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Array Element Coupling in Radio Interferometry: Interpretation and Mitigation

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Radio interferometers are instruments used to advance the fields of cosmology, astrophysics, astronomy, and ionospheric physics. The study of the 21cm emission of the hyperfine splitting of the ground state of neutral hydrogen in the intergalactic medium (IGM) is an active area of research with direct and implications on all such disciplines. Ameasurement of the 21cm signal probes the era of the formation of the first luminous objects (the 'Cosmic Dawn') and the subsequent phase transition of the Universe, during which photons from the first stars ionized the neutral hydrogen of the IGM at z~6 (the 'Epoch of Reionization' (EoR)). The Earth's ionosphere can Faraday-rotate polarized foreground emission, which can leak into the intrinsically unpolarized 21cm power spectrum, at levels several orders of magnitude greater than the expected 21 cm signal.

The angular-resolution-dependent 21cm power spectrum has yet to be measured -plagued, at the very least, by the fact that astrophysical foregrounds are several orders of magnitude brighter than the theoretical 21cm signal. 21cm experiments must carefully mitigate instrumental systematics in order to address the dynamic range challenges posedby foregrounds. This work focuses on first-order antenna-antenna coupling in radio interferometers, an important instrumental systematic which affects tomographic measurements of the 21cm power spectrum. Upper limits from all first-generation interferometers, such as PAPER, the MWA, and LOFAR, and current limits from second generation interformeters such as HERA, report excess noise in their power spectrum measurements with a spectral correlation which is distinct from thermal noise. All such upper limits cite mutual coupling as one possibility for the excess power.

In this work, we present the semi-analytic model of the interferometric visibility equation derived in Josaitis et. al 2022 (MNRAS, in review) which considers first-order antenna-antenna coupling. Our model is not only helpful to the field of 21cm cosmology, but any study involving interferometric measurements, where coupling effects in visibility data at the level of at least 1 part in 10^4 could corrupt the scientific result. We simulate such coupling on a HERA-like redundant array and present a phenomenological analysis of the coupling features. We also compare HERA Phase II data to the simulations of the array configuration and observational parameters. Contrary to previous studies, such as Kern et. al 2019 (ApJ, 884, 105), we find mutual coupling features manifest themselves at nonzero fringe rates. For all LSTs, baseline lengths, and baseline orientations, we find coupling features at delays which are outside the foreground 'wedge' which has been studied extensively and contains the astrophysical foreground features associated with non-coupled visibilities. If not mitigated, these first-order coupling effects threaten our ability to average data from baselines with identical length an orientation.

We present a fringe-rate filter and baseline orientation selection strategy to both the observed and simulated data. This strategy reduces coupling systematics in visibility space by several orders of magnitude at specific k// modes. For certain LST ranges, predict that array element coupling effects can be mitigated for all k-modes outside of the wedge to at least a dynamic range of 10^6 against peak foreground power, and down to 10^{10} for some k-modes, which is equivalent to the fiducial dynamic range predicted to contain the 21cm cosmological signal at low-k modes.