Improvements to the Search for Cosmic Dawn Using LWA-SV

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Christopher DiLullo

THE UNIVERSITY OF NEW MEXICO

LWA Long Wavelength Array

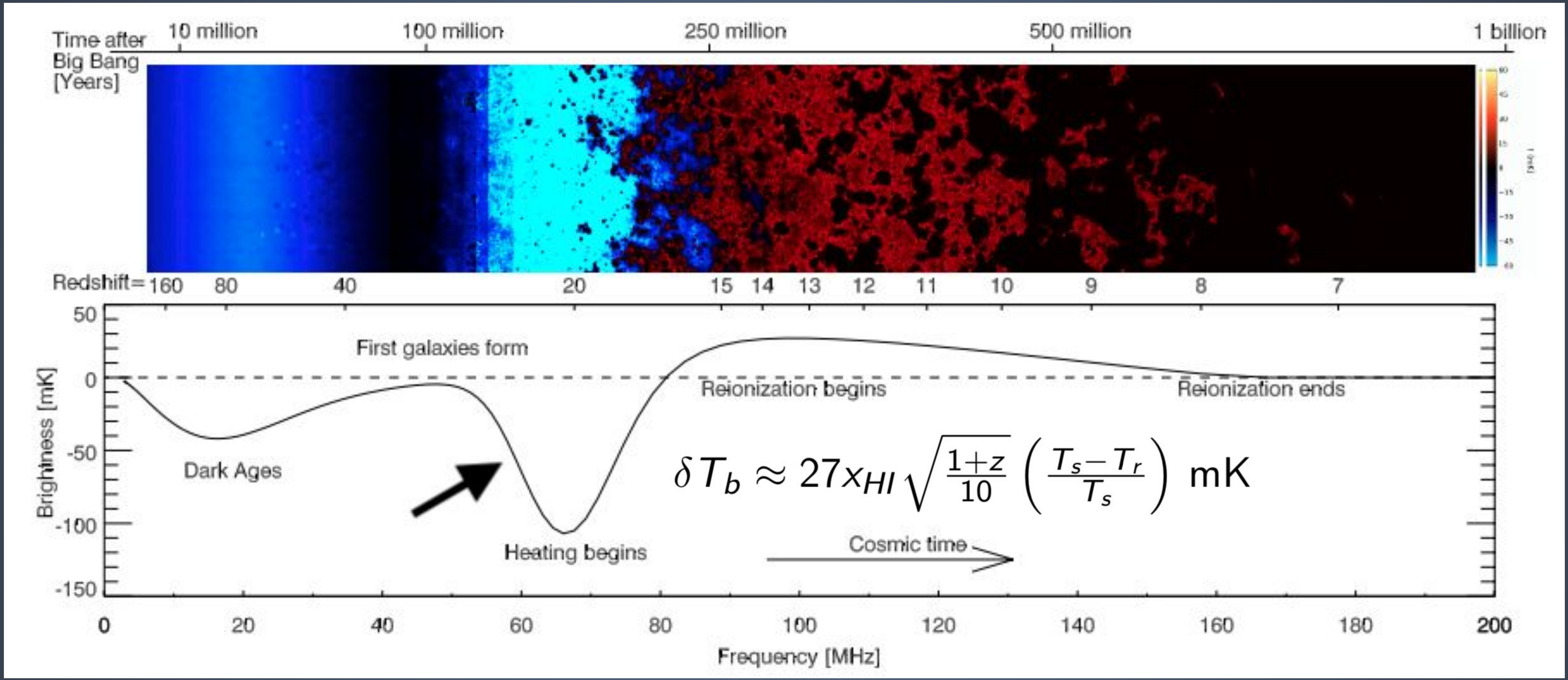
NSF

Image Credit: NASA/STScI

Outline

- Introduction
- Achromatic Beamforming Implementation at LWA-SV
- Results from Spring 2021 Observing Campaign
- Future Work

