PAPER Memo 2

Calibration Requirements for HI 21cm imaging of Cosmic Reionization

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Abstract.
I calculate the calibration requirements for imaging of the HI 21cm signal from the neutral intergalactic medium (IGM) during cosmic reionization. The dynamic range (DNR) requirements are very demanding. The expected signal at $z \sim 8$ (158MHz) is about 73μJy, assuming a $10'$ 'bubble' of 10mK brightness. For a typical $20^o \times 20^o$ field of view, the expected brightest source is 34Jy. Hence, assuming we require a 4σ detection, the dynamic range requirements = Brightest source/rms noise = 34Jy/18μJy $= 1.9 \times 10^6$. This DNR requirement then sets a requirement to residual antenna-based phase errors resulting from self-calibration of $< 0.023^o$, assuming an array of 9500 dipoles arranged in 3×3 tiles.

1. Introduction

Cosmic reionization is the last major phase of cosmic evolution that remains to be explored. Reionization sets a critical benchmark in cosmic structure formation, indicating the formation of the first luminous objects which act to reionization the neutral intergalactic medium (IGM). Recent observations of the Gunn-Peterson effect toward the most distant ($z > 6$) SDSS QSOs, plus large scale polarization of the CMB, as well as other studies, have set the first observational constraints on cosmic reionization, indicating an extended process in time and space, from $z \sim 14$ down to $z \sim 6$ (Fan, Carilli, Keating 2006).

It is widely recognized that the most direct and telling probe of cosmic reionization will be through the HI 21cm line emission from the neutral IGM. Figure 1 shows a recent simulation of the expected HI 21cm signal from reionization. The fluctuating signal includes large scale structure due to standard density fluctuations, plus large scale ionized regions surrounding the first groups of galaxies and AGN, plus variations in the spin temperature.

Detecting the HI 21cm signal from cosmic reionization is demanding both in terms of the raw sensitivity, and the dynamic range requirements. In this memo I consider the calibration requirements for imaging the HI 21cm IGM structures during reionization. In a future memo I will consider the requirements for a power spectral analysis. These calculations are

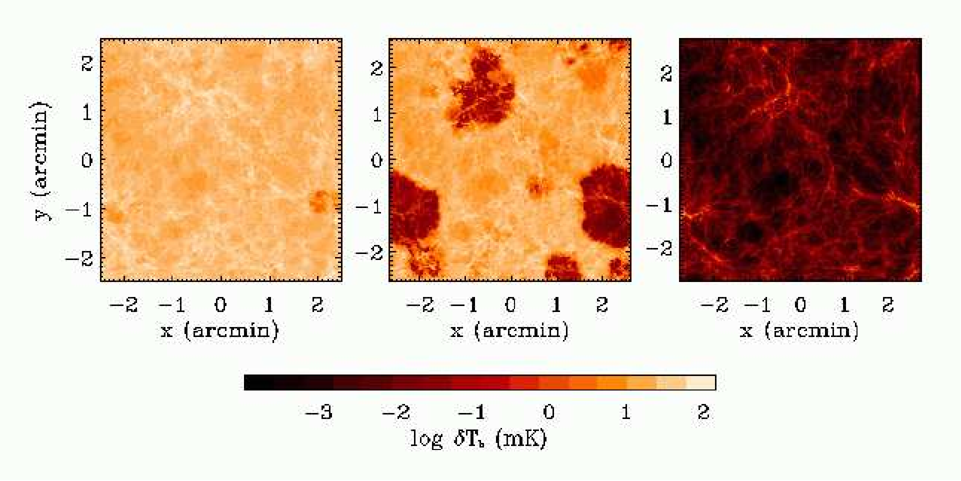

Figure 1. The simulated HI 21cm brightness temperature distribution during reionization at $z = 12, 9, 7$ (left to right; Zaldariagga, M., Furlanetto, S., Henquist, L. 2004)

purposefully order-of-magnitude, in order to get a general understanding of the demands of the science, without being too specific about the exact telescope design (stations, baselines, dipole design, uv coverage...).

2. Typical signals, sensitivities, and the mean foreground

A number of groups have calculated the expected HI 21cm signals from cosmic reionization, including large bubbles associated with bright QSOs, and clustering of star forming galaxies (Wyithe & Loeb 2006; Zaldarigga et al. 2004; Wyithe, J.S., Loeb, A., Barnes, D. 2005). The larger structures will vary from a few to 15 arcmin in size, with a depth of 20×f(HI) mK, where f(HI) is the overall neutral fraction of the IGM by volume.

