template

obtained when no smearing is present represents a bias that can be estimated and removed. The bias is estimated by first calculating the expected arrival time based on the model of the pulsar, and then comparing that with the arrival time expected for a pulsar with a constant period and constant Doppler shift. The mean of the differences is the estimate of the bias.

The expected arrival time t_k of the k^{th} pulse arriving after the starting epoch t_0 is given by

$$t_k = t_{bk} + \frac{1}{c} [d(t_k) - d(t_0)] \quad (15)$$

where t_{bk} is the elapsed time between k pulses at the barycenter of the solar system, $d(t)$ is the distance of the received wavefront from the barycenter, and c is the velocity of light. Expanding the barycentric pulse period $P(t)$ in a Taylor series about t_0 ,

$$P = P_0 + \dot{P}_0(t - t_0) + \ddot{P}_0(t - t_0)^2/2 + O(\ddot{P} t^3)$$

It can then be shown that

$$t_{bk} \approx k P_0 + k^2 P_0 \dot{P}_0/2 + O(k^3 P) \quad (16)$$

The quantity $d(t)$ can be replaced with the scalar product $-\bar{r}_a(t) \cdot \bar{u}_p(t)$, where $\bar{r}_a(t)$ is the position vector of the antenna relative to the barycenter at time t . The unit vector \bar{u}_p is the direction vector of the pulsar as seen from the barycenter. Referring to Figure 34, note that $|\bar{r}_a| = a \sim 1 \text{ AU}$, and $R/a \gg 1$. Using the facts that

$$Y = -a \cos \theta - d$$

$$2(R-d)Y = X^2 + Y^2$$

and

$$X^2 + Y^2 = Z^2 = d^2 + a^2 + 2ad \cos \theta,$$

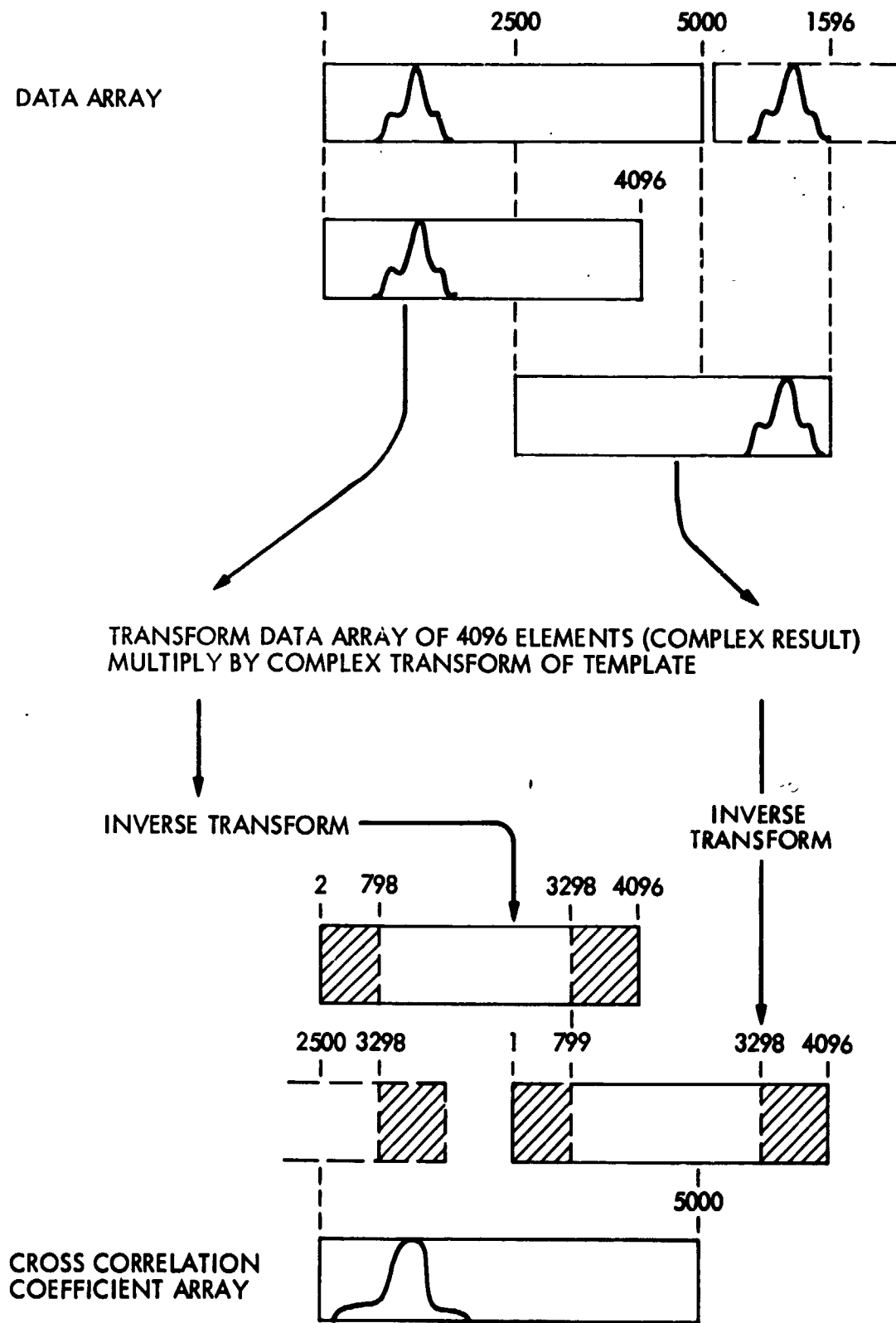


Figure 31. Computing the Cross Correlation Coefficients

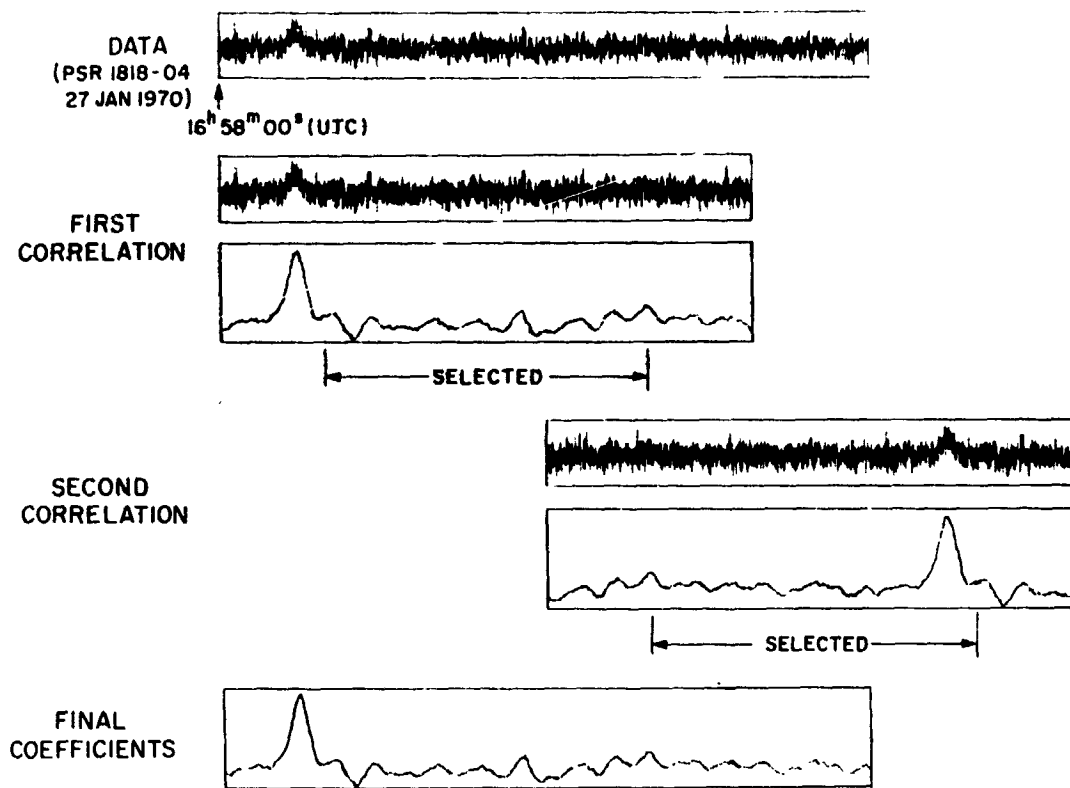


Figure 32. An Example of the Cross Correlation Process;
PSR 1818-04 on 27 Jan. 1970 at 16^h 58^m 00^s UT

B. ESTIMATING THE DELAY

The correlation coefficients are examined to determine the position in the array of the largest coefficient. In the cases of PSR 0355+54 and PSR 0833-45, two and three pulses, respectively, occur per data record. In these cases two or three positions are determined, each separated by a pulse period, and averaged together at the end of the estimation process.

