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A Unified Calibration Framework for 21 cm Cosmology

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Calibration precision is currently a limiting systematic in 21 cm cosmology experiments. While there are innumerable calibration approaches, most can be categorized as either "sky-based," relying on an extremely accurate model of astronomical foreground emission, or "redundant," requiring a precisely regular array with near-identical antenna response patterns. Both of these classes of calibration are inflexible to the realities of interferometric measurement. In practice, errors in the foreground model, antenna position offsets, and beam response inhomogeneities degrade calibration performance and contaminate the cosmological signal.

We show that sky-based and redundant calibration can be unified into a highly general and physically motivated calibration framework, which we call "unified calibration," based on a Bayesian statistical formalism. Our new framework includes sky-based and redundant calibration as special cases but can additionally operate in an intermediate regime between the two methods. This relaxes the rigid assumptions implicit in each sky-based and redundant calibration. It improves upon sky-based calibration by becoming more resilient to sky model errors while simultaneously leveraging the sky model to reduce redundant calibration error.

In addition to combining elements of sky-based and redundant calibration, the unified calibration framework enables a number of extensions to calibration with far-reaching implications. It allows for baseline-dependent weighting, capturing scale-dependent sky model uncertainties. It enables new parameterizations of the calibration model, including modeling sources with uncertain intensities. It supports an extension to redundant calibration that relaxes the assumption of perfect redundancy: rather than assuming nominally redundant baselines measure the same signal, we can instead define a physically-motivated correlation between the measurements. It also allows for a novel method of calibrating compact, non-redundant arrays. These compact arrays have substantial baseline overlap in the uv plane, which introduces covariances between baseline measurements. Unified calibration can capture those covariances as a constraint on the calibration solutions.

Bandpass calibration is of particular importance for 21 cm calibration. We discuss the implications of unified calibration for bandpass calibration and propose a variation on redundant calibration that imposes cross-frequency constraints on the calibration solutions. We also discuss extensions to the calibration framework that perform fully-polarized calibration.

As a proof-of-concept, we present simulation results from a simple implementation of the unified calibration framework. Our simulations demonstrate that unified calibration can improve upon sky-based and redundant calibration by mitigating the effect of sky model error and measurement noise.

Unified calibration represents a broad framework for formulating calibration models. It has wide-reaching implications for enabling a large class of new calibration techniques with the potential to improve calibration performance. By reducing calibration error, unified calibration can mitigate a dominant systematic limiting current 21 cm cosmology experiments and facilitate the next generation of precision cosmological measurements.