APPENDIX - B

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A Digital Signal Pre-Processor for Pulsar Search

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Abstract. A fast digital signal processor has been designed and built for survey and some observations of pulsars. The processor obtains spectral information over a bandwidth of 16 MHz (256 channels) every 256 μsecs. We describe the design of this processor and present some test observations made with the Ooty Radio Telescope.

Key words: Pulsars — instrumentation: signal processing.

1. Introduction

During the last twenty seven years since the pulsar was discovered, the number of detected pulsars has risen to about 550. Practically, all of them are observed at radio wavelengths, with the peak emission around 100 MHz. Statistical estimates based on the observed population suggest that less than 1% of the galactic population has so far been discovered, and a significant increase in the number of detected pulsars would improve the statistics to a great extent. Millisecond pulsars, in particular, form a very interesting class, owing to their rich evolutionary history. While the estimated total number of millisecond pulsars in the galaxy exceeds $\sim$ 10,000 (Lorimer 1994), only about 20 of these have so far been found. Not surprisingly, therefore, several major surveys are at present underway in different parts of the globe in an effort to increase the size of the observed population (Bailes 1994; Camilo 1994), in particular of the short period pulsars.

Various selection effects play a major role in restricting the observability of pulsars. At low frequencies, where the emission from pulsars is the strongest, the galactic background radiation limits the detection sensitivity. In addition, dispersion and scattering in the interstellar medium broaden the pulse and thereby limit the distance to which pulsars can be seen, as well as the minimum detectable period. Currently ongoing surveys attempt to optimize data collection methods to keep good sensitivity to as short a period as possible, given the above limitations.

In India, two major radio telescopes offer large collecting area at metre wavelengths, suitable for deep survey of pulsars. These are the recently refurbished Ooty Radio Telescope (ORT) (Selvanayagam et al. 1993), a 550 x 30 meter, single polarisation parabolic cylinder working at 327 MHz and the Giant Metre Wave Telescope (GMRT), consisting of 30 dishes of 45 metre diameter, operating at frequencies from 38 MHz to 1.4 GHz, nearing completion at Pune (Swarup et *al.*

1991). In this paper we describe the design and performance of a pulsar search pre-processor we have built, primarily for use at ORT, but based partly on the pulsar instrumentation being built by us for the GMRT (Deshpande 1993). This machine is capable of conducting a survey for millisecond pulsars and being fully digital in construction, is easily programmable to suit different requirements. It has been in use with the ORT since March 1993.

In section 2 we discuss the design considerations for this machine and in section 3 we describe the actual hardware. Section 4 presents some of the results obtained using this machine.

2. Design considerations

Pulsar signals are usually buried in the noise contributed by the galactic background and the receiver. Deep searches for weak pulsars therefore require high-sensitivity receivers. Searches for short-period pulsars also require a high time resolution. Presently known pulsar periods vary from about 1.5 ms to over 5 secs, and the intrinsic pulse duty cycle is typically between 1% to 5%. The observed pulse duty cycle is usually higher due to propagation effects in the intervening medium and the limited bandwidth of the receiver. If the width of time-smearing due to dispersion in the intervening medium is $\Delta\tau_D$, that due to interstellar scattering is $\Delta\tau_S$ and the pre-detection bandwidth is Δf, then the resultant pulse smearing has a width $\Delta\tau_{\mathrm{Smear}} = \sqrt{(\Delta\tau_D)^2 + (\Delta f)^{-2} + (\Delta\tau_S)^2}$. When this width is comparable to or greater than the intrinsic pulse width, the apparent peak intensity is reduced.

Many techniques are known for reducing the smearing due to dispersion (e.g. pre-detection (coherent) dedispersion, post-detection (incoherent) dedispersion etc.). In incoherent dedispersion (a method more convenient for pulsar searches), the total band is divided into a large number of narrow channels, outputs from which are 'detected' and combined after appropriate dispersion delay corrections; An optimal choice for channel bandwidth is given by Δf (MHz) $= (10^{-4}/9.1) \times \sqrt{f_0^3(\mathrm{MHz})/DM}$ (Deshpande 1989), i.e., when $(\Delta f)^{-1} = \Delta\tau_D$ (ignoring scattering effects), where f_0 is the centre frequency of observation.

