Prospects of Detecting Individual Ionized Bubbles in HI 21-cm Maps Using uGMRT

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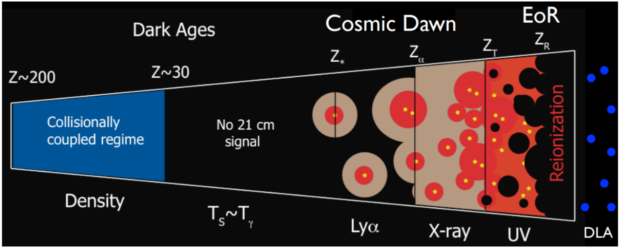
Outline

Motivation



[Pritchard and Loeb, 2012]

- Around redshift z=15-30[Barkana and Loeb, 2001] first luminous sources formed.
- UV radiations from first stars, galaxies, quasars starts to ionize the neutral hydrogen in the Inter Galactic Medium.
- Expected that there are ionized regions around the sources of reionization like stars, galaxies or quasars.
- Motivation is to study individual ionized bubbles in 21-cm maps or observations.
- Introducing a technique here to detect individual ionized bubbles efficiently.

Modelling Ionized Bubbles in 21-cm Maps

- Simulated an ionized bubble(comoving radius = 25 Mpc) inside a 3D box centered at redshift z=7.085(Mortlock quasar[Mortlock et al., 2011]).
- Mimicking the uGMRT observations:
  - Field of view=$3.36^\circ \times 3.36^\circ$
  - Box size in grid points=512×512
  - Box size in comoving scale=527.15 Mpc
  - Angular resolution=23.64 arcsecond
  - Spatial resolution=1.0296 Mpc
- Considered the sky at 175 MHz and used 256 channels with a total bandwidth of 16 MHz, resulting in a channel width of 62.5 kHz.

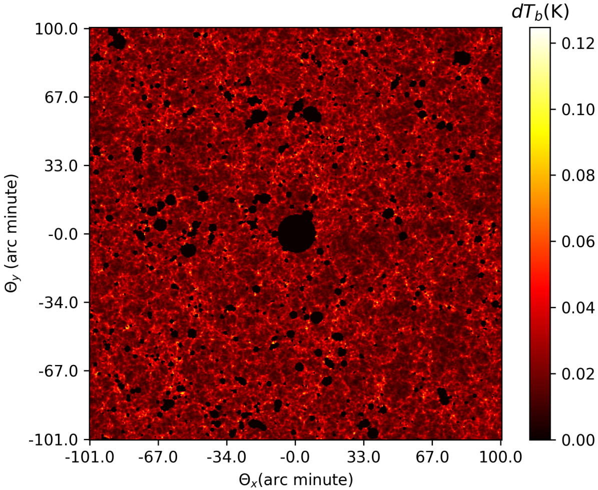


Figure: This shows the differential brightness temperature map at redshift 7.085 and the ionized bubble of bubble size 25 Mpc at its center.

[Image credit: Chandra Shekhar Murmu]

Modelling Galactic Foregrounds

- Three primary contributors to the Galactic foregrounds:
  - Diffuse Galactic Synchrotron Emission (DGSE)
  - Radio synchrotron emission from point-like sources
  - Free-free radio emission from diffuse ionized gas
- Only the Diffuse Galactic Synchrotron Emission has been considered here as galactic foreground as it is most prominent and most significant.
- We model the angular power spectrum corresponding to the diffuse galactic synchrotron emission as a power law given by the following equation[Choudhuri et al., 2014].

$$C_l{}^M = A_{150} \times \left(\frac{1000}{l}\right)^{\beta} \left(\frac{\nu_0}{\nu}\right)^{2\alpha} \tag{1}$$

Where, Here, $\nu_0 = 150$ MHz, the power law index $\beta = 2.34$, $A_{150} = 513$ mK^2 and $\alpha = 2.8$ [Ghosh et al., 2012].

- To generate the Fourier components on the grid, we used the following equation[Choudhuri et al., 2014]:

$$\Delta \tilde{T}(U) = \sqrt{\frac{\Omega {C_l}^M}{2}}[x(U) + iy(U)] \tag{2}$$

  Here, Ω denotes the total solid angle, while $x(U)$ and $y(U)$ are independent Gaussian random variables with zero mean and unit variance.
- Applied the inverse Fourier transform on the grid points to obtain the brightness temperature fluctuation on the sky due to the GDSE.

