Exploring the Dark Ages and Epoch of Reionization with the HI 21 cm signal

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Abstract. Observations of the HI 21 cm transition line promises to be an important probe into the cosmic Dark Ages and Epoch of Reionization. Detection of this redshifted 21 cm signal is one of the key science goal for several upcoming and future low frequency radio telescopes like Murchison Widefield Array (MWA), Precision Array to Probe Epoch of Reionization (PAPER), Low Frequency ARray (LOFAR) and Square Kilometer Array (SKA). One of the challenges for the detection of this signal is the accuracy of the foreground source removal. Here, we investigate the level of accuracy for the calibration and bright source removal algorithms from the reionization data-sets. We also put forward constraints for the design of the cosmic reionization data reduction scheme for the upcoming low frequency arrays such as, MWA, PAPER, etc. We show that the efficient foreground source removal strategies can only tolerate a frequency independent antenna based mean residual calibration error of 0.2% in amplitude or 0.2 degrees in phase. In order to extract the spherically averaged HI signal power spectrum, bright foregrounds need to be removed with calibration accuracies of 0.05% in amplitude. We also demonstrate the advantages of probing the cosmic reionization with the two dimensional HI power spectrum.

1. Introduction
The cosmological Epoch of Reionization (EoR) marks the transition from a fully neutral to a highly ionized intergalactic medium (IGM) due to the ultra-violet and X-ray radiation of early stars, galaxies, and black holes. Detection of the Gunn-Peterson effect, i.e., Lyα absorption by the neutral IGM, toward the most distant quasars (z ∼ 6), and the large scale polarization of the CMB, corresponding to Thompson scattering during reionization, have set the first constraints on the reionization process. These results suggest significant variance in both space and time, starting perhaps as far back as z ∼ 11 (WMAP 7 year data) and extending to z ∼ 6 [3]. In case of the Gunn-Peterson effect, the IGM becomes optically thick to Lyα absorption for a neutral fraction as small as ∼ 10^{-3} at z ∼ 6. Alternately, it has been widely recognized that mapping the red-shifted HI 21 cm line has great potential for direct studies of the neutral IGM during reionization [4,5].

There are number of upcoming low-frequency arrays with key science goals to detect the HI 21 cm signal from the EoR. This includes the Murchison Widefield Array [MWA], Precision Array to Probe Epoch of Reionization [PAPER], Low Frequency Array [LOFAR] and Giant Meterwave Radio Telescope [GMRT]. One of the major challenges for all of these upcoming arrays will be the removal of the continuum foreground sources in order to detect the faint HI signal from the EoR.
A variety of continuum foregrounds complicate redshifted 21 cm measurements of the EoR. Diffuse Galactic synchrotron emission dominates the low-frequency radio sky and is approximately four orders of magnitude brighter than the $\sim 10$ mK HI 21 cm signal at the frequency relevant to reionization ($\nu \approx 150$ MHz). In addition, Galactic and extragalactic free-free emission contribute additional flux to the diffuse foreground. Radio point sources from AGN, radio galaxies, and local Galactic sources are numerous and particularly challenging. The brightest of these sources have fluxes well above 1 Jy and are seven or eight orders of magnitude above the EoR signal in low-frequency radio maps. The distribution of point sources also extends to very faint levels such that the brightness temperature due to confused sources in upcoming arrays will be $\sim 10$ K, or three orders of magnitude brighter than the 21 cm background.

In this paper we discuss how the radio interferometric imaging techniques are going to affect the foreground source modeling and subsequent removal from the data-set in order to search for the EoR signal. Extensive research is ongoing on foreground source modeling at these low frequencies and their subsequent removal from the EoR datasets. Since attempting to observe a signal below the confusion limit of foreground sources is a novel aspect of 21 cm experiments, most of these works primarily focus on the removal of faint and confused sources that fall below a specified cutoff flux limit of 1 Jy. Most of the other works implicitly assume that the bright foreground sources above 1 Jy have been removed perfectly from the raw EoR data-sets. In reality, imperfect instrument calibration or any errors in the subtracted foreground model will introduce artifacts and leave residual contamination in the data after bright source removal. These residuals may interfere with either the subsequent faint source subtraction or the ultimate detection and characterization of the redshifted HI 21 cm signal.

In [1] we dealt with removal of the bright point sources above 1 Jy and the limitations that will be caused due to imperfect removal of such sources in the image plane. In [2] we have extended these initial analysis in order to estimate the residual contamination in the power spectral domain of improper bright source subtraction.

2. Method of Simulation

For our simulations, we have used a simple sky model that only includes bright radio point sources. No diffuse emission from the Galaxy is included as a part of the sky model; and the 21 cm signal and thermal noise are also omitted. Our sky model is derived from the log $N$–log $S$ distribution of source counts from the 6C survey at 151 MHz.

We have assumed a fiducial MWA configuration for these simulations. The details of the array parameters are included in Table 1. For a field-of-view of 15$^\circ$, total number of point sources above 1 Jy is $\sim 170$. In our sky model all the foreground sources are flat spectrum, i.e. with zero spectral index. Hence, the only frequency dependent contribution is from the point spread function or the array beam.

