



Improved Limits on the 21 cm Signal at $z = 6.5$ – 7.0 with the Murchison Widefield Array Using Gaussian Information

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Abstract

We explore the properties of interferometric data from high-redshift 21 cm measurements using the Murchison Widefield Array (MWA). These data contain the redshifted 21 cm signal, contamination from continuum foreground sources, and radiometric noise. The 21 cm signal from the Epoch of Reionization (EoR) is expected to be highly Gaussian, which motivates the use of the power spectrum as an effective statistical tool for extracting astrophysical information. We find that foreground contamination introduces non-Gaussianity into the distribution of measurements and then use this information to separate Gaussian from the non-Gaussian signal. We present improved upper limits on the 21 cm EoR power spectrum from the MWA using a Gaussian component of the data, based on the existing analysis from C. D. Nunhokee et al. 2025. This is extracted as the best-fitting Gaussian to the measured data. Our best 2σ (thermal+sample variance) limit for 268 hr of data improves from $(30.2 \text{ mK})^2$ to $(23.0 \text{ mK})^2$ at $z = 6.5$ for the East–West polarization, and from $(39.2 \text{ mK})^2$ to $(21.7 \text{ mK})^2 = 470 \text{ mK}^2$ in North–South. The best limits at $z = 6.8$ ($z = 7.0$) improve to $P < (25.9 \text{ mK})^2$ ($P < (32.0 \text{ mK})^2$) and $k = 0.18h \text{ Mpc}^{-1}$ ($k = 0.21h \text{ Mpc}^{-1}$). Results are compared with realistic simulations, which indicate that leakage from foreground contamination is a source of the non-Gaussian behavior.

Unified Astronomy Thesaurus concepts: Reionization (1383); H I line emission (690); Interferometers (805)

1. Introduction

The first billion years of the Universe witnessed the birth of the first stars and galaxies, and the transformation of the dominant hydrogen component of the neutral intergalactic medium to ionized. Data from the James Webb Space Telescope (JWST) over the past 2 yr have opened a new observational window on this period, probing details of the first generations of galaxies on galactic and cluster scales. In that time, we have learned that massive galaxies existed earlier than previously understood (M. Tang et al. 2021; S. Fujimoto et al. 2024; Y. Harikane et al. 2023; K. Boyett et al. 2024) and that there appears to be an overdensity of detected Ly α emitting galaxies relative to the expected distribution of neutral hydrogen in the intergalactic medium (IGM) (M. Tang

et al. 2024). Measurements of the ionizing efficiency of early galaxies, and hence the fraction of ionizing photons that escape them to ionize the IGM, also exceed measurements from other tracers, leading to a tension in the observations of the early parts of Reionization (J. B. Muñoz et al. 2024), and pointing to a model where Reionization started early. These optical/IR observations motivate improved measurements of the IGM neutral hydrogen itself, via its 21 cm hyperfine emission line, as the tracer that provides the radiative and thermal conditions of the IGM as it responds to the ionizing light from the galaxies. While the JWST (and other) observations provide the small-scale information about galaxies, and limited information about the IGM through Ly α measurements, 21 cm studies with low-frequency radio telescopes provide the large-scale information directly about the IGM. Progress in both of these observational fields therefore provides the complete and complementary picture of the early evolution of the Universe.

Several international experiments have been pursuing this redshifted IGM signal using low-frequency radio interferometers,



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noting that the rest 21 cm emission is redshifted to 1.5–2.0 m (50–200 MHz). These include the Murchison Widefield Array¹⁷ (MWA; J. D. Bowman et al. 2013; S. J. Tingay et al. 2013; D. C. Jacobs et al. 2016); the Precision Array for Probing the Epoch of Reionization¹⁸ (A. R. Parsons et al. 2010); the Low Frequency Array¹⁹ (LOFAR; M. P. van Haarlem et al. 2013; A. H. Patil et al. 2016); the Long Wavelength Array²⁰ (S. W. Ellingson et al. 2009), HERA (D. R. DeBoer et al. 2017; L. M. Berkhout et al. 2024), and the under-construction SKA-Low (L. Koopmans et al. 2015). These experiments all have unique challenges and approach the observations and analysis in different ways. They are also optimized to produce their best results at different redshifts and wavenumbers. As such, together they provide more independent constraints on the early Universe. Results from all three current experiments have ruled out certain cold Reionization models, whereas the HERA results at $z = 10.4$ have provided the most stringent constraints on the heating of the IGM above the adiabatic limit at early times (HERA Collaboration et al. 2023).

The brightness temperature fluctuations of the redshifted 21 cm line as a function of scale are expected to be highly Gaussian distributed early in cosmic dawn before strong nonlinear evolution and small-amplitude higher-order terms emerge later in the Reionization epoch (J. S. B. Wyithe & M. F. Morales 2007), although note that this work made oversimplifying assumptions about the signal (e.g., X-ray heating effects). The variance (second-order moment) therefore contains most of the information across time, thereby motivating use of the power spectrum as a useful statistic to probe this epoch, and provide astrophysical constraints on conditions at early times. Even at late times, non-Gaussianity of the 21 cm is difficult to detect, with only the SKA projected to be able to explore it at high signal-to-noise ratio (Q.-B. Ma & L. Peng 2023; J. H. Cook et al. 2024). A. Liu & J. R. Shaw (2020) reviewed a range of approaches to the analysis of 21 cm interferometric data sets, discussing the properties that can be used. More recently, H. Fronenberg & A. Liu (2024) explored non-Gaussianity of foregrounds in their work to use cross correlations to extract 21 cm signal.

The spherically averaged power spectrum encodes the distribution of signal power as a function of spatial scale. Several recent and current experiments have reported upper limits on the 21 cm cosmological power at different redshifts, with none yet claiming a detection. From the LOFAR telescope, with its core based in the Netherlands, the most recently reported result at $z = 9.1$ improved on an earlier analysis of the same data set with an upper limit of $\Delta_{21}^2 < (80 \text{ mK})^2$ at $k = 0.075 h \text{ Mpc}^{-1}$ (A. Acharya et al. 2024). From the HERA telescope, based in South Africa, the most recently reported results were ($z = 7.9$) $\Delta_{21}^2 < 457 \text{ mK}^2$ at $k = 0.34 h \text{ Mpc}^{-1}$, and ($z = 10.4$) $\Delta_{21}^2 < 3,496 \text{ mK}^2$ at $k = 0.36 h \text{ Mpc}^{-1}$ (HERA Collaboration et al. 2023). In C. M. Trott et al. (2020) 110 hr of MWA data were used to place a limit of $\Delta_{21}^2 < (45 \text{ mK})^2$ at $k = 0.075 h \text{ Mpc}^{-1}$ at $z = 6.5$. This was then improved in C. D. Nunhokee et al. (2025), where a set of 268 hr of data were used to report a 2σ upper limit of $\Delta_{21}^2 <$

$(30.2 \text{ mK})^2$ at $k = 0.17 h \text{ Mpc}^{-1}$ at the same redshift. These data are used in this work.

