URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, October 22–25, 2024

Discoveries from GCGPS survey and its application for pulsar search with SPOTLIGHT

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Abstract

The SPOTLIGHT project is a commensal survey for the discovery and localization of hundreds of FRBs and pulsars using the uGMRT. The pulsar search happens in quasi-real time, where we are building an end-to-end GPU-based pipeline to process the pulsar data in one and a half days for all the data collected over five and a half days. It will be a multibeam pulsar search pipeline using 10% of the SPOTLIGHT field of view. The single-beam "GCGPS" (Globular Clusters GMRT Pulsar Survey) pulsar search pipeline is being replicated for SPOTLIGHT to support multi-beam searches. For GCGPS, we have built an end-to-end pipeline, establishing it as an extremely successful pulsar search survey conducted with uGMRT. This has led to the discovery of seven MSPs within a one-year timeframe. In this paper, we first discuss the GCGPS project, highlighting the potential for pulsar searches with the uGMRT. We then move on to the multi-beam SPOTLIGHT project, detailing the pulsar search pipeline and its current status.

1. Introduction

Pulsars are rapidly rotating neutron stars that emit beamed emission from their poles, and when the beamed emission crosses our line of sight, we see them as pulsed emission. The first pulsar was discovered by Hewish, Bell, et al. in 1968 [8], and since that discovery, ~ 3700 pulsars have been discovered [1]. The distribution of the pulsars in the period-period derivative plane shows a bimodal distribution. One mode is called millisecond pulsars (MSPs having a spin period of 1.4 ms to 30 ms), and the other mode is normal pulsars (spin period of 30 ms to tens of seconds). Multiple surveys have scanned the sky, both blindly and in a targeted manner, to efficiently search for pulsars. To detect more pulsars, we need both a wide-field blind survey and a deep-targeted survey with greater sensitivity and an efficient search pipeline.

Targets such as globular clusters, FERMI-LAT sources, and supernova remnants are always attractive for searching for new pulsars, requiring a manageable amount of telescope time. The Globular Clusters GMRT Pulsar Survey (**GCGPS** [2]) is one such targeted survey discussed below.
A blind survey to achieve a similar sensitivity limit to a targeted one requires a huge amount of telescope time. A commensal system can overcome this barrier by using a dedicated backend to perform pulsar searches simultaneously with other ongoing observations. Moreover, a commensal survey with multiple beams increases the instantaneous field of view, enhancing the discovery potential. **SPOTLIGHT** [3] is a multi-beam commensal survey instrument designed to find FRBs and pulsars with the GMRT.

2. Pulsar searches with the uGMRT

Benefited by the steep spectral nature of pulsars, the properties that make uGMRT unique are its sensitive low-frequency coverage (300 MHz–500 MHz for band-3 and 550 MHz–750 MHz for band-4) and simultaneous low-to-high baseline length coverage for probing different angular scales of the sky. For pulsar searches, we can strategically select the uGMRT array configuration to form beams according to the specific search requirements.

For the blind pulsar search to optimize the sky coverage and sensitivity to detect new pulsars, one can form an incoherent array (IA) beam. This IA beam will have larger sky coverage with reduced sensitivity compared to a beam formed by the phased addition of antenna voltages called the phased array (PA) beam. The very productive GMRT High-Resolution Southern Sky (GHRSS, Bhattacharyya et al. 2016 [4]) survey performed with an IA beam resulted in the discovery of 31 sources.
For targeted pulsar searches, two prominent surveys with uGMRT are the Fermi-directed survey (Bhattacharyya 2013 [5], 2021 [6], 2022 [7]) and the GCGPS, which resulted in the discovery of 8 and 7 MSPs, respectively.

Since the most recent and notable pulsar search survey conducted with uGMRT is GCGPS, which shares a common software development program with SPOTLIGHT, we describe this survey and its discoveries below.