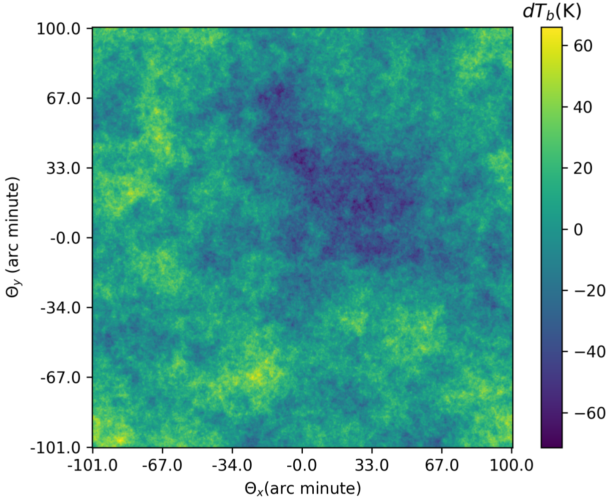


Figure: This shows the differential brightness temperature fluctuations for the Diffuse Galactic Synchrotron Emission for the central frequency channel.

Simulating Noise

- Simulated the noise contribution in the Fourier plane.
- Considering it to be Gaussian random noise with zero mean.
- Calculated the rms value using the following equation[Datta et al., 2007],

$$\sqrt{< N^2 >} = \frac{\sqrt{2} k_B T_{sys}}{A_{eff} \sqrt{\Delta\nu \Delta t}} \quad (3)$$

  Where, T_{sys} →total system temperature,
  k_B →Boltzman constant,
  A_{eff} →effective collecting area of the antenna,
  $\Delta\nu$ →channel width,
  Δt →integration time.
- Considering the uGMRT parameters[Datta et al., 2007], $T_{sys} = 320$K, $\frac{A_{eff}}{2k_B} = 0.33$K/Jy, $\Delta\nu = 62.5$kHz and Δt=16 sec.
- Calculated the rms value of the noise to be 0.685 Jy.

Simulating Visibility

- Simulating the Sky:
  - Combined simulated 21-cm maps including ionized bubble and foreground data at 175 MHz.
  - Obtained a more realistic representation of the sky.

- Mock Visibility Data Generation:
  - Considered uGMRT baseline distribution.
  - Performed Discrete Fourier Transform on each of the 256 frequency channels.
  - Added the Gaussian random noise.
  - Generated mock visibility data at uGMRT baselines.

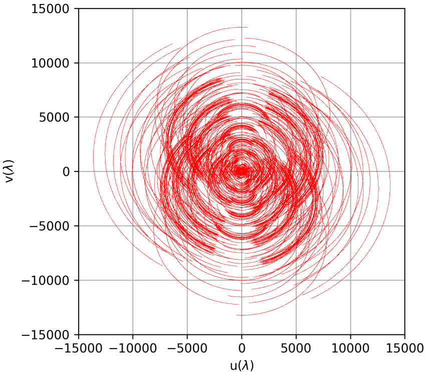
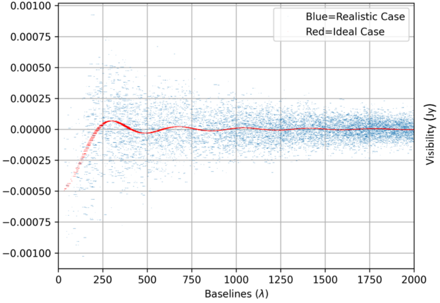
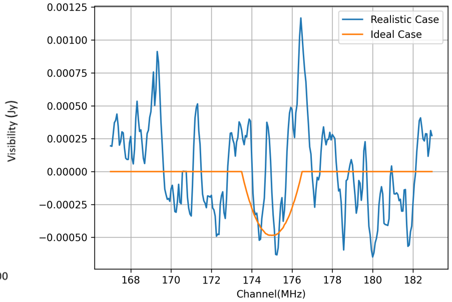


Figure: This shows the baseline coverage for 8 hours of uGMRT 175 MHz observation

Simulating Visibility:21-cm Signal



(a) Visibility vs baseline plot for analytical and simulated scenarios



(b) Visibility vs channel plot for analytical and numerical scenarios

Figure: Comparing analytical scenario with uniform background HI distribution and simulated visibility data with non-uniform HI distribution considering only the signal from the HI map.