Search observations with high time resolution (as required for millisecond pulsars) result in very high data rates at the output and require massive data storage. Considerable reduction in the effective data rate and size is possible by quantizing the data to a smaller number of bits (1 or 2) per sample; This however, results in some degradation of the search sensitivity (Biggs et al. 1989).

The design philosophy adopted in this exercise was aimed at reducing the size, complexity and the cost of the machine while retaining flexibility and operational simplicity. Many extensive, and high-speed computations are achieved through the use of look-up tables at various stages of the machine. At places where the look-up table approach is not appropriate, dedicated logic has been designed, and programmed into 'Erasable Programmable Logic Devices' (EPLDs) which have the advantages mentioned above. In addition, the use of these devices makes it possible to design the entire machine using only 2 layer PCBs and reducing development time substantially. The design has been made modular to facilitate quick replacements in the field and PC based automated test jigs have been developed for quick diagnosis.

With the above points in view, the processor is equipped with hardware capability to generate 256 complex spectral channels over 16 MHz pass-band from two polarization channels. It further detects and sums up the power in these two polarization channels, then performs pre-integration, mean subtraction and gain calibration of data in individual frequency channels. The parameters related to these operations are programmable. The instrument is configured and diagnosed under software control, a few milliseconds before every observation session using a set of' PC/AT based parallel 1/0 ports. During the observation the same PC/AT also computes the running mean and gain calibration factors for the spectral channels besides displaying these on the screen. The data is acquired by a PC/AT based dedicated hardware and is stored on a hard disk. The data is later backed up into a *2.5* GB video cartridge tape. Choice of a PC/AT to setup the configuration of the machine is due to the large software base available under MS-DOS in addition to the hardware flexibility. Similarly the data acquisition hardware is also based on a PC/AT on a MS-DOS platform to allow the use of a variety of 1/0 devices that are readily available for a PC/AT.

3. Hardware description

The following description of the hardware is based on the block diagram given in Fig. 1.

3.1 Digital front-end

The digital front-end for this machine is a pair of A/D converters which sample the baseband signals at the Nyquist rate and feeds them to an FFT engine. The FFT engine uses VLBA FFT chips and produces 256 point complex spectra in each polarization channel, which are then sent out serially. The A/D convertors and the FFT engine were supplied to us by National Center for Radio Astrophysics (NCRA), Pune. To initialize, supply twiddle-factors and run this FFT engine, we developed a controller based on state-machine approach using look-up tables.

3.2 Search pre-processor

In the Search Pre-processor (SP), the complex numbers corresponding to the spectrum produced by the FFT are used to compute a power spectrum in each polarization channel using look-up tables. The power terms of the two polarizations are summed in each frequency channel, and the resultant power spectra are pre-integrated over a programmable number of successive spectra for a time span of t_{int} ($256\,\mu s \leqslant t_{\text{int}} \leqslant 4$ ms). The output consists of integrated values in each of the 256 spectral channels at the chosen output sampling rate. The width of the output word representing the data sample increases with the integration. High speed digital design can be simplified by retaining less number of bits to represent the data with little effect on the signal-to-noise ratio. For this purpose a set of sliding windows are provided before and after' the pre-integration to choose the most significant bits of the word and thereby reduce the word widths to manageable sizes. The data at the output of the pre-integrator

