THE PRECISION ARRAY FOR PROBING THE EPOCH OF RE-IONIZATION: EIGHT STATION RESULTS

Aaron R. Parsons1,8, Donald C. Backer1, Griffin S. Foster1, Melvyn C. H. Wright1, Richard F. Bradley2,9, Nicole E. Gugliucci2, Chaitali R. Parashare2, Erin E. Benoit3, James E. Aguirre4, Daniel C. Jacobs4, Chris L. Carilli5, David Herne6, Mervyn J. Lynch6, Jason R. Manley2,10, and Daniel J. Werthimer2,11

1 Astronomy Department & Radio Astronomy Laboratory, University of California, Berkeley, CA 94720-3411, USA; aparsons@astron.berkeley.edu
2 Astronomy Department & Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA 22904-4325, USA
3 National Radio Astronomy Observatory, Charlottesville, VA 22903-4608, USA
4 Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104-6396, USA
5 National Radio Astronomy Observatory, Socorro, NM 87801-0387, USA
6 Department of Imaging and Applied Physics, Curtin University of Technology, Perth, WA 6845, Australia
7 Berkeley Wireless Research Center, University of California, Berkeley, CA 94720-1302, USA
8 Berkeley Wireless Research Center, University of California, Berkeley, CA 94720-1302, USA
9 Berkeley Wireless Research Center, University of California, Berkeley, CA 94720-1302, USA
10 Berkeley Wireless Research Center, University of California, Berkeley, CA 94720-1302, USA
11 Space Science Laboratory, University of California, Berkeley, CA, USA.

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ABSTRACT

We are developing the Precision Array for Probing the Epoch of Re-ionization (PAPER) to detect 21 cm emission from the early universe, when the first stars and galaxies were forming. We describe the overall experiment strategy and architecture and summarize two PAPER deployments: a four-antenna array in the low radio frequency interference (RFI) environment of Western Australia and an eight-antenna array at a prototyping site at the NRAO facilities near Green Bank, WV. From these activities we report on system performance, including primary beam model verification, dependence of system gain on ambient temperature, measurements of receiver and overall system temperatures, and characterization of the RFI environment at each deployment site. We present an all-sky map synthesized between 139 MHz and 174 MHz using data from both arrays that reaches down to 80 mJy (4.9 K, for a beam size of 2.15e ﹣100 for a 1.46 MHz band centered at 164.5 MHz). This sensitivity level is approximately 3 orders of magnitude above the level of the fluctuations in 21 cm emission associated with re-ionization.

Key words: cosmology – observations – instrumentation: interferometers – radio continuum: general – techniques: interferometric – site testing – telescopes

1. INTRODUCTION

The Epoch of Re-ionization (EoR) marks the transition of the primordial intergalactic medium (IGM) from a neutral to a highly ionized state as a result of radiation from the first stars and massive black holes (Loeb & Barkana 2001). This phase transition represents a key benchmark in the history of cosmic structure formation and a major frontier of cosmic evolution yet to be explored. Observations of Gunn–Peterson (GP) absorption by the IGM toward distant quasars (Becker et al. 2001; Fan et al. 2006) and large-scale cosmic microwave background (CMB) polarization from Thompson scattering (Page et al. 2007) have constrained cosmic re-ionization between redshifts 6 < z < 14. However, deeper exploration of re-ionization via these probes faces fundamental limitations: the GP-effect saturates at low neutral fractions and CMB polarization is an integral measure of the Thompson optical depth to recombination.

The most incisive probe of EoR is direct observation of the neutral IGM using the hydrogen 21 cm line (Furlanetto et al. 2006; Barkana & Loeb 2005a). The rich astrophysics traced by H1 and the intrinsic three dimensionality of the signal make this approach especially appealing (Barkana & Loeb 2005b; Loeb & Zaldarriaga 2004). However, the challenges of exploring re-ionization with redshifted 21 cm emission in an observing band below 200 MHz are daunting. EoR detection experiments require unprecedented levels of instrumental calibration and foreground characterization. The brightness temperatures of polarized galactic synchrotron emission, continuum point-sources, and galactic-extra-galactic free–free emission can exceed the expected ∼10 mK fluctuations of the 21 cm EoR signal by more than 5 orders of magnitude (Zahn et al. 2007; Santos et al. 2005). Wide fields of view (FoVs), large fractional bandwidths, large numbers of antennas, significant radio frequency interference (RFI) environments, and ionospheric variation all present challenges for next-generation low-frequency arrays.

The Precision Array to Probe the Epoch of re-ionization (PAPER) is a first-generation experiment focused on statistical EoR detection, but with sufficient sky coverage and sensitivity to detect the very rare, largest-scale structures formed at the end of re-ionization. PAPER represents a focused effort to overcome the substantial technical challenges posed by using large, meter-wave interferometric arrays to detect the 21 cm EoR signal.

In Section 2, we present the principle deployments of the PAPER instrument. We then outline the architectures of the analog (Section 3) and digital (Section 4) signal paths and describe the calibration pipeline (Section 5) that is applied to the data. Finally, we present observational results in Section 6 that include an all-sky map and angular power spectra measured toward a colder patch of the synchrotron sky.
2. PAPER DEPLOYMENTS

PAPER is being developed as a series of deployments of increasing scope to address the instrumentation, calibration, and foreground characterization challenges that must be surmounted in order to detect a 21 cm signal from EoR. By characterizing and optimizing each component in the array with careful engineering, we hope to reduce the complexity of data calibration and analysis. Our staged approach allows for a systematic investigation of observational challenges, with a capacity for adaptation as the characteristics of our instrument and of interfering foregrounds are better understood.