In C. M. Trott et al. (2019) we used a kernel density estimator (KDE) to extract information about the distribution of visibility data from 21 cm observations. We explored the properties of the data across real and imaginary components of visibilities and also other measures of the difference between distributions. In this work, we apply such techniques to a large data set of 268 hr of data from the EoR0 observing field (C. D. Nunhokee et al. 2025), showing that we can obtain improved upper limits on the power spectrum at $z = 6.5\text{--}7.0$. We study the distributions of data with a view to extracting second-order statistics of the cosmologically redshifted 21 cm signal. Despite growing non-Gaussianity near the end of Reionization, we expect the 21 cm signal to be highly Gaussian in k -space, where each measurement provides a realization of the 21 cm field at a particular spatial scale (i.e., for a given spatial scale, the individual measurements in 3D k -space can be used to form an empirical distribution, which we expect to be zero mean and Gaussian). Non-Gaussianity of the 21 cm signal at $z < 7$ is not expected to be detectable with less than 1000 hr of MWA observations (Q.-B. Ma & L. Peng 2023). We use the distributions of the data to extract the Gaussian component of the measured signal, potentially avoiding some of the foreground contaminants that may have non-Gaussian components.

Exploration of the distributions of data sets can be undertaken at different stages of processing. At the basic level, each calibrated visibility contributing to a particular spatial mode can be used to estimate the underlying distribution via some standard technique; here KDEs are employed. While this retains maximal information, it comes at the cost of coherent integration, because each measurement is treated as an independent measure; effectively producing a fully incoherent power spectrum estimate. An intermediate approach is to estimate the distributions from the coherently averaged data, i.e., take the gridded visibilities and use those averaged values as the realizations from which to estimate the underlying distribution. This approach is justified if (1) there are sufficient independent samples (i.e., uv cells with data) for a robust estimate; (2) there is a good distribution of angles sampled (i.e., a well-filled uv plane) for the ensemble of measurements to reflect the full distribution. Both of these requirements are justified for large integrations of data with the MWA telescope, which has excellent instantaneous and synthesized uv coverage.

There are a priori properties of the Gaussian fits that would provide confidence that the results are isolating the 21 cm signal (and residual Gaussian foregrounds) while removing the bulk of the contamination: (1) consistent power between the real and imaginary components of the visibilities; (2) consistent power between the North–South (NS) and East–West (EW) polarizations at a given scale; and (3) consistent power between two independent observing fields in the sky, for a comparable amount of data. The first two can be verified with the data used in this work, whereas the latter will need to wait for deep analysis of a separate observing field. Residual Gaussian-distributed foreground contamination is expected to remain in the data, and therefore, this approach will only be partly successful in removing non-21 cm signal components. There is no unique decomposition of data into a Gaussian and non-Gaussian component, or multiple Gaussian components,

¹⁷ <http://www.mwatelescope.org>

¹⁸ <http://eor.berkeley.edu>

¹⁹ <http://www.lofar.org>

²⁰ <http://lwa.unm.edu>

due to the convolution properties of Gaussians. In this work, we find that the data are close to Gaussian distributed, with a single main peak and long tails. As such, we fit the widest Gaussian that is consistent with a Gaussian fit to the bulk of the distribution and only fit a single Gaussian component. In this way, we are separating Gaussian signal from non-Gaussian foregrounds but not attempting to separate the Gaussian 21 cm signal and Gaussian foregrounds.

2. Methods

We follow a similar approach as outlined in C. M. Trott et al. (2019). We present a brief overview here and refer the reader to the earlier work for more details. Individual observations from the MWA comprise 2 minutes of data with 0.5 s/10 kHz or 2 s/40 kHz native sampling (depending on the phase of the array). The data are calibrated and combined according to prescription in C. D. Nunhokee et al. (2025). Briefly, the data are calibrated using Hyperdrive to obtain per-channel direction-independent complex gains for each tile and have a visibility-based source model directly subtracted from them. The calibration model contains 8000 point sources and extended source components, and the subtraction model contains the brightest 4000. Data are also averaged to 8 s/80 kHz for the remainder of the analysis. After calibration, each observation passes through a set of quality metrics that assess the health of the telescope, radio frequency interference (RFI) conditions, and calibration goodness of fit (C. D. Nunhokee et al. 2024). Observations that pass are then gridded onto a common uv plane using the CHIPS pipeline (C. M. Trott et al. 2016) with a Blackman–Harris gridding kernel. A grid is produced for each frequency channel, yielding a complex-valued cube of gridded visibilities with dimensions (u, v, ν) . In order to form power spectra with no noise power bias, data are time interleaved to produce two sets with different noise realizations. In practice, the two sets are “totals” (whereby each set of two consecutive time steps is added) and “differences” (whereby each set of two consecutive time steps is differenced). The cross power spectrum can be extracted by the subtraction of the differences power from the totals power. A real-valued weights cube is also retained for optimal weighting of data to the final power spectrum. Finally, each uv cell is spectrally transformed along the frequency axis (using a weighted Fourier transform) to yield a cube in wavenumber space $(u, v, \eta) \propto (k_x, k_y, k_z)$. At this point, the analysis diverges from that of the normal power spectrum estimation.

Each cell of the (u, v, η) cube consists of a realization of the underlying data distribution on a given vector spatial scale. An estimate of the true underlying distribution can be obtained by constructing a histogram from the independent sample realizations (i.e., cells) that correspond to the scalar spatial scale, $k^2 = k_x^2 + k_y^2 + k_z^2$. The KDE is a tool for this and represents each sample in the histogram by a predefined kernel. Each data sample is thermal noise dominated, rendering a Gaussian kernel to be a natural choice for our purposes. Moreover, the use of a KDE to construct the power spectrum necessitates a Gaussian kernel from which the variance can be equated to the power.

