The GMRT Search for Reionization

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Abstract. We present an overview for the reionization search at GMRT. The forecast sensitivities are promising for an early detection. RFI mitigation has been successful. Several hundred hours of telescope time have already been invested in this ongoing effort, and analysis of the data is in progress.

Keywords: cosmology, reionization

INTRODUCTION

A current frontier in observational and theoretical astrophysics is the search for structures during the epoch of reionization (EoR). The WMAP satellite has measured polarization in the Cosmic Microwave Background (CMB) at large angular scales. This polarization is believed to arise from Thomson scattering of the CMB photons near the EoR [1, 2]. The observed optical depth $z \sim 0.089 \pm 0.016$ corresponds to an instantaneous reionization redshift of $z_{\rm reion} = 10.8 \pm 1.4$. The redshifted neutral hydrogen 21cm line is accessible to existing radio telescopes.

One way to study the reionization transition is by imaging redshifted 21cm emission. At redshifts above the EoR transition the gas is neutral and is predicted to glow with about 25 mK sky brightness temperature. After reionization is complete this glow is absent. At redshifts close to the transition a patchy sky is expected. Simulations [3] suggest that with existing telescopes a measurement near 150 MHz may allow for statistical detection of \sim 20 Mpc patchiness in the neutral hydrogen. This detection would pin down the reionization redshift and begin the process of a more detailed study of the transition.

Several programs¹ are underway to measure the collective 21cm emission during the epoch of reionization, z > 6, when the neutral fraction of the universe was closer to

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¹ Giant Metrewave Radio Telescope (GMRT; http://www.ncra.tifr.res.in), Low Frequency Array (LOFAR; http://www.lofar.org), Murchison Widefield Array (MWA; http://web.haystack.mit.edu/arrays/MWA), Primeval Structure Telescope/21CMA (PAST; http://web.phys.cmu.edu/~past/), and Square Kilometre Array (SKA; http://www.skatelescope.org).

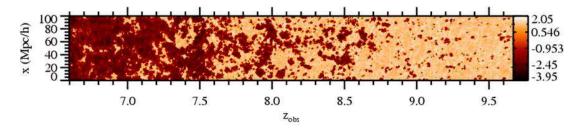


FIGURE 1. A simulation [3] of the 21cm brightness field. The colour scale is in log milli Kelvin. The vertical scale is just under one degree. Redshifts in the range $6 \le z \le 10$ are accessible at GMRT, with some windows that are filtered for radio interference. Reprinted with permission.

unity. At the low frequency of these observations the continuum sources are very bright, so under these programs effective tools for continuum removal are being developed.

FORECAST

Over the past five years, the CITA group has invested in realistic forecasts for reionization scenarios. This group has performed large scale radiative transfer reionization simulations [3], which allows for quantitative forecasts of signals visible to GMRT. Figure 1 shows how the universe might look through a slice visible to GMRT.

These simulations found that reionization power is present on large (20 Mpc) scales, and that the optimal redshift to search for spatial structure is at redshifts slightly less than the equivalent instantaneous reionization redshift.

Estimated noise levels can be comparable to the signal per pixel on scales down to 20 Mpc in a 100 hour observation. Maps will be noisy, but the power spectrum may still be accurately measurable. Figure 2 shows the expected error on a reconstructed power spectrum in a 100 hour observation, assuming that thermal limits are reached, and that all foregrounds have been subtracted.

TELESCOPE

Our group has initiated an effort to search for 21cm structures at the epoch of reionization using the Giant Metrewave Radio Telescope (GMRT) in India. This effort began in the summer of 2005, through a series of visits and agreements. At the time, a major challenge in the 2m band was broad band interference, which was thought to be a significant limitation for imaging dynamic range, especially on the short base lines of interest for reionization studies.

The telescope consists of 30 antennae of 45m diameter each. 14 are designated "central core" antennae, which are within a 1 km area. Figure 3 shows a view of several central core antennae. The dense layout of the core allows high brightness sensitivity, which is needed for the search for reionization. For this experiment, the 150 MHz feeds were used. These consist of orthogonal pairs of folded dipoles, backed by a ground plane. These antennas couple to X and Y linear polarizations, but the two signals pass

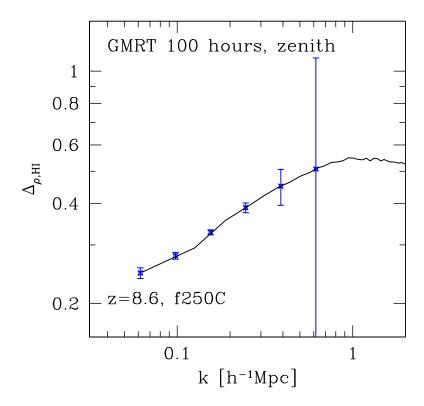


FIGURE 2. Observability of the 21-cm signal: the 3D power spectrum of the neutral hydrogen density, $\Delta_{p,HI}$, at redshift z=8.59 (where the mean spin temperature $\overline{T_b}=16.3$ mK) with the forecast error bars for 100 hours observation with GMRT vs. wavenumber k. We assumed 15 MHz observing bandwidth (the full utilized 150 MHz bandwidth of GMRT), $T_{\rm sys}=480$ K and $T_S\gg T_{\rm CMB}$. The array configuration is assumed pointed to the zenith, but the sensitivity is only weakly dependent on the pointing.

through a hybrid coupler before entering the amplifiers. For each antenna this results in a pair of right and left circularly polarized signals which are amplified, up-converted and transmitted optically to the receiver room. Later processing allows measurement of the full set of Stokes parameters.