There have been three principal PAPER deployments, whose characteristics, along with a planned 64 antenna deployment, are outlined in Table 1; \( N_{\text{ant}} \) is the number of antennas in each deployment; \( N_{\text{pol}} \) is the number of polarization cross-multiples computed in the correlator; \( \Omega_b \) denotes the solid angle of the primary beam at 150 MHz; \( \Delta v_{\text{corr}} \) is the correlated bandwidth; \( N_{\text{chan}} \) is the number of frequency channels computed over the correlated bandwidth; \( \tau_{\text{int}} \) is the integration time per visibility; \( \tau_{\text{obs}} \) is the longest continual operation; \( d_{\text{max}} \) is the approximate maximum baseline length. In its initial 2004 deployment at the NRAO facilities in Green Bank \(^{12} \) (latitude 38°26′, longitude −79°51′) the PAPER instrument consisted of four sleeved dipoles above planar ground-screens arranged on an east–west line with integrated differential amplifiers. This minimum-redundancy array, dubbed PGB-4, had a longest baseline of 100 m and provided initial field experience and a means by which to evaluate our analog and digital electronics. PGB-4 established PAPER’s basic architecture as that of a transit array of zenith-pointing dipoles connected to a central correlator via fixed-length cables running above ground.

The second PAPER deployment, PGB-8, began in 2006 and underwent continual development until it was upgraded to PGB-16 in 2008 October. PGB-8 consisted of eight antennas deployed on a 300 m diameter circle (Figure 1) at the NRAO Green Bank Galford Meadow site, with a small hut for rudimentary climate control built at the center of the array to house the receivers and correlator. As discussed in Section 3, antenna signals propagate to the hut over 75 ohm coaxial cable. The correlator itself went through several cycles of improvement parallelling the development of the scalable correlator architecture described in Section 4. In its final state, the PGB-8 correlator employed a packetized correlator (PaCo-8) that processed 2048 spectral channels across 150 MHz of bandwidth, computing all four Stokes parameters, although the analog system only supported one polarization. In early 2008, we improved the forward gains of antennas by adding 45° side reflectors to the ground screens. Data used for the PGB-8 analysis presented in this paper were collected starting at JD 2454565.0 and ending at JD 2454568.0.

Our third deployment, PWA-4, was near the Murchison Radio Observatory (MRO) site\(^ {13} \) in Western Australia (latitude −26°44′, longitude 116°40′) in 2007 July. This path-finding array gave us firsthand experience with the logistics of deploying and operating an array at a very remote site. The success of this deployment gave us confidence in the low RFI levels and data quality that can be expected from a much larger array at this site. PWA-4 consisted of four antennas with planar ground screens (no side reflectors) arranged in a trapezoid pattern with a maximum baseline of 150 m. The four-input “Pocket Correlator” (PoCo) described in Section 4 correlated signals from these four elements. Data used for the PWA-4 analysis presented in this paper were collected starting at JD 2454301.0 and ending at JD 2454304.0.

A fourth deployment, PGB-16, is underway. A total of 16 sleeved dipole antennas using ground screens with side reflectors have been deployed at Galford Meadow. Initial operations are proceeding in single-polarization mode using PaCo-8, but will evolve to dual-polarization with a PaCo-16 correlator.

3. THE ANALOG SYSTEM

The levels of instrumental calibration and foreground characterization that will be required to model and remove signals interfering with an EoR detection are unprecedented in the 100–200 MHz band expected to encompass re-ionization. With this in mind, we have taken care that each stage of our analog system (see Figure 2) exhibits smooth responses as a function of frequency and direction, thereby minimizing the number of parameters needed to describe these responses.

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12 The National Radio Astronomy Observatory (NRAO) is owned and operated by Associated Universities, Inc. with funding from the National Science Foundation.

13 We acknowledge the Wajarri-Yamatji people of Australia as the Native Title Claimants of the proposed MRO lands and we thank them for allowing scientific activity on the site.
and limiting the magnitude of errors introduced by imperfect calibration.

3.1. Antenna Design

PAPER antennas are designed as rugged dual-polarization versions of the sleeved dipole (Johnson 1993). Crossed dipoles made from copper tubing are encased between two thin aluminum disks, creating a dual-resonance structure that broadens the antenna’s frequency response. The dimensions of the tubing and disks have been tuned for efficient operation over a 120–170 MHz band. This design produces a spatially smooth primary beam pattern that evolves slowly with frequency.

The antenna design includes a grounding structure that alleviates the gain variations that result from the effects of climatic conditions on the dielectric properties of earth ground. PGB-4 and PWA-4 deployments employed simple wire-mesh ground planes (0.25′′ grid spacing, 23 gauge wire, TWP Part 004X004D0250W48T) supported by a wooden framework (Figure 3, top). This design was improved to include planar wire-mesh reflectors that attach to the original ground screen (now supported by a steel framework) and rise outward at a 45° angle (Hall 1988). This design produces a primary beam (Figure 4) whose angular size more closely matches the angular size of colder patches in galactic synchrotron emission, effectively reducing PAPER’s sky-noise-dominated system temperature. Reduction of horizon gain also mitigates susceptibility to some RFI sources. We have ensured that these side-reflectors have not compromised the spatial and spectral smoothness of the primary beam.

The smoothness of the primary beam as a function of frequency and direction enable it to be effectively parameterized using low-order spherical harmonics and frequency polynomials according to the equation:

\[
a(\hat{s}) = \sum_{k=0}^{7} \nu^k \sum_{\ell=0}^{8} \sum_{m=0}^{\ell} a_{\ell m}(k) Y_{\ell m}(\hat{s}),
\]

where the frequency dependence of the antenna response is modeled by a seventh-order polynomial and the spatial variation of each polynomial coefficient is described by \(a_{\ell m}(k)\) coefficients of low-order spherical harmonic functions \(Y_{\ell m}(\hat{s})\). This parameterization smoothly interpolates to any chosen pointing and frequency. A numerical electro-magnetic code (CST) was used to model the antenna primary beam. The interpolating parameterization of this model has been assumed for all of the analysis presented in this paper.

Figure 5 illustrates the result of fitting, as a function of time, the perceived flux densities of the strongest four celestial sources visible with the PGB-8 array and comparing the observed attenuation of each source to the attenuation predicted by the assumed primary beam model. The model predicts the perceived flux densities of sources with approximately 93% accuracy for zenith angles less than 45°. Errors in the beam model are primarily the result of the spectral response of the primary beam being steeper as a function of zenith angle than what is predicted by the model. This systematic effect is currently impeding the accurate measurement of spectral indices of calibrator sources.