For a set of N identically and independently distributed (iid) data, x_j , an estimate of their distribution over abscissa x can be

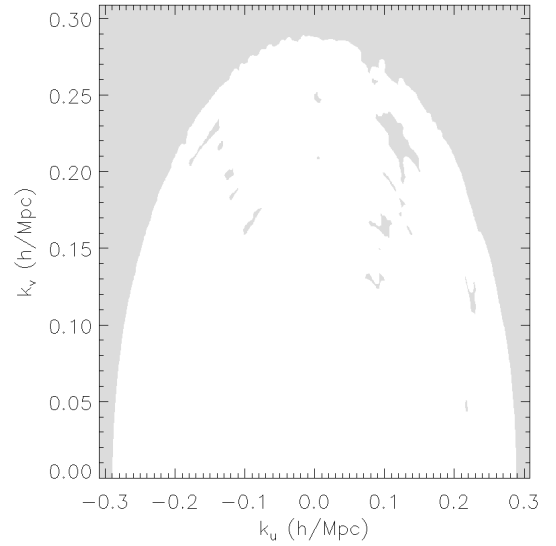


Figure 1. Occupancy of measurements in the uv plane for the 8036 observation data set for a single frequency channel. The white-shaded region shows the parts of the plane where there are measurements available, demonstrating that complete uv coverage is obtained for $k_{\perp} < 0.12h \text{ Mpc}^{-1}$.

found via

$$\hat{f}(x) = \frac{1}{Nh} \sum_{j=1}^N K\left(\frac{x_j - x}{h}\right), \quad (1)$$

where the summation extends over the iid data, $K()$ denotes the compact kernel function, and h is a scaling of the breadth of the kernel, for which an optimal value for Gaussian-distributed data is found to be (B. W. Silverman 1986)

$$h \approx 1.06\sigma(N)^{-1/5}, \quad (2)$$

where σ is the standard deviation of the data. For radio interferometric visibilities, for which the real and imaginary components contain an equal share of 21 cm signal and Gaussian noise measured in Janskys,²¹ S:

$$\hat{f}(S_i) = \frac{1}{N_i h} \sum_{j=1}^{N_i} K\left(\frac{S_{ij}(k_{\perp}, k_{\parallel}) - S}{h}\right), \quad (3)$$

with

$$K\left(\frac{S_i(k_{\perp}, k_{\parallel}) - S}{h}\right) = \exp\left(-\frac{(S_i(k_{\perp}, k_{\parallel}) - S)^2}{2h^2}\right), \quad (4)$$

and for $i \in [k_{\perp}, k_{\parallel}]$. We then connect the variance to the power and equate

$$\begin{aligned} & A_i \exp\left(-\frac{(S_i(k_{\perp}, k_{\parallel}) - S)^2}{2P_S(k_{\perp}, k_{\parallel})}\right) \\ &= \sum_{j=1}^{N_i} w_j \exp\left(-\frac{(S_{ij}(k_{\perp}, k_{\parallel}) - S)^2}{2h^2}\right), \end{aligned} \quad (5)$$

where $P_S(k_{\perp}, k_{\parallel})$ is the power measured in units of Jy^2 and A is the amplitude that depends on the number of visibilities

²¹ Strictly, the signal here is in units of $\text{Jy} \cdot \text{Hz}$, because the spectral transform from ν to η space has already been performed. However, in practice, we retain the Jy unit and incorporate the spectral units in the final cosmological normalization (including the $\Delta\nu$ multiplication).

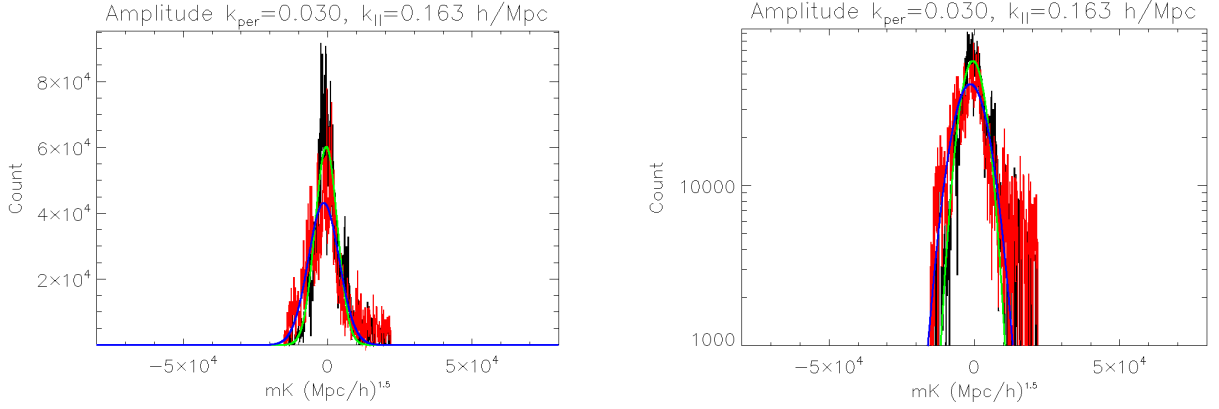


Figure 2. (Left) Histograms of the real (red) and imaginary (black) components of the data in the cell at $k_{\perp} = 0.03h \text{ Mpc}^{-1}$, $k_{\parallel} = 0.17h \text{ Mpc}^{-1}$, and the EW polarization, and their Gaussian best fits (green, blue solid). (Right) Same, but using a logarithmic scale for the count axis to highlight the outliers.

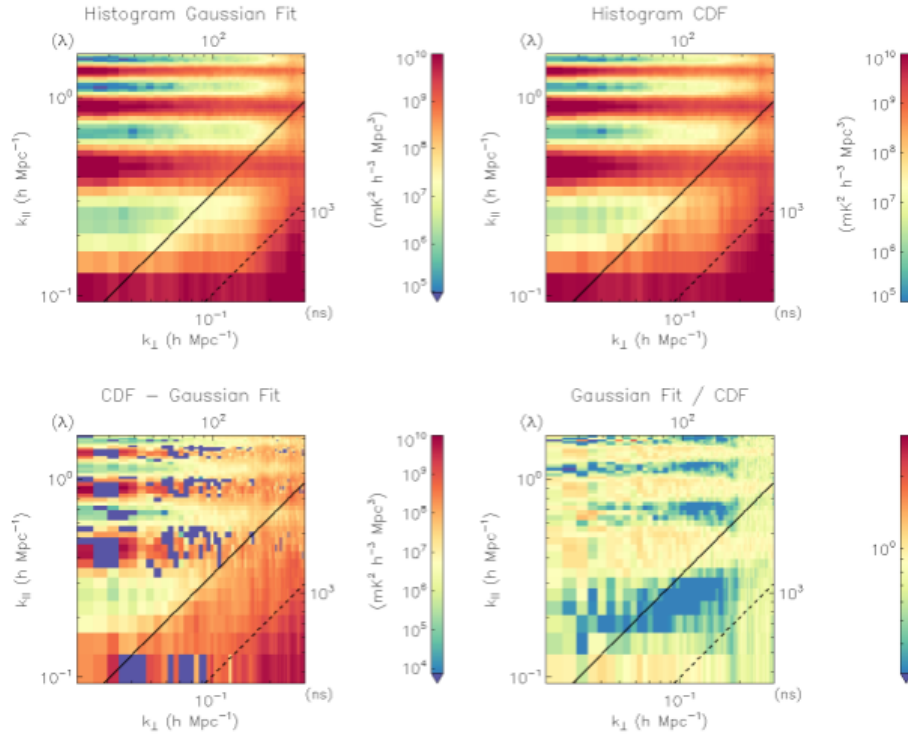


Figure 3. 2D power for the 8036 high-band EoR0 observations in the EW polarization. (Top left) Power extracted from Gaussian fitting to distributions; (top right) power extracted by integrating over full histogram CDFs; (bottom left) difference: integrated power–fitted power; and (bottom right) ratio: fitted power/integrated power.