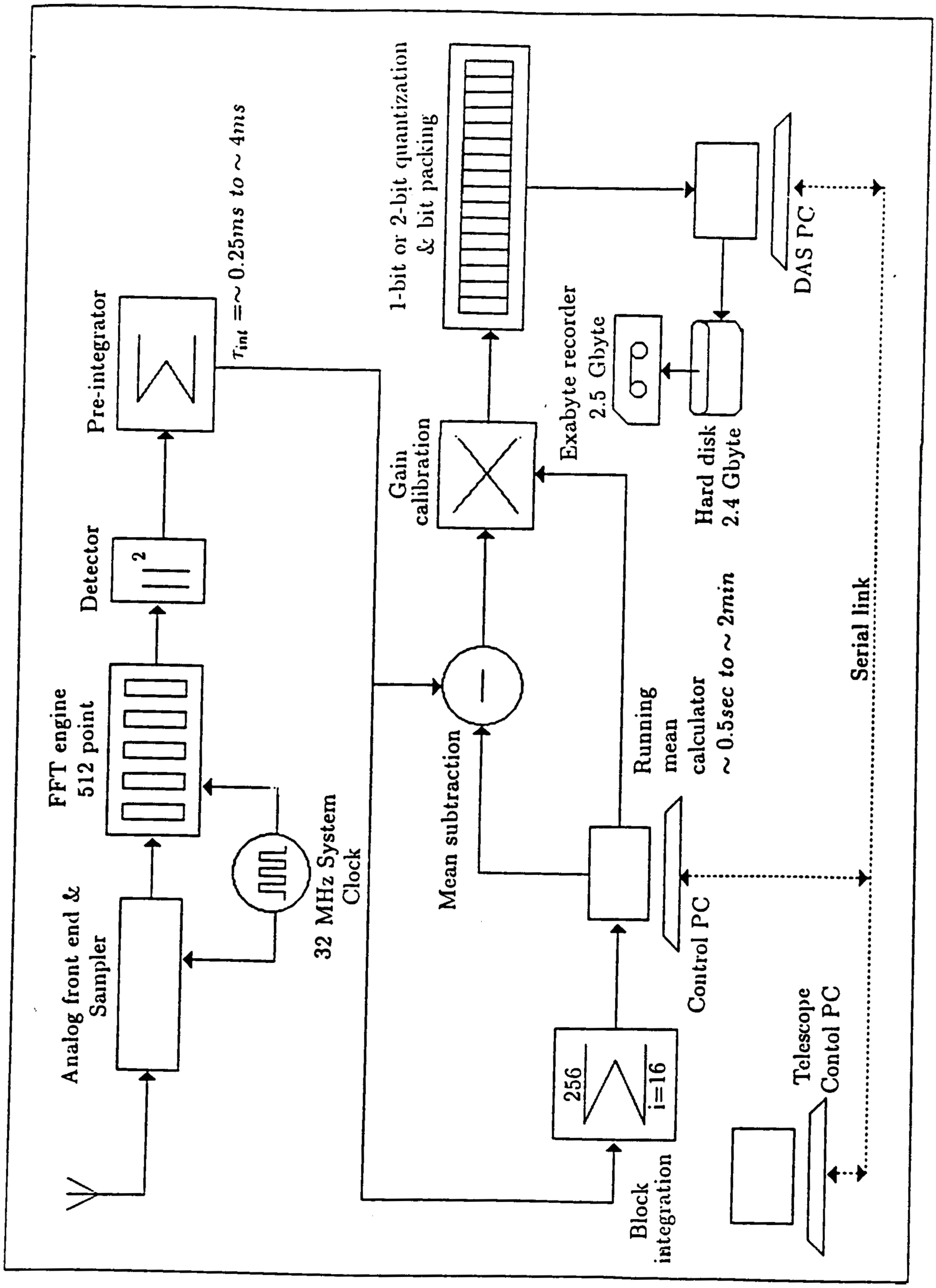

Figure 1. Block diagram showing architecture of the machine.

can be quantized further to a much smaller number of bits after removing its mean value as we are interested mainly in the time variation of the signal rather than its mean value.

The pre-integrated data is sent to a pulsar search preprocessor (PSP) control PC/AT, after block integration over a programmable number of pre-integrated samples (16 to 256 pre-integrated samples) for calculation of the running mean/median for each of the 256 channels. Before the next block-integrated data is ready, the PC/AT computes the running mean over a pre-specified time (0.5 secs to 2 mins) and supplies these values through a dual port RAM (DPRAM) to a mean subtractor (housed in an EPLD) which removes the mean from the pre-integrated data stream. The same PC/AT also computes scaie factors to equalize the gains of the spectral channels (only when the output is 2 or more bits per sample) in the pass band and supplied them through another DPRAM that is used as a gain calibration look-up table for correcting the bandshape of the mean subtracted data. In one-bit mode of operation, gain calibration scale factors are set to unity for all channels. This stream of deviation from the mean spectrum is then quantized to one bit two-level or two bit four-level representation per spectral channel. The output bits of consecutive channels are packed to form sets of 16-bit words that are transmitted to the data acquisition system. This logic is programmed into an EPLD.

