Detection of Cosmic Structures using Bispectrum Phase: Theory and Application

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The epoch of reionization (EoR; $z \gtrsim 6$) is a critical period in the universe's history, and its characterization is a key science goal of many current and planned low-frequency radio telescopes. Many low frequency radio interferometry experiments like the Hydrogen Epoch of Reionization Array (HERA), the Square Kilometre Array (SKA), the Murchison Widefield Array (MWA), the Low Frequency Array (LOFAR), and the Long Wavelength Array (LWA) are gearing up to detect the large-scale cosmic structures on a wide range of spatial scales at these early epochs using the redshifted 21 cm spectral line of neutral Hydrogen (H I).

The primary challenge to detecting this spectral signal, which is typically very faint, is the overwhelmingly bright (by 4-5 orders of magnitude) foreground emission at these frequencies, placing stringent requirements on the quality of the instruments and the analyses. Due to the very high dynamic range needed to isolate the faint cosmic spectral line signal from the bright foregrounds, spectral systematics from the instrument or the analysis, rather than thermal noise, are the primary limitations to sensitivity. Particularly, achieving a fractional inaccuracy $\lesssim 10^{-5}$ in the spectral calibration has been and will remain a dominant limitation.

The interferometric bispectrum phase is immune to antenna-based calibration and its errors, and provides a novel measure of the EoR H I signal while avoiding calibration systematics. By developing a theoretical framework to interpret the bispectrum phase fluctuations, we have established that they measure the intrinsic dissimilarity in the transverse structure of the cosmic signal relative to the foregrounds. Using a range of sky models, we detail the behavior of the bispectrum phase fluctuations using standard Fourier-domain techniques and find it comparable to existing approaches. However, the key difference and advantage is that our approach does not require calibration altogether and can work with raw, uncalibrated data because of the intrinsic invariance of bispectrum phase to antenna-based calibration.

We have demonstrated this technique on a subset of HERA data to place approximate constraints on the brightness temperature variance of the intergalactic medium (IGM). At $z = 7.7$ we infer its "1σ" upper limit to be $\leq (316\,\mathrm{mK})^2$ at $k_\parallel \approx 0.33\,h$ Mpc^{-1} (data-limited) and $\leq (1000\,\mathrm{mK})^2$ at $k_\parallel \approx 0.875\,h$ Mpc^{-1} (noise-limited). Via parallel forward-modeling, we confirm that our results are mainly limited by thermal noise and data volume, and not by calibration or other systematics, and the dynamic range required to separate the cosmic H I signal from the foregrounds is similar to that in standard approaches. We plan to analyze a larger amount of data to further improve the sensitivity towards an independent detection.