contributing to cell i and is unused except to estimate the noise uncertainty. The factor w_j denotes the weight of each gridded visibility and provides an optimal estimate of the histogram. In this work, we use an abscissa of flux density, F , with range $[-150, 150]$ Jy and a resolution of 1 mJy for each of the real and imaginary components of the gridded data. 150 Jy was empirically determined by inspection of the data; other ranges of histogram were trialed, and the results found to be robust to this choice (which captured all of the data that were not affected by RFI and flagged). At $z = 6.8$, this corresponds to a resolution of $57 \text{ mK Mpc}^{1.5}$ (corresponding to a power resolution of $3300 \text{ mK}^2 \text{ Mpc}^3$), which oversamples the expected 21 cm signal power in the Epoch of Reionization (EoR) window by a factor of 50–100 (an expected signal level

in these modes is $10^5 \text{ mK}^2 \text{ Mpc}^3 \text{ h}^{-3}$). The kernel width h is set to 3 times the abscissa resolution. Both the binning and h values were tested to ensure robustness of the results.

The parameters of the Gaussians (amplitude, mean, and variance) are fitted using the IDL GAUSSFIT routine. In this work, a separate estimate of P_S is obtained for the real and imaginary components of the visibility and for the totals and difference sets of gridded data. As such, the final cosmological power spectrum is obtained as

$$P = \frac{1}{4}(\sqrt{P_{\text{tot},r}^2 + P_{\text{tot},i}^2} - \sqrt{P_{\text{diff},r}^2 + P_{\text{diff},i}^2}). \quad (6)$$

As an alternative to the fitted Gaussian approach, we also use the histogram, $h(f)$, to estimate the variance via a basic

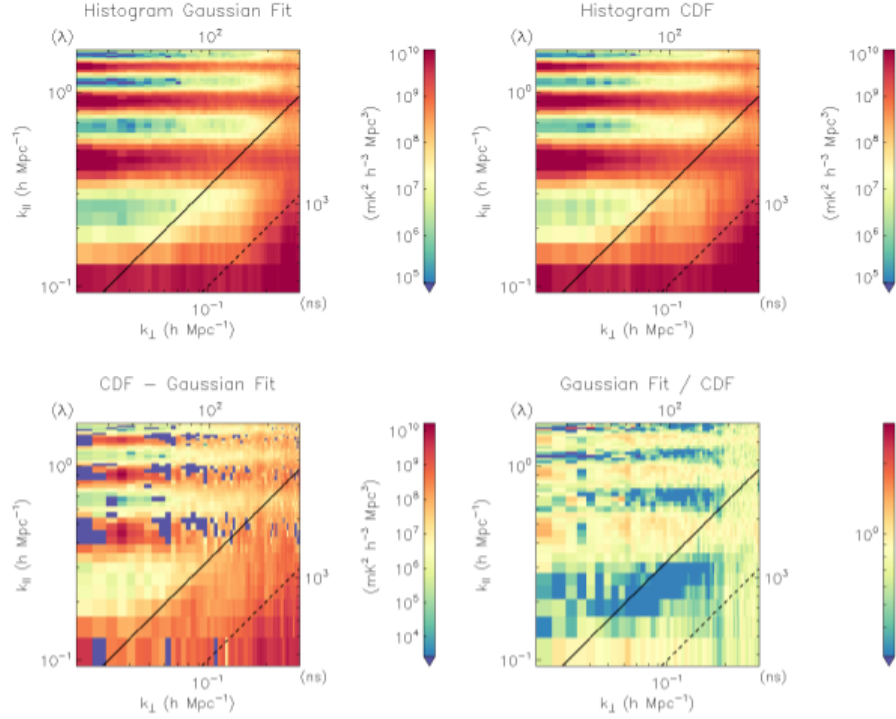


Figure 4. 2D power for the 8036 high-band EoR0 observations in the NS polarization. (Top left) Power extracted from Gaussian fitting to distributions; (top right) power extracted by integrating over full histogram CDFs; (bottom left) difference: integrated power–fitted power; (bottom right) ratio: fitted power/Integrated power.

cumulative distribution function (CDF), such that

$$P_S = \frac{\sum_{f=0}^{N_f} h(f) F^2(f)}{\sum_{f=0}^{N_f} h(f)}, \quad (7)$$

where $N_f = 300,000$ is the size of flux density abscissa and $F(f)$ is the histogram flux density value at index f . In the case of a purely Gaussian distribution, the fitted Gaussian and CDF approaches should yield the same value for the variance. The CDF will be used as a “blind” benchmark statistic where any non-Gaussianity is ignored in the estimate, thereby producing results that are more akin to the normal CHIPS power spectrum estimator.²² Throughout, the CDF, fitted histograms, and CHIPS power spectra use the exact same underlying data sets.

In addition to estimating the power separately from the NS and EW polarizations, we can combine the two histograms. The individual samples are incoherent realizations of the signal power, thereby allowing for data from different polarizations, and different observing fields (if available) to be included in the same histogram. In this work, we consider the polarizations separately before combining them into a common estimate. In this work, we also study the behavior across the real and imaginary components and across the redshift.

3. Results

In this work, all 8036 observations (268 hr) are used that passed quality assurance from C. D. Nunhokee et al. (2025). Figure 1 shows the density of measurements in the uv plane for the 8036 observation data set for a single frequency channel.

²² Note that the results will not be identical, due to the CDF using the histogram of the values and CHIPS using the coherently gridded weights.

