THE PRECISION ARRAY FOR PROBING THE EPOCH OF REIONIZATION

Presented by James Aguirre
University of Pennsylvania
26 March 2013
SKA1 Low Workshop

The PAPER Team

UVa / NRAO
- **Bradley**
- **Carilli**
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- **Parsons**
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- **Moore**

SKA-SA
- Jonas
- Curtolo
- Walbrugh
- Manley

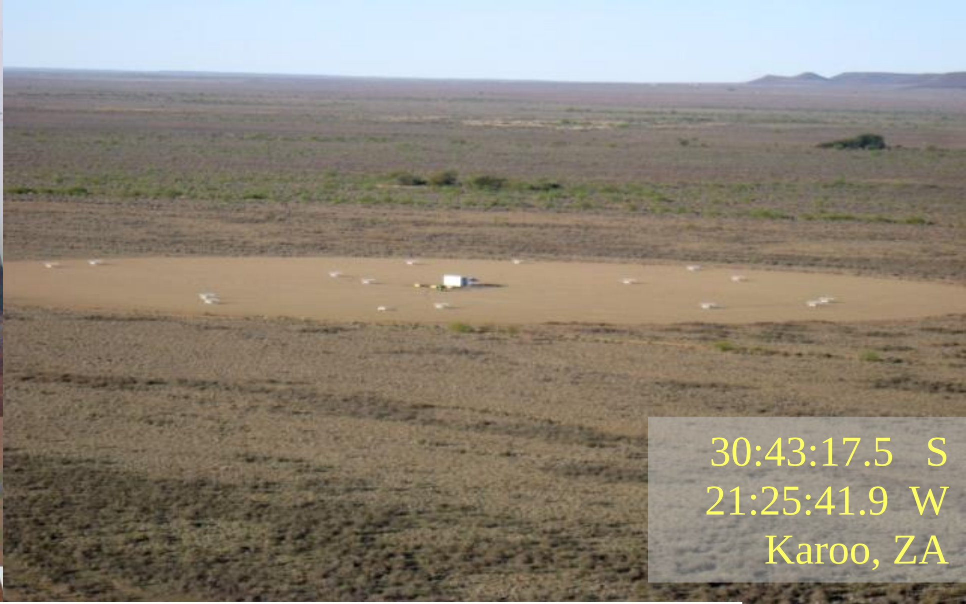
NRAO-GB
- Ford
- Lacasse
- Greenberg
- Treacy
- Klopp

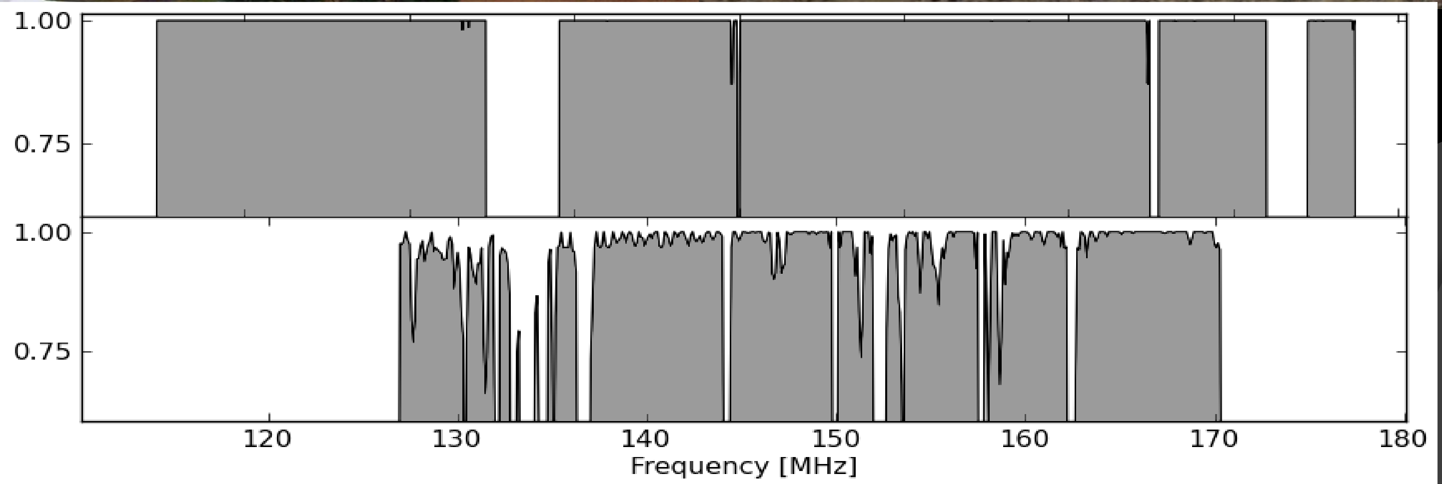
Sites

Technical Development
PGB: PAPER Green Bank

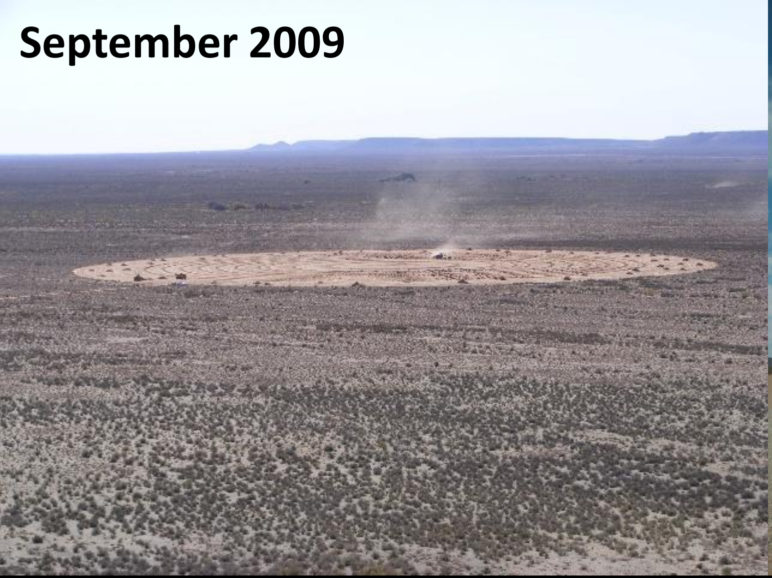
Radio-quiet site
PSA: PAPER South Africa


38:25:59.24 N
-79:51:02.1 W
Green Bank, WV


30:43:17.5 S
21:25:41.9 W
Karoo, ZA



South Africa Site

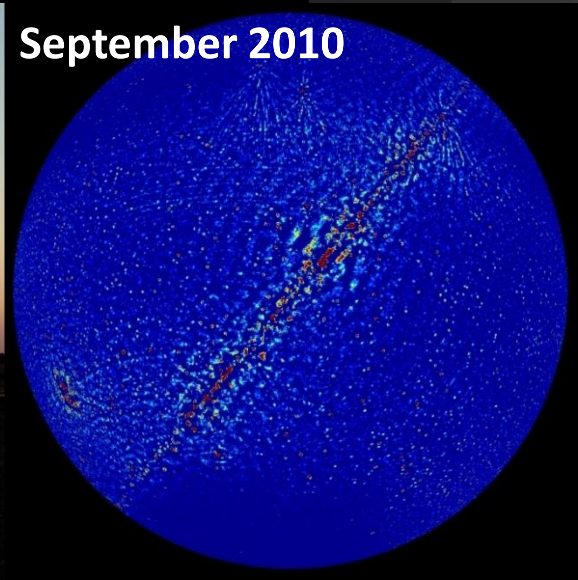


September 2009

October 2009

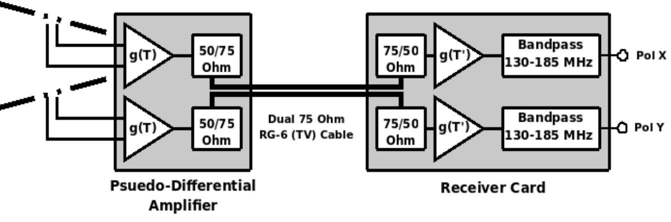
February 2010

May 2010

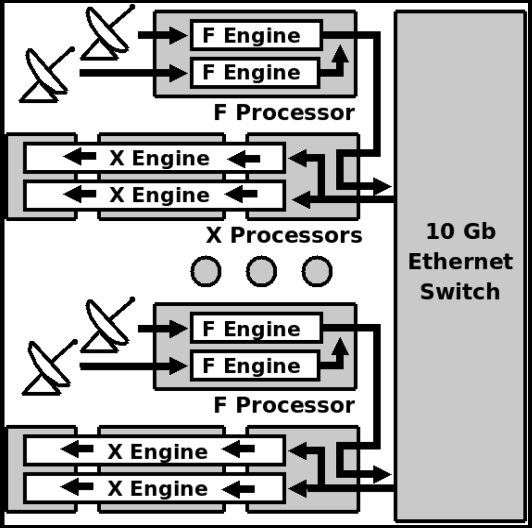


September 2010

The PAPER Architecture



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

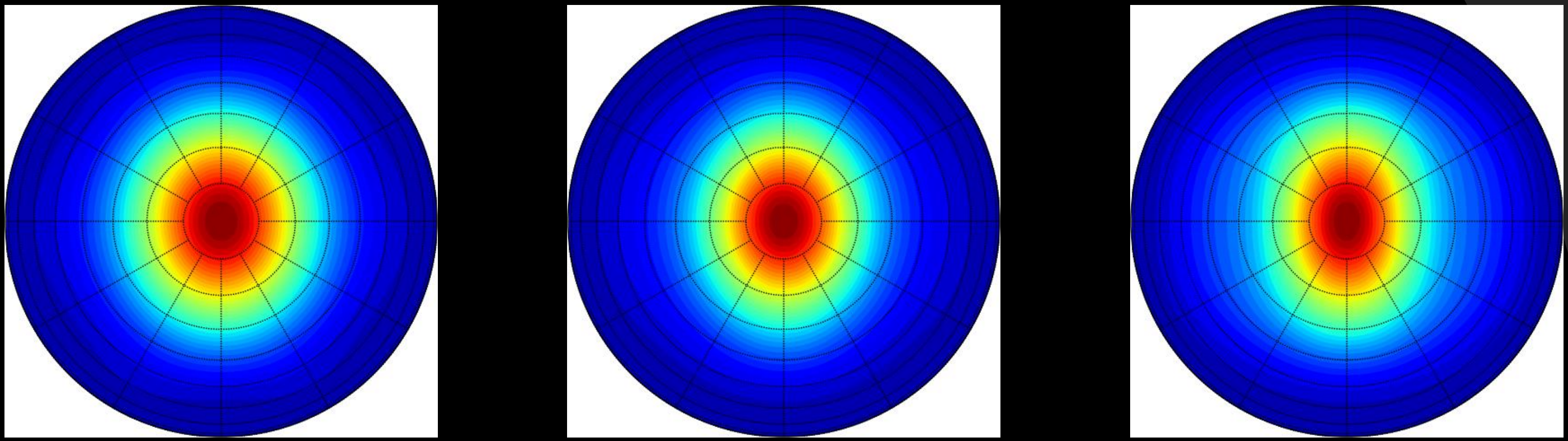


Flexible FPGA-based
Packetized Correlator
Full-Stokes
Large # Ants (scalable)
Wide Band (up to 200 MHz)
2048 Channel Polyphase
Filter Banks
4-bit Cross-Multipliers

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

Antenna Primary Beam (Sleeve Dipole + Flaps)

138 MHz 156 MHz 174 MHz



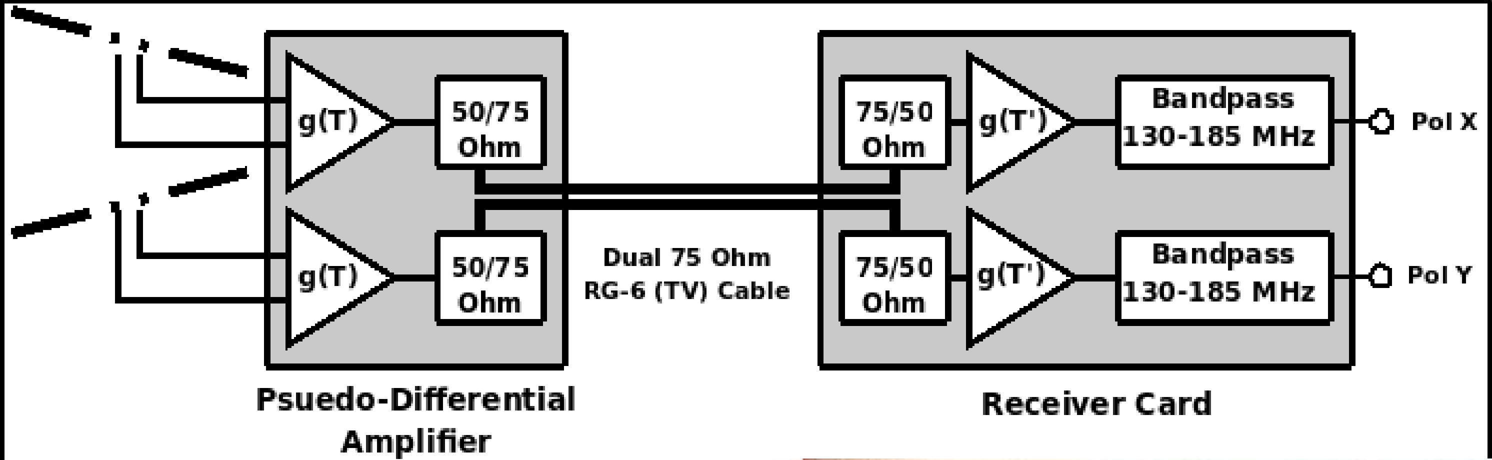
Beam experimentally verified in Pober et al 2012 AJ 143 53

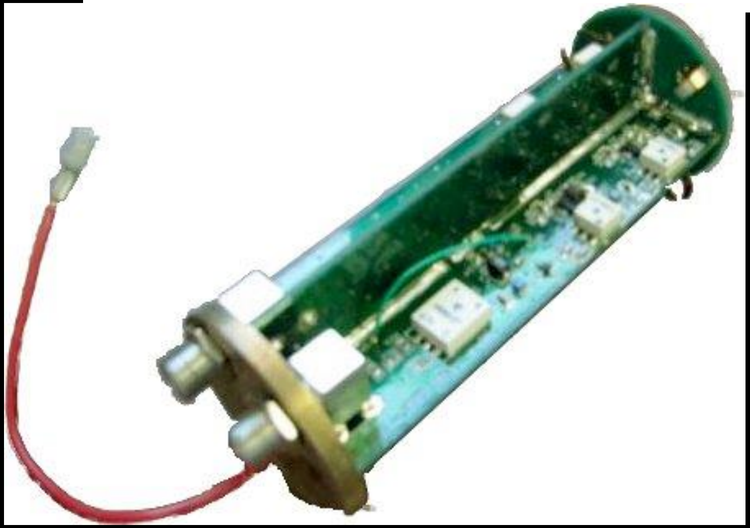
- 40dB zenith to horizon
- 60 degree FWHM
- spectrally/spatially smooth

