A multi-pixel beamformer using an interferometric array and its application towards localisations of newly discovered pulsars

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ABSTRACT

We have developed a multi-pixel beamformer technique, which can be used for enhancing the capabilities for studying pulsars using an interferometric array. Using the Giant Metre-wave Radio Telescope (GMRT), we illustrate the application of this efficient technique, which combines the enhanced sensitivity of a coherent array beamformer with the wide field-of-view seen by an incoherent array beamformer. Multi-pixel beamformer algorithm is implemented using the recorded base-band data. With the optimisations in multi-pixelisation described in this paper, it is now possible to form 16 directed beams in real-time. We discuss a special application of this technique, where we use continuum imaging followed by the multi-pixel beamformer to obtain the precise locations of newly discovered millisecond pulsars with the GMRT. Accurate positions measured with single observations enable highly sensitive follow-up studies using coherent array beamformer and rapid follow up at higher radio frequencies and other wavelengths. Normally, such accurate positions can only be obtained from a long-term pulsar timing program. The multi-pixel beamformer technique can also be used for highly sensitive targeted pulsar searches in extended supernova remnants. In addition this method can provide optimal performance for the large scale pulsar surveys using multi-element arrays.

Key words: Stars: pulsar: individual: PSR J1544+4937, PSR J1536−4948 – instrumentation: interferometers – techniques: interferometric

1 INTRODUCTION

A radio interferometric array is primarily designed to map the sky brightness distribution by measuring the instantaneous cross-correlations (visibilities) for all possible baselines connecting individual antenna pairs. Each baseline vector changes with time due to the rotation of the Earth, providing new sets of visibility measurements, and thereby implementing a multi-element Earth rotation aperture synthesis telescope (Ryle and Vonberg 1946). In addition to the interferometric imaging mode, such a multi-element radio telescope array is required to be configured to work as a single dish (called “beamformer”) for studying compact objects like pulsars, which are effectively point sources even for the largest baseline of the array, but demand higher time resolution observations. With a flexible back-end design, an interferometric array provides the opportunity of combining the imaging mode with beamforming modes that enable new types of pulsar studies.

The GMRT is a multi-element aperture synthesis telescope consisting of 30 antennas, each of 45 m diameter, spread over a region of 25 km diameter and operating at 5 different wave bands from 150 MHz to 1450 MHz (Swarup et al. 1997). The dual polarised voltage signals from individual antennas are eventually converted to base-band signals and are fed to the digital signal processing back-end. The recently developed GMRT Software Back-end (GSB), built using a Linux cluster of 48 Intel Xeon servers, is a fully real-time back-end for up to 32 dual polarized antenna signals, Nyquist sampled at 33 or 66 MHz (Roy et al. 2010). The GSB supports an FX correlator (where the cross-multiplication (X) is done after the frequency analysis (F), Thompson et al. (1994)) and a beamformer. The GSB beamformer provides two modes of operation: (i) an incoherent array mode, where the voltage samples from the selected antennas are added after converting to intensities, (ii) a single-pixel coherent array mode, where the voltage signals from the selected antennas are first added coherently then converted to intensity samples by squaring (Gupta et al. 2000). Finally the intensity products are integrated to desired time resolution.

We have developed an efficient technique, the multi-pixel beamformer, which is currently implemented using the recorded base-band data. The optimisation techniques employed in multi-pixelisation makes it capable of forming 16 directed beams in real-time. The multi-pixel beamformer combines the enhanced sensitivity of a coherent array with the wide field-of-view seen by an incoherent array. Pulsars originally discovered in surveys with the incoherent array have large uncertainties in positions because of the large primary beam, which prevents highly-sensitive follow-ups of those pulsars using the coherent array or at higher frequencies with
narrower primary beams. The multi-pixel beamformer can be used to rapidly localise the pulsar, to an accuracy equal to the synthesized beam of the array (\(< 10''\)), using a single snapshot observation. With traditional single-dish pulsar observations, such precise localisations can only be achieved from long-term pulsar timing programs. We have successfully demonstrated this efficient technique by determining accurate positions of two newly discovered Fermi millisecond pulsars (MSPs) using the GMRT.

