LWA Long Wavelength Array

The University of New Mexico

NPP NASA Postdoctoral Program

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Modeling Beam-Dependent Effects for 21 cm Cosmology with LWA-SV

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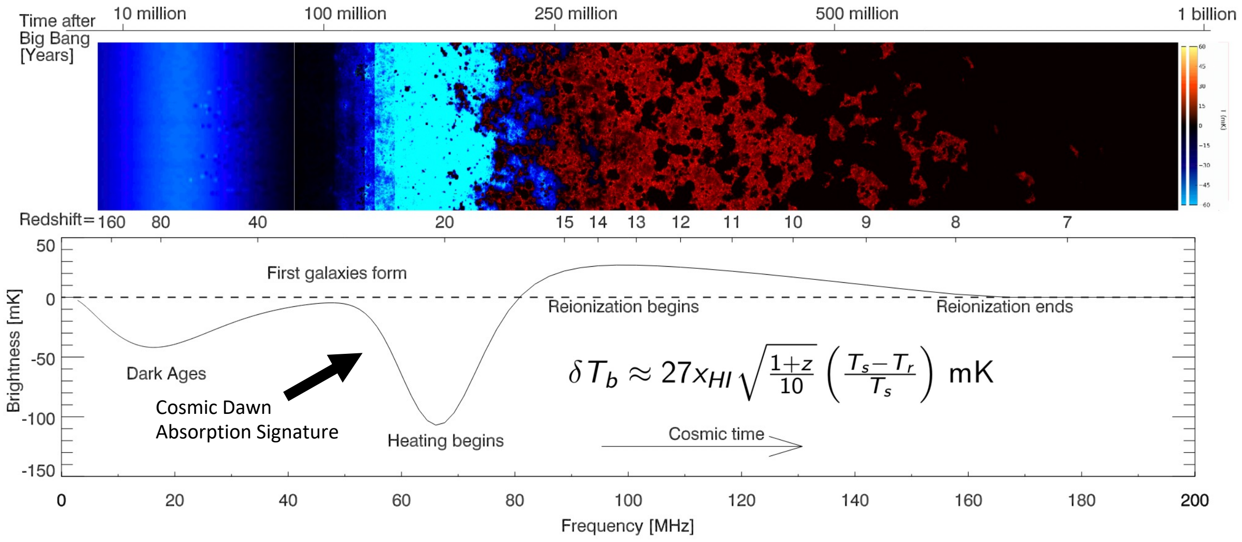
Outline

- Introduction to 21 cm Cosmology
- Current Limits (DiLullo et al 2020, 2021)
- Current Efforts
  - Modeling the sidelobe contribution to the beam response
- Future Work and Summary

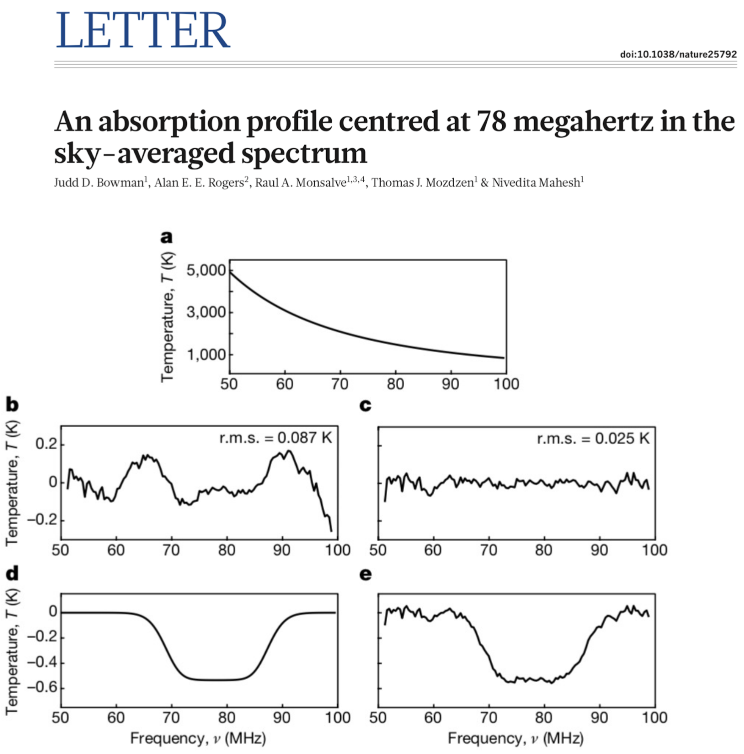
21 cm Cosmology



Cosmic Dawn
Absorption Signature

$$\delta T_b \approx 27 x_{HI} \sqrt{\frac{1+z}{10}} \left(\frac{T_s - T_r}{T_s}\right) \text{ mK}$$

Pritchard & Loeb (2012)