3.3 Data *acquisition* system

A PC/AT based data acquisition card accepts the data sent by the search preprocessor into a set of First-In-First-Out (FIFO) memories through latches/counters, and their mode of operation can be decided by software: in the counter mode, a deterministic data pattern can be fed to perform self tests to enable easy diagnosis of the acquisition hardware. During observational sessions they work as latches. FIFOs are used as buffers to accommodate the response delays caused by the latency and seek times in the data-storing on the hard disk. The size of the buffer therefore depends on the input data rate, the storage capacity per cylinder of the hard-disk and the seek + latency time. In our case the input rate is about 64 kbytes/sec (in one-bit mode of operation), the capacity is about 36,352 bytes/cylinder and has about 20 msec seek + latency time per cylinder. FIFOs of 8 k x 16 bits are sufficient to handle this data rate. This limit of 64 kB/sec can be enhanced by providing higher density FIFOs which do not alter the external circuitry. Our tests with higher density FIFOs (upto 32 k $\times$ 16 bits) indicate that data rate of above 256 kB/s are achievable. Whenever the FIFO is half-filled, the acquisition software transfers the data to a 1.2 Gbyte hard disk drive. A memory mapped I/O protocol is used to enable 16 bit zero watt state data transfer (directly to the hard disk drive controller without the intervention of the microprocessor) to achieve high data throughputs. The PC/AT is equipped with an exabyte recorder to facilitate the backup of the data stored in the hard disk drive to an 8 mm tape cartridge.

The Data Acquisition System (DAS) PC/AT, the PSP PC/AT and a PC/AT controlling the telescope beam direction are linked through serial ports and interact for command and message transfers under software control. The telescope control PC points the antenna beam to a required direction and instructs the PSP PC to start observation. The PSP PC/AT in turn sets up the entire machine, runs preliminary diagnostics and waits till the running mean stabilizes, before signalling to the DAS PC/AT. Then the DAS initiates data acquisition which is synchronized automatically to the first frequency channel of next time sample and sends a message back to the PSP PC/AT which in turn informs the status to the antenna control PC. During observation the PSP PC/AT continuously displays the running mean of a chosen spectral channel. The power spectra (i.e., bandshape) at the beginning and at the end of an observation are also recorded in a routine manner.

4. Tests and results

All the modules of the entire machine were independently tested on PC/AT based test jigs with the help of 144-line I/O cards to setup the configuration, provide the clock, to send data to the module and to read back the status and results, and also to help locate errors, under software control. The SP module was tested with different pre-integrations, and sliding window positions. The running mean calculation, mean subtraction and gain calibration were checked with data representing different mean values and bandshapes. The DAS was tested at 256 kB/sec with both internal and external text patterns. After all these tests proved successful, the modules were integrated and tested with pulse-modulated baseband noise input to simulate a 'zero DM' pulsar signal with various S/N ratios, periods and duty cycles. The system was then used in conjunction with the ORT and initial test observations were made on known pulsars for different combinations of period and flux density. Since the ORT accepts only one polarization, one of the two polarization channels in this receiver was preset to zero. The ORT operates at 327 MHz and the associated RF front end and baseband system provide an 8 MHz passband. This 8 MHz band is sampled at the Nyquist rate and the sampled time sequences are transformed to provide a complex spectrum every 16 μs. The number of points in the frequency spectrum is chosen to provide 256 frequency channels of 32 kHz resolution which is an optimal choice for observation of pulsars with dispersion measure (DM) upto 70 pc cm^{-3} (the total bandwidth would be reduced for search at higher DM).

We have attempted to calibrate the observed profile in flux units considering the architecture of the machine and the statistics of the pulsar signal (development of the procedure used is illustrated in the Appendix). Presently continuum calibration sources and background cold-sky regions have been chosen at the same declination to avoid any declination dependent factor entering into the calculation of sensitivity for a calibration source. Further, to avoid nonlinear quantization effect at FFT and power detection stages, we have chosen sources with flux densities less than a few Jansky. These effects are considered small, and ignored now, but have to be measured for more accurate flux measurements. Also, the observations of the calibration source and the pulsar were spaced many days apart, hence the flux estimates shown in the plots are tentative and may not be accurate.

Results for some combinations observed with sampling interval of 0.5 ms, one-bit quantization mode are shown in Figs. 2a, 2b and 2c. The rms error due to the noise in the profile is indicated by vertical bars in the respective profiles.

