Observing Pulsars and Transients at Low Radio frequencies using 1-bit digitization

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Abstract

The Gauribidanur Pulsar System (GAPS) is a new Radio telescope at the Gauribidanur Radio Observatory (Lon:77.4° E; Lat:13.6° N)) in India. Its purpose is to observe Pulsars and other astrophysical transients at low radio frequencies (<100 MHz). The system was recently upgraded to a "Digital Radio telescope" where raw voltages from each antenna are recorded separately using 1-bit digitization, and the beamforming is done in the software. Such a software-based binary system offers distinct advantages, like simultaneously probing different directions in the sky with reduced data rate/volume, making it suitable for transient surveys. We present a summary of the 1-bit raw voltage recoding receiver of GAPS with its initial results.

1. Introduction

The first Pulsar was detected in 1967 at ~80 MHz [1]. However, the majority of pulsars, since then, have been observed and studied in frequencies above 100 MHz. Due to various practical reasons, observations of Pulsars below 100 MHz are limited. These include unavailability of big radio telescopes in this frequency range, increased effects of the Interstellar medium (ISM), increased galactic background emission, and Radio frequency interference (RFI). Observations of Pulsars below 100 MHz are necessary to understand their emission mechanism which is still debated. Such observations are also useful in studying the ISM as the propagation effects are more prominent at low frequencies.

One of the most fascinating phenomena in the Universe is the Fast Radio Burst (FRB)- subsecond radio flashes that are extremely bright and highly dispersed. The first FRB was detected in 2007 in archival data [2]. Since then, FRBs have been eluding astronomers about their origin. Much like Pulsars, most of our knowledge and understanding of FRBs come from high frequency observations. It was long believed that FRBs might not have low frequency emissions. However, recently FRB emission was detected at 120 MHz and 110 MHz [3,4], which suggests there might be a possibility to detect them at even lower frequencies. This will require continuous monitoring of the sky at low frequencies.

In this light, a new observing facility, the Gauribidanur Pulsar System (GAPS), was commissioned at the Gauribidanur Radio Observatory [5]. GAPS consists of 16 Log-Periodic Dipole antennas (LPDAs) on a North-South baseline with 5m spacing between each antenna. It has a wide field of view (110° x 80^0) in its operating frequency band (50-80 MHz). At the back-end, an FPGA (Field programmable gate array) based digital spectrometer with high temporal and spectral resolution (≈36 kHz and 1msec, respectively) is used. Pulsars B1919+21, B0834+06, B0950+08, and B1133+16 were successfully detected with the prototype system. The prototype system had analog beamforming, where switching between different lengths of cables was used to point the beam in different directions. The system was upgraded to have a digital beamforming facility, where simultaneous beams were formed on-board the FPGA [6]. Simultaneous Pulsars and Solar bursts were observed using the digital beamformer. Such a digital beamformer allows different parts of the sky to be probed simultaneously, but the number of beams that can be formed is limited by the resources available on the FPGA, and once the beams are formed in certain directions, the observations are limited to the corresponding directions.

If raw voltages are recorded from the individual antenna, any number of beams can be formed offline, within the field of view of the individual antenna. However, the resulting data volume and subsequent data processing and management costs will be enormous in this case. A solution to this is to record fewer bits from the analog-to-digital converter (ADC). 1-bit digitization can significantly reduce the data rate but it will introduce the well-known non-linearities in the system [7]. To test the feasibility of a such binary system and its effects on Pulsars and transient observations, we implemented a 1-bit raw voltage recording receiver in GAPS [8].

2. The 1-bit raw voltage recording system

The front-end for the 1-bit raw voltage recording system consists of 8 LPDAs on a North-South baseline with 5 m spacing between them. The half-power beam width (HPBW) of each LPDA is ~80° in the E-plane i.e. the plane in which arms of the LPDA are oriented, and ~110° in the orthogonal H-plane. The antennas are mounted with their

E-planes North-South direction and H-planes in the East-West direction. As shown in Figure 1, the signal from each antenna passes through a set of filters to suppress the unwanted signal at frequencies < 35 MHz and > 85 MHz and a pre-amplifier with a gain of ~30 dB. The signals further pass through a high pass filter to suppress the RFI < 35 MHz and one more stage of amplification. The RF signals are then brought to the receiver building via low-loss coaxial cables, where they are individually sampled and later combined in the software. The result is fan-beam, with HPBW in North-South to be ~6° and that in East-West ~110^0. The wide beam in the East-West direction allows continuous observation of a radio source for ~7 hrs.