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

PAPER Antennas/Analog Electronics

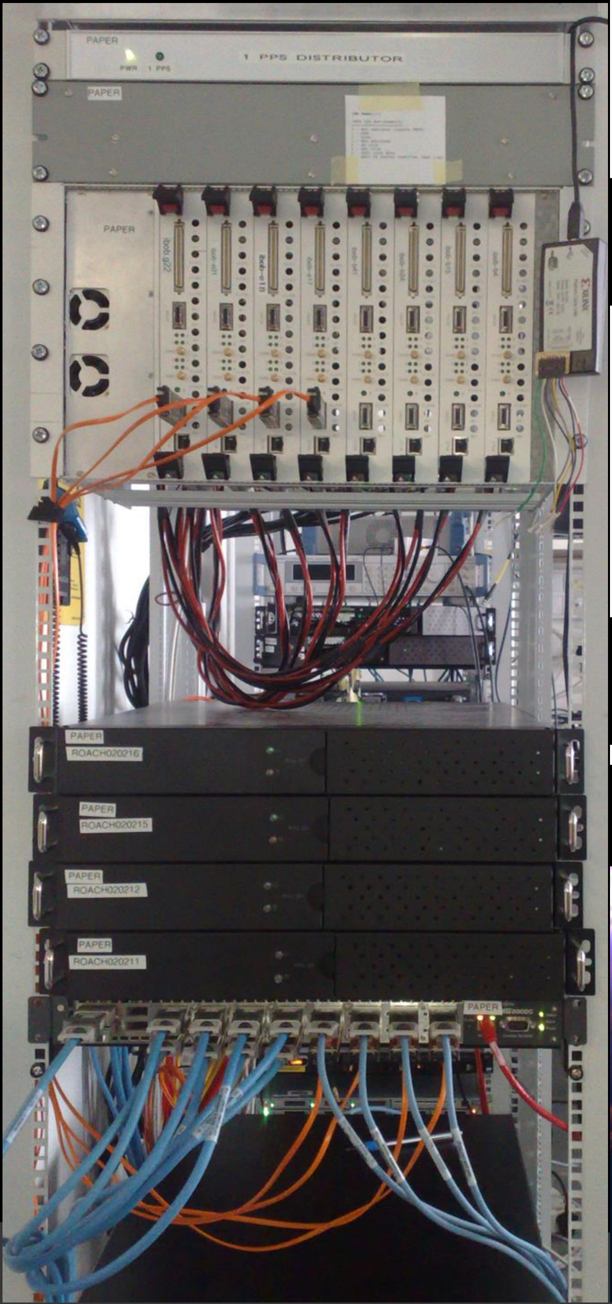
Developed by the Charlottesville (NRAO,UVA) Team

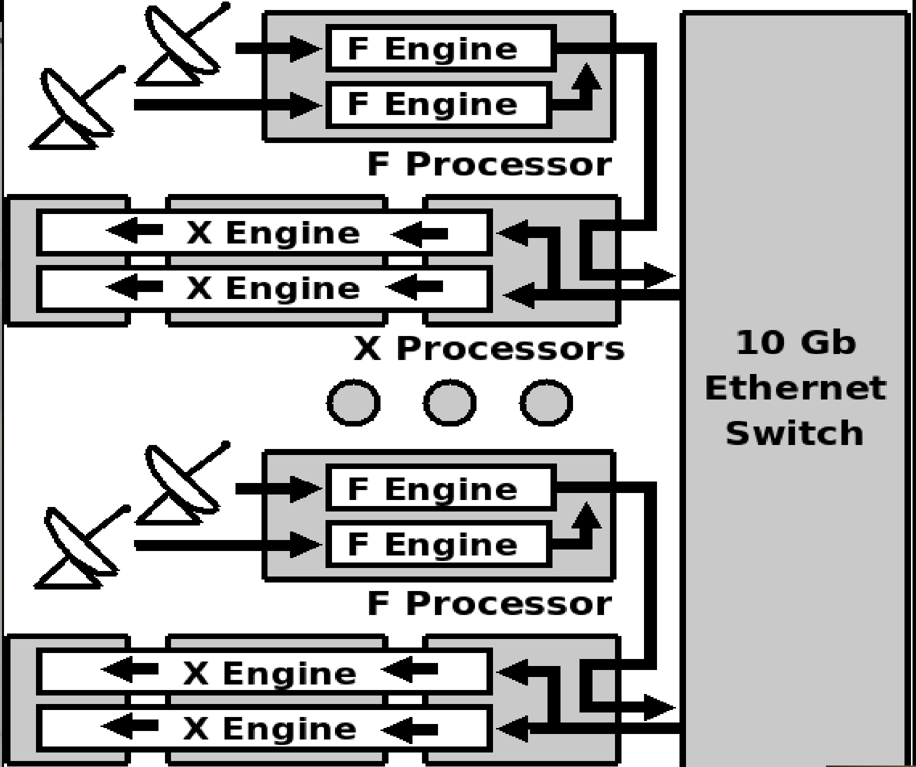




- smooth spectral response
- characterized gain versus ambient temperature

PAPER/CASPER Packetized Correlator





F Engine

F Engine

F Processor

X Engine

X Engine

X Processors

10 Gb Ethernet Switch

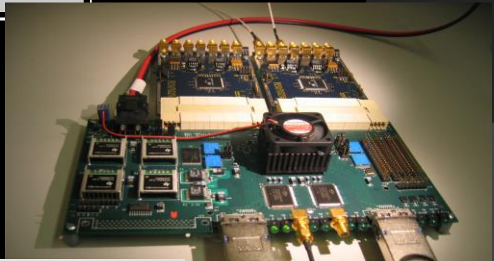
F Engine

F Engine

F Processor

X Engine

X Engine



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

AIPY

Power Spectrum
Pipeline Development

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

CASA
Common Astronomy
Software Applications

Imaging and Cataloging

Builds on NRAO development
for ALMA and EVLA

Challenges for the power spectrum measurement

- Problem: Radio frequency interference
- Solution: Quiet site

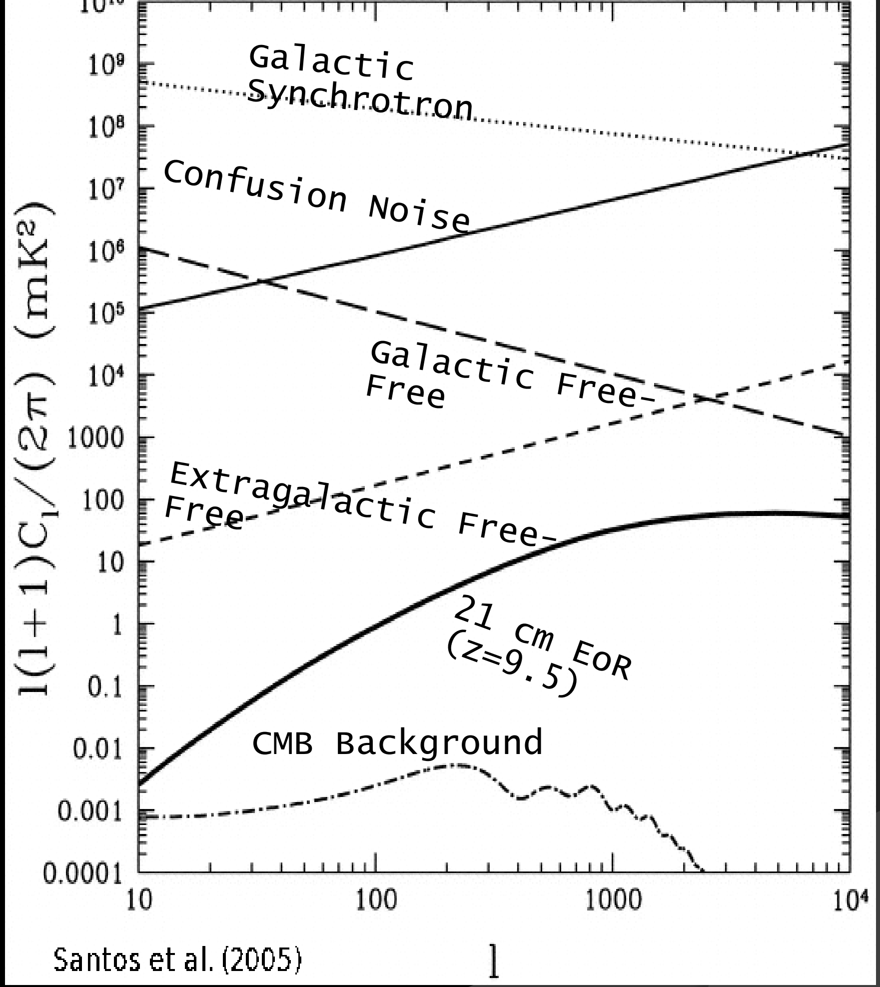
- Problem: Thermal noise (sensitivity)
- Solution: Redundant baselines

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

- Problem: Strong foregrounds
- Solution: Delay Transform Isolation

Foregrounds

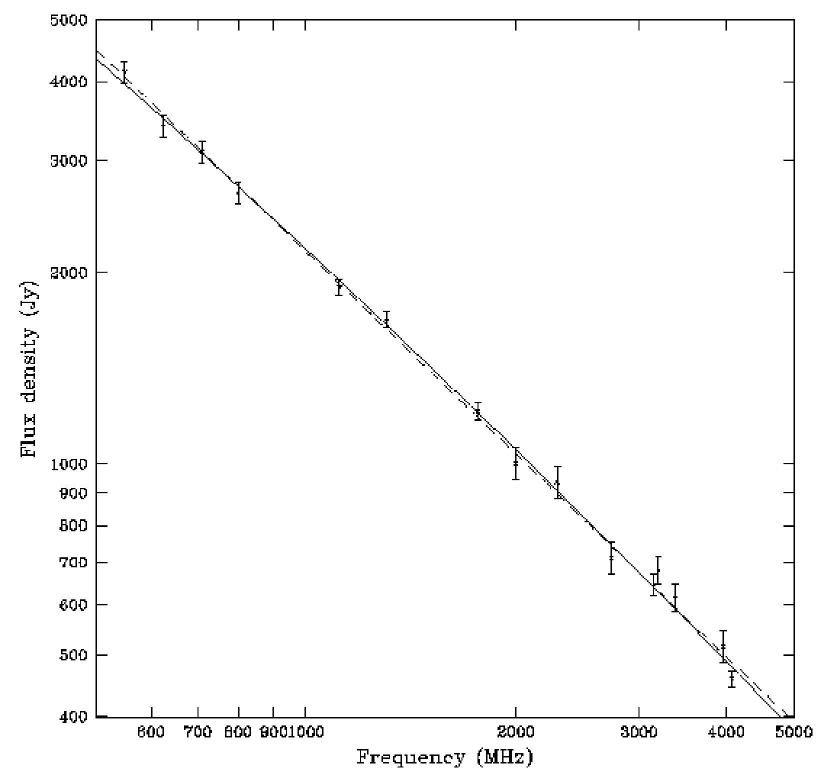
- Smooth with frequency, but improperly calibrated linear polarization can produce frequency-dependent structure.
- Smooth power spectrum can allow further rejection.
- Need a factor of ~1000 suppression

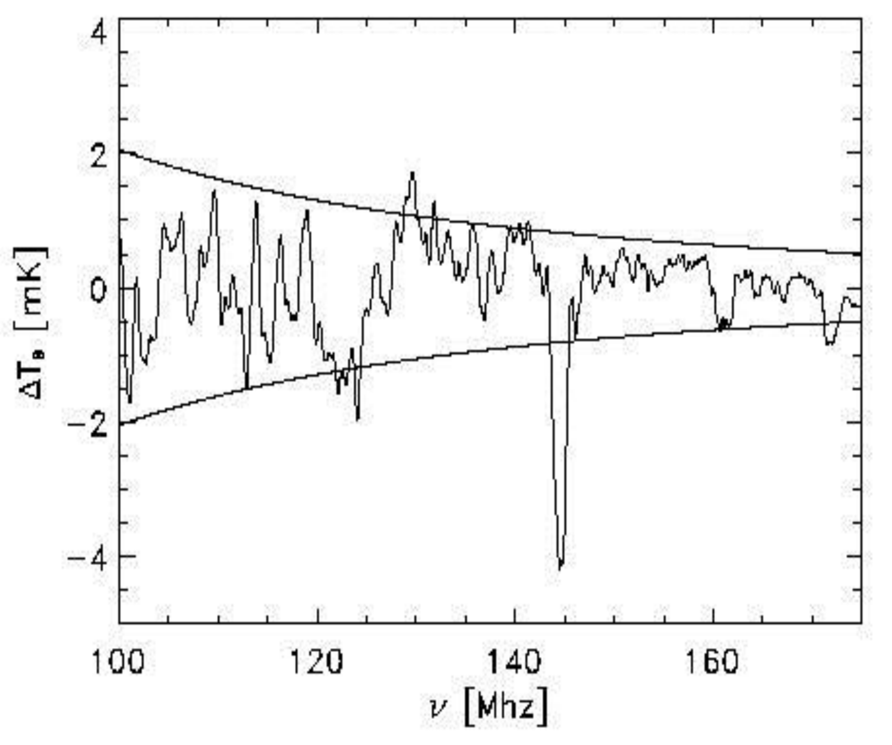


Santos et al. (2005)

Solution: spectral decomposition (eg. Morales, Gnedin…)

