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A digital pulsar backend based on FPGA

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Abstract A digital pulsar backend based on a Field Programmable Gate Array (FPGA) is developed. It is designed for incoherent de-dispersion of pulsar observations and has a maximum bandwidth of 512 MHz. The channel bandwidth is fixed to 1 MHz, and the highest time resolution is 10 µs. Testing observations were carried out using the Urumqi 25-m telescope administered by Xinjiang Astronomical Observatory and the Kunming 40-m telescope administered by Yunnan Observatories, targeting PSR J0332+5434 in the L band and PSR J0437–4715 in the S band, respectively. The successful observation of PSR J0437–4715 demonstrates its ability to observe millisecond pulsars.

Key words: instrumentation: miscellaneous — methods: data analysis — pulsars: general

1 INTRODUCTION

Pulsars are unique and versatile objects which emit radio pulses with very stable periods (Lorimer & Kramer 2005). The precise measurement of pulse arrival time can be used for astrometry and gravitational wave detection. Observations of pulsars have been used for revealing the interstellar medium and studies of super-dense matter and plasma physics under extreme conditions.

The radio emission from pulsars suffers dispersion as it propagates through the interstellar medium, so that emission at a higher frequency arrives earlier than that at a lower frequency. It is necessary for any pulsar observation system to compensate the pulse delay between different frequencies. Otherwise the pulse profile will be broadened, or even completely smoothed out.

The interstellar medium is cold ionized plasma, with electron number density, $n_{\rm e}$, which is typically about $0.03\,{\rm cm}^{-3}$. The dispersion measure (DM) is defined as

$$\mathrm{DM} = \int_0^d n_{\rm e} dl, \tag{1}$$

where d is the distance to the pulsar. The time delay of pulses at two frequencies, f_1 and f_2 in MHz, is

$$\Delta t \simeq 4.15 \times 10^6\,\mathrm{ms} \times \left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \times \mathrm{DM}. \tag{2}$$

The dispersion can be removed both coherently and incoherently. The key point is to split the observing band into multiple channels, and then compensate the pulse delay. In the early days, de-dispersion was performed with an analog circuit, for example the filterbank system used at Xinjiang Astronomical Observatory (Zhang et al. 1999). Nowadays, high speed analog-to-digital (A/D) convertors, together with digital signal processing devices such as a Field Programmable Gate Array (FPGA) and Digital Signal Processor (DSP), are replacing analog circuits for pulsar signal processing. Digital pulsar backends have been developed in several countries, for example the Pulsar Digital Filter Bank (Hampson 2005) developed in Australia and GUPPI for the Green Bank Telescope in the USA (DuPlain et al. 2008).

With this paper we report the development of a digital pulsar backend based on the FPGA platform.

This backend has been tested via observations using the 25-m Urumqi telescope administered by Xinjiang Astronomical Observatory and the 40-m Kunming telescope administered by Yunnan Observatories.

2 THE BACKEND SYSTEM

A schematic diagram of the digital pulsar backend is shown in Figure 1. The system consists of three parts: frequency conversion, channelization and interface. The intermediate frequency (IF) signal from the telescope and receiver is adjusted for gain in the RF AGC unit, and then sent to the A/D convertor. The A/D convertor operates with a 1024 MHz clock, which is generated and locked by the frequency synthesis unit using a 5 MHz signal from an H maser clock. The sampled digital IF signal is then converted to the baseband with the Digital Down Conversion (DDC) unit. The channelization part computes fast Fourier transform (FFT) and splits the baseband signal into channels which are 1 MHz wide. To reduce the data rate of the output, the data in each channel are accumulated according to the time resolution requirement (1 ms or 10 μs). To record the data with Mark5B/Mark5B+, the accumulated data are transformed into a specific format. In the interface part, the output selection unit works to determine the total frequency bandwidth of the observation by selecting the output channels. All these three parts are controlled through the system control unit. The dedispersion is implemented using pulsar analysis software in post-processing which is carried out with computers.

The digital pulsar backend is implemented on a hardware platform developed at Shanghai Astronomical Observatory. The platform was initially created for China's Very Long Baseline Interferometry (VLBI) Digital Base Band Convertor (DBBC) project. The key part of the platform is the digital signal processing board, which is shown in Figure 2. This board is equipped with one high speed A/D convertor and five Xilinx FPGA chips, one of which works as the controller and the other four work as the signal processor. Our digital pulsar backend uses these signal processors to do the channelization. Each processor provides an available bandwidth of 128 MHz in the 1 ms mode, or 127 MHz in the 10 μs mode. The VLBI Standard Interface (VSI), which is used to connect the DBBC to the Mark5B/Mark5B+ system, has a 32-bit capability. This 32-bit interface can support four processors in 1 ms mode or one processor in 10 μs mode. The maximum available bandwidth for our backend is determined by the number of VSI interfaces.

