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Optimal tiling of SPOTLIGHT field-of-view with multi-beam synthesis

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Abstract

Fast Radio Bursts (FRBs) are highly energetic transient signals lasting only a few milliseconds. Their origins are not fully understood, making them a forefront of astronomical research. SPOTLIGHT is a real-time multi-beam commensal project that will run parallel to regular GMRT observations and will search for FRBs and pulsars within the full-width-half-maximum (FWHM) of the field-of-view (FoV). It uses a state-of-the-art parallel multi-node computer cluster for real-time processing, including forming visibilities, generating 2000 of post-correlation high-time resolution beams. The dynamic tiling of the FoV maximises the effective FoV while maintaining uniform fluence limit across all the 2000 beams. This real-time beam synthesis code ensures the precise shape and location of the phased array beams, providing on-the-fly localisation of the burst with up to arc-minute accuracy.

1. Introduction

Fast Radio Bursts (FRBs) are millisecond duration highly energetic dispersed radio pulses originating from extragalactic sources [1, 2]. Since their discovery in 2007 [3], FRBs have intrigued astronomers due to their mysterious origins and extreme energy levels. Despite their transient nature, the high luminosity of FRBs makes them detectable across vast distances. However, the precise mechanisms behind these bursts and their exact origins remain one of the major puzzles in modern astronomy.

Several hypotheses have been proposed regarding the progenitors of FRBs, including neutron stars, black holes, and exotic astrophysical phenomena [4, 5, 6, 7]. The study of FRBs not only has the potential to uncover new astrophysical events but also provides unique opportunities to probe the intergalactic medium (IGM), which can offer insights into the distribution of matter in the universe, including the elusive dark matter.

One of the significant challenges in FRB research is their localisation. Accurate localisation is crucial for identifying host galaxies and understanding the environments in which these bursts occur. 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.

2. The SPOTLIGHT Project

The SPOTLIGHT [8] project leverages the capabilities of the Giant Metrewave Radio Telescope (GMRT) to address the challenges in detecting and localising FRBs. GMRT, with its array of thirty fully steerable parabolic radio telescopes, enables high-sensitivity observations across a wide range of frequencies (300 - 1460 MHz). By running parallel to regular GMRT observations, SPOTLIGHT aims to conduct real-time searches for FRBs and pulsars within the full-width-half-maximum (FWHM) of the FoV of the primary beam.

SPOTLIGHT employs a state-of-the-art parallel multi-node computer cluster for real-time processing [9]. This advanced computational infrastructure is crucial for handling the vast amounts of data generated during observations, forming visibilities, and generating post-correlation beam-formed high-time resolution data. The project also uses machine learning techniques to classify events of interest and effectively mitigate radio frequency interference (RFI).

3. Phased Array Beam Strategies

The correlator and beamformer module [9] of the SPOTLIGHT system forms 2000 post–correlation beams [12] covering the FoV. However, due to the temporal evolution of the effective baseline lengths causing variation in beam shapes, a strategy for continuous beam shape synthesis needs to be devised to ensure optimal FoV coverage. This optimal beam shape estimation also aids to localisation of the detected FRBs. One of the ways in which SPOTLIGHT addresses this need is by forming 2000 beams within the observation field, via software beamforming aided with a multi-beam synthesis module. The array configuration, including antenna layout, observation frequency and the source directions with respect to the array, determines parameters such as beam size (major and minor axes) and orientation (position angle). With the Earth's rotation, the configuration of the array relative to the source being observed changes systematically over time, and across different celestial targets (e.g., calibrators, target fields). Therefore, the dynamic and efficient computation of phased array beams and tiling thousands of such beams becomes crucial in efficiently searching for FRBs across FoV.

4. Beam Simulation and Tiling

We have developed a multi-beam simulation package to model and optimise phased array beam shapes for various observational setups. This package supports two distinct modes of SPOTLIGHT:

1. **Survey mode** - This mode covers a broad FoV comparable to the primary beam-width (with up to 23 antennas). The overlap ratio among beams is adjusted to maintain sensitivity across moderate baselines (while ensuring maximum FoV coverage), typically maintaining a 50% overlap ratio.
2. **Targeted mode** - This mode focuses on smaller FoVs, such as those for observing sources like globular clusters. In this mode, we optimise the beam overlap ratios to enhance sensitivity towards the target with a full GMRT array.

The basic functionality of the modelling technique for phased array beam shapes is validated through offline processing of base-band sampled voltage data by steering beams away from the pulsar at the phase centre using legacy GMRT data [10]. We carried out a detailed tilling analysis of beam patterns assuming various antenna configurations, source directions, and observing frequencies. We tested the simulation of phased array beam patterns by observing a field with pulsar with 100 steered beams away from the phase centre and compared the SNRs of these beams with simulated beam patterns.

Coincidence filtering is an essential part of the FRB search process to eliminate false positives. For this purpose, steered beams closely spaced in the sky need to be processed on the same compute node. Hence, clustering of simulated beams in close proximity (Figure 1) is a crucial part of this simulation.

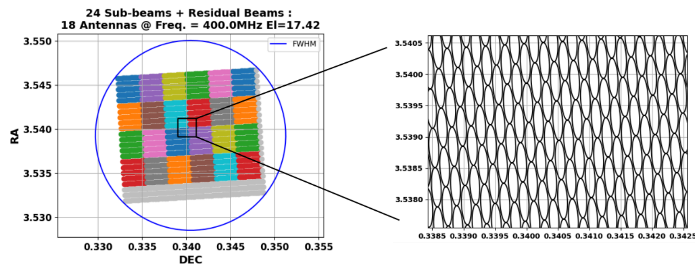

Figure 1. Illustrates the arrangement of 2000 beams simulated for an 18-antenna configuration operating at 400 MHz where the beams in each coloured squared box are processed within a given node to apply coincidence filtering.

The beam simulation package models the phased array beam shape and optimally tiles the beams such that it effectively covers a larger fraction of the FoV while maintaining high sensitivity. This ensures that any faint FRB events occurring across the field of view are not missed.

5. Scientific Implications

The beam tiling strategies developed above have important scientific implications. In survey mode, we can maintain uniform sensitivity across the entire FoV, which enhances SPOTLIGHT's discovery potential. It also allows for the immediate localisation of a burst up to arcminute to sub-arcminute accuracy. This can be compared to the localisation accuracy that CHIME can achieve via baseband data, which is about 15 to 30 arcminutes. This can be improved, depending on the SNR of the FRB, by mapping the signal intensity around the initial detection. In targeted mode, we can use tiled beams to cover objects which have a larger angular size, such as globular clusters, while retaining the sensitivity of GMRT's phased array beam. We also get the same localisation perks as we do in SPOTLIGHT's survey mode. 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 in the absence of the former type of localisation.

6. Acknowledgements

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7. References

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