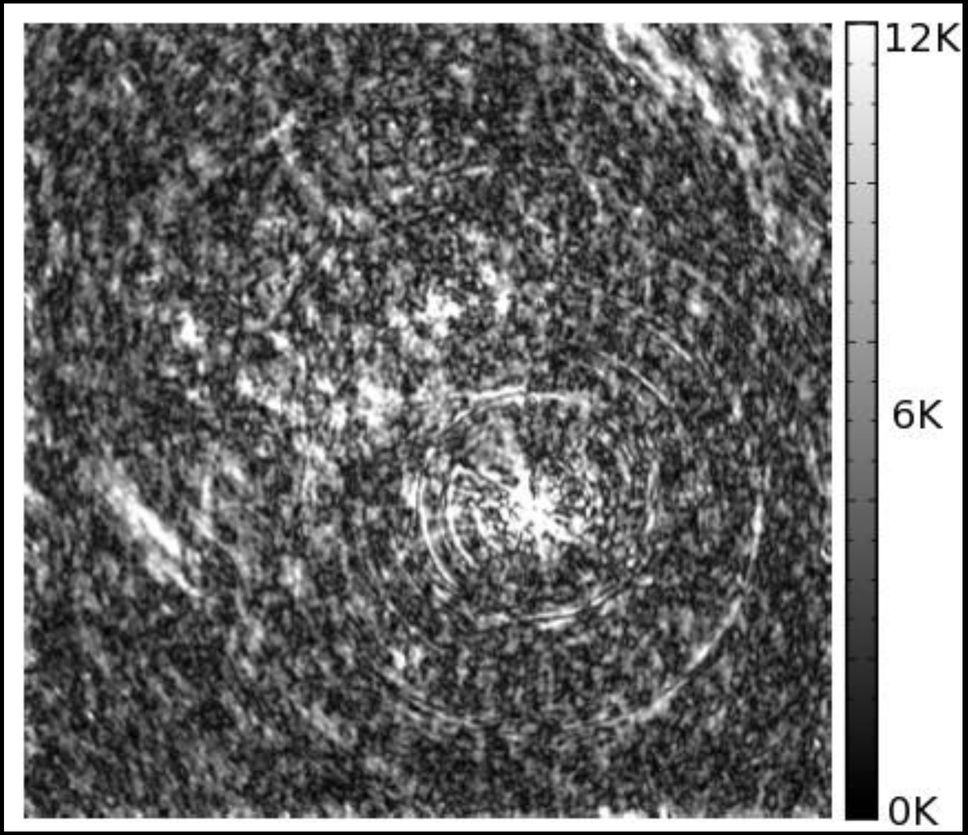
- Foreground = non-thermal = featureless over ~ 100’s MHz
- Signal = fine scale structure on scales ~ few MHz





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

Polarized Galactic Synchrotron

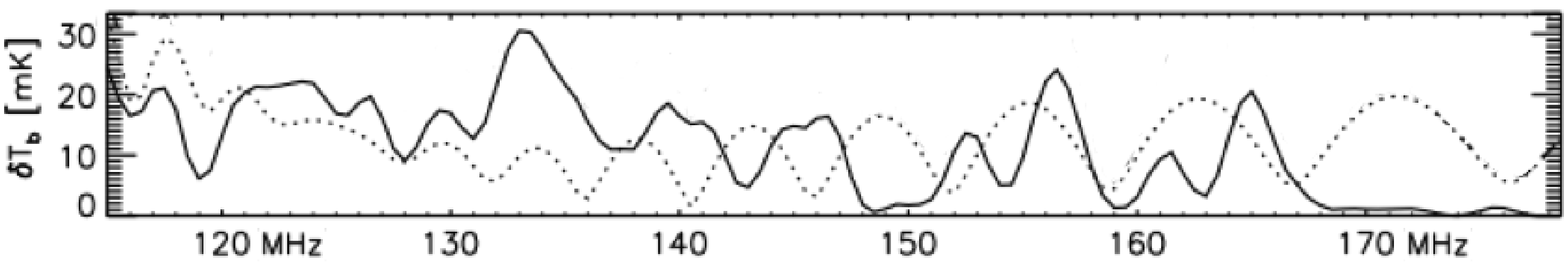


150MHz Polarized Intensity, 12° field (Bernardi et al. 2010)

Faraday Rotation :

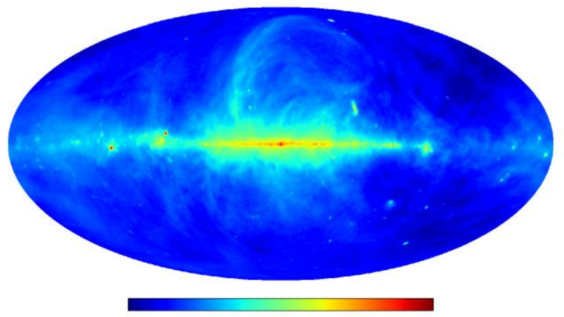
$$\Delta\theta = \frac{2\,\pi\,e^3}{m^2\,c^2\,\omega^2}\int_0^d n_e\,B_\parallel\,ds$$

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

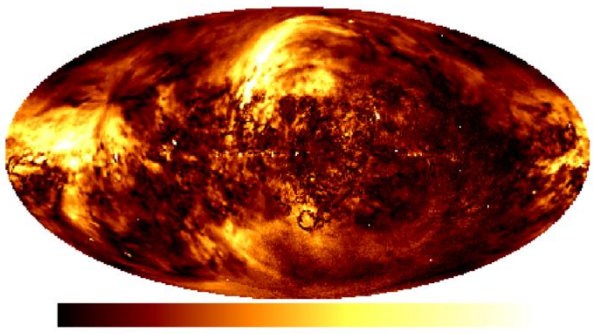


Polarization Effects on EoR

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



1.4 GHz Stokes I



1.4 GHz

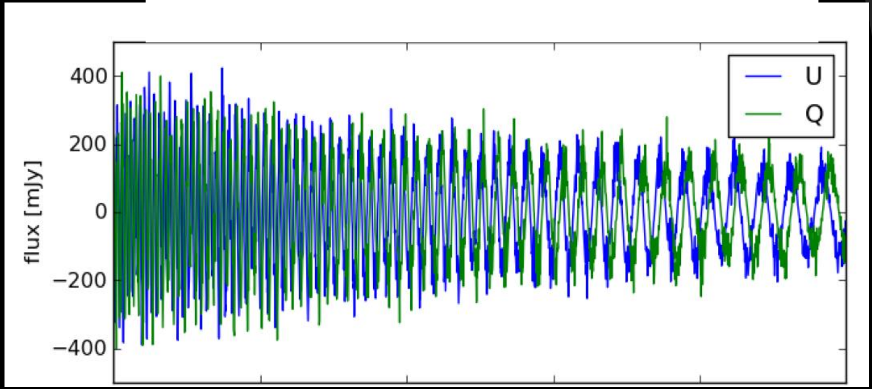
Fractional polarization

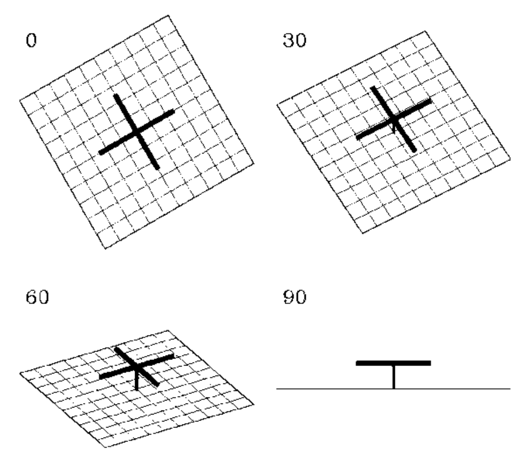
Polarization effects are mitigated by:

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

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

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



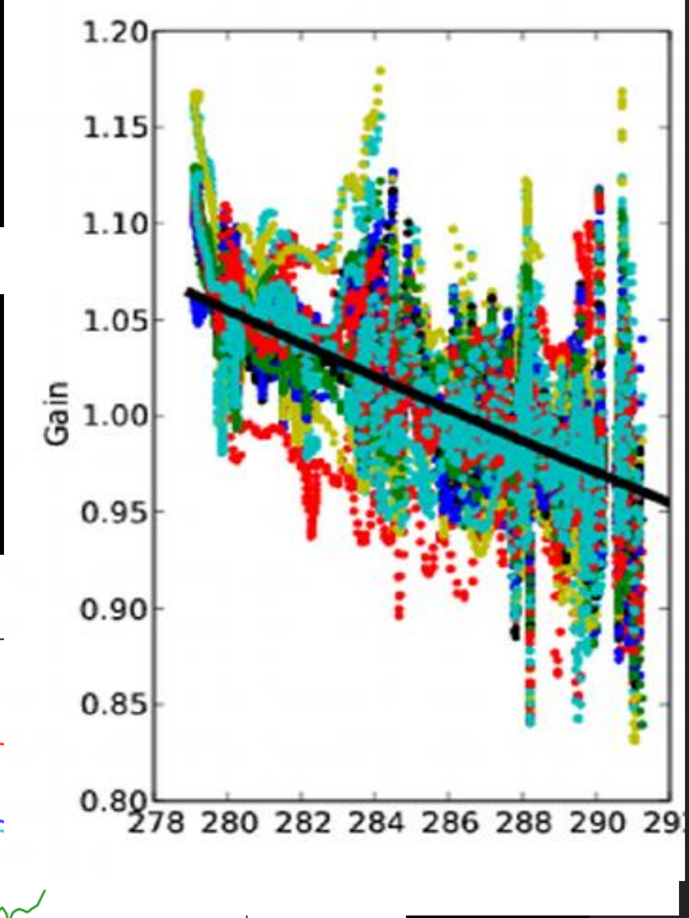


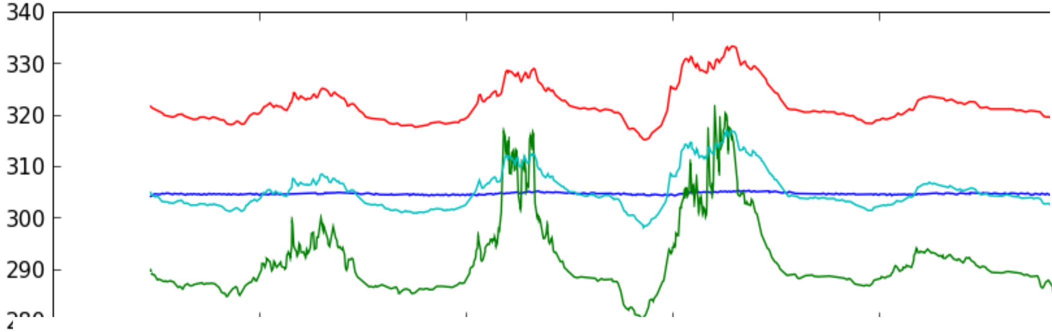
The polarization response is a function of the location in the primary beam, but this is a purely geometric effect.

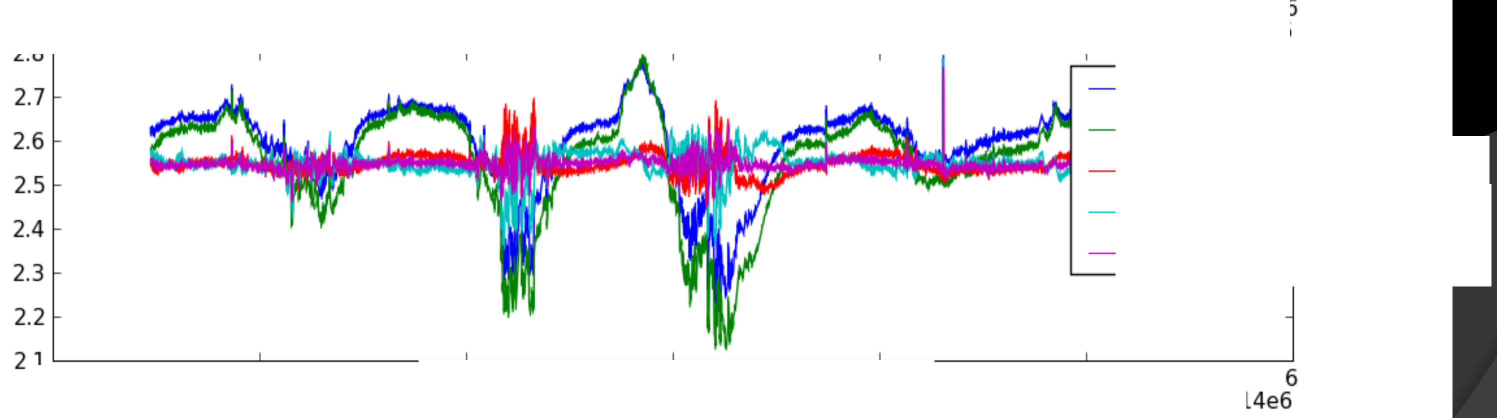
Calibration Example:

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 system performance





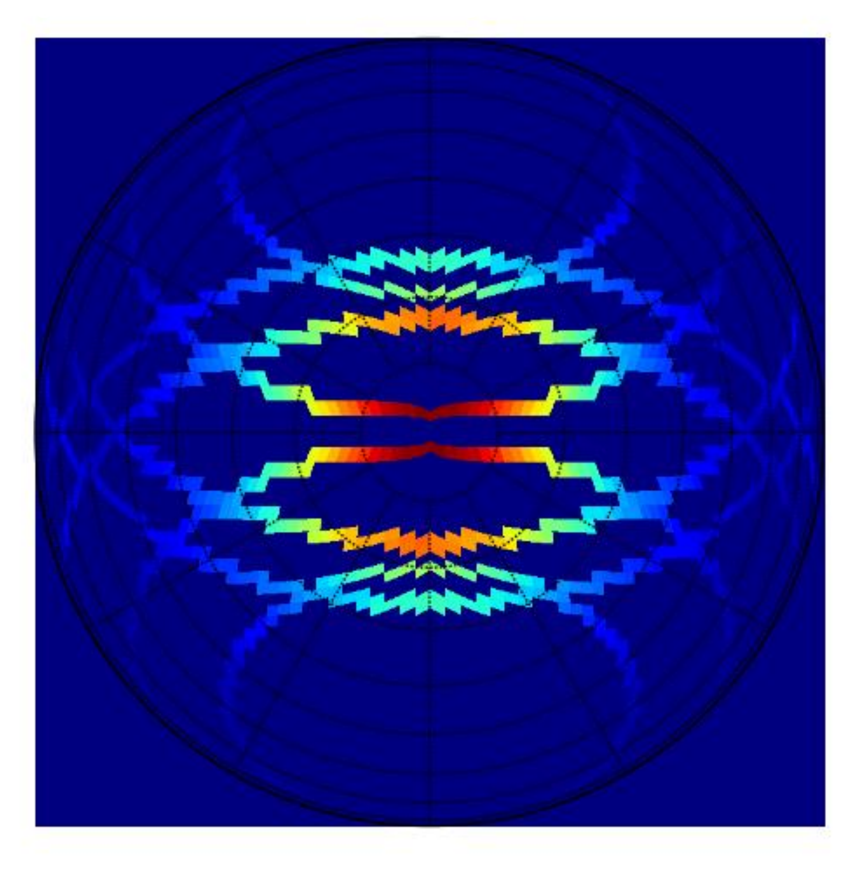


Calibration Example 2:

Beam Modeling with Celestial Sources

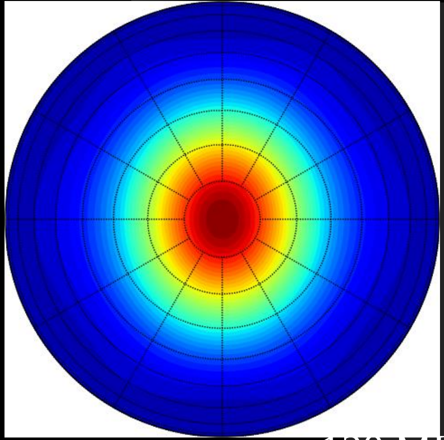
- Use calibrator sources to create beam model at various frequencies

