The PAPER Team

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NRAO-GB
- Ford
- Lacasse
- Greenberg
- Treacy
- Klopp
Sites

Technical Development
PGB: PAPER Green Bank

Radio-quiet site
PSA: PAPER South Africa

Green Bank, WV
Karoo, ZA
South Africa Site
The PAPER Architecture

Non-tracking Crossed Dipoles
Wide Bandwidth (125-205 MHz)
Movable (unburied TV cable)
Smooth Beam

Flexible FPGA-based
Packetized Correlator
Full-Stokes
Large # Ants (scalable)
Wide Band (up to 200 MHz)
2048 Channel Polyphase Filter Banks
4-bit Cross-Multipliers

AIPY: Model-based Imaging/Calibration
Open-Source toolkit for interferometry
http://pypi.python.org/pypi/aipy
Antenna Primary Beam (Sleeve Dipole + Flaps)

- 40dB zenith to horizon
- 60 degree FWHM
- spectrally/spatially smooth

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

Beam experimentally verified in Pober et al 2012 AJ 143 53
PAPER Antennas/Analog Electronics
Developed by the Charlottesville (NRAO,UVA) Team

- smooth spectral response
- characterized gain versus ambient temperature
PAPER/CASPER Packetized Correlator

Diagram showing the F Processor, X Engines, and a 10 Gb Ethernet Switch.
Computing & Storage

- 16 node dual quad-core, 2.5 GHz, 8 GB RAM per node. Currently used at ~10% capacity.
- to be upgraded to 32 dual quad-core, each with 16 GB RAM, plus 32 Tesla C1060 graphics cards (>4x speed-up adequate for PSA-128)
- 70 TB of storage space using Dell HPC NFS Storage Solution (NSS), with 10 Gbe connection to compute nodes and parallel access, with full RAID backup
- to be upgraded (with scalable solution) to 120 TB for PSA-128
Data Analysis

Power Spectrum Pipeline Development

AIPY: Model-based Imaging/Calibration Open-Source toolkit for interferometry
http://pypi.python.org/pypi/aipy

Imaging and Cataloging

Builds on NRAO development for ALMA and EVLA
Challenges for the power spectrum measurement

- Problem: Radio frequency interference
  Solution: Quiet site

- Problem: Thermal noise (sensitivity)
  Solution: Redundant baselines

- Problem: Instrument calibration and stability
  Solution: Redundant baselines, temperature calibration

- Problem: Strong foregrounds
  Solution: Delay Transform Isolation
Foregrounds

- Smooth with frequency, but improperly calibrated linear polarization can produce frequency-dependent structure.
- Smooth power spectrum can allow further rejection.
- Need a factor of ~1000 suppression

![Graph showing foreground contributions](image)
Solution: spectral decomposition (eg. Morales, Gnedin...)

- Foreground = non-thermal = featureless over ~ 100’s MHz
- Signal = fine scale structure on scales ~ few MHz

- Simply remove low order polynomial or other smooth function
- Can also avoid smooth spectrum foregrounds entirely (foreshadowing)
Faraday Rotation:

\[
\Delta \theta = \frac{2 \pi e^3}{m^2 c^2 \omega^2} \int_0^d n_e B_\parallel ds
\]

150MHz Polarized Intensity, 12° field (Bernardi et al. 2010)

Simulated Leakage (dotted) and 21cm EoR (solid) (Jelić et al. 2008)
Polarization Effects on EoR

Spatial structure in polarization (Stokes Q & U) need not follow Stokes I.

Faraday rotation of polarized sources could introduce frequency dependent structure. Individual sources produce a periodic signal as a function of $\nu^{-2}$. Leakage of this signal could produce non-smooth structure.

\[ \Delta \theta = \frac{2\pi e^3}{m^2 c^2 \omega^2} \int_0^d n_e B_\parallel ds \]

The polarization response is a function of the location in the primary beam, but this is a purely geometric effect.

Polarization effects are mitigated by:

- Primary beam dilution
- Low intrinsic polarization of sources
- Precision calibration made possible in maximum redundancy array (a la Westerbork)
Calibration Example: Temperature Dependence

- Antenna gain is sensitive to balun, cable, and receiver card temperatures
- Record temperatures to correct for these effects and reduce gain variations
- Celestial data *confirm* engineering measurements of temperature dependence and demonstrate improvement in system performance

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature (K)</th>
<th>Data RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balun</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing temperature dependence and data RMS values](image)
Calibration Example 2:
Beam Modeling with Celestial Sources

Use calibrator sources to create beam model at various frequencies
→ Compare and update theoretical model perceived source fluxes (and mirror images)
Beam Modeling with Satellite Transmission Mapping

- satellite transmissions cover whole beam
- only at 1 frequency (137MHz)
- no absolute scale
- map antenna-to-antenna and temporal variations with dedicated satellite monitoring subsystem
Imaging

\[ V_{ij}(\nu, t) = \sum_{s=srcs} g_i(\nu)g_j^*(\nu)I_{s,s_0}\left(\frac{\nu}{\nu_0}\right)^{\alpha_s}e^{2\pi i(\vec{b}_{ij}(\nu,t)\cdot\hat{s} + \nu\tau_{ij} + \phi)} \]

what an interferometer measures

u, \nu: interferometer sampling plane
m, \ell: sky plane

imaging

power spectrum pipeline

image cube

3D power spectrum

(u, v): interferometer sampling plane

(freq)−1: sky plane
Minimally redundant array
uv Coverage of minimum redundancy array

- Instantaneous 64-element, narrow band
- Instantaneous 64-element, full band
Work in Progress: Complete Northern/Southern Hemisphere Source Catalogs

Jacobs et al. 2011
Centaurus A
what an interferometer measures

Each baseline is one track through this space
The Delay Transform
Relation to Sources

- Delay space: FT of frequency axis
- Delay is geometric delay between two antennas of baseline
- Point sources map to (nearly) delta functions because they are *smooth* in frequency space
- Note *maximum* delay caused by horizon
Example Spectra in Delay Space
Delay/Delay-Rate Transform: Pseudo-imaging and Compression

Example: 1 hour of data with Cas A, Cyg A, Tau A

- Phase to a source (here, Cas A)
- FFT of frequency axis = “Delay Image”
- FFT of time axis = “Delay/Delay-Rate”
- Cas A is confined to a region near origin
- PSF determined by bandpass + time variability

*Useful as a form of optimized compression, specific to baseline*
Frequency Range

- Digitization and correlator 100 – 200 MHz. Useful range 118 – 188 MHz (11 > z > 6.6)
- Currently set by ADC clock, receiver bandpass
- Can be adjusted within modest limits with some work
Array layout:
maximum and minimum redundancy
DDR Filters Used as Source Estimators and for mapping primary beam

![Graph showing the output of DDR filters for different sources. The x-axis represents LST (radians) ranging from 0 to 6, and the y-axis represents the intensity on a logarithmic scale from $10^0$ to $10^4$. The graph includes multiple lines indicating different sources such as Sun, crab, and vir. The y-axis is labeled with logarithmic markers.]
The Delay Transform Relation to Power Spectrum

- Point sources/synchrotron are spectrally smooth
- If primary beam smooth spatially/spectrally, then delay transform of foregrounds tightly confined to group-delays above the horizon
- At delays beyond the horizon, non-smooth spectra ("sidelobes" of EoR) come to dominate
- Delay-space is very nearly k-space

A Per-Baseline, Delay-Spectrum Technique for Accessing the 21cm Cosmic Reionization Signature
Parsons, Pober, Aguirre, Carilli, Jacobs & Moore
arXiv:1204.4749
We are interested in obtaining the Fourier components $\tilde{I}(k)$ of some spatial field $I(x)$

$$\tilde{I}(k) = \int I(x) \exp[-i k \cdot x] dx$$

$$I(x) = \int \tilde{I}(k) \exp[i k \cdot x] dk$$

The square of $\tilde{I}(k)$ is proportional to the power spectrum.

An individual visibility associated with a definite physical length baseline $b$ is defined as

$$V(b, \nu) = \int d\Omega A(\Omega, \nu) I(\Omega, \nu) \exp[-2\pi i \nu b \cdot \hat{\Omega}/c]$$

Assuming no $w$-term, and thus that

$$x = C \cdot (\hat{\Omega}, \nu)$$

where $\hat{\Omega} = (l, m)$ and $C$ is a matrix containing the cosmology that maps between physical units $x$ and observers’ units $(\hat{\Omega}, \nu)$. Similarly

$$(\hat{\Omega}, \nu) = C^{-1} \cdot x$$

We will also find it convenient to write

$$k \cdot x = k \cdot C \cdot (\hat{\Omega}, \nu) = k_{\perp} C_{\perp} \Omega + k_{\parallel} C_{\parallel} \nu$$

where $k_{\perp} C_{\perp} \Omega$ is shorthand for

$$k_x C_{\perp} l + k_y C_{\perp} m$$
Now, Fourier transform the visibility with respect to $\nu$

$$V(b, \tau) = \int d\Omega d\nu A(\Omega, \nu) I(\Omega, \nu) \exp[-2\pi i \nu b \cdot \hat{\Omega}/c] \exp[-2\pi i \tau \nu] \quad (1)$$

$$= \int d\Omega d\nu A(\Omega, \nu) I(\Omega, \nu) \exp[-2\pi i (b \cdot \hat{\Omega}/c + \tau) \nu] \quad (2)$$

which defines the delay transform. Substituting in, we get

$$V(b, \tau) = \int d\Omega d\nu A(\Omega, \nu) \left( \int \tilde{I}(k) \exp[i k \cdot x] dk \right) \exp[-2\pi i (b \cdot \hat{\Omega}/c + \tau) \nu]$$

Rearrange

$$V(b, \tau) = \int dk \tilde{I}(k) \int d\Omega d\nu A(\Omega, \nu) \exp[i k \cdot C \cdot (\hat{\Omega}, \nu) - 2\pi i (b \cdot \hat{\Omega}/c + \tau) \nu]$$

This we can write as

$$V(b, \tau) = \int dk \tilde{I}(k) K(b, \tau, k)$$

where

$$K(b, \tau, k) = \int d\Omega d\nu A(\Omega, \nu) \exp[i (k \cdot C \cdot (\hat{\Omega}, \nu) - 2\pi (b \cdot \hat{\Omega}/c + \tau) \nu)] \quad (3)$$
For some foregrounds (confusion noise), smooth spectrum is only way to...
Using Delay Transform to Evade Foregrounds

The exact cutoff in k-space is determined by:
- Length of the baseline
- Spectrum of sources
- Primary beam of the interferometer
- Windowing filter in delay transform
- Effects of RFI excision
- Errors in calibration
Foregrounds in $k$-space

$P(k)$ [mK$^2$($h^{-1}$Mpc)$^3$]

$k_\parallel$ [$h$Mpc$^{-1}$]

$k_\perp$ [$h$Mpc$^{-1}$]

300 m

Pober et al 2013
arxiv:
A Sensitivity and Array-Configuration Study for Measuring the Power Spectrum of 21cm Emission from Reionization
Parsons, Pober, McQuinn, Jacobs & Aguirre
arXiv:1103.2135
Maximally redundant array
Advantages of a maximally redundant array

- Ease of calibration: ratio of visibilities cancels the sky contribution, leading to the required calibration (to within an overall amplitude and phase)
- Power spectrum measurement is more forgiving of calibration errors
- Baselines average coherently on a given $k$ before squaring, allowing the signal-to-noise per mode to be brought closer to unity, which is optimal for the power spectrum measurement
PAPER Approach to the Power Spectrum

- Foregrounds are isolated to low delay on a single baseline \textit{without imaging or sky modeling}
- 21 cm power spectrum is extracted from individual baseline spectra without gridding
- Redundant baselines aid in calibration and increase integration on selected modes
Calibration Pipeline:
Simplify, simplify, simplify

- **Pre-processing**
  - Remove known RFI transmission bands and analog filter edges
  - Coarse RFI flag (6 sigma)
  - DDR filter to suppress foregrounds
  - Re-flag (4 sigma)
  - Compress (x40!!)

- **Phase, amplitude and bandpass calibration**
  - Temperature dependence of electronics removed
  - Redundant calibration of relative amplitude and phase (0.1 ns stability)
  - Phase to Pictor A for absolute amplitude and phase and (per antenna) bandpass
- Foreground suppression
  - delay transform and deconvolution over the entire observing band
  - delay-domain filter to suppress emission that falls inside of 15 ns beyond the horizon limit for each baseline
- Average redundant baselines and times
- Final RFI flag, crosstalk removal, delay-rate filter
- Power spectrum!!
Status and Plans

- 32 antennas deployed in PGB, 64 in PSA (July 2011)
- PSA-32 data (max redundancy) being analyzed for power spectrum upper limits
- PSA-64 integration has been running for 135 days in maximum redundancy
- Full system of 128 dual pol correlated antennas planned for science observation in fall 2013. Upgrade includes temperature control for receivers
What is the maximum baseline length, why?
- ~300 m, though the maximum used for power spectrum analysis is 30 m

Any other specific configuration issues?
- Power spectrum analysis done on highly redundant array

What frequency range was chosen, why?
- 114 – 188, roughly covering the likely epoch of x ~ 0.5

Specify total collecting area
- 128 x 7 m² = 896 m²

What FoV/station size was chosen, why?
- ~60° FWHM; single element dipoles

What data products are to be produced?
- Primarily the power spectrum (of I, Q, U, V)
- Very minimal imaging

How are foregrounds anticipated to be handled?
- Avoidance: stay beyond the horizon

How is ionospheric calibration handled?
- Avoidance: stick to large scales