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A Low Frequency Southern Sky Survey Using the Mauritius Radio Telescope

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Abstract. The Mauritius Radio Telescope (MRT) is a Fourier synthesis instrument which has been built to fill the gap in the availability of deep sky surveys at low radio frequencies in the southern hemisphere. It is situated in the north-east of Mauritius at a southern latitude of $20^\circ.14$ and an eastern longitude of $57^\circ.73$. The aim of the survey with the MRT is to contribute to the database of southern sky sources in the declination range $-70^\circ \leq \delta \leq -10^\circ$, covering the entire 24 hours of right ascension, with a resolution of $4' \times 4'.6 \sec(\delta + 20.14^\circ)$ and a point source sensitivity of 200 mJy (3σ level) at 151.5 MHz.

MRT is a T-shaped non-coplanar array consisting of a 2048 m long East-West arm and a 880 m long South arm. In the East-West arm 1024 fixed helices are arranged in 32 groups and in the South arm 16 trolleys, with four helices on each, which move on a rail are used. A 512 channel, 2-bit 3-level complex correlation receiver is used to measure the visibility function. At least 60 days of observing are required for obtaining the visibilities up to the 880 m spacing. The calibrated visibilities are transformed taking care of the non-coplanarity of the array to produce an image of the area of the sky under observation.

This paper will describe the telescope, the observations carried out so far, a few interesting aspects of imaging with this non-coplanar array and present results of a low resolution survey ($13' \times 18'$) covering roughly 12 hours of right ascension, and also present an image with a resolution of $4' \times 4'.6 \sec(\delta + 20.14^\circ)$ made using the telescope.

1. Introduction

The Mauritius Radio-Telescope (MRT) has been constructed and is operated collaboratively by the Raman Research Institute, the Indian Institute of Astrophysics and the University of Mauritius. It is situated in the North-East of Mauritius (Latitude 20.14° South, Longitude 57.74° East), an island in the Indian Ocean. It is a T-shaped array with an East-West (EW) arm of length 2048 m having 1024 helical antennas and a South (S) arm of length 880 m consisting of a rail line on which 16 movable trolleys each with four helical antennas are placed. Presently the telescope is operated at 151.5 MHz which allows maximum interference-free observations. The helices are mounted with a tilt of 20° towards the south so that they point towards a declination of -40° on the meridian. The declination coverage corresponding to the Half Power Beam

Width (HPBW) of the helices is from $-70°$ to $-10°$ of declination (Golap et al., 1998).

The EW arm is divided into 32 groups of 32 helices each. All the EW groups are not at the same height, a situation imposed by the uneven terrain. Each trolley in the S arm constitutes one S group. Both EW and S group outputs are heterodyned to an intermediate frequency (IF) of 30 MHz, using a local oscillator (LO) at 121.6 MHz. The 48 group outputs are then amplified and brought separately to the observatory building via coaxial cables. In the observatory, the 48 group outputs are further amplified and down converted to a second IF of 10.1 MHz. The 32 EW and 16 S group outputs are fed into a 32×16 complex, 2-bit 3-level digital correlator sampling at 12 MHz. The 512 complex visibilities are integrated and recorded at intervals of 1 second. At the end of 24 hours of observation the trolleys are moved to a different position and new visibilities are recorded.

To ensure that the array responds to structures of all sizes in the sky, the array should provide all spacings available in a square aperture. To meet this requirement at MRT, a 15 m North extension with one trolley almost touching the EW arm has been built and is used to measure the low spatial frequencies. However, this trolley cannot approach the EW array nearer than 2 m. Hence baselines with 1 m spacing in the S direction are not measured. Non-zero EW baselines with zero-spacing along the S direction are obtained by multiplying the groups of the eastern arm with the output of four helices which are a part of the first group (closest to the center) of the western arm. This has the same primary beam as a trolley and ensures a weighting similar to baselines with non-zero spacing along the S direction. Baseline with zero spacing in both EW and S directions is obtained by measuring the total power of any one of the trolley outputs.

The last group of the East array (E16) is fed to the correlator in the place of the 16^{th} trolley. This gives a set of baselines formed between E16 and the E-W array on all observing days. This helps to check the repeatability of data. These baselines with each trolley give 31 independent closure information which are used in the calibration. This mode of observing reduces the number of usable trolleys to only 15.

For signals arriving from zenith angles greater than 10° on north-south baselines longer than about 175 m, there will be bandwidth decorrelation greater than 20%, if the delays between the EW and S group outputs are not compensated. To image the declination range $-70° \leq \delta \leq -10°$ with the MRT, using a 1 MHz band, one requires visibility measurements with four delay settings. For a given delay compensation, we will be able to observe a part of the sky with a small decorrelation (worst case around 20% on longer baselines) referred to as the delay zone around the point at which the geometrical delay has been compensated. Each delay zone is approximately 15° in extent.

