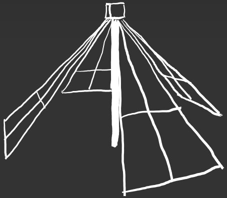


m-Mode Analysis Imaging with the Owens Valley LWA

Michael Eastwood
California Institute of Technology

Science at Low Frequencies III – December 7, 2016

Caltech

- Gregg Hallinan
- Sandy Weinreb
- Stephen Bourke → Chalmers
- Jake Hartman → Google
- Harish Vedantham
- Jonathon Kocz
- Kate Clark
- Marin Anderson
- Ryan Monroe
- David Wang

Harvard/SAO

- Lincoln Greenhill
- Ben Barsdell → NVIDIA
- Danny Price → Berkeley
- Hugh Garsden

OVRO

- Dave Woody
- James Lamb
- OVRO staff

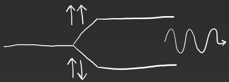
JPL

- Larry D'Addario
- Joe Lazio

and the rest of the LWA team

Foregrounds in 21 cm Cosmology

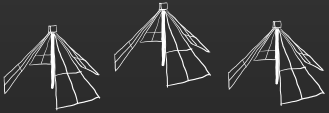
Cosmological signal



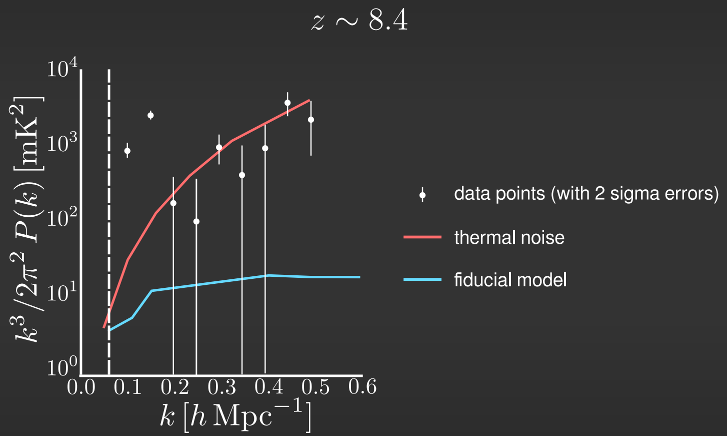
Extragalactic point sources

Galactic synchrotron emission

Ionosphere

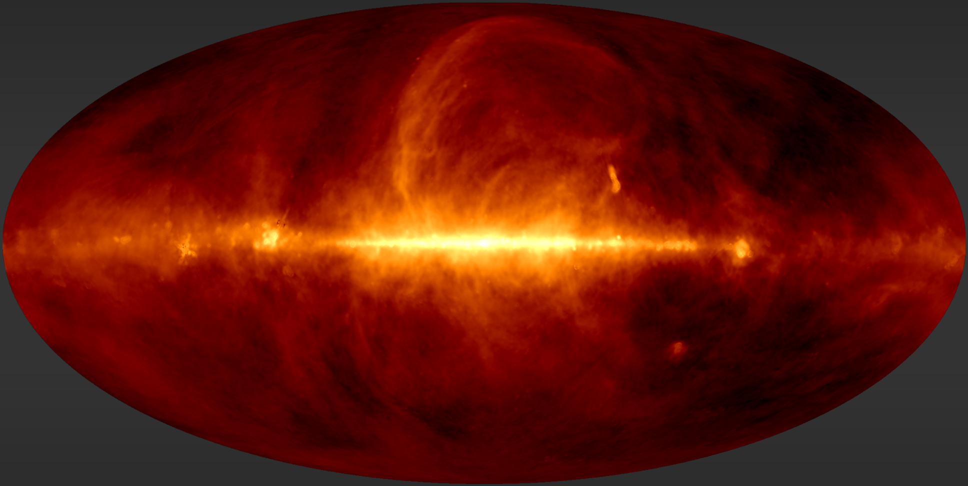


Foreground Leakage is a Problem



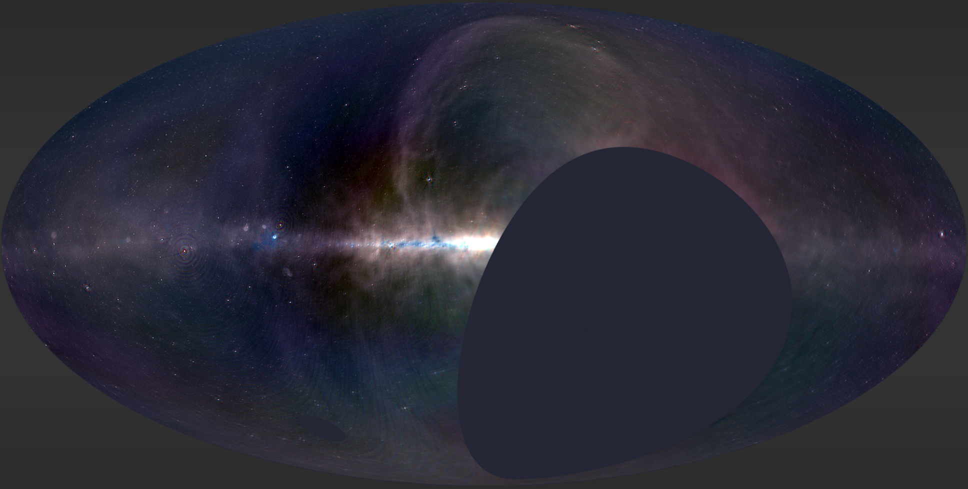
Ali et al. (2015)

Our understanding of the VHF sky is an **extrapolation** of this map.



Haslam et al. (1981, 1982)

We need a **measurement** of the VHF sky.

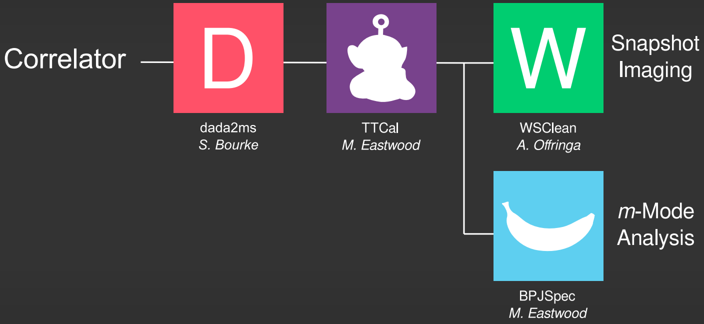


Eastwood et al. (in prep.)

The OVRO LWA 100 Hour Dataset

Observing Period	2016-03-19 through 2016-03-23
Total Observation Time	100 hours
Integration Time	13 seconds
Frequency Range	25 – 82 MHz
Resolution	10 – 20 arcminutes

The Data Reduction Pipeline



Calibration

- Gain calibration occurs once per day
- Bright sources are peeled from the dataset (Cyg A, Cas A)
- Near-field sources of RFI (arcing power lines) subtracted
