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TESTS OF A NEW DISPERSION-REMOVING RADIOMETER ON BINARY PULSAR PSR 1913+16

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ABSTRACT

We describe a technique for the predetection removal of dispersion from pulsar signals, and an implementation of the method designed explicitly for binary pulsar PSR 1913+16. Initial observations have yielded time resolutions improved by an order of magnitude over previous measurements, and pulse arrival times can now be measured to ~50 μs accuracy. Observations of this accuracy over the next year or two should provide good estimates of the masses of the pulsar and its companion, the orbital inclination, and the derivative of the orbital period.

Subject headings: instruments — pulsars

I. INTRODUCTION

Attempts to achieve high time resolution in radio-frequency observations of pulsars are nearly always limited by dispersion in the interstellar medium. The basic problem, of course, is that a broad-band pulse propagates more slowly through the partially ionized interstellar medium at low frequencies than at high, and thus over any finite bandwidth the pulse is smeared out in time. In the weak-magnetic-field, low-density limit (which is an exceedingly good approximation in the interstellar medium), the dispersive time delay at frequency ν is given in cgs units by

$$t = e^2\,\mathrm{DM}(2\pi\, mc\, \nu^2)^{-1}\,, \tag{1}$$

where e and m are the electron charge and mass, c is the speed of light, and DM is the dispersion measure, or integral of electron density along the line of sight. Thus the instantaneous frequency of a narrow pulse appears to sweep downward in frequency at a rate

$$\dot\nu = -\pi\, mc\, \nu^3(e^2\,\mathrm{DM})^{-1}\,, \tag{2}$$

and if the radiometer has bandwidth B, the received pulses will be smeared in time by an amount

$$t_s = B/|\dot\nu| = B\, e^2\,\mathrm{DM}\,(\pi\, mc\, \nu^3)^{-1}\,. \tag{3}$$

A number of observational techniques have been devised to combat the dispersive distortions imposed on pulsar signals. Most of them involve compromises with respect to receiver bandwidth, center frequency, and complexity and expense of "back ends" and/or recording and data-processing equipment. Reducing the bandwidth reduces t_s proportionately until the limit $t_s \approx 1/B$ is approached, at which point the uncertainty principle comes into play and further reduction of B will in fact degrade the resolution. Furthermore, small values of B may severely limit the attainable signal-to-noise ratio. Bandwidth restrictions may be relaxed considerably by moving to higher observing frequencies (eq. [3]), but pulsar flux densities typically decrease as $\nu^{-1.5}$ or even more steeply, so that observations at high frequencies ($\nu \gtrsim 1$ GHz) are usually severely sensitivity-limited.

By using a total bandwidth $B = n\Delta\nu$ arranged as n independent, contiguous frequency channels each equipped with its own detector, it is possible to improve the time resolution by a factor $1/n$ without impairing sensitivity (e.g., Taylor and Huguenin 1971). Such postdetection de-dispersing systems rely on delaying circuitry (or software) that provides time delays as large as t_s with an effective (postdetection) bandwidth of n/t_s. A typical observing setup (e.g., Taylor and Huguenin 1971; Boriakoff 1973) might have $n = 32$, $B = 8$ MHz, $\Delta\nu = 0.25$ MHz, and $\nu = 400$ MHz, and would provide time resolution of about 1 ms for a nearby pulsar with DM = 40 cm^{-3} pc. In this method the time resolution is limited to $\geq\Delta\nu^{-1}$, so the use of very large values of n (and hence small $\Delta\nu$) can be self-defeating as well as expensive in terms of hardware. For pulsars with large dispersion measure the method becomes prohibitively difficult.

True dispersion removal, providing time resolution of B^{-1}, can be obtained only by processing the received signal before its phase information is discarded in the detection process. Hankins (1973, and references therein) has accomplished this feat by recording a digitized version of the undetected signal on magnetic tape and performing the necessary complex convolution in a digital computer. The method works well, but commonly available equipment limits it to bandwidths $\lesssim 1$

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MHz. Also, large amounts of computer time are required for the signal processing—several orders of magnitude more than the observing time, in fact. The technique is thus practical only for detailed study of the structure of individual pulses from strong pulsars.