For the sake of calculation, I will assume a target signal for detection of 10mK and $10'$ in size at $z = 8$. This implies an observing frequency of $\nu = 157.8$MHz, or observing wavelength, $\lambda = 1.9$m. For reference, at $z \sim 8$, $10' = 3.2$ Mpc physical size, or in co-moving coordinates $10' = 3.2/(1+z) = 0.36$ Mpc co-moving, and in terms of the Hubble expansion, 3.2 Mpc (physical) = 1.6 MHz. The angular size of $10'$ corresponds to a baseline length of 650m at 157.8MHz.

The relationship between brightness temperature and flux density is given by:

$$\mathrm{T_B} = 1360 \frac{\mathrm{S}_\nu}{\theta^2} \lambda^2 \ \mathrm{K}$$

where S_ν is the flux density in Jy, θ is the angular size, in arcseconds, and λ is the observing wavelength in centimeters. In this case, a 10mK signal at 1.9m and $10'$ in size corresponds to 73μJy.

The sensitivity of a radio telescope is given by the radiometry equation:

$$\mathrm{rms} = 3000 \frac{\mathrm{T_{sys}}}{\epsilon \mathrm{NA}} (\Delta\nu\ \mathrm{t})^{-1/2}\ \mathrm{Jy}$$

where ϵ is the antenna efficiency, N is the number of antennas, A is the area of each antenna, in m^2, $\Delta\nu$ is the bandwidth (Hz), and t is the integration time (seconds). The system temperature is the sum of the receiver temperature, which I assume is of order 100 K, and the contribution from the sky foreground. The sky is about 90% diffuse Galactic emission, and 10% extragalactic radio sources. In the coldest regions, the sky contributes: $\mathrm{T_{sky}} \sim 100(\frac{\nu}{200\mathrm{MHz}})^{-2.8}$, or about 200K at 157.8MHz. Note that the expected signal is roughly 2×10^4 times weaker than the diffuse foreground brightness temperature.

What collecting area is needed to detect the 73μJy signal at 4σ at 157.8MHz in 1000 hrs, assuming a bandwidth of 1.6MHz and an efficiency of 60%? The required area $= 3.4 \times 10^4$ m^2. This corresponds to roughly 9500 dipoles, assuming the dipole collecting area is of order λ^2.

3. Dynamic range

A significant challenge to wide field, low frequency interferometric imaging is image dynamic range, set by residual calibration errors. Besides the diffuse background, every field will have bright extragalactic and Galactic continuum sources.

As a rough estimate for the number of sources expected in a given field, I adopt a field size of $20^o \times 20^o$, corresponding to the field of view of a receptor 'tile' of 3×3 dipoles. Using the 3C catalog, the bright source counts at 1.9m follows roughly:

$$\mathrm{N}(> \mathrm{S}) = 0.29\ \mathrm{S}^{-1.36}\ \mathrm{deg}^{-2}$$

where N is the number of source per deg^{-2} brighter than S in Jy. Hence, in a typical 400 deg^2 region, I expect one source brighter than 34 Jy at 157.8 MHz.

The dynamic range requirement = (Peak in field)/(rms required). The rms required for a 4σ detection = 73/4 = 18 μJy. Hence, the DNR = 34 Jy/18 μJy = 1.9×10^6.

Perley (1999) derives the dynamic range limit for a synthesis array assuming 'random' antenna based phase errors, $\Delta\phi$ (in radians) (equ. 13-8):

$$\mathrm{DNR} \sim \frac{\mathrm{N}}{2^{1/2}\Delta\phi}$$

where, again, N is the number of elements in the array. Assuming 9500 dipoles grouped in 3x3 tiles implies N = 1055 elements. The requirement then on the phase calibration is: $\Delta\phi < 0.023^o$.

4. Some other issues

Low frequency arrays such as LOFAR, MWA, PAPER, and PAST are considering calibration schemes to reach this extremely demanding calibration requirement of phase errors $< 0.02^o$. Most schemes involve some form of self-calibration using sources in the FoV, with continuous updating of a global sky model using the observing data itself. Signal-to-noise may also be increased by using some form of smoothing in time and space, since errors caused by eg. the ionosphere will have a characteristic spatial and temporal coherence. I briefly raise some issues concerning the wide fields required.

Wider fields allow for more bright sources for calibration, and for more 'statistics' when measuring the power spectrum. This latter issue will be considered in a future memo. However, the increased number of sources also increases the dynamic range requirements, eg. if we use a $30^o \times 30^o$ FoV, the brightest source in a typical field increases by a factor of 1.7. Also, ionospheric isoplanatic patch issues become more problematic over wider fields. Overall, there should be an optimal FoV, that balances the needed measurement set with the demanding calibration requirements.

Lastly, I have not considered the issue of frequency dependent calibration. The octave, or larger, fractional bandwidths of the telescopes under construction will require either independent calibration per channel, or some form of multi-frequency synthesis calibration, including estimates of the spectral indices of the sources in the global sky model.

References

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