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A multi-beam backend for SPOTLIGHT, enabling fast transient surveys with the GMRT

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Abstract

SPOTLIGHT is a time-domain survey instrument to perform real-time 24/7 commensal search for Fast Radio Bursts (FRBs) and Pulsars with the GMRT [1]. It uses a state-of-the-art GPU-based compute cluster which is expected to generate 2000 post-correlation beams in real-time. We present here details of four main components of the SPOTLIGHT system – 1. the design and architecture of the correlator and post-correlation beamformer, 2. real-time beam synthesis ensuring precise beam shape and tiling of the field-of-view, providing on-the-fly localisation of the burst with up to arc-second accuracy, 3. online control and monitoring system to ensure piggy-back operation with the main backend, the GMRT Wideband Backend (GWB) [2], 4. real-time web-based monitoring tool that visualises the run-time status of the SPOTLIGHT system to track the proper run-time functionality of this fully automated system.

1. Introduction

SPOTLIGHT is a time-domain survey instrument designed to conduct real-time 24/7 commensal search for FRBs (Fast Radio Bursts) and Pulsars with a PetaFlop system hosting 60 C-DAC's indigenously developed Rudra servers equipped with 90 A100 GPUs connected to a 2 PB storage over a 100 Gbps Infiniband network. The system runs real-time HPC and AI applications to ensure simultaneous time-domain detection and arc-second imaging localisation of the detected bursts across the GMRT observing band ranging from 300 to 1460 MHz. The project is funded under the National Supercomputing Mission (NSM) of the Government of India.

The 60 Rudra servers are arranged in three sub-clusters implementing the correlator-beamformer, transient, pulsar search and imaging analysis. The first cluster, comprising 16 servers, handles correlation and beamforming, and will generate 2,000 beams at 1.3-millisecond time resolution. These beams are then transmitted to the second cluster, consisting of 24 servers, for the multi-beam transient detection pipeline followed by Machine Learning (ML) or Deep Learning (DL) classifiers. The 2000 beams are optimally located within the half-power beamwidth of the primary beam of a GMRT antenna. Imaging localisation on the detected FRBs and candidate confirmation is done on the 20 servers of the third cluster. One of the significant challenges in FRB research is their localisation. Traditional single-dish radio telescopes, while capable of detecting FRBs, often lack the resolution to pinpoint their exact origins. While the radio interferometric array provides higher spatial resolution, tiling the field-of-view (FoV) with multiple beams is necessary for devising an efficient time-domain survey. The dynamic tiling of the FoV maximizes the effective FoV while maintaining uniform fluence limit across all the 2000 beams.

GMRT has a dedicated central control and monitoring system that sends appropriate instructions to the general purpose GMRT Wideband Backend (GWB, [2]) to compute and record real-time visibility for imaging of field and beam-formed data for time-domain astronomy. SPOTLIGHT operates in piggy-back mode alongside the GWB, ensuring full GMRT functionality while enabling commensal operation. We have developed a fully automated system to control and monitor SPOTLIGHT alongside the existing GWB operation. To monitor the live status and functionality of the system, we have developed a web-based tool that also maintains a detection repository and the SPOTLIGHT discovery database for generating transient alerts via the Virtual Observatory Event (VOEvent) Service.

2. Correlator and Beamformer

The first stage of the system is equipped to accept Nyquist sampled baseband signals of both polarisations from all antennas of GMRT at the rate of 25 GB/s over 32 ten gigabit fibre links to perform correlation and beamforming [Figure 1]. Data ingestion to the SPOTLIGHT system is done via UDP packet broadcasting from the GMRT samplers, ensuring piggy-back operation with the GWB. The received digitized data on each server over two ten gigabit fibre links is buffered, time-sliced and shared between the servers on a 100 Gbps network such that each server gets a slice of contiguous time series digitized data of all antennas, on which it performs operations like FFT, Multiplication and Accumulation (MAC) and beamformation using dual A100 GPUs. MAC is designed to provide visibilities at 1.3 ms time resolution. The post-correlation beams [3] are formed using the phased addition of the 1.3 ms time resolution visibilities. The post-correlation beams reduce the effects of radio frequency interferences (RFIs) and systematics in the data by eliminating the auto-correlation products [Figure 2]. Cleaning the dynamic spectrum and, more importantly, the dispersion measure-time image significantly increases the efficiency of the AI classifier. The beam-steering implemented at the post-correlation stage significantly minimizes computational costs. The 2000 beams thus formed are distributed across the servers of the second stage such that each server receives data of ~84 beams. The beam data received is buffered in a shared memory which is accessed by the multi-beam transient detection pipeline for pulsar and FRB searches [4].