→ Con

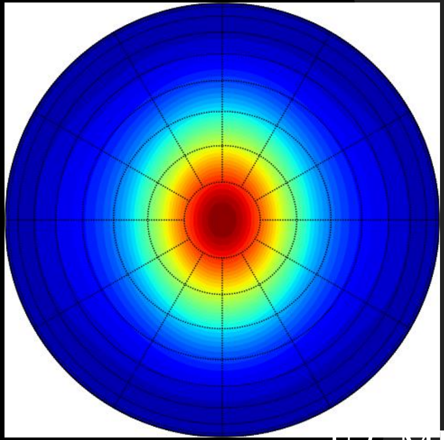


perceived source fluxes (and mirror images)

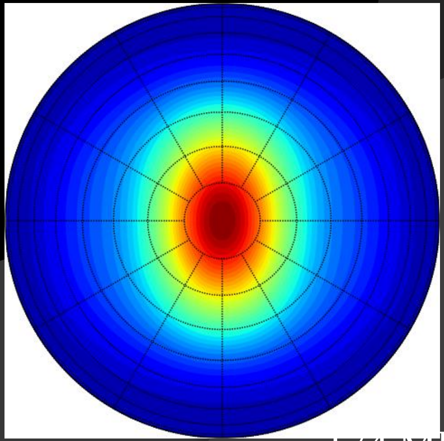
↔



138 MHz

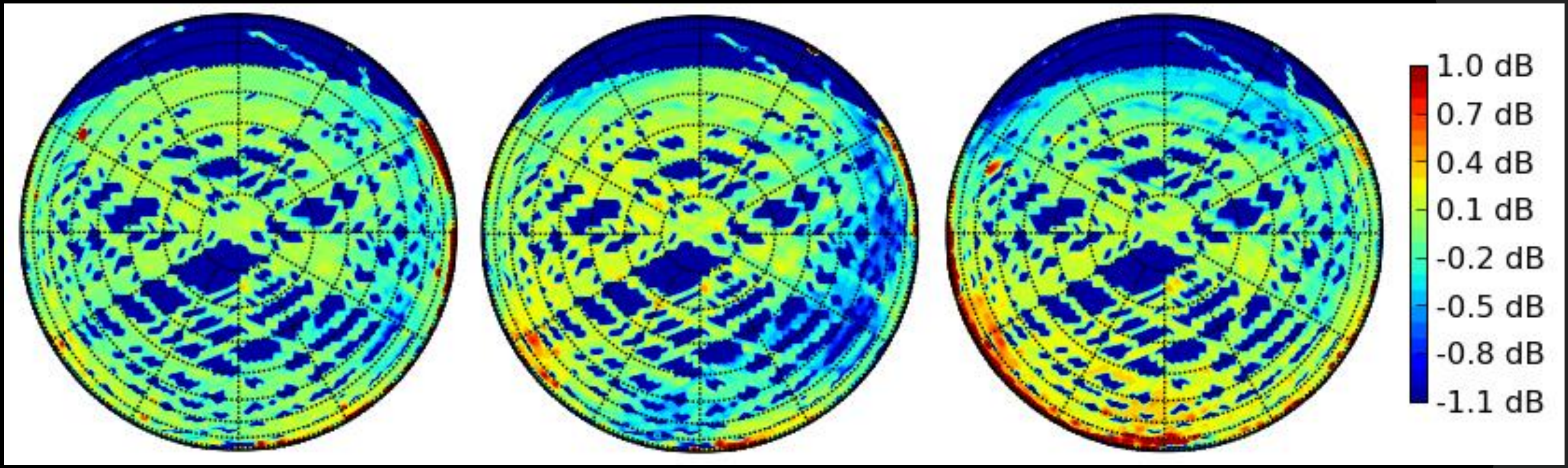


156 MHz



174 MHz

Beam Modeling with Satellite Transmission Mapping

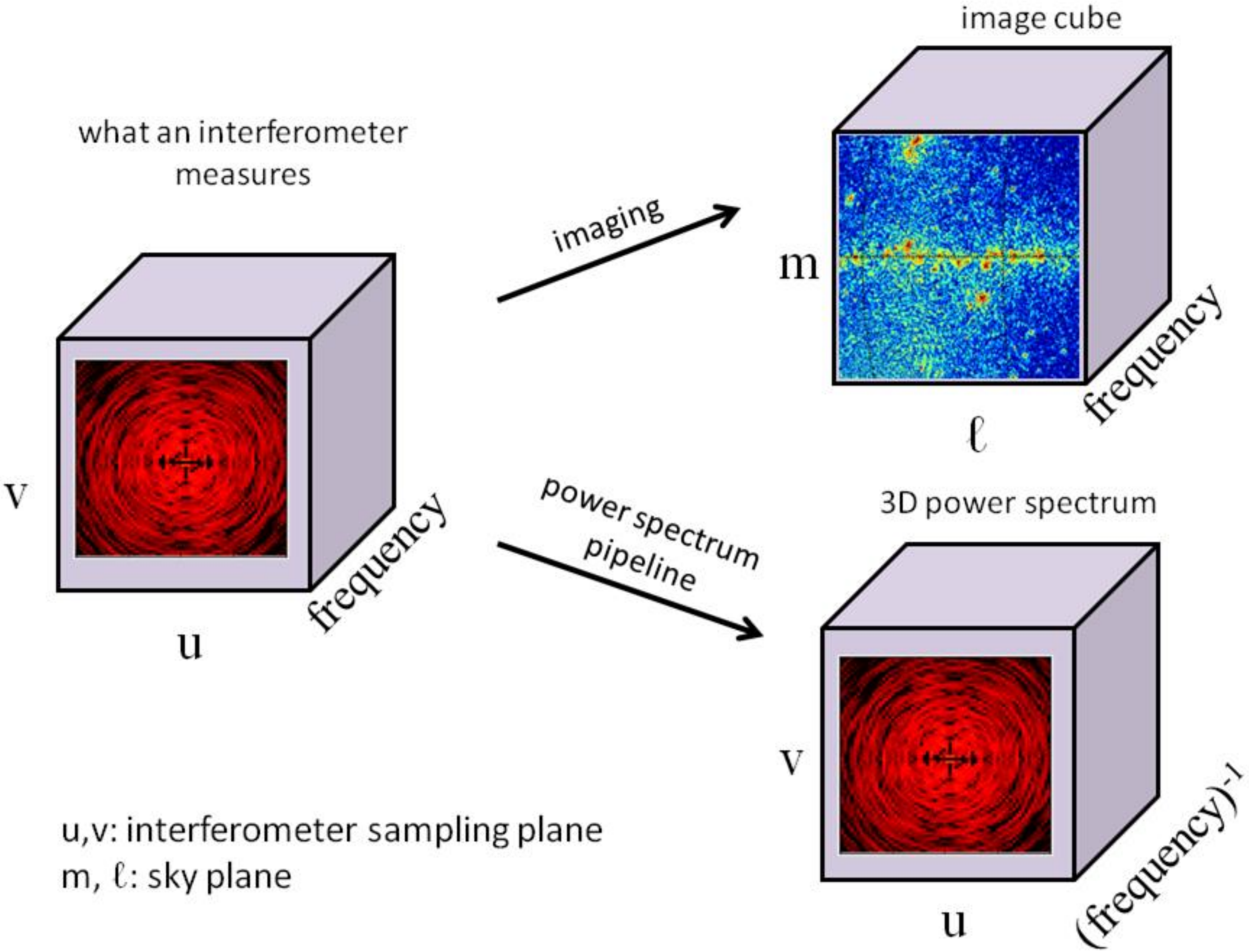


Antenna 1 Antenna 2 Antenna 3

- 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

Imagin

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

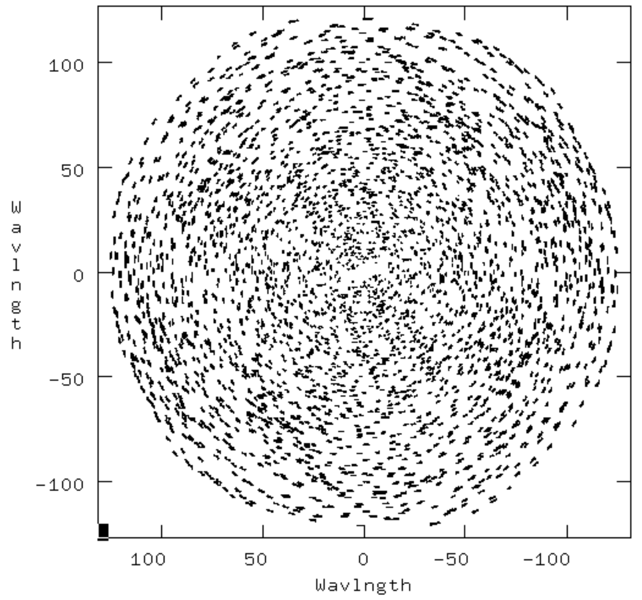


u,v: interferometer sampling plane
m, ℓ: sky plane

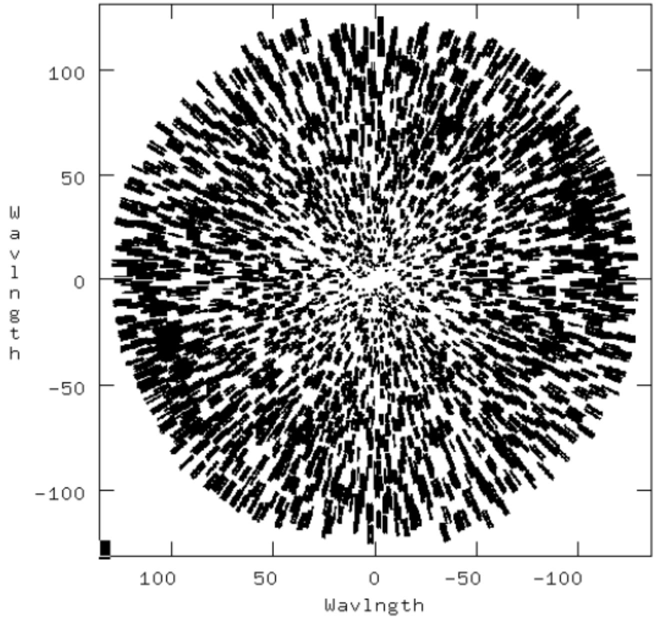