Subsequent refinement of the estimate of the pulse position is obtained through interpolation. Interpolation is obtained by fitting, in a least-square sense, a fourth-order polynomial to M coefficients either side of the largest coefficient. At position x_1 (measured relative to the position of the largest coefficient) in the array of

correlation coefficients, a predicted value of $C_i = \sum_{\ell=0}^4 a_{\ell} x_i^{\ell}$ is obtained.

Note that $x_{i+1} - x_i = 1$. We have for the $2M + 1$ coefficients involved,

$$C_{-M} = a_0 + a_1 x_{-M} + \dots + a_4 x_{-M}^4$$

⋮

$$C_0 = a_0$$

$$C_1 = a_0 + a_1 x_1 + \dots + a_4 x_1^4$$

⋮

$$C_M = a_0 + a_1 x_M + \dots + a_4 x_M^4$$

The polynomial coefficients a_j need to be determined. Denoting the measured coefficient by \hat{C}_i , we want to minimize the quantity

$$S = \sum_{i=-M}^M (\hat{C}_i - C_i)^2 = \sum_i \left[\hat{C}_i - \sum_{\ell=0}^4 a_{\ell} x_i^{\ell} \right]^2$$

Requiring $\frac{\partial S}{\partial a_{\ell}} = 0$ for $\ell = 0$ to 4 , we find the set of equations

$$\begin{aligned} \ell = 0; \quad \sum_{i=-M}^M \hat{C}_i &= a_0 \sum_i 1 + a_1 \sum_i x_i + a_2 \sum_i x_i^2 + a_3 \sum_i x_i^3 + a_4 \sum_i x_i^4 \\ \ell = 1; \quad \sum_{i=-M}^M \hat{C}_i x_i &= a_0 \sum_i x_i + a_1 \sum_i x_i^2 + \dots + a_4 \sum_i x_i^5 \\ &\vdots \\ \ell = 4; \quad \sum_{i=-M}^M \hat{C}_i x_i^4 &= a_0 \sum_i x_i^4 + a_1 \sum_i x_i^5 + \dots + a_4 \sum_i x_i^8 \end{aligned} \quad (14)$$

Since the x_i occur at uniform intervals, the sums of odd powers of x_i are zero, and the sums of even powers of x_i are precomputed for each pulsar. The size of M is chosen separately for each pulsar. Within the range $x_{-M} < x_i < x_M$, the fourth-order polynomial provides a good fit to the correlation coefficients obtained when the template is correlated with itself.

The system of equations in Eq. (14) is solved for the polynomial coefficients a_k . The curvature of the resulting polynomial is computed. A positive second derivative indicates a distortion due to a low signal-to-noise ratio, and the interpolation is not attempted. Otherwise, the position x_p at which the polynomial peaked is determined. Then, stepping in intervals of 0.01 between $x_p - 1$ and $x_p + 1$, the refined estimate x_d of where the polynomial reaches its peak is determined.

The arrival time t_a of the first pulse occurring after the start time t_s is readily calculated. The separation between data array elements is $P_a/5000$ seconds. Hence, $t_a = t_s + x_d P_a/5000$.

The interpolation performed near the peak coefficient in Figure 32 is presented in Figure 33. The measured values of the cross-correlation coefficients (solid circles) are displayed versus the corresponding array location, which is proportional to time delay. The solid curve is the polynomial resulting from the least-squares fit. The p.c.a. of the polynomial is near $x = 589.0$. The region near this value of x is enclosed by the broken box, and reproduced on a finer scale in the inset. Progressing from $x = 589$ to $x = 590$ in steps of 0.01, the peak, denoted by the vertical arrow, is found at $x_d = 589.79$.

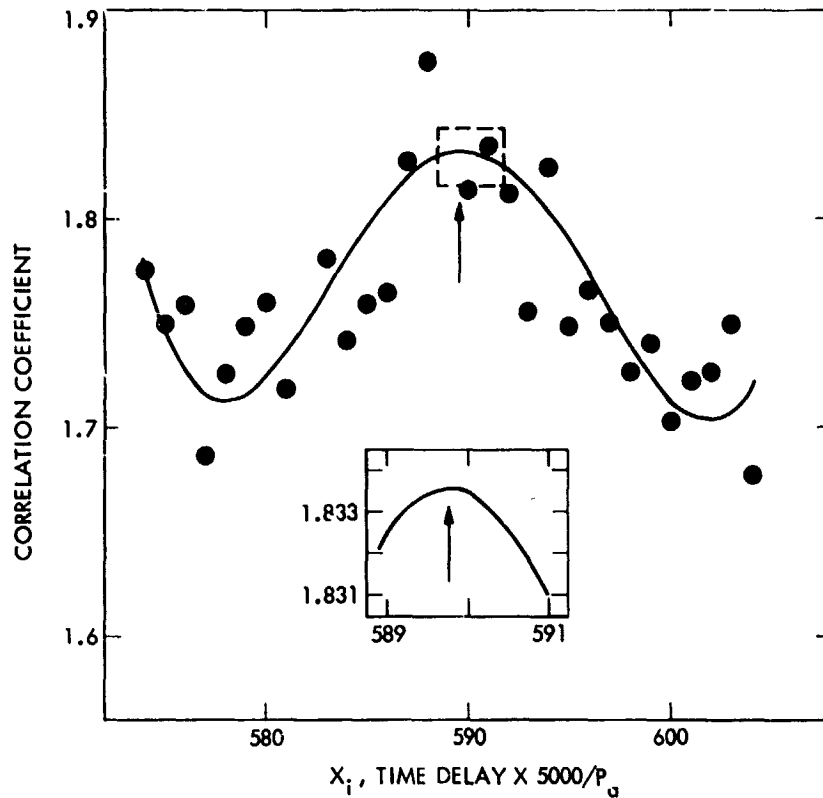


Figure 33. Correlation Coefficients Versus Time Delay Near the Peak Shown in Figure 32

C. ADJUSTMENTS

If the template has been shifted due to a large asymmetry about the zero-phase position, the effect of that shift is removed at this point in the data reduction. If two or three estimates of x_d were made, they are averaged together at this point.

D. UNCERTAINTY IN THE ARRIVAL TIME

Each estimate of the arrival time $\hat{\tau}$ is accompanied by an estimate of the uncertainty σ_{τ} . A modification of Eq. (13) is used. The scale factor \hat{g} and the baseline level \hat{N}_g are first estimated using Eq. (10). Quantities dependent on the template $U(\tau)$ only, having been computed earlier in the template generating process, are on magnetic tape with

the template itself. Note that the quantity $\int S(t)U(t - \hat{\tau}) dt$ is merely the maximum correlation coefficient. The root-mean-square (rms) noise level σ_n includes a contribution by the template. The denominator of Eq. (13) is another quantity computed earlier.

SECTION VI

GEOCENTRIC ARRIVAL TIMES

Now that the arrival time of the pulse has been measured relative to an epoch defined by a particular clock, it is time to consider referring these station arrival times to the geocenter. There are several corrections which must be applied to the measured arrival time before useful geocentric results are obtained: (a) A bias in the arrival time, caused by the smearing of the pulse during superposition, must be estimated and removed; (b) the geometric correction, changing the spatial reference from the antenna to the geocenter, must be applied; (c) an extra delay must be removed which is caused by using frequencies lower than 2388 MHz; (d) a small annual effect caused by the interaction of the Doppler and dispersion phenomena must be removed; (e) the clock epochs used in the measurements must be expressed as Coordinated Universal Time (UTC) epochs; (f) UTC epochs must then be expressed as ephemeris time (ET) epochs. The result is then the arrival time that would have been obtained had the measurement been performed at the geocenter using a clock running on ephemeris time.

A. CORRECTION FOR PULSE SMEARING

A small amount of smearing is inevitable as the received pulses are superimposed. The Doppler shift caused by Earth's rotation and orbital motion changes over the interval of integration. Also, differences can exist between the actual pulse period and the assumed period. The result is a slow drift in the pulse phase relative to the starting epoch, causing the centroid of the integrated signal to drift forward or backward in time as pulses are superimposed. The difference between the phase of the centroid of the superimposed pulses and the phase

obtained when no smearing is present represents a bias that can be estimated and removed. The bias is estimated by first calculating the expected arrival time based on the model of the pulsar, and then comparing that with the arrival time expected for a pulsar with a constant period and constant Doppler shift. The mean of the differences is the estimate of the bias.