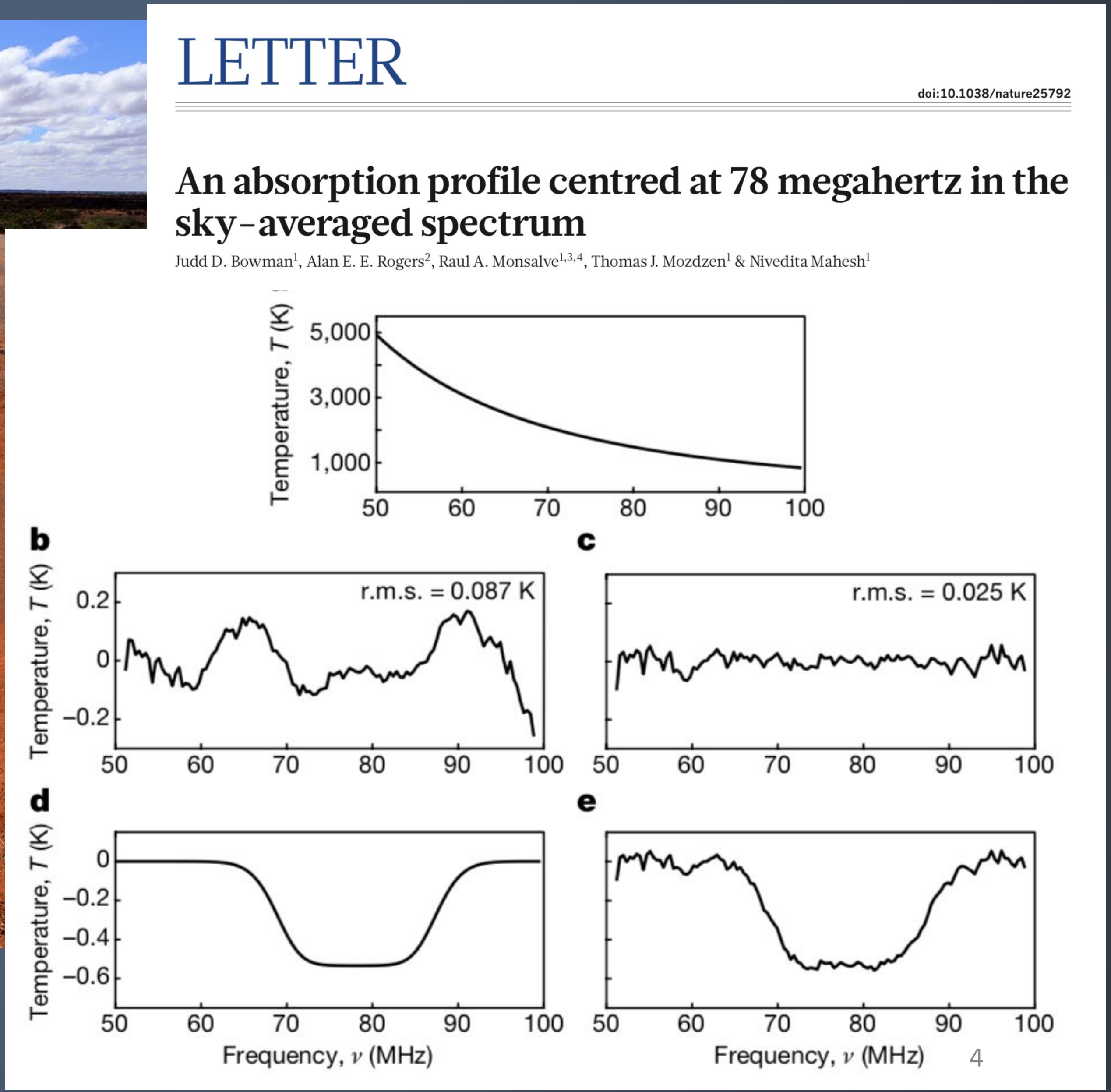
21 cm Cosmology



Pritchard & Loeb (2012)

A Possible Detection! – Bowman et al. 2018

Image Credit: Experiment to Detect the Global EoR Signature (EDGES) Collaboration



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]