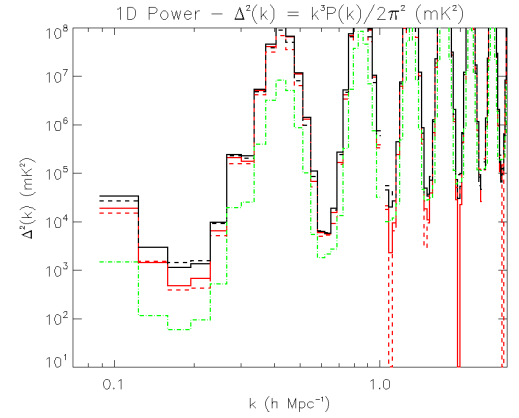


Figure 5. 1D power for the EW (solid) and NS (dashed) polarizations for 8036 observations at $z = 6.5$ and the noise level (green). The black lines denote the CDF approach, whereas the red denote the fitted Gaussians.

The white-shaded region shows the parts of the plane where there are measurements available, demonstrating that complete uv coverage is obtained for $k_{\perp} < 0.12 h \text{ Mpc}^{-1}$. This motivates the use of a KDE to be able to robustly reproduce the underlying data distribution.

Figure 2 shows examples of the histograms produced from the gridded data for a cell in the EoR window, at $k_{\perp} = 0.03 h \text{ Mpc}^{-1}$ and $k_{\parallel} = 0.16 h \text{ Mpc}^{-1}$ for data from $z = 6.5$. This is a cell that shows some improvement between the CDF approach and the fitted Gaussian approach, and the reasons for this can be observed in the fits to the histograms and the tail of signal. The corresponding 2D power spectrum across all cells is shown in Figure 3. The ratio (bottom left) demonstrates that

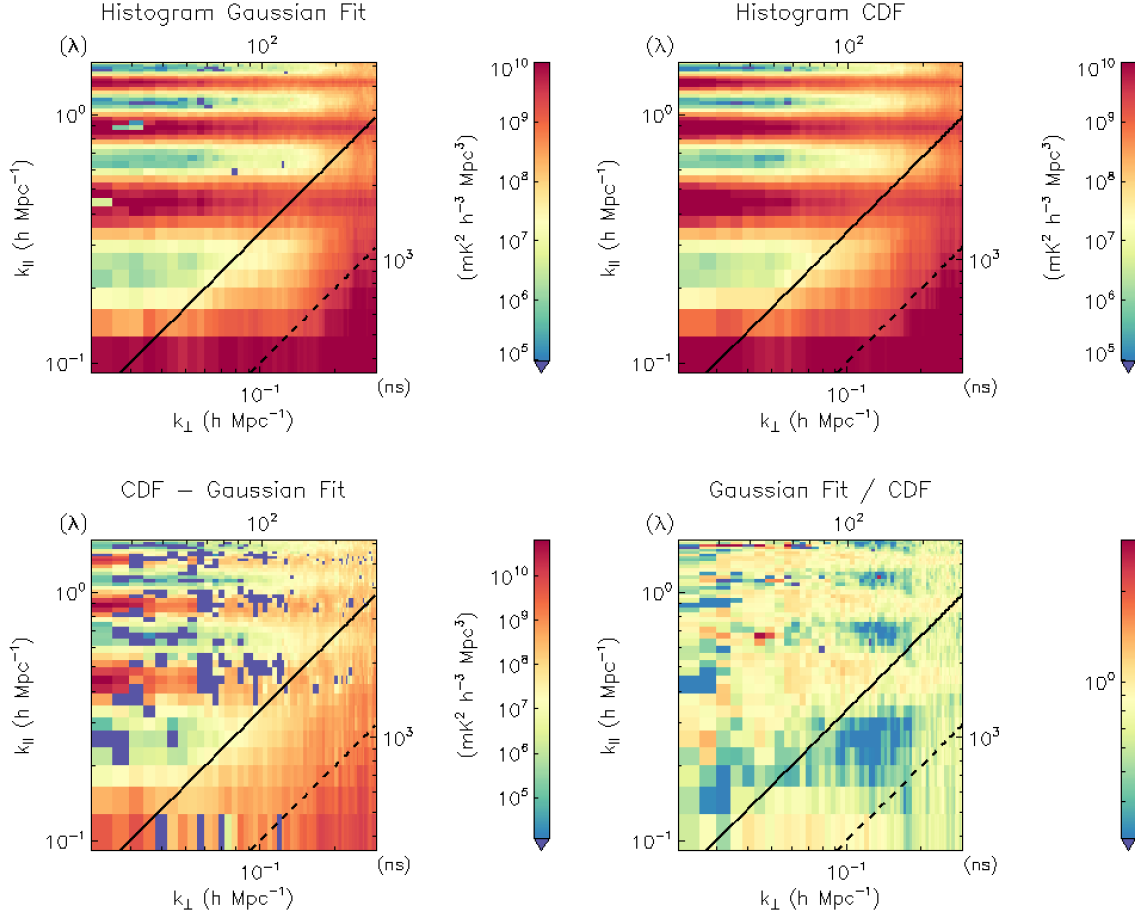


Figure 6. 2D power spectra from the fitted Gaussians and CDF approaches for 8036 NS and EW visibilities at $z = 6.5$. Similar behavior is observed in the ratio as for the EW and NS separately.

foreground-dominated modes tend to produce similar results across the two estimation approaches, except for modes near the edge of the wedge (horizon power), and modes in the lower EoR window. In some cells, the ratio of power estimates is nearly 3. These are modest improvements with respect to the overall power level but will improve limits in the EoR window.

Similar analysis can be performed for the NS polarization, in which there was more contamination seen in C. D. Nunhokee et al. (2025). The results are shown in Figure 4 and demonstrate greater improvement than EW for $k_{\perp} < 0.02h \text{ Mpc}^{-1}$. The 1D power spectrum for both of those polarizations and $z = 6.5$ is shown in Figure 5. There is overall improvement in both polarizations for $k_{\perp} \sim 0.15\text{--}0.20h \text{ Mpc}^{-1}$, but the improvement is greater for the NS polarization. Note that both polarizations exhibit similar behavior, as expected. The final step is to combine the two polarizations to produce NS+EW power spectra. The resultant 2D and 1D spectra are shown in Figures 6 and 7, respectively. In Table 1, we present the existing limits (where available) from C. D. Nunhokee et al. (2025) and the improved limits of this work. The best limit improvements are factors of 1.5 ($z = 6.5$), 1.9 ($z = 6.8$), and 2.0 ($z = 7.0$).