Another method of obtaining predetection dispersion removal is to sweep the receiver local oscillator (LO) downward in frequency in synchronism with the received pulses, offset by a small amount in frequency (see Fig. 1). A narrow dispersed pulse is thus converted to a "spectral line" in the receiver intermediate-frequency (IF) passband, and time structure in the pulse is transformed into frequency structure in the spectral line (see Fig. 1). If the IF spectrum is analyzed by a multichannel filter bank or an autocorrelation-type spectrometer, the pulse structure can be recovered with an effective time resolution equal to t_s/n, where n is the number of independent frequency elements ("channels") in the analyzed spectrum. In this situation, the time resolution can be much less than the inverse channel bandwidth, because the signal being analyzed has been converted from an impulsive to a continuous one.

Such a scheme has been used successfully in observations by Sutton *et al.* (1970). However, as these authors discovered, various subtleties prevent a simple, straightforward implementation of the technique. Perhaps the greatest difficulty is that the sweep rate $\dot{\nu}$ must be varied throughout the sweep, and at a given instant should even be different for different parts of the pulse. Thus the relation between spectrometer resolution and time within the pulse, $\Delta t = \Delta\nu/|\dot{\nu}|$, is a complicated one. To avoid additional smearing, the channel bandwidths $\Delta\nu$ must be continuously adjusted in proportion to $\dot{\nu}$. Such a procedure is impossible with a standard filter-bank spectrometer, but can be approximated with an autocorrelator by varying its clock rate in synchronism with the LO sweep. If the fractional bandwidth B/ν is not too large, the remaining uncorrectable distortions will be negligible.

II. EQUIPMENT DETAILS

We have implemented a dispersion-removing system based on the principles outlined above, optimized specifically for observations of binary pulsar PSR 1913+16 at the Arecibo Observatory. The system was designed to operate at a center frequency of 430 MHz, to take advantage of the most sensitive feed for the Arecibo telescope. A special purpose controller was built to generate the sweeping LO signal and to synchronize the autocorrelator. The controller, in turn, is kept synchronized to the apparent pulsar period by an on-line computer. A block diagram of the controller is shown in Figure 2.

The system was designed to keep overall timing errors <10 μs and errors from any individual cause $\lesssim 2$ μs. The sweep rate $\dot{\nu}$ for the binary pulsar at 430 MHz is about -58 MHz s^{-1}, and hence the LO must track the pulsar within an error of $\lesssim 116$ Hz. The 430 MHz receiver at Arecibo derives its LO by summing a fixed 380 MHz oscillator and a variable 20 MHz oscillator, to allow for tuning. It was sufficient for our purposes, therefore, to generate a variable frequency signal centered on 20 MHz which could be stepped by about 116 Hz every 2 μs. We had available a Rockland model 5100 frequency synthesizer which can be stepped as often as every 0.625 μs in a manner such that the output phase changes continuously. Because its maximum output frequency is 2.0 MHz, we chose to generate a signal at $\sim$1.25 MHz and then to multiply the frequency by 16. The frequency steps at the fundamental are 8.0 Hz.

