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Results From PAPER/HERA

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Abstract. The Precision Array for Probing the Epoch of Reionization (PAPER) was a first-generation 21 cm cosmology experiment with the specific goal of detecting the power spectrum of the 21 cm emission from the Epoch of Reionization. Analysis of PAPER data is still ongoing, but lessons learned from PAPER to date have played a critical role in designing the next-generation Hydrogen Epoch of Reionization Array (HERA) experiment. This article reviews five key design choices made by PAPER: use of a non-imaging configuration, redundancy, short baselines, small antenna elements, and a large instantaneous bandwidth. We describe the impact of these choices and the role they played in designing HERA.

Keywords. instrumentation: interferometers, techniques; interferometric, methods: data analysis

1. Introduction

The Donald C. Backer Precision Array to Probe the Epoch of Reionization (PAPER) is an experiment specifically designed to detect the power spectrum of highly redshifted 21 cm emission from the Epoch of Reionization (EoR). After initial deployments in Western Australia and Green Bank, WV (Parsons *et al.* 2010), the experiment conducting several observing campaigns with 32, 64, and finally 128 antenna-element arrays in the Karoo Desert of South Africa (Pober *et al.* 2013, Parsons *et al.* 2014, Ali *et al.* 2015). The experiment completed observations in April 2015; analysis of 128-element data from the final two seasons is ongoing. The Hydrogen Epoch of Reionization Array (HERA; Pober *et al.* 2014, DeBoer *et al.* 2017) is a new, second-generation experiment on the PAPER site (and much of the PAPER hardware was reused in the first versions of HERA before a complete signal chain refurbishment). This article will detail lessons learned from the PAPER experiment and how those lessons affected the design of HERA.

2. Lessons from PAPER

We highlight five key design decisions made in the PAPER experiment and the lessons learned from those choices.

Non-Imaging Configuration. As an experiment to detect the power spectrum of the 21 cm signal from the EoR, PAPER is not required to function as an imaging interferometer. While imaging configurations are valuable for foreground modeling and calibration, PAPER utilizes the delay spectrum approach, where single baselines are used as individual probes of the power spectrum (Parsons *et al.* 2012b). Hand-in-hand with this approach is the idea of "foreground avoidance": rather than attempting to remove foregrounds from the data, the PAPER approach accepts certain modes of the power spectrum as irreparably contaminated but attempts to localize this contamination to as small a region as possible. The chromatic nature of the interferometer significantly increases the number of contaminated modes (creating so-called "wedge" region in Fourier space), but studies have suggested that enough signal will remain uncontaminated to make cosmologically interesting measurements using this technique (Parsons *et al.* 2012a, Pober *et al.* 2014).

The delay spectrum approach opens the door to new analysis techniques like the wide-band delay filter used in Parsons *et al.* (2014 and Ali *et al.* (2015). This filter removes all signal (foreground and cosmological) from inside the wedge region, making these modes unsuitable for cosmological studies, but can significantly mitigate residual contamination in modes outside the wedge. The delay spectrum approach and foreground avoidance are not mutually exclusive of techniques like foreground modeling and foreground subtraction, however, and work by Kerrigan *et al.*(in prep.) demonstrates the potential for a model-based foreground subtraction before a delay spectrum style analysis.

Figure 1. The final 128-element PAPER layout in South Africa.

Redundancy. The PAPER experiment uses a highly redundant array layout (shown in Fig 1) for several reasons. First, redundant arrays can boost the power spectrum sensitivity of a delay spectrum approach. Physically redundant baselines can be combined coherently, providing a greater reduction in noise compared with the case when each baseline is used to estimate the power spectrum independently. Redundancy also allows for the redundant calibration (Wieringa 1992, Liu *et al.* 2010, Zheng *et al.* 2014), which has many potential advantages for calibrating 21 cm experiments. Redundancy between baselines also provides a valuable axis for jack-knifing and bootstrapping as well as for real-time system diagnostics. Although redundant arrays typically have poor point spread functions, the delay spectrum approach mitigates the importance of the PSF, allowing PAPER to take advantage of these other benefits to redundancy.

