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Validating a novel angular power spectrum estimator using simulated low frequency radio-interferometric data

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HIGHLIGHTS

- Validate a novel angular power spectrum estimator using numerical simulations.
- Both diffuse emission and compact sources are used to simulate realistic sky models.
- Various imaging strategies are used to check the point source subtraction accuracy.
- Diffuse emission power spectrum is successfully recovered by removing point sources.
- This analysis may be extended for the EoR foreground characterization and removal.

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ABSTRACT

The "Tapered Gridded Estimator" (TGE) is a novel way to directly estimate the angular power spectrum from radio-interferometric visibility data that reduces the computation by efficiently gridding the data, consistently removes the noise bias, and suppresses the foreground contamination to a large extent by tapering the primary beam response through an appropriate convolution in the visibility domain. Here we demonstrate the effectiveness of TGE in recovering the diffuse emission power spectrum through numerical simulations. We present details of the simulation used to generate low frequency visibility data for sky model with extragalactic compact radio sources and diffuse Galactic synchrotron emission. We then use different imaging strategies to identify the most effective option of point source subtraction and to study the underlying diffuse emission. Finally, we apply TGE to the residual data to measure the angular power spectrum, and assess the impact of incomplete point source subtraction in recovering the input power spectrum C_ℓ of the synchrotron emission. This estimator is found to successfully recovers the C_ℓ of input model from the residual visibility data. These results are relevant for measuring the diffuse emission like the Galactic synchrotron emission. It is also an important step towards characterizing and removing both diffuse and compact foreground emission in order to detect the redshifted 21 cm signal from the Epoch of Reionization.

1. Introduction

A detailed investigation and analysis of the Galactic diffuse synchrotron emission power spectrum can be used to study the distribution of cosmic ray electrons and the magnetic fields in the interstellar medium (ISM) of the Milky Way, and is very interesting in its own right (Waelkens et al., 2009; Lazarian and Pogosyan, 2012; Iacobelli et al., 2013). On the other hand, at a very differ-

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ent scale, 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 of $200 \geq z \geq 0$. Accurate cosmological HI tomography and power spectrum measurement, particularly from the Epoch of Reionization (EoR), by ongoing or future low-frequency experiments will provide us a significant amount of information about various astrophysical and cosmological phenomena to enhance our present understanding of the Universe. Interestingly, since one of the main challenges in statistical detection of the redshifted 21 cm signal arises from the contamination by Galactic and extragalactic "foregrounds" (Shaver et al., 1999; Di Matteo et al., 2002; Santos et al., 2005), these two aspects are also quite related. The two major foreground components for cosmological HI studies are (1) the bright compact ("point") sources and (2) the diffuse Galactic synchrotron emission (Ali et al., 2008; Paciga, 2011; Bernardi et al., 2009; Ghosh et al., 2012; Iacobelli et al., 2013). Detection of the weak cosmological HI signal will require a proper characterization and removal of point sources as well as this diffuse foregrounds.

Naturally, a significant amount of effort has gone into addressing the problem of foreground removal for detecting the 21 cm power spectrum from EoR (Morales et al., 2006; Jelić et al., 2008; Liu et al., 2009a; 2009b; Harker et al., 2010; Mao, 2012; Liu and Tegmark, 2012; Chapman et al., 2012; Paciga et al., 2013). In contrast, foreground avoidance (Datta et al., 2010a; Vedantham et al., 2012; Morales et al., 2012; Trott et al., 2012; Parsons et al., 2012; Pober, 2013; Dillon et al., 2013; Hazelton et al., 2013; Thyagarajan et al., 2013; Liu et al., 2014a; 2014b; Ali et al., 2015; Trott et al., 2016) is an alternative approach based on the idea that contamination from any foreground with smooth spectral behaviour is confined only to a wedge in cylindrical ($k_{\perp}$, $k_{\parallel}$) space due to chromatic coupling of an interferometer with the foregrounds. The HI power spectrum can be estimated from the uncontaminated modes outside the wedge region termed as the *EoR window* where the HI signal is dominant over the foregrounds. With their merits and demerits, these two approaches are considered complementary (Chapman et al., 2016).

