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Appendix A

Empirical Fit of the Maximum Baseline Contours

Here we present the details of the fitting function used to fit the results given in chapter 4. We use the following function to model the $U(\sigma_\delta, \sigma_\phi)$ as obtained from simulation for fixed values of $(\alpha_\delta, \alpha_\phi)$:

$$U_{max}(\sigma_\delta, \sigma_\phi) = A_0 + A_1 \exp \left[-b \sqrt{\sigma_\delta^2 + \left(\frac{\sigma_\phi}{d}\right)^2} \right] + A_2 \exp \left[-c \left(\sigma_\delta^2 + \left(\frac{\sigma_\phi}{d}\right)^2 \right) \right]. \quad (\text{A.1})$$

The best fit values of the parameters and corresponding errors are given in Table A.1.

Table A.1 Values of the fitting parameters defined in equation 23. Values are given in the second row and the corresponding errors in the parameter are in the third row.

	A_0 ($\times 10^2$)	A_1	A_2 ($\times 10^1$)	b	c	d
values	6.35	2.20	6.46	9.35	9.18	0.577
errors	0.67	0.03	0.07	0.10	0.16	0.006

We use the following function to model the $U(\alpha_\delta, \alpha_\phi)$ as obtained from simulation for fixed values of $(\sigma_\delta, \sigma_\phi)$:

$$U_{max}(\alpha_\delta, \alpha_\phi) = \sum_{m=0}^1 \sum_{n=0}^2 a_{mn} \alpha_\phi^m \alpha_\delta^n. \quad (\text{A.2})$$

The best fit values of the parameters and corresponding errors (designated by Δ) are

$$a_{mn} = \begin{bmatrix} -12.8 & 17.5 \\ 31.6 & -43.9 \\ -19.6 & 28.1 \end{bmatrix} \quad \Delta a_{mn} = \begin{bmatrix} 1.9 & 2.2 \\ 4.2 & 4.9 \\ 2.3 & 2.7 \end{bmatrix} .$$

Appendix B

Calculation of the Bias and Variance of the Power Spectrum

Here we present the steps to calculate the bias \mathcal{B}_{C_i} and variance $\sigma_{C_i}^2(U)$ of the 21-cm power spectrum measurements in presence of strong foreground and residual gain errors. The calculations presented here is for the expressions shown in chapter 6. Most of the assumptions made in appendix B are relevant for this calculation as well. Along with those we further make a few assumption and keep all the assumptions in this calculation in the italic font. We note that we use a foreground subtraction approach here (Bowman et al., 2009; Choudhuri et al., 2017b; Morales et al., 2006), and calculate the power spectrum by correlating the visibilities in the different frequency channel.

The recorded visibility is expressed in terms of the ‘sky’ visibility, gain $\tilde{G}_i(t)$ and correlator noise in eqn 6.1. Expressing the gain in terms of the antenna based gains using eqn 6.3, we write

$$\tilde{G}_i = \langle \tilde{g}_A(t) \tilde{g}_B^*(t) \rangle = 1 + \tilde{G}_i^R, \quad (\text{B.1})$$

where \tilde{G}_i^R can be interpreted as the excess over unity in the residual gain. Here the angle brackets represent the average over the integration time for each visibility measurements.

We consider the following assumptions

Assumption I: Antenna gains from the different antennas are uncorrelated,

Assumption II: Real and imaginary parts of the gains are uncorrelated.

For the compact source foreground, it is, in principle, possible to build up a good sky model over largely repeated observations at a given direction in the sky. However, for the diffuse galactic synchrotron emission, it may be challenging to build up such a sky model with interferometric observations, and an alternative approach may be necessary (Jelić et al., 2008). In this work, we deal with a power spectrum estimation that assumes the preexistence of a sky visibility model and uses foreground subtraction. Hence,

Assumption III: We have a known model for the foreground sky visibilities.