2020 LWA Users Meeting Results

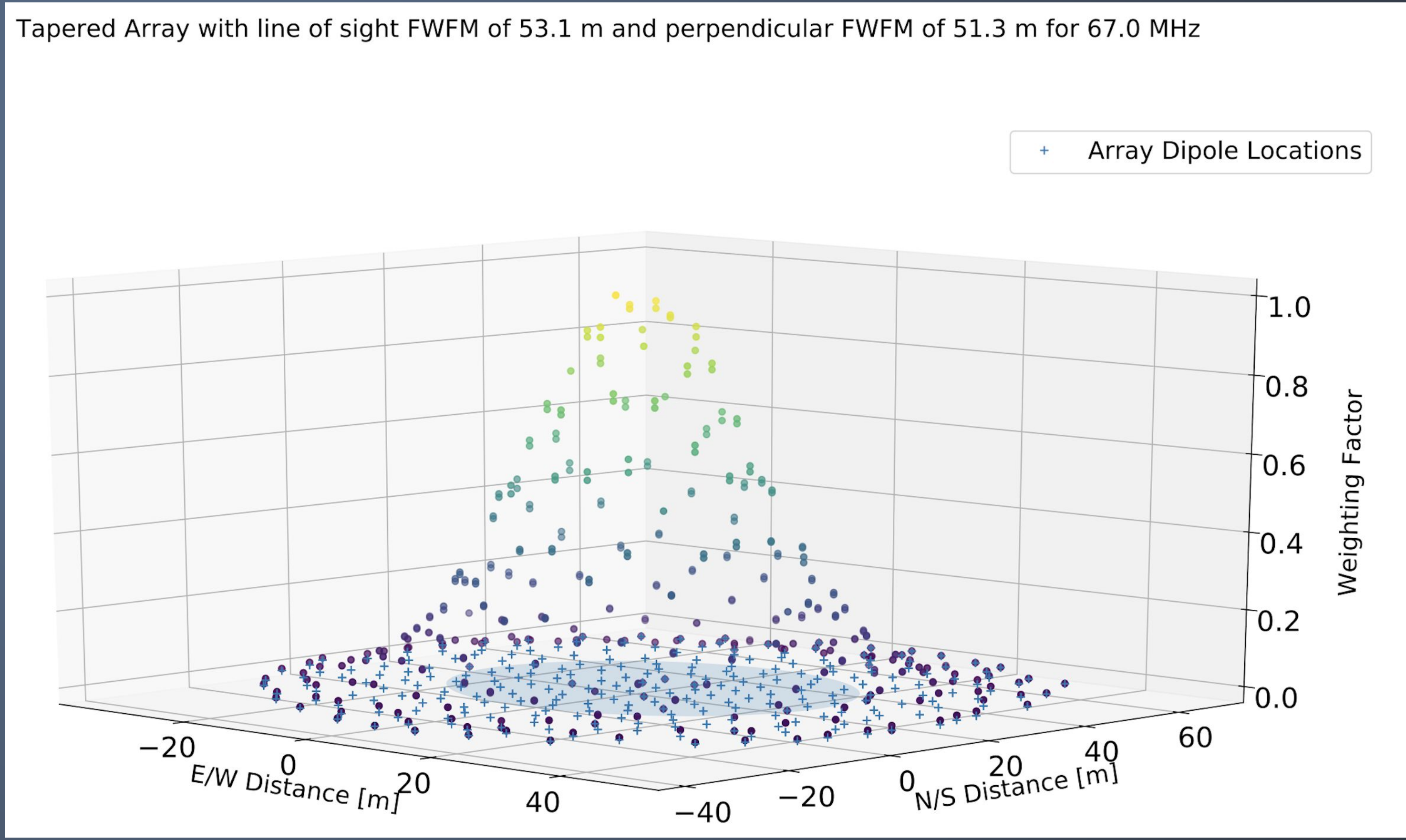
- Simultaneous Observations of Science Field and Virgo A
- Calibration using Virgo A *at transit*
- 2 foreground models fit: Power Law and Smooth Polynomial
- ~10 K residual RMS after 2 minute integration
- Achromatic beamforming was beginning to be developed

An Idea for Improvement: Custom Beam Forming

- Sets the size/shape of the beam
  - Make the beam achromatic
- $Y(\theta, \phi) = R(\theta, \phi) \times (\mathbf{W} \cdot \mathbf{V}(\mathbf{k}))$
  - R – antenna gain pattern
  - **W** – weighting vector
  - **V** – steering vector