LETTER

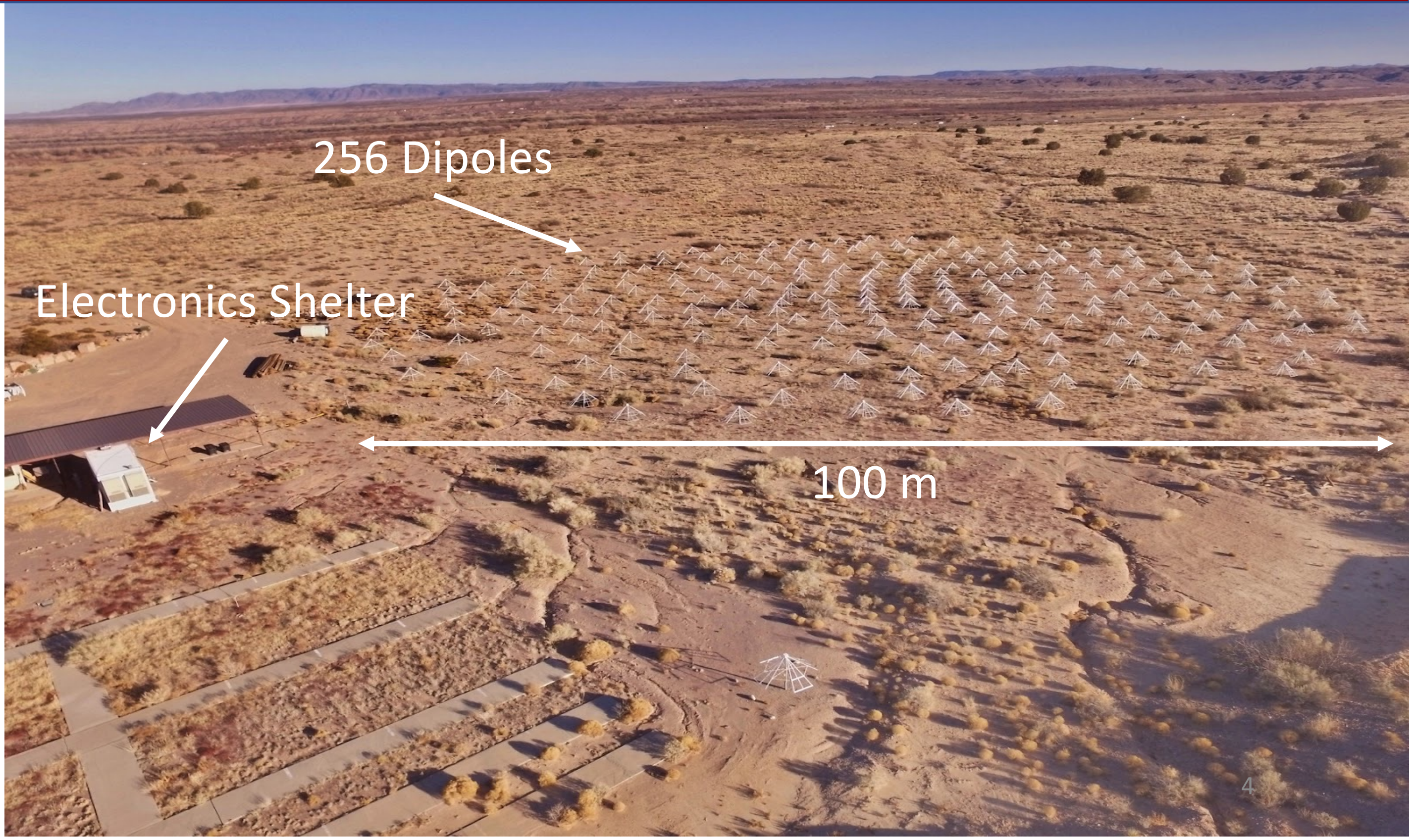
doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

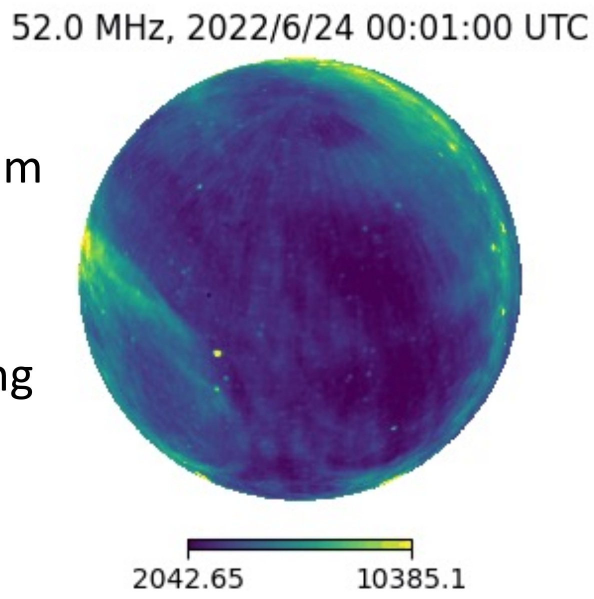
The Long Wavelength Array (LWA-SV)

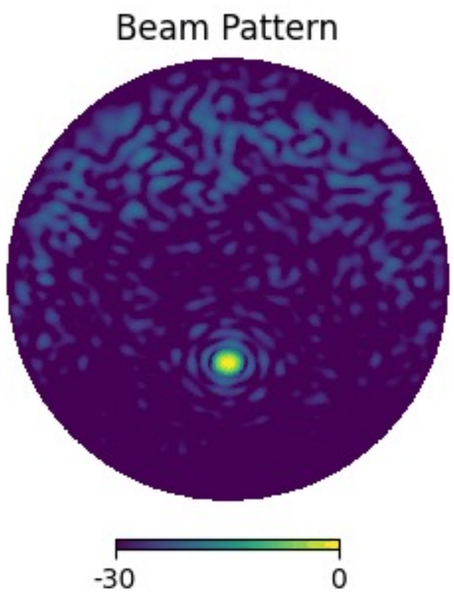
- Located on Sevilleta National Wildlife Refuge in New Mexico, USA
- 3 – 88 MHz
- 2 simultaneous dual polarization beams
  - 2 tunings each with ≈20 MHz bandwidth



