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Precision Calibration for HERA and 21 cm Cosmology

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Abstract. Here I discuss progress in both the theory and practice of data analysis for the Hydrogen Epoch of Reionization Array (HERA), focusing on techniques to calibrate the instrumental response and preserve the spectral smoothness that is essential to separating the cosmological 21 cm signal from foregrounds that are five orders of magnitude brighter. I explain how mis-calibration can create ruinous spectral structure and how we take advantage of HERA's highly-redundant configuration for calibration. This proceeding draws from a talk I gave on October 3, 2017. Slides for it and all my talks are available at joshdillon.net.

Keywords. cosmology: dark ages, reionization, first stars – instrumentation: interferometers

1. The Problem of Calibration

While 21 cm cosmology promises to provide a transformational new window on our Cosmic Dawn and the Epoch of Reionization (EoR), its promise cannot be realized without tackling the problem of foregrounds which are $\sim 10^5$ times stronger (Furlanetto *et al.* 2006; Morales and Wyithe 2010). The key to separating the foregrounds from the 21 cm signal is that the foregrounds are intrinsically spectrally smooth while the signal has spatial and thus spectral structure on many scales.

Regardless of one's strategy for mitigating foregrounds, the problem becomes far more difficult if the spectral structure imparted by the instrument cannot be calibrated out or restricted to a limited part of Fourier space. In general, measured interferometric visibilities $V_{ij}^{\rm obs}(\nu)$ are related to the true-sky visibilities $V_{ij}^{\rm true}(\nu)$ by

$$V_{ij}^{\rm obs}(\nu) = g_i(\nu) g_j^*(\nu) V_{ij}^{\rm true}(\nu) + n_{ij}(\nu) \tag{1.1}$$

where $g_i(\nu)$ is the complex bandpass associated with antenna i and $n_{ij}(\nu)$ is the noise on that visibility. Accurate estimation of $g_i(\nu)$ is essential to 21 cm cosmology.

2. The Chromatic Effect of Calibration Errors

The traditional approach to bandpass or "direction-independent" calibration has been *self-cal*, the iterative process of forward-modeling a source catalog, solving for gains, imaging, and updating the source catalog (Braun 2013). However, Barry *et al.* (2016) and Ewall-Wice *et al.* (2016) showed that even small foreground model errors below the classical confusion limit of the instrument can bias the 21 cm power spectrum. Small modeling errors on long baselines create gain errors that have the same intrinsic chromaticity as those long baselines. That creates spectral structure on calibrated short baselines beyond what the instrument normally imparts (Figure 1).

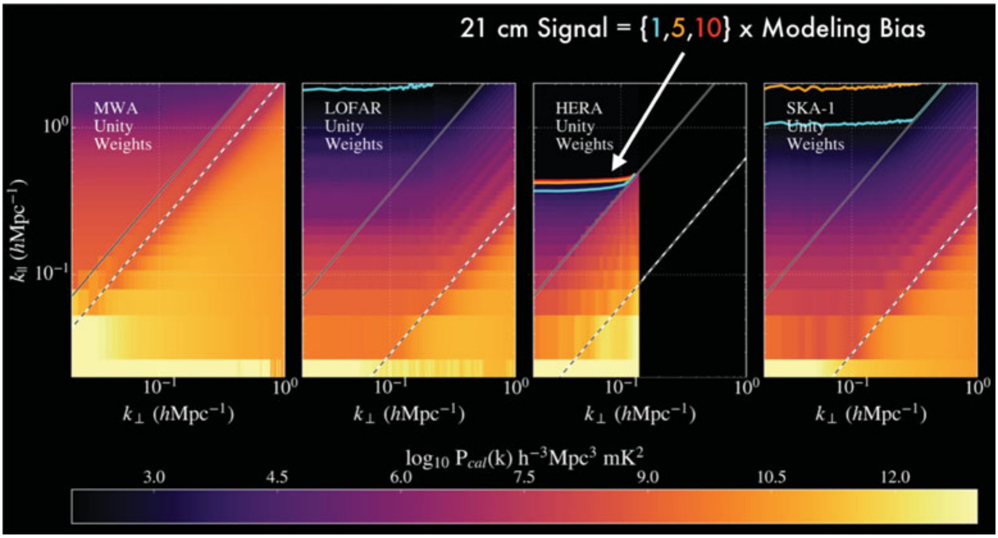

Figure 1. Small errors in the foreground model can create dramatic effects on instrumental calibration and can dramatically reduce the region of Fourier space accessible to 21 cm experiments due to foreground bias. Figure modified from its original form in Ewall-Wice *et al.* (2016).