The expected arrival time t_k of the k^{th} pulse arriving after the starting epoch t_0 is given by

$$t_k = t_{bk} + \frac{1}{c} \left[d(t_k) - d(t_0) \right] \quad (15)$$

where t_{bk} is the elapsed time between k pulses at the barycenter of the solar system, $d(t)$ is the distance of the received wavefront from the barycenter, and c is the velocity of light. Expanding the barycentric pulse period $P(t)$ in a Taylor series about t_0 ,

$$P = P_0 + \dot{P}_0(t - t_0) + \ddot{P}_0(t - t_0)^2/2 + O(\ddot{P} t^3)$$

It can then be shown that

$$t_{bk} \approx k P_0 + k^2 P_0 \dot{P}_0/2 + O(k^3 P) \quad (16)$$

The quantity $d(t)$ can be replaced with the scalar product $-\bar{r}_a(t) \cdot \bar{U}_p(t)$, where $\bar{r}_a(t)$ is the position vector of the antenna relative to the barycenter at time t . The unit vector \bar{U}_p is the direction vector of the pulsar as seen from the barycenter. Referring to Figure 34, note that $|\bar{r}_a| = a \sim 1 \text{ AU}$, and $R/a \gg 1$. Using the facts that

$$Y = -a \cos \theta - d$$

$$2(R-d)Y = X^2 + Y^2$$

and

$$X^2 + Y^2 = Z^2 = d^2 + a^2 + 2ad \cos \theta,$$

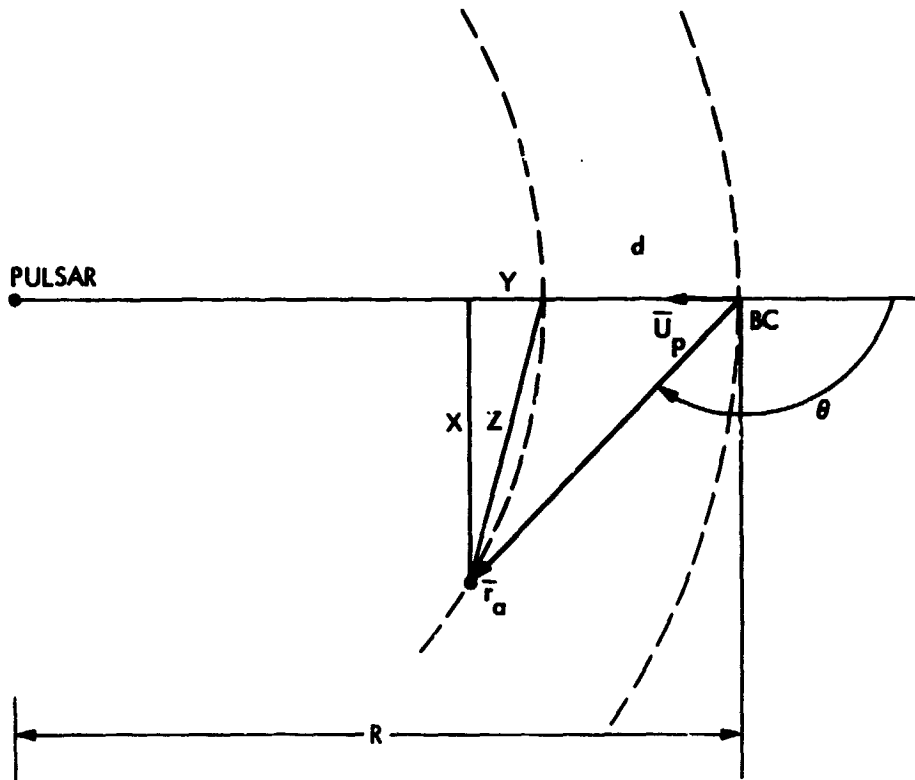


Figure 34. Geometry for Calculating the Phase Drift

the distance d becomes

$$d \approx -a \cos \theta = -\bar{r}_a \cdot \bar{U}_p$$

where $R/a \gg 1$. (The smallest value of this ratio is about 10^7 .)

Consider the arrival time obtained if $P(t) = P_a$ over the entire interval of integration. Suppose there is a delay of l pulses from the time the timing pulses are started to the time when the data collection is started (usually a few seconds at most). Then M groups of N pulses (usually 500) are superimposed, with n pulses elapsing between groups to allow for a visual display of the progress of the observation. Figure 35 displays the numerology used in counting these pulses. Under the

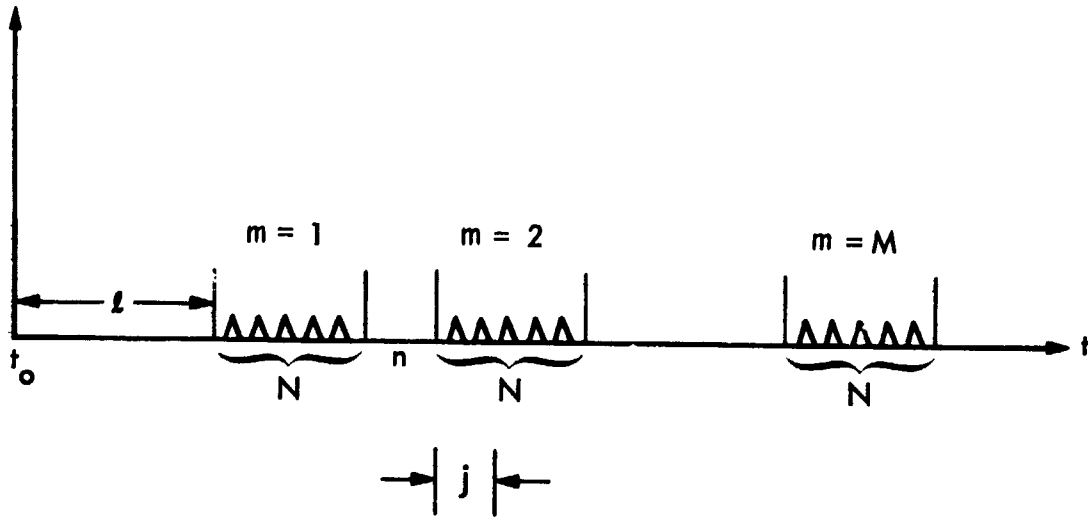


Figure 35. Nomenclature for Enumerating Pulses

assumption of a constant period, the arrival time t_{ak} of the k^{th} pulse after the start epoch t_0 is

$$t_{ak} = [\ell + j + (N + n)(m - 1)] P_a = kP_a$$

where j is the pulse in question in the m^{th} block of N pulses, and P_a is the assumed constant period. (The synthesizer frequency f_s used in the observation, as per Figure 2, is $10^6/P_a$.)

The mean of the difference $t_k - t_{ak}$ is given by

$$E \{t_k - t_{ak}\} = \overline{t_k - t_{ak}} = \frac{1}{NM} \sum_{m=1}^M \sum_{j=1}^N (t_k - kP_a)$$

Let $D = \overline{t_k - t_{ak}}$, representing the bias caused by the smearing. Substituting Eqs. (15) and (16) into the expression for D yields

$$D = \frac{(P_0 - P_a)}{NM} \sum_{m=1}^M \sum_{j=1}^N \{j + \ell + (N + n)(m - 1)\} + \frac{P_0 \dot{P}_0}{2NM} \sum_{m=1}^M \sum_{j=1}^N \quad (17)$$

$$\{j + \ell + (N + n)(M - 1)\}^2 + \frac{1}{cNM} \sum_{m=1}^M \sum_{j=1}^N \{d(t_k) - d(t_0)\}$$

The mean of the distances $d(t_k)$ can be replaced by the distance near the midpoint of the range of j , yielding for the third term of Eq. (17),

$$-\frac{1}{cM} \sum_{m=1}^M \left\{ \bar{r}_a \left[\frac{t_{N+1}}{2} + \ell + (N+n)(m-1) \right] - \bar{r}_a(t_0) \right\} \cdot \bar{u}_p(t_0)$$

Performing the indicated summations, Eq. (17) becomes

$$\begin{aligned} D = & \left[\frac{N+1}{2} + \ell + \frac{(N+n)(M-1)}{2} \right] (P_0 - P_a) \\ & + \frac{P_0 \dot{P}_0}{2} \left\{ \left[\frac{N+1}{2} + \ell + \frac{(N+n)(M-1)}{2} \right]^2 + \frac{(N^2-1) + (N+n)^2(M^2-1)}{12} \right\} \\ & - \frac{1}{cM} \sum_{m=1}^M \left\{ \bar{r}_a \left[\frac{t_{N+1}}{2} + \ell + (N+n)(m-1) \right] - \bar{r}_a(t_0) \right\} \cdot \bar{u}_p(t_0) \end{aligned} \quad (18)$$

It has been assumed that the signal strength is constant over the range of k . Large fluctuations cause Eq. (18) to be in error, and if the drift is large, the results may be rejected.

The expression derived above for the drift is applied to all the data. In all cases, $N = 500$. The delay ℓ is usually 0. The plot time n is equivalent to 30 seconds before Julian date 2440195.5, and 17 seconds thereafter. The number M of 500-pulse integrations varies depending on pulse strength, ranging from the equivalent of a few minutes to over two hours.

The Jet Propulsion Laboratory ephemeris DE 96 is used to compute barycentric positions \bar{r}_a . One major export from this observing program is ephemeris independent, geocentric arrival times. However, the drift correction is needed, and is best done by the observer early in the reduction process. The use of a different ephemeris of similar quality

will not change the corrections of Eq. (18) significantly. A large drift correction is on the order of a few milliseconds, and a velocity difference between two ephemerides of greater than 0.1 percent would be required to produce a 1 μ sec change in the drift estimate. This is usually less than the error estimates encountered in these measurements. Note also that this correction is dependent on a good knowledge of the pulse period and its derivatives. These have been well-determined in a separate data analysis effort.