Further characterization of the primary beam is currently a work in progress. The improved imaging capabilities of larger PAPER arrays are being used to extend the number of celestial sources available for characterizing the primary beam over a broad range of frequencies. Another parallel effort will use narrowband satellite transmissions to characterize the variation of beam profiles between antennas.
Figure 4. Illustrated above are simulated primary beam profiles of a linear YY polarization at 150 MHz for PW A-4 antenna elements without side reflectors (top) and PGB-8 antennas with them (bottom). Radial lines denote azimuth in 30° intervals from north (top of the page); circles denote altitude from the horizon in 10° intervals. Simulated profiles generated in 10 MHz intervals were interpolated using Equation (1) and assumed for all analysis in this paper. Work is proceeding on refining these models using measured data from celestial sources and orbiting satellites, with results to be presented in a forthcoming paper.

3.2. Pseudo-differential Amplifier Design

A pseudo-differential amplifier (PDA, Figure 6) is housed within the riser suspending each dipole element above its ground screen. Amplifiers employ three cascaded gain stages where the initial stage consists of a differential amplifier based on NEC NE46100 bipolar junction transistors. This circuit features an inherent direct-current pathway from input to ground, making the amplifier tolerant of electrostatic charge build-up that can pose a serious problem in dry climates (Jackson & Farrell 2006). The total ∼32 dB gain through the PDA unit is sensitive to ambient temperature with a coefficient $H = -0.02 \pm 0.003 \text{ dB K}^{-1}$ over the range 5–50 °C, as measured in our laboratory using an environmental chamber to vary physical temperature. This coefficient enters into the voltage gain $g_v$ of an antenna as

$$g_v(t) = g_v(t_0)H(T(t) - T(t_0)),$$

where $T(t)$ is the ambient temperature as a function of time $t$ and $t_0$ represents a fixed time at which static gain calibration is performed. Although not corrected for in the PWA-4 and PGB-8 systems, gain variation with temperature can be partially offset by recording the average ambient temperature of the array and applying a correction to all recorded visibilities. We are currently developing a system for using one antenna input as a “gain-o-
correlation power $P_{\nu}$ for per-antenna gain correction. Could also record the ambient temperature at each PDA unit and using the gain variation of this input to normalize meter” by swapping dipoles for a load attached at the front of the PDA to allow for per-antenna gain correction.

We have estimated the receiver temperature of the antenna/PDA system by modeling the frequency-dependent auto-correlation power $P_{\nu}$ as a function of time $t$, as described in Rogers et al. (2004):

$$P_{\nu}(t) = |g_{\nu}(t)|^2 k_B T_{\text{sky}}(t) + T_{\text{rx}} \sqrt{\Delta \nu},$$

(3)

where $g_{\nu}(t)$ is defined in Equation (2), $T_{\text{sky}}(t)$ is the temperature of a model galactic synchrotron sky weighted by the primary beam of an antenna, $T_{\text{rx}}$ is the receiver temperature, and $\Delta \nu$ is the bandwidth of a channel. $T_{\text{sky}}$ was modeled by scaling a 408 MHz sky map (Haslam et al. 1982) to 162 MHz using a spectral index of $-2.52$ (Rogers & Bowman 2008). As the galactic synchrotron sky rotates through the primary beam, the perceived $T_{\text{sky}}$ varies, providing a modulation that enables the separation of sky and receiver temperatures. After applying a first-order correction for the temperature dependence of amplifier gain using measured temperatures from a nearby weather station, we fit an average receiver temperature of $110 \pm 12 \text{ K}$ for the PGB-8 system.

### 3.3. Signal Transmission

Coaxial cables transport antenna signals from each PDA unit to a central processing location. Because these cables are not buried, they must be rugged to withstand harsh environmental conditions and the occasional chew from local fauna. We chose RG-6, 75 ohm cable with a polyethylene jacket for its stable propagation characteristics as a function of temperature and humidity and for its low cost. Signal attenuation over a 150 m cable run is approximately $12 \text{ dB}$ at 150 MHz, with a slope of $+0.034 \text{ dB MHz}^{-1}$, as measured in our laboratory. This cable also contains a wire suitable for delivering DC power to PDA units.

On the receiving end, dual-channel receiver boards consisting of amplifier stages and band-limiting filters prepare signals for digitization in the correlator. The high gain of these receiver cards poses a significant regenerative feedback concern not found in heterodyne systems (Slurzberg & Osterheld 1961). This issue was mitigated by mounting the receivers inside a special shielded enclosure (Bradley 2006). The gain of the amplifiers in the receiver cards is also sensitive to temperature, with a coefficient of $-0.045 \pm 0.003 \text{ dB K}^{-1}$. To avoid a second temperature dependence in signal gain, a thermal enclosure with thermoelectric heat pumps will be employed to stabilize the temperature of all receiver boards. The “gain-o-meter” approach described in Section 3.2 will also provide a first-order correction.

### 4. THE DIGITAL SYSTEM

A series of real-time digital FX correlators employing Field-programmable Gate Array (FPGA) processors addresses the growing digital signal processing (DSP) needs of visibility computation in PAPER deployments. These correlators are based on the architecture described in Parsons et al. (2008), wherein DSP engines transmit packetized data through 10 Gbit ethernet (10-GbE) links to commercial switches that are responsible for routing data between boards. This architecture, along with a set of analog-to-digital converters and modular FPGA-based DSP hardware and a software environment for programming, debugging, and running them, were developed in collaboration with the Center for Astronomy Signal Processing and Electronics Research (CASPER; Parsons et al. 2006). The flexibility of this correlator design shortens development time, allowing a series of correlators of increasing scale to be developed parallel to PAPER’s incremental build-out.

