Abstract

The Epoch of reionization (EoR; $6 \leq z \leq 13$) and the post-reionization (post-EoR; $z \leq 6$) neutral hydrogen (HI) 21-cm intensity mapping signal holds the potential to probe a large number of astrophysical and cosmological problems, such as the properties of the first galaxies, the structure formation and evolution of the large scale structures, the expansion history of the Universe etc. In this work, we apply the visibility-based Tapered Gridded Estimator (TGE) to measure the high redshift HI power spectrum $P(k_{\perp}, k_{\parallel})$ from the EoR and post-EoR using data from the Giant Metrewave Radio Telescope (GMRT) and the upgraded GMRT (uGMRT).

We first present a new approach to estimate the power spectrum $P(k)$, which first measures the multi-frequency angular power spectrum (MAPS; $C_{\ell}(\nu_a, \nu_b)$) of redshifted HI 21-cm brightness temperature fluctuations. We generalize the already existing two-dimensional (2D) TGE for the angular power spectrum C_{ℓ} to develop the TGE for MAPS $C_{\ell}(\nu_a, \nu_b)$. Under the flat-sky approximation and assuming ergodicity along the line of sight direction, the HI power spectrum $P(k_{\perp}, k_{\parallel})$ is related to the MAPS $C_{\ell}(\Delta\nu)$ through a Fourier transform along $\Delta\nu$, where $\Delta\nu = \mid \nu_a - \nu_b \mid$. We implement this using a maximum likelihood estimator, which we use to estimate $P(k_{\perp}, k_{\parallel})$ and $P(k)$. We use realistic simulations of 150 MHz GMRT observations to validate our TGE estimator for the MAPS and power spectrum of the HI 21-cm signal. Considering $P(k)$, we find that this estimator is able to recover the input model power spectrum $P^m(k)$ with an accuracy of $5 - 20\%$ over a reasonably large k range in presence of the system noise, and even when the data in 80% randomly chosen frequency channels is flagged.

We next apply the TGE to 153 MHz GMRT observations, corresponding to redshift $z = 8.28$ for the HI signal, to measure the MAPS, and from it the power spectrum for the 21-cm signal. We find that the data is much too small for making a detection. However, using this data we could successfully demonstrate the salient features of our TGE, which shows that the TGE can faithfully subtract out the noise bias to produce unbiased estimates of the measured quantities. Secondly, the estimated MAPS and power spectrum do not show any artifacts in them, even though more than 47% of the frequency channels are flagged from the data due to radio-frequency interference. Lastly, we demonstrate the capability of the TGE to suppress the wide-field foreground contributions in the estimated MAPS and power spectrum by tapering the primary beam pattern at the large angular distances away from the phase center. We also identify some k modes in the "21-cm window" to be relatively foreground-free, and bin them spherically to constrain $\Delta^2(k)$ the dimensionless power spectrum of the HI brightness temperature fluctuations. We obtain the best 2σ upper limit for $\Delta^2(k) = (77.66)^2\ \mathrm{K}^2$ at $k = 1.59\ \mathrm{Mpc}^{-1}$.

We next apply the TGE to measure the MAPS and power spectrum from a 432.8 MHz uGMRT observation of the field European Large-Area ISO Survey-North 1, corresponding to $z = 2.28$ for the HI signal in the post-EoR. Similar to the previous data, the salient features of the TGE is demonstrated here as well. Using the foreground avoidance technique, we obtain a 2σ upper limit of $\Delta^2(k) \leq (133.97)^2 \mathrm{mK}^2$ for the 21-cm brightness temperature fluctuation at $k = 0.347 \mathrm{Mpc}^{-1}$, which corresponds to $[\Omega_{\rm HI}\, b_{\rm HI}\,] \leq 0.23$, where $\Omega_{\rm HI}$ is cosmic HI mass density, and $b_{\rm HI}$ is the bias parameter. The upper limits presented here are still orders of magnitude larger than the expected signal corresponding to $\Omega_{\rm HI} \sim 10^{-3}$ and $b_{\rm HI} \sim 2$.

Keywords: Cosmology: large-scale structure of the Universe, diffuse radiation, neutral hydrogen, observations, methods: statistical, data analysis, techniques: interferometric.