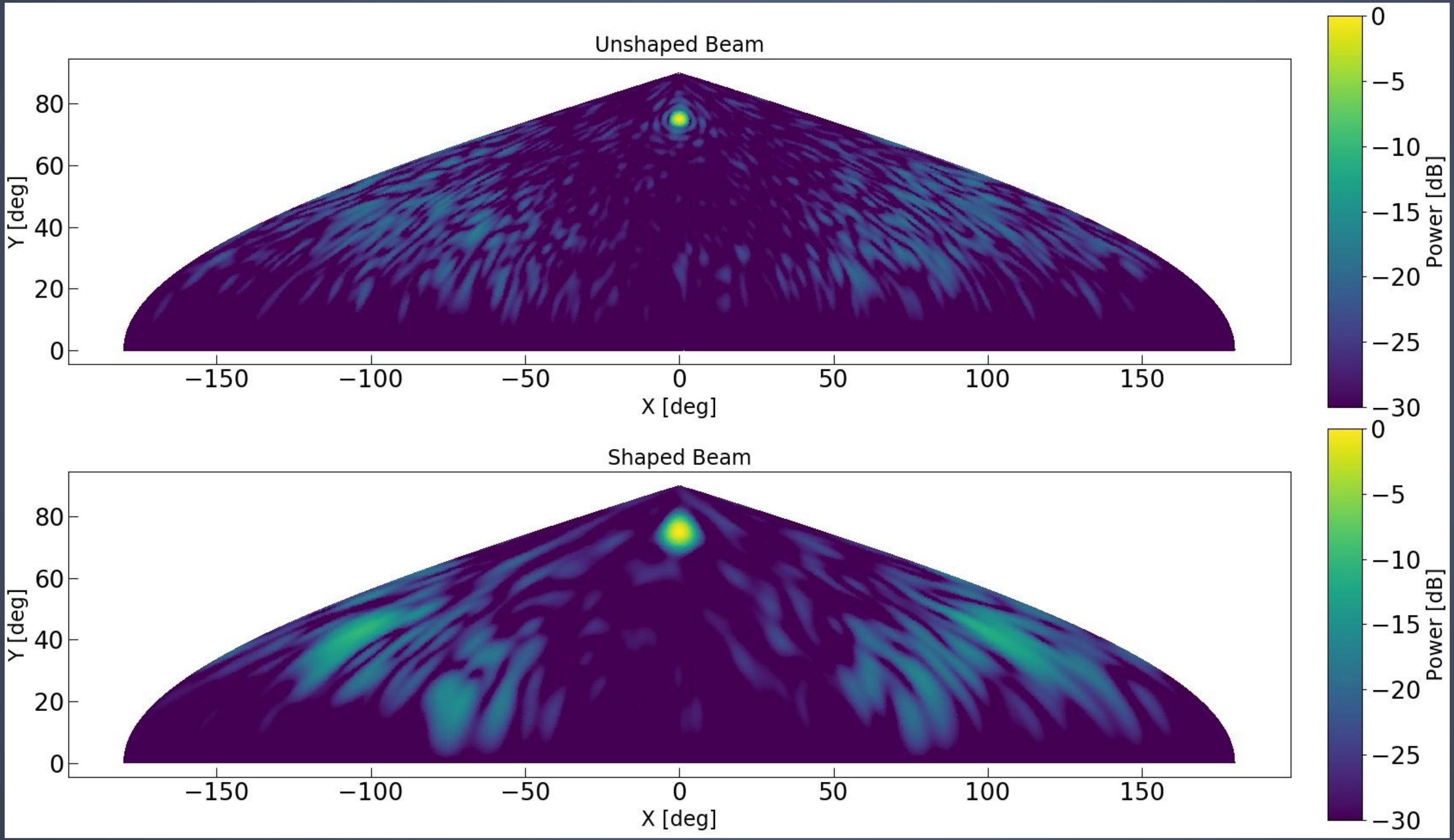
$$R(\theta, \phi) \sum_{j=1}^{N} w_j \cdot e^{-2\pi i \nu r_j / c}$$

- DFT of weighting vector!



DiLullo, Taylor, & Dowell (2020) *Journal of Astronomical Instrumentation* Vol. 9 No. 2