4. Foreground Sky Simulation

To support the hypothesis that non-Gaussianity is due to foreground signal observed through the telescope, we undertake realistic simulations of the diffuse (Galactic emission) and compact (point source, double, extended sources) sky and

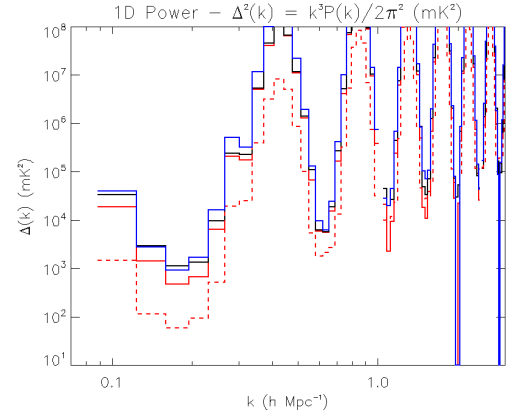


Figure 7. Spherically averaged power spectrum for the 8036 observations at $z = 6.5$ using both polarizations. Solid blue denotes the result from C. D. Nunhokee et al. (2025) using a subset of 6395 observations, solid black denotes the CDF-derived power, and solid red denotes the Gaussian fitted power. The dashed line is the 2σ noise corresponding to the Gaussian fitted power.

observe them through the MWA. We use data simulated with the WODEN software²³ (J. L. B. Line 2022; J. L. B. Line et al. 2024) and include a diffuse sky map derived from M. A. Kriele et al. (2022), along with the compact sky model used for the

²³ <https://woden.readthedocs.io/en/latest/index.html>

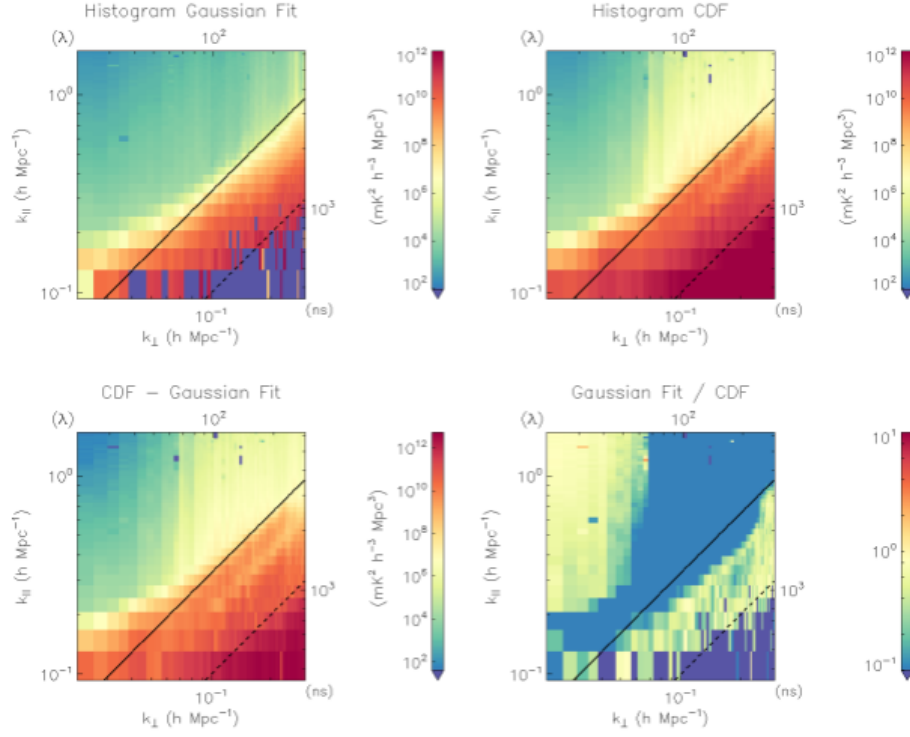


Figure 8. 2D power spectrum for the Gaussian fit (top left), CDF (top right), the fractional difference (bottom left), and the ratio (bottom right) for the EW polarization data containing diffuse and compact emission. Note the different color scale than other similar plots. The purple modes close to $k_{\parallel} = 0$ are those not fitted by the algorithm and can be ignored.

MWA, comprising GLEAM (N. Hurley-Walker et al. 2017), GLEAM-X (K. Ross et al. 2024), and LoBES (C. R. Lynch et al. 2021), and with additional modeling from J. H. Cook et al. (2022) and J. L. B. Line (2022). The simulation spans five observations across the LST range of the observations and are noise free. These simulated data have uv coverage that is complete for $k_{\perp} < 0.1 h \text{ Mpc}^{-1}$ and $>90\%$ complete radially and 100% complete azimuthally for $k_{\perp} < 0.2 h \text{ Mpc}^{-1}$. Figure 8 shows the same set of cylindrical power spectra as were presented for the data. Note that the color bar scales have changed to represent the amplitudes of the power and ratios.

Aside from a few modes at $k_{\parallel} = 0$, which have not converged in their Gaussian fitting (due to the breadth of the distributions), the simulations demonstrate similar behavior to the data near the edge of the wedge and in the EoR window, i.e., there are non-Gaussian foregrounds that reside in this part of the parameter space and the Gaussian fitting therefore estimates a smaller variance than a blind CDF approach. Figure 9 shows the same uv cell as used in Figure 2 for these simulations. The clear non-Gaussian components can be observed and look qualitatively similar to the data.

These simulations therefore support the hypothesis that leaking non-Gaussian foregrounds are contaminating the results.

5. 21 cm Validation

The techniques presented here intend to reproduce the Gaussian component of data. We can compare a simulation of the 21 cm signal with both methods to validate the approach. We again use data simulated with the WODEN software. The underlying 21 cm simulation was produced to match the MWA’s large field of view and presented in B. Greig et al. (2022). It uses a large 21 cm FAST cube (A. Mesinger &

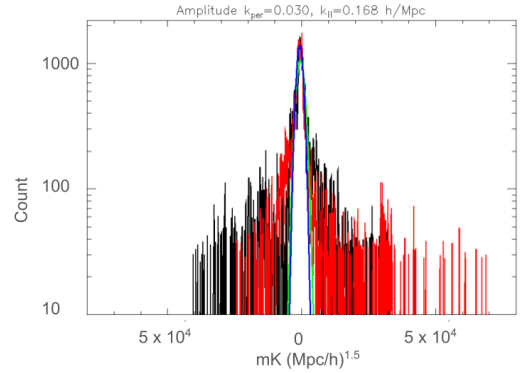


Figure 9. The same uv cell as used in Figure 2 for the diffuse plus compact emission simulations. The clear non-Gaussian components can be observed and look qualitatively similar to the data.

S. Furlanetto 2007; A. Mesinger et al. 2011) sampled at the MWA spectral resolution. Thirty observations, covering the pointings and LSTs to match those for the data used here, were simulated and combined into a single data set.

