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SPOTLIGHT: A Transformative Exploration of the Fast Radio Transient Sky with the GMRT

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Abstract

SPOTLIGHT is a commensal survey for FRBs, pulsars, and other objects via the GMRT, powered by a dedicated, petaFLOPS-capable computational backend. The SPOTLIGHT system has the capability to search for, detect, and localise transient time-domain events in real-time, using transient search and imaging pipelines optimised for high performance computing (HPC). Using the unparalleled senstivity and frequency coverage of the uGMRT, the SPOTLIGHT system will enable the detection and localisation of hundreds of FRBs over its operation, building a large dataset that will enable their use as cosmological probes. The system's AI-optimised triggers will allow capturing high-resolution voltage samples across the duration of the detected events, which will be used for a thorough spectro-temporal-polarimetric analysis. Such analyses will help probe the emission mechanisms and progenitors of these sources. With the successful execution of the SPOTLIGHT project, we expect that the GMRT will enable transformational, high impact science in the field of time-domain astronomy, while also enabling cutting edge technological developments across various fronts.

1 Introduction

Fast radio bursts (FRBs) are transient sources in the radio sky, spanning timescales from a few microseconds to a few milliseconds with an energy range of 10^{27} erg/s to 10^{42} erg/s. Their emission is coherent, wideband, and often highly polarised (e.g.: [1], [2]). Their high dispersion measures (DMs; defined as the integrated column density along the line-of-sight) indicated that these were extragalactic sources, and this was confirmed through their localisation, and subsequent association with their respective host galaxies (e.g.: [3], [4]). Since their serendipitous discovery in 2007 [5], a total of 838 FRBs have been detected, as per the Transient Name Server. 93% of these are one-off events, while only 7% are known to repeat; these are known as *repeaters*. The first such repeater was detected in 2012 through Arecibo observations at 1.4 GHz [6].

Due to their short timescales, it is well established that the emission region of FRBs is compact. This has naturally led to the suggestion of compact astrophysical objects, such as neutron stars, as possible progenitors. In recent years, particular attention has been given to magnetars, a subset of neutron stars, in no large part due to the detection of the first galactic FRB, and its association with magnetar SGR 1935+2154 [7]. Further investigation into the origin of these events requires a large sample localised, and associated with their respective host galaxies. Given the large areal density of galaxies on the sky at the large distances that are typical of FRBs [8], one cannot associate an FRB with a host galaxy successfully unless one has a localisation precision of a few arcseconds or better. However, telescopes leading the discovery of these sources have low localisation accuracy and wide FoVs; for instance, the CHIME telescope has an FoV of $120^\circ \times 2^\circ$, but its localisation accuracy is only a few arcminutes [9]. On the other hand, interferometers are good at localising sources up to a few arcseconds, but have very narrow FoVs, which leads to poor survey speed. Thus, the idea of commensal surveys has gained traction in recent years, wherein one can search for FRBs and other sources any time the telescope is operational, via a dedicated parallel backend that carries out searches in real-time. Examples of such surveys are CRAFT at the ASKAP, MeerTRAP at the MeerKAT, and realfast at the VLA. In order to further increase their survey speeds, many of these telescopes have come up with ways to increase their FoV, either via hardware (for example, by using phased array feeds at the ASKAP [10]), or via software (for example, by using tiled beams at the MeerKAT [11]).