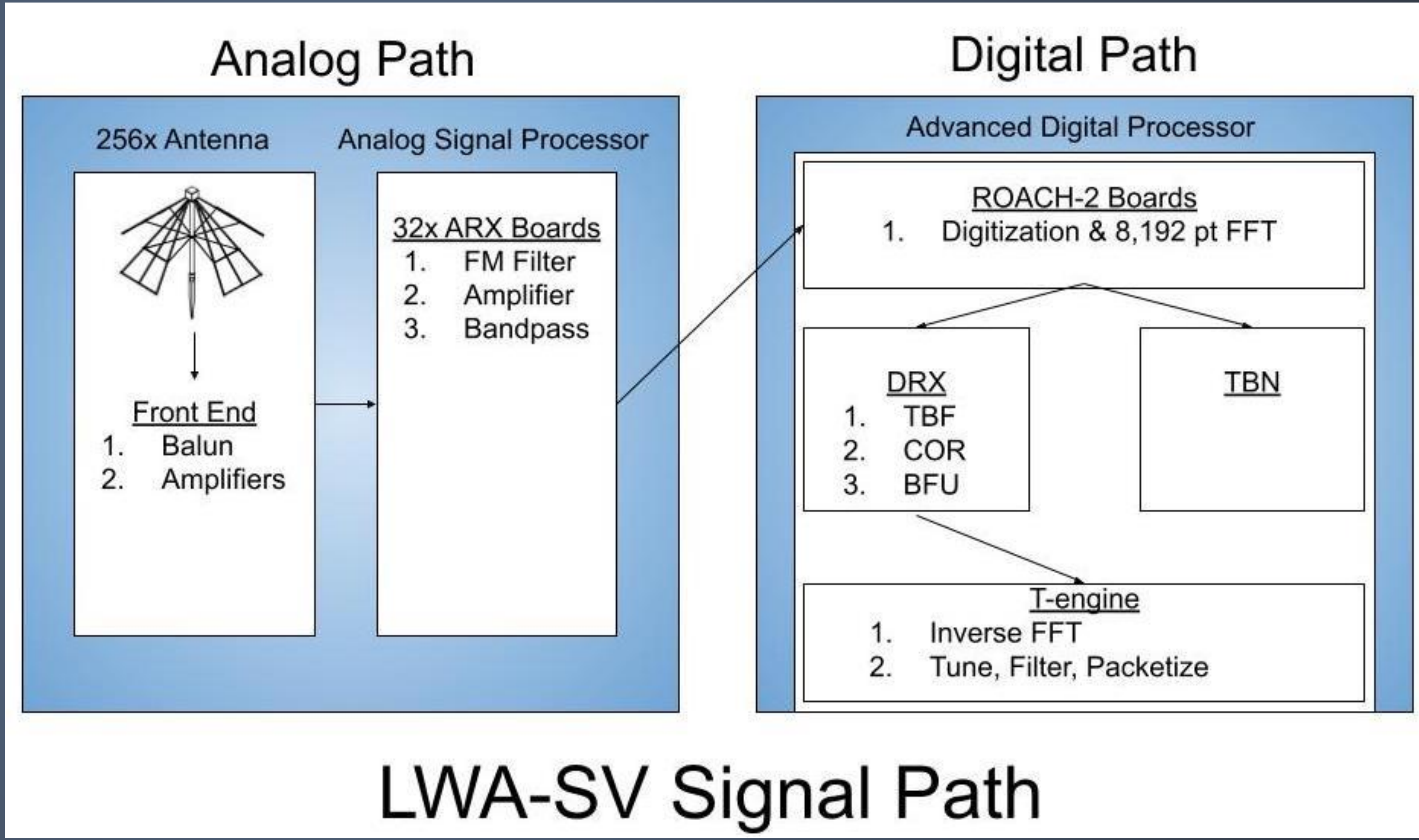
Custom Beam Forming



DiLullo, Taylor, & Dowell (2020) *Journal of Astronomical Instrumentation* Vol. 9 No. 2

Achromatic Beamforming Implementation at LWA-SV

- BF coefficients normally come from MCS
- Modified DRX pipelines
  - Precompute BF coefficients for each frequency/pointing
  - “Trigger code” in Beam Step gains