Beam Chromaticity

- Main lobe FWHM $\propto \nu^{-1}$
- Frequency-dependent structure introduced into the measured spectrum
- Single antenna experiments must correct for this
- Can be minimized via custom weighting schemes

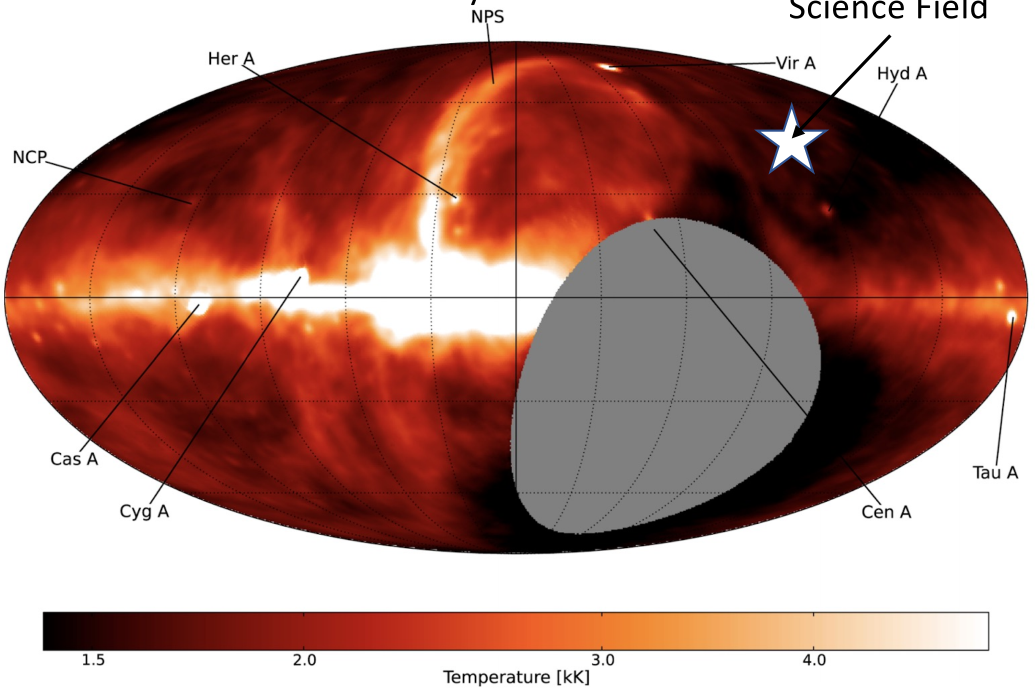




Observational Strategy

- Custom beamforming mode to measure total power
- Observe a cold region of the sky (Science Field)
  - Helps avoid Galactic foregrounds
- Observe a bright calibrator source (Virgo A) to set temperature scale *in situ*
  - Helps avoid lab dependent calibration
- Observe each source at the same local hour angles
- 2 tunings each with 19.6 MHz bandwidth
  - Continuous frequency coverage between 52 – 83 MHz