- Flux scale tied to Perley & Butler 2016

TTCal

Freely available under an open source license (GPLv3+)
`https://github.com/mweastwood/TTCal.jl`

The Challenge of Widefield Imaging

$$\text{visibility} = \int (\text{sky brightness}) \times (\text{beam}) \times (\text{fringe pattern})\, \mathrm{d}\Omega$$

We want to solve this equation **quickly** and **accurately.**

Transit telescopes can exploit a symmetry that greatly simplifies the necessary computation for all-sky synthesis imaging.

m-Mode Analysis Fundamentals

$$\text{visibility} = \int (\text{sky brightness}) \times (\text{beam}) \times (\text{fringe pattern})\,\mathrm{d}\Omega$$

For a telescope that does not steer its beam, visibilities are a periodic function of the sidereal time.

$$\text{visibility} \xrightarrow{\text{sidereal time Fourier transform}} \text{m-mode}$$

$$\begin{pmatrix} \vdots \\ \text{m-modes} \\ \vdots \end{pmatrix} = \begin{pmatrix} \ddots & & \\ & \text{transfer matrix} & \\ & & \ddots \end{pmatrix} \begin{pmatrix} \vdots \\ a_{lm} \\ \vdots \end{pmatrix}$$

Shaw et al. (2014, 2015)

The Fundamental Equation

$$v = \boldsymbol{B}a + \text{noise}$$

- v is the vector of m-modes. This is what is measured by the interferometer.
- $\boldsymbol{B}$ is the transfer matrix. It describes the response of the interferometer to the sky. This matrix is **block diagonal**.
- a is the vector of spherical harmonic coefficients (for the sky brightness).

Shaw et al. (2014, 2015)

Regularizing the Problem

Goal: Estimate a given the observations v, but unmeasured modes should be (smoothly) set to zero.