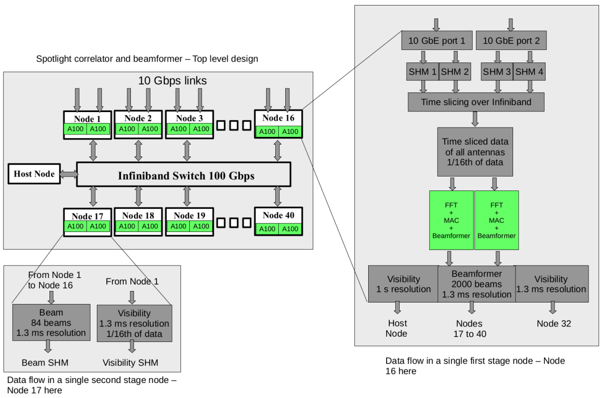

Figure 1. SPOTLIGHT correlator and beamformer design and data flow

The 1.3 ms time resolution visibilities formed in the first stage are integrated up to 1 second or higher and sent to a dedicated host node for archiving. This visibility data at this reduced time-resolution is used for real-time phase and amplitude calibration of the data and also for detecting non-working antennas. In the first stage, in parallel to performing correlation and beamforming, the digitized Nyquist data is written to a transient buffer capable of holding 400 seconds of data. Candidate events detected by the AI pipeline trigger the flushing of the corresponding section of data (i.e. for a time interval covering the dispersion sweep) to a 2 PB storage via a 100 Gbps link. The availability of the full Nyquist samples from the full array opens up the possibility of probing the underlying emission physics aided with full polarisation information and the propagation effects at an unprecedented sensitivity [5,6]. In addition to this baseband buffering, the 1.3 ms time resolution visibilities are also buffered in another shared memory. Visibility data for candidate events are also written to the 2PB storage based on the AI trigger. This facilitates real-time imaging localisation of the FRB at arc-second resolution [7], enabling host galaxy association, which is essential for cosmological studies [8,9]. The sizes of shared memory for the beam data (~2.4 TB) and 1.3 millisecond resolution visibilities (~5 TB) in the second stage and the baseband shared memory (~4.8 TB at 4 bits per sample) in the first stage are large enough to hold the data in Random Access Memory to accommodate detection of bursts even at high dispersion measure.

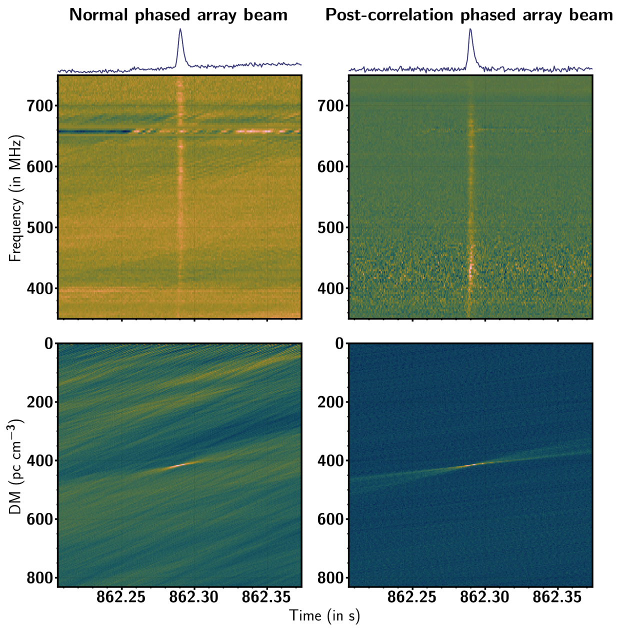

Figure 2. A comparison of phased array (PA) beam (left panel) and post-correlation (PC) beam (right panel) data from FRB 201124A in GMRT's Band 4 (550 to 950 MHz).

The SPOTLIGHT system is being realized in a phased manner. The entire hardware installation was complete by October 2024, following which the software pipelines are being tested with increasing number of beams progressively. The real-time system currently being tested at the GMRT can generate 800 beams, along with all promised data products, using 32 A100 GPUs, achieving 40% of the final specification.

3. Beam Simulation and Tiling

The correlator and beamformer module of the SPOTLIGHT system needs to form 2000 post-correlation beams covering the FoV. However, because the effective baseline lengths change over time, leading to variations in

beam shapes, a strategy for continuous beam shape synthesis must be developed to ensure optimal FoV coverage. The current system calculates the beam for each observing scan (typically a few tens of minutes or shorter at the GMRT) using the provided array configuration, hour angle, center frequency etc. This package supports two distinct modes of SPOTLIGHT:
1. Survey mode - This mode covers a contiguous area, with the hexagonally packed beams overlapping at a user-specified threshold level.
2. Targeted mode - This mode focuses on smaller fields of view or specific sets of targets, such as pulsars in globular clusters. In this mode, we optimize the beam overlap ratios to enhance sensitivity with a full GMRT array. Observations of multiple separated targets within a single GMRT antenna field of view are supported.