3 TESTING OBSERVATIONS AND RESULTS

Two observations were made to test the digital pulsar backend. One targeted PSR J0332+5434 in the L band using the Urumqi 25-m telescope, managed by Xinjiang Astronomical Observatory, on 2010 August 14. The other targeted PSR J0437–4715 in the S band using the Kunming 40-m telescope, managed by Yunnan Observatories, on 2010 October 20.

In the observation carried out with the Urumqi 25-m telescope, one of the dual polarization channels from the telescope's low temperature receiver was sent to the digital pulsar backend. In the observation made with the Kunming 40-m telescope, one circular polarization channel was fed to the backend. The parameters associated with these two observations are listed in Table 1.

The flowchart of the data acquisition and processing is shown in Figure 3. The output from the digital pulsar backend was recorded with the Mark5B system, and then transferred to a server through the network. Channelized data streams are recovered from decoding the recorded data, and then folded to produce the average profile of each channel. The analysis is mainly done with the pulsar software PSRCHIVE (Hotan et al. 2004).

For pulsar J0332+5434, four DBBC processors were used to provide the 512 MHz bandwidth for the observation. With this setup, the 512 MHz-wide band was divided into four 128 MHz-wide sub-bands. All of these four sub-bands successfully captured this pulsar's signal, as shown in Figure 4, but some channels were removed to improve the signal-to-noise ratio of the average profile. These plots are made from a 10-minute span of data recorded during the observation. Additionally, this observation obtained individual pulses of PSR J0332+5434, as shown in Figure 5.

Only one DBBC processor was used in the observation for PSR J0437–4715. As the time resolution increases to 10 μs, the data rate of the processor's output increases greatly. The VSI interface cannot support more than one processor in this situation. Because we used one channel to store the packet information, the available bandwidth then becomes 127 MHz in the observation. The pulsar signal appears in about 110 channels, as shown in Figure 6. The average profile is shown in Figure 7.

4 SUMMARY

A digital pulsar backend is developed on an FPGA-based platform. This backend provides two available time resolutions: 1 ms for observing normal pulsars and 10 μs for observing millisecond pulsars. Two pulsars, the normal

Table 1 Parameters of the Test Observations

Telescope	Pulsar	Period (s)	DM	Time resolution	Bandwidth	Channel number
Urumqi 25-m	J0332+5434	0.7145	26.8	1 ms	512 MHz	512
Kunming 40-m	J0437−4715	0.005757	2.6	10 μs	127 MHz	127

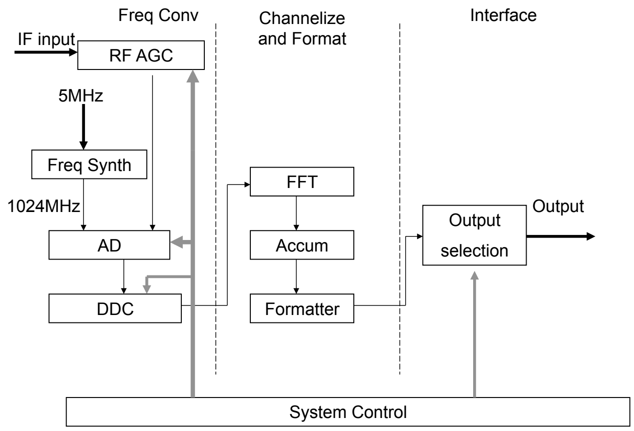


Fig. 1 Schematic diagram of the digital pulsar backend.

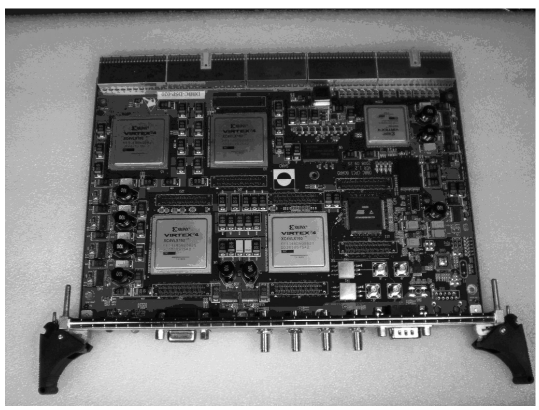


Fig. 2 The digital signal processing board.