Simulating Visibility:Total Signal

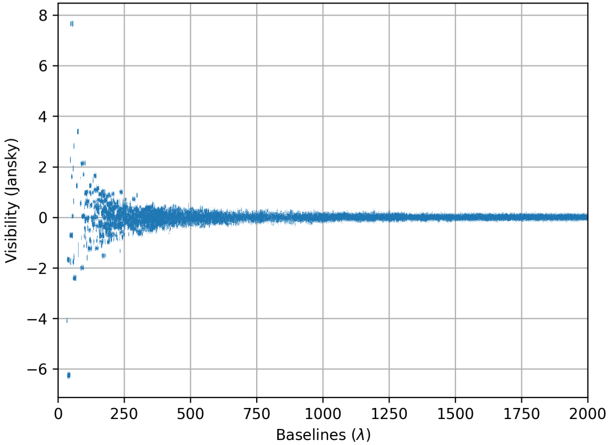
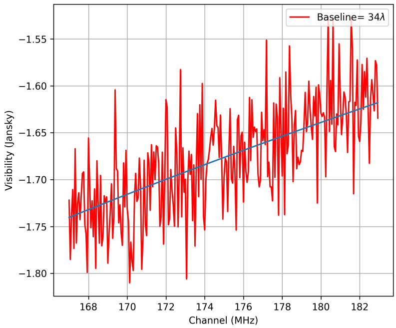
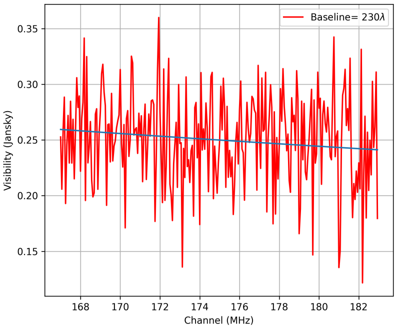


Figure: Visibility vs baselines considering the visibility data of total signal for the central frequency channel.



(a) Visibility vs Channel plot for total signal with a small baseline value.



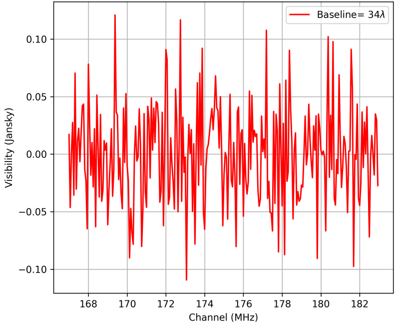
(b) Visibility vs Channel plot for total signal with a larger baseline value.

Figure: Here, it is shown that at large baselines noise dominates over 21-cm signal and foreground, and at low baselines galactic foreground dominates.

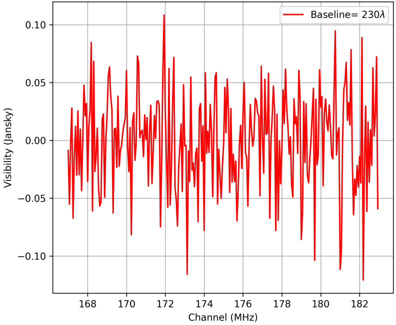
Subtracting foreground contribution

- Foreground contributions are several times stronger than the HI 21-cm signal originating from the Epoch of Reionization (EOR).
- Applying the curve fitting method in each baseline, leveraging the frequency dependency of the considered diffuse galactic synchrotron emission.

Subtracting Foreground Contribution: Residual Signal



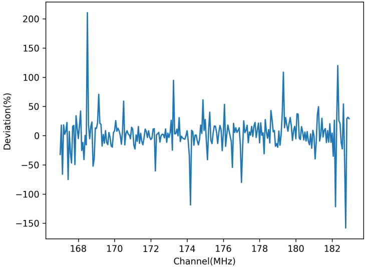
(a) Visibility vs Channel plot for residual data with a smaller baseline value.



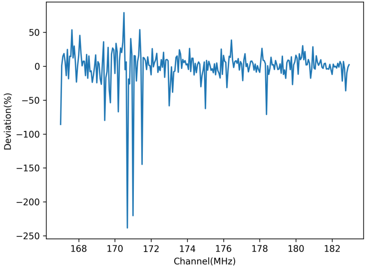
(b) Visibility vs Channel plot for residual data with a larger baseline value.

Figure: Here, the Visibility plots for the data after the foreground subtractions are shown for two different baselines.

Subtracting Foreground Contribution: Deviation



(a) Deviation of the residual data for smaller baseline(34λ).