The basic functionality of the beam shape modelling technique is validated through the 800 beam SPOTLIGHT system. We compared the signal-to-noise ratio (SNR) map generated from the simulation results with the one from observations of pulsars [see Figure 3]. We conducted a detailed analysis of beam tiling, considering various antenna configurations, source directions (both on-axis and off-axis), and observing frequencies.

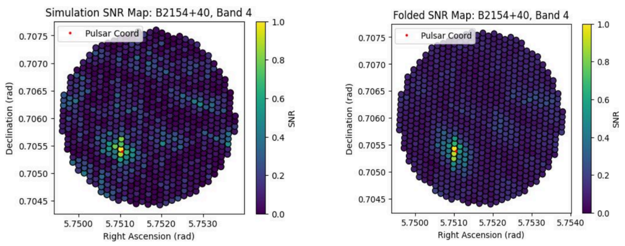

Figure 3. Plot showing source off-axis beam tiling SNR map. Simulation SNR map (Left side) and actual folded SNR map (Right side). Source is off from phase centre by 2 arcmin in both RA and DEC (El = 27 deg)

The beam tiling strategies that we developed have important scientific implications. When operating in survey mode, we can maintain high sensitivity across the entire FoV, which enhances SPOTLIGHT's discovery potential. It also allows for the immediate localisation of a burst with accuracy ranging from arcminute to sub-arcminute accuracy, which is further improved to a few arcseconds from the imaging data. While localisations up to an accuracy of a few arcseconds are important for associating FRBs with their respective host galaxies, accuracies of up to a few arcminutes can allow other telescopes to follow up these sources, even without the more precise localization data.

4. Control and monitoring system

The Tango-based GMRT Control (TGC, [10]) is the main control and monitoring system central to all GMRT operations. It supplies metadata information (such as frequency of observation, source coordinates, antenna configuration, etc.) for the real-time processing of astronomical signals in the GWB. The SPOTLIGHT master node accesses this information from the GWB master node through a socket and performs necessary actions for the SPOTLIGHT correlator. This includes starting and executing all operation stages in a coordinated manner with the GWB.

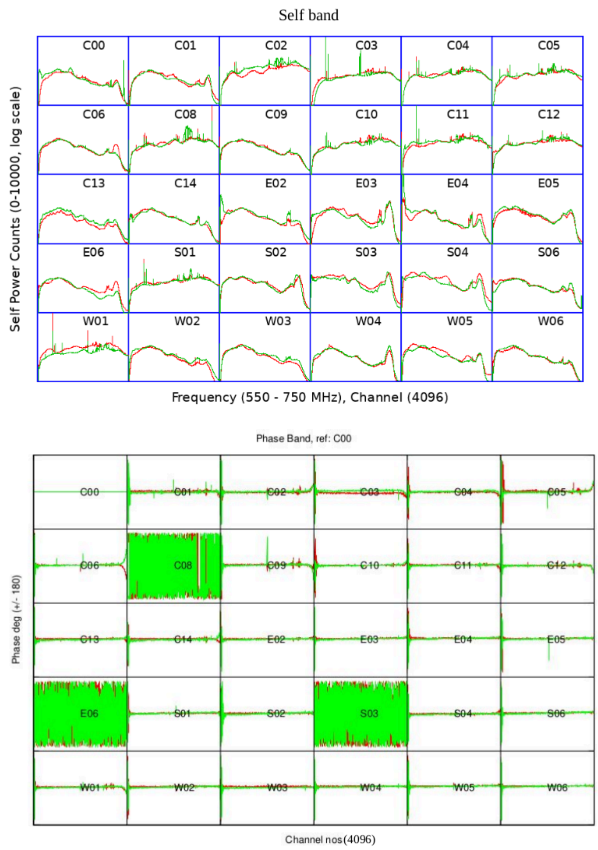

Figure 4. Sample plots on SPOTLIGHT web interface showing self spectrum (top plot) of all antennas of GMRT and cross phase spectrum (bottom plot) for all baselines with respect to one antenna (C00) after phasing operation.