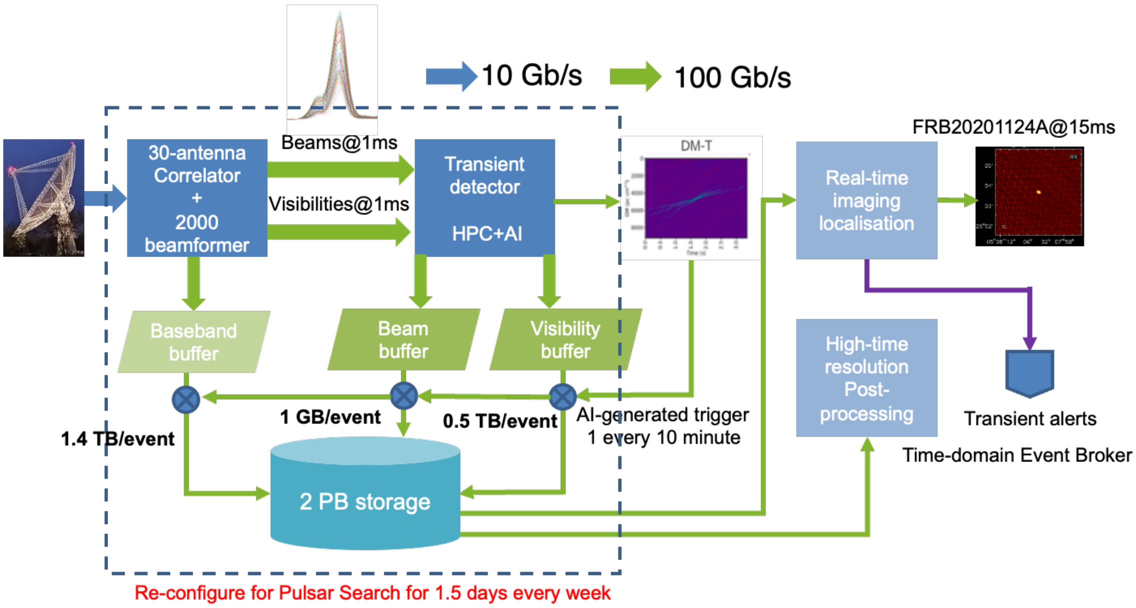

Figure 1. Flowchart of the entire SPOTLIGHT system. It consists of 3 clusters. The second cluster houses the transient detection system discussed in this paper. Upon detection, triggers are generated, which result in the dumping of beamformed data, baseband data, and visibilities to the 2 PB storage.

2 The SPOTLIGHT Project

The SPOTLIGHT project [12][1], is a commensal survey for FRBs, pulsars, and other fast transient sources using the upgraded Giant Metrewave Radio Telescope (uGMRT). Both construction and operation are funded by the National Supercomputing Mission (NSM), under the Ministry of Electronics and Information Technology (MeitY), and the Department of Science and Technology (DST) of the Government of India. Powered by a dedicated, petaFLOP-capable backend consisting of 60 indigenously developed Rudra servers and 90 top-of-the-line NVIDIA A100 GPUs, the SPOTLIGHT system operates at a computational load that is 20$\times$ that of the existing uGMRT backend [13], and requires 80 kW of IT power and 40 kW power for cooling. The hardware has been placed inside a shielded room at the GMRT, which provides $\sim$100 dB isolation over a frequency range of 14 kHz to 10 GHz. Work on integrating the system with the present control and monitoring system of the uGMRT is ongoing [14], and is expected to be operational by April 2025, providing seamless commensal operation.

The SPOTLIGHT system is capable of forming 2000 beams (each with 4096 spectral channels at 1.3 milliseconds) in real-time [15], ingesting data at a rate of 25 GB/s. This leads to a FoV of 1 deg^2 at 300 MHz, thanks to our optimal beam-tiling strategy [16]. Each beam is a post-correlation phased array beam [17], which leads to higher sensitivity, and a higher immunity to radio frequency interference (RFI), and systemic effects. With the unparalleled sensitivity and frequency coverage of the uGMRT across the entire 300 to 1460 MHz range, we expect to detect $\sim$300 FRBs in 3 years of operation, up to a projected redshift of $\sim$3 [18]. The system comes with a real-time transient search pipeline [19], as well as a quasi real-time pulsar search pipeline [20]. The former is capable of searching for events up to a DM of 2000 pc cm^{-3}, and up to a width of 500 milliseconds, across the entire frequency range, and all 2000 beams. The latter performs a Fourier domain acceleration search [21] of the data recorded over 200 beams (i.e. 10% of SPOTLIGHT's FoV) for 5 days of operation in just 1.5 days, when the GMRT is under weekly maintenance. Both pipelines are being developed in collaboration with the Oxford e-Research Centre (OeRC) at the University of Oxford. A Deep Learning (DL) based Artificial Intelligence (AI) system optimises triggers from the transient search pipeline to capture Nyquist-sampled baseband data for each event, along with high-time-resolution (at 1.3 milliseconds) visibilities for real-time imaging and localisation [22]. Fig. 1 illustrates the functional modules of the SPOTLIGHT fast transient detection and localisation system, along with the corresponding data rates based on the expected AI-assisted trigger rate. To enable fully automated operation, a web-based real-time monitoring and discovery database is being developed to generate prompt alerts for source detections in SPOTLIGHT via the Virtual Observatory Event (VOEvent) service [23].

