Chapter 7

Summary and Future Scope

Detecting the faint redshifted 21- cm signal of neutral hydrogen originating from the epochs of Cosmic Dawn and Reionization and thus studying these unexplored epochs is expected to revolutionize our understanding of structure formation in the first one billion years of the Universe. Although detecting the redshifted 21- cm signal opens a new window to the high redshifted Universe, the detection itself is a formidable task due to the presence of bright astrophysical foregrounds and the demanding calibration of instrumental and ionospheric corruptions. Precise determination and mitigation of the instrumental and ionospheric effects in the context of EoR observations is a topic of intense research in current times. This thesis presents our efforts toward understanding the effect of time and frequency-correlated calibration/gain errors in estimating the power spectrum of the sky brightness distribution in high dynamic range observations, such as EoR observations. In what follows, I summarise the main results from my thesis and provide an outlook for continued research.

- This thesis attempts to understand the effect of residual gain errors in visibility-based power spectrum estimators by identifying their reason and discussing ways to modify the estimators to reduce them.

- We study the effect of residual gain errors in primary calibration and analytically calculate the amplitude and variance of the visibility. The visibility amplitude decreases with the phase gain error, and the variance of the visibility increases with both amplitude and phase gain error. The results are verified through simulations considering a point source at the phase center and a given gain error model.

- We quantify the effect of time and frequency correlated gain errors by considering a model in the presence of bright foregrounds in 21- cm power spectrum estimation methods using visibility correlations. The presence of time and frequency-correlated gain errors introduces a scale-dependent bias and further enhances the error in the 21- cm power spectrum measurements. These depend on the foreground model, the gain error properties, and the array configuration of the telescope.

- We consider the contributions from various types of baseline pairs involved in the visibility measurement and find that for the visibility correlation-based power spectrum estimator, the bias in the power spectrum arises mainly from those types of baseline pairs with at least one antenna in common.

- In the presence of time-correlated gains, the detection of redshifted 21- cm signal power spectrum using uGMRT baseline configuration will require more than 10000 hours of observation with the present calibration accuracy ($\sim 1\%$).

- We discuss a methodology to analytically estimate the bias and variance of the power spectrum estimates of the redshifted 21-cm signal from neutral hydrogen in the presence of bright foregrounds. We perform the simulated observations using GMRT baseline configuration in the presence of point source foreground, thermal noise, and time-correlated gains. The analytical estimates of bias and variance are in accordance with the simulation results. Given the direct simulations of gain errors in visibilities are computationally expensive, the analytical method presented can be used as an alternative fast assessment tool for gain error in any observation.

- With the increase in the standard deviation of the residual gain errors, the bias in the estimates increases and supersedes the variance. An optimal choice of the time over which the gain solutions are estimated minimizes the statistical risk.

- The bias and variance increase with the error and correlation of the gains; for frequency-correlated gains, the bias is more at low-frequency separations and decreases at larger frequency separations, while variance shoots up at larger frequency separations due to the larger noise correlations.

- Interferometers with higher baseline densities are preferred instruments for these studies. A comparison of the performance of GMRT and SKA-1 Low baseline configurations shows that the SKA-1 Low baseline configuration will require ~ 50 times less observation time than the uGMRT. This is primarily because of the baseline configuration and the larger collecting area of the SKA- 1 Low.

Although the analytical framework discussed here largely depends upon the foreground model, array configuration, and gain properties, the methodology we present in this work is rather general and applicable for any high dynamic range observations. One can use it to estimate the bias and variance of the power spectrum estimates for any telescope, given the antenna gain properties are known. The analytical framework can also be used to estimate the bias and variance for a telescope with given observation parameters without performing the full simulations, saving expansive computation time and helping us tune the observation parameters accordingly.

Studying and mitigating the effect of time and frequency correlated gain errors in the context of EoR observations are of prime importance, and our works are a few steps in that direction. The calibration/gain errors introduce complex temporal and spectral structures, which show various effects in the 21- cm power spectrum estimation methods. Numerous works on studying such calibration errors and their effects (Barry et al., 2016; Byrne et al., 2019; Dillon et al., 2018, 2020; Ewall-Wice et al., 2017; Gehlot et al., 2018; Joseph et al., 2018; Patil et al., 2016; Trott and Wayth, 2016), the effect of primary beam errors (Charles et al., 2022; Choudhuri et al., 2021; Joseph et al., 2020; Nasirudin et al., 2022), etc., for EoR 21- cm experiments are being done. Various calibration strategies are being developed and tested to solve such errors (Byrne et al., 2021; Ewall-Wice et al., 2021; Kern et al., 2019; Orosz et al., 2019; Spreeuw et al., 2020). Studying such errors and developing mitigation techniques is essential to avoid hindrances in the 21- cm signal detection. We plan to work on modeling the time and frequency correlated gain errors considering various realistic instrumental and ionospheric effects. The effect of residual gain errors is crucial for high dynamic range observations such as EoR experiments. It is essential to study and characterize the gain error properties of the telescopes. In the future, we plan for a detailed study of the antenna gain properties from actual observations for various telescopes involved in the quest to detect the H I 21- cm signal of cosmological origin. Once the realistic gain properties are known, we would like to work on developing advanced calibration algorithms and other possible mitigation techniques to solve the issue of gain errors. Finally, it would also be interesting to work on the aspects of polarization calibration and leakage and the challenges introduced in observing the H I 21 cm signal from reionization.

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