Hence, the residual visibilities \tilde{V}_i^R from the i^{th} baseline, after subtraction of the known foreground components, are given by

$$\tilde{V}_i^R = \tilde{V}_i^{HI} + \tilde{G}_i^R \tilde{V}_i^S + \tilde{N}_i, \quad (\text{B.2})$$

where \tilde{V}_i^{HI} is the redshifted 21-cm signal. Correlating the residual visibilities, in principle, gives the H I power spectrum P . Owing to the finite beam of the antenna, the nearby ‘sky’ visibilities remain correlated within a baseline region of $1/(\pi\theta_0)$. The power spectrum estimator we use here (Choudhuri et al., 2014) first grid the visibilities in baseline grids and estimate visibility correlation in each grid. To avoid noise bias, here we exclude the visibility auto-correlations (Bharadwaj and Ali, 2005). Estimate of the power spectrum P'_g over a grid can be written as

$$P'_g = \mathcal{R}[\langle \tilde{V}_i^R \tilde{V}_j^{R*} \rangle_g], \quad (\text{B.3})$$

where $\mathcal{R}[\]$ denotes the real part of the visibility correlation, i, j denotes two different baselines and $\langle \rangle_g$ denotes average over the grid. Here we further assume the followings:

Assumption IV: Noise in different baselines are uncorrelated.

Assumption V: The sky signal, antenna gains and noise have no cross correlations.

Hence, the power spectrum estimates in each grid can be written as

$$P'_g = \langle \tilde{V}_i^{HI} \tilde{V}_j^{HI*} \rangle_g + \langle \tilde{G}_i^R \tilde{G}_j^{R'*} \rangle_g \langle \tilde{V}_i^S \tilde{V}_j^{S*} \rangle_g. \quad (\text{B.4})$$

Note that the sky visibilities \tilde{V}_i^S contain both the redshifted 21-cm signal as well as the foreground. We can use the following assumptions to simplify this expression further.

Assumption VI: Foreground and redshifted 21-cm signals are uncorrelated.

Assumption VII: We can neglect the contribution from the 21-cm signal from \tilde{V}_i^S in the last term above.

Bias

The bias \mathcal{B}_{P_g} in the estimate of the power spectrum in a grid can be written as

$$\mathcal{B}_{P_g} = P'_g - P_g = \langle \tilde{G}_i^R \tilde{G}_j^{R'*} \rangle_g P_{F_g}, \quad (\text{B.5})$$

where P_g and P_{F_g} are the redshifted 21-cm and foreground power spectrum in the grid. As mentioned in the section 5.2.1, in each grid, four types of baseline pairs contribute to the visibility correlations. To calculate the contribution from the different baseline pairs in a grid, we need to estimate $\langle \tilde{G}_i^R \tilde{G}_j^{R'*} \rangle_g$. Here we show the calculation for the baseline pair of Type I. In this type the pair of baselines contributing in the visibility correlation originates from the same antenna pairs but at different time. The quantity $\tilde{G}_i^R \tilde{G}_j^{R'*}$ for a particular baseline pairs i, j constructed by antenna pairs A, B can be written as

$$\begin{aligned} \tilde{G}_i^R(t) \tilde{G}_j^{R'*}(t') &= \langle \delta_{AR}(t) \delta_{AR}(t') \rangle \\ &+ \langle \delta_{BR}(t) \delta_{BR}(t') \rangle + \langle \delta_{AI}(t) \delta_{AI}(t') \rangle + \langle \delta_{BI}(t) \delta_{BI}(t') \rangle, \end{aligned} \quad (\text{B.6})$$

where we have used assumptions I and II. If we assume that there are a total of N_g number of visibility correlations in a grid with N_{g1} giving the visibility pairs of Type 1, the contribution to $\langle \tilde{G}_i^R(t) \tilde{G}_j^{R'*}(t') \rangle_g$ from the baseline pairs of type 1 can be written as

$$\langle \tilde{G}_i^R(t) \tilde{G}_j^{R'*}(t') \rangle_{g1} = 2 n_1 \frac{\sigma_R^2 + \sigma_I^2}{N_{g1}} \sum_{A=1}^{N_{g1}} \xi_{AR}, \quad (\text{B.7})$$

where $n_1 = N_{g1}/N_g$ is the baseline pair fraction of type 1 and we have used the definitions of σ_{AR}^2 and ξ_{AR} from eqn 6.8. The above eqn B.7 is obtained using the following additional assumptions:

Assumption VIII: Statistical properties of the gains i.e. σ_R and ξ_R , for all antenna are similar.

Assumption IX: Gain correlation function ξ is the same for real and imaginary parts of the gain, though the variances can be different.

Since each antenna here contributes a factor of ξ and we assume all antennae have similar statistical properties, a factor of 2 for every baseline pair is coming in eqn B.7. Note that the angular brackets $\langle \rangle$ used above denote average over integration time over one visibility measurement, whereas $\langle \rangle_g$ is considered as the average over baseline pairs of type 1 in a particular grid. A pair of antennae traces an ellipse in the baseline plane as time progresses. Part of this ellipse would trace through a particular grid giving rise to different baselines arising from the same antenna pairs. This gives rise to the next simplifying assumption in our calculation:

Assumption X: If the time for the baseline to trace the arc in a grid T_D is much larger than the integration time $\Delta\tau$, then we can approximate

$$\chi(U) = \frac{1}{N_{g1}} \sum_{A=1}^{N_{g1}} \xi_{AR} \quad (\text{B.8})$$

The quantity $\chi(U)$ gives the integrated effect of the time-correlated residual gain errors over the uv-grids. If the correlation time of the residual gain errors T_{corr} are larger than the integration time $\Delta\tau$ then

$$\chi(U) = \frac{1}{T_D^2} \int_{\Delta\tau}^{T_D} (T_D - \tau) \xi(\tau) d\tau. \quad (\text{B.9})$$

Here $T_D = \frac{\Delta U \times T_{24}}{2\pi U}$ is the time taken by baseline track of an antenna pair to cross a uv-grid of size ΔU at baseline U . T_{24} corresponds to one sidereal day. Hence, the contribution to $\langle \tilde{G}_i^R(t) \tilde{G}_j^{R*}(t') \rangle_g$ from the baseline pairs of type 1 is

$$\langle \tilde{G}_i^R(t) \tilde{G}_j^{R*}(t') \rangle_{g1} = 2 n_1 (\sigma_R^2 + \sigma_I^2) \chi. \quad (\text{B.10})$$

Considering contribution from the other three baseline pairs in a similar way we can write for a given day of observation for a given baseline grid

$$\langle \tilde{G}_i^R \tilde{G}_j^{R*} \rangle_g = [(2n_1 + n_3)\chi + n_2] (\sigma_R^2 + \sigma_I^2). \quad (\text{B.11})$$

Considering the grids to have independent estimates of the power spectrum and a further assumption that

Assumption XI: The gain errors do not have any long term correlation

we use an azimuthal average around a certain baseline U to estimate the power spectrum.

This then, gives a bias in the power spectrum estimate as

$$\mathcal{B}_P = [(2n_1 + n_3)\chi + n_2] \frac{(\sigma_R^2 + \sigma_I^2)}{N_d} P_F, \quad (\text{B.12})$$

where N_d is the number of days of observation and P_F is the foreground power spectrum.

Variance

We first calculate the variance of the estimator in a grid, where

$$\sigma_{P_g}^2 = P'_{g2} - \langle P'_{g/g} \rangle^2, \quad (\text{B.13})$$

where P_{g2} is given as

$$P'_{g2} = \frac{1}{4} \langle [\tilde{V}_i^R \tilde{V}_j^{R'*} + \tilde{V}_i^{R*} \tilde{V}_j^R]^2 \rangle_g. \quad (\text{B.14})$$

Note that the quantities \tilde{V}_i^R depend on the gain errors. In calculating the four-point functions above, we do a further simplifying assumption:

Assumption XI: The gain errors are Gaussian random variables.