Figure 2a is a profile of PSR 1237–41, chosen for its low flux density ($S_{avg} \sim 2.5$ mJy). It has a DM of 44 pc cm^{-3}, period of ~ 512 ms;

Figure 2b is a profile of PSR 0740–28, chosen as a candidate for high flux density

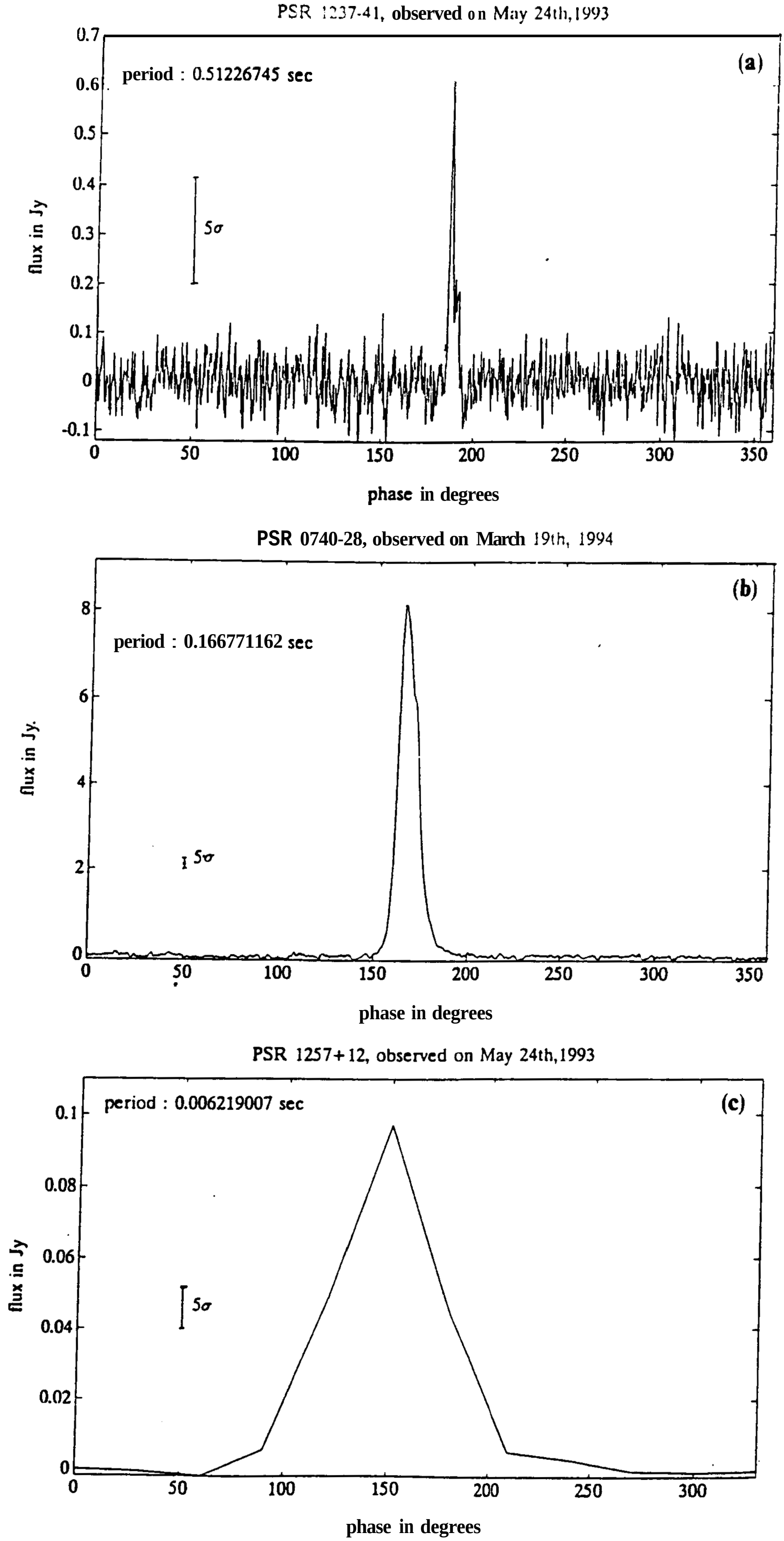

Figure 2 Profiles of observed pulsars: 0.5 ms sampling interval, 9 minutes integration, recording with 1-bit quantization. Flux calibrations was obtained using the procedure outlined in the Appendix.