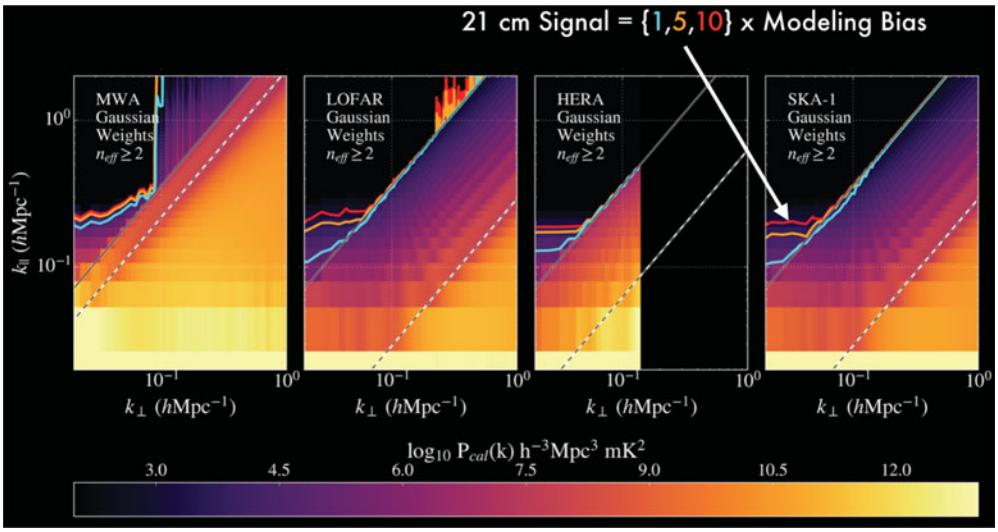

Figure 2. Downweighting long baselines can restore the EoR window by preventing foreground power leaking from right to left via calibration. Figure modified from its original form in Ewall-Wice *et al.* (2016).

Barry *et al.* (2016) and Yatawatta (2016) suggest addressing this problem by limiting the number of degrees of freedom of calibration. Another approach, developed by Ewall-Wice *et al.* (2016), is to downweight long baselines during calibration, preventing the "right-to-left" leakage in $k_\perp$ that we see in Figure 1. Doing so can restore the *wedge* structure (Liu *et al.* 2014), keeping the so-called *EoR window* mostly free of foreground bias, as we see in Figure 2.

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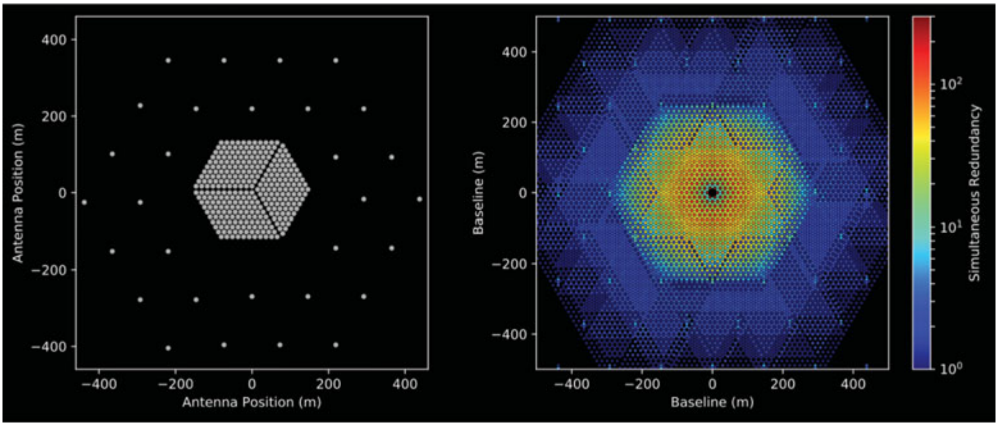

Figure 3. HERA's array layout and instantaneous redundancy in the uv-plane. HERA's split core configuration provides sub-aperture unique baseline coverage out to ∼300 m. All of HERA's antennas, including the outriggers, are redundantly calibratable. Figure modified from its original form in Dillon and Parsons (2016).