We have designed and built a recirculator system which measures visibilities with different delay settings using the available correlators. To implement this, a dual-buffer memory system is employed between the sampler and the correlator. The data is sampled at a slower rate and stored in one bank while the data from the other bank is fed to the correlators at a rate which is 4 times faster than the input rate. The recirculator ensures that the observations at each trolley location, even on longer baselines, can be carried out in one day.

2. Observations

In the T configuration, we are interested in sampling baselines with north-south components from 0 m to 880 m with a sampling of 1 m. This ensures that the grating response will be confined well outside the primary beam response. Each day the trolleys are spread over 84 m with an inter-trolley spacing of 6 m. 512 complex visibilities are recorded with 1 sec of integration. After obtaining data for 24 sidereal-hours the trolleys are moved by one meter. After 6 days of successful observing we get visibilities measured over 90 m. The trolleys are then moved en bloc to measure the next set of visibilities.

A minimum of 60 days of observing are needed to obtain visibilities up to the 880 m spacing. We observe for at least three days at each allocation of the trolleys to obtain interference free observations. Thus a period of 180 days is required to obtain visibilities on all the baselines. In this time period, Sun moves through half the observable sky. This forces one to observe all the baselines once again with a time gap of six months to obtain the data required to survey the observable sky. Thus the minimum period required to acquire one set of valid data for the survey is roughly one year.

We have completed two rounds of observations on all the baselines. The observations were carried out continuously during the period between July 1994 to Dec 1997 and intermittently during the period Jan 1998 to Dec 1998. This has resulted in 20,000 hours of data. Analysis shows that we have 10,000 hours of observations, which we call class I data. This covers all allocations for all the 24 hours of sidereal time, when the Sun is at least 6 hours away from the phase centre.

3. Imaging with the MRT

The visibilities measured are processed off-line using MARMOSAT, the MAuRitius Minimum Operating System for Array Telescopes (Dodson, 1997). This is designed in-house to transfer the measured visibilities to images which can be ported to AIPS.

The sampling of the visibilities on the EW grid is at intervals equal to the size of each EW group. This gives grating responses which fall on the nulls of the primary beam while synthesizing on the meridian. For synthesis away from the meridian, one of the grating response starts moving into the main lobe of the primary beam. This leads to the synthesized beam being a function of the hour angle. To simplify matters, imaging is presently done on the meridian only. The scanning in right ascension is provided by the motion of the earth.

The u,v coverage of MRT (EW and the NS components of the baseline) can be thought of as a pleated sheet, extended in both u and v, with discrete steps in w (height) as we move from one EW group to the one at a different height. As we are imaging a very large field of view (60° field), the approximate coplanar approach, wherein the phase term due to the heights is assumed to be a constant over the synthesized field of view, is invalid. Thus for MRT, an equivalent of a 3D imaging method is required.

At MRT we transform the measured visibilities using a Fast Fourier Transform (FFT) along the regularly sampled v axis, apply a Direct Fourier Transform (DFT) along the w axis and finally sum along u to obtain the image on the meridian. A DFT on w is required as the sampling in w is not uniform. The direct transform corrects every term along the zenith angle on the meridian for the group heights. This is equivalent to declination dependent phasing of the groups to a common (and artificial) 2D plane.

4. Data Processing

The analysis of data acquired so far is being carried out with the following objectives

- To obtain low resolution images of the sky (Golap, 1998).
- Mapping of a few selected Supernova remnants (SNR) associated with young Pulsars (Dodson, 1997).
- Solving problems related to wide field and high resolution imaging with the MRT (Sachdev, 1998)
- Data analysis leading to an all sky survey with the full resolution of the MRT

4.1. A Low Resolution Survey

We are processing the available data to make a low resolution survey of the sky. Observations, up to a baseline of 178 m along the S arm, do not require the recirculator. We have taken this as a natural cutoff and have made low resolution images using only the eight central groups of the EW arm and trolley positions up to 178 m in the S arm. A part of the survey covering the RA range 18:00 to 24:00 hrs and 00:00 to 05:00 hrs has been completed.

The survey has a resolution of $13' \times 18' \sec(\delta + 20.14°)$. MRC1932-464, with a flux density of 81 Jy/beam was used as the primary flux calibrator (Golap, 1998). The expected RMS noise in the images due to contributions from the confusion and receiver noise (for a 1 MHz bandwidth with an integration time of 19 seconds) are expected to be 0.7 Jy. The noise seen on the map is 0.8 Jy and is very close to the expected value.

This survey has a resolution comparable with the 408 MHz survey of Haslam et al.(Haslam et al., 1982) and the 34.5 MHz survey of the Gauribidanur Telescope (Dwarakanath and Udaya Shankar, 1990). Hence this will provide a valuable data base to study the spectral indices of the Galactic radio continuum emission between 408 MHz, 150 MHz and 34.5 MHz. Most Supernova remnants in our Galaxy have been discovered from their radio emission and for majority of them this remains the only means of studying them. This survey can contribute in the identification of large diameter faint SNRs, especially far from the Galactic plane. We also hope to identify a few new Galactic loops.