Short Baselines. Because short baselines have less high frequency structure in their spectral response compared with long baselines, they cause less “bleed” of foregrounds to high $k_{||}$ modes. (This is the explanation for the wedge shape of foreground contamination.) Short baselines therefore have the potential to access more of the 21 cm signal, and so PAPER uses a highly compact configuration to maximize the number of short baselines. There are also other reasons to avoid long baselines in a 21 cm experiment. They are computationally expensive in that they require shorter time and frequency averaging lengths and they are also more corrupted by ionospheric effects. Longer baselines are also potential sources of calibration errors with significant spectral structure (Barry *et al.* 2016, Ewall-Wice *et al.* 2017).

Small Elements. In order to preserve the distinct spectral structure of the foregrounds, the PAPER philosophy was to build an instrument with a maximally spectrally smooth response. Small antenna elements limit standing waves and reflections to short travel times, minimizing spectral structure in their response patterns. PAPER used very small ($\sim 4\,\mathrm{m}^2$) single dipole elements for this reason. And while these elements were successful in generating a very smooth instrumental bandpass, they also come at considerable expense in terms of sensitivity. While spectral smoothness is still of the utmost importance for 21 cm experiments, trade-offs with sensitivity must be considered to build the most effective instrument.

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Large Instantaneous Bandwidth. PAPER had the largest instantaneous bandwidth of any first-generation 21 cm experiment, running from 100 – 200 MHz. This choice was not only a good one from a scientific perspective (the predicted redshift of reionization has changed rather significantly in the decade since PAPER was designed), but also enabled powerful analysis techniques. The wide-band delay filter described above uses the large bandwidth as a lever-arm to constrain and remove foregrounds in the band of interest using measurements at higher and lower frequencies.

3. Designing HERA

These design choices by PAPER led to several analysis advantages, but may also have hindered the experiment in terms of raw sensitivity and flexibility. HERA was designed to use the delay-spectrum analysis technique developed for PAPER, but also to make up for several shortcomings in the PAPER design.

Increase Sensitivity. HERA was designed to be significantly more sensitive than PAPER. This was accomplished by both increasing the number of antenna elements from 128 to 350, but also by increasing the size of each element by nearly a factor of 40. Each element still uses only one dipole antenna, but it is now placed at the focal point of a 14 m dish. These elements were carefully designed not to degrade the spectral response of the instrument and affect the spectral smooth of the foreground emission. Criteria based on delay reflectometry were simulated and tested in the field (Thyagarajan *et al.* 2016, Ewall-Wice *et al.* 2016b, Patra *et al.* 2017).

Increase Bandwidth. HERA will further increase the instantaneous bandwidth over that of PAPER, targeting 50 – 250 MHz. This larger band will support Epoch of X-ray heating studies at redshifts higher than the EoR (Ewall-Wice *et al.* 2016) and also allow for a powerful "null test," looking for the absence of the 21 cm signal in the post-reionization universe (Pober *et al.* 2016). This bandwidth increase will require newly designed feeds which will have to meet our requirements for spectral smoothness.

Increase Resolution. HERA will retain a highly redundant layout like that used by PAPER to maximize the number of short baselines and to enable techniques like redundant calibration. HERA will consist of a nearly filled hexagonal core with a diameter of ~ 300 m (shown in Figure 2), but will also include outrigger antennas to bring the longest baseline up to 1 km in length. As described in Dillon & Parsons (2016), the core is faceted into three offset regions, providing *uv* spacings below the antenna scale. The outrigger antennas are also configured such that they can be redundantly calibrated with the rest of the array. The increased resolution of HERA can therefore enable imaging-based and other power spectrum analysis techniques, while still retaining all the successful features of PAPER for the delay spectrum approach.

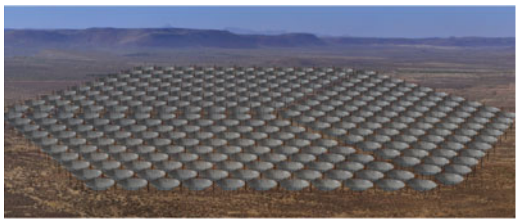

Figure 2. Rendering of the 331-element core of HERA. Outriggers will extend the array out to ~ 1 km.

4. Summary

HERA commissioning took place with 19 elements from October 2016 – 2017, at which point first science observations began with ~ 61 elements. Building on the lessons from

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the PAPER experiment, HERA is primed to capitalize on its increased sensitivity towards a first detection and eventual characterization of the 21 cm signal from the EoR.

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