3. The single-beam pulsar survey: GCGPS and its discoveries

In the GCGPS, we target the Milky Way Globular Clusters (GCs) to search for new pulsars in them. GCs are clusters of stars bound together by gravity and have a very high concentration of stars, making them the formation hub for MSPs. The typical angular size (half-light radius) for globular clusters, being a few arc minutes, can be covered with a PA beam. Using longer integration times allows for the search for generally fainter pulsars within them. Thus far, in a year of science operation with the GCGPS project, we have found 7 MSPs (Figure 1). This makes it one of the most effective surveys to search for MSP with uGMRT, with only 10 hours of uGMRT observation time per MSP discovery.

The pulsar search pipeline (GCPSS [9]) developed for the GCGPS efficiently searches for accelerated MSPs in compact binaries. This has led to the discovery of unique systems such as J1617-2258A in NGC6093, a compact binary with an orbital period of approximately 18.95 hours in a highly eccentric orbit (e ~ 0.534). The search in a compact GC like NGC6681 produces 3 MSPs. The highly compute-intensive CPU-based Fourier Domain Acceleration Search (FDAS) pipeline used in the GCGPS project illustrates the need to employ GPU-based search to achieve quasi-real-time implementation while also enhancing the number of simultaneous beams in the sky.

4. Overview of SPOTLIGHT multi-beam pulsar search project

From GCGPS, we now have a fully operational single-beam, end-to-end CPU-based pulsar search pipeline, whose effectiveness has been verified through exciting discoveries. This sets the gold standard for developing the GPU-based multi-beam quasi-real-time pulsar search pipeline for SPOTLIGHT. In single beam pulsar searches, there is a trade-off between sky coverage and sensitivity. Maximizing sensitivity typically involves reducing sky coverage by using a narrower beam (PA beam), as employed in the GCGPS survey. Conversely, maximizing sky coverage often requires compromising on sensitivity by using a wider primary beam (IA beam), as done in the GHRSS survey.