Least squares with Tikhonov regularization

$$\hat{a} = \operatorname{argmin}\left\{\|v - Ba\|^2 + \lambda\|a\|^2\right\} = (\boldsymbol{B}^*\boldsymbol{B} + \lambda\boldsymbol{I})^{-1}\boldsymbol{B}^*v$$

Problem: How do we choose λ? (come talk to me!)

Summary of m-Mode Analysis Imaging

- Block-diagonal matrix equation
- Exact treatment of widefield effects
- Automatic deconvolution of large scale structures
- Coherent synthesis imaging of a full sidereal day

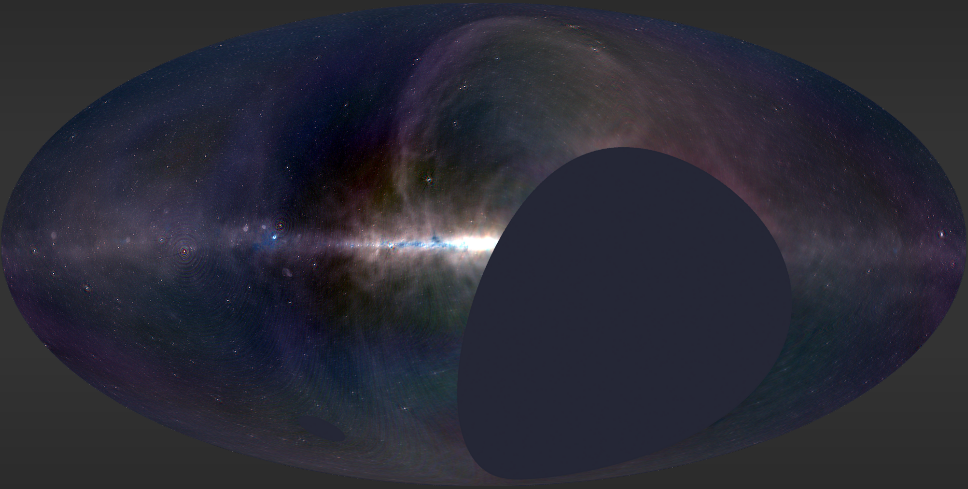
m-Mode Analysis at the OVRO LWA

- Use spherical harmonics with $l \leq 1000$
- Transfer matrix is 500 GB per frequency channel
- Computations parallelized over 160 workers
- 12 hours to compute elements of the transfer matrix
- 10 minutes to solve the imaging equations

BPJSpec

Freely available under an open source license (GPLv3+)
`https://github.com/mweastwood/BPJSpec.jl`

Preliminary Map

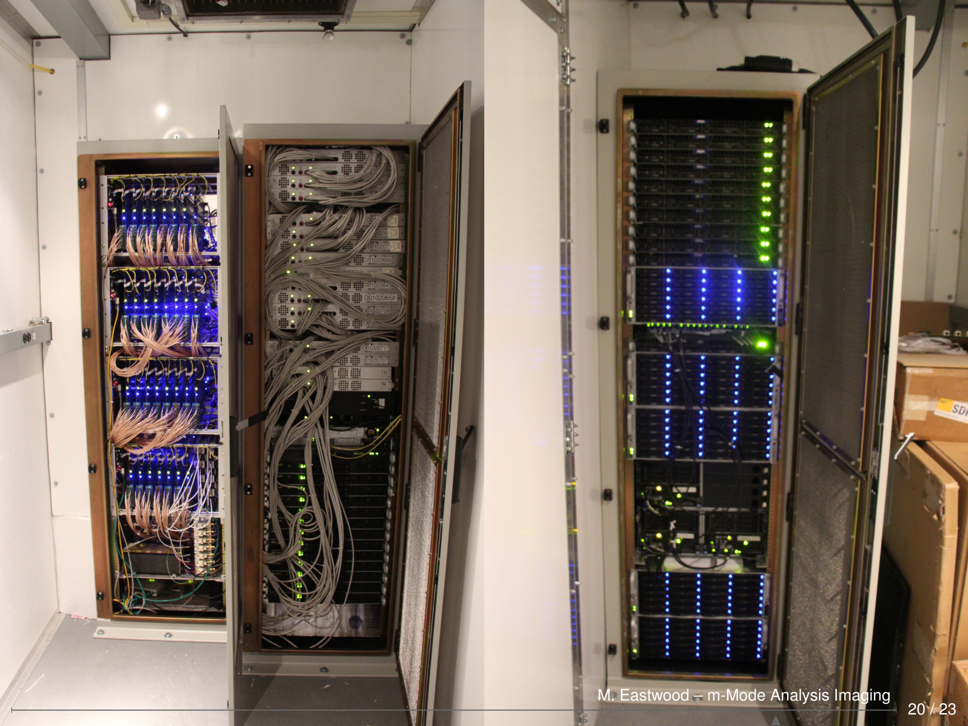


Eastwood et al. (in prep.)