The Sky at 74 MHz

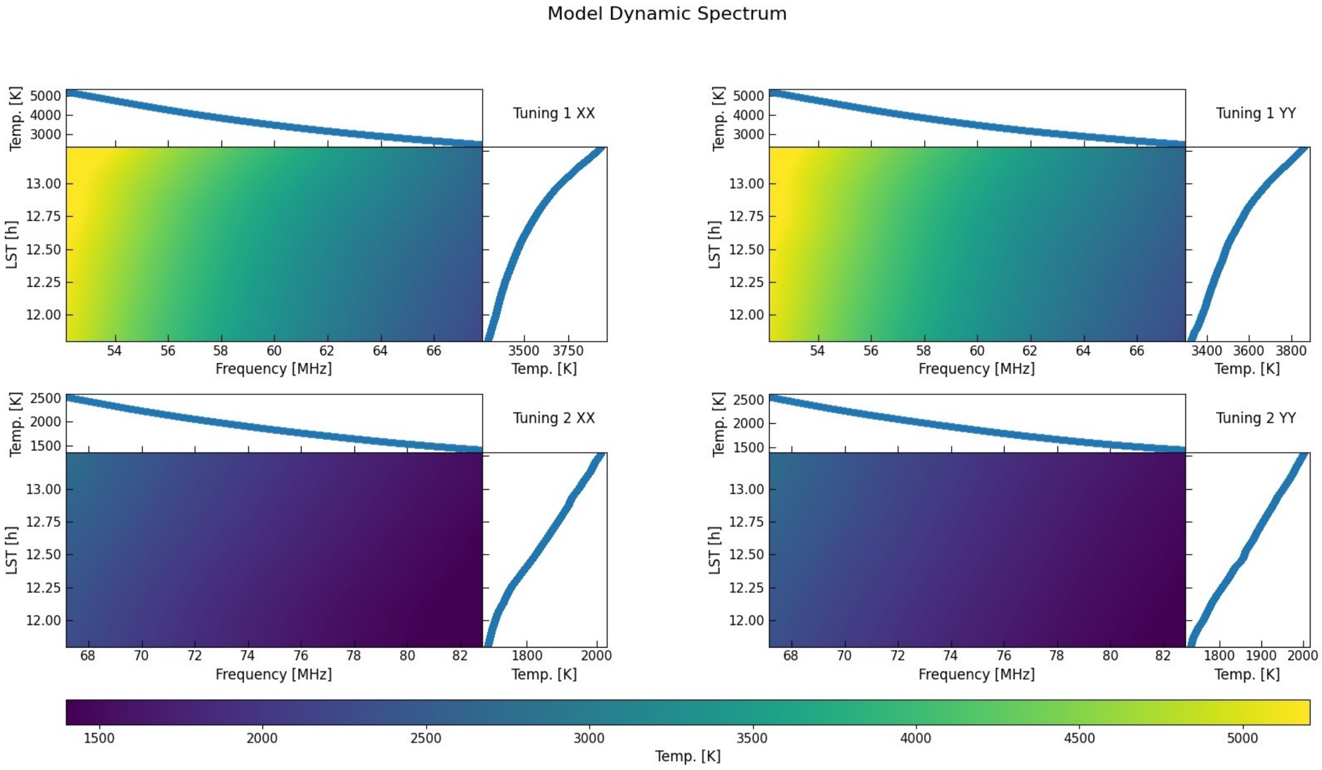


Science Field

Dowell et al. (2017)

Calibration Strategy

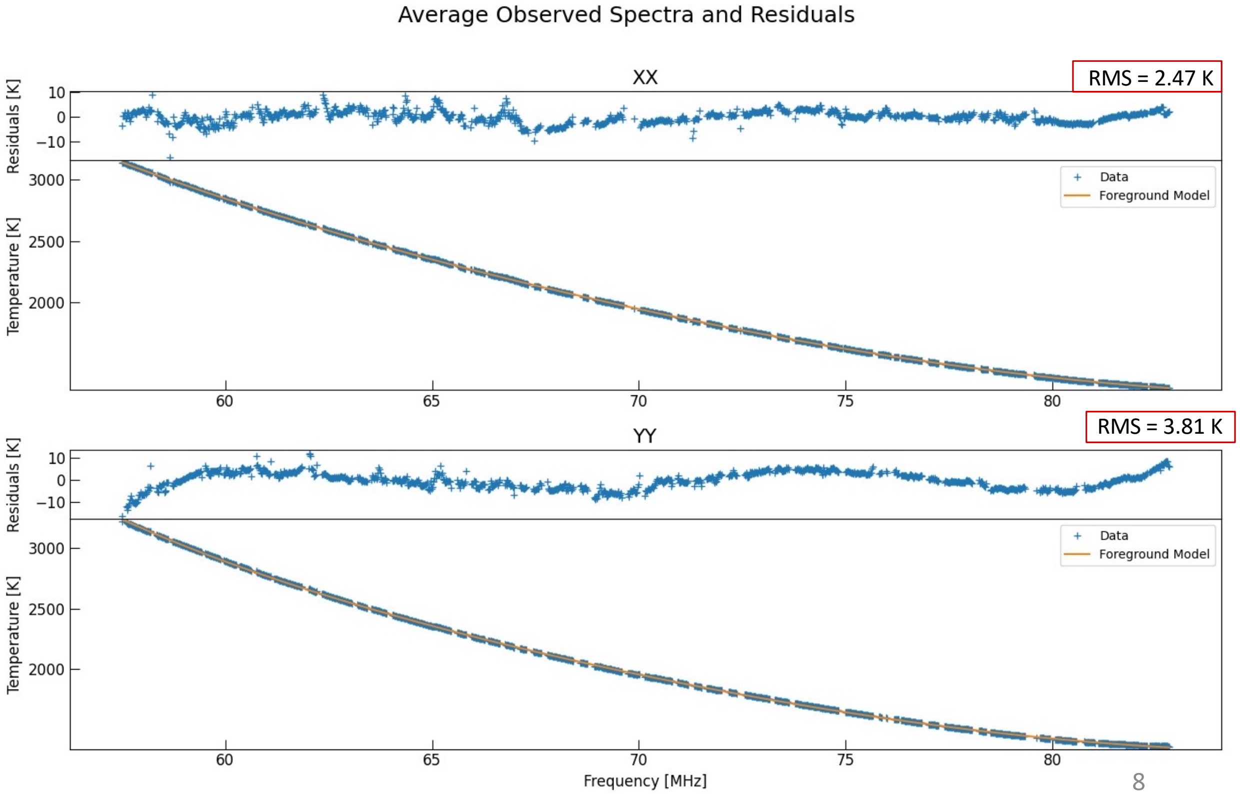
- Simulate the beam pattern across frequency throughout Virgo A observations
- Convolve each simulated beam with the Global Sky Model across frequency to simulate the dynamic spectrum, T(t, ν)
- Set temperature scale by comparing to raw Virgo A data



DiLullo et al. (2021)

2021 Campaign Results

- Bootstrap full data set to pull random samples and compute average spectrum
- Repeat bootstrapping 10,000 times and compute the average spectrum across the 10,000 samples
- Fit a smooth foreground model to data via MCMC methods
- Compute residual RMS
- Also investigate performance of Maximally Smooth Functions (MSF) to model foregrounds