2.1 Science Goals

The SPOTLIGHT system is capable of localising FRBs in real-time to arcsecond or sub-arcsecond precision. An example where we successfully incoherently dedispersed and imaged a single pulse from the known pulsar B0329+54 using 1.3 ms visibilities, after detecting it through a time-domain search can be seen in Fig. 2. Thus, SPOTLIGHT's

[1]https://spotlight.ncra.tifr.res.in

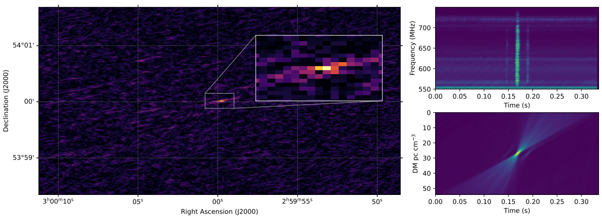

Figure 2. On the left, the localisation plot for a single pulse detected from pulsar B0329+54 using the SPOTLIGHT system, whose dedispersed dynamic spectrum can be seen in the top right plot, and whose dispersion measure (DM) transform can be seen in the bottom right plot.

real-time detection and localisation capabilities will help build a sizeable dataset of localised FRBs, which can prove to be quite promising as a late-time cosmological probe. Such a dataset would be capable of constraining numerous cosmological parameters, such as the baryon density [24], [25], the Hubble constant, or the dark energy equation-of-state. For each detected event, the SPOTLIGHT system will dump beamformed data with a time resolution of 1.3 ms, and Nyquist-sampled baseband data. The former will be used for preliminary parameter estimation, using an automated burst-fitting pipeline called `burfi`. The latter will be used for detailed coherently dedispersed spectro-temporal and polarimetric analysis of each of the detected events, which can help us narrow down plausible emission mechanisms. A data analysis toolkit, `scarab`[2], has been developed for this purpose. A recent demonstration of its capabilities is presented in [26]. Lastly, imaging the field of the bursts with low-resolution ($\sim$ 1 second) SPOTLIGHT visibilities can lead to the detection and association of persistent radio sources (PRS) with FRBs. The detection of a PRS can indicate an extreme magneto-ionic medium at the vicinity of the FRB, and provide clues regarding its possible progenitors [27].

The SPOTLIGHT system will also search for pulsars through its quasi real-time pulse search, and help probe the populations of double neutron stars, normal pulsars exhibiting phenomena such as mode-changing, sub-pulse drifting, and nulling, as well as long-period pulsars grazing or crossing the death line.

2.2 Global Perspectives

Recent years have seen the development of an increasing number of dedicated instruments and backends for the detection, localisation, and study of time-domain astrophysical events, such as CRAFT @ ASKAP, MeerKAT @ MeerTRAP, realfast @ VLA, EuroFlash @ LOFAR, DSA-110, BURSTT, CRACO, CASATTA, CHORD etc. The shift towards commensal surveys using interferometers has also started to pay off, with a drastic increase in the number of localised FRBs from just 13 in 2020 to 93 in 2025. The next generation of facilities, such as the ngVLA and the SKA, have also started construction, and will be starting science observations in the coming decades, producing unprecedented volumes of data. Thus, SKA pathfinders, such as ASKAP, MeerKAT, and the GMRT, play a crucial role in leading the development of hardware and software that can deal with these high data volumes, and prepare astronomers for the SKA era. The SPOTLIGHT project is a leap in this very direction. In order to leverage the performance capabilities, coupled with the large data rates, of the SPOTLIGHT system, our team is developing highly optimised software pipelines for time-domain searches, radio imaging, and data analysis. This includes the development of new algorithms and techniques, as well as the optimisation of existing algorithms. These include machine learning (ML), deep learning (DL), and artificial intelligence (AI) models as well, which play important roles in our transient and pulsar search pipelines.

With the detection of bursts at microsecond scales [28], [29], as well as the detection of long period transients [30], [31], we are seeing the transient parameter space being pushed in all directions. With its state-of-the-art sensitivity, as well as its ability to produce spectrotemporal polarimetric data at high resolutions, the SPOTLIGHT system will help expand the parameter space even further. It will also help populate the parameter space more uniformly, by providing a large dataset of objects and events across a wide range of energies, frequencies, and timescales. In summary, the SPOTLIGHT project, with its complementary frequency coverage, will not only serve as a platform for developing new time-domain algorithms, techniques, and software but will also expand the transient parameter space while providing a valuable astronomical dataset to the international community.

3 Current Status

The SPOTLIGHT system is currently going through the commissioning phase, and will start operating commensally from April 2025, with a limited capacity of 160 beams. In addition, the SPOTLIGHT system offers 100 hours of open-sky time from April 2025, which can be used for targeted observations. Based on population synthesis analyses using `frbpoppy` [32] and `PsrPopPy2` [33], we estimate that the commensal SPOTLIGHT system will detect approximately 18 FRBs and 50 pulsars during the next six months of its science operations.

4 Acknowledgements

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[2] https://github.com/astrogewgaw/scarab

Institute of Fundamental Research, India. The data centre was jointly built by team members from C-DAC and the GMRT. We thank the GMRT telescope operators for supporting the observations during the software prototyping and commissioning phases.

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