The sum of the barycentric position vector of the geocenter and the geocentric position of the antenna, \bar{r}_g , yields \bar{r}_a . The computation of \bar{r}_g is discussed in the next section. The direction vector \bar{U}_p is derived from a model-fitting procedure, which is beyond the scope of this report. All the pulsar positions used here are known to at least 1 arc-sec, an error that will produce a geocentric arrival time error of 0.1 μ sec or less.

An example of phase drift and the subsequent correction for the effect is shown in Figure 36. Sixteen groups of 500 pulses of PSR 0833-45 were examined separately to estimate τ . The solid circles represent these estimates relative to the estimate for $m = 1$. The line through the solid circles represents a fit-by-eye to the linear drift. The triangle is the result of examining the accumulation of the 16 blocks of data. As one would expect in a well-behaved situation, this estimate of τ has drifted about one-half the distance from "0" as the estimate for the $m = 16$ case alone. This line through the triangle and the zero for this example (0 at $m = 1$) delineates the hypothetical drift one would find in examining an accumulation of the preceding blocks of data. The quantity D , derived from Eq. (18), is the amount the result represented

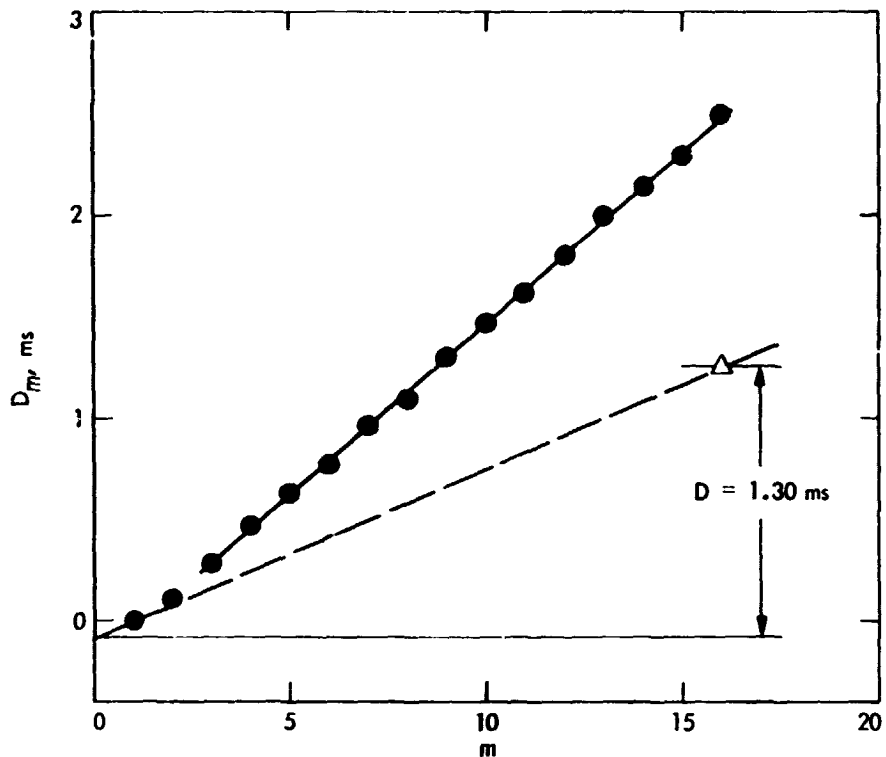


Figure 36. An Example of Drift in the Phase of PSR 0833-45 on 1 Dec. 1968 at 11^h 00^m 00^s (UT)

by the triangle is shifted to correct for drift. Note that by shifting the datum down by D ms, it is nearly in line with the intersection of the dashed line and the $m = 0$ axis. In a later analysis the resulting $\hat{\tau}$ was found to be only 15 μ sec away from the arrival time predicted by a smooth model, which was fitted to several months of data.

B. ANTENNA POSITION

The referral of the measured arrival time to the geocenter requires the addition of the time delay $\bar{r}_g \cdot \bar{U}_{pg} / c$, where \bar{r}_g is the geocentric position of the antenna and \bar{U}_{pg} is the geocentric direction vector of the pulsar. In practice $\bar{U}_{pg} \approx \bar{U}_p$. The coordinate system used here is the right-handed rectangular system (X, Y, Z) . The coordinate X is in the direction of 0^h Right Ascension (RA) at 1950.0. The station position at a particular UTC epoch is calculated from the antenna coordinates in

Table 5 and the knowledge of the Greenwich Hour Angle (GHA). The station coordinates are a version of Location Set (LS) 44, which are based on the ephemeris DE 96 (Ref. 19). The GHA is computed as outlined in Table 6 (see Ref. 20).

Table 5. Geocentric Antenna Coordinates

Antenna	West Longitude β (deg)	Latitude λ (deg)	Radius R (km)
DSS 11 (26m)	116.849390	35.208047	6372.011
DSS 12 (34m)	116.805462	35.118665	6371.994
DSS 13 (26m)	116.794863	35.066546	6372.117
DSS 14 (64m)	116.889507	35.170847	6366.227
DSS 62 (26m)	4.367811	40.263145	6369.963
DSS 63 (64m)	4.247991	40.241318	6370.048

Table 6. Relations Used in Computing the GHA of an Observing Station

<p>At the epoch $d + \text{SEC}/86400$,</p> $\text{GHA} = 100.0755426 + d(0.985647346 + 2.9015 \times 10^{-13} d)$ $+ \dot{\theta} \text{ SEC} + \delta\psi \cos(\epsilon) \text{ degrees}$ <p>where: (1) d = Julian days past 2433282.5</p> <p>(2) SEC = seconds past 0^h on day d</p> <p>(3) $\dot{\theta} = 4.17807417 \times 10^{-3} / (1 + 5.21 \times 10^{-13} d)$ deg/sec</p> <p>(4) $\delta\psi$, the nutation in longitude, is taken from ephemeris DE 96</p> <p>(5) $\dot{\epsilon} = 4.09205684 \times 10^{-1}$</p> $+ T[-2.28534 \times 10^{-4} + T(-1.5 \times 10^{-8} + 8.7 \times 10^{-9})]$ radians <p>where T is in Julian centuries of 36525 days past 2433282.5.</p>

The components of the geocentric antenna vector are computed in the 1950.0 coordinate system, requiring rotations for precession and nutation. Considering an antenna at longitude β and latitude λ at a given epoch,

$$\bar{r}_g = \begin{bmatrix} r_{gx} \\ r_{gy} \\ r_{gz} \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{bmatrix} \times \begin{bmatrix} 1 & -\delta\Psi\cos(\bar{\epsilon}) & -\delta\Psi\sin(\bar{\epsilon}) \\ \Delta\Psi\cos(\bar{\epsilon}) & 1 & -\delta\epsilon \\ \Delta\Psi\sin(\bar{\epsilon}) & \delta\epsilon & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} r'_{gx} \\ r'_{gy} \\ r'_{gz} \end{bmatrix}$$

where

$$\begin{bmatrix} r'_{gx} \\ r'_{gy} \\ r'_{gz} \end{bmatrix} = \begin{bmatrix} R\cos(\lambda)\cos(\text{GHA} - \beta) \\ R\cos(\lambda)\sin(\text{GHA} - \beta) \\ R\sin(\lambda) \end{bmatrix}$$

The elements P_{ij} of the precession matrix, given in Table 7, are from Ref. 21. An approximation to the nutation matrix has been used, where $\delta\Psi$ and $\delta\epsilon$ are taken from the ephemeris DE 96, while $\bar{\epsilon}$ is computed as in Table 6.

The approximations to the precession and nutation matrices are accurate to a few parts in 10^9 in both angular position and radial magnitude. Since $|\bar{r}_g| \sim 6 \times 10^3$ km, the corresponding error in arrival time is on the order of picoseconds.

Table 7. Elements of the Precession Matrix

$$P_{11} = 1.0 - T^2(2.9697 \times 10^{-4} + 1.3 \times 10^{-7}T)$$

$$P_{12} = T \left[2.234988 \times 10^{-2} + T(6.76 \times 10^{-6} - 2.21 \times 10^{-6} T) \right]$$

$$P_{13} = T \left[9.71711 \times 10^{-3} - T(2.07 \times 10^{-6} + 9.6 \times 10^{-7}T) \right]$$

$$P_{21} = -P_{12}$$

$$P_{22} = 1 - T^2(2.4976 \times 10^{-4} + 1.5 \times 10^{-7} T)$$

$$P_{23} = -T^2 (1.085 \times 10^{-4} + 3 \times 10^{-8}T)$$

$$P_{31} = -P_{13}$$

$$P_{32} = P_{23}$$

$$P_{33} = 1 - T^2 (4.721 \times 10^{-5} - 2 \times 10^{-8}T)$$

Note: T is in Julian centuries of 36525 days past 2433282.423.