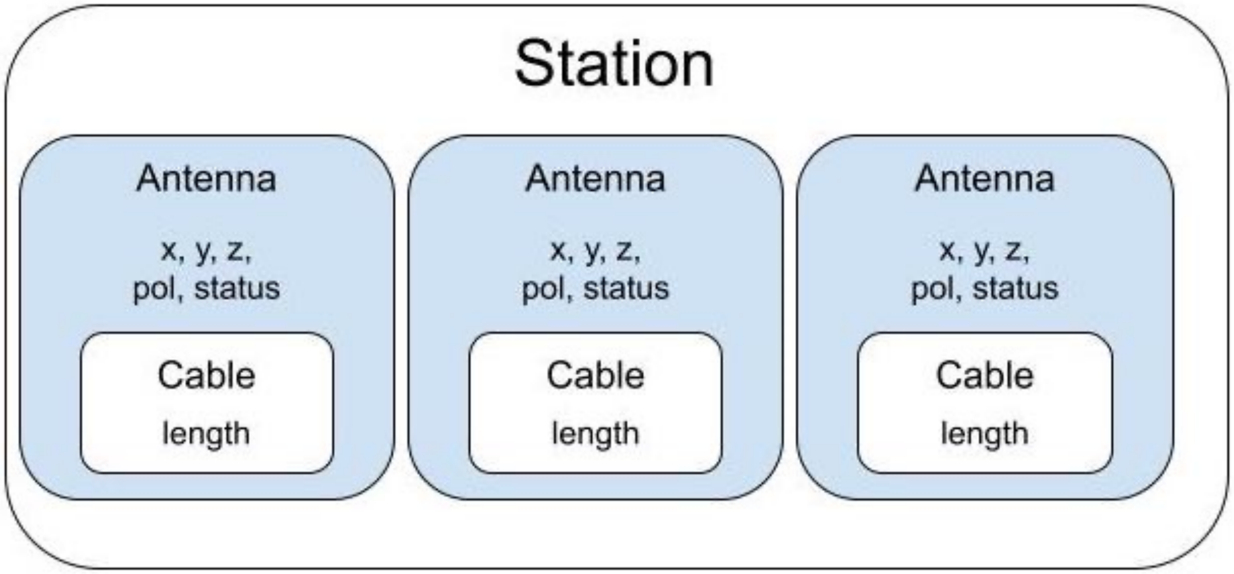
RMS = 2.47 K

RMS = 3.81 K

DiLullo et al. (2021)

Beam Simulator

- Python package to easily model an array beam pattern
- Hierarchical objects for building the entire array
- Utilities for handling NEC models of LWA dipole gain pattern
- Module to represent the sky over a station and easily compute a spectrum or driftcurve



Station

Antenna
x, y, z,
pol, status
Cable
length

Antenna
x, y, z,
pol, status
Cable
length

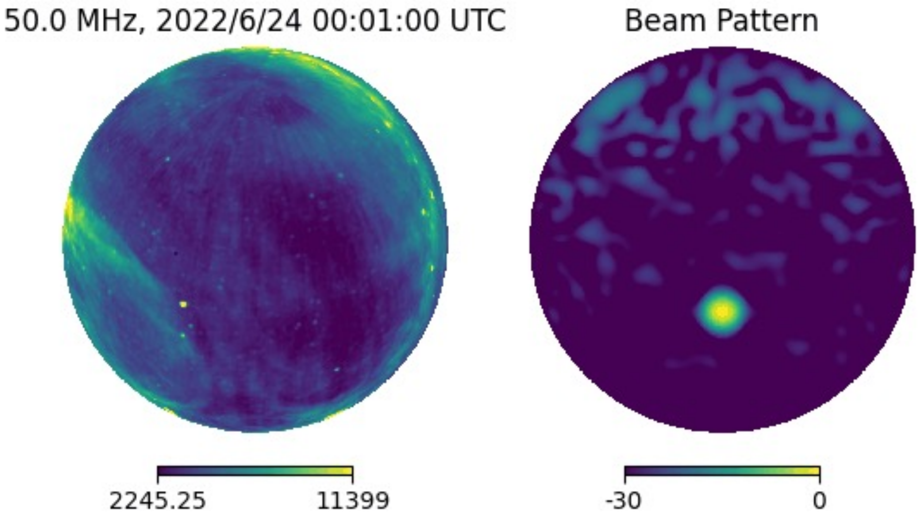
Antenna
x, y, z,
pol, status
Cable
length