The observed visibilities are simulated for a 6 hour observation ($\pm 3$ hours in Hour-angle) using the sky model and the array specifications. Next, we generate the foreground model corrupted with calibration errors that will be subtracted from the observed visibilities. Here, we assume that the residual errors in a given antenna are perfectly correlated for the duration of one 6-hour observing night, but perfectly uncorrelated between successive observing nights. We further assume that the residual errors between antennas are perfectly uncorrelated at all times. The residual visibilities are calculated by subtracting the model visibilities from the simulated visibilities. Resultant images from the above steps followed in the simulations are shown in panels (a) of Figures 5, 7, and 9 in [1]. Now, intermediate image cubes are obtained from these intermediate residual visibilities and are subjected to the second stage of redshifted 21 cm foreground subtraction that aims to remove faint and confused sources by fitting and subtracting a low-order polynomial along the frequency axis for each line of sight in the data cube. Thus we obtain the final residual image cubes (as shown in panels (b) of Figures 5, 7,
Table 1. Array Specifications

| Parameters                  | Values                                      |
|-----------------------------|---------------------------------------------|
| No. of Tiles                | 512                                         |
| Central Frequency           | 158 MHz ($z \sim 8$)                        |
| Field of View               | $\sim 15^\circ$ at 158 MHz. ($\propto \lambda$) |
| Synthesized beam            | $\sim 4.5'$ at 158 MHz. ($\propto \lambda$) |
| Effective Area per Tile     | $\sim 17 m^2$                               |
| Maximum Baseline            | $\sim 1.5$ km                               |
| Total Bandwidth             | 32 MHz                                      |
| $T_{sys}$                   | $\sim 250$ K                                |
| Channel Width               | $\sim 32$ kHz                               |
| Thermal Noise               | $\sim 7.55$ mK $(5000$ hours & $2.5$ MHz)   |

The final step in our simulations is to calculate power spectra from the intermediate and final residual image cubes. These residual foreground power spectra are compared with the theoretically predicted 21 cm power spectrum and expected thermal noise power spectrum for the MWA. We calculate three forms of the residual power spectra from our final data cubes: the derived angular power spectrum for a narrow frequency channel (shown as Figure 6 in [2]), the spherically averaged three-dimensional power spectrum from the entire data cube (shown as Figure 8 in [2]), and the two-dimensional power spectrum found by averaging over transverse modes in the full three-dimensional power spectrum (shown as Figure 11 in [2]).

In order to simulate the observed visibilities, we have used the simulator tool in the CASA software. We have also used CASA to perform the imaging, visibility subtraction and polynomial subtraction. The rest of the operations are performed using separately written Python scripts.

3. Results and Conclusions

In [1], we explored the calibration accuracy needed to allow direct imaging of cosmic Stromgren spheres with very deep integrations by the MWA. Our simulations demonstrated that a calibration accuracy of 0.2% systematic error in gain amplitude per night of observing (or 0.2 degree in phase) is needed for the residual contamination to be below the thermal noise in a part of the image map far from any bright sources for a long integration by the MWA. In other words, the above accuracies will allow detection of HI 21 cm features from EoR by direct imaging using the MWA.

In [2], we focus our attention on the residual contamination that can be tolerated in measurements of HI 21 cm power spectra, rather than direct imaging of the HI 21 cm background. The information in the HI 21 cm signal field is expected to be effectively compressed in a power spectrum by averaging over many Fourier modes. Hence, the signal-to-noise ratio (SNR) in a properly chosen power spectrum measurement can be significantly higher than the per-pixel SNR in a direct imaging observation. In fact, detection of the HI 21 cm power spectrum can be achieved with the sensitivity of first generation EoR telescopes like MWA, PAPER and LOFAR. But for direct imaging of the HI 21 cm background we might need the sensitivity of next generation telescopes like the SKA.

The spherically-averaged three-dimensional 21 cm power spectrum is the primary reionization
observable targeted by the MWA. Our results show that the residual calibration accuracy of < 0.05 % would allow the detection of HI 21 cm signal in spherically-averaged three-dimensional power spectrum (Figure 8 in [2]). In comparison to the angular power spectrum, we infer that the spherically-averaged power spectra has a better tolerance for the residual calibration errors. This also reflects the fact that the angular power spectrum has been produced using a single channel map of 125 kHz, whereas the spherically-averaged spectrum is produced with the total bandwidth of 32 MHz.

However, the spherically-averaged power spectrum mixes the contribution from the line-of-sight and the transverse modes of the three-dimensional power spectrum. It should be noted that both the foregrounds and the predicted redshifted 21 cm signal that includes redshifted-space distortions have aspherical structure in the Fourier domain [6]. Hence, it is critical to decouple the contributions of these two modes by constructing the two-dimensional power spectrum. In Figure 1, we have shown the results of the obtained two-dimensional power spectra from the final residual visibilities (for 0.1% calibration error). Figure 2 shows the expected HI 21 cm power spectrum. These results show clear advantages of the two-dimensional power spectrum over the spherically-averaged power spectrum. The results for residual calibration errors indicate that at transverse $k < 0.05 \, \text{Mpc}^{-1}$, we are able to probe most of the line-of-sight $k$ scales where the HI signal is dominant over the residual foreground power.

![Figure 1.](image1.png)  
**Figure 1.** The two-dimensional power spectrum from the final residual image cube is shown for a fiducial calibration error level of 0.1% (as in Figure 11-b of [2]).

![Figure 2.](image2.png)  
**Figure 2.** Predicted theoretical two-dimensional power spectrum of the HI 21 cm signal (as in Figure 9-b of [2]).

We expect to build on our present analysis in future work by exploring other arrays like LOFAR or SKA, addressing foreground removal issues of extended bright sources and including calibration issues such as wide-field gain calibration of the primary beam and the ionosphere.

References

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