Achromatic Basket Weaves

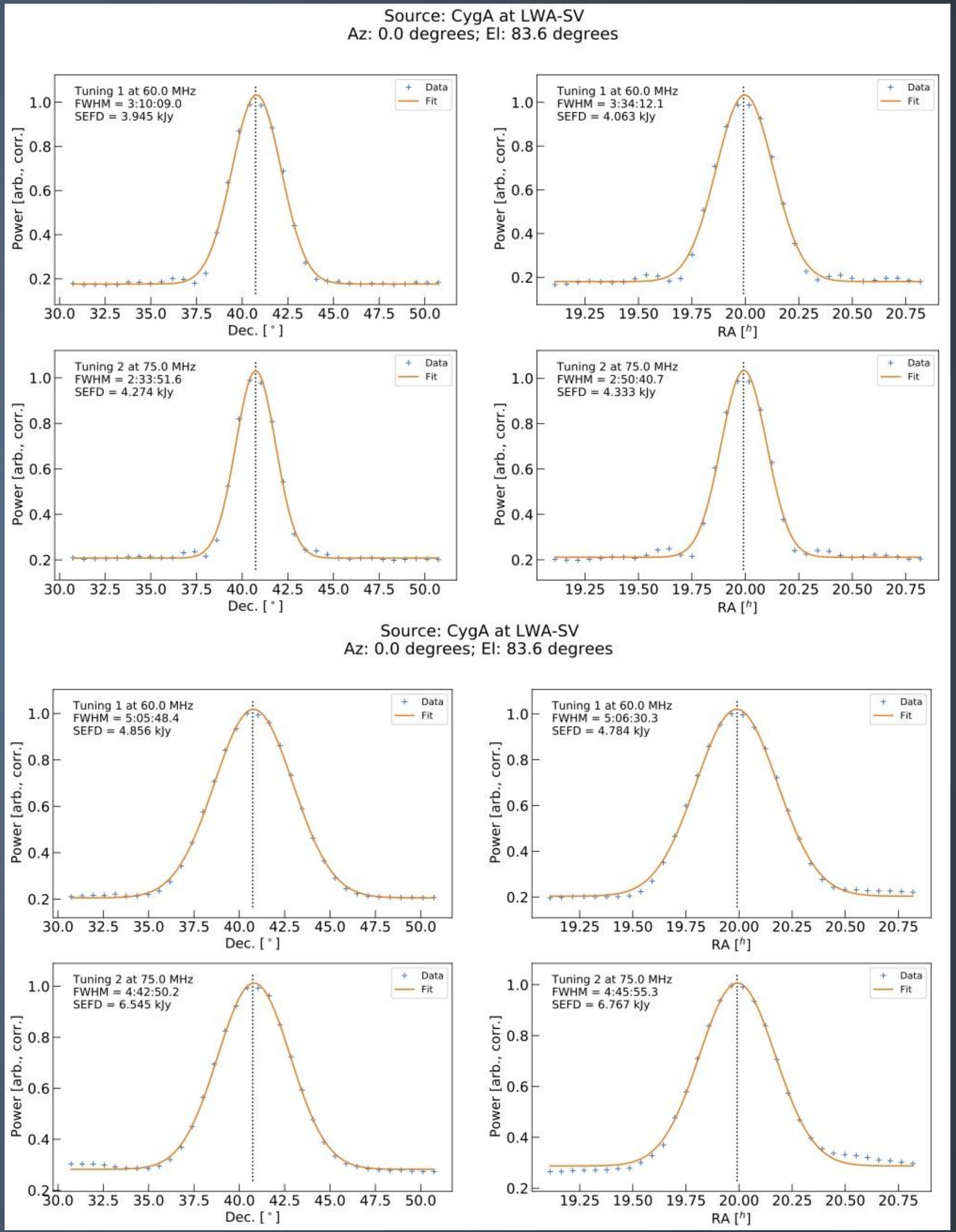
- Observe Cygnus A using "basket weave" pointings
- Probes different regions of the beam pattern in both RA and Dec directions
- Estimate station SEFD using:

$$SEFD = \frac{S_\nu}{\frac{P_{on}}{P_{off}} - 1},$$

Table 1: Beam-Dipole Mode Basket Weave Results

Frequency	Standard Beamforming	Achromatic Beamforming
60 MHz	SEFD: 4.0 kJy FWHM: 3°22′10.6″	SEFD: 4.8 kJy FWHM: 5°06′09.3″
75 MHz	SEFD: 4.3 kJy FWHM: 2°42′16.1″	SEFD: 6.7 kJy FWHM: 4°44′22.7″

