A SOFTWARE BASEBAND RECEIVER FOR PULSAR ASTRONOMY AT GMRT

B. C. Joshi[1], **Sunil Ramakrishna**[2,3], **Sunil Patil**[4]

[1]**National Centre for Radio Astrophysics (TIFR), Post Bag 3, Ganeshkhind, Pune 411 007, India**

email : bcj@ncra.tifr.res.in

[2]**International Institute of Information Technology (I2IT), P-14, Infotech Park, Hinjewadi, Pune - 411 057, India**

[3] **Intoto Software(I) Pvt Ltd., Uma Plaza, Nagarjuna Hills, Panjagutta, Hyderabad 500 082, India**

email : dextersunil@yahoo.com

[4]**International Institute of Information Technology (I2IT), P-14, Infotech Park, Hinjewadi, Pune - 411 057, India**

email : sunilp@isquareit.ac.in

Abstract

High time resolution studies of pulsars usually employ specialized digital hardware to counter the degradation in the quality and time resolution of their radio signals due to dispersion in the inter-stellar medium. A new alternative is provided by the availability of cheap computer hardware in recent years. In this approach, the required signal processing is implemented in modular and portable software using commercially off-the-shelf available computing hardware. A pulsar instrument for Giant Meterwave Radio Telescope based on this approach is described in this paper. The salient features and the modes of operation of this receiver are discussed followed by illustration of test observations demonstrating its capability. Lastly, the future extensions of this concept are discussed.

1 INTRODUCTION

High time resolution data is required in a variety of pulsar studies such as high precision astrometry [1, 2], pulse emission mechanism studies [3, 4] and studies of pulsar polarization [5]. In addition, such data are useful in experiments involving tests for general theory of relativity [6] and the detection of primordial gravitational wave background [7]. The time resolution and quality of pulsar data is however limited due to dispersion in the interstellar medium (ISM). Therefore, high time resolution studies of pulsars usually employ specialized digital hardware to implement coherent dedispersion algorithms to counter the effect of ISM. The functionality of such hardware is frozen at the time of design, making them inflexible to changing demands of pulsar astronomy. A new alternative is provided by the availability of cheap computer hardware in recent years. In this approach, the required signal processing is implemented in modular and portable software using commercially off-the-shelf available computing hardware. Since the functionality of the receiver is defined in software, such a receiver is more flexible. One of the first such pulsar backends was Coherent Baseband Receiver for Astronomy (COBRA) and similar backends have been made operational at Westerbok, Arecibo, Parkes and Green Bank Observatories recently [8, 9]. A pulsar instrument for Giant Meterwave Radio Telescope (GMRT) based on this approach is described in this paper.

2 A PULSAR SOFTWARE BASEBAND RECEIVER FOR GMRT

Pulsar Software Baseband Receiver (PSBR) implements the signal processing, required for obtaining high time resolution high signal to noise ratio (SNR) pulsar data, using portable, open-system, flexible and upgradeable software. PSBR consists of a high speed data acquisition card and a Beowulf cluster of 4 off-the-shelf commodity personal computers (PC) connected by a Gigabit ethernet switch as shown in Fig. 1. The existing analog and digital data pipeline of GMRT is used to obtain baseband data for the two polarizations of the received radio frequency signal. A 512 point Fast Fourier