#### 4.1. CASPER Hardware and Gateware

The generic FX correlator architecture (Figure 7) on which PAPER correlators are based consists of a set of modules responsible for digitizing, down-converting, and channelizing antenna inputs (“F” engines), followed by a set of signal processing modules that cross-multiply all antenna and polarization samples for each frequency and accumulate the results (“X” engines). The problem of transmitting data from every F engine to every X engine is solved by packetizing data according to the 10 GbE protocol and then using a commercial switch to sort data streams. This approach, unique to the CASPER architecture for correlators of this size and bandwidth, avoids custom backplanes and communication protocols that are tailored to a single application, which are the traditional solution to the cross-connect problem in correlators.

Signals from PAPER antennas are digitized by Atmel AT84AD001B dual 8 bit ADC chips capable of digitizing two streams at 1 G sample s$^{-1}$. While overrated for this application, this chip has been used in many CASPER applications and is extensively tested. The wide bandwidth of this ADC allows the entire PAPER bandwidth to be Nyquist-sampled as a single, real voltage and then a 75–225 MHz band is digitally mixed to baseband with perfect in-phase and quadrature-phase components. Two ADC boards connect to each of the CASPER Interconnect Break-out Board (IBOB) processing boards used as F engines in PAPER’s correlator. On the IBOB, one FPGA is responsible for the signal flow outlined in Figure 8—namely, digitally down-converting four digitized signals, spectrally decomposing

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14 http://casper.berkeley.edu/wiki/ADC2x1000-8
15 http://casper.berkeley.edu/wiki/IBOB
the resulting baseband signals using a Polyphase Filter Bank (PFB; Crochiere & Rabiner 1983; Vaidyanathan 1990), and re-quantizing spectral data to 4 bits. PAPER correlators equalize antenna spectra before re-quantization to ensure optimal linearity of the output power with respect to input power, as described in Section 5.1. Output data are passed briefly to the BEE2 board (described below) where they are formatted into 10 GbE packets and transmitted to a commercial switch. A 12 port Fujitsu CX600 10 GbE switch is employed for routing packets between F and X engines. Each port on this switch carries data for two antennas. The performance of this switch was evaluated over a period of 16 hr, with pseudo-random data transmitted and received on each data link. During this time, no errors were detected, placing a limit on the bit-error rate of transmission at $2.2 \times 10^{-16}$ bits s$^{-1}$. Furthermore, the asynchronous correlator architecture employed by PAPER is tolerant of dropped packets, so errors that do occur do not cause system failures.

We rely on CASPER’s Berkeley Emulation Engine (BEE2) boards16 for implementing X engine processing. Each of four FPGAs on a BEE2 operates independently to unscramble packets received from the 10 GbE switch. Two X engine cores inside each BEE2 FPGA then compute cross-multiplications for all $N$ antennas for $1/N$th of the frequency channels and the results are accumulated for a selectable time interval. Output of accumulated data over a 100 Mbit ethernet connection currently imposes a 14 s minimum integration time. We are currently migrating this output to 10 GbE, which will allow shorter integrations that more adequately resolve ionospheric fluctuations.

4.2. PoCo and PaCo-8

The PoCo (Figure 9, top) used with the PWA-4 deployment is a single IBOB system for correlating and accumulating four input signals (Figure 8). ADCs sample each analog input at 600 MHz and a 75 MHz to 225 MHz band is extracted digitally. A four-tap PFB decomposes this sub-band into 2048 channels, which are then equalized to remove per-channel scaling differences before being re-quantized to 4 bits. Limited buffer space on the IBOB permits only 1024 channels (selectable from within the 2048) to be accumulated. Accumulated visibilities are output via serial connection to a host computer after being integrated for 7.16 s.

The eight-antenna packetized correlator (PaCo-8; Figure 9, bottom) used with the PGB-8 deployment employs four IBOBs and one BEE2 board that communicate through a Fujitsu XG700 10 GbE switch, following the architecture outlined in

16 http://casper.berkeley.edu/wiki/BEE2

Figure 8. Digital processing in an F engine of PAPER’s PaCo (Figure 7) also doubles as a stand-alone PoCo for correlating four signal inputs. In both designs, data are re-quantized to 4 bits after spectral decomposition. To avoid signal distortion caused by bit truncation, signals are equalized before truncation and the inverse equalization is applied in post-processing.

Figure 7. Each IBOB in this system operates identically to PoCo, but branches data from the equalization module to a matrix transposer for forming frequency-based packets. Packet data for each antenna are multiplexed through a point-to-point connection to a BEE2 FPGA and then relayed in 10 GbE format to the switch. A central CPU on each BEE2 board collects all visibility data after it has been accumulated for 14.32 s and transmits it over 100 Mb ethernet to a server where it is written to disk in MIRIAD format (Sault et al. 1995). In field
deployments, correlators are housed inside a special shielded enclosure (Bradley 2006) to mitigate self-interference.

5. THE CALIBRATION PIPELINE

The greatest challenge of using low-frequency interferometry to detect the cosmic re-ionization lies in characterizing the celestial sky and modeling the system response such that foregrounds to the EoR signal can be effectively suppressed. Various methods for estimating the effects of instrumental calibration on a statistical EoR detection have been analyzed (Morales 2005; Morales et al. 2006; Bowman et al. 2006), but improving the calibration and stability in early instruments remains an open problem (Yatawatta et al. 2008; Bowman et al. 2007). Wide FoVs, large fractional bandwidths, strong RFI environments, and ionospheric variation all complicate the calibration of next-generation low-frequency arrays such as PAPER, the Murchison Widefield Array (MWA), the Long Wavelength Array (LWA), and the LOw Frequency ARray (LOFAR). Obtaining an accurate sky model requires accurate models of primary beams, receiver passbands, gain variation, and array geometry. However, characterization of these often depends on the availability of an accurate sky model. The PAPER approach to this problem has been to emphasize precision, with the goal of characterizing system components to within 1% in order to facilitate further model refinement via sky modeling and self-calibration.