We have detected around 900 sources with flux densities above 3Jy/beam level in the low resolution survey. Many of them have been identified with Molongolo and Culgoora sources. A comparison of the flux densities of the sources common to MRT and Culgoora lists showed that the error in the estimated flux densities is less than 25%.

Apart from the scientific motivation, one of the main reasons for making low resolution images is to develop techniques for imaging with a non-coplanar array like MRT. The main outcome of the low resolution survey is the development of an algorithm for deconvolving the MRT images. The Point Source Function (PSF)of a non-coplanar array like MRT is declination dependent. We have developed an algorithm to transform the PSF estimated at one declination to the PSF at any other declination. This has enabled us to "clean" the MRT images made by restricting ourselves to simple cleaning algorithms.

5. SNRs associated with young Pulsars

This aspect is covered else where in this proceedings by R. Dodson.

6. Wide Field Imaging with the MRT

For wide field imaging a recirculator system which measures visibilities with different delay settings using the available correlator has been built. (section 1). The recirculator data is calibrated by doing a least square fit of the expected visibilities to the measured visibilities. Because of the lack of suitable calibrators over the wide field of view of the MRT, we could not calibrate the different delay zones independently. We were forced to use the complex antenna gains estimated for one zone in which we have a strong calibrator to calibrate other zones. Since we have a Single Side Band receiver, we measured the centroids of all the 512 bandshapes and used this information to estimate the complex gains for different zones (Sachdev, 1998).

The band-centers for different baselines were not identical. Most of them were centered at 10.1 MHz while some ranged from 10 MHz to 10.2 MHz. For small delays, the variation in the center frequencies does not affect the calibration. However, at larger delays this effect cannot be ignored and has to be taken into account while calibrating. In an array, small variations in the center frequencies of different baselines can be dealt with by looking at them as having different spatial frequencies. We have incorporated the variations in the band-centers in our calibration and imaging programs.

7. Present Status

The figure shows an MRT image with a resolution of $4' \times 4'.6 \sec(\delta + 20.14°)$. This is a dirty image. The MOST source 2013-557, a giant complex source with a strong core, with an integrated flux density of 2.43 Jy at 843 MHz (Jones and McAdam, 1992), is seen in the image with a signal to noise ratio close to that expected.

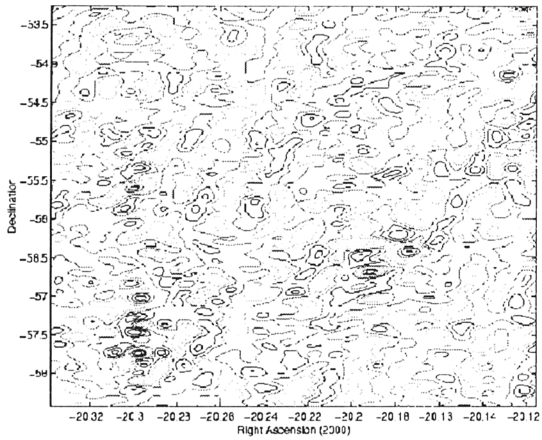

Figure 1. An MRT image with a resolution of $4' \times 4'.6 \sec(\delta + 20.14°)$ of a typical region away from the galactic plane. Sources MRC 2006-566, 2007-568, 2013-579 are seen in the image.

A few aspects of the data processing required to get the final images with the expected sensitivity and dynamic range, which are under progress are listed below.

- Improving the Calibration: Instead of using a single source calibration we need to do a 'field of view' calibration which would take into consideration contribution of several sources in the field of view. Since the flux and positions of sources are not known at this frequency, there is a need to produce an initial image with the final resolution and make estimates of the position and flux densities of the sources and then use them in the calibration process. The process may require more than two iterations of calibration and imaging.

  In the second round of observations the recirculator has been configured to measure visibilities in the NS × NS mode and in the EW × EW mode along with the EW × NS mode . This will enable us to carry out redundant baseline calibration. However the limitations due to the baselines not being entirely redundant because of height variations and due to variation in band-shapes need to be understood thoroughly.

- Deconvolving the Images: The deconvolution process for the MRT images is complicated mainly due to three reasons. 1) The non-coplanarity makes the beams different for different declinations. 2) The PSF also varies with declination due to different decorrelations. 3) The effect of precession on the PSF, especially when the observations on different baselines are separated by more than an year.

  All these factors can be corrected for in principle. However, incorporating these in the deconvolution scheme is time consuming and laborious. Also, standard deconvolution tools available in softwares like AIPS cannot be used. Development of software to carry out deconvolution is under progress.

- 2-D synthesis: To improve the sensitivity so that the noise in the images reach the confusion limit, we need to image the full 2° available (Beam of an east-west group) instead of imaging only on the meridian. Imaging away from the meridian would require a deconvolution scheme to take into account the variation of the synthesized beam with hour angle.

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