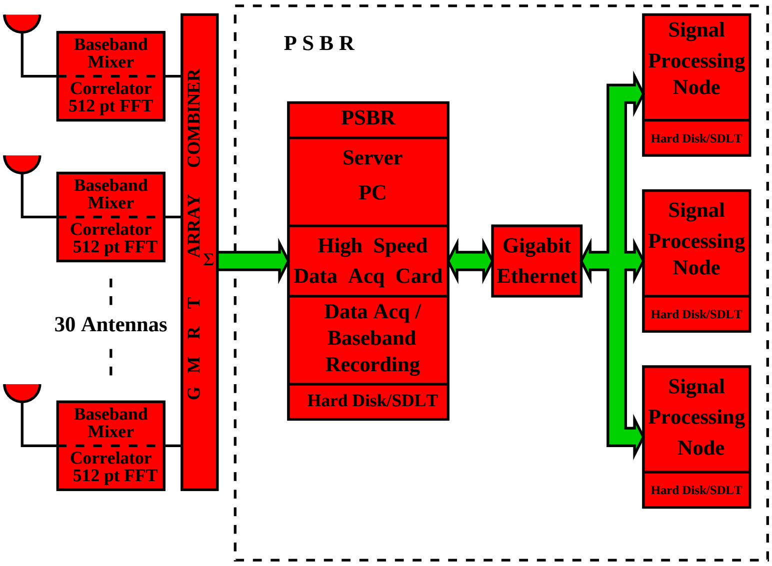

Figure 1: The schematic diagram of PSBR

Transform (FFT) is carried out in this pipeline and the data from different antennas are added in phase using GMRT Array combiner. These data are acquired at a rate of 64 Mbytes/s (corresponding to a bandwidth of 16 MHz) using a high speed acquisition board mounted in the server PC, which farms out data by either a Transmission Control Protocol (TCP) or Message passing interface (MPI) over the Gigabit switch to compute PCs.

The PSBR has three modes of operations : (1) high time resolution baseband recording mode, (2) Polarimeter and Incoherent array mode and (3) online coherent dedispersion mode. The acquired data are recorded to local hard-disk or SDLT tape with a sampling time of 125 ns in the baseband recording mode for off-line coherent dedispersion. In the polarimeter mode, the acquisition software carries out relevant multiplications online to generate full stokes parameter time series, which can then be integrated upto a desired sampling time (in excess of 128 μs). This reduced data is then farmed over the Gigabit ethernet to signal processing PCs, where different software modules carry out online incoherent dedispersion / folding and simultaneous display in one of three different formats - bandshapes, collapsed integrated profiles and full 256 channel integrated profiles, providing an online feel for the data to the observing astronomer. In the online coherent dedipersion mode, the baseband data for 2 MHz bandwidth is dynamically farmed to one of the three compute nodes using MPI protocols for coherent dedispersion and subsequent display and recording of reduced average pulse profiles. The data acquisition is synchronized with the minute pulse from Global Positioning System (GPS) for generating time-stamps for all three modes of PSBR and can be controlled from Telescope control using simple commands.

The signal processing for each of this functionality is implemented in software in a modular form so as to allow modification / upgradation by replacement with new functional modules. The definition of functionality of the receiver in software makes it flexible as opposed to earlier hardware implementations. Thus, the design of the receiver both in its hardware and software components resembles the concept of a Software Defined Radio (SDR), which is fast becoming popular in industry.

3 Results

The baseband recorder and the polarimeter mode of PSBR have been under test since October 2004 and have given a stable performance. The online coherent dedispersion mode is being tested currently and efforts are on to enhance bandwidth in this mode. As the design is modular, a similar receiver for the second sideband of GMRT can be commissioned very rapidly.

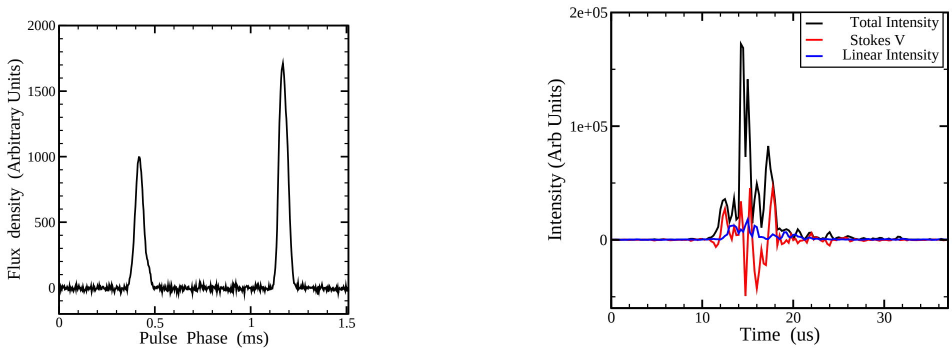

Figure 2: (a) The left plot shows the average profile of MSP PSR B1937+21 at 610 MHz obtained with PSBR. The time resolution of the profile is 3 μs (b) The right plot shows uncalibrated stokes profiles of a Giant pulse in PSR B0531+21. The time resolution is 250 ns. The solid line shows the total intensity, the red line circular polarization and the blue line total linear polarization