Although many standard tools exist for calibrating interferometric data, we are developing an open-source software project called Astronomical Interferometry in PYthon (AIPY) that modularizes interferometric data reduction to facilitate the exploration of new algorithms and calibration techniques. The niche targeted by this package is developing arrays whose evolving instrumental characteristics require flexible, adaptable tools. AIPY uses the dynamically interpreted Python programming language to wrap together interfaces to packages such as MIRIAD (Sault et al. 1995) and HEALPix (Gorski et al. 2005) using a common numerical array interface. AIPY also includes object-oriented implementations of a wide range of algorithms useful for radio interferometry, including W-projection (Cornwell et al. 2003), CLEAN (Höggbom 1974), maximum-entropy deconvolution (Cornwell & Evans 1985; Sault 1990), aperture synthesis imaging, faceted map-making, visibility simulation, and coordinate transformations. AIPY relies heavily on third party, public-domain modules for scientific computing, allowing its development to focus on interferometry-specific functionality.

AIPY analysis centers around parameterizing interferometric measurement equations for the instrument in question. However, before data from a PAPER correlator are ready to be compared to the measurement equation shown in Equation (4), it requires gain linearization, RFI excision, and crosstalk removal.

5.1. Gain Linearization

Mitigating the effects of data quantization in the PAPER correlator requires that power levels be carefully set for optimal signal-to-noise ratio (S/N) and that output data be converted to a linear power scale (see chapter 8 of Thompson et al. 2001). Correction factors for gain nonlinearities in digital systems employing 1 bit and 2 bit quantization of voltage samples are well known (Van Vleck & Middleton 1966). The nonlinear power response of the PAPER correlator, with its 4 bit correlation, is still significant. Our approach to gain linearization is detailed in Parsons et al. (2008). Inside the correlator, optimal SNR during re-quantization is ensured by applying an equalization function that shifts data samples to the region of maximal linearity in the 4 bit quantization response curve. This equalization function is updated hourly to adjust for changing mean power levels as the galactic synchrotron sky traverses the dipole beam. The first steps of PAPER calibration are to deduce an average 4 bit value from the accumulated output of the correlator, to invert the known quantization response for this value (Figure 13 in Parsons et al. 2008), and then to remove the equalization function used in the correlator.

5.2. RFI Excision

As a general solution to identifying data points that depart from an otherwise smooth function, we employ an algorithm that iteratively fits a smooth polynomial to visibility amplitudes, subtracts that polynomial to identify and exclude outlying points, and repeats. This algorithm identifies outlying points by finding the mean and standard deviation of the logarithm of all data points and defining a threshold in units of the standard deviation. The effectiveness of this technique is improved by first subtracting simulated visibilities using accurate models of the array response and the celestial sky.

This RFI excision algorithm is applied to spectra of cross-correlation data to identify narrowband interference and to time series in auto-correlation data to identify integrations where strong RFI such as aircraft communication saturates the ADC input. Such saturation events result in wide-band “drop-outs” where signal is lost across all frequencies. In both cases, detection of an interference event in a given channel/integration on any baseline results in that data being flagged for all baselines. Figure 10 illustrates the usable fraction of data averaged over a full day for the PGB-8 and PWA-4 deployments. The RFI environment in Western Australia represents a marked
improvement over that of the NRAO Green Bank Galford Meadow site, with fewer channels occupied by continuous RFI and almost no ADC saturation events. Such events cause approximately 40% of PGB-8 integrations to be unusable.

5.3. Crosstalk Removal

The inadvertent introduction of a correlation between two independent inputs via a cross-coupling pathway is unavoidable in radio interferometers. Many systems use phase switching to help remove crosstalk introduced along the signal path from an antenna to the ADC. PAPER does not currently implement phase switching, although we are exploring options for doing so. However, in the absence of (or in addition to) phase switching, there are other techniques for removing crosstalk from visibility data, provided that such crosstalk is adequately stable with time. PAPER’s crosstalk is modeled as an additive component of measured visibilities that varies slowly on the timescale of several hours. Because this crosstalk is stable on a timescale much longer than the typical 20 minute fringe period of a source over the shortest baseline and because its power is concentrated at low delays, PAPER crosstalk is easily suppressed using frequency-based time-averages or delay/delay-rate filters (Parsons & Backer 2009). As with RFI, crosstalk removal is facilitated by the subtraction of simulated visibilities.

5.4. PAPER’s Measurement Equation

At the heart of the PAPER analysis model is a measurement equation for the single polarization visibility response \( V_\nu(t) \) of a baseline at channel center frequency \( \nu \) and time \( t \):

\[
V_\nu(t) = G_\nu(t) \sum_n A_n(\tilde{s}_n) S_n(\tilde{s}_n)e^{2\pi i(v(\tilde{b} + \tilde{t}) + t) + \phi},
\]

(4)

where \( \tilde{s}_n \) is a time-dependent unit vector pointing in the direction of a source \( n \) whose flux density is \( S \); \( G_\nu(t) \equiv g_\nu(t)g^*_\nu(t) \) is the frequency-dependent baseline response, which is expressed in terms of the voltage gain of each antenna \( (g_{ij} \text{; Equation (2)}) \) for constituent antennas indexed by \( i, j \); \( A_n(\tilde{s}_n) \equiv a_n(\tilde{s}_n)a^*_n(\tilde{s}_n) \) is the direction-dependent response of a baseline’s primary beam, expressed in terms of the electric field response of each antenna \( (a_{ij} \text{; Equation (1)}) \); \( \tilde{b} \) represents the baseline vector separating antenna positions in units of light propagation time; \( t \) is the relative electronic delay of antenna signals into the correlator; and \( \phi \) is a relative instrumental phase between antenna signals.

The design of our antenna and analog electronics leads to antenna-based gains \( (a_{ij}, g_{ij}) \) that can be modeled by smooth functions in time and frequency with a modest number of parameters. The degrees of freedom in these parameters are over-constrained by wide-band visibility data, even when using a sky model that includes only a small number of point sources. However, the larger FoV of PAPER elements has complicated early calibration by decreasing the extent to which a single source dominates the correlated signal between antennas. Without isolation of sources, self-calibration cannot proceed as a direct computation using raw data, but rather must proceed by fitting models of the array and the observed sky to remove baseline-dependent interference patterns (Cornwell & Fomalont 1989). To address this problem, we employ a two-tiered calibration process wherein initial coarse calibration that employs source-isolation techniques is followed by multi-source, least-squares fitting to visibilities for the parameterization described in Equation (4).