Larger errors appear when referring the arrival times to the solar system barycenter. Since one normally works in 1950.0 coordinates and solves for pulsar positions and proper motions in these coordinates, barycentric arrival times are not highly sensitive to the recent increase in the accepted value of the general precession in longitude by 1.1 arc-sec/century. However, changes in the Earth's barycentric position can vary significantly as ephemerides are improved. For example, the difference in the angular position of Earth in DE 108 and that in DE 96 adds up to

about 0.5 arc-sec/century.* In a ten-year observing program, the difference is then 0.05 arc-sec, similar to the errors in pulsar positions derived from the arrival time data.

C. DISPERSION

Considerable effort was expended in the early observations to obtain one frequency, 2388 MHz. This was not always possible, for several observations occurred at 2295 and 2328 MHz. All observations are now at 2295 MHz. Integration of Eq. (1) provides the corrections in time to be added to an arrival time measured at F MHz to refer it back to 2388 MHz. Performing the integration, the correction ΔT_D becomes

$$\Delta T_D = \frac{DM}{2.410086 \times 10^{-4}} \left[\frac{1}{(2388)^2} - \frac{1}{F^2} \right] \text{ sec} \quad (19)$$

where the values of DM are from Table 4.

In the application of ΔT_D to PSR 0833-45 it was found that an additional 250 μsec had to be subtracted from the measurement when $F = 2295$ MHz. No significant addendum was needed when $F = 2328$ MHz. The average pulse shape must be independent of observing frequency if the correction ΔT_D is to be perfectly adequate. Most shapes do change significantly with frequency, including that of PSR 0833-45, thus creating the need to measure an addendum to ΔT_D .

D. DOPPLER DISPERSION

The actual frequency of observation varies with the component of antenna velocity laying along the direction of the pulsar. The measured arrival time then has a varying component since the interstellar medium

*E.M. Standish, private communication.

is dispersive. The Doppler-shifted observing frequency F_0' is related to the mean observing frequency F_0 by

$$F_0' = F_0 \left(1 + \frac{\bar{V}_a \cdot \bar{U}_p}{c} \right)$$

where \bar{V}_a is the barycentric velocity of the antenna. In this situation, integration of Eq. 1 leads to a form similar to Eq. (19). Performing that operation,

$$\Delta T_{DD} = \frac{DM}{1.205043 \times 10^{-4} F_0^2} \left[\frac{1}{1 + \frac{\bar{V}_a \cdot \bar{U}_p}{c}} - 1 \right]$$

where ΔT_{DD} , the correction for Doppler dispersion is added to the measured arrival time. Using the fact that $|\bar{V}_a/c| < 10^{-4}$, and setting $F_0 = 2388$ MHz, the correction becomes

$$\Delta T_{DD} \approx 1.455220 \times 10^{-3} DM (\bar{V}_a \cdot \bar{U}_p) / c \quad (20)$$

The magnitude of this yearly oscillation is about 6 μ sec for PSR 0833-45 and about 18 μ sec for PSR 1933+16. This correction is not small in all cases compared to the measurement accuracy, nor is it small compared to the desired uniformity of the approximation to ephemeris time.

E. ARRIVAL TIME IN UTC

The epoch at which the data sampling process begins is defined by a 1-sec pulse from the station clock. A sequence of 1-second pulses (clock pulses) is sent continuously via microwave link from the Standards Laboratory at the Goldstone complex to the individual tracking stations. Allowing for the delay over the links, these pulses define a UTC which is within 5 μ sec of UTC as disseminated by the National Bureau of

Standards (NBS). The 1-second pulses generated at DSS 14, UT(DSS 14), are kept within 5 μ sec of the Standards Laboratory pulses. Therefore, at DSS 14 the 1-sec pulses are assumed to be within 10 μ sec of UTC (NBS). The 1-sec pulse used at DSS 13, UT(DSS 13), is frequently synchronized with the Standards Laboratory pulses to within 1 μ sec. A piece-wise linear curve approximating the deviation in this 1-sec pulse from UTC(NBS) is used to correct epochs at DSS 13 to UTC (NBS). The correction is at most 100 μ sec.

The correction equal to the width of the clock pulse at DSS 14 is subtracted as part of this correction. (See the discussion of system codes 2, 3, and 5, and Fig. 3.) The small correction equal to $P_a/5000$ is then added if appropriate.

F. CONVERSION FROM COORDINATED UNIVERSAL TIME TO EPHEMERIS TIME

Coordinated Universal Time (UTC) is an approximation to a uniform time based on the rotation of Earth. Several steps are necessary to convert to the truly uniform ephemeris time (ET). Of prime importance is the correction for annual effects due to the orbital motion of the Earth-based clocks about the Sun. The correction ΔET is given in (Ref. 16) as

$$\Delta ET = 0.001658(\sin E + 0.0368) \text{ sec} \quad (21)$$

where E is the eccentric anomaly of the Earth in a heliocentric orbit.

Letting M represent the mean anomaly of Earth and e the orbital eccentricity,

$$\sin E = \sin M (1 + e \cos M)$$

Letting an ET epoch be represented by a Julian ephemeris date (JED) plus the number of seconds (SEC) past 0^h ET,

$$M = 358.000682 + 0.9856002628d - T^2(1.55 \times 10^{-4} + 3.33 \times 10^{-6}T) \text{ degrees}$$

$$e = 0.0167301085 - T(4.1926 \times 10^{-5} + 1.26 \times 10^{-7}T)$$

where

$$d = (JED - 2433282.5 + SEC/86400) \text{ days}$$

$$T = d/36525 \text{ centuries}$$

(see Ref. 17)

Eq. (21) omits a monthly term of 1.5 μ sec, a 12-year term of 21 μ sec, and a 29-year term of 5 μ sec (Ref. 10).

The ET epoch corresponding to each UTC arrival time, represented by a Julian date JD plus the number of seconds SEC past 0^h, is computed from

$$ET - UTC(USNO) = \begin{cases} \Delta ET + 38.662738 + 0.002592d \text{ sec; } JD < 2441317.5 \\ \Delta ET + 32.184 + n \text{ sec; } JD > 2441317.5 \end{cases} \quad (22)$$

where ΔET is computed using Eq. (21), $d = JD - 2440000.5 + SEC/86400$, n is an integral number of seconds, increasing once or twice a year by 1 second (Ref. 15), and UTC(USNO) is the UTC kept by the U.S. Naval Observatory. The following assumptions and relations were used in computing Eq. (22) before 1 Jan. 1972:

- (1) $|UTC(NBS) - UTC(USNO)| < 10 \mu\text{sec}$ (Refs. 12, 13)
- (2) $A.1 - UTC(USNO) = 6.5131177 + 0.002592d \text{ sec}$ (Ref. 14)
- (3) $IAT - A.1 = -0.03439 \text{ sec}$ (Ref. 15)
- (4) $ET - IAT = 32.184 \text{ sec}$ (Ref. 15)

After Jan. 1972, the appropriate number of integral seconds is added to the UTC epoch to obtain IAT (Ref. 15) under the assumption that $|\text{UTC(NBS)} - \text{UTC (Bureau de l'Heure)}| < 10 \mu\text{sec}$ (Ref. 12). Then ET is obtained from $\text{ET} - \text{IAT} = 32.184 \text{ sec.}$

G. AN EQUIPMENT IDIOSYNCRASY

The equipment problem of system code 3 requiring a correction of -0.996550 seconds is taken into account along with the corrections discussed above.

H. A TEST OF THE MEASUREMENT CONSISTENCY

The consistency of the measurements is determined by comparing the results using the procedures described earlier in the editing process (Sec. III). This comparison led to the correction of 0.996550 sec for the equipment failure, and the additional $250 \mu\text{sec}$ correction at 2295 MHz for PSR 0833-45. The question finally arises concerning the consistency of arrival times measured at different stations. Six epochs exist for PSR 0833-45 for which measurements were made at DSS 13 and DSS 14 within 1 day of each other. Results of three of these measurements showed DSS 14 results differing significantly from those at DSS 13. There were, however, serious receiver tuning problems at DSS 14 at two of the three epochs. Of the three results showing agreement, two are presented in Figure 37, where the difference (residual) between the measured and predicted arrival times is presented for each Julian date (JD) of observation ($\text{MJD} = \text{JD} - 2440000.5$). The agreement is remarkably good, leading to the conclusion that no systematic differences between DSS 13 and DSS 14 measurements remain in this data set.