To attempt the EoR experiment, and for other work at GMRT, we built a new signal processing system for the telescope. This consists of 16 commercial Analog to Digital sampling boards installed in an array of off-the-shelf computers, as shown in Figure 4, called the GMRT Software Backend (GSB, Roy et al 2008, in prep). The AD boards have 4 input channels, and are connected to a common clock and trigger signal, allowing synchronous sampling. The GSB is in principle a fully flexible software signal processing system, and can be arbitrarily reconfigured in software. The codes are written in C with vendor library calls for FFT and inline vector assembly directives to achieve close to theoretical peak speed of 4.77 Tera 16 bit fixed point operations/sec on 16 nodes of dual quad core 2.33 GHz processors. The data is interchanged through dual channel gigabit ethernet. Initially, the GSB allows three modes of operation: fully real time correlations, gated observations for pulsar and power line RFI folding, and a raw recording mode for



FIGURE 3. GMRT central square antennae. The closely spaced antennae provide the high brightness sensitivity to search for EoR.

off-line processing.

For this experiment, only 16 MHz out of potentially possible width of 32 MHz of RF bandwidth are used. The bandwidth was throttled by an IF filter. All 60 signals were sampled with 8 bit precision at 33 MSample/s. Each AD board transfers the digitized data into its individual host computer. These streams are Fourier transformed in blocks of length 4096 samples at 16 bit precision. The 2048 complex Fourier coefficients are then rescaled to 4 bits, and sent over a gigabit network to correlation nodes. Each block of 128 frequencies is sent to one of 16 software correlation nodes. These products, which we call visibilities, are accumulated for 1/4 second in 16 distinct gates. Thus the initial visibilities have a frequency and time resolution of 7.8 kHz and 1/4 second (without counting for the gates), respectively.

To simplify calibration, fields are taken along the lines of sights through pulsars. The "gates" are essential to our polarization calibration technique. These gates in time are synchronized so each covers one of 16 segments of the pulsation cycle of a pulsar in the field. The pulsar is a known source of polarized emission. By comparing pulsar-on to pulsar-off we can measure the system gain and phase directly using a sky source. The raw 1/4 second averaged visibilities are stored on disk, as well as 16 fringe-stopped gated visibilities integrated for 16 seconds, and averaged over frequency into 128 frequency channels. The GSB allows allows decoding of the GMRT noise source injection system, which enables a direct measurement of the variable pulsar amplitude.

All these signal processing calculations occur simultaneously, and are structured as individual asynchronous pipelined processes. The processor and network speeds are sufficient that each calculation is completed in real time and there is less than 10 % data loss.

INTERFERENCE REMOVAL

In the EoR project, a two pronged effort has been implemented to address broad band interference problems. The first is a software processing step. The second, which is still under development, is an effort to localize the sources physically based on their inferred near field position. New near field calibration and localization algorithms have been implemented and tested for this purpose (Pen et al 2008, in prep). Figure 5 shows the calibration source setup, and a targeted RFI source, probably the transformer, in the



FIGURE 4. The newly installed GMRT software back end. It allows a wide variety of modes, including software correlation, and recording of all raw voltages to disk.

background,

Interference is removed in two stages. First, line RFI is flagged. In each frequency bin, the distribution of intensities are calculated. The upper and lower quartile boundaries are used to estimate the amplitude of the noise. Any outliers further than 3σ on a Gaussian scale are masked. Each mask is 8 kHz wide, and 4 seconds long. Approximately 1% of the data is flagged by this process.

A bigger problem at GMRT has been broad band interference. These are particularly problematic at short baselines. A singular value decomposition (SVD) based approach was used. The data can be considered as a matrix. Each hour scan has 14400 time records, which we call the rows of our matrix, and each record has 2048x60x61 entries that correspond to the number of frequency channels and baselines in complex visibilities. This 14400x7495680 matrix is then SVD decomposed. The first 100 right eigenvectors are tagged as "noise", and removed. This removes 0.7% of the information. The rationale is that sources on the sky fringe rotate, and do not factor easily into vectors with large eigenvalues, while sources on the ground modulate coherently with time. Empirically, this works very well, and no broad band RFI is visible in the data after this process.



FIGURE 5. RFI localization setup. Power lines are thought to be the primary cause of broadband interference.

CURRENT STATUS

The new signal processing system has been fully installed and functioning since August 2007; in December 2007, we acquired 100 hours of EoR data suitable for the pulsar-calibration technique. Initial analysis shows that this new technique works well and the pulsar-only data is able to achieve thermal noise limits. The EoR analysis is currently underway.

CONCLUSIONS

The GMRT effort is well underway in for a sensitive search for reionization in redshifted 21cm structures. Significant progress has been achieved in interference removal, calibration, and forecasting. Data acquisition is in progress, and the forecast sensitivities may deliver early reionization detections.

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