2 SINGLE-PIXEL BEAMFORMER AND BASE-BAND RECORDER AT THE GMRT

The GMRT correlator utilises an FX approach as described in Roy et al. (2010). The integral parts of the antenna-dependent geometric path delays are compensated prior to spectral decomposition (FFT), whereas the fractional parts are combined with fringe derotation and applied at the post-FFT stage. In parallel with the multiply-accumulate operations, the spectral voltages, after correcting for antenna-based gain offsets and time delays, are fed to an array combiner to generate the incoherent and coherent beamformer output. In addition to the gain calibration the antenna-based phase offsets are also calibrated out for the coherent beamformer mode. The visibilities obtained from a calibrator source are used to solve for both the broadband and narrowband phase offsets, which are then applied at the post-FFT stage along with the fringe correction. Such interleaved calibrator observations in every 2 h are required to optimise the coherent array sensitivity at lower frequencies (e.g. 325 MHz). The GSB produces an incoherent beam and a single-pixel coherent beam (formed for the pointing centre of the array) at 30μs time resolution with 512 spectral channels, which translates to 32 MB/s output rate for total intensity products (after adding two polarised intensities). Then the incoherent and coherent array outputs have to be corrected for the frequency-dependent delays due to the dispersion in the interstellar medium for the target pulsar.

In addition to the correlator and the single-pixel beamformer, the GSB cluster also supports base-band recording, which is direct streaming of raw Nyquist samples from the antennas into the array of storage disks. The aggregate streaming rate is 3.3 TB/h. The raw voltage samples are piped to an off-line cluster, where the multi-pixel beamformer algorithms are implemented.

3 MULTI-PIXEL BEAMFORMER

We have achieved the multi-pixelisation of the field-of-view by forming multiple beams steering the phase centre. For the GMRT specifications, the arithmetic computational cost for the coherent beamformer is \(\sim 62\) times lower than that of the cross-multiplier-adder (Roy et al. 2010). However, including the non-arithmetic overheads due to the input/output memory operations, the coherent beamformer is 1.8× cheaper than the cross-multiplier-adder. Thus we preferred a multi-pixel beamformer over combining the auto and cross visibilities with different phases (Roy et al. 2010) estimated the compute cost for a single beamformer at around 193 Gflops, with a break up of 181 Gflops for the FFT, 8.25 Gflops for the antenna-based phase centre correction, and 4.5 Gflops for the coherent beamforming operation. We employ multi-pixelisation at the post-FFT stage, thus the phase centre correction and the beamforming cost scale with the number of beams, whereas the FFT cost remains fixed, as seen in Fig. 1.

Figure 1. Compute cost for the multi-pixel beamformer as a function of the number of beams. Approximately 600 beams are required to cover the full field-of-view using around 50% of the GMRT array. We achieve a \(>30\%\) reduction in the compute cost for multi-pixelisation while uniformly covering large fraction of the field-of-view. This can be seen from the solid red-line (plotting total optimised compute cost) and dash-dot sky-blue-line (plotting the total compute cost using regular brute-force beam-forming).

For a 325 MHz operating frequency, the pixelisation can be done efficiently up to an angular scale of 1′, which uses around 72% of the GMRT array. The perturbations in the ionospheric phases (which are severe at lower frequencies) limits the baseline length over which the array can be coherently added with optimal efficiency. Thus 6400 coherent beams are required for multi-pixelisation (with 1′ resolution) of full field-of-view (80′ at 325 MHz) with a sensitivity improvement \(\sim 5\times\) with respect to the incoherent array. The required number of beams is independent of the operating frequency, since the pixel angular size and the field-of-view scale similarly with frequency. The array configuration of the GMRT allows us to employ further optimisations in this technique, as described below.