($S_{avg} \approx 290$ mJy), DM of 73.6 pc cm^{-3} (for which the smearing within the chosen channel bandwidth will be close to the sampling interval) and period of ~ 166 ms;

Figure 2c shows a profile of PSR 1257 + 12, a candidate with a short period ($p \approx 6$ ms) low flux density ($S_{avg} \approx 15$ mJy), and a low DM of 10 pc cm^{-3}.

Though the intended use of this machine is to search for new pulsars, it can also be used with simple modifications for timing and other studies of known pulsars.

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APPENDIX

Flux calibration procedure

For a total power receiver with each recorded sample represented by many bits, the flux calibration can be done by pointing to known continuum sources and background cold sky regions by knowing the relation between the deflection in some counts and the actual source flux causing the deflection, as follows

$$\text{Counts/Jansky} = \frac{\mu_{cal} - \mu_{bsky}}{S_{source}}$$

where, μ_{cal}, μ_{bsky} are mean counts when pointed to the calibration source and background sky respectively, S_{source} = flux of the calibration source.

Considering the fact that in our system the data are one-bit samples representing deflections from the mean power, we tap 16-bit data before it goes for mean subtraction and integrate further for about a minute, then record it for a few minutes.

In a given frequency channel, the sensitivity measured from this data can be represented as

$$SNR_{cal} = \frac{\mu_{cal} - \mu_{bsky}}{\sigma_{bsky}}$$

where, σ_{bsky} is standard deviation of the power received from background sky, in counts.

If there are N_{ch} frequency channels, then the average signal-to-noise ratio is

$$SNR_{calavg} = \frac{1}{N_{ch}} \sum_{i=1}^{N_{ch}} SNR_{cal[i]}$$

In case of a pulsar, the contribution of pulse energy changes the running mean by only a very small amount, hence the threshold set for mean subtraction is about the same as the mean contribution from the background and the receiver.

The l-bit stream generated from this mean subtracted data represents samples which exceed the mean by 0 and those which are less than the mean by 1s.

Keeping this in mind, we know that after folding N pulses, in the off pulse region (refer Fig. 3a) we get a mean integrated count (M)

$$M_{offpulse} = N[P(W > \mu_{offpulse}) \times 0 + P(W < \mu_{offpulse}) \times 1]$$

$$= N[P(W < \mu_{offpulse})] = \frac{N}{2}$$

where, W is the power before mean subtraction, $P(W > \mu_{offpulse})$ is the integrated probability of W being greater than $\mu_{offpulse}$, and the threshold for l-bit quantization is equal to the mean of the distribution of W, $\mu_{offpulse}$.

For on-pulse locations, the mean count will be (refer Fig. 3b)

$$M_{onpulse} = N[P'(W < \mu_{offpulse})]$$

where, $P'(W > \mu_{offpulse})$ is the integrated probability of W being greater than $\mu_{offpulse}$. The mean of the distribution of W is $\mu_{onpulse}$, while the threshold for l-bit quantization