https://github.com/cdilullo/beam_simulator

DiLullo et al. 2021, Journal of Astronomical Instrumentation Vol. 10 Is. 4

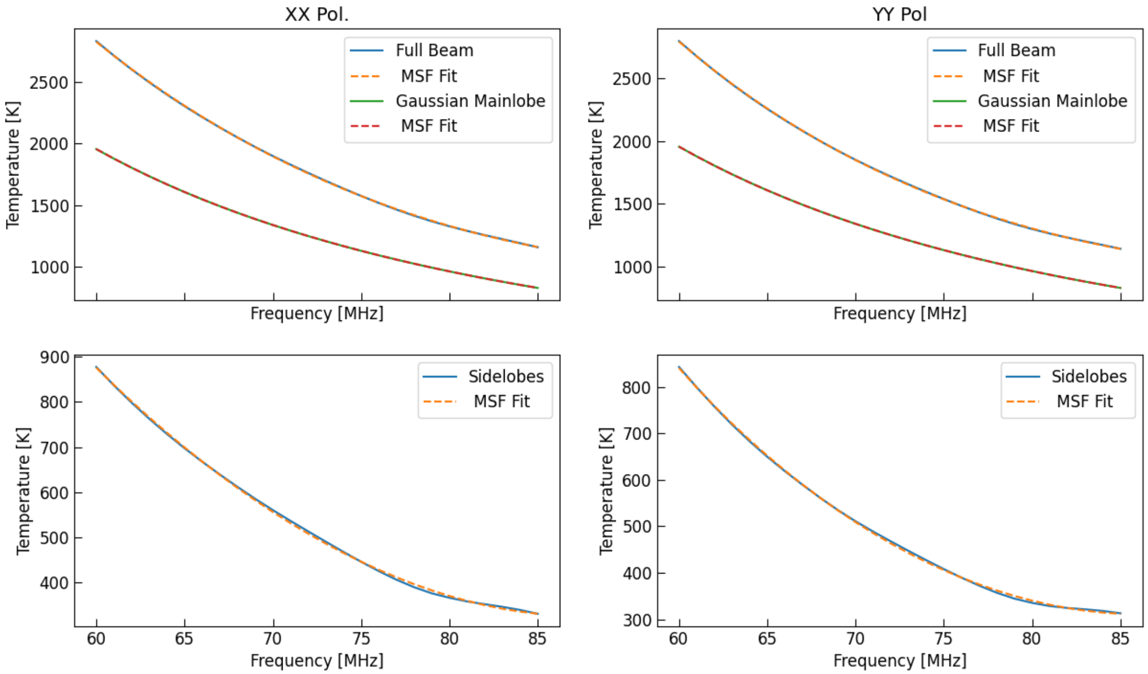
Simulating the Sidelobes of the LWA-SV Beam

- Custom “achromatic” beamforming framework keeps main lobe constant, but sidelobes have lots of structure
- What contribution do the sidelobes have to the measured spectrum/residuals?
- Following methods of Price, D. (2022, PASA, 39, E060)