The maximum geometrical delay for the GMRT array is 128μs, corresponding to the longest baselines of \(\sim 30\) km. Hence the maximum residual delay at the edge of the field-of-view is lower than the Nyquist sampling resolution and we can retain the integral delay calculated for the pointing centre across the field-of-view. The phase center correction cost (including the fractional delay compensation) is optimised by grouping the GMRT array. For example, at 325 MHz considering compact core of the GMRT array (which consists of 6 antennas) we apply the same phase correction up to 10′ from the pointing centre (in order to maintain the phase error at less than a degree). In addition, a trade-off between the search sensitivity and computational load can be done by generating relatively fat beams of 3′ in size (i.e. \(\sim 600\) such beams will cover the full field-of-view) using around 50% of the GMRT array. This provides a sensitivity improvement of 3× with respect to the incoherent array, whereas for 72% of the GMRT array with coherent beams of 1′ in size, the sensitivity improvement is 5×. This compromise in sensitivity improvement allows a reduction in the total compute cost by an order of magnitude. In view of the available compute power, our current multi-pixel beamformer is designed to generate such fat beams of 3′ in size. Fig. 1 illustrates the scaling...
of compute cost of each module (such as phase centre correction, beam-forming) with the number of beams. The effect of the optimisation in phase centre correction is shown by the growing difference between the solid red line (total optimised compute cost) and dash-dot sky-blue line (the total compute cost using regular brute-force beam-forming). The total compute cost for multi-pixelisation is reduced by > 30%, while uniformly covering large fraction of the field of view.

The multi-pixel beamformer is currently designed to produce coherently added intensity beams (2 bytes/sample) at 30 µs time resolution with 512 spectral channels using the recorded base-band data. This implies 512 MB/s of output streaming rate for 16 beams, which is supported by the quad gigabit networks. Hence with employed optimisation and with available network bandwidth, we are currently capable of forming and streaming 16 directed beams in real-time. Our off-line analysis pipeline uses full floating point version of the real-time code (real-time code uses fixed point arithmetic to extract the full vectorized power of the CPU) and it is benchmarked to produce 1.5× lower flops than the real-time; i.e. for 16 beams the off-line pipeline takes 1.5× of the observing time. In addition to the sensitivity gain from multi-pixelisation, we expect to get further improvements in detection significance of a pulsed signal from the fact that the incoherent array, being a sum of individual total power detectors, is more vulnerable to the instrumental gain fluctuations and the terrestrial radio frequency interference (RFI). However, for the coherent array these effects are reduced and the array provides some built-in immunity to RFI as the processing pipeline adjusts the antenna phases to correct for the effect of rotation of the sky signals, which in turn de-correlates the terrestrial signals.

4 LOCALISATION OF PULSARS USING MULTI-Pixel BEAMFORMER

The optimised multi-pixel beamforming technique described above can be very useful for large scale blind pulsar surveys, to achieve coherent array sensitivity with telescope observing time commensurate with an incoherent array coverage of the survey area. Possible future applications of this are discussed in §5. However, in parallel with multi-pixel beamforming, an interferometric array like the GMRT also allows simultaneous imaging of the field-of-view, which provides a priori information about the possible locations of interest. Continuum imaging followed by multi-pixel beamforming leads to a drastic reduction in the compute cost, as we do not need to uniformly cover the field-of-view when candidate source locations can be provided from the image. We illustrate the application of multi-pixel beamformer to obtain precise locations of the Fermi MSPs recently discovered at the GMRT.

With the GMRT, as a part of Pulsar Search Consortium, recently we have discovered six millisecond pulsars (Ray et al. 2012) in a 325 and 610 MHz survey of the error boxes of Fermi LAT gamma-ray sources. The error boxes of the LAT sources can be as large as 18′, which are conveniently covered by the wide incoherent array beam of the GMRT (e.g. the beam-width is 80′ at 325 MHz and 40′ at 610 MHz). The large solid angle of the incoherent beams also provide the possibility of discovering in-beam pulsars at large offsets from the pointing centre that are unrelated to the target LAT source. A few of the Fermi MSP discoveries have been found to be serendipitous and are not associated with the corresponding gamma-ray sources.