Figure 10 shows the 2D power spectrum for the Gaussian fit (top left), CDF (top right), the fractional difference (bottom left), and the ratio (bottom right) for the EW polarization data. Figure 11 shows the corresponding 1D power spectrum over $k_{\perp} = 0.02\text{--}0.035 h \text{ Mpc}^{-1}$. Unlike the actual EoR data, these simulated 21 cm visibilities show a high degree of Gaussianity, as expected, and no systematic difference between the histogram fit and CDF approaches. The mean ratio in the bottom-right plot is 0.96 across the full parameter space and exceeds unity in the EoR window (Gaussian fitting slightly overestimating the power).

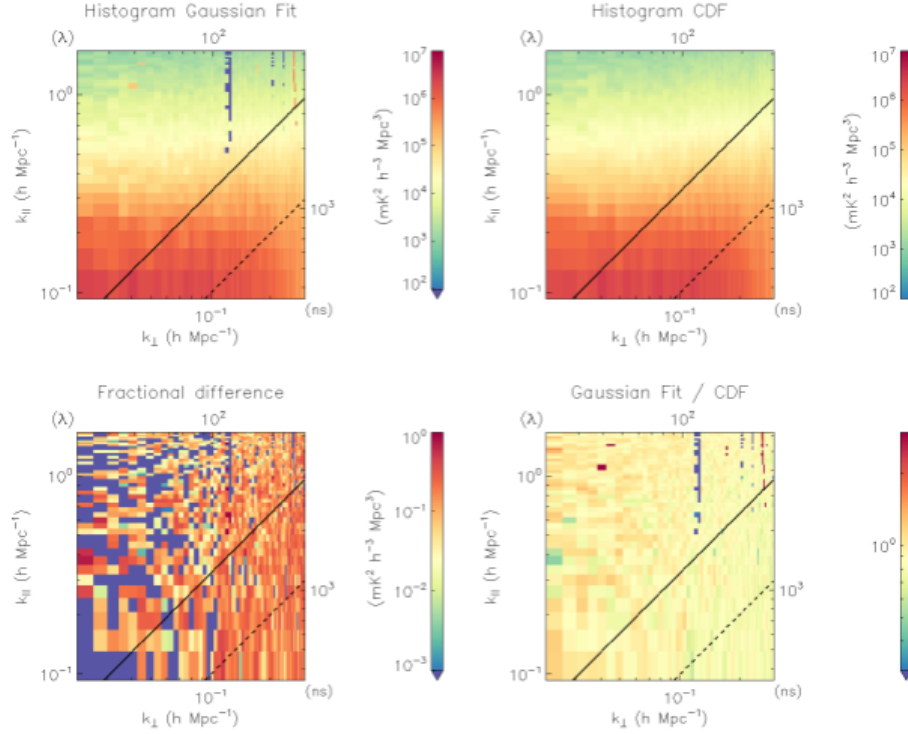


Figure 10. 2D power spectrum of 21 cm signal for the Gaussian fit (top left), CDF (top right), the fractional difference (bottom left), and the ratio (bottom right) for the EW polarization data. The purple modes are those not fitted by the algorithm and can be ignored.

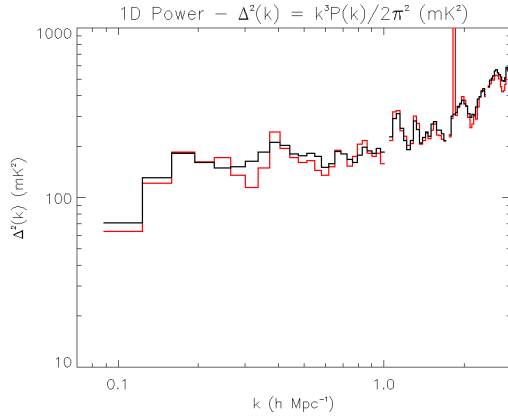


Figure 11. Gaussian fit (red) and CDF (black) of a 21 cm simulation using the WODEN software tool and encompassing the same range of pointings as the data. The two fits match well across the wavenumber.

The final check is to extend this analysis to include the 21 cm signal and diffuse and compact foregrounds in the simulation and to show that the 21 cm signal can be recovered in the EoR window. The results of that simulation are shown in Figure 12, where the full simulation (left) and the 21 cm-only simulation (center) are differenced (right) to show recovery of the 21 cm signal in the EoR window. The consistency of the two sets of simulations demonstrates that the Gaussian-like 21 cm signal can be recovered adequately.

We chose the $z = 6.5$ range of the Greig simulation for the validation to match with the redshift at which we had the most competitive results. The neutral fraction in that box is 40%–45% (J. H. Cook et al. 2024). The work of J. H. Cook et al. (2024), which postprocessed these boxes to study the power

spectrum and skew spectrum, shows nonzero skew at these late redshifts. In configuration space, half of the voxels will have zero contrast temperature. The other half will encode the fluctuations in the remaining signal. In Fourier space, we are performing a weighted sum over the voxels, where the weight is a sinusoidal function. The average of the box is not measured (contained in the autocorrelation, which we discard), and each Fourier mode that a histogram is produced for would be a sum over signal and zeros. In configuration space, one may guess that the distribution would be a spike at $T=0$, embedded within a Gaussian distribution. The Fourier transform of this is a flat line (equal power across k) summed with a Gaussian by the linearity of the Fourier transform, leading to some small non-Gaussianity on top of a Gaussian distribution. The degree of non-Gaussianity we estimated based on the work of J. H. Cook et al. (2024) and Q.-B. Ma & L. Peng (2023) suggested that this broadening would not be measurable with the precision of our data.

6. Discussion and Conclusions

The realistic simulations produced by WODEN are crucial to support use of this approach and also to target the source of the non-Gaussianity. At the level of the signal we can probe with 268 hr of data, any non-Gaussianity in the 21 cm signal itself is insignificant. However, even if there was substantial non-Gaussianity, the power spectrum statistic is not intended to measure it but instead extract the second moment of the distribution. While the 21 cm simulations show no measurable deviation from Gaussianity, the diffuse + compact emission simulations demonstrate clear non-Gaussianity in foreground-dominated modes but also in the modes close to the edge of the wedge, and in the EoR window. These modes are the ones where we find the most improvement in the 268 hr of MWA

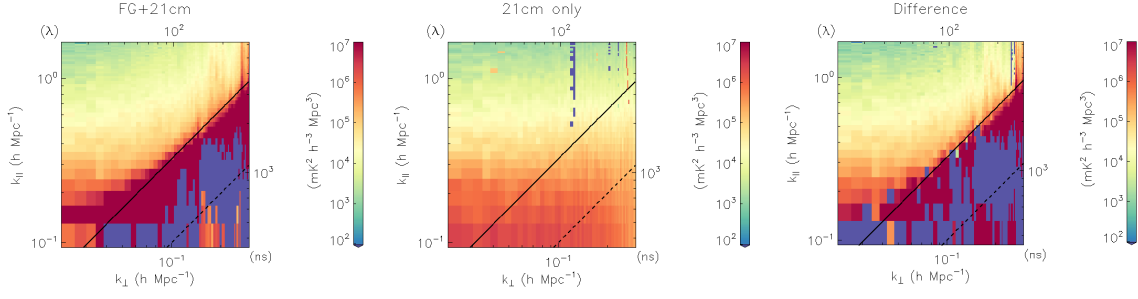


Figure 12. Full 21 cm + compact and diffuse foregrounds simulation (left), the 21 cm-only simulation (center), and the difference (right), showing recovery of the 21 cm signal in the EoR window, even in the presence of strong foregrounds.

