Peering towards Cosmic Dawn
Proceedings IAU Symposium No. 333, 2018
V. Jelić & T. van der Hulst, eds.

doi:10.1017/S1743921317011127

Status of Foreground and Instrument Challenges for 21cm EoR experiments – Design Strategies for SKA and HERA

Nithyanandan Thyagarajan[1]

Jansky Postdoctoral Fellow
[1]National Radio Astronomy Observatory,
1003 Lopezville Rd, Socorro, NM 87801, USA
email: `t_nithyanandan@nrao.edu`

Abstract. Direct detection of the Epoch of Reionization (EoR) via redshifted 21 cm line of H I will reveal the nature of the first stars and galaxies as well as revolutionize our understanding of a poorly explored evolutionary phase of the Universe. Projects such as the MWA, LOFAR, and PAPER commenced in the last decade with the promise of high significance statistical detection of the EoR, but have so far only weakly constrained models owing to unforeseen challenges from bright foreground sources and instrument systematics. It is essential for next generation instruments like the HERA and SKA to have these challenges addressed. I present an analysis of these challenges – wide-field measurements, antenna beam chromaticity, reflections in the instrument, and antenna position errors – along with performance specifications and design solutions that will be critical to designing successful next-generation instruments in enabling the first detection and also in placing meaningful constraints on reionization models.

Keywords. cosmology: observations, dark ages, reionization, first stars – instrumentation: interferometers – techniques: interferometric

1. Introduction

During the cosmic dawn and epoch of reionization (EoR), the Universe witnessed the production of a significant number of ionizing photons from the first astrophysical objects that completely re-ionized it. However, it is a poorly explored phase in the history of the Universe. Direct detection of H I via the redshifted 21 cm line promises to be one of the most direct probes of these epochs. Current experiments to detect the EoR signal in power spectra include the Murchison Widefield Array (MWA), the Low Frequency Array (LOFAR), and the Precision Array for Probing the Epoch of Reionization (PAPER).

Despite having theoretical sensitivity to detect the EoR power spectrum with high significance (Beardsley *et al.* 2013; Thyagarajan *et al.* 2013), it was recently learnt that these studies are severely limited by instrumental systematics and bright foregrounds (for example, Ali *et al.* 2015). Foregrounds – primarily Galactic and extragalactic synchrotron radiation – overwhelm the faint EoR H I signal by ~ 5 orders of magnitude. The latter, along the line-of-sight direction (redshift), imprint small spectral fluctuations that are superimposed on the smooth synchrotron and free-free foreground spectrum. Due to the extreme dynamic range requirement, any spectral signature unaccounted for or mis-subtracted will contaminate the EoR signal and thus severely degrade sensitivity. Future instruments such as the Hydrogen Epoch of Reionization Array (HERA; DeBoer *et al.* 2017) and the Square Kilometre Array (SKA) must be designed robustly.

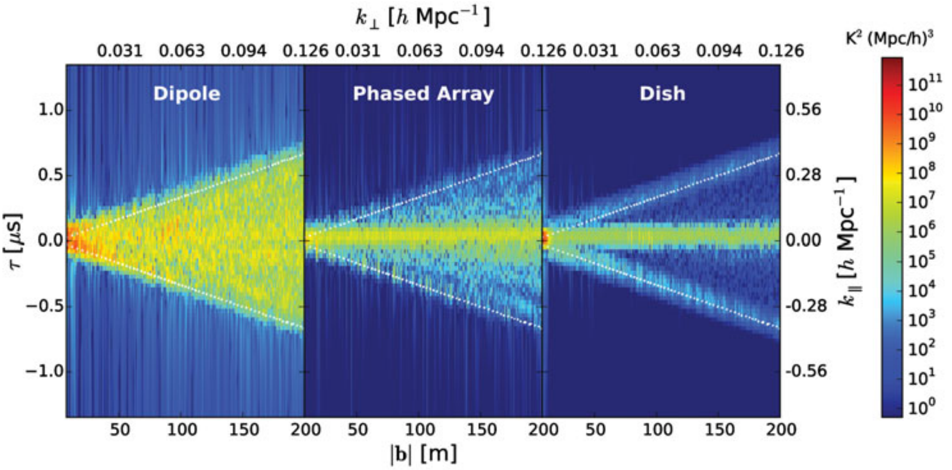


Figure 1. Simulated delay power spectra for different antenna shapes – dipole (left), phased array (middle), and dish (right) – at 185 MHz. White dotted lines mark the boundaries of the *foreground wedge* determined by the horizon delay limit and antenna spacing. Foreground power close to the horizon delay limits in all three cases is significant even on long baselines due to the wide-field *pitchfork* effect. The amplitude of this feature strongly depends on the shape of the antenna element. The contamination due to this feature both inside the *foreground wedge* and beyond is highest for a dipole (due to strong response near the horizon), intermediate for a phased array, and least for a dish. Figure adopted from Thyagarajan *et al.* (2015a).