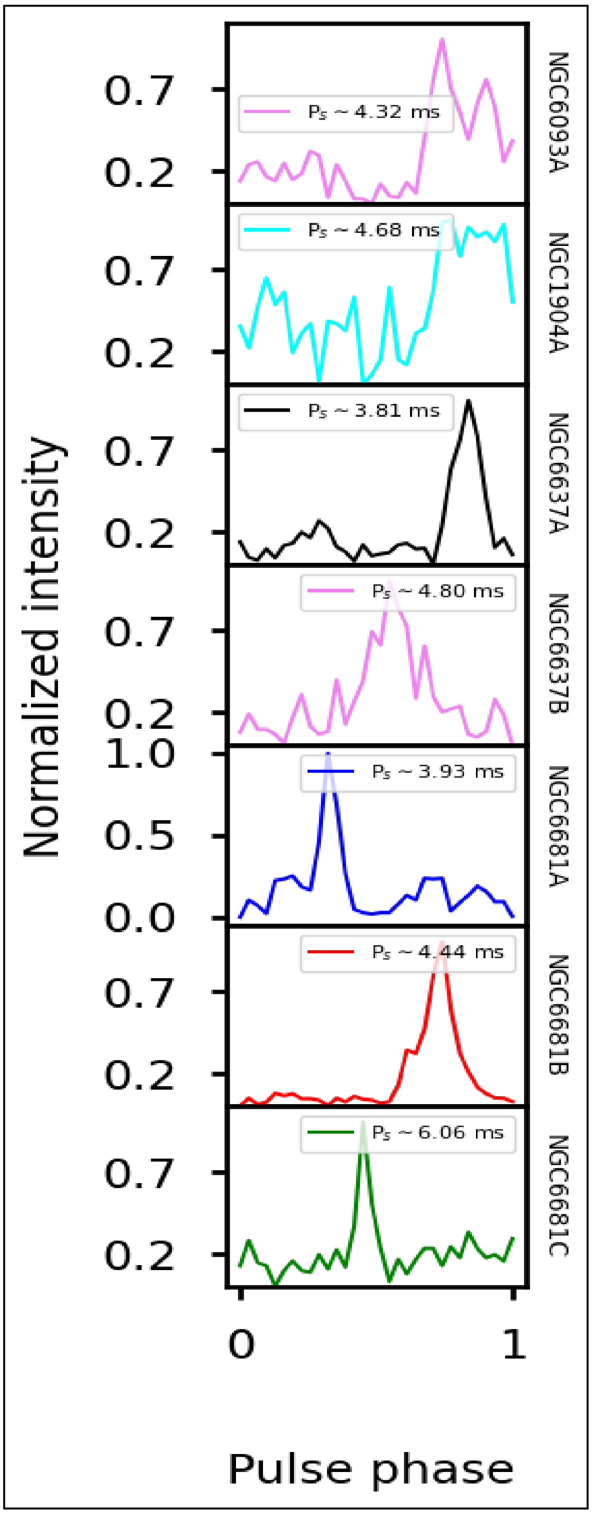

Figure 1: The pulse profiles of seven newly discovered MSPs from the GCGPS project.

This trade-off between sky coverage and sensitivity can be eliminated by using the multi-beam technique. This approach allows us to form an N number of PA beams distributed within the Half Power Band Width (HPBW) of the IA beam, optimized for a specific array.

SPOTLIGHT (**S**urvey for s**P**oradic radi**O** burs**T**s via a commensa**L**, mult**I**beam, **G**PU-powered **H**PC at the GMR**T**) is a commensal survey to search and localize FRBs in real-time and search for pulsars in quasi-real time. In this survey, we will be forming 2000 post-correlation beams (Roy, Chengalur, and Pen 2018 [13]) within 50% of the area of the IA beam to increase our sensitivity while maximizing the sky coverage. SPOTLIGHT funded by the National Supercomputing Mission (NSM), covers the frequency range from 300 MHz to 1460 MHz to search for FRBs and pulsars, piggybacking on ongoing GMRT observations. There will be 60 Rudra servers and 90 A100 GPUs with 2 PB of storage to facilitate the computing and storage requirements of the project. While the FRB search will be fully in real-time, the pulsar search will be performed in quasi-real time. The aim is to process five and a half days' worth of GMRT data during the one-and-a-half days of the weekly maintenance break by utilizing the full computing resources. The pulsar search will utilize 10% of the SPOTLIGHT field-of-view by recording data from 200 selected beams (filtered from 2000 beams) to meet storage and compute constraints.

5. SPOTLIGHT quasi-real-time pulsar search pipeline

The quasi-real-time pulsar search pipeline for SPOTLIGHT is a fully GPU-based pipeline. The pipeline will consist of the following two main components:

1. Beam filtration with PULSCAN

To optimally select the 200 beams from the 2000 beams for offline pulsar search, we need to rank them in real-time by evaluating the likelihood of detecting periodic accelerated or non-accelerated signals. The real-time ranking of the beams is achieved by a tool called PULSCAN [10] developed by White, Adamek, Roy et al. [11]. It uses a very fast, unmatched boxcar to quickly scan the FFT spectra for any periodic signal. This approach will enable us to quickly scan the beams while the data is still in the memory for any accelerated signals, rank them accordingly, and capture the approximate period (P) and period-derivative (P-dot) values for each periodic candidate. The CPU implementation of PULSCAN (with Zmax = 1200) is ~ 100 times faster than typical PRESTO FDAS (with Zmax = 200) (Zmax = maximum acceleration range to search for; higher the Zmax, higher the copuring cost), while it also results in enhanced sensitivity for massive compact binaries (as seen in Fig. 2), while the GPU version is expected to be 200 times faster than the CPU version, thus comfortably meeting the additional real-time compute requirement.