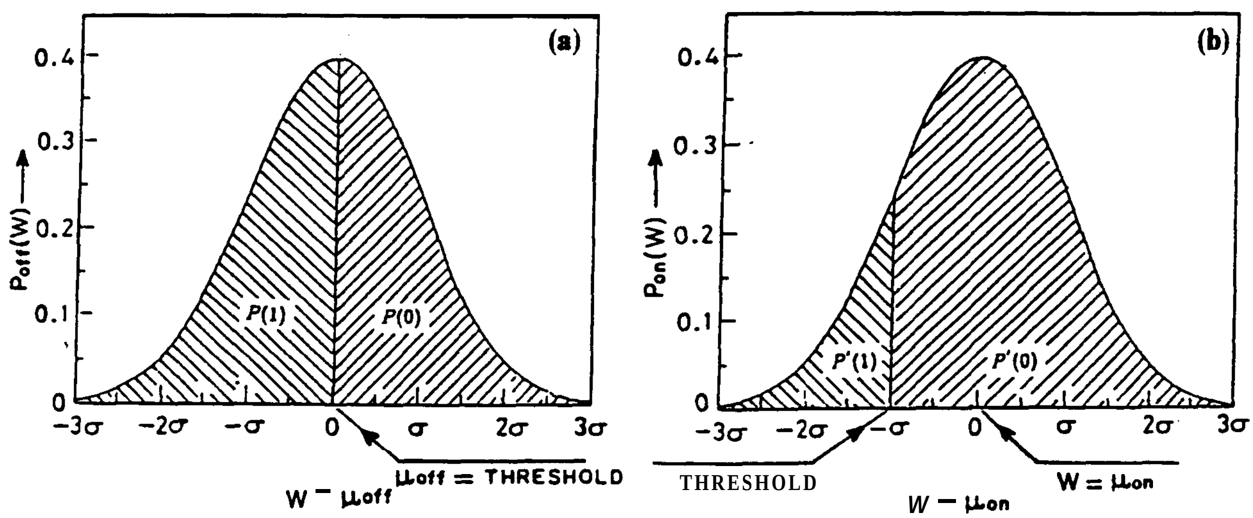

Figure 3a & b Probability distribution functions of l-bit data: **a)** In the off-pulse regions, the threshold for 1-bit quantization is equal to the mean $\mu_{offpulse}$, and the probability density' is $p_{off}(W)$ **b)** During the on-pulse region, the threshold is still close to the off-pulse mean $\mu_{offpulse}$, while the actual mean has shifted to $\mu_{onpulse}$, and the distribution has a probability density $p_{on}(W)$. The shaded areas indicate the integrated probability when (i) sampled power exceeds the running mean (marked as $P(0)$ $[P'(0)]$), (ii)sampled power is less than the running mean (marked as $P(1)[P'(1)]$).

is close to the off-pulse mean μ_{offpulse}. Thus, the change in mean count value is given by

$$\Delta M = \frac{N}{2} - N[P'(W < \mu_{\text{offpulse}})]$$
$$= N[P'(W < \mu_{\text{onpulse}}) - P'(W < \mu_{\text{offpulse}})]$$
$$= N[P'(\mu_{\text{offpulse}} < W < \mu_{\text{onpulse}})]$$
$$\Delta M = \left[\frac{1}{\sqrt{2\pi}\,\sigma_{\text{onpulse}}} \int_{\mu_{\text{offpulse}}}^{\mu_{\text{onpulse}}} e^{-[(W-\mu_{\text{onpulse}})^2/2\sigma^2_{\text{onpulse}}]} \, dW \right]$$

After some manipulation, we get

$$\Delta M = \frac{N}{2} \operatorname{erf}\left[\frac{K}{\sqrt{2}}\right]$$

where

$$K = \frac{\mu_{\text{onpulse}} - \mu_{\text{offpulse}}}{\sigma_{\text{onpulse}}}$$

For typical pulsar flux densities, the rms fluctuations are about the same during both off-pulse and on-pulse regions. Hence,

$$K \approx \frac{\mu_{\text{onpulse}} - \mu_{\text{offpulse}}}{\sigma_{\text{offpulse}}}$$

Hence the signal-to-noise power ratio (**SNR**) after folding over N periods of this 1 bit data stream, is given by

$$SNR_{1\text{bit}} = \frac{\Delta M}{\sigma_{\text{offpulse}}} = \frac{N}{2}\left[\frac{\operatorname{erf}(K/\sqrt{2})}{\sigma_{\text{offpulse}}}\right]$$

Thus, the analog (multibit) sensitivity of this machine 'K' is then given by

$$K = \sqrt{2}\left[\operatorname{erf}^{-1}\left(\frac{2SNR_{1\text{bit}}}{N(\sigma_{\text{offpulsc}})}\right)\right] \quad *$$

For N_{ch} frequency channels, the average value of K is

$$K_{\text{avg}} = \frac{1}{N_{\text{ch}}} \sum_{i=1}^{N_{\text{ch}}} K_i$$

The ratio of K to the SNR measured on a calibrator source can be used and the deflection in the pulse profile can then be calibrated directly in flux units as

$$S_{\text{PSR}}(\text{Jy}) = S_{\text{cal}}(\text{Jy}) \times \frac{K_{\text{avg}}}{SNR_{\text{calavg}}}$$

* Typographical error : actually. $K = \sqrt{2}\left[\operatorname{erf}^{-1}\left(\frac{{}_{1\text{bit}}\,\sigma_{\text{offpulse}}}{N}\right)\right]$

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