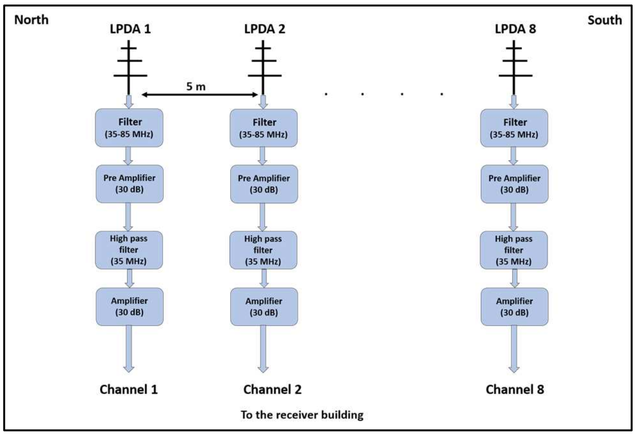

Figure 1. Array configuration of GAPS used for raw voltage recording

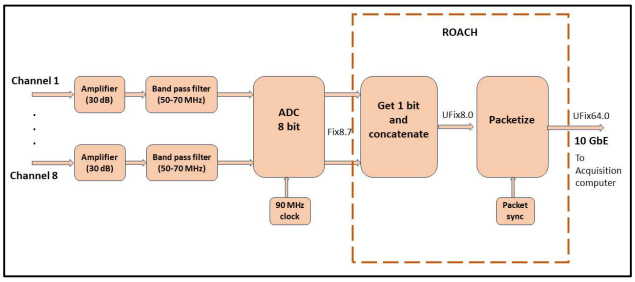

Figure 2. Schematic of the 1-bit raw voltage recording receiver.

At the back-end, the RF signals from each antenna pass through an amplifier and bandpass filter of 50-70 MHz before being fed to ADC. Two Quad-ADC cards, each containing four AD9480 ICs, are used to sample the eight RF channels at 90 MHz sampling frequency. Figure 2 shows the digital receiver, which is implemented on Reconfigurable Open Architecture Computing Hardware (ROACH) from the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) with the Xilinx Virtex-5 FPGA. The ADC converts the input voltage to an 8-bit Fixed point number (Fix 8.7) between −1 and +1. The sign bit from each of these numbers is taken, so we have 1 bit from each antenna channel. These 8 bits are concatenated together, forming an unsigned 8-bit number (UFix8.0). Such 1024x8 8-bit numbers are packetized together and sent to the recording computer over 10 Gigabit Ethernet (10GbE). This resulting data rate is ~0.72 Gbits/s, which is significantly smaller compared to the data rate of ~5.6 Gbits/s, which would have resulted if 8 bits were recorded from each antenna channel. Table 1 summarizes the characteristics of the system.

Table 2. Characteristics of the voltage recording system of GAPS.

Number of antennas	8
Samling rate	90 MSPS
Observation band	45-90 MHz (50-70 MHz usable)
Sampled bits	1
FFT size	Variable (8192 in present case)
Frequency resolution	10.98kHz
Time resolution	Variable (91.02μs one spectrum)
Declination coverage	−26.4° S to +53.6° N

3. Software beamforming

The recorded data file is processed using a Python-based pipeline to perform beamforming. As the antenna array is oriented in the North-South, the beamforming is performed along the declination. Each packet is unscrambled to get the voltage time series of the individual antenna channels. Based on the declination, the geometric delays are calculated as

$$t_n = d_n \sin\theta / c \,, \tag{1}$$

where t_n is the delay required for the n^{th} antenna at a distance of d_n from the reference antenna for the source at angle θ, and c is the velocity of light. The delays are applied to the individual time series according to the desired declination The sampling interval is 1/90MHz = 11.11ns. So, the time series are delayed by the closest integer multiple of 11.11 ns. The uncompensated fractional delays (Δt_n) are compensated by applying a phase gradient in the spectral domain. To do that the delayed voltage streams are Fourier transformed using FFT and multiplied by $\exp(-i\phi_n)$ where

$$\phi_{n,k} = 2\pi F_k \Delta t_n \,, \tag{2}$$

where F_k is the k^{th} frequency bin. In the present case, an 8192-point FFT is performed, resulting in 4096 positive frequency bins with a resolution of 10.986 kHz. After the phase compensation, the individual spectra from each antenna are added together, modulo-squared, and integrated according to the desired temporal resolution. Multiple beams pointing at different declinations can be formed by changing the delay and phase values and a separate file is stored for each beam containing the corresponding power spectrum series. These are further processed using PRESTO [9] to search for Pulsar signals.