Here we have considered the issue of estimating the angular power spectrum directly form the radio-interferometric "visibility" data. In this endeavor, we have developed a novel and fast estimator of angular power spectrum that consistently avoids the noise bias, and tested it with simulated diffuse Galactic synchrotron emission (Choudhuri et al., 2014). Here, we have further developed the simulations to include the point sources in the sky model (as well as instrumental noise) to investigate the effectiveness of the estimator of recovering the diffuse emission power spectrum in presence of the point sources. This paper describes the details of the simulations and analysis, including the adopted point source modeling and subtraction strategies, and their effects on the residual diffuse emission. We demonstrate that, by using this newly developed Tapered Gridded Estimator (hereafter TGE), we can avoid some of the complications of wide field low frequency imaging by suitably tapering the primary beam during power spectrum estimation. A companion paper has reported the usefulness of the new estimator in recovering the diffuse emission power spectrum from the residual data in such situation (Choudhuri et al., 2016a). A further generalization of the estimator to deal with spherical and cylindrical power spectrum is presented in Choudhuri et al. (2016b). Please note that this is part of a coherent effort of end-to-end simulation of realistic EoR signal and foreground components, and finally using suitable power spectrum estimator to recover the signal. However, even though these exercises are in the context of EoR experiments, for the sake of simplicity, we have so far not included the weak cosmological signal in the model. Here we establish the ability of the developed estimator to recover the diffuse emission power spectrum accurately after point source subtraction. Thus, apart from EoR experiments, these results are also relevant in more general situation, e.g. detailed study of Galactic synchrotron emission (Choudhuri et al., 2017).

The current paper is organized as follows. In Section 2, we discuss the details of the point source and diffuse emission simulation. Section 3 and 4 present the analysis using different CLEANing options for point source subtraction and the results of power spectrum estimation. Finally, we present summary and conclusions in Section 5.

2. Multi-frequency foreground simulation

In this section we describe the details of the foreground simulation to produce the sky model for generating visibilities for low radio frequency observation with an interferometer. Even if the simulation, described in this paper, is carried out specifically for 150 MHz observation with the Giant Metrewave Radio Telescope (GMRT), it is generic and can easily be extended to other frequency and other similar telescopes including the Square Kilometre Array (SKA).

Earlier studies (Ali et al., 2008; Paciga, 2011) have found that, for 150 MHz GMRT small field observations, the bright compact sources are the dominating foreground component for EoR signal at the angular scales $\leq 4°$, the other major component being the Galactic diffuse synchrotron emission (Bernardi et al., 2009; Ghosh et al., 2012; Iacobelli et al., 2013). We build our foreground sky model keeping close to the existing observational findings. The sky model includes the main two foreground components (i) discrete radio point sources and (ii) diffuse Galactic synchrotron emissions. The contributions from these two foregrounds dominate in low frequency radio observations and their strength is $\sim 4-5$ orders of magnitude larger than the $\sim 20-30$ mK cosmological 21-cm signal (Ali et al., 2008; Ghosh et al., 2012). Galactic and extragalactic free-free diffuse emissions are also not included in the model, though each of these is individually larger than the HI signal.

2.1. Radio point sources

Most of the earlier exercise of numerical simulation conducted so far have not included the bright point source foreground component in the multi-frequency model. In such analysis, it is generally assumed that the brightest point sources are perfectly subtracted from the data before the main analysis, and the simulated data contains only faint point sources and other diffuse foreground components, HI signal and noise. We, however, simulate the point source distribution for sky model using the following differential source counts obtained from the GMRT 150 MHz observation (Ghosh et al., 2012):

$$\frac{dN}{dS} = \frac{10^{3.75}}{\mathrm{Jy.Sr}} \left(\frac{S}{\mathrm{Jy}}\right)^{-1.6} . \tag{1}$$

The full width half maxima (FWHM) of the GMRT primary beam (PB) at 150 MHz is $\approx 3.1°$. To understand and quantify how the bright point sources outside the FWHM of the PB affect our results, we consider here a larger region ($7° \times 7°$) for point source simulation. Initially, 2215 simulated point sources, with flux density in the range 9 mJy–1 Jy following the above mentioned source count, are randomly distributed over this larger region. Out of those sources, 353 are within $95'$ from the phase centre (where the PB response falls by a factor of e). We note that the antenna response falls sharply after this radius. For example, the primary beam response is $\lesssim 0.01$ in the first sidelobe. Hence, outside this "inner" region, only sources with flux density greater than 100 mJy are retained for the next step of the simulation. In the outer region, any source fainter than this will be below the threshold of point source subtraction due to primary beam attenuation. With