Minimally redundant array

uv Coverage of minimum redundancy array

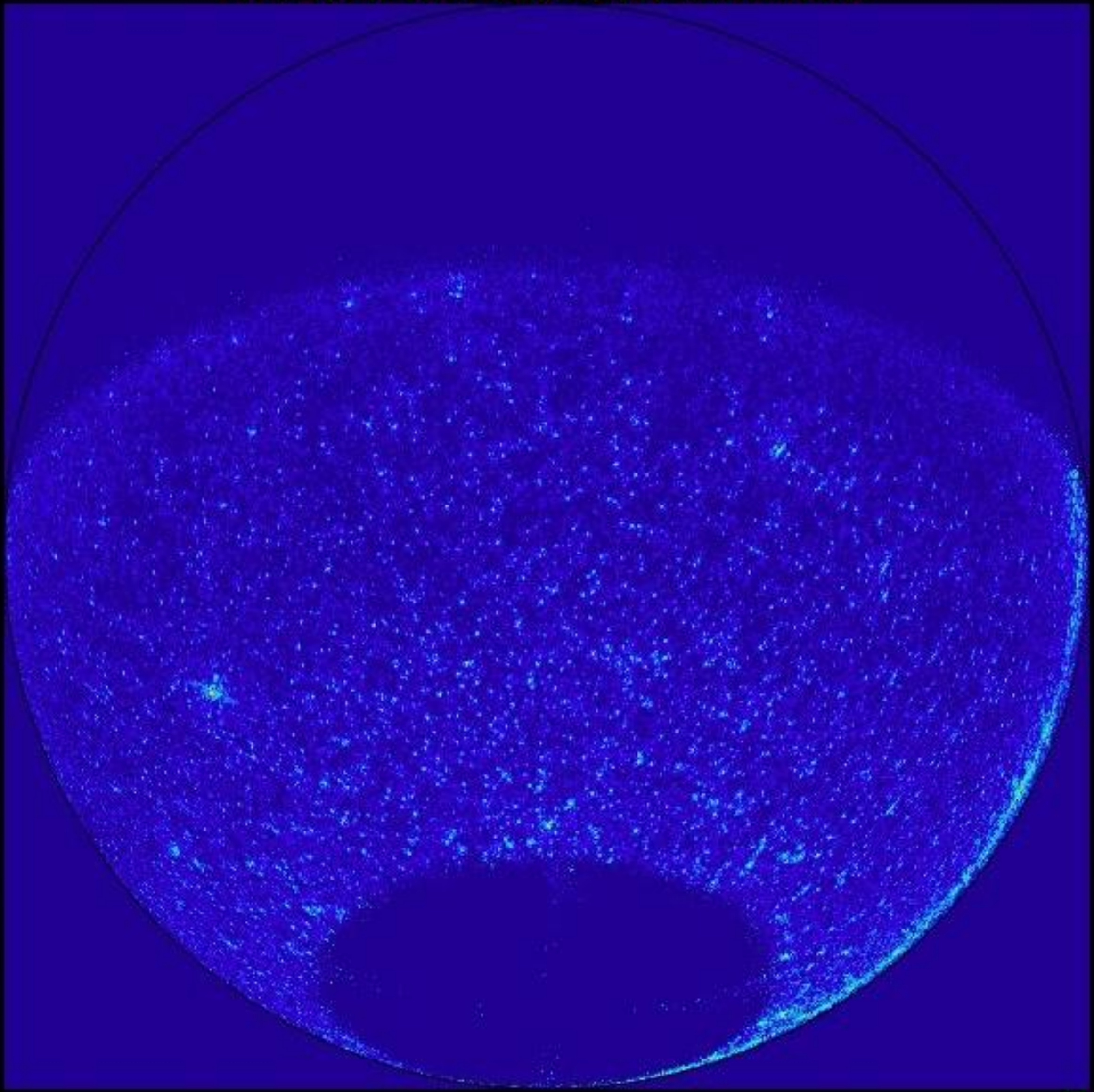
Instantaneous 64-element, narrow band



Instantaneous 64-element, full band



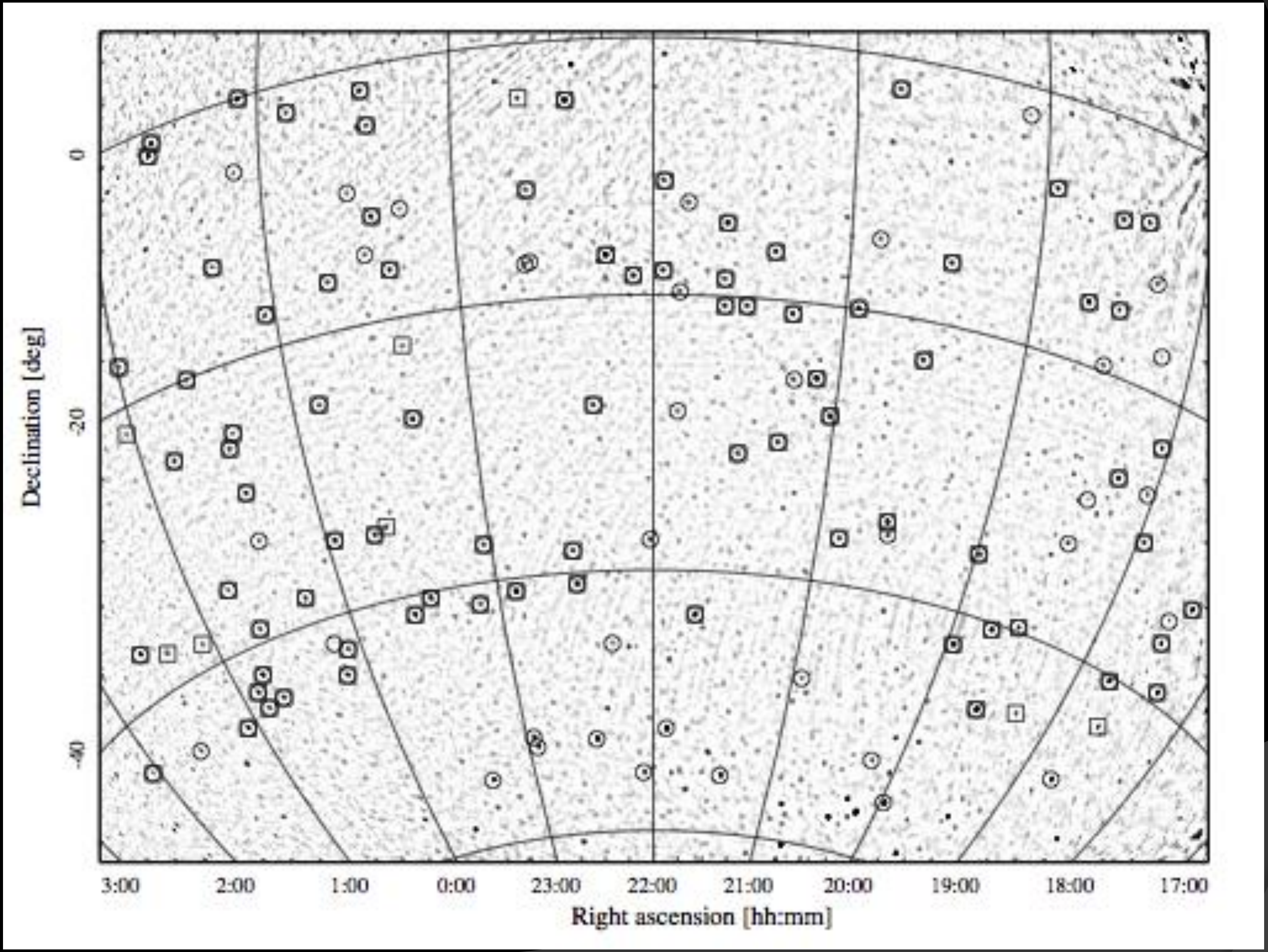
PAPER South Africa



0h-30d

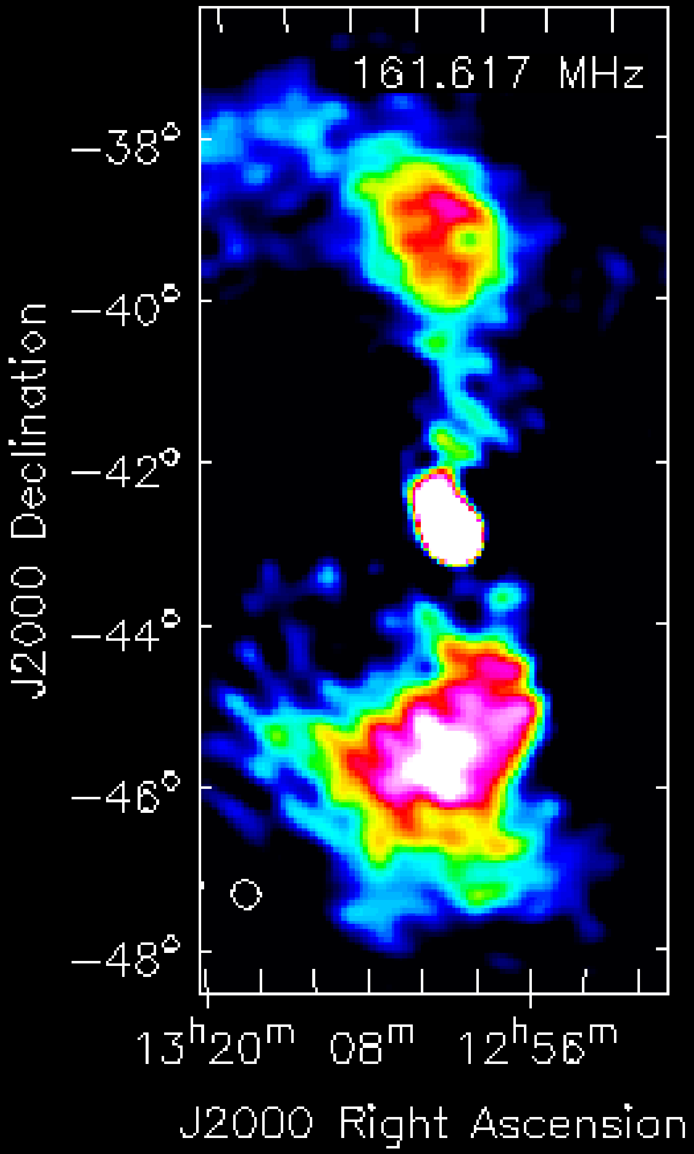
D. Jacobs 2012

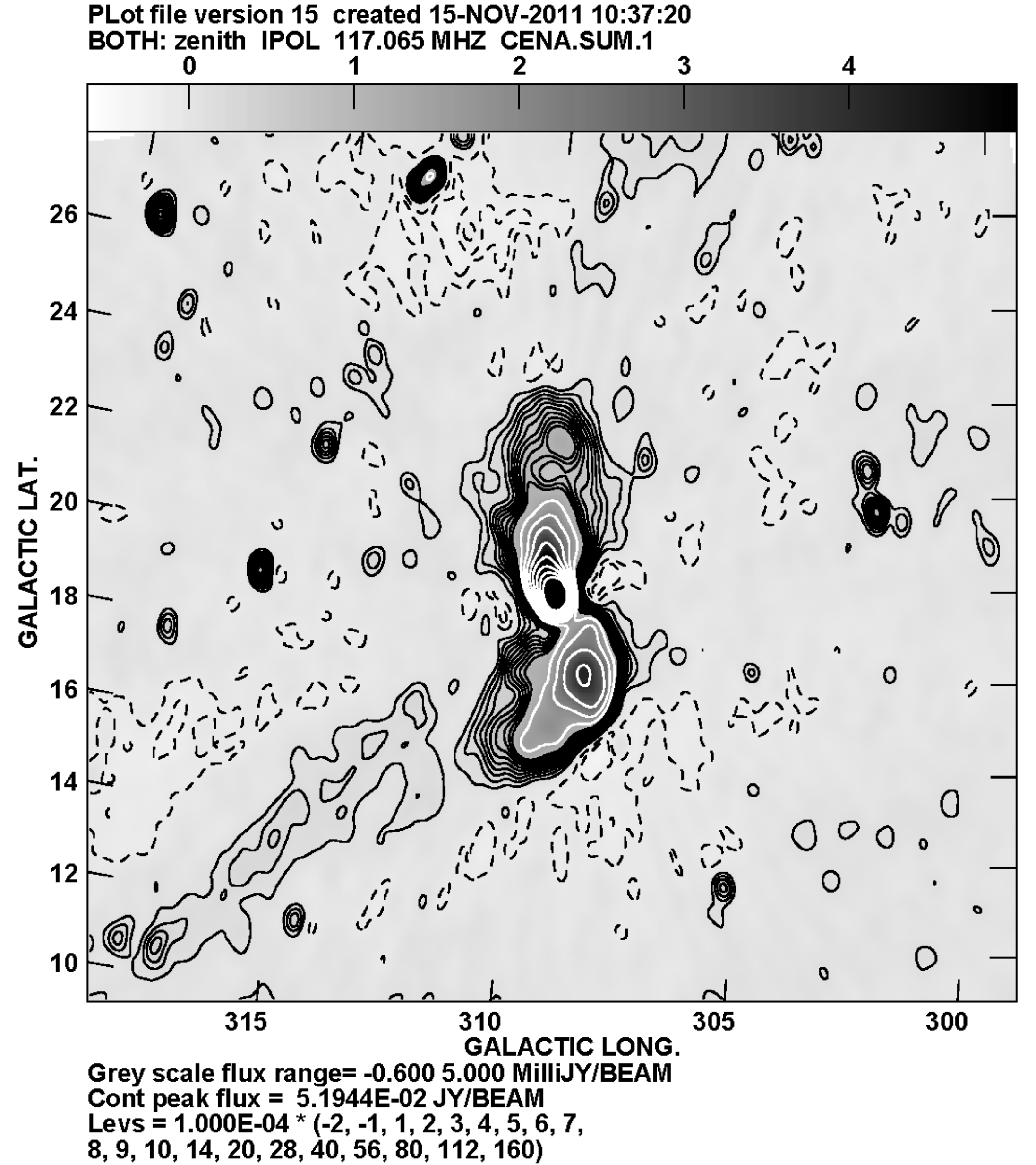
Work in Progress: Complete Northern/Southern Hemisphere Source Catalogs



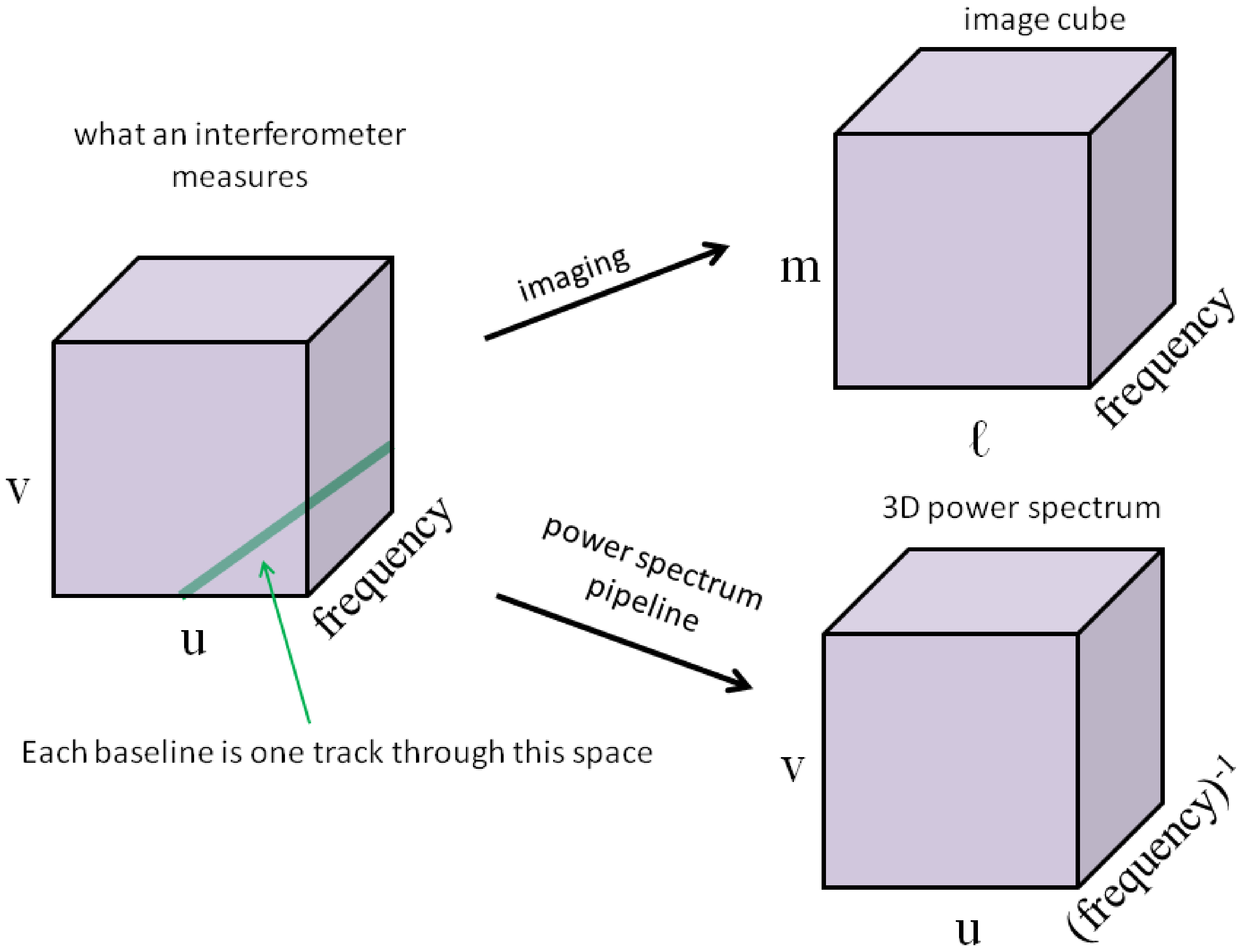
Jacobs et al. 2011

Centaurus A




PLot file version 15 created 15-NOV-2011 10:37:20
BOTH: zenith IPOL 117.065 MHZ CENA.SUM.1