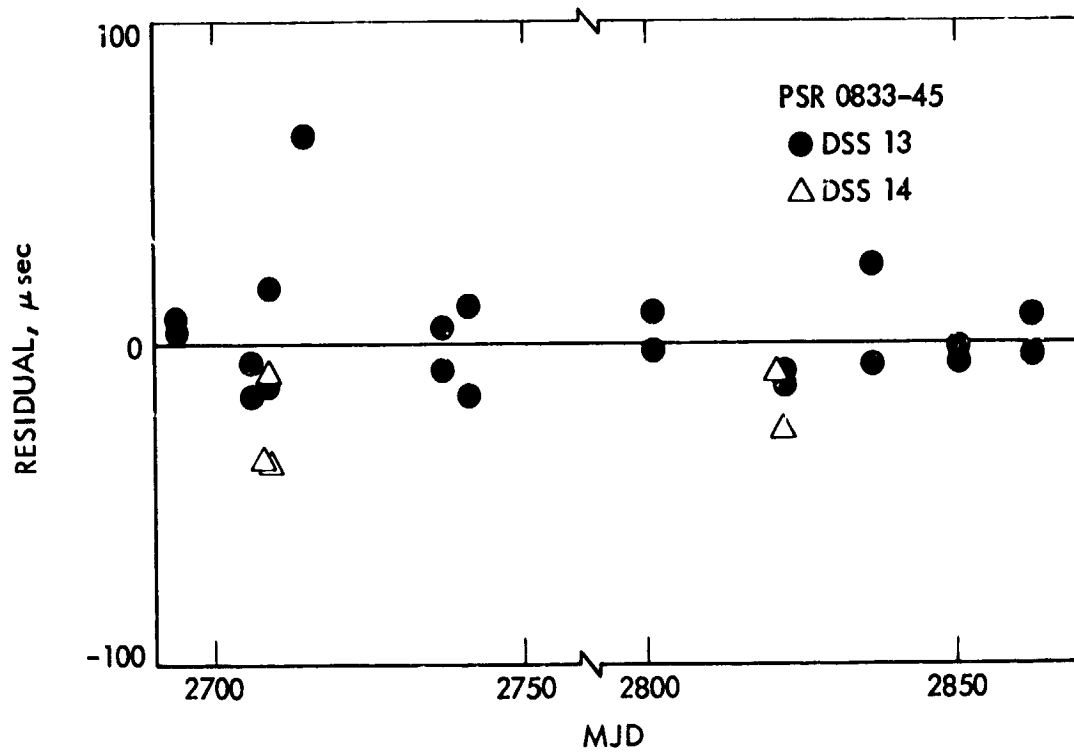


Figure 37. Time-of-arrival Residuals of Measurements Made at DSS-13 and DSS-14 on the Modified Julian Date (MJD) of Observation for PSR 0833-45

SECTION VII
THE TABULAR RESULTS

An example of the observational results is presented in Table 8. Columns 1 and 2 list the ephemeris time of the pulse arrival at the geocenter as a Julian ephemeris date and the number of seconds past 0^h (ET). (Note that no complete removal of the dispersion effect has been applied. That is, these arrival times refer to $F = 2388$ MHz, not $F = \infty$.) The estimate of the expected standard deviation of the measurement (defining the 67 percent confidence interval if the measurement errors are Gaussian) appears in Column 3. In Column 4, all of the time conversions from UTC to ET discussed in Section VI are listed. Column 5 contains the applied drift correction, while the configuration code appears in Column 6. Barycentric arrival times are listed in Column 7 for analysts satisfied with the accuracy of DE 96.

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Table 8. PSR 0823+26 Biocentric Times-of-Arrival

EPOCHS TIME		ET/TC		DRIFT SVS		BI-CENTRIC		EPOCHS TIME		ET/TC		DRIFT SVS		BI-CENTRIC	
YJD	SEC PAST	(SEC)	(μ SEC)	(μ SEC)	CDE	YJD	SEC PAST	(SEC)	(μ SEC)	(μ SEC)	CDE	YJD	SEC PAST	(SEC)	(μ SEC)
264	3739445552	39.355111	-1404	39.355111	0	37853337786	394	58439363284	39.75337	63	12	68307843332			
266	39394822707	39.361662	-1286	39.361662	0	412934654283	478	61240157935	39.73421	39	12	607594355339			
276	21394822326	39.393329	-732	39.393329	0	5848855729	614	51240356941	39.73125	24	12	60747324923			
276	54394638974	39.392411	-1139	39.392411	0	310474767934	614	54840192166	39.754860	11	12	64347320024			
283	326394589416	39.399716	-949	39.399716	0	221440284885	671	51340328639	39.755954	17	12	67347321497			
283	54394638974	39.411178	24	39.411178	0	44134422579	671	51340328639	39.755954	15	12	503723219317			
283	9394984439	39.414541	-6	39.414541	0	94134497270	678	43240332258	39.912363	43	12	423144335259			
283	1839497448	39.427318	32	39.427318	0	2173449422	678	46540336417	39.915353	15	12	46514421973			
293	54394638974	39.433990	9	39.433990	0	57224413610	693	39540319826	39.950319	77	12	39421487175			
293	9394984439	39.434412	-4	39.434412	0	93724438468	693	43240333111	39.954884	25	12	43224337432			
293	125394504558	39.436219	-42	39.436219	0	129724272477	699	396403484830	39.954884	25	12	39459447228			
297	54394638974	39.450641	-5	39.450641	0	3224435923	699	396403484830	39.954884	23	12	39459447228			
297	9394984439	39.453201	-21	39.453201	0	3224435923	699	396403484830	39.954884	23	12	39459447228			
303	792394529201	39.457139	35	39.457139	0	794784210658	699	396403484830	39.954884	23	12	39459447228			
303	828394832748	39.461303	27	39.461303	0	830784205944	699	396403484830	39.954884	23	12	39459447228			
304	36394938226	39.468632	19	39.468632	0	38774464574	699	396403484830	39.954884	23	12	39459447228			
310	928394519278	39.471489	24	39.471489	0	777644931364	699	396403484830	39.954884	23	12	39459447228			
310	72394722479	39.493292	-11	39.493292	0	930244794362	699	396403484830	39.954884	23	12	39459447228			
324	25239459177	39.517531	-50	39.517531	0	25315465774	699	396403484830	39.954884	23	12	39459447228			
332	6940306446	39.546251	-158	39.546251	0	108504217859	699	396403484830	39.954884	23	12	39459447228			
332	10839473435	39.546097	-104	39.546097	0	108504217859	699	396403484830	39.954884	23	12	39459447228			
332	14139469332	39.545077	-90	39.545077	0	141494859461	699	396403484830	39.954884	23	12	39459447228			
338	72394722479	39.561746	-92	39.561746	0	7200144622	699	396403484830	39.954884	23	12	39459447228			
338	10839466074	39.541200	-101	39.541200	0	17799484946	699	396403484830	39.954884	23	12	39459447228			
338	92439484552	39.559963	-89	39.559963	0	827924586570	699	396403484830	39.954884	23	12	39459447228			
345	928394877574	39.575297	-76	39.575297	0	79134409741	699	396403484830	39.954884	23	12	39459447228			
346	72394722479	39.582161	-91	39.582161	0	71324737249	699	396403484830	39.954884	23	12	39459447228			
352	75520092979	39.593141	-910	39.593141	0	74357487343	699	396403484830	39.954884	23	12	39459447228			
352	75520092979	39.593347	-485	39.593347	0	793774113437	699	396403484830	39.954884	23	12	39459447228			
352	83140313154	39.595551	-253	39.595551	0	82977407997	699	396403484830	39.954884	23	12	39459447228			
352	94339422935	39.597251	-357	39.597251	0	841764929557	699	396403484830	39.954884	23	12	39459447228			
359	6940306446	39.609665	-1	39.609665	0	682234548123	699	396403484830	39.954884	23	12	39459447228			
359	72394722479	39.612337	-39	39.612337	0	718234366835	699	396403484830	39.954884	23	12	39459447228			
359	75520092979	39.612205	-33	39.612205	0	792224653721	699	396403484830	39.954884	23	12	39459447228			
365	72394722479	39.614897	-57	39.614897	0	717714556749	699	396403484830	39.954884	23	12	39459447228			
365	72394722479	39.620115	-51	39.620115	0	717714556749	699	396403484830	39.954884	23	12	39459447228			
365	75520092979	39.641351	-60	39.641351	0	74371431534	699	396403484830	39.954884	23	12	39459447228			
365	79403151305	39.639342	-81	39.639342	0	32784525561	699	396403484830	39.954884	23	12	39459447228			
381	3640307368	39.672274	-64	39.672274	0	57222422555	699	396403484830	39.954884	23	12	39459447228			
381	5764030855	39.682741	-325	39.682741	0	57222422555	699	396403484830	39.954884	23	12	39459447228			
394	546394784743	39.694515	-25	39.694515	12	544074350878	699	396403484830	39.954884	23	12	39459447228			

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TABLE 8 (CONTINUED) - P&R 0823+26