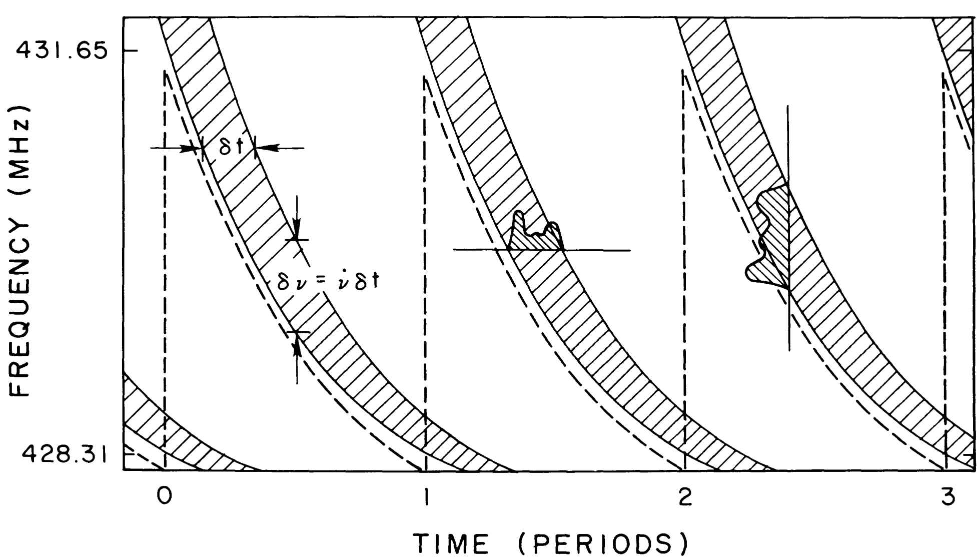

FIG. 1.—Dispersed pulses are represented in the frequency-time plane as shaded bands. The drawing is approximately to scale for PSR 1913+16 except that curvature is greatly exaggerated. *Broken line*, effective frequency of the repetitively swept local oscillator. Pulse widths in time (δt) and in frequency ($\delta\nu$) are illustrated schematically.

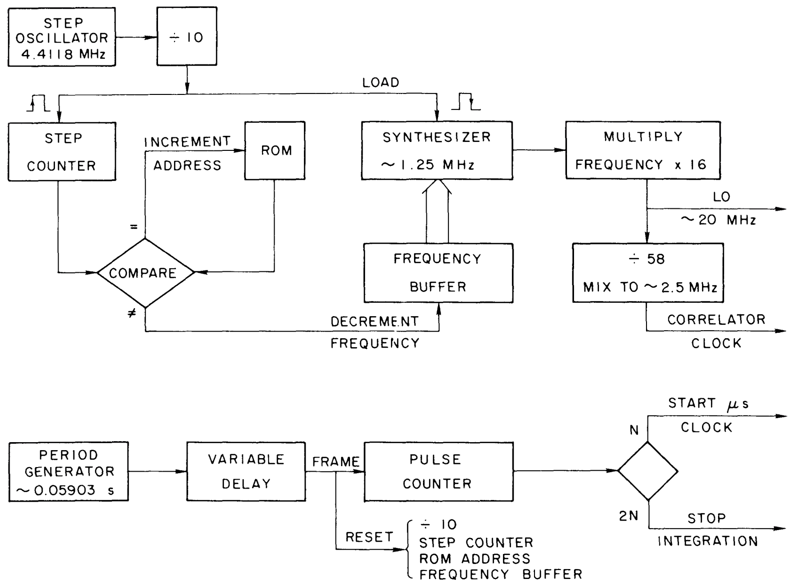

FIG. 2.—A simplified block diagram of the swept local oscillator controller. Sequences of events are described in the text.

The nonlinear sweep in frequency was approximated by a modified "staircase" pattern. Each sweep begins (at the maximum pulsar sweep rate) with the synthesizer frequency being decreased in 8 Hz steps at a constant rate. The curvature is then obtained by omitting some of the steps. In this way the derived 400 MHz LO signal is kept at the correct frequency to within ± 64 Hz. To follow the binary pulsar for one period (0.059 s) required sweeping the LO through about 3.3 MHz, or about 26,500 step intervals (including 330 intervals when the frequency decrement was omitted). The index numbers of these omitted steps were calculated and stored in read-only memory (ROM) in the controller.

Over the 431.652 to 428.305 MHz range swept by our system, $\dot{\nu}$ changes by a factor of 1.024. We therefore chose to generate the autocorrelator clock signal (nominally at 2.5 MHz) by dividing the sweeping synthesizer frequency by 58 and mixing the result (0.37331 to 0.31561 MHz) with the output of a fixed 2.12672 MHz oscillator. The resulting signal covers the desired range of 2.50003 to 2.44233 MHz with an accuracy sufficient to limit pulse smearing to $< 2\ \mu$s.