Grey scale flux range= -0.600 5.000 MilliJY/BEAM
Cont peak flux = 5.1944E-02 JY/BEAM
Levs = 1.000E-04 * (-2, -1, 1, 2, 3, 4, 5, 6, 7,
8, 9, 10, 14, 20, 28, 40, 56, 80, 112, 160)



what an interferometer measures

imaging

image cube

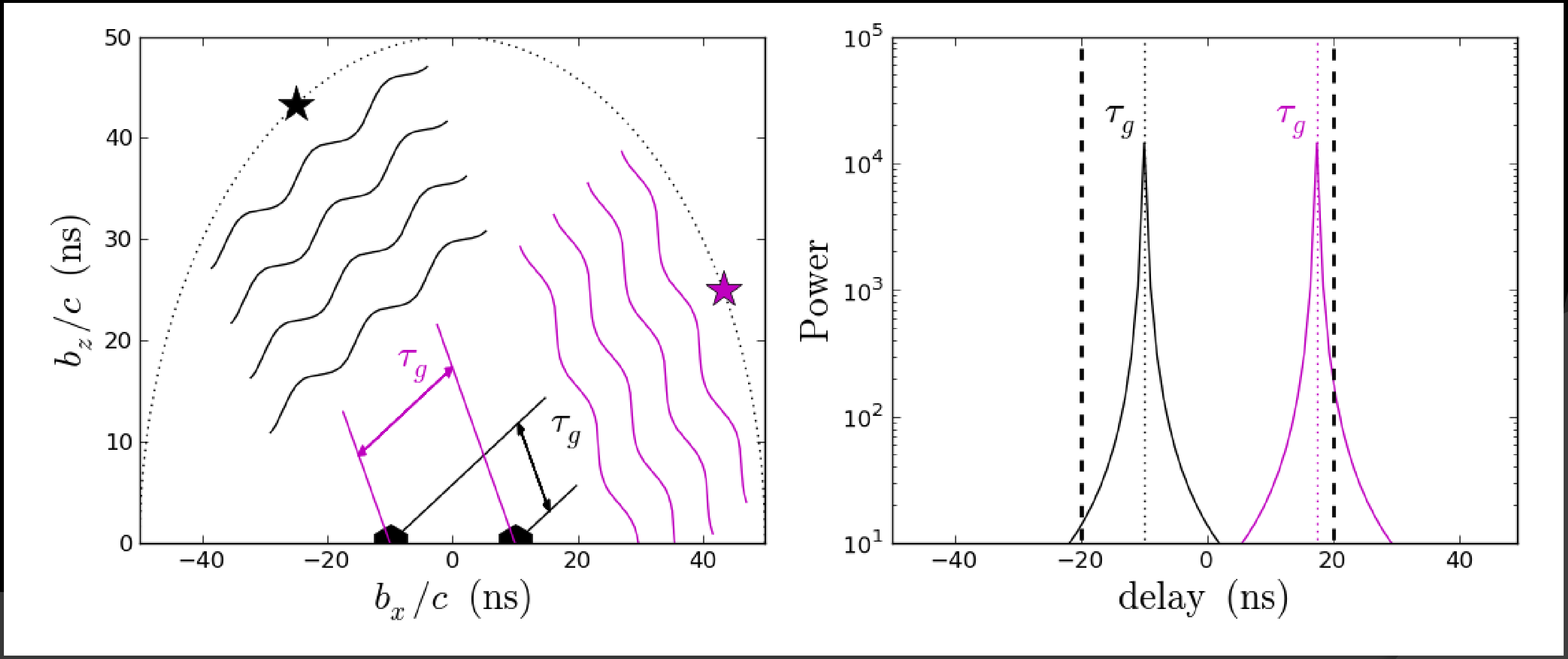
power spectrum pipeline

3D power spectrum

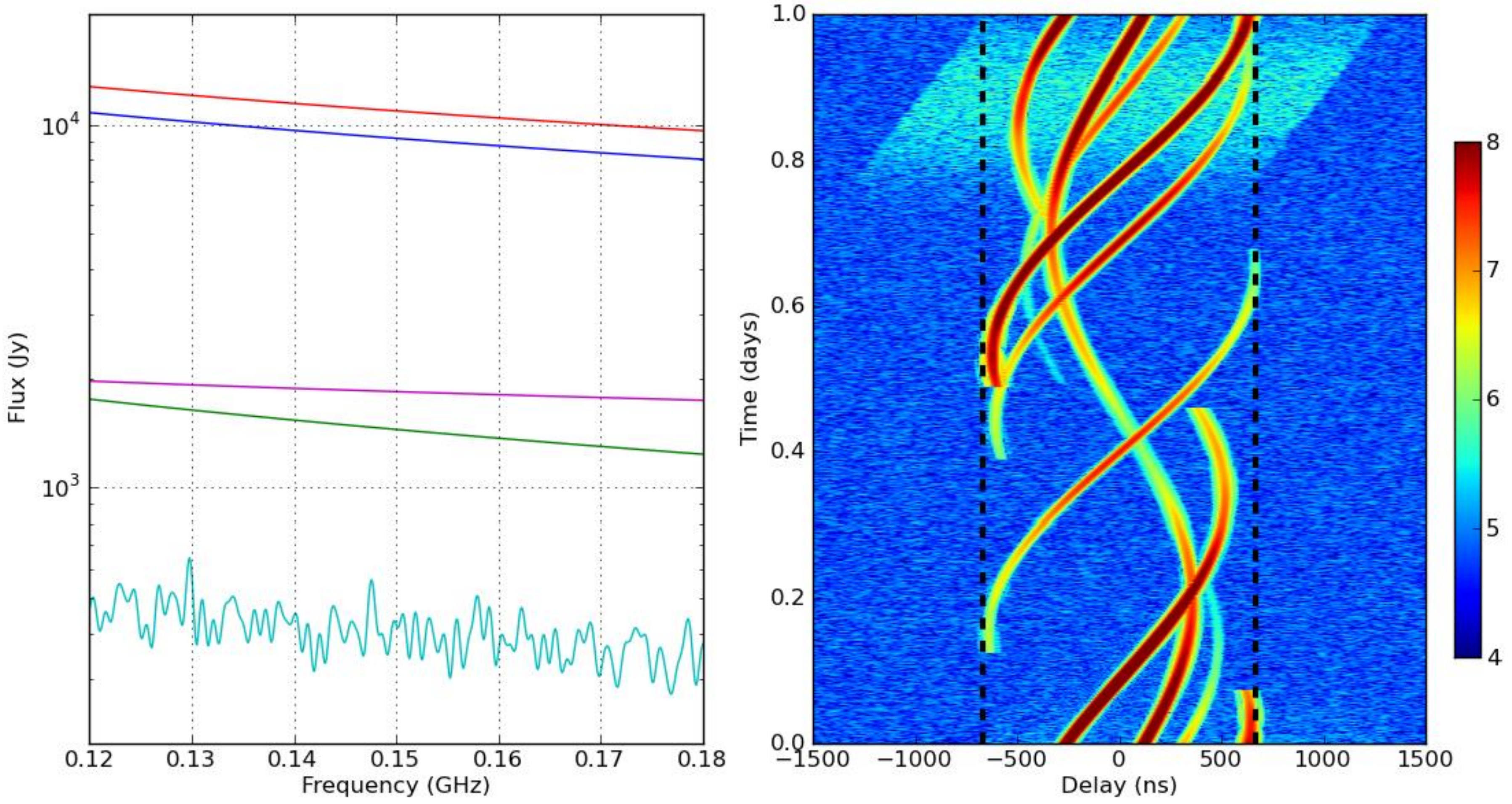
Each baseline is one track through this space

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



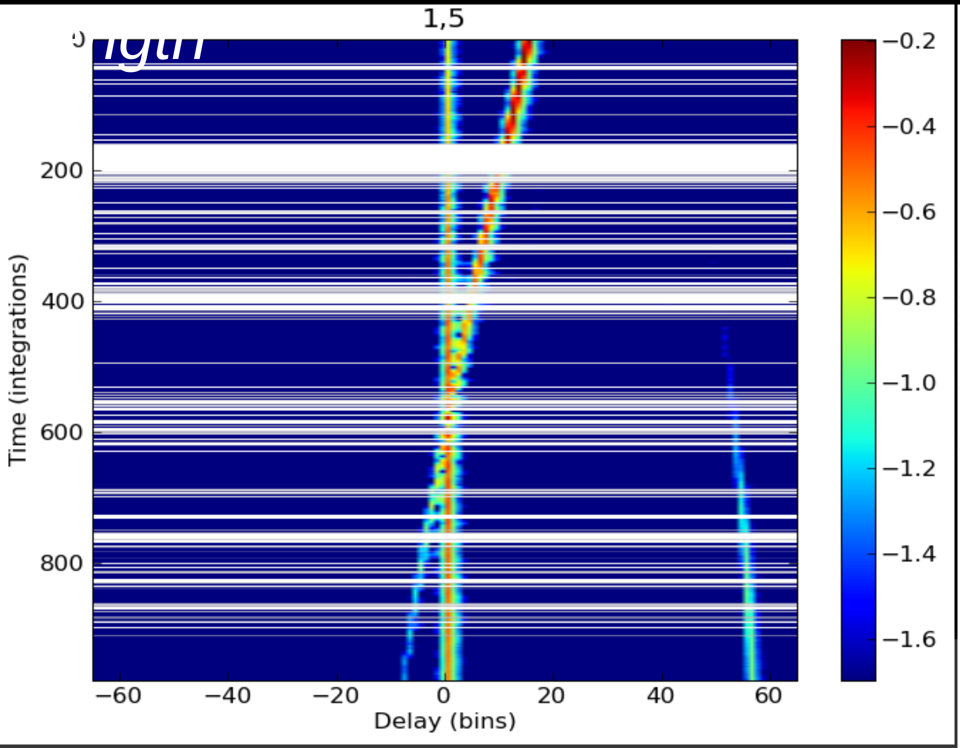
Delay/Delay-Rate Transform:

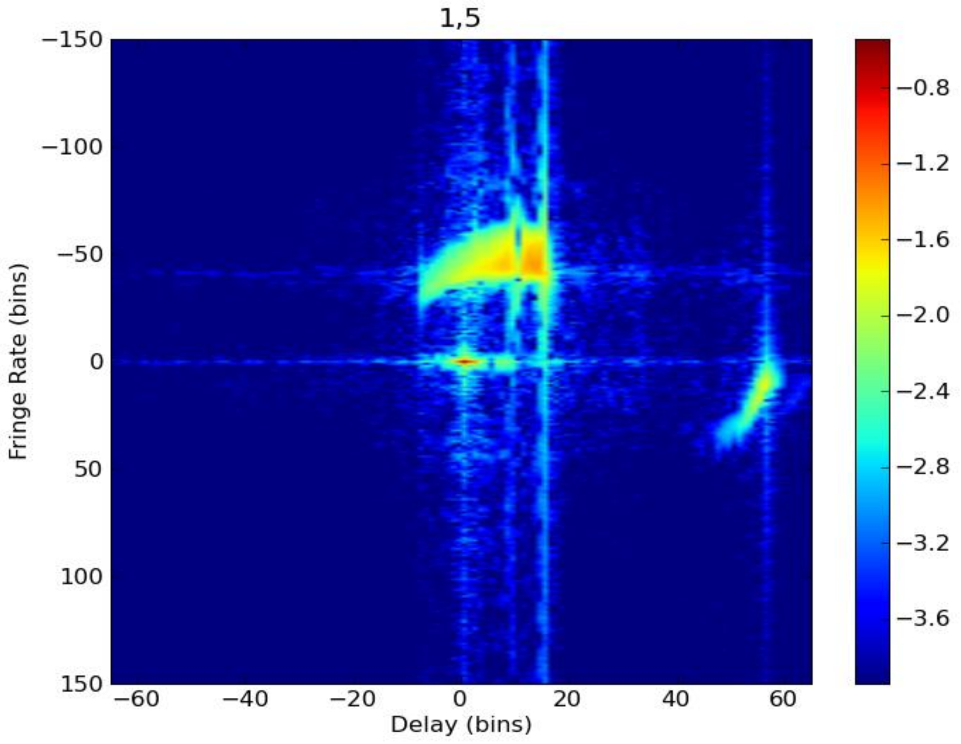
Pseudo-imaging and Compression

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 variabliity

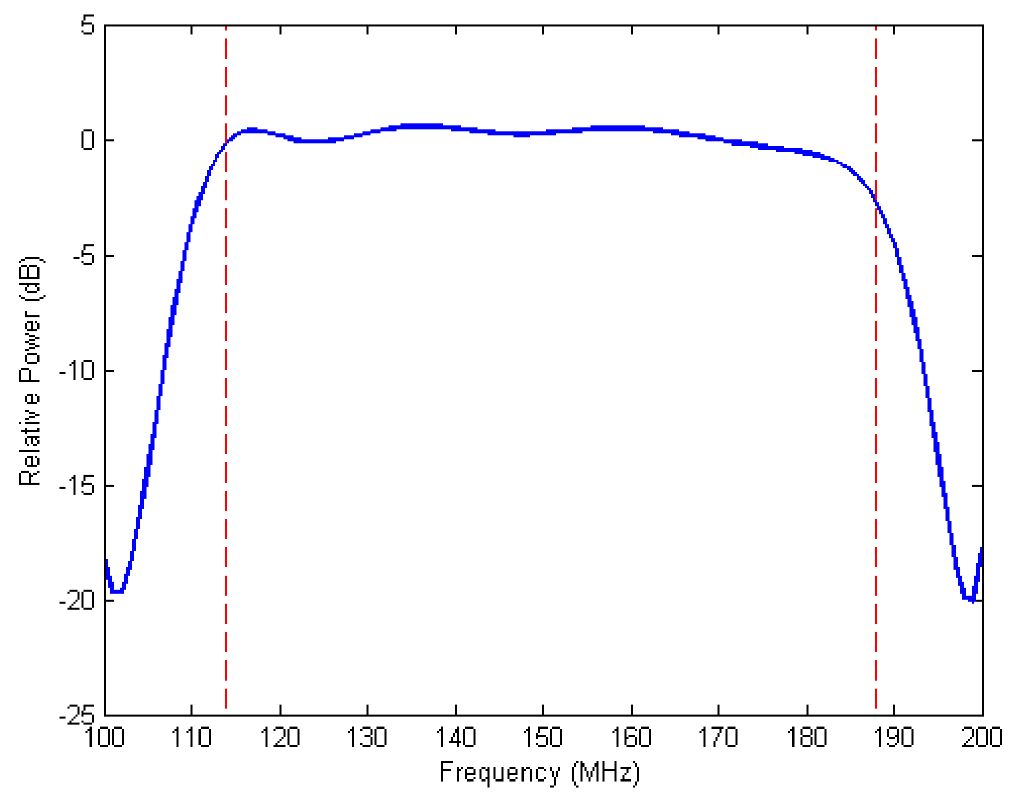
Useful as a form of optimized compression, specific to baseline
igth