5.5. First-order, Time-independent Self-calibration

Phase calibration involves solving for the position and electronic signal delay associated with each antenna. The parameter space associated with phase calibration contains many local minima separated by wavelength increments projected toward calibrator sources. To speed the phase calibration process, we rely on theodolite-surveyed antenna positions. When initial antenna positions include errors greater than a wavelength, we have developed a procedure for fitting positions that is reasonably robust against converging to non-global minima. First, a single source is isolated in data either by selecting a time when one source is dominant, or by using coarse delay/delay-rate filtering (Parsons & Backer 2009). Baseline components \( b_x, b_y \) and a throw-away phase term are then fit for a pair of nearby antennas using a narrow set of frequency channels and a range of time over which fringes wrap several times. Next, data including a few other sources are used to separate \( b \) out of the remaining phase term. As a final step in single-baseline phase calibration, wide-bandwidth data are used to account for the final phase as a combination of electronic signal delay \( \tau \) and a small, frequency-independent phase term \( \phi \).

Following accurate phase calibration for a subset of antennas, another antenna is added and the procedure outlined above is repeated using data for all baselines that connect this antenna to the calibrated subset. With phase calibration for four antennas, preliminary antenna-based gain calibration is possible. PGB and PWA visibilities have been flux-calibrated using Cygnus A with a value of 1.09e4 Jy at 150 MHz and a spectral index of \( -0.69 \), which are derived from the data in Baars et al. (1977). The beam model described in Section 3.1 provided a first-order correction for the effects of the primary beam on the Cygnus A spectrum. In addition to an initial gain model that incorporated the measured responses of the analog and digital filters in the PAPER pipeline, fourth-order polynomials in frequency were fit for the bandpass functions \( (g_\nu) \) of antennas in the array.

At each stage, the residuals remaining after flux-calibration can help to highlight baselines with poorer fit scores—a hallmark of convergence to a non-global minimum. Once all problematic baselines have been eliminated, simultaneous fitting of phase and gain parameters can proceed until time-variable effects such as ionospheric distortion and changing primary beam response toward strong sources dominate residual visibilities.

5.6. Excision of Strong Point Sources

Strong point sources, while useful for initial calibration, complicate further calibration by degrading sensitivity toward other positions on the sky. This is especially true for small arrays, since the sidelobe response toward a source scales approximately as \( \sqrt{N_{vis}} \), where \( N_{vis} \) is the number of independent locations in the uv-plane that are being phased and summed. For PWA-4 and PGB-8, sources stronger than a few hundred Jy can dominate the response of a synthesized beam, even when using earth rotation synthesis.

Deep removal of the strongest sources is essential for improving primary beam models using sources at a variety of declinations. A time-invariant model of source position, flux density, and spectral index is moderately effective at removing these sources, depending on the accuracy of current beam models and the activity of the ionosphere. For PGB-8, we were able to achieve \( \sim 95\% \) suppression of sources using static modeling. However, the residual flux densities of the strongest five sources (Sun, Cygnus A, Cassiopeia A, Virgo A, Taurus A) were still...
strong enough to introduce noticeable imaging sidelobes. Improving source removal required fitting for offsets in the source position and flux spectrum as a function of time. We attribute these variations to ionospheric refraction (Figure 11) and defects in the primary beam model, respectively. All of these components were necessary to achieve source suppression at a level of $10^{-3}$ to $10^{-4}$, depending on the source’s position within the primary beam.

6. OBSERVATIONAL RESULTS

Results were obtained using three-day observations with a single east–west linear polarization for both PWA-4 (JD $2454301.0$ to JD $2454304.0$) and PGB-8 (JD $2454565.0$ to JD $2454568.0$) deployments. For both sets of data, the five strongest sources visible from the northern hemisphere (Sun, Cygnus A, Cassiopeia A, Virgo A, and Taurus A) were removed following the procedure described in Section 5.6; no southern-hemisphere sources were removed. Residuals associated with these sources reflect deviations of their spectra (as viewed through an imperfectly calibrated primary beam) from a strict power law. The Sun was further suppressed via the application of a delay/delay-rate filter (Section 5.5). Although these filters potentially corrupt wider areas of the map, the strength and variability of the Sun are such that their application greatly improves imaging of the daytime sky.

6.1. PWA-4/PGB-8 All-sky Map

The all-sky map in Figure 12 illustrates average flux density per beam area over a band between 138.8 MHz and 174.0 MHz. The northern hemisphere was imaged using PGB-8 data with peak beam response at declination $+38.5^\circ$. The southern hemisphere was imaged with data from PWA-4, which employed both a more compact array configuration and a broader primary beam. Peak beam response in the southern hemisphere lies at declination $−26.7^\circ$. Imaging over the full 35.2 MHz bandwidth was performed by generating full maps in 1.46 MHz intervals and then summing maps. Each map was generated using 200 facets, with phase centers equally spaced around the sphere. While each imaged facet employed W-projection (Cornwell et al. 2003) to correct for the curvature of the sky, facet imaging was nonetheless required to incorporate differences in data weighting between phase centers. This weighting optimizes SNR by accounting for the array’s direction-dependent gain toward that location as it drifts through the primary beam. As the sky drifts through the primary beam of PAPER antennas, widely separated points will be observed with substantially different gains and so will require different data weightings to optimize SNR. Faceting was required to allow regions of the sky separated by more than $15^\circ$ to be imaged with independent weightings.