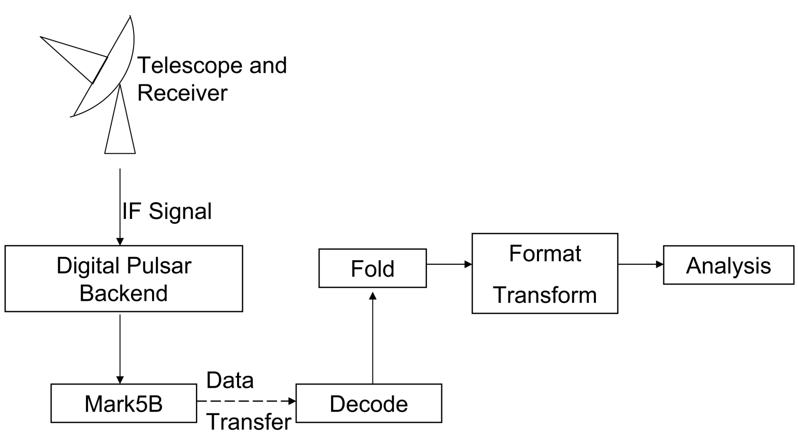


Fig. 3 A flowchart showing data acquisition and processing.

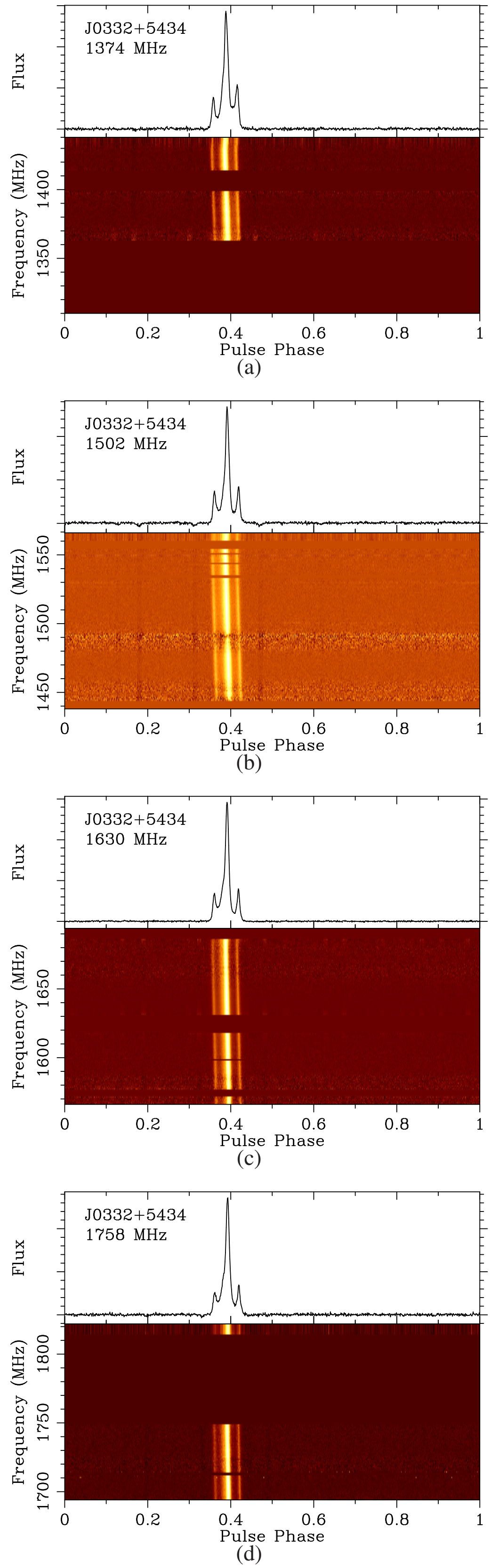
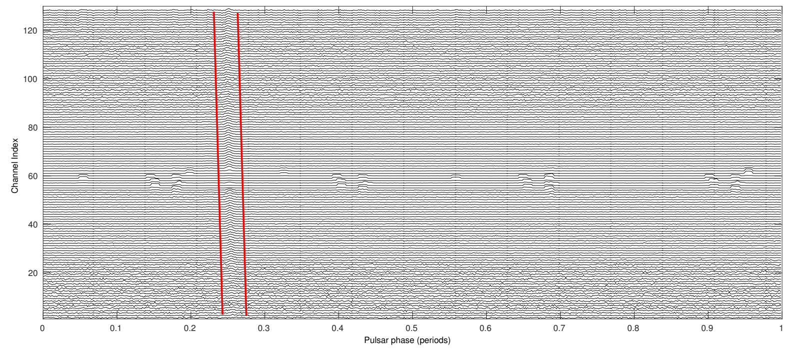
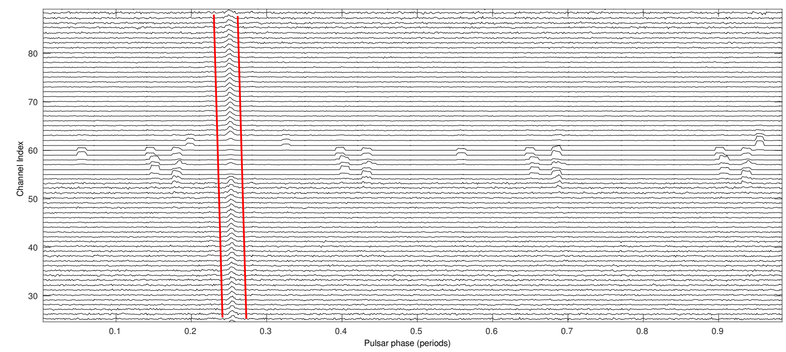