DiLullo, Taylor, & Dowell (2021), JAI, in review



Spring 2021 Observing Campaign

DiLullo, Taylor, & Dowell (2021), JAI, in review

Observational Setup

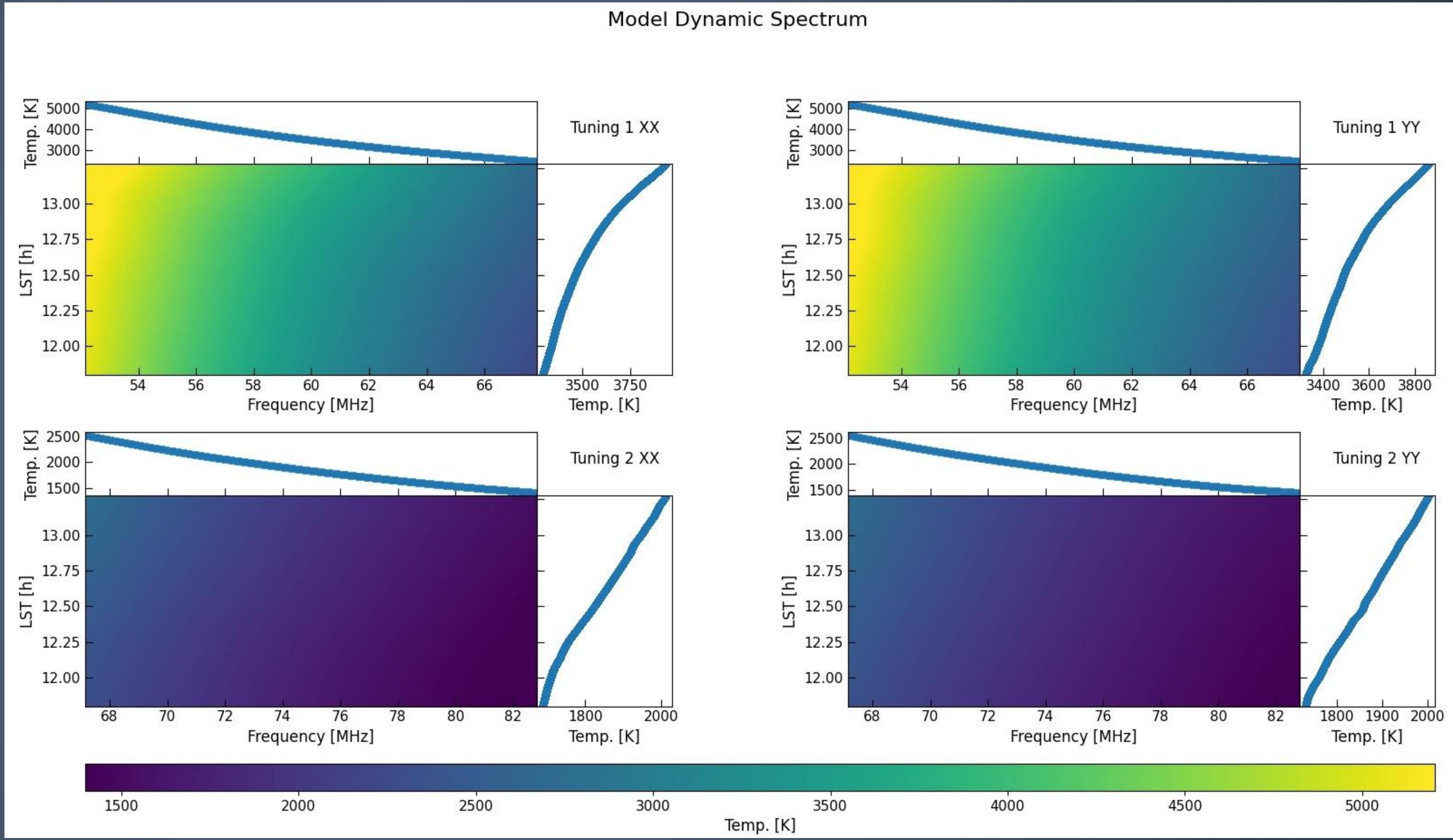
- 2 beams with 19.6 MHz bandwidth per tuning.
    - Now have continuous coverage from 52 - 83 MHz.
- New observing strategy:
    - Stepped Beam observing mode.
    - New Science Field center pointing, same large cold region on the sky.
    - No longer simultaneously observe the SF and Virgo A.
- March 10th - April 10th, 2021 using achromatic beamforming

Method

- Model waterfalls for calibration.
- Bootstrapping algorithm to generate “typical” spectrum.
- Bayesian framework to do MCMC foreground modelling.

Model Dynamic Spectra

- Simulate beam pattern at every n^{th} pointing and m^{th} frequency
- Convolve each pattern with GSM at 7.5 s resolution for duration of pointing
- 2-D linear interpolation in time and frequency



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