Thermal noise and point-source sidelobes both contribute to the noise level seen in this all-sky map. As mentioned in Section 6, only the strongest five sources have been removed from this map prior to imaging. Image-domain CLEAN deconvolution was used to achieve modest suppression of sidelobes from other sources. The complexities of wide-field imaging with drift-scan data make further post-imaging deconvolution impractical, since CLEAN components of gridded visibilities may not be directly applied to ungridded visibility data. Our plan is to use imaging as a pathway for identifying sources that may then be fit and removed from raw visibilities. With this in mind, we have devoted little additional effort toward suppressing sidelobes of imaged sources. From the map in Figure 12, we measure an rms flux density of noise between point sources of 80 mJy (4.9 K using a beam area of 2.15e$^{-5}$ sr calculated using the full width at half-maximum (FWHM) area of a Gaussian beam fit to the main lobe of the PGB-8 synthesized beam at 156.4 MHz). As we discuss in Sections 6.2 and 6.3, this noise level exceeds the thermal noise level by 2 orders of magnitude, and is dominated by point-source sidelobes, with only a small contribution from galactic synchrotron emission at lower frequencies.

The position-dependent response of primary beams in each array is evidenced by changing noise levels in the map as a function of declination. Noise levels in the map also change with right ascension because system temperature depends on the average temperature of galactic synchrotron emission across the primary beam. To illustrate the levels of thermal noise in the all-sky map, we repeated the map-making process detailed above, but with alternating integrations added with opposite signs, so that celestial sources with slow time variation were heavily suppressed relative to thermal noise. The map generated by this technique, illustrated in Figure 13, shows that for the PGB-8 portion of the map, noise levels range from 10 mJy to 50 mJy.
Figure 12. Illustrated above is an all-sky equatorial (J2000) map (see Section 6.1) averaged between 138.8 MHz and 174.0 MHz, in units of log$_{10}$ (Jy beam$^{-1}$) ranging from $-1$ (white) to 1 (black). Northern hemisphere data were obtained with data from PGB-8 (JD 2454565.0 to JD 2454568.0) and southern hemisphere with data from PWA-4 (JD 2454301.0 to JD 2454304.0), both using a single east–west linear polarization. Models of Cygnus A (19h59m40s44), Cassiopeia A (23h23m58s49), Taurus A (05h35m22s01), Virgo A (12h31m12s23), and the Sun (1h10m7s27) have been subtracted/filtered from visibilities prior to imaging. In the northern hemisphere, SNR peaks near (12h00m40s00); sensitivity degrades with declination because of declining primary beam response and with right ascension because of increasing levels of sky-noise from galactic synchrotron emission. In the region of peak SNR, measured temperatures reach a minimum of 4.9 K, as measured by the incompletely sampled aperture of PGB-8. Thermal noise in this same area is measured to be 620 mK (see Figure 13), indicating that point-source sidelobes and diffuse galactic synchrotron emission dominate the noise-floor in this map.

Figure 13. Plotted above (top, grayscale) is a noise map obtained by imaging the PGB-8 data used to produce Figure 12, but with consecutive integrations added with alternating signs. The map is in units of log$_{10}$ (Jy beam$^{-1}$) ranging from $-2$ (white) to 0 (black). Flux densities in this map are indicative of thermal noise in the northern hemisphere of Figure 12. The lower line-graph illustrates a the cut through the map at declination $+38.5^\circ$, where PGB-8 is optimally sensitive. Flux densities in this cut range from 10 mJy to 50 mJy, corresponding to temperatures of 620 mK and 3.1 K at 156.4 MHz, using a synthesized beam size of 2.15e$^{-5}$ sr.

(620 mK to 3.1 K using a synthesized beam area of 2.15e$^{-5}$ sr as calculated above) in the declination range of peak sensitivity of the array.

6.2. Thermal Noise Contributions to PGB-8 Map

The map statistics in the direction of a colder patch of the galactic synchrotron were evaluated using 1.46 MHz facet
images with phase centers at (11h20, 30°00), (11h20, 40°00), (12h00, 30°00), and (12h00, 40°00). Each frequency interval and phase center were imaged twice with independent sets of alternating (odd and even time index) 14 s integrations from sky-noise and the 110 K receiver temperature measured present before integration in the correlator. A comparison of this temperature with the $T_{\text{sky}}$ predicted for a colder patch of the galactic synchrotron (see Section 6.2) shows that this estimate of the PGB-8 system temperature contains substantial noise in excess of what is predicted from sky-noise and the 110 K receiver temperature measured in Section 6.2. A probable cause of this excess noise is integration variation in the broadband gain levels as a result of RFI saturating ADC inputs (see Section 5.2).

The thermal noise images produced by differencing integrations yield the $T_{\text{rms}}$ estimates plotted in Figure 14 for each 1.46 MHz band. From each measured $T_{\text{rms}}$ we also inferred the system temperature $T_{\text{sys}}$ present before integration in the correlator. A comparison of this temperature with the $T_{\text{sky}}$ predicted for a colder patch of the galactic synchrotron (see Figure 15) shows that this estimate of the PGB-8 system temperature contains substantial noise in excess of what is predicted from sky-noise and the 110 K receiver temperature measured in Section 3.2. A probable cause of this excess noise is integration variation in the broadband gain levels as a result of RFI saturating ADC inputs (see Section 5.2).

Finally, the standard deviation of pixel values in the summed facet images exceeds thermal noise in the differenced facet images, implying contributions from celestial point sources, their sidelobes, and galactic synchrotron emission. The temperature associated with this pixel distribution reflects a sky temperature as perceived by the partially filled aperture of PGB-8. This perceived temperature is approximately a factor of 100 lower than the temperature of the galactic synchrotron because sparse samplings of short $uv$-spacings cause much of the emission from this source to be resolved out.

6.3. Angular Power Spectra

The angular power spectra illustrated in Figure 15 are measured using the PGB-8 data described in Section 6. Our analysis follows the techniques developed in White et al. (1999) for calculating angular power spectra with interferometric data in the flat-field approximation. To make this approximation, for system temperature calculations, but can misrepresent the apparent noise in an image; it effectively compensates for sidelobes that contribute to point-source confusion, which appear to be noise in the image domain.