As indicated in Figure 2, the start of each sweep is synchronized to the pulsar phase by means of a programmable period generator that produces one pulse per pulsar period. The period generator is updated every second to account for Doppler effects due to the Earth's motion and the motion of the binary pulsar in its orbit. The synchronizing system incorporates a variable delay, accurate to 1 μs, to allow the pulse to be positioned within the receiver bandpass. The delayed synchronized pulse is called a frame pulse.

When the controller receives a start command from the on-line computer, it immediately issues start and inhibit commands to the autocorrelator. It enforces a short delay to allow the autocorrelator memory to be cleared, and on receipt of the next frame pulse removes the inhibit, and starts the sweep. The sweep rate of the local oscillator is controlled by the step oscillator, there being one step every 10 cycles of this oscillator. The divide-by-ten circuit allows subsequent sweeps to be in phase with the initial sweep within a small fraction of a step period. The step pulse has a duration of about 0.5 μs; counters within the controller are clocked on the leading edge of the pulse, and the synthesizer frequency is changed on the trailing edge. Each step pulse increments the step counter, which is then compared with the contents of the ROM. If these numbers are different, the buffer holding the local oscillator frequency is decremented by 8 Hz. Otherwise the address buffer of the ROM is incremented.

Subsequent frame pulses reset the counters and the ROM address to zero and the frequency buffer to 1.353249 MHz, and inhibit the autocorrelator for a few μs during flyback. The pulse counter is also incremented. At the end of a selectable number (N) of sweeps, a timer is started to count the microseconds until the next UTC second. A request is then sent to the computer to read the counter and the time, thereby recording the precise time at the mid-point of the observation. After another N sweeps the autocorrelator memory contents are transferred into the computer, and the system is ready to start the next observation.

III. OBSERVATIONS

Preliminary observations of the binary pulsar were made using this equipment on 4 days in 1978 June. Typical integrations were made over $2N = 1024$ pulse periods, or approximately 1 minute. A number of different configurations were investigated, with the best system using the autocorrelator in a 2×504-channel mode, recording both polarizations with a total bandwidth of 1.25 MHz. The time resolution in this mode was $B\,(n\,|\dot{\nu}\,|)^{-1} \approx 43.2\ \mu s$ per channel, so that the pulse occupied about 240 channels.

Individual integrations were cross-correlated with a standard profile to determine their offsets due to drifts in arrival time. These offsets were removed and all the data summed to give a high-resolution pulse profile. This profile is shown in Figure 3, together with a profile obtained in 1977 August by using standard signal-averaging techniques (Fowler, Cordes, and Taylor 1978; Fowler 1978). The total integration time for the 1977 data is approximately twice that for the 1978 data. The improved time resolution can be seen in the narrow leading component, the steepest gradients of which are now clearly resolved, and in the more rapid decay on both the leading and trailing components. In fact, the decay on the extreme trailing edges of the components has the exponential characteristic normally attributed to interstellar scattering. If this explanation is correct, the scattering time constant is about 600 μs.

Careful comparison of the two profiles shows that there appears to be another significant difference. The central component of the 1978 profile is considerably broader and shifted somewhat to the left. This shape change is not an artifact produced by the improved time resolution, and if real it represents a change in pulse shape with epoch. Such an effect has been predicted (see, for example, Esposito and Harrison 1975; Hari-Dass and Radhakrishran 1975; Smarr and Blandford 1976) as a result of precession of the pulsar rotation axis owing to geodetic spin-orbit coupling. The predicted period of this precession is about 200 years, so the changes seen on a time scale of 1 year imply that much more significant changes should be seen in the future—including the possibility of the complete "turn-off" of the pulsar for many years if precession takes us out of the radiation cone. Unfortunately, all data on this pulsar taken prior to 1977 had substantially poorer time resolution and cannot be used to confirm the secular change in pulse shape.