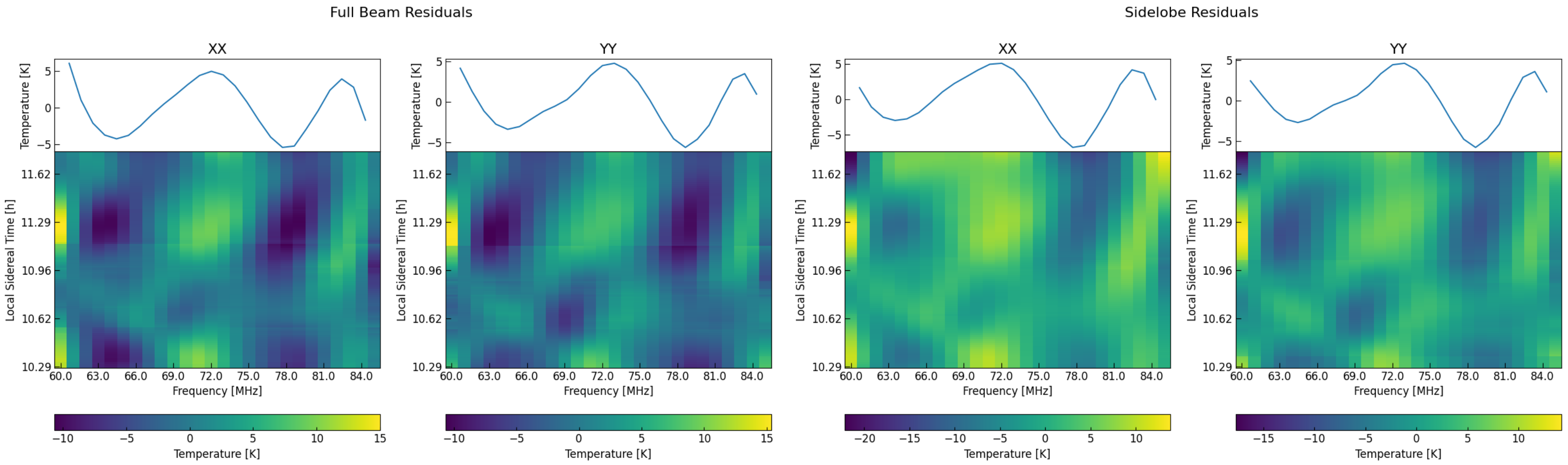


Simulating the Sidelobes of the LWA-SV Beam

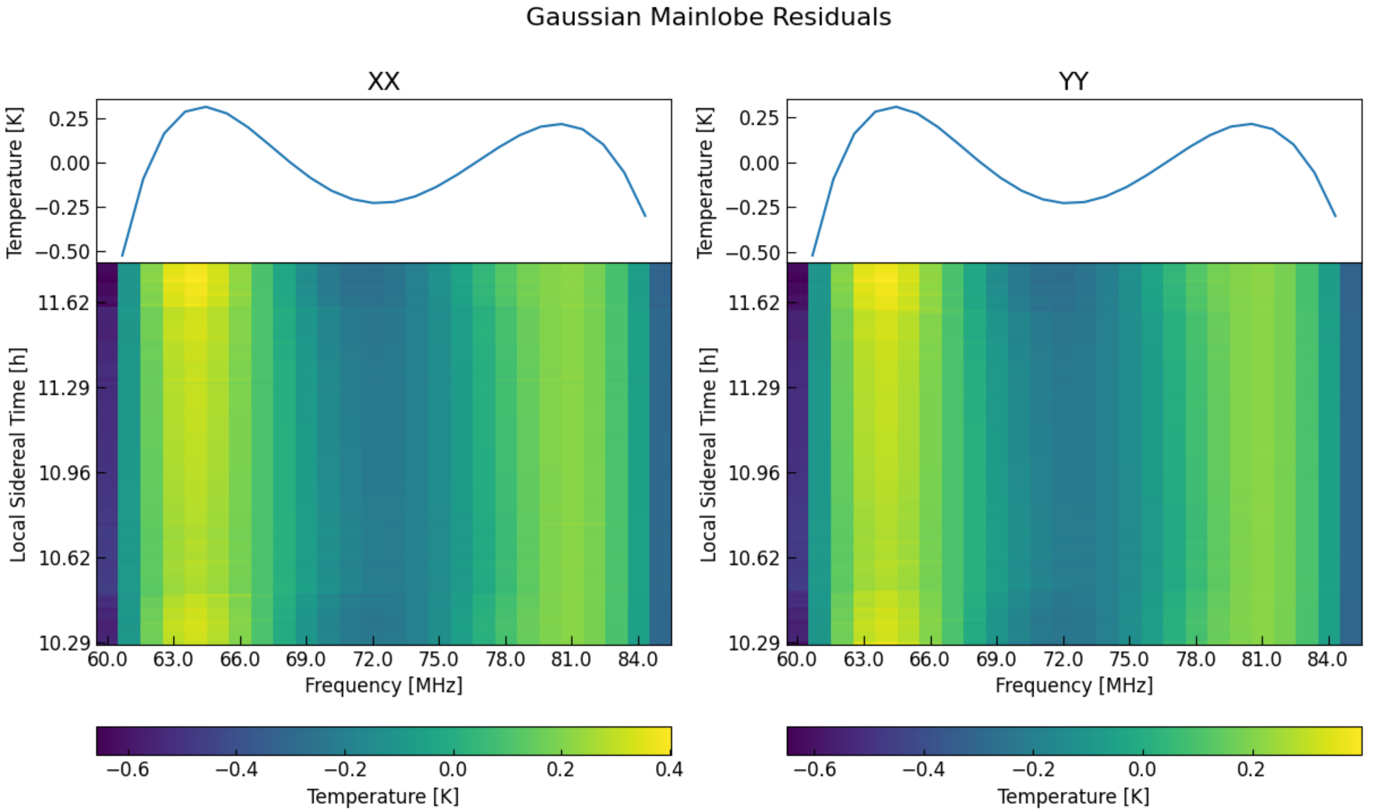
- Simulate beam pattern across frequency for given pointings and LSTs
- Fit 2-D Gaussian to the main lobe
- Multiply each with a sky model to simulate the observed spectrum
- Difference yields approximate sidelobe contributions
- Fit a N=5 MSF to the sidelobe contributions to estimate contribution to residuals after foreground subtraction



