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A real-time imaging localisation pipeline for the SPOTLIGHT

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Abstract

SPOTLIGHT is a commensal project that carries a real-time search for FRBs and pulsars in the target field that GMRT is observing in 24 x 7 mode. FRBs are searched in 2000 phased array beams steered across the Field of View (FoV) in time-domain data using a combination of HPC and AI techniques. The detection pipeline, on detection of FRB, sends a trigger to a high-time resolution visibility recording system split across the recording cluster. We report here a real-time imaging of the field following a detection trigger to localise FRB in FoV.

1. Introduction

Fast Radio Bursts (FRBs) are millisecond-duration radio transients. The host galaxy association of several FRBs with the sub-arcsecond localisation [1, 11] confirmed the extragalactic nature of FRBs which was already hinted at by the high excess dispersion measures (DMs). FRBs come into two broad classifications - repeaters, which emit more than one single burst, and non-repeaters, which go away after a single burst. To date, we have ~800 FRBs reported with ~ 65 repeaters (TNS). Still, the exact emission mechanism behind these elusive bursts is to be pinpointed but from the observed properties, several progenitor models have been proposed. The proposed progenitor models can be grouped as follows -

a. Neutron Star Models: Large rotational energy, high magnetic fields, and turbulent surrounding media make neutron stars a plausible candidate. Isolated neutron stars [12], interacting neutron stars with the surrounding plasma [13], as well as merging neutron stars [14] can produce FRBs.

b. Black Hole Progenitors: Evaporating black holes or black holes interacting with accreting media [15] can produce FRBs via shock waves.

c. White Dwarf Progenitors: White Dwarfs have a problem with the energy budget to produce FRBs at Mpc or Gpc distances. Accretion-based models where the materials of the white dwarf are being accreted onto a neutron star are proposed to explain FRBs [16].

Long and thorough follow-up of repeaters has been very rewarding to accurately deduce the emission mechanisms [16, 17]. Using the precise localisation of FRBs, the host galaxies are studied to weigh the possibilities of progenitor models. Bochenek et al. [18] argued that the localised sample of FRBs discovered to date is consistent with the population of magnetars born through the collapse of giant, highly magnetic stars. Precise-sub-arcsecond localisation of FRBs is also useful to look for multi-wavelength counterparts that can differentiate between the progenitor models [19].

Radio surveys with large field-of-view can discover a huge number of FRBs but the poor localisation accuracy limits them to robustly associate FRBs with the host galaxies. As noted in [5], associating an FRB with a host galaxy to a chance coincidence probability of $\lesssim$ 1% requires localising it to within 0.5 arcseconds, given the number of galaxies present in the FoV at typical FRB distances. The unavailability of robust host galaxy association limits progenitor modelling, the study of propagation effects, and the prospects of any cosmological implications. On the other hand, commensal surveys with interferometric arrays detect a small number of FRBs but provide precise localisations. However, the huge amounts of data involved, as well as current processing methodologies, introduce a substantial pipeline delay between discovery and localisation. Here, we introduce the 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**) [1], a radio commensal survey with uGMRT. We discuss the aspects of the real-time localisation of FRBs and the uniqueness of SPOTLIGHT compared to the other existing commensal surveys.

2. Need for real-time imaging

Typical search instruments like CHIME have a large field of view which compromises the localisation accuracy. Therefore, even after the discovery alert, high-resolution and highly sensitive multiwavelength follow-ups are not feasible until interferometers provide more precise localisations. As a result, only repeaters are localised precisely with interferometric follow-ups. On the other hand, commensal surveys with interferometers like CRAFT at the ASKAP [6], MeerTRAP at the MeerKAT [7, 8], and realfast at the VLA [9] limit the discovery rate but provide precise arc-second localisation for both repeaters and non-repeaters. For traditional commensal surveys (MeerTRAP, CRAFT), the raw voltage data is saved after the discovery trigger from the beamformed data. Localisation is done by post-processing the beam-formed voltages. This step is computationally expensive and adds a substantial delay between detection and localisation of the FRBs (typically a week). The delay of localisation limits the chance of observing any rapid afterglow in other wavebands. Also, for many active repeating FRBs, it is seen that the FRBs remain active for a short duration after the discovery. The rapid real-time localisation maximises the chance for the FRB to get followed up by a maximum number of facilities covering a wide range of frequencies, most useful to constrain the emission mechanisms.

3. Methodology

The SPOTLIGHT correlator produces visibilities and post-correlation beamformed data for real-time time-domain search across Field of View (FoV) split into 2000 isolated phased array beams [2]. During the operation, the SPOTLIGHT controller [3] carries a phasing of an array while the array is tracking the primary gain calibrator. That deals with all required calibration e.g. correcting for the frequency response, setting the flux scale and correcting for complex gains for each of the individual antennas. Time-dependent instrumental and ionospheric gain calibration is also part of the phasing process which is triggered periodically whenever the telescope is tracking the secondary gain calibrators. Periodic phase calibration provides refined (time-variable) gain solutions prior to target source observation. Any antenna failing to give a reliable gain solution is excluded from the phased array beams formed in the SPOTLIGHT correlator. This calibrated visibility data enables real-time imaging.

When a detection pipeline [4] triggers an FRB candidate, the SPOTLIGHT correlator [2] saves high-time resolution (1.3 ms) half-float visibilities for the duration accounting for the dispersion delay and burst width of FRB across 16-node cluster, followed by stitching them into a single 32-bit float visibility file. The visibility data is then de-dispersed at the candidate DM and only the part containing the burst and about 10 times the width of the burst on either side are saved to the disk. The dedispersed visibilities are then converted into CASA measurement sets and imaged to precisely localise the burst. This allows us to localise the FRBs in real time to enable rapid triggers essential for multiwavelength follow-ups.

In the SPOTLIGHT system, we expect to get 1 trigger per 10 minutes of observing duration and expect to process ~100 such triggers per day. We have 8 servers with 384 CPUs to facilitate real-time imaging localisation. Each trigger, considering the data volume, the simplicity of the imaging, and the capability of the computing servers is expected to be completed within approximately 1.5 minutes, satisfying the requirement of real-time imaging. With the successful implementation, the SPOTLIGHT will be the first and only running survey to have real-time localisation of FRBs.

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7. References

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