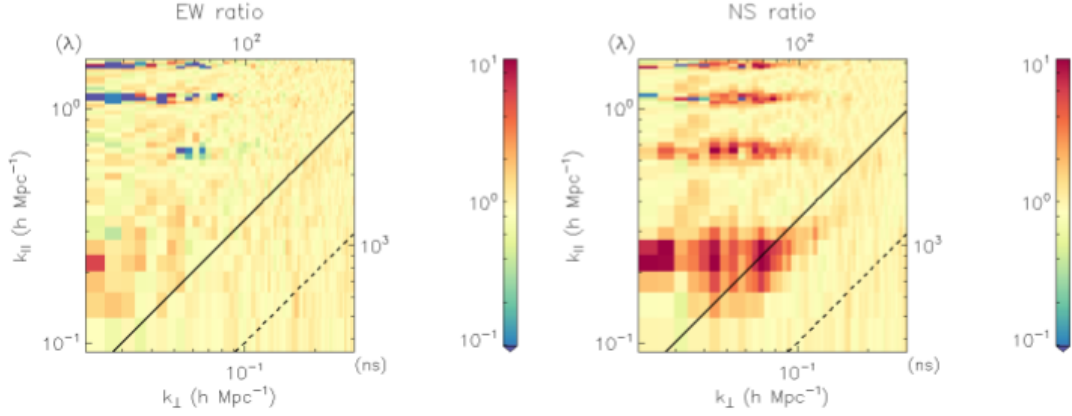


Figure 13. The ratio of the CDF-derived power to the Gaussian fitted power for the EW (left) and NS (right) polarizations at $z = 6.8$. There is clear improvement shown in the NS polarization relative to the EW.

Table 1

Best 2σ Upper Limits for Each Redshift and Each Polarization, Where Both the Thermal Noise and Sample Variance Are Included in the Error Budget

z	k ($h \text{ Mpc}^{-1}$)	P_{UL} (mK^2)	P_{therm} (mK^2)	P_{sample} (mK^2)	P_{CDF} (mK^2)	P_{orig} (mK^2)	Pol.
6.5	0.18	(23.0) ²	(6.7) ²	(6.1) ²	(34.5) ²	(30.2) ²	EW
6.8	0.18	(28.4)²	(9.3) ²	(6.9) ²	(35.4) ²	(31.3) ²	EW
7.0	0.21	(35.4) ²	(14.2) ²	(9.4) ²	(40.8) ²	(39.1) ²	EW
6.5	0.18	(21.7)²	(8.4) ²	(5.8) ²	(39.0) ²	(39.2) ²	NS
6.8	0.18	(32.4) ²	(9.3) ²	(8.6) ²	(86.5) ²	(79.3) ²	NS
7.0	0.21	(35.3) ²	(14.2) ²	(8.9) ²	(61.0) ²	(55.3) ²	NS
6.5	0.18	(23.0) ²	(7.1) ²	(6.4) ²	(35.3) ²	...	NS,EW
6.8	0.18	(30.5) ²	(7.8) ²	(8.4) ²	(52.8) ²	...	NS,EW
7.0	0.18	(34.9)²	(9.1) ²	(10.3) ²	(44.8) ²	...	NS,EW

Note. “UL” denotes the upper limits from this work; “CDF” denotes the output of the cumulative distribution function of the histograms from this work; and “orig” denotes the limits from the same underlying data set from C. D. Nunhokee et al. (2025). Bold-faced values are the best limits for each redshift.

data and therefore are used to derive the improved upper limits.

The comparison of the results from the two polarizations is also interesting. Both use the same underlying observations but have slightly different responses to the sky. The results from C. D. Nunhokee et al. (2025) showed a large difference between the polarizations with the NS polarization, which has a relatively larger response to the Galactic plane emission near the western horizon, yielding poorer performance. Galactic emission, being spatially localized and nonstochastic, would be expected to produce some non-Gaussianity (compare with

point sources distributed across the sky, which would produce a Gaussian response according to the central limit theorem). Under this hypothesis, fitting a Gaussian model to the distributions for NS may avoid a lot of that Galactic emission and produce results that were more similar to the EW polarization. Indeed, the results from Table 1 show much more consistency between polarizations for each redshift than the CDF or results from C. D. Nunhokee et al. (2025), particularly for $z = 6.5, 7.0$. This can be observed in Figure 13, which shows the ratio of the CDF-derived power to the Gaussian fitted power for the EW (left) and NS (right)

polarizations at $z = 6.8$. There is clear improvement shown in the NS polarization relative to the EW.

We are proceeding from the intuition that any additional Gaussian or non-Gaussian component will always broaden the distribution, and so we are safe to make that assumption as a conservative estimate. This work is motivated by the intuition that any Gaussian or non-Gaussian foreground signal will work to broaden the distribution of the data. This will not be the case if somehow the foregrounds are anticorrelated with the 21 cm signal and work to narrow the distribution. In addition to there being no physical motivation for this, the work undertaken in C. M. Trott et al. (2019) looked at the performance of this histogram approach to both the EoR0 and EoR1 fields, finding similar behavior for both. Anticorrelation of 21 cm signal and foregrounds would need to conspire to produce this effect in both of these fields, adding weight to this not being the explanation. Additionally, the results of the 21 cm validation are also suggestive that this conspiracy is not at play.

The approach used in this research will work well with other foreground-dominated data sets and will reach its limit in the regime where a detection of the 21 cm second moment only is possible (higher-order statistics are not yet detectable). In those future studies with increased sensitivity currently unavailable to us, an exploration of the distribution of data will provide more information about the early Universe than the power spectrum alone and provides the large-scale cosmic statistical information to complement the more localized tomographic studies.

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Software: IDL, WODEN (J. L. B. Line et al. 2024).

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