PSR J1544+49 is one of the MSPs we discovered having a period of 2.16 ms and dispersion measure (DM) of 23.2 pc cm$^{-3}$. From our discovery observations, the estimate of the mean flux of this pulsar is around 2.5 mJy at 610 MHz. Considering the beam size at 610 MHz, the position of this MSP is determined to be within ±20′ of the pointing centre. Since the pulsar is at high Galactic latitude (i.e. we are not limited by sky background temperature) and expected to have a steep radio spectrum, we chose 325 MHz as the frequency for follow-up observations. For the imaging and multiple pixel beamforming, we recorded base-band data for the nominal target position for a duration of one hour. The central 40′ region of the field-of-view was imaged. The flagging of erroneous visibilities, e.g. those affected by RFI and the calibration for the complex gain are handled by flagcal pipeline (Prasad and Chengalur 2011). The calibrated visibilities are imaged and deconvolved using standard imaging package AIPS. To select potential pulsar candidate locations, we identified the sources in the image with similar flux values to the mean flux of the MSP (≈ 10 mJy is estimated with the incoherent array generated from the base-band data). Fig. 2 illustrates the PSR J1544+49 field. We have chosen 16 candidate locations (circled) for follow-up with multi-pixel beamforming. The coherent beams (3′ in size using 50% of the GMRT array) are formed simultaneously for all the candidate sources with the multi-pixel beamformer pipeline (described in §3) using the recorded base-band data. Such fat beams can span more than one point source of interest within a single beam. The optimisation technique used for reducing the phase correction cost is also effective while forming beams near the pointing centre (within a ∼10′ region), which is applicable for most of the Fermi MSPs. The multi-pixel beamformer outputs are fed to a search pipeline, which is designed to search for periodicity and acceleration in parallel on all these beams. In this search we have used the DM of this pulsar obtained from the discovery search analysis. The beam with pulsar at the center gives maximum signal to noise. The MSP is found at 15°44′04″166, +49°37′57″45. The zoomed image of a 1′ region around the position of the MSP is shown in the top right panel. The three contours represent 80%, 60% and 50% of the peak flux. The pulsar is detected with 20σ significance in the continuum image at an offset of 4′3 from the search pointing centre. The sensitivity improvement with the number of antennas added in the coherent array (i.e. with reducing the beam-width) validates the correctness of the candidate pulsar position, shown in the bottom right panel of Fig. 2. The initial incoherent array uncertainty of 80′ first reduces to 8′ using the coherent array consisting of the innermost core of the GMRT array. Eventually, the sensitivity becomes 4 times that of the incoherent array with the beam-width being 1′4. The final positional uncertainty is decided by the synthesized beam used for the continuum imaging. Using this technique we have determined the position for PSR J1544+4937 with an accuracy 5″, which is half of the synthesized beam used in the imaging.

This method is also successfully applied for localising another MSP, J1536−49, which has a period of 3.08 ms and a DM of 38.0 pc cm$^{-3}$. From the discovery observations, we estimate the mean flux of this pulsar to be around 12 mJy at 325 MHz. We recorded one hour of base-band data for this MSP. Fig 3 illustrates the 80′ field for this pulsar. Coherent beams were formed on 16 chosen candidates (circled) having estimated fluxes similar to the pulsar flux. The MSP was found at 15°36′24″016, −49°48′45″39. The zoomed image of 1′ region around this MSP is shown in the top right panel. The three contours represent 90%, 60% and 50% of the peak flux. The pulsar is detected with 11 σ significance in the continuum image at an offset of 1′8 from the search pointing centre. Similar to PSR J1544+4937, the sensitivity improvement (up
Figure 2. Figure for localisation of the Fermi MSP J1544+4937 (discovered by us with the GMRT) using continuum imaging followed by a multi-pixel search. The central plot shows the field of PSR J1544+4937, with 16 candidate point sources (circled) on which coherent beams are formed. One of these beams has the pulsar at the center and has maximum signal to noise in the search output. The MSP is found at 15$^{h}$44$^{m}$04$.166$, +49$^\circ$37$'$57$.45$. The top right panel presents a zoomed image of $1'$ region around the MSP. The bottom right panel illustrates the sensitivity improvement with the number of antennas added in coherent array (i.e. when reducing the beam-width).