Full Beam vs Sidelobe Residuals

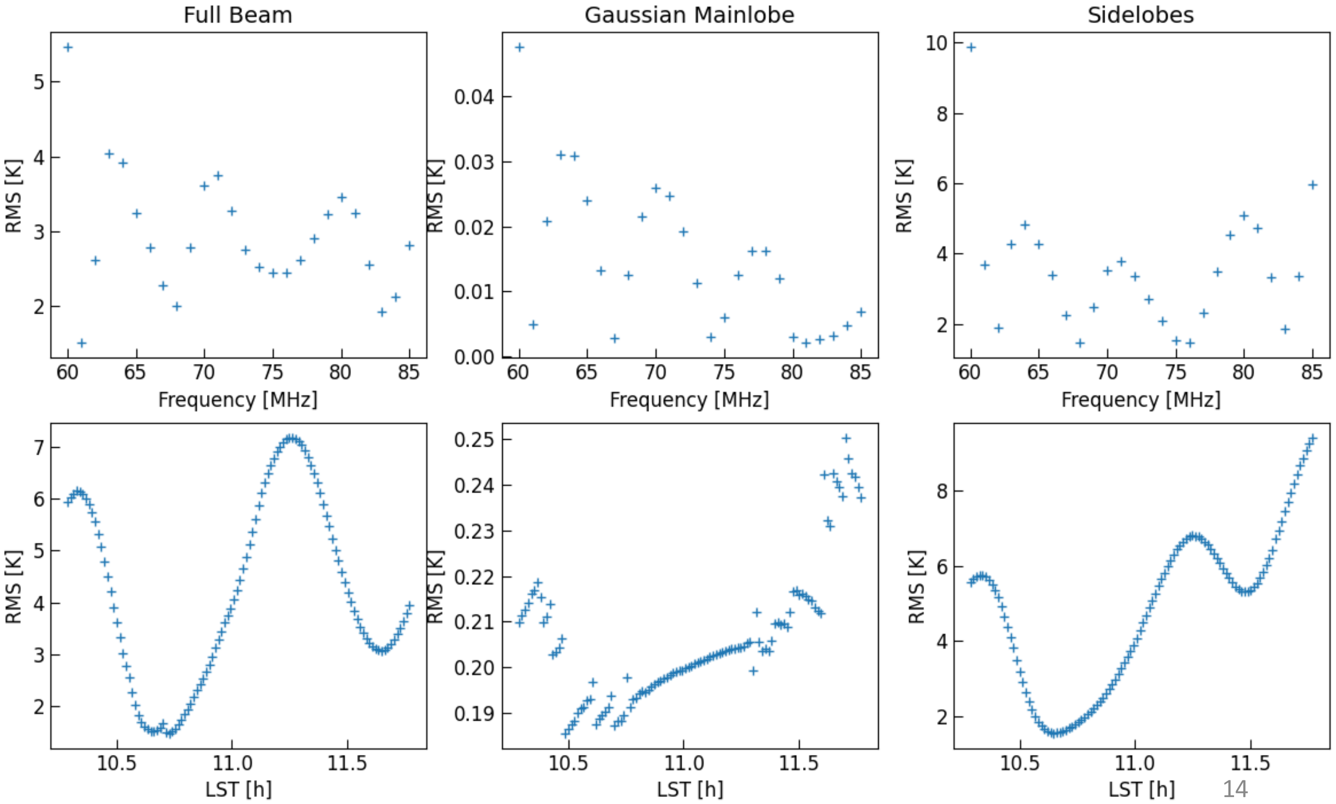


Gaussian Mainlobe Residuals

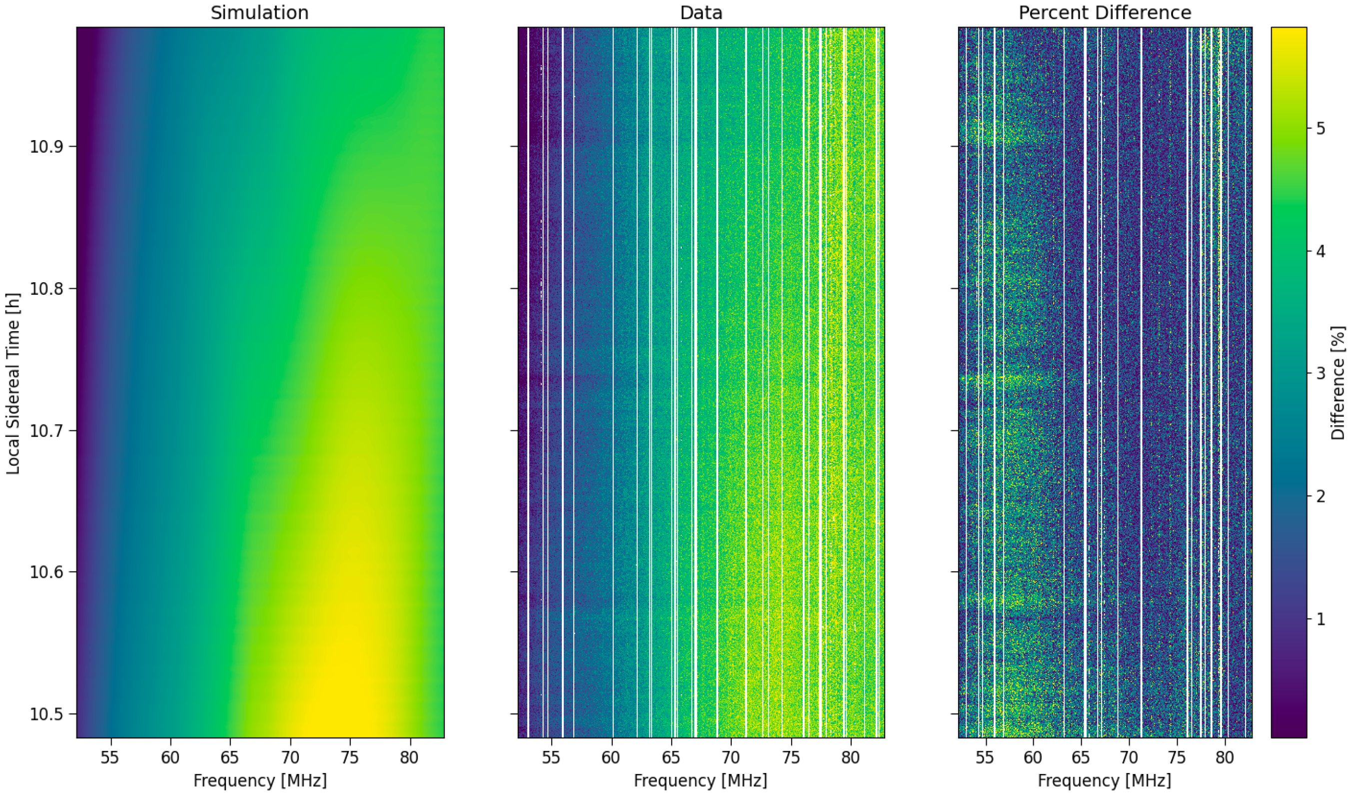


Residual RMS

- Compute the RMS across frequency and time for each of the residuals
- Obvious drifts in RMS across LST
    - Limiting the data LST range may yield better results?
- Gaussian main lobe has RMS on the order we want



Comparing the Ratio of Beams



Future Work

- How does the ionosphere affect calibration?
  - Scintillation obvious in calibrated data
  - Beginning to think about modeling its effects
  - Orville Wideband Imager should help
- Can we do better in terms of custom beamforming?
  - Probably yes, but it’s a challenging optimization problem

Summary

- LWA offers novel advantages (and challenges) to detect the global 21 cm signature
- Current RMS limits are ≈3 K, want 50 mK
- Simulations suggest we are dominated by the sidelobe response
  - Need better characterization of the beam
  - Perhaps beam optimization is a path forward? → Challenging

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More information: DiLullo et al. (2020), *Journal of Astronomical Instrumentation* Vol. 9 No. 2
DiLullo et al. (2021), *Journal of Astronomical Instrumentation* Vol. 10 No. 4