821	6600-0535612	272	40-012299	-60	0	6799-337469	1422	12882-317328	5	42-2036381	-89	0	12803-889737
821	71921-287457	38	40-011001	-59	0	71479-993327	1-22	16682-303103	7	42-2035118	-110	0	16123-053023
842	52749-923931	18	40-0847259	-74	0	4748-964203	1422	19424-597596	7	42-202623	-93	0	19303-892577
842	92581-235131	36	40-0843652	-22	0	51729-595303	1440	3442-330059	12	42-203648	-93	0	3471-053595
842	55751-894111	10	40-0846665	-56	0	55449-519153	1440	7122-707136	34	42-2035776	-108	0	6951-072772
869	86641-246828	31	40-0932897	-28	0	44913-240000	1440	10302-533206	15	42-2034135	-105	0	10431-138812
869	86641-246828	18	40-0935017	-43	0	48510-765046	1475	84762-579207	10	42-2035887	-177	0	844-0-07048
869	86641-246828	5	40-0945975	-24	0	57091-533143	1476	3822-533266	13	42-2034078	-83	0	3148-0-05375
909	28641-352901	63	41-0330667	-24	0	29093-891073	1476	7242-719003	6	42-2031609	-60	0	4989-033044
909	32121-104461	13	41-034137	-59	0	30523-897402	1545	83363-535255	37	42-202917	-31	0	82302-033042
909	36241-023108	18	41-037082	-34	0	36244-352557	1375	46323-420093	19	42-20092	-55	0	85942-045031
909	39641-020077	58	41-039108	-72	0	39844-827574	1546	41223-293310	10	42-20192369	-20	0	3941-033615
982	34361-963150	34	41-229535	-79	0	34844-395952	1340	72223-350013	18	42-203368	-44	0	71745-037949
982	36701-275954	13	41-227499	-84	0	27184-065220	1340	75463-432427	4	42-20182	-35	0	74995-016325
1009	25621-050916	36	41-200478	-85	0	27813-703193	1540	79443-271617	149	42-190083	-17	0	78755-036477
1010	29381-883716	60	41-030961	-36	0	29774-599402	1549	40483-616120	31	42-199107	-23	0	03100-893805
1032	27701-575934	105	41-030650	-66	0	27971-902812	1549	66823-732943	34	42-202263	-27	0	66472-088835
1032	30341-823238	171	41-034327	-87	0	30511-934824	1549	70303-545275	84	42-200216	-27	0	69922-015652
1032	27441-531839	20	41-035758	-64	0	27557-571295	1597	59883-562153	27	42-202356	-11	0	55344-033885
1032	30981-093079	22	41-032796	-62	0	30837-245921	1597	63223-233093	35	42-20098	-19	0	63074-023359
1051	14041-711599	16	41-039706	-113	0	14550-313520	1597	66703-418800	50	42-197853	-8	0	66555-03157
1051	17211-579079	18	41-038337	-108	0	18033-844226	1540	36030-359637	3	42-201802	-201	0	136511-044848
1051	21581-993086	20	41-039938	-79	0	21583-803953	1549	39443-239961	5	42-20444	1	0	13999-035100
1079	54011-605979	5	41-042131	-72	0	4576-269156	1559	40483-288570	11	42-204312	27	0	14023-023374
1079	97011-793300	18	41-041122	-35	0	9576-047472	1572	40443-657659	20	42-204027	12	0	14155-07594
1079	12641-926498	18	41-027654	-73	0	12535-942320	1572	41003-435970	25	42-203929	12	0	14155-07594
1107	30211-061248	24	41-039485	-137	0	84693-001269	1549	31444-171591	20	42-200298	18	0	14203-0331654
1108	48411-657450	1	41-046163	-14	0	64618-854409	1548	31444-532015	11	42-03594	12	0	14203-0331654
1135	68411-971144	68	41-050005	-62	0	68098-923919	1596	26444-473627	6	42-204303	-8	0	14203-0331654
1135	69281-823224	68	41-025340	-88	0	68812-941178	1596	27344-641023	14	42-204004	-4	0	14203-0331654
1135	79192-150305	16	41-049092	-85	0	78712-971113	1596	27704-241604	15	42-204004	25	0	14203-0331654
1135	82661-805074	9	41-067172	-94	0	89192-505904	1745	18444-471207	5	42-203853	-80	0	14203-0331654
1163	12081-90999	15	41-056659	-108	0	64582-376544	1745	15004-249987	13	42-203667	-14	0	14203-0331654
1163	13061-933339	20	41-059951	-64	0	65969-043956	1773	82044-49004	9	42-203509	-114	0	14203-0331654
1192	55372-197767	15	41-070944	-45	0	54886-209954	1773	9404-439732	20	42-203500	-100	0	14203-0331654
1219	43122-153845	36	41-033404	-20	0	42871-909145	1747	12244-729429	23	42-206039	-32	0	12999-572734
1219	41681-937939	18	41-043045	-21	0	61233-256650	1747	13144-451651	24	42-20507	-25	0	13248-062003
1219	64661-909932	18	41-041731	-38	0	64113-510458	1747	13144-423570	37	42-20611	-21	0	13248-062003
1279	3272-23355	9	41-094583	-69	0	3292-13885	1548	44-327828	21	42-205856	-4	0	13248-062003
1279	38142-293106	6	41-094005	-28	0	38382-713009	1544	464-55910	24	42-205733	-2	0	13248-062003
1279	46782-293070	51	41-094915	-78	0	47023-447714	1548	484-442724	44	42-205336	32	0	13248-062003
1308	21042-017302	16	42-065733	-108	0	21453-111823	1548	83684-03349	4	42-203379	-5	0	13248-062003
1308	39755-53409	16	42-074672	-108	0	40193-287395	154	93844-23997	4	42-203317	-2	0	13248-062003
1308	43042-091121	19	42-073371	-88	0	43560-33482	194	44894-615553	4	42-205849	-2	0	13248-062003
1337	3242-231159	18	42-033387	-114	0	32930-661474	1945	5924-746830	15	42-193529	-4	0	13248-062003
1337	3522-36584	22	42-024111	-124	0	36410-724171	1945	63714-27948	9	42-20503	21	0	13248-062003
1337	3032-02330	10	42-031932	-117	0	30950-798813	1945	64004-31406	14	42-202752	30	0	13248-062003
1393	5932-50577	16	42-024077	-44	0	60563-59442	1945	52544-516475	5	42-200525	15	0	13248-062003
1393	1122-513419	9	42-024663	-79	0	11939-645200	1945	5374-618237	15	42-201191	24	0	13248-062003
1393	2102-027937	39	42-024274	-77	0	21743-020444	1945	4944-646632	7	42-201846	54	0	13248-062003

TABLE 8 (CONTINUED). 523 0323-26

194	53226	209992	7	65203487	2	50441	19986	2585	62155	441375	155	65203231	12	61900	318605
205	20235	50324	16	65198706	3	21355	19415	2585	63035	630169	15	65203108	10	63990	322607
206	20236	49274	29	65198407	15	21355	20415	2789	58575	41169	15	65203076	13	58575	413351
207	10225	51920	37	65203030	10	15007	4189	2789	60315	38019	73	65199777	15	60302	173984
208	16125	33552	18	65203135	23	14307	65737	2116	58335	627254	15	65199662	27	58335	627851
209	553	542516	14	65198777	15	935	3037	2116	50355	247214	67	65199552	16	60301	397593
210	2085	314427	31	65203219	22	2335	1037	2781	46945	317637	134	65202652	19	47892	74921
211	16395	337997	9	65206679	36	16395	4527	2781	48766	211438	209	65201862	6	49381	793483
212	17465	47517	5	65205051	48	18388	4527	2781	48355	211175	82	65202729	80	48355	212296
213	12723	71793	35	65206552	60	12723	52200	2781	46945	217549	47	65201523	61	47393	613059
214	7185	65470	38	65206002	38	7342	23268	2781	46945	217254	27	65205220	60	32933	313803
215	7295	32658	46	65202845	33	9382	23445	2846	51327	319790	15	65202727	23	51327	319790
216	8085	24534	57	65201803	17	8084	11036	2846	2017	636230	16	65202624	64	4855	519785
217	43	37753	22	65202803	23	104	533621	2846	79787	634138	294	65203191	33	79787	634138
218	1845	63079	11	65207163	23	1395	444675	2945	91997	674232	39	65203067	37	81755	314433
219	5233	25271	78	65207267	18	5233	105414	2945	71137	723371	14	65203458	62	6312	318204
220	8445	33570	159	65207143	21	8445	14779	2947	6222	687081	1	65203193	13	6312	318204
221	7445	38943	37	65202883	10	7445	105414	2947	65307	289258	2	65203193	20	65322	383161
222	76725	55237	10	65201442	10	76725	152243	2947	64137	433691	37	65203193	20	63700	323009
223	70364	33832	16	65200957	18	70364	33847	2947	65997	458422	22	65198383	17	65600	323142
224	7245	77424	18	65199938	4	71662	174217	2945	76727	72696	19	65203402	14	70253	317353
225	56785	61997	18	65199938	14	66564	67857	2945	78457	676632	29	65203402	17	73357	393921
226	53395	32677	2	65203390	36	53315	735317	2949	73447	674446	231	65203444	37	72045	323815
227	61725	37463	52	65199938	40	61725	65581	2949	73447	674446	166	65203367	17	76415	311578
228	53895	73719	23	65199676	27	53895	69258	3022	66647	459636	52	65203359	19	73369	315807
229	35185	42675	20	65200408	10	35185	627133	3017	67007	443507	8	65203277	3	67193	319092
230	5845	697428	11	65197500	7	58473	73692	3017	59357	466991	7	65203264	3	68333	323827
231	19735	23519	22	65194216	18	20313	646342	3085	66447	531277	18	65203081	3	66330	310007
232	2245	62951	32	65195937	16	22455	610092	3085	68387	273922	31	65203081	13	61330	387162
233	2531	63190	14	65204443	1	25327	676664	3085	65447	64553	30	65199336	12	64000	49824
234	2551	33455	16	65204597	5	26337	52058	3089	68447	72557	20	65197750	1	66204	77624
235	3595	720134	18	65204443	3	37307	115324	3084	59347	247694	15	65198708	22	59347	247694
236	37591	65271	17	65200974	10	38362	11529	3145	61317	33928	4	65197750	43	61317	33928
237	20295	59499	48	65200401	13	20313	52349	3145	58007	511972	20	65203593	4	58007	511972
238	20700	60530	44	65200451	20	20313	52349	3145	50307	293323	42	65203593	15	60344	45554
239	7454	31219	51	65191208	19	7454	47915	3122	45277	335247	61	65202835	25	45277	335247
240	7395	33433	24	65191545	21	7395	76522	3122	46157	245192	14	65202835	24	45503	359314
241	78138	33311	26	65203083	28	7395	65842	3122	46757	330388	18	65202201	23	46757	330388
242	95420	70741	6	65203083	18	77396	83774	3143	27032	619551	14	65205585	7	27032	619551
243	96110	31370	7	65205952	17	85114	39444	3143	22449	554890	4	65205252	14	22449	554890
244	9723	34924	14	65204115	12	9723	20667	3217	2379	49732	5	65204432	4	2379	49732
245	9723	73494	15	65203744	12	9723	20667	3217	2379	49732	5	65204432	4	2379	49732
246	7645	60252	3	65204459	16	7645	612301	3245	9274	335234	25	65203932	15	9274	335234
247	7846	53494	20	65203353	17	77307	45026	3345	8755	35120	52	65203932	49	8755	35120
248	7338	43417	25	65203652	3	7312	711942	3345	9548	35544	3	65192351	41	9548	35544
249	74795	70134	24	65203130	11	74795	31667	3399	9648	237648	4	65191834	43	9648	237648
250	7545	63511	23	65200477	4	74165	71944	3344	58442	51451	14	65202652	63	58442	51451
251	7545	58853	24	65197769	19	77345	44333	3344	51152	249232	3	65202652	63	60374	35353
252	58445	54479	22	65203145	6	58015	139601	3347	73594	403508	32	65199349	13	73594	403508