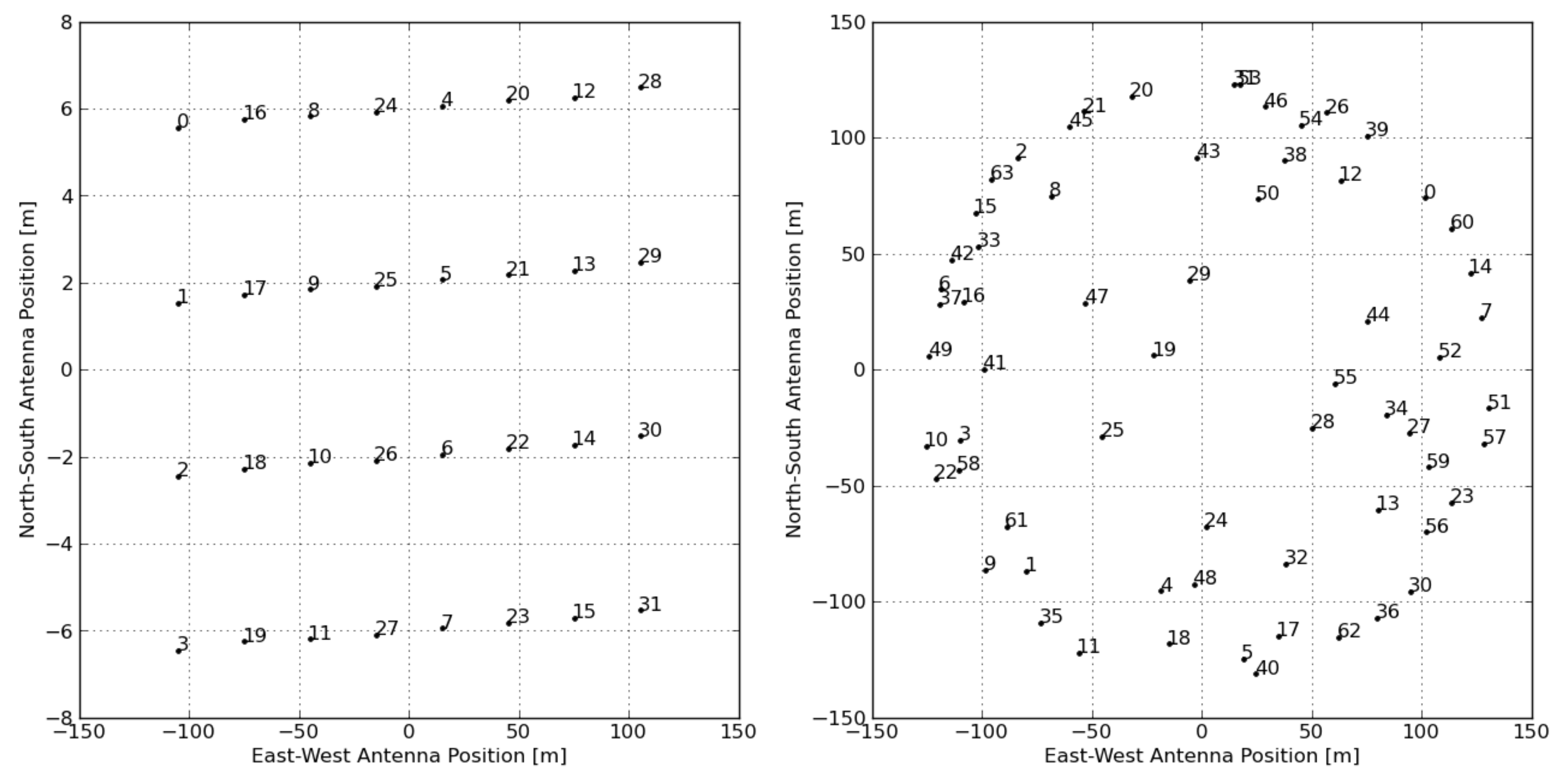


Frequency Range

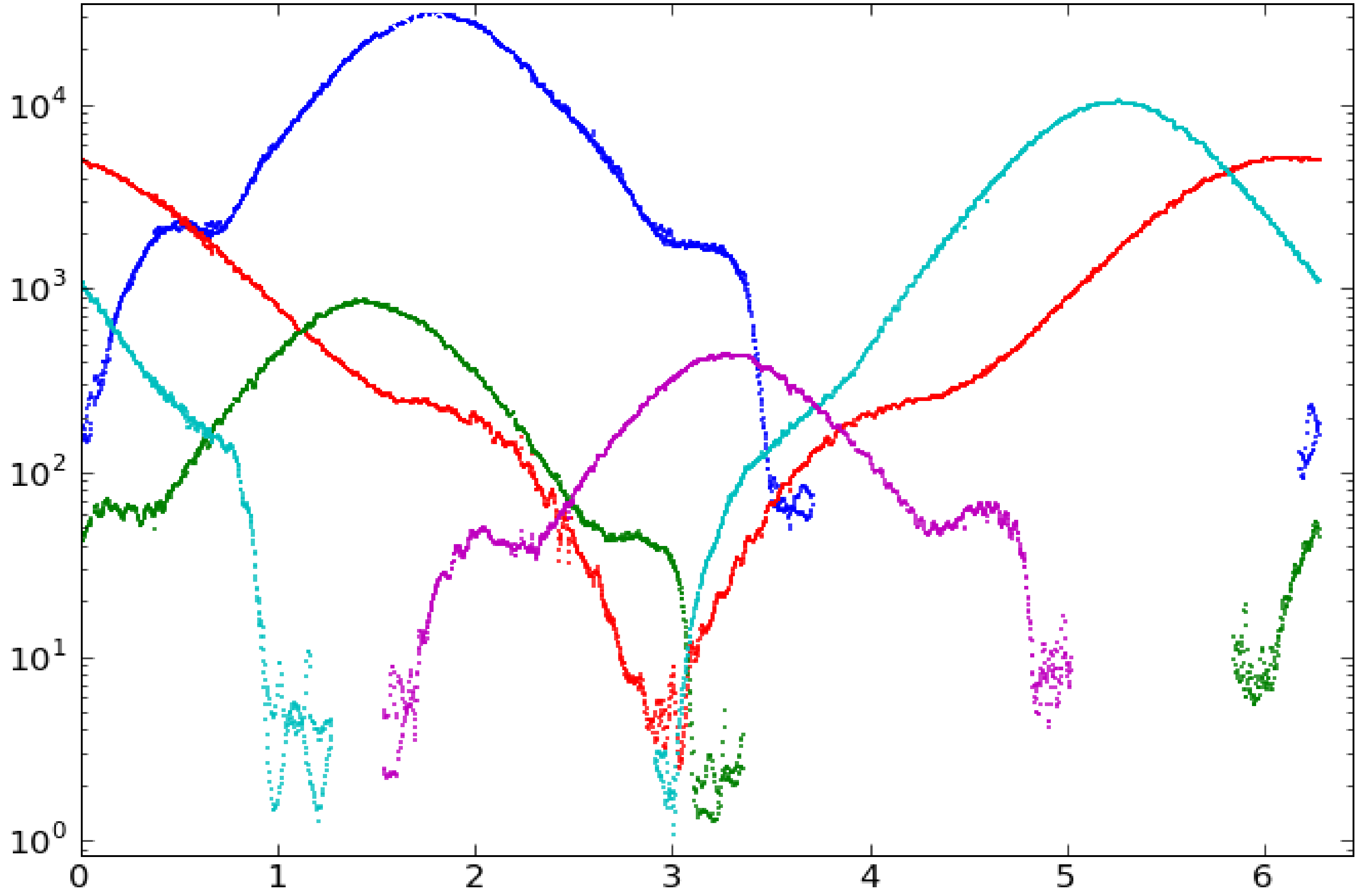
- Digitization and correlator 100 – 200 MHz. Useful range 118 – 188 MHz ($11 > z > 6.6$)
- Currently set by ADC clock, receiver bandpass
- Can be adjusted within modest limits with some work



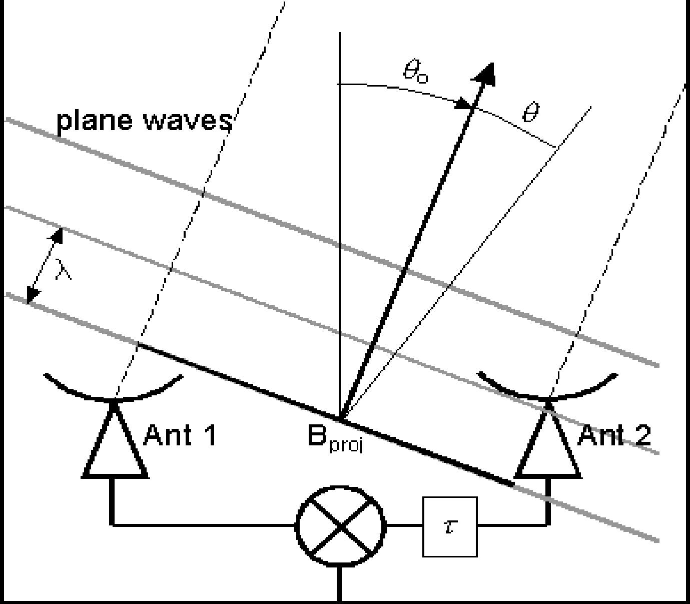
Array layout:
maximum and minimum redundancy



DDR Filters Used as Source Estimators and for mapping primary beam



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 $\tilde{I}(\mathbf{k})$ of some spatial field $I(\mathbf{x})$

$$\tilde{I}(\mathbf{k}) = \int I(\mathbf{x}) \exp\left[-i\mathbf{k} \cdot \mathbf{x}\right] d\mathbf{x}$$

$$I(\mathbf{x}) = \int \tilde{I}(\mathbf{k}) \exp\left[i\mathbf{k} \cdot \mathbf{x}\right] d\mathbf{k}$$

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

An individual visibility associated with a definite physical length baseline $\mathbf{b}$ is defined as

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

Assuming no w-term, and thus that

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

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

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

We will also find it convenient to write

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

where $k_\perp C_\perp \Omega$ is shortand for

$$k_x C_\perp l + k_y C_\perp m$$

Now, Fourier transform the visibility with respect to ν

$$\begin{aligned} V(\mathbf{b},\tau) &= \int d\Omega d\nu\, A(\Omega,\nu) I(\Omega,\nu) \exp[-2\pi i \nu \mathbf{b}\cdot\hat{\Omega}/c] \exp\left[-2\pi i \tau \nu\right] \quad (1) \\ &= \int d\Omega d\nu\, A(\Omega,\nu) I(\Omega,\nu) \exp[-2\pi i (\mathbf{b}\cdot\hat{\Omega}/c + \tau)\nu] \quad (2) \end{aligned}$$

which defines the delay transform. Substituting in, we get

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

Rearrange

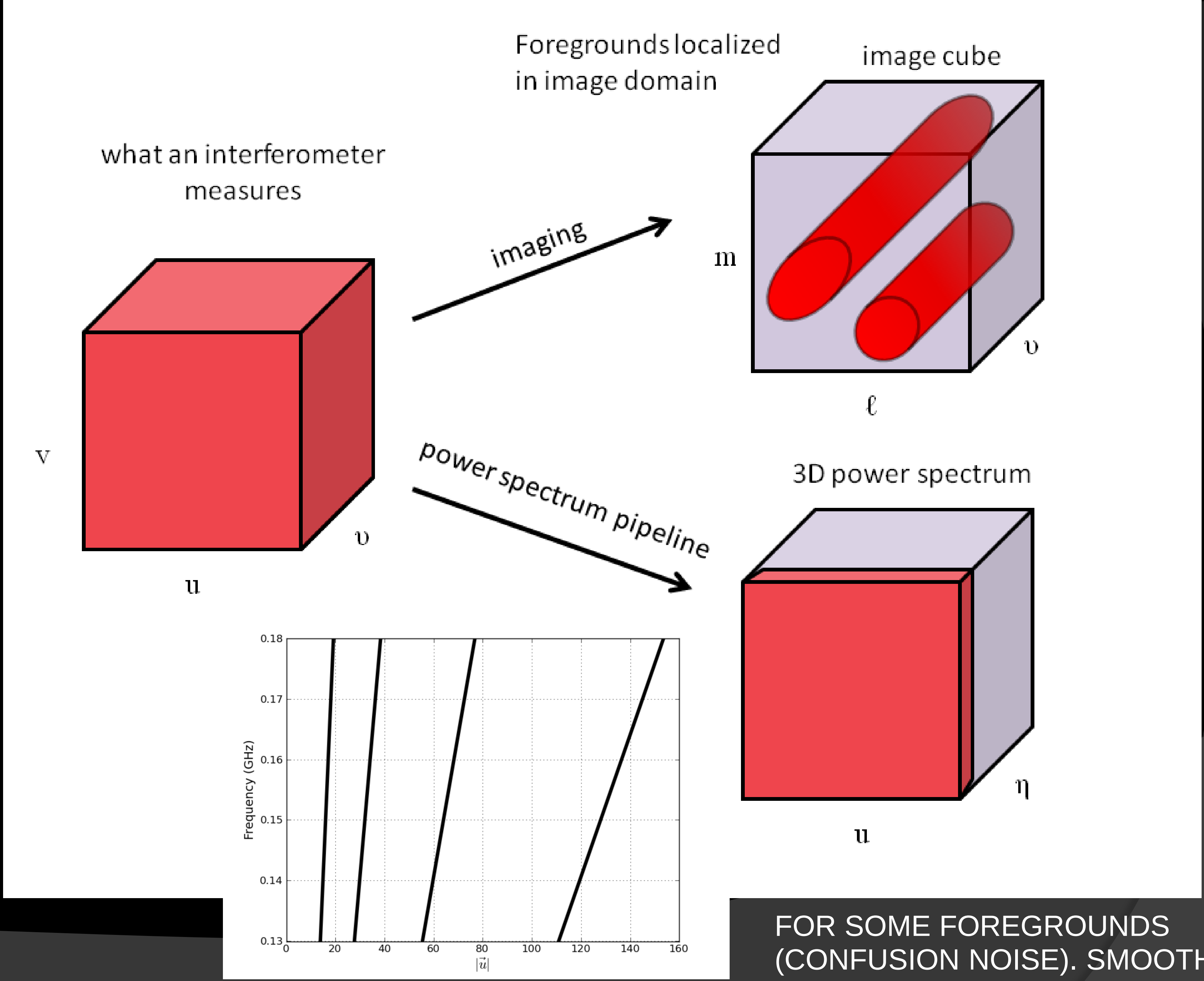
$$V(\mathbf{b},\tau) = \int d\mathbf{k} \tilde{I}(\mathbf{k}) \int d\Omega d\nu\, A(\Omega,\nu) \exp\left[i\mathbf{k}\cdot\mathbf{C}\cdot(\hat{\Omega},\nu) - 2\pi i (\mathbf{b}\cdot\hat{\Omega}/c + \tau)\nu\right]$$

This we can write as

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

where

$$K(\mathbf{b},\tau,\mathbf{k}) = \int d\Omega d\nu\, A(\Omega,\nu) \exp\left[i(\mathbf{k}\cdot\mathbf{C}\cdot(\hat{\Omega},\nu) - 2\pi(\mathbf{b}\cdot\hat{\Omega}/c + \tau)\nu)\right] \quad (3)$$

