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Spectro-Temporal-Polarimetric Study of FRBs with SPOTLIGHT

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Abstract

The SPOTLIGHT project, a commensal survey for FRBs and pulsars at the GMRT, utilises high-performance computing and AI for simultaneous time-domain detection and arc-second image-domain localisation of FRBs across 300 to 1460 MHz. Studying the high-resolution spectro-temporal-polarimetric properties of these bursts will help differentiate between proposed emission mechanisms and progenitor models. To support this, we are developing *BurFi*, an automated pipeline for processing SPOTLIGHT's beamformed and baseband data. *BurFi* will efficiently estimate key parameters such as burst widths, peak emission frequencies, emission bandwidths, frequency drift rates, scattering timescales, and polarisation properties, offering both rapid online parameter estimation and detailed offline analysis of high-resolution data.

1. Introduction

Fast Radio Bursts (FRBs) are millisecond-duration radio signals originating from extragalactic sources [1, 2, 3], presenting both significant challenges and opportunities for astrophysical research. They are classified into two types: repeaters and one-off events, whose distinction as either distinct classes or variations of a single class remains unanswered. The polarisation study at high resolution (spectro-temporal-polarimetric characteristics) of FRBs provide useful insights into the progenitor models, possible emission mechanisms, and the local environment at the vicinity of the sources [4, 5]. Precise arc-second localisation using radio interferometers not only allows the identification of host galaxies and their redshifts but also enables FRBs to serve as cosmological probes. This capability provides critical insights into phenomena such as dark matter, the distribution of missing baryons, etc. [6]. In recent years, significant progress has been made in FRB observation, with the detection of numerous new events up to 787 recorded, including 54 repeaters, and the localization of 45 FRBs to external galaxies (from the Transient Name Server) [7]. Furthermore, commensal surveys with localisation capabilities, such as VLA's realfast [8], ASKAP's CRAFT [9], and MeerKAT's MeerTRAP [10] are increasingly recognized for their importance in uncovering a broader FRB population. The emergence of theoretical frameworks has enriched our understanding, encompassing phenomena such as the magnetosphere of young magnetars, collapsing neutron stars, binary systems, supernova explosions, relativistic shocks, and others [11, 12, 13, 14]. Despite this progress, fundamental questions about FRBs remain unanswered, including their classification, progenitor systems, emission mechanisms, and propagation properties. To address these fundamental questions, our study utilises the advanced capabilities of SPOTLIGHT [15] to perform an extensive spectro-temporal-polarimetric analysis of FRBs.

2. SPOTLIGHT & its data products

The SPOTLIGHT project, facilitated by cutting-edge developments in High Performance Computing (HPC) and Artificial Intelligence (AI), provides a way to efficiently use the sensitivity and resolution of the uGMRT at low frequencies to explore and understand the FRB population [15]. The project generates three types of data products: time-domain beamformed data, baseband data, and visibilities. The real-time detection pipeline utilises beamformed data to identify short-duration dispersed signals [16], while visibility data enables precise arc-second localisation of the detected events [17]. The successful detection and localisation of genuine astrophysical events trigger the dumping of Nyquist sampled baseband data, which is then analysed offline.

3. The ***BurFi*** pipeline for FRB analysis

For each event it detects, the SPOTLIGHT system will dump both beamformed data (with a resolution of ~1.3 ms), and Nyquist sampled baseband data (at a resolution of a few nanoseconds). In order to analyse these data products, we are developing an automated data processing pipeline called ***BurFi*** (**Bur**st **Fi**tting). *BurFi* will enable rapid estimation of preliminary burst parameters via its analysis of beamformed data, and also allows us to conduct a thorough spectro-temporal-polarimetric study of the detected bursts, using high resolution baseband data. The flowchart in Figure 1 illustrates the steps involved in both variants of the *BurFi* pipeline.

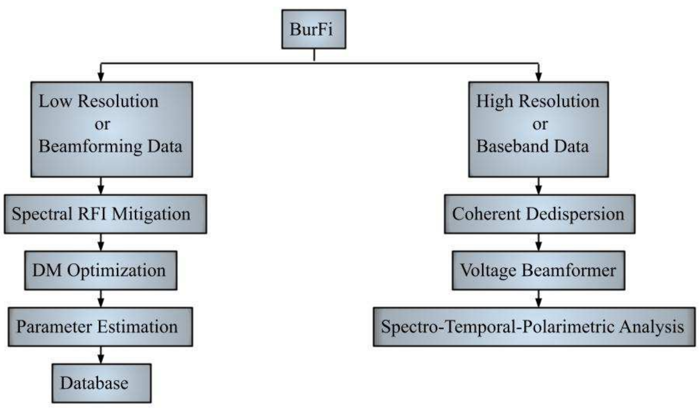

Figure 1. This flowchart outlines the *BurFi* pipeline for analysing features in beamforming and baseband data at both low and high resolutions respectively.

3.1 ***BurFi*** at low-time resolution (online processing)

Immediately after the detection of a real event, *BurFi* will promptly estimate its morphological and spectral characteristics.

At low-resolution, *BurFi* optimises the dispersion measure (DM) to improve parameter estimation and facilitate preliminary redshift determination for FRBs by correcting for the expected dispersion effects caused by intergalactic medium (IGM), interstellar medium (ISM) and Milky Way (MW). Parameter estimation in *BurFi* involves extracting key features like burst morphology, spectral characteristics (such as peak emission frequency and emission bandwidth), drift rate and scattering properties. Drift rate analysis with *BurFi* at low-resolution examines the frequency evolution of bursts, revealing information about the dynamics of the emitting region. This analysis helps discriminate between intrinsic spectral features and effects induced by propagation through turbulent media. Together, these low-resolution analyses conducted by *BurFi* provide a comprehensive view of FRB characteristics and, more importantly, aid in designing follow-up strategies by identifying any repeater-like characteristics.

To study high time resolution data, we will transition to offline processing using baseband data. This approach allows for a more detailed examination of the micro-structures and polarimetric properties of the bursts.

3.2. ***BurFi*** at high-time resolution (offline processing)

The phased array beam, directed towards the FRB location using the full sensitivity of GMRT generated from the baseband data, enables coherent de-dispersed spectro-temporal-polarimetric study of burst emission. This approach allows us to distinguish propagation effects from intrinsic emission features. The high time resolution data from offline processing can reveal micro-structures within an apparent single burst structure [5]. By studying these micro-structures, we can investigate potential quasi-periodicities between bursts [18]. Moreover, higher time resolutions have shown an increase in linear polarisation fraction, indicating its correlation with temporal resolution [5]. These features collectively provide fundamental insights into the emission mechanisms and local environment of FRB sources.

4. SPOTLIGHT on FRB Repeatability & Multi-Wavelength Studies

With SPOTLIGHT, we will be able to determine whether a detected event will exhibit repeating behaviour or be a one-off occurrence based on database information. If the event shows repeating behaviour, this will allow us to re-observe the same event to gain more insights into the source and its properties. SPOTLIGHT can also identify periodicity in FRBs, a phenomenon observed in only a limited number of cases to date, by analysing the recurrence patterns of detected bursts. Additionally, SPOTLIGHT's design allows for efficient follow-up observations with other telescopes, enhancing our ability to conduct multi-wavelength studies of FRBs. This capability not only deepens our understanding of FRB sources but also helps refine our models of their emission mechanisms and propagation properties.

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7. References

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