TABLE 8 (CONTINUED). PER 08-3-26

3387	75865.672177	56	68.197649	3	4	75145.396854	•	3549	27199.233574	9	49.235862	•	6	5	27489.621832
3435	66331.275757	13	68.195133	20	4	64377.320570	•	3349	27519.231557	11	49.235784	•	5	5	27378.433928
3438	68555.445358	46	68.193137	24	4	64504.375026	•	3533	81357.641882	76	49.232721	•	28	4	81240.444317
3462	5.1153.315225	124	68.200071	•	40	58325.135197	•	3347	84935.718833	35	49.235665	•	25	4	84574.392173
3492	58377.265377	51	68.197027	7	4	58869.414443	•	3373	78431.658231	24	49.235257	•	29	4	78528.733524
3495	55284.569613	53	68.195065	5	4	56121.572023	•	3710	69528.402858	63	49.234142	•	13	4	69523.563972
3495	55284.569613	53	68.195065	5	4	59025.874833	•	3710	71111.370993	37	49.234437	•	21	4	70836.552344
3496	42898.272922	71	68.274003	7	5	49940.457242	•	3741	74626.231148	31	49.199729	•	1	4	74219.328809
3502	13939.331298	16	68.194981	20	5	14361.500764	•	3751	76265.405992	69	49.197232	•	3	4	75839.332142
3504	40795.493684	50	68.203976	17	5	40512.739279	•	3751	74907.406192	22	49.194700	•	8	4	74439.337470
3507	53270.681783	47	68.192587	3	4	55714.533604	•	3740	64173.543635	83	49.199379	•	12	13	63920.751395
3507	53270.681783	47	68.192587	3	4	58011.4230514	•	3740	64503.595238	20	49.199692	•	6	13	64232.933333
3513	40589.300999	44	69.199753	11	5	45551.038613	•	3740	66435.546548	13	49.198350	•	3	13	66214.935446
3539	38529.563805	127	69.204681	1	5	37018.769388	•	3848	58337.586499	76	49.200551	•	31	4	58348.304540
3539	38529.563805	127	69.204681	1	5	38608.863339	•	3948	57306.479417	209	49.200009	•	18	4	59317.329496
3569	26479.235367	14	69.205850	63	5	27338.4633461	•	3947	47629.4567435	14	49.202230	•	14	4	47741.010358

REFERENCES

1. Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., and Collins, R. A., "Observation of a Rapidly Pulsating Radio Source," Nature, Vol. 217, 1968, p. 709.
2. Pilkington, J. D. H., Hewish, A., Bell, S. J., and Cole, T. W., "Observations of Some Further Pulsed Radio Sources," Nature, Vol. 218, 1968, p. 126.
3. Gold, T., "Rotating Neutron Stars as the Origin of the Pulsating Radio Sources," Nature, Vol. 218, 1968, p. 731.
4. Moffet, A. T. and Ekers, R. D., "Detection of the Pulsed Radio Source CP 1919 at 13-cm Wavelength," Nature, Vol. 218, 1968, p. 227.
5. Bracewell, R. N., The Fourier Transform and Its Applications, McGraw-Hill, New York, 1965, p. 339.
6. Foster, C. F., "Automated Pulsar Receiver," DSN Progress Report 42-20, Jet Propulsion Laboratory, Pasadena, California, April 15, 1974.
7. Sleky, A., A New Pulsar Timer, JPL Technical Report 32-1526, Vol. X111, Jet Propulsion Laboratory, Pasadena, California, Feb. 15, 1973.
8. Brokl, S. S., "Automated Pulsar Data Collector," DSN Progress Report 42-25, Jet Propulsion Laboratory, Pasadena, California, Feb. 15, 1975.
9. Reichley, P. E., Downs, G. S., and Morris, G. A., "Time-Of-Arrival Observations of Eleven Pulsars," Ap. J., Vol. 159, 1970, p. L35.

10. Cooley, J. W., Lewis, P. A. W., and Welch, P. D., "The Fourier Transform Algorithm: Programming Considerations in the Calculation of Sine, Cosine and Laplace Transform," J. Sound Vib., Vol. 12, 1970, p. 315.
11. Brigham, E. O., The Fast Fourier Transform, Prentice-Hall, Englewood Cliffs, New Jersey, 1974.
12. NBS Time and Frequency Bulletin, U. S. Dept. of Commerce, National Bureau of Standards, Boulder, Colorado, 1968 to 1979.
13. Daily Phase Values and Time Differences, Series 4, U. S. Naval Observatory, Washington, D. C., 1968 to 1970.
14. Times Services Bulletin, Series 11, No. 220, U. S. Naval Observatory, Washington, D. C.
15. Preliminary Times and Coordinates of the Pole, Series 7, No. 210, U. S. Naval Observatory, Washington, D. C.
16. Melbourne, W. G., Mulholland, J. D., Sjorgren, W. L., and Sturms, F. M., Constants and Related Information for Astrodynmic Calculations, 1968, JPL Technical Report 32-1306, Jet Propulsion Laboratory, Pasadena, California, July 15, 1968.
17. Sturms, F. M., Jr., Polynomial Expressions for Planetary Equators and Orbit Elements with Respect to the Mean 1950.0 Coordinate System, JPL Technical Report 32-1508, Jet Propulsion Laboratory, Pasadena, California, January 15, 1971.
18. Moyer, T.D., Transformation from Proper Time on Earth to Coordinate Time in Solar System Barycentric Space-Time Frame of Reference, JPL Technical Memorandum 33-786, Jet Propulsion Laboratory, Pasadena, California, Dec. 1, 1976.

19. Koble, H. M., Pease, G. E., and Yip, K. W., "LS44-An Improved Deep Space Network Station Location Set for Viking Navigation," in Deep Space Network Progress Report 42-35, Jet Propulsion Laboratory, Pasadena, California, Oct. 15, 1976.
20. White, R. J., Rosenberg, A. D., Fisher, P. S., Harris, R. A., and Newhall, N. S., SPACE-Single Precision Cowell Trajectory Program, JPL Technical Memorandum, 33-198, Jet Propulsion Laboratory, Pasadena, California, Jan. 15, 1965.
21. Holdridge, D., Space Trajectories Program for the IBM 7090 Computer, JPL Technical Report 32-223, Rev. 1, Jet Propulsion Laboratory, Pasadena, California, September 1, 1962.
22. Taylor, J. H., and Manchester, R. N., "Observed Properties of 147 Pulsars," Astron. J., Vol. 80, 1975, p. 794.