Fig. 4 Average profiles for J0332+5434 in four 128-MHz sub-bands centered around: (a) 1374 MHz; (b) 1502 MHz; (c) 1630 MHz; (d) 1758 MHz. The data span 10 minutes. Please note the flux is uncalibrated.



(a)



(b)

Fig. 5 Individual pulses of J0332+5434 in one single period, as indicated with the two red lines: (a) an overview; (b) a detailed view. This sub-band starts from 1566 MHz.

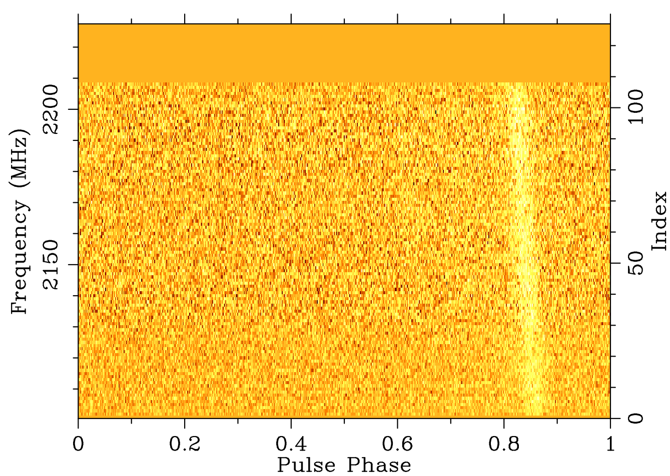


Fig. 6 Frequency-phase plot of PSR J0437–4715.

pulsar J0332+5434 and the millisecond pulsar J0437–4715, have been successfully observed with this digital backend. The observation of J0332+5434 obtained individual pulses of the pulsar, in addition to obtaining average profiles within the bandwidth of 512 MHz. The successful observation of J0437–4715 indicates this digital pulsar backend has sufficient time resolution to observe millisecond pulsars.

In the future we plan to simplify the data processing procedure in order to make it easier to use. The plan includes incorporating a high-speed network, like a 10 Gbps ethernet, to improve the data output capability and increasing the available bandwidth.

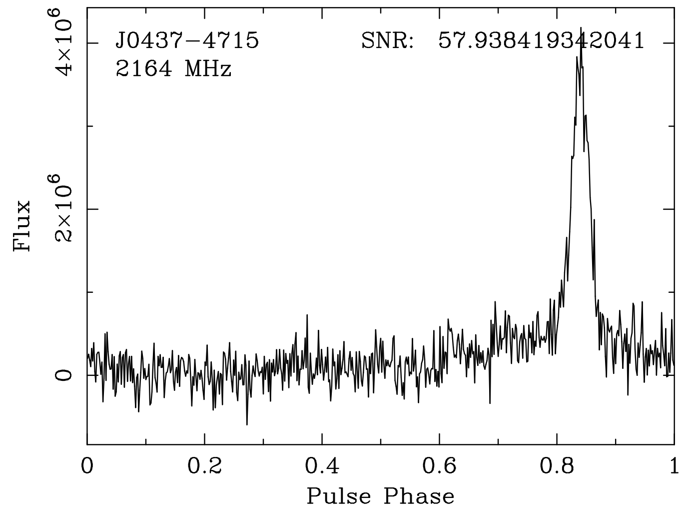


Fig. 7 The average profile of PSR J0437–4715. Please note the flux is uncalibrated.

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