2. Limiting Systematic Spectral Artifacts

Here, I identify some of the important sources of spectral artifacts that contaminate the cosmological signal and degrade the sensitivity severely, as well as provide inputs to instrument design that mitigates these problems. I developed the Precision Radio Interferometry Simulator – PRISim (`https://github.com/nithyanandan/PRISim`) – to model these different effects into an end-to-end signal propagation through the instrument.

2.1. *Wide-field "pitchfork" effect and aperture design*

In wide-field measurements, diffuse foreground emission from wide off-axis angles appears enhanced in the delay spectrum near the edges of the *foreground wedge* even on wide antenna spacings (Thyagarajan *et al.* 2015a,b). Called the *pitchfork* effect, this arises due to severe foreshortening of baseline vectors towards the horizon along the line joining the antenna pairs, thereby enhancing their sensitivity to large scale structures in these directions. This translates to enhanced diffuse foreground power from near the horizon appearing at the horizon limits of the *foreground wedge*. Since these modes lie adjacent to those considered sensitive to the EoR signal, they cause a significant contamination of line-of-sight modes critical for EoR signal detection.

Because the *pitchfork* depends on the antenna's angular sensitivity at wide angles close to the horizon, the levels of foreground contamination in the *EoR window* caused by the "pitchfork" effect vary substantially across different antenna shapes (Thyagarajan *et al.* 2015a). Figure 1, for example, shows that the *pitchfork* effect is severe in a dipole (such as in PAPER), intermediate in a phased array (such as in MWA), and least in a dish (such as in HERA). Thus, an aperture with highly suppressed sensitivity at wide angles close to the horizon is preferred.

2.2. *Contamination from antenna beam chromaticity*

With spectral features in the antenna beam, the foreground contamination inherently extends farther along $k_{\|}$, spilling over into and contaminating the clean cosmological modes. The effects of antenna beam chromaticity were studied in Thyagarajan *et al.* (2016) using an achromatic *Airy* pattern, a chromatic *Airy* pattern, and a more realistic HFSS model (DeBoer *et al.* 2017), and found that this spectral structure degrades power spectrum sensitivity by many orders of magnitude.

This significant contamination is not bound by the horizon limits as this is caused by spectral structure in the antenna beam pattern and is independent of geometric phases. Hence, delay-based complex deconvolution techniques (Parsons & Backer 2009; Parsons *et al.* 2012b) that rely on smoothness of foreground spectra and the spectral window will have inadequate information to accurately deconvolve the intrinsic spillover arising from the chromaticity of the antenna beam. Thus, the chromaticity of antenna beam needs to be controlled in EoR experiments to keep this contamination sufficiently low.

2.3. *Design specifications to suppress reflections in the instrument*

Reflections in the instrument are a primary and inevitable cause of spectral structure in antenna power patterns and the signal chain. Patra *et al.* (2017) and Ewall-Wice *et al.* (2016) discuss the measured and simulated reflections respectively between a dish and its feed for HERA. Reflections between different antennas also causes chromaticity in the antenna beam. Reflections replicate foreground power at larger line-of-sight $k_{\|}$ modes and thus contaminate these critical modes which is in addition to that already present due to spectral structures in the foregrounds and the instrument. This is equivalent to standing-wave ripples in the spectrum.

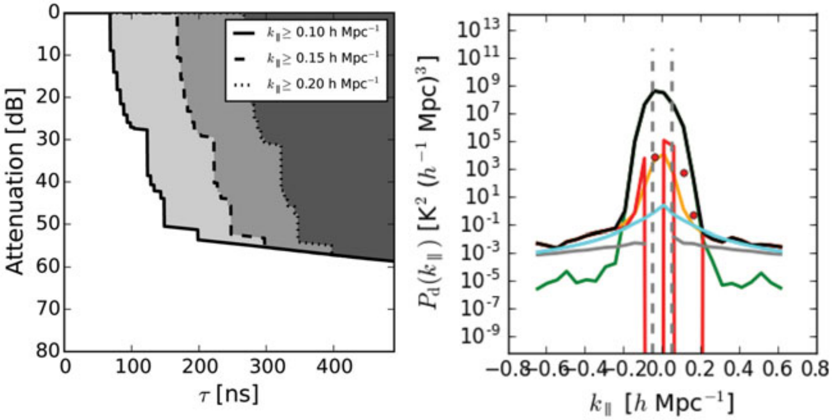
Thyagarajan *et al.* (2016) presented a cosmologically motivated approach to obtain design specifications on instrument systematics caused by such reflections. Figure 2a shows the amount of suppression required as a function of delay (spectral modes) in order to keep the effects of dish–feed reflections below the level of the cosmological signal.