3. Redundant Calibration of HERA

Another approach to calibration relies on internal consistency of redundant baselines to calibrate both gains and visibilities simultaneously without a sky model (Liu *et al.* 2010). The key idea is that baselines with the same separation should be sensitive to the same mode on the sky, up to their individual antenna gains. If the array itself is highly redundant, then the system of equations in Equation 1.1 becomes overdetermined. HERA was designed for redundant calibration (see Figure3), though it also has very dense-uv coverage that helps with imaging of diffuse structure (Dillon and Parsons 2016).

While redundant-baseline calibration still requires an additional sky-based absolute calibration to solve for the last few degrees of freedom per frequency, the method still vastly reduces the number of calibration parameters. It has been used successfully both with MITEoR (Zheng *et al.* 2014) and PAPER (Ali *et al.* 2015). In Figure 4 we show preliminary relative gain calibration solutions from HERA, which have the overall delay taken out but still need to be absolutely calibrated. Much work needs to be done validating this result, but it is encouraging that little obvious small-scale (i.e. high k) spectral structure is being detected by the calibration solution—which means that the instrument's performance appears roughly consistent with its design (DeBoer *et al.* 2016).

4. Discussion

This proceeding and the talk it draws upon focused on the challenges of antenna calibration and their fundamental importance to the realization of 21 cm cosmology. I focused on the paradigm of *foreground avoidance* where the chief goal is to keep the EoR window clean. A detection of the EoR does not require perfect calibration, but it does require careful control of the spectral structure of our calibration errors, especially on the short baselines that have the least instrumental chromaticity and the greatest sensitivity to the cosmological signal.

I am leading a number of efforts to push this technique forward that I touched on briefly in the talk. One is an investigation of the effect of non-redundancy on redundant-baseline calibration and how those errors can be mitigated analogously to those in Section 2 (Orosz *et al. in prep.*). Another is the possibility of using redundancy in the uv-plane of different baselines at different frequencies to solve for the degeneracies of

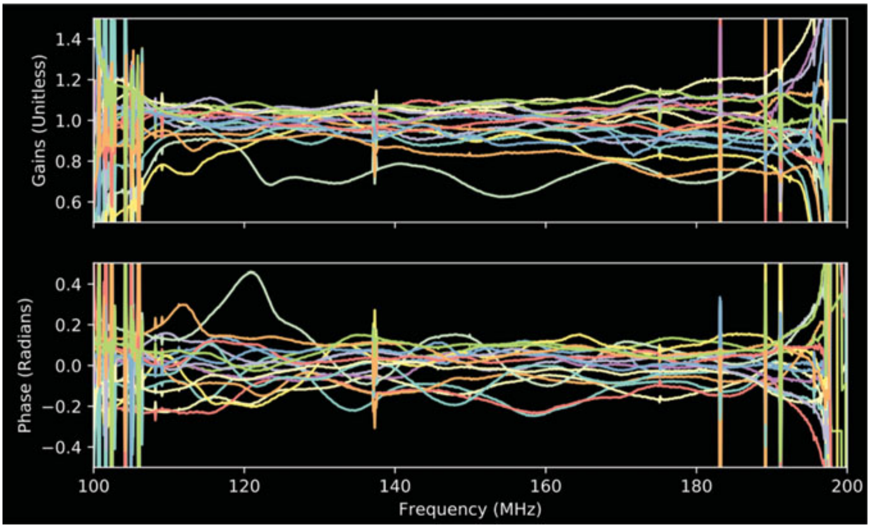

Figure 4. Average results from 10 minutes of redundant baseline calibration of HERA's first 19 elements. Redundant baseline calibration appears to uncover real structure, though there's little evidence for fine spectral structure besides a known bandpass ripple due to 150 m cables that will be eliminated in future observing seasons. Much work remains to turn this relative antenna bandpass calibration into an absolute, sky-referenced calibration solution.

redundant-baseline calibration and produce an overall bandpass for the array (Dillon and Parsons (*in prep.*).

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