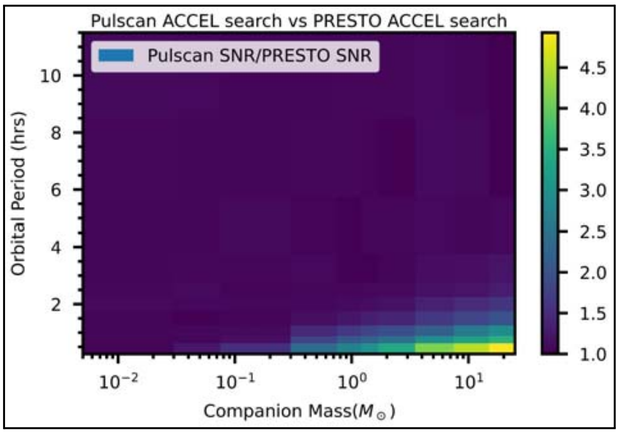

Figure 2: Performance of PULSCAN (Zmax = 1200) compared to PRESTO FDAS (Zmax = 200) for 100 simulated binary orbits ranging from mildly compact to very compact orbits. **The PULSCAN is demonstrating a 4-5 times sensitivity enhancement for massive compact orbits.**

2. 2D FDAS search at finer P-Pdot

After real-time filtration by PULSCAN, the top 200 beams are recorded on disk, along with a candidate list that includes each candidate's period (P) and period derivative (P-dot) values for each beam. Due to Pulscan's boxcar filtration, the period and period derivative values are not as accurate as full 2D FDAS. Having a priori information about the P and P-dot for each candidate for 200 beams, we will then do a localized FDAS around the P-Pdot value for precise measurement of P and P-dot. The GPU-based Astro-accelerate [12] pipeline is used for the FDAS. This code was recently upgraded with 2D harmonic summing, making it a complete pipeline to perform FDAS. We have rigorously tested the harmonic summing version, and it is working perfectly. Figure 3 illustrates the enhanced sensitivity of harmonic summing for a large number of synthesized binary systems. The Astro-accelerate FDAS code with 2D harmonic summing is ready to be integrated into the SPOTLIGHT main pipeline.
After this, all the candidates will go through a sorting code (i.e., GCGPS sorting code) to eliminate all the redundant and spurious candidates with appropriate filters. The folded profiles of all the sorted candidates will go

through a trained ML classifier, giving us real detections. This part of the pipeline is under development.

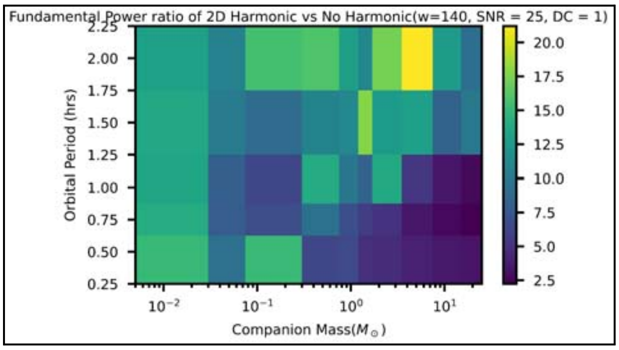

Figure 3: Performance of Astro-accelerate 2D harmonic summing compared to no harmonic summing for 50 simulated binary MSPs with different compactness.

8. Acknowledgements

The GMRT is an international telescope facility run by the National Centre for Radio Astrophysics (NCRA) of the Tata Institute of Fundamental Research (TIFR), India. For the GCGPS project, we thank GMRT operators for continuous support during the observing session, along with the NCRA Computer Section for providing enough computing power for analyzing the data for quick reporting of the discoveries. For SPOTLIGHT, we thank the National Supercomputing Mission (NSM) for funding the data centre. We also acknowledge the support of the Department of Atomic Energy, Government of India, under project no. 12-R&D-TFR-5.02-0700 for the contributions toward the overhead cost. We acknowledge the C-DAC team, GMRT backend, mechanical, and electrical teams for building the data centre jointly.

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