4. Observation and results

In the initial run of the voltage recording system, six pulsars (B0834+06, B0919+06, B0950+08, B0943+10, B1133+16 and B1919+21). The first five pulsars were detected in a single 6 hr observation by forming beams at the corresponding declinations. The pulsar average profiles shown in Figure 3 and the pulsar parameters closely match with those obtained using multi-bit digitization observations in a similar frequency range [10]. As evident from Table 2, the 1-bit quantization does not have an effect on the parameters of a pulsar, like period, Dispersion measure (DM), etc.

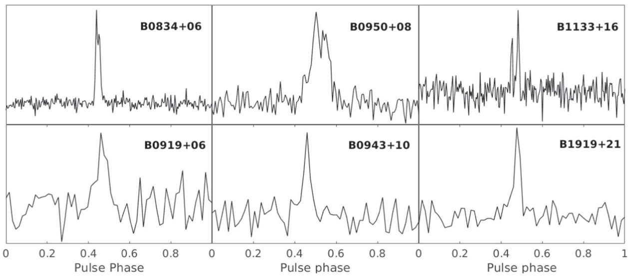

Figure 3. Average profiles of the pulsars observed with GAPS using 1-bit raw voltage recording system and offline beamformation

During this observation, a Solar type III burst was also recorded in the beam pointed toward the declination of the Sun (15.7° N). This burst was detected in a single pulse search pipeline developed using PRESTO routines to search for dispersed single pulses like FRBs. The burst was detected at a DM of 13.2 pc/cm^3. The de-dispersed dynamic spectrum is shown in Figure 4

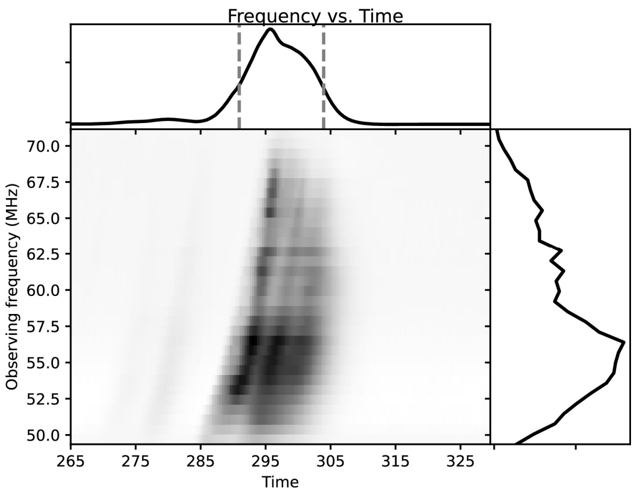

Figure 4. De-dispersed dynamic spectrum of the type III Solar radio burst observed with the GAPS on 10 August 2023. The time in the x-axis starts from 11:02:30 LST.

Table 2. Parameters of Pulsars detected using 1-bit raw voltage recoring with GAPS. The numbers in brackets are the parameters observed with the international LOFAR station FR606 at 60 MHz [10].

Pulsar	Period (s)	DM (pc/cm^3)	Duty Cycle (%)
B0834+06	1.274 (1.274)	12.873 (12.864)	6.4 (6.9)
B0919+06	0.432 (0.432)	27.330 (27.296)	14.4 (15.4)
B0950+08	0.253 (0.253)	2.965 (2.971)	15.2 (14.6)
B0943+10	1.098 (1.098)	15.348 (15.329)	12.9 (15.2)
B1133+16	1.188 (1.188)	4.848 (4.846)	12.7 (18.7)
B1919+21	1.337 (1.337)	12.420 (4.846)	7.8 (8.4)

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5. Summary

We successfully demonstrated 1-bit raw voltage recording with the Gauribidanur Pulsar System for the observation of Pulsars and transients at low radio frequencies. Raw voltage recording preserves the full instrumentation resolution and offers flexibility, allowing multiple simultaneous beams in different directions, different temporal and spectral resolutions, and different filtering algorithms to be used. Apart from a reduction in sensitivity, 1-bit quantization does not have any effect on the Pulsar parameters. 1-bit recording reduces the data volumes allowing archival of the observed data with minimal resources for reanalysis in the future. Absolute flux measurements can be difficult in 1-bit receivers, but in a wide-field multi-beam system where the primary requirement is to cover the maximum area of the sky with high temporal and spectral resolution, this type of receiver can be beneficial. For transient surveys where the direction of the source is not known a priori, such a software-based binary radio telescope is better suited.

6. Acknowledgements

We are grateful to the Gauribidanur Observatory team for their help in installation and maintenance of the facility. We express our gratitude to A. A. Deshpande for his encouragement and suggestions.

7. References

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