Characterizing the diffuse foreground for redshifted 21-cm HI signal: GMRT 153 MHz observation

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Abstract. Detailed knowledge of the foreground structure on the angular scales of $\sim 1^\circ$ to sub-arcminute will be essential for extracting the redshifted 21-cm HI signal from the observed data. We have presented results from the GMRT observations at 153 MHz, which was used to characterize the statistical properties of the diffuse radiation, using the multi-frequency angular power spectrum, across sub-degree angular scales. We have detected fluctuations in the diffuse emission on angular scales greater than 10$'$ in a low galactic latitude area. The total intensity angular spectrum shows a power-law behaviour, while the detection of diffuse emission at smaller angular scales is limited by residual point sources. Also, we have estimated the level of foreground contamination.

1. Introduction

Observations of redshifted 21-cm radiation from neutral hydrogen (HI) hold the potential of tracing the large scale structure of the Universe over a large redshift range. The 21-cm radiation is expected to have an rms brightness temperature of a few mK on angular scales of a few arcminutes [1]. This signal is, however, buried in the emission from other astrophysical sources, which are collectively referred to as foregrounds. Individual sources (mostly point sources) can be identified, and removed from the image at a flux level, which depends on the sensitivity of the instrument. The rest of the foreground emission is dominated by the diffuse galactic synchrotron radiation from our galaxy [2]. Our present knowledge of the galactic diffuse radio emission at metre wavelength is not adequate. Estimates of the spatial fluctuations on arcminute scales are required for reionization experiments. In this paper, we have presented the first results from the Giant Metrewave Radio Telescope (GMRT\textsuperscript{1}, [3]) observations at 153 MHz with arcminute angular resolution, aimed at characterizing the properties of the diffuse foregrounds for reionization experiments.

Section 2 describes the observations and data analysis part, while Section 3 contains a detailed discussion on the diffuse galactic foreground component with a power spectrum analysis.

\textsuperscript{1} http://www.gmrt.ncra.tifr.res.in
2. GMRT observations and data analysis

On January 8, 2008, we have observed a field centred on \( \alpha_{2000} = 05^h 30^m 00^s, \delta_{2000} = +60^\circ 00' 00'' \) for a total time of \( \sim 11 \) hours (including calibration). The galactic coordinates of this field are \( l = 151.80^\circ \) and \( b = 13.89^\circ \). From the 408 MHz Haslam map, the sky temperature at this location is \( \sim 40 \) K [4], and there is no structure visible at the angular resolution (\( \sim 0.85^\circ \)) of the Haslam map.

In this analysis, the data reduction was carried out using a software called FLAGCAL [5], which identifies and removes bad visibilities, computes calibrated solutions using known flux and phase calibrations, and interpolates these onto the target source. The flagged and calibrated visibility data have been used to make continuum images using the standard tasks in the Astronomical Image Processing Software (AIPS).

3. Diffuse galactic foreground

We have characterized the fluctuations in the diffuse galactic foreground in our observed field. Figure 1 shows the continuum image of this field, where hundreds of point sources are visible inside the field of view of \( 4.0^\circ \times 4.0^\circ \). Several hundreds of sources were identified through a CLEAN de-convolution in a \( 8.0^\circ \times 8.0^\circ \) image, and all the point sources are removed down to a level of \( \sim 20 \) mJy from the continuum image. We have noted that below 20 mJy, the field is dominated by the residual imaging artifacts (see Figure 2). Figure 3 shows the resulting image, where all the point sources down to 20 mJy level are removed. No diffuse structure appears in this map. However, it is not clear whether diffuse structure exist on arcminute scales. In order to investigate this point, we have made an image including only the baseline with \( |U| > 170 \). This restriction imposes a condition such that all the angular scales > 10' are absent in the resulting image (Figure 4). No diffuse structures were noticed in this map, which signify absence of diffuse power on smaller scales. The most relevant contributions left are all from residual point sources. To characterize the diffuse structures on large angular scales, we have started to taper the uv plane. We have noticed that diffuse structures begin to appear on > 10' angular scales. The corresponding image, which has a synthesized beam of FWHM of \( 620'' \times 540'' \) is shown in Figure 5, where the contribution from individual point sources...
sources have completely disappeared, and on the other hand, we have noticed that the pattern of fluctuations have started dominating the whole image. This pattern does not correlate with the distribution of point sources shown in Figure 1, indicating that possible unsubtracted sources do not contribute significantly to the diffuse emission. Then, we have continued tapering the uv plane (at $|U| = 100$) to see if diffuse structures appear at even higher angular scales. Figure 6 shows the continuum image, where the synthesized beam has FWHM $1070'' \times 864''$. In this map, we have detected fluctuations in the brightest structure $> 10\sigma$ level compared to the local rms value, which is around $35 \, mJy/beam$ ($\sim 2.24 \, K$) in the inner region of the map. We have noticed that the rms value on the lowest resolution map accounts for diffuse emission only, whereas there is a clear indication of significant contribution from unsubtracted point sources in the highest resolution map ($rms \sim 1.3 \, mJy/beam \equiv 223.34 \, K$). Based on these observations,
we have concluded that the observed fluctuations represent structure in the galactic foreground radio emission on scales of $10' - 20'$, but there is a clear absence of diffuse power on arcminute scales.

3.1. Power spectrum
We have used the correlation between pairs of visibilities after subtracting all the identified sources above 20 mJy to estimate the angular power spectrum $C_\ell(\Delta \nu = 0)$ (Hereafter, this will be $C_\ell$) [6]. The problem of noise bias is avoided by correlating visibilities at two different baselines for which the noise is expected to be uncorrelated [7].

The total intensity angular power spectrum $C_\ell$ (see Figure 7) clearly shows two different scaling behaviour as a function of the angular scale. At large angular scales ($>10'$), we have found a power law behaviour, which is typical of the galactic diffuse emission observed at higher frequencies and lower angular resolutions [8]. Above $\ell \sim 800$, the power spectrum flattens and then it remains flat down to angular scales of $\sim 1'$. Also, we have noticed similar behaviour,

![Figure 7](image.png)

where the dominant contribution from the diffused emission has disappeared from the image (see Figure 4) made by discarding the short baseline ($|U| > 170$). It seems that the clear break in the angular power spectrum at $\ell \sim 800$ (equivalently $\theta > 10'$) agrees well with our image plane analysis in Section 3. Based on these facts, we have concluded that the power spectrum down to $\ell \sim 800$ is representative of the diffuse galactic foreground emission, whereas, it is dominated by residual point sources at higher $\ell$ values. The total intensity power spectrum of the diffuse emission was fitted with a power-law $C_\ell = (891 \pm 71) \times (\frac{\ell}{800})^{-2.37 \pm 0.29}$ mK$^2$ down to $\ell = 800$. The amplitude and the slope of the power-law also remains unchanged if we correlate two visibilities, which are sampled at different time intervals. This indicates that our estimate of the total intensity power spectrum is free from any RFI contaminations, which are mostly expected to be correlated within short time intervals. Earlier, Bernardi et al [9] have reported total intensity and polarization fluctuations in the galactic diffuse foreground emission at a low galactic latitude area ($b = 6.4'$), which have been measured at the frequencies and angular scales relevant for upcoming reionization experiments. We have found that the break in the total intensity angular power spectrum and the power-law slope agrees well with their results.

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