The main objective of this receiver was to obtain high time resolution pulsar data for studies of the kind indicated in Sec. 1. Hence, test observations of millisecond pulsars (MSPs) were carried out and the results, highlighting this capability of the instrument, are discussed in this section. PSR B1937+21, an MSP with the shortest known period (1.5 ms) and a high Dispersion Measure (DM $\sim$ 71 $\mathrm{pc\,cm^{-3}}$), is best suited to characterize the high time resolution capability of PSBR. The current backends give only 12 bins across its average profile, which has a dispersion smear of about 2 bins. Fig. 2(a) shows the coherently dedispersed average profile of this pulsar obtained at 610 MHz with a sampling time of 250 ns and folded to 512 bins with an effective bin-size of 3 μs. The profile is consistent with similar observations at this frequency. Such profiles will be useful to study the components, particularly their evolution with frequency, in average profiles of a much larger sample of MSPs available now as compared to those reported in [3]. Moreover, PSBR gives the full Stokes profile and this will be useful in polarization studies [5].

A handful of pulsars show narrow intense single pulses, called Giant Pulses (GPs), with intensities exceeding the average intensity by a factor of 100. Fig. 2(b) shows a high resolution profile of a GP of PSR B0531+21 in data obtained at 610 MHz with 250 ns time resolution. The GP profile clearly shows the nano-pulses reported earlier [10] and is consistent with their observations. This figure also shows uncalibrated linear and circular polarization profile suggesting that GPs are highly polarized.

As PSBR is likely to play an important role in high precision pulsar timing, test observations of PSR B1937+21 to characterize its timing accuracy were also carried out. Time of Arrival (TOA) data, acquired during these tests, were analyzed together with older low time resolution data on this pulsar using the pulsar timing package TEMPO to estimate the improvement in timing errors for MSPs. Fig. 3 shows TOA residuals obtained with PSBR for this pulsar after a suitable pulsar model fit in comparison with low time resolution data. As is evident from the figure, residuals better than 1 μs are routinely possible, even at low frequencies, for short observations.

4 Planned Improvements

As has been known since the time COBRA was designed, the bottleneck in extending the bandwidth of such a system without multiple copies is the rate at which data can be transfered to PC Random Access Memory (RAM) through Peripheral Connect Interface (PCI) bus ($\sim$ 32 Mbytes/s:[8]). Recently, PC manufacturers adopted a new standard for this bus, known as PCI Express (PCIe), which promises to push this bandwidth to beyond 16 Gbytes/s. This bus has been adopted enthusiastically by the industry and an extension of PSBR using PCIe based data acquisition cards is planned. The higher PCIe bandwidth will make a 30-antenna software correlator cost-effective and its feasibility is being examined.

The current signal processing software uses a standard FFT algorithm which uses overlap-add method for deconvolution of ISM filter function. This method effectively carries out FFT of the observed data sequence twice and a better

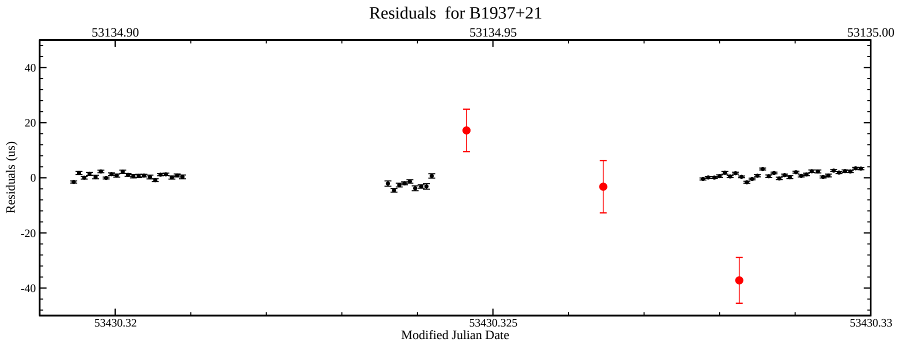

Figure 3: The TOA residuals for PSR B1937+21. The black circles represent recent measurements using PSBR with the corresponding MJD indicated along the bottom x-axis. The typical errors are 1 μs. The red circles are measurements carried out in May 2004 with the low resolution backend. The corresponding MJD is indicated along top x-axis

algorithm eliminating this redundancy is being experimented, almost halving the computation time for coherent dedispersion. Since the FFT lengths are long for low frequency, such an improvement will allow observations of pulsars with much larger DM.

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