Summary

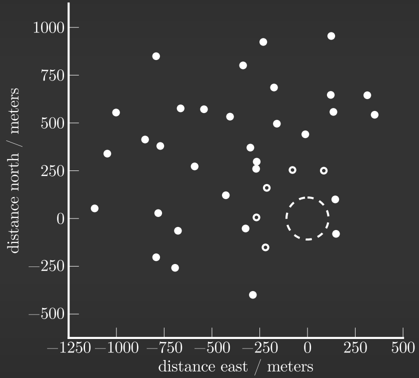
- Need a low frequency anchor to foreground maps for 21 cm cosmology
- (Preliminary) all-sky maps with $\sim$10 arcminute resolution
- Source removal remains the largest challenge
- Data release coming "soon"

Backup Slides

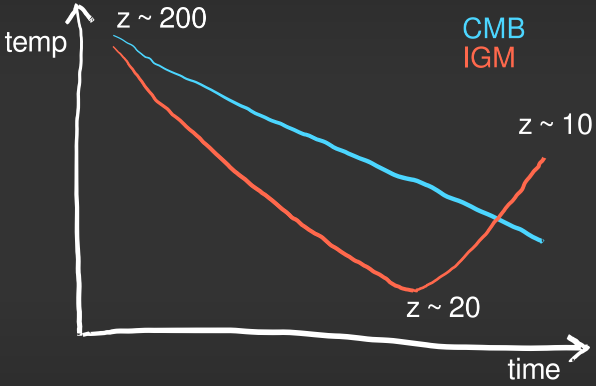


System Parameters

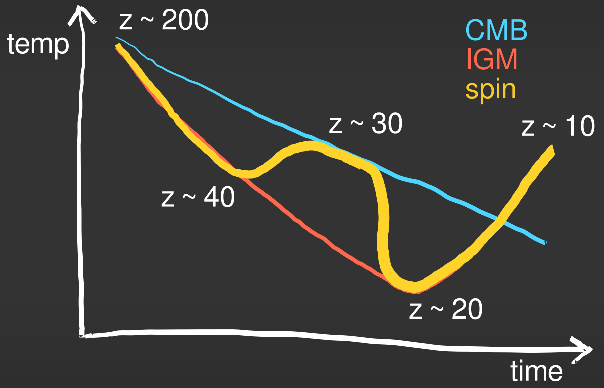
- 288 crossed-dipole antennas (expanding to 352)
- 1.5 km maximum baseline (expanding to 2.5 km)
- 512-input LEDA correlator
- 24.7 MHz to 82.3 MHz instantaneous
- 5 antennas have noise-switched front ends



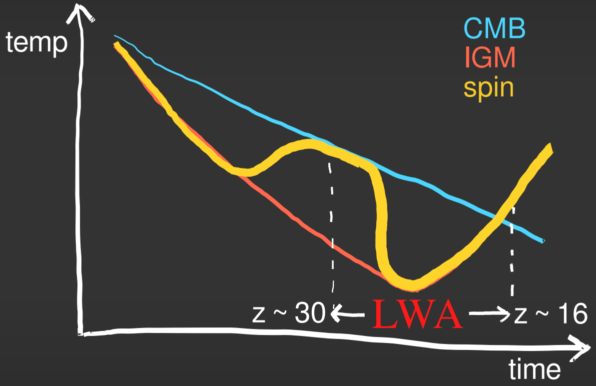
Temperature History



Temperature History

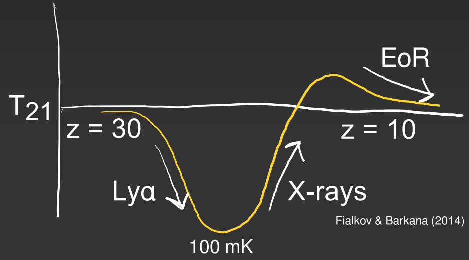


Temperature History



The 21 cm Signal

"COBE"
globally averaged brightness temperature



"WMAP"
amplitude-squared of brightness temperature fluctuations