2.4. *Effects of antenna position errors*

Redundant arrays like HERA and phase II of the MWA rely on the accuracy of the antenna layout to calibrate their data using redundant calibration schemes (Zheng *et al.* 2014), which usually assume the gains are entirely antenna-based. Deviations from redundancy invalidate this assumption by introducing baseline-dependent errors. This will result in calibration errors especially along the spectral axis. Even small spectral artifacts may cause contamination at levels larger than the EoR signal. Figure 2b shows the additional spectral contributions in delay spectrum on a 14.6 m HERA baseline due to random deviations of rms $\approx$ 2.4 cm in antenna positions. Also shown are the delay spectra of fiducial cosmological models for reference (Mesinger *et al.* 2011; Lidz *et al.* 2008). It can be seen that the spectral contamination introduced by antenna position errors can completely overwhelm the cosmological signal if the antenna positions are not accurate to within a few cm (Thyagarajan *et al.* in preparation).

3. Summary

Systematic spectral signatures from the instrument and radio emission from bright foreground objects pose the biggest challenges to EoR, and more generally intensity mapping experiments, at low frequencies. Lessons from contemporary experiments have shown that the best solutions to tackle these challenges are provided by robust instrument design rather than in post-processing alone.



(a) Constraints on dish–feed reflections (b) Effects of antenna position errors

Figure 2. (a) Minimum required attenuation (in dB) for dish-feed reflections required to keep the reflected foreground power below EoR H I signal power for all $k_\parallel$-modes greater than $0.1\,h$ Mpc^{-1} (solid), $0.15\,h$ Mpc^{-1} (dashed) and $0.2\,h$ Mpc^{-1} (dotted). Figure adopted from Thyagarajan *et al.* (2016). (b) Antenna position errors of rms 2.4 cm add spectral structure (in red and orange) to the ideal power spectrum (in green) leading to a contaminated result (black). Fiducial EoR models are shown in solid gray (Mesinger *et al.* 2011) and cyan (Lidz *et al.* 2008).

Studies using PRISim have shed light on a number of foreground and instrument characteristics critical for 21 cm EoR experiments. The wide-field *pitchfork* effect can be mitigated by a careful design of aperture. The chromaticity of antenna beams and reflections in the mechanical structures and the signal chain cause non-negligible spectral structures that can severely hinder EoR detection. A performance specification metric has been derived that will allow the experiment to detect EoR despite the reflections by adequate suppression. In measurements relying on redundant sampling of spatial modes, deviations from redundancy in the layout can cause severe spectral artifacts and thus require a precision of the order of a few cm. Inputs from these analyses have been integrated into the HERA design and similar studies are underway for the SKA as well.

References

Ali, Z. S., Parsons, A. R., Zheng, H., *et al.* 2015, *ApJ*, 809, 61
Beardsley, A. P., Hazelton, B. J., Morales, M. F., *et al.* 2013, *MNRAS*, 429, L5
DeBoer D. R., *et al.* 2017, *PASP*, 129, 045001
Ewall-Wice, A., Bradley, R., DeBoer, D., *et al.* 2016, *ApJ*, 831, 196
Lidz, A., Zahn, O., McQuinn, M., Zaldarriaga, M., & Hernquist, L. 2008, *ApJ*, 680, 962
Mesinger, A., Furlanetto, S., & Cen, R. 2011, *MNRAS*, 411, 955
Parsons, A. R. & Backer, D. C. 2009, *AJ*, 138, 219
Parsons, A. R., Pober, J. C., Aguirre, J. E., *et al.* 2012b, *ApJ*, 756, 165
Patra N., Parsons A. R., DeBoer D. R., *et al.* 2017, *arXiv* e-prints, arXiv:1701.03209
Thyagarajan, N., Udaya Shankar, N., Subrahmanyan, R., *et al.* 2013, *ApJ*, 776, 6
Thyagarajan, N., Jacobs, D. C., Bowman, J. D., *et al.* 2015a, *ApJ*, 804, 14
—. 2015b, *ApJL*, 807, L28
Thyagarajan N., Parsons A. R., DeBoer D. R., *et al.* 2016, *ApJ*, 825, 9
Zheng, H., Tegmark, M., Buza, V., *et al.* 2014, *MNRAS*, 445, 1084