Figure 3. Same as Fig. 2 for Fermi MSP J1536−4948 (discovered by us with the GMRT).
to 10 times) with the reduction in the beam-width (illustrated in the bottom right panel of Fig. 3), shows that the pulsar position is correctly estimated. In addition to the sensitivity gain from multi-pixelisation, we obtained further improvement of the detection significance for this extreme southern pulsar due to fact that the incoherent array being a sum of individual total power detectors with large beam-width is more affected by the terrestrial RFI coming from near the horizon. We have determined the accurate position for PSR J1536−4948 with an accuracy 14″.

5 SUMMARY AND FUTURE SCOPE

We have developed a multi-pixel beamforming technique, which can be used for enhancing the capabilities of studying pulsars using an interferometric array. As an example of the application of this technique, we have used continuum imaging followed by multi-pixel beamforming to determine the accurate positions of two MSPs, which we have discovered at the GMRT in searches of Fermi LAT unassociated gamma-ray sources as part of the Fermi Pulsar Search Consortium. With a single snapshot observation this technique enables us to significantly reduce the large positional uncertainties associated with incoherent array detection (e.g. from 80′ or 40′ to ∼ 10″). With single dish telescopes, such precise position determinations can be achieved with long-term pulsar timing program. The initial position of a newly-discovered pulsar can also be improved up to certain extent using a grid of observations at higher frequency. This costs substantial telescope time and can be hindered by scintillation and the steep spectra of pulsars. Prompt knowledge of accurate positions allows us to make highly sensitive follow-up observations of these pulsars using single-pixel coherent beam investing much less telescope time. In addition more efficient timing for the pulsar can be carried out by reducing two degrees of freedom in parameter space (Lorimer and Kramer 2004) for getting the initial solution. This is very helpful in timing the MSPs in tight binaries with large degrees of freedom. Knowledge of the accurate pulsar positions allows for rapid follow-up at higher radio frequencies at different telescopes. Such arcsecond localization also facilitates the study of X-ray and optical counterparts for these MSPs. In addition, large positional uncertainties associated with the discoveries of pulsars from low frequency wide field surveys will get benefited from the multi-pixelisation of the field of view.

Searching for young pulsars in the extended Galactic Supernova Remnants (SNRs) can benefit from the multi-pixel beamforming technique. The conventional single-pixel search with narrow field-of-view can miss a young pulsar if the positional uncertainty within the remnant is larger than the beam width. Pulses in SNRs with large birth velocities may travel significant distances from the remnant centroids (Lorimer and Kramer 1994) and are detected at the peripheries of SNRs (Caraveo 1993, Lorimer, Lyne and Camilo 1998), which creates a selection bias. Thus simultaneous multi-pixel search with reasonably wide field-of-view is necessary for such candidate SNRs. For example, in case of a filled-centre SNR with an evidence of centrally bright emission region of size ∼ 10′, about 40 beams (each with 1.5′ in size) are needed to be synthesized at 610 MHz. This gives a sensitivity gain of a factor of 3 with respect to the incoherent array, resulting in a saving in observing time at least by a factor of 9, which is very important for reducing the required telescope time for a multi-purpose telescope like the GMRT.

The simultaneous highly sensitive multi-pixel search uniformly covering the full field-of-view can be a very useful technique for getting optimum performance from blind pulsar surveys with multi-element radio telescope arrays of the future. This technique will be particularly essential in finding weaker pulsars below the incoherent array detection threshold. Moreover this multi-pixel coherent search can overcome the sensitivity degradation seen by the incoherent array due to instrumental gain fluctuations and variable RFI environments. Our current studies using the GMRT can work as a test-bed for the future developments of bigger arrays. With the aid of further optimisation, GPU (graphical processing unit) based processing and the availability of 10G base-T or infi-band networks, our current design holds promises for large scale pulsar surveys using interferometric arrays.

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