(b) Deviation of the residual data for larger baseline(230λ).

Figure: Here, the deviation of the residual data (signal+noise) from the real Visibility data considering signal and noise is illustrated for two different baselines.

Detecting Ionized Bubbles: Match Filtering Technique

- **Match Filter:** A promising method for detecting ionized bubbles in the HI map is the application of the match filter, providing maximum signal-to-noise ratio [Datta et al., 2007].
- **Estimation Formula:** The estimator for detecting the ionized bubble is given by:

$$\hat{E} = \frac{\sum_{a,b} S_f^*(\vec{U}_a, \nu_b)\hat{V}(\vec{U}_a, \nu_b)}{\sum_{a,b} 1} \tag{4}$$

  where $S_f(\vec{U}, \nu)$ is a filter constructed for detecting the specific ionized bubble. $\vec{U}_a$ and ν_b represent different baselines and frequency channels in observations.
- **Variance Calculation:** The variance of the estimator, considering uncorrelated noise in different baselines and frequency channels, is given by:

$$\left\langle (\Delta\hat{E})^2 \right\rangle_{NS} = < N^2 > \frac{\sum_{a,b} \left| S_f(\vec{U}_a, \nu_b) \right|^2}{\left[\sum_{a,b} 1\right]^2} \tag{5}$$

Detectibility

- Signal to noise ratio(SNR) is given by the following ratio:

$$SNR = \frac{\left\langle \hat{E} \right\rangle}{\sqrt{\left\langle (\Delta \hat{E})^2 \right\rangle_{NS}}} \tag{6}$$

- The SNR is maximum if we use the signal that we wish to detect as the filter.

$$S_f(U, \nu) = -\pi \bar{I}_\nu x_{HI} {\theta_R}^2 \left[\frac{2J_1(2\pi U\theta_R)}{2\pi U\theta_R} \right] \Theta \left(1 - \frac{|\nu - \nu_c|}{\Delta \nu_b} \right) \tag{7}$$

Where, $\bar{I}_\nu$ is radiation from uniform background HI distribution, x_{HI} is neutral hydrogen fraction, θ_R is angular bubble radius, J_1 is first order bessel function and $\Delta\nu_b$ is bubble size in frequency space.

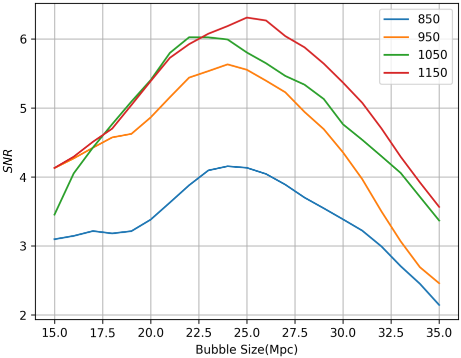


Figure: SNR values for 4 different noise realizations with 2048 hours of observation time.

Peak SNR	**Original Bubble Size(Mpc)**	**Extracted Bubble Size(Mpc)**
4.2	25	24
5.6	25	24
6.0	25	22
6.3	25	25

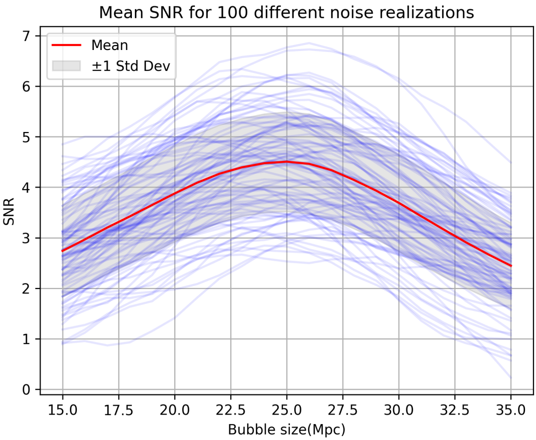


Figure: Here, mean SNR is depicted, considering 100 different noise realizations for a 2048-hour observation time. The SNR peaks at a bubble size of 25 Mpc which is same as the original bubble size.

Conclusion

- We have investigated the possibility of detecting individual HII bubbles in 21-cm map using uGMRT.
- We simulated HI maps around quasar HII regions that is consistent with Mortlock quasar.
- We have also simulated mock data considering signal, foreground and noise.
- Then we have subtracted foregrounds and applied match filtering technique.
- Found that uGMRT can detect bubbles of size around 25 Mpc with 2000 hours of observational data analysis.

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