The operation of the SPOTLIGHT correlator and beamformer requires periodic phasing of the array each time the antennas are pointed at a phase calibrator. This phasing ensures the robust calibration necessary for real-time imaging for FRB localization [7]. The source and calibration code information (such as band-pass and phase calibrator) provided to TGC is transferred along with metadata from TGC to SPOTLIGHT via the GWB master node. Upon receiving the source calibration code, the SPOTLIGHT controller conducts the phasing of the array during a phase calibrator scan. The metadata information (phase center coordinates, frequency, array configuration, etc.) and the list of bad antennas identified through phasing (as shown in Figure 4) is then sent through the SPOTLIGHT correlator and beamformer and parsed into the beam tiling simulation package, which synthesizes 2000 steered directions (RA and Dec) for FRB search. In addition to the high-time resolution visibility and time-domain data, the SPOTLIGHT correlator produces intermediate-resolution (~1 second) visibility data for real-time monitoring of visibility fringes and auto-correlation spectrums. We have developed software to retrieve real-time self and cross-visibilities from shared memory on the control master node of SPOTLIGHT for web-based monitoring. This ensures the seamless integration of the SPOTLIGHT system into the observatory's control and monitoring system, facilitating fully automated commensal observations.

5. Web-based monitoring tools

The output results from the multi-beam SPOTLIGHT detection systems, are stored on disk along with the data products from the correlator and beamformer. The web-based real-time monitoring tools include the display of the antenna's current position (Azimuth-Elevation), self spectrum and phase spectrum (as shown in Figure 4). This tool helps track the target field and ensure the proper functionality of the correlator and beamformer during the ongoing observation. To enable a fully automated observing strategy with quick fault detection, the run-time status of each functional module for a given observing session is displayed on this web interface. The real-time monitoring tool also displays the results from the transient detection system with plots of the genuine classified candidates [Figure 5] along with the respective parameters (metadata) like dispersion measure (DM), SNR, target position, observing frequency, etc. The output from the real-time imager, which localizes genuine events, is also linked here.

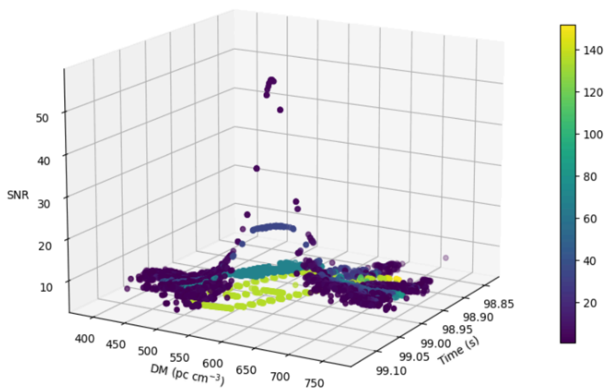

Figure 5. Sample plot showing Multi-dimensional transient detection

6. Acknowledgements

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References

[1] J. Roy, J.N. Chengalur, and the SPOTLIGHT team, "SPOTLIGHT: A Probe of the Fast Radio Transient Sky", URSI-RCRS 2024

[2] Reddy et. al, J. Astron. Instrum. 06, 1641011 (2017) "A Wideband digital back-end for the upgraded GMRT".

[3] Jayanta Roy et. al, The Astrophysical Journal, Volume 864, Number 2, 2018 "A Post-correlation Beamformer for Time-domain Studies of Pulsars and Transients".

[4] U. Panda, K. Ajudiya and the SPOTLIGHT team, "A multi-beam FRB detection pipeline with real-time injection for the SPOTLIGHT", URSI-RCRS 2024

[5] Nimmo, K., Hessels, J.W.T., Keimpema, A. et al. Highly polarized microstructure from the repeating FRB 20180916B. Nat Astron 5, 594–603 (2021). https://doi.org/10.1038/s41550-021-01321-3

[6] C. Dudeja, S. Bhattacharyya and the SPOTLIGHT team, "Spectro-Temporal-Polarimetric Study of FRBs with the SPOTLIGHT", URSI-RCRS 2024

[7] A. Pal, S. Kudale and the SPOTLIGHT team, "A real-time imaging localisation pipeline for the SPOTLIGHT", URSI-RCRS 2024

[8] Macquart, JP., Prochaska, J.X., McQuinn, M. et al. A census of baryons in the Universe from localized fast radio bursts. Nature 581, 391–395 (2020). https://doi.org/10.1038/s41586-020-2300-2

[9] S. Bhattacharyya, S. Sarkar and the SPOTLIGHT team, "An FRB Population Synthesis for SPOTLIGHT and Its Cosmological Inference", URSI-RCRS 2024

[10] J. Kodilkar et al., "Tango-based GMRT Control", https://ieeexplore.ieee.org/document/8738570