We follow a similar procedure to calculate the variance in a grid as like for the variance for N_d days of observations. Since the grid size is chosen in a way that in an annulus in baseline U the estimates of the power spectrum from different grids remains uncorrelated, the variance in the power spectrum estimate can be written as

$$\sigma_P^2 = \frac{1}{N_G} \sum_{g=1}^{N_G} \sigma_{P_g}^2, \quad (\text{B.15})$$

where N_G is the total number of grid points in an annulus. Writing the total number of baseline pairs to estimate the power spectrum in a given annulus as N_B , the analytical expression for the variance in H I power spectrum estimates in an annulus is

$$\begin{aligned} \sigma_P^2 &= \left[\frac{P_{HI}^2}{N_G} + \frac{2\sigma_N^2 P_{HI}}{N_B N_d} + \frac{2\sigma_N^4}{N_B N_d^2} \right] + \left[\frac{4\sigma_N^2 (\sigma_R^2 + \sigma_I^2) P_F}{N_B N_d^2} \right] \\ &+ \left[[(4n_1^2 + n_3^2)\chi^2 + n_2^2] [3\sigma_R^4 + 3\sigma_I^4 + 2\sigma_R^2 \sigma_I^2] \right] \\ &+ 8(\sigma_R^4 + \sigma_I^4) \frac{4\sigma_N^2 P_F^2}{N_G N_d^2} \end{aligned} \quad (\text{B.16})$$

As noted in the main text, the first three terms in bracket [] give the variance of the power spectrum estimator in absence of either any residual gain error or foreground. Importantly, all the factors in the above expressions, but σ_N , Σ_R and Σ_I are baseline dependent. The term $\frac{P_{HI}^2}{N_G}$ is a contribution from the sample variance and decreases with the baseline. In all our investigations presented in the main text, this term is negligible.

List of Publications

1. **Jais Kumar**, Prasun Dutta, Nirupam Roy, “Calibration requirements for epoch of reionization 21- cm signal observations-I. Effect of time-correlated gains”, *Monthly Notices of the Royal Astronomical Society*, Volume 495, Issue 4, July 2020, Pages 3683-3694
2. **Jais Kumar**, Prasun Dutta, Samir Choudhuri, Nirupam Roy, “Calibration requirements for Epoch of Reionization 21- cm signal observations – II. Analytical estimation of the bias and variance with time-correlated residual gains”, *Monthly Notices of the Royal Astronomical Society*, Volume 512, Issue 1, May 2022, Pages 186–198
3. Pavan Kumar Vishwakarma, **Jais Kumar**, “Trans-Alfvénic magnetohydrodynamic turbulence in the vicinity of supernova remnant Cassiopeia-A shocks”, *Monthly Notices of the Royal Astronomical Society*, Volume 498, Issue 1, October 2020, Pages 1093–1100
4. **Jais Kumar**, Prasun Dutta, Saamyadeep Das and Nirupam Roy, “Instrumental Calibration for Observations of Redshifted 21-cm Signal from Neutral Hydrogen”, *2020 URSI Regional Conference on Radio Science (URSI-RCRS)*, 2020, pp. 1-3
5. Abinash Kumar Shaw, Arnab Chakraborty, Mohd Kamran, Raghunath Ghara, Samir Choudhuri, Sk. Saiyad Ali, Srijita Pal, Abhik Ghosh, **Jais Kumar**, Prasun Dutta & Anjan Kumar Sarkar, “Probing early Universe through redshifted 21-cm signal: Modeling and ob-

servational challenges". *Jouranal of Astrophysics and Astronomy*, Volume 44, Issue 4 (2023)