The observations also yield absolute pulse arrival time measurements. Mean profiles representing about 5 minutes of observing were generated by summing the 1 minute records. An arrival time for each of these profiles was then obtained by cross-correlation with the standard profile. These arrival times were used to solve for the orbital parameters of the binary system. A least-squares fit was accomplished with a residual error of about 50 μs, a factor of 3 better than the best published timing measurements on this pulsar (Fowler, Cordes, and Taylor 1978). The fitted orbital parameters are fully consistent with those previously obtained. Furthermore, the rms residual of $\sim$50 μs is consistent with theoretical expectations, given the observational signal-to-noise ratio and the maximum gradients in the pulse profile. A modest additional improvement is expected when the acquisition of more data permits us

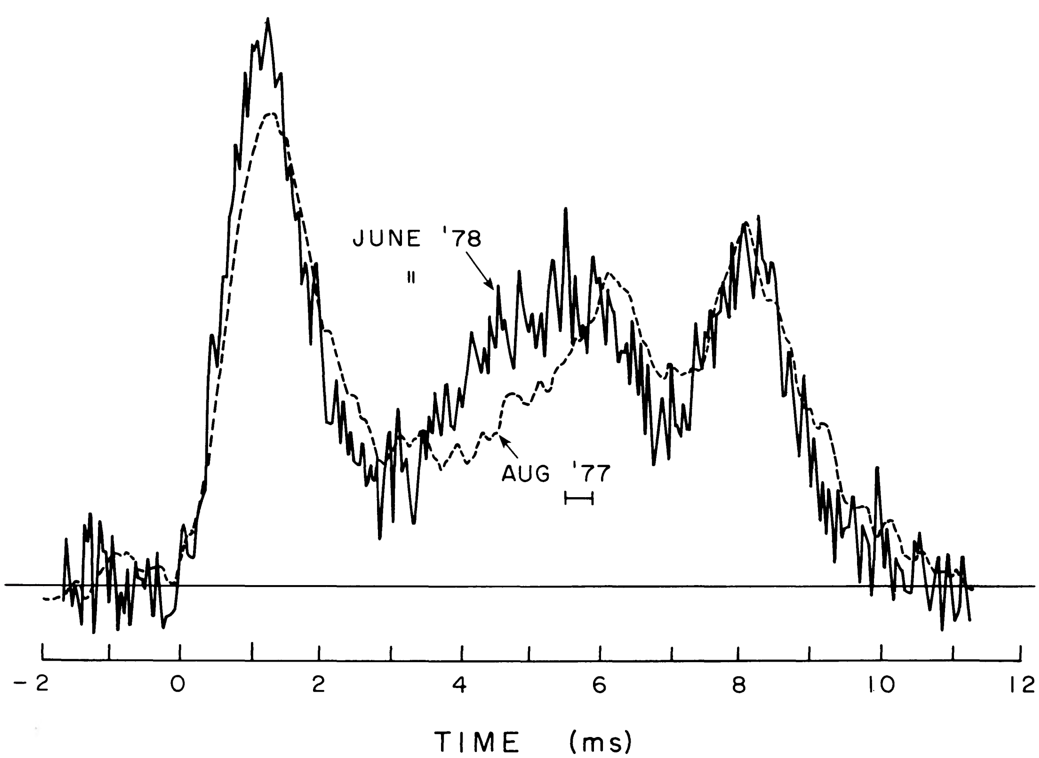

FIG. 3.—Average pulse profile observed in 1978 June with the swept local oscillator system (*solid line*) and in 1977 August with standard signal-averaging techniques (*broken line*). The effective time resolutions are indicated below the dates.

to form a more noise-free standard profile. Data of $\lesssim 50$ μs quality obtained over the next year or two should allow confirmation of the apparent change of pulse shape and should permit unambiguous measurement of the binary system masses, the orbital inclination, and the rate of change of orbit period (Taylor *et al.* 1976).

We wish to draw attention to the fact that if the orbital period derivative is found to be approximately -2×10^{-12} s s^{-1}, the value expected owing to decay of the orbit via gravitational radiation (Wagoner 1975), this system would confirm a previously untested prediction of general relativity and would furnish an indirect proof of the existence of gravitational waves. Available data yield a value consistent with the prediction, with an uncertainty of $\sim 80\%$. Continued measurements should reduce this uncertainty to $< 20\%$ within the next 2 years.

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