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gridded visibility data projected toward each of the four phase centers defined in Section 6.2 were limited to a 10° diameter FoV by applying a circular boxcar windowing function \( W \), whose effect in the \( uv \)-plane is to convolve by the complementary Fourier kernel \( \tilde{W}(\tilde{u}) \). Within each facet, angular power spectra were calculated using the equation (White et al. 1999):

\[
C_\ell = \frac{1}{2\ell + 1} \sum_m |a_{\ell m}|^2
\]

\[
C(u) \simeq \left( \frac{\lambda^2}{2k_B \Omega_W} \right)^2 \frac{\int |V(\tilde{u}) \ast \tilde{W}(\tilde{u})|^2 d^2u}{2\pi u},
\]

(7)

where \( \Omega_W \) represents the solid angle spanned by \( W \), \( \tilde{W}(\tilde{u}) \) represents the measured visibility as a function of position \( \tilde{u} \equiv (u, v) \) in the \( uv \)-plane, and \( f \) denotes integration around a ring of \( |\tilde{u}| = u \). The relationship between \( uv \)-coordinates and angular wavenumber is defined by \( \ell \simeq 2\pi |\tilde{u}| \). In practice, \( V(\tilde{u}) \) is accompanied by sample weights \( B(\tilde{u}) \), so that Equation (7) becomes

\[
C(u) \simeq \left( \frac{\lambda^2}{2k_B \Omega_B} \right)^2 \frac{\int |B(\tilde{u}) V(\tilde{u}) \ast \tilde{W}(\tilde{u})|^2 d^2u}{\int |B(\tilde{u}) \ast \tilde{W}(\tilde{u})|^2 d^2u},
\]

(8)

where \( \Omega_B \) represents the solid angle spanned by the primary beam.

For each facet, separate \( C(u) \) spectra were formed in 1.46 MHz intervals by integrating around rings in the \( uv \)-plane that were logarithmically spaced in radius and width. Within each ring, data were weighted by the square of the primary beam response toward phase center for optimal SNR. We estimated the contribution of thermal noise to the error in each \( C(u) \) measurement by generating power spectra for thermal noise images. This was done using the technique of adding integrations with alternating signs described in the previous section. The error from sample variance was much larger than the error from thermal noise, owing to the limited aperture sampling of the PGB-8 array and the limited area on the sky employed for this analysis. Error contributions from sample variance were estimated by measuring the standard deviation of all \( C(u) \) measurements in rings of constant \( u \) in the \( uv \)-plane for each facet, and dividing this by the square root of the number of independent \( C(u) \) measurements made. We estimated independent measurements by calculating the size of a coherence patch in the \( uv \)-plane that arises from \( \tilde{W}(\tilde{u}) \) and then degrading the pixel resolution in the \( uv \)-plane to a corresponding size. At the lower resolution, each pixel sample was considered an independent measurement, with the caveat that for a real-valued sky, only half of the samples in a \( |\tilde{u}| = u \) ring are independent.

The approximate \( \ell^2 \) power-law in \( \ell(\ell+1)C_\ell/2\pi \) of the angular power spectra plotted in Figure 15 suggests that PGB-8 angular power spectra are dominated by unclustered point sources. At lower radio frequencies near \( \ell = 100 \), there may be a flattening of these spectra to a shallow, negative power law that would show qualitative agreement with the \( C_\ell \propto \ell^{-2.4} \) model adopted by Tegmark et al. (2000) and Santos et al. (2005). Progress in modeling point sources and in subtracting spectrally smooth emission associated with synchrotron sources will facilitate the suppression of these foregrounds, with a fundamental limit placed by the thermal limit of these observations (Figure 15, dot-dashed), which we measure to be 310 mK for \( \ell \sim 100 \) at 160 MHz with a bandwidth of 1.46 MHz. Overall, our measurements indicate that over the range \( 10^2 < \ell < 10^3 \), the fundamental sensitivity level of these observations is between 2 and 3 orders of magnitude in temperature above the fiducial model of re-ionization at \( z = 9.2 \) (\( \nu = 140 \) MHz) used by Santos et al. (2005).

7. CONCLUSION

PAPER is following an incremental build-out strategy that emphasizes the characterization and optimization of instrumental performance at each stage of development. We have given special attention to designing antenna elements whose smooth spatial and spectral responses are conducive to calibration that will be required to model and remove strong foregrounds to the 21 cm EoR signal. Facilitating the incremental build-out of PAPER is a series of digital correlators that take advantage of the scalability and reusability of CASPER’s packet-switching correlator architecture. We are developing post-correlation calibration, imaging, and analysis pipelines as part of the open-source AIPY software package. This package emphasizes the needs of low-frequency interferometry and facilitates experimentation with new analysis architectures and calibration techniques.

With results from the PWA-4 and PGB-8 deployments in Western Australia and the NRAO Green Bank Galford Meadow site, respectively, we demonstrate a first level of calibration that is sufficient for modeling strong sources to a level where ionospheric refraction and temperature-dependent gains must be taken into account. This calibration relies heavily on a static model of the primary beam. Next steps in calibration will focus on the first-order removal of temperature dependence in antenna gains and on measuring deviations of the primary beam of each antenna from the computed model.

Data from the PWA-4 and PGB-8 deployments have been used to generate an all-sky map that attains a thermal noise level of 10 mJy beam\(^{-1}\) (corresponding to 620 mK, for a 2.15e−5 sr synthesized beam size at 156.4 MHz) integrated across a 138.8 MHz to 174.0 MHz band. This achievement represents a first iteration in a cycle of improvement wherein sky models are used to improve array calibration, which in turn allows increasingly accurate sky models to be generated. In analyzing the noise characteristics of this map, we find the system temperature of the PGB-8 array to be consistent with a model of galactic synchrotron emission. Angular power spectra generated from these data indicate that point sources are currently the dominant foreground to the EoR signature, with evidence for contributions from galactic synchrotron emission at lower radio frequencies and angular wavemodes. Errors in \( C_\ell \) measurements are dominated by sample variance, but by differencing integrations, we measure the thermal noise level at \( \ell = 100 \) and 160 MHz to be 310 mK—a sensitivity threshold that lies between 2 and 3 orders of magnitude in temperature above fiducial re-ionization models. These results demonstrate the need for a next level of calibration, modeling, and foreground suppression that will be pursued in the next PAPER deployments.

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