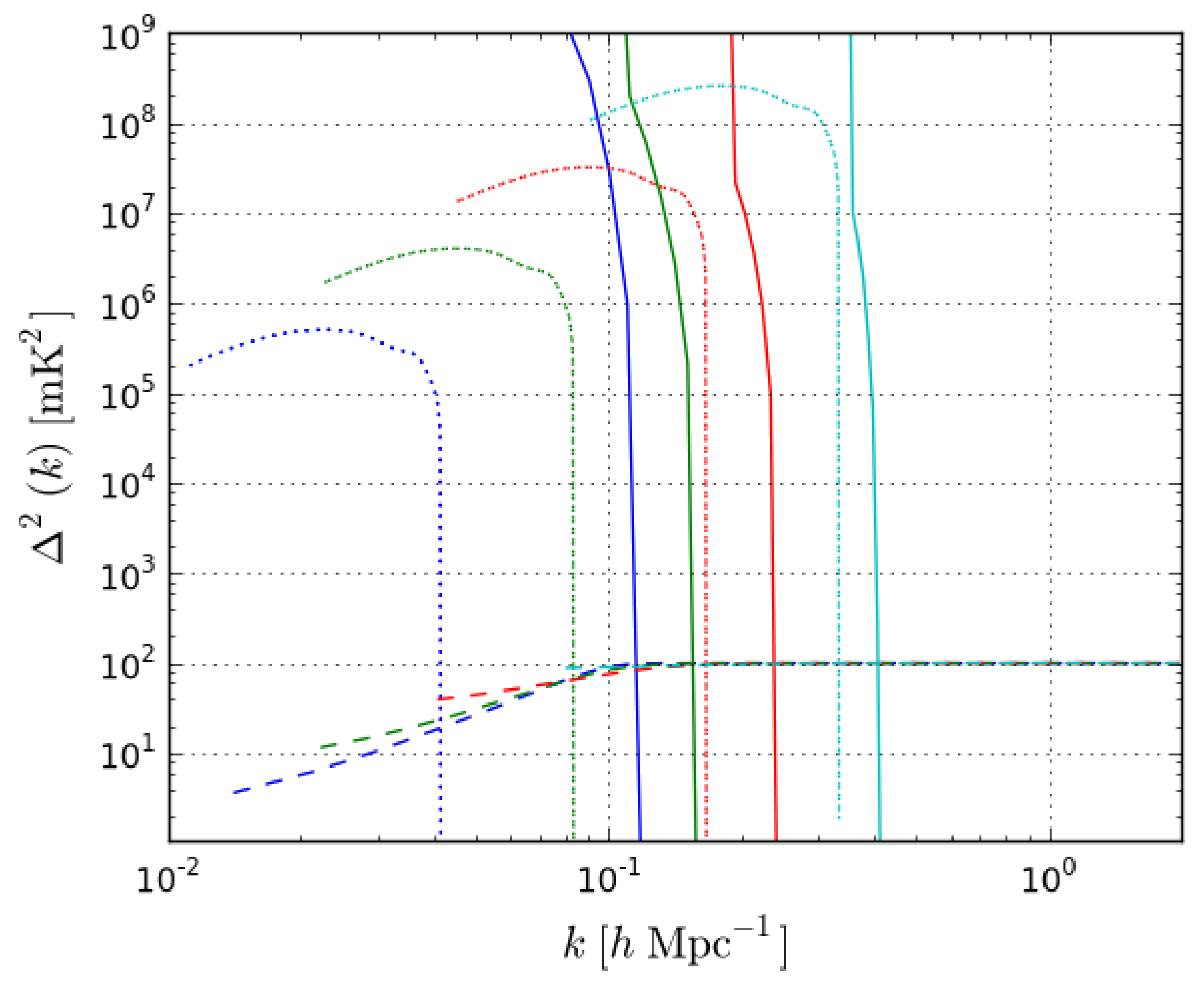


FOR SOME FOREGROUNDS (CONFUSION NOISE). SMOOTH SPECTRUM IS ONLY WAY TO

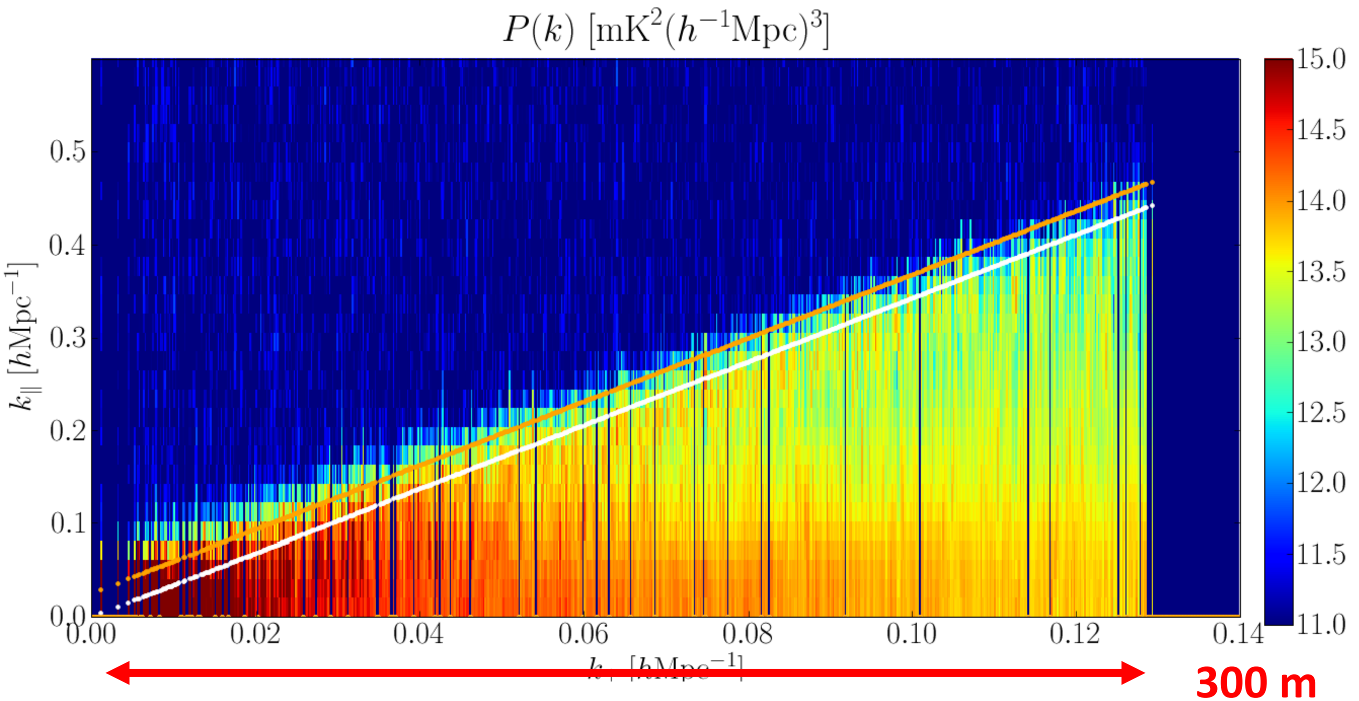
Using Delay Transform to Evade Foregrounds

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

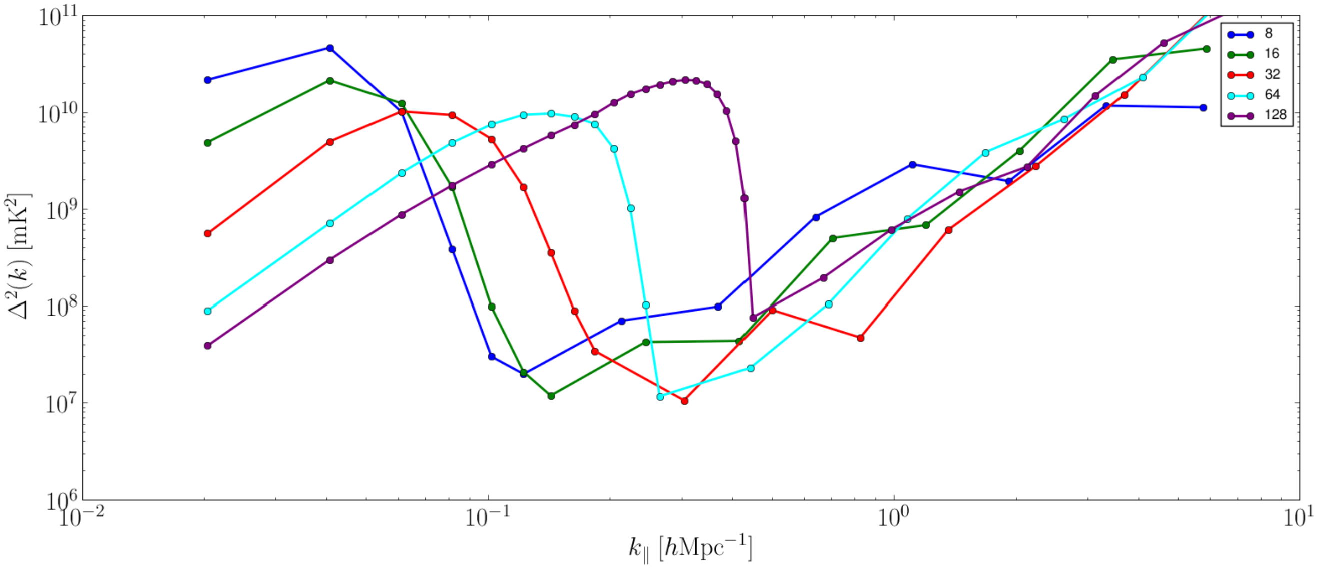


Foregrounds in *k*-space

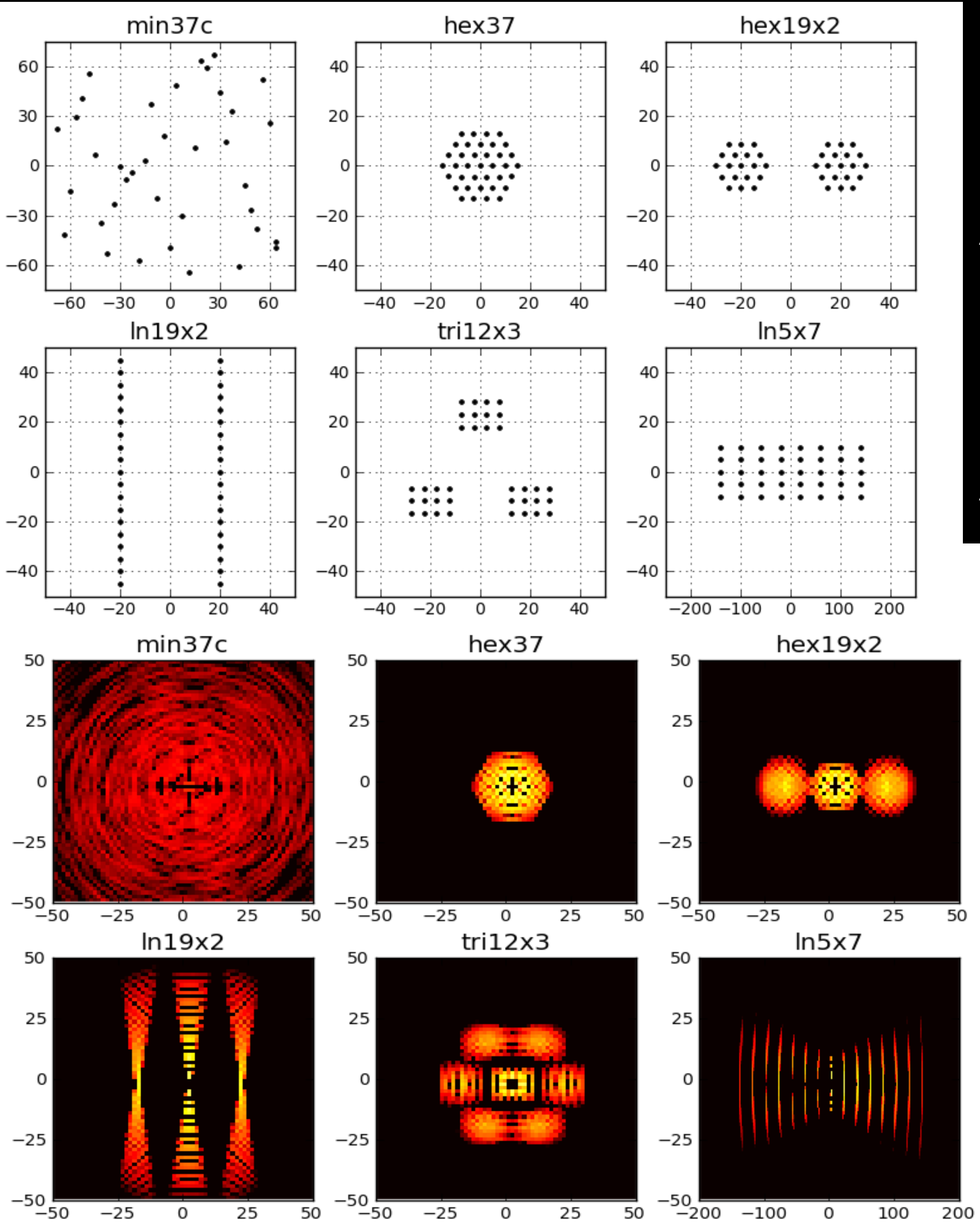


300 m

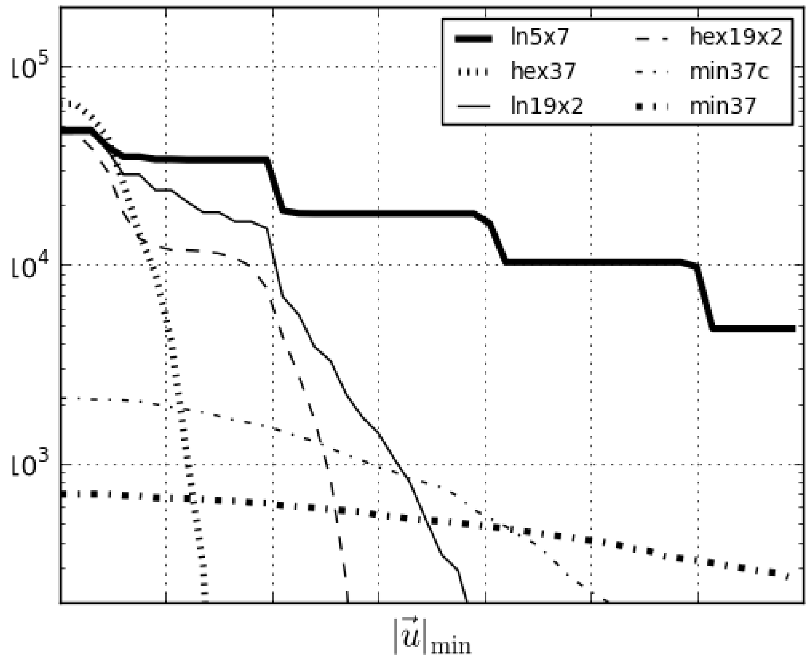
Pober et
al 2013
arxiv:



PAPER Configuration Studies



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 *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 m^2 = 896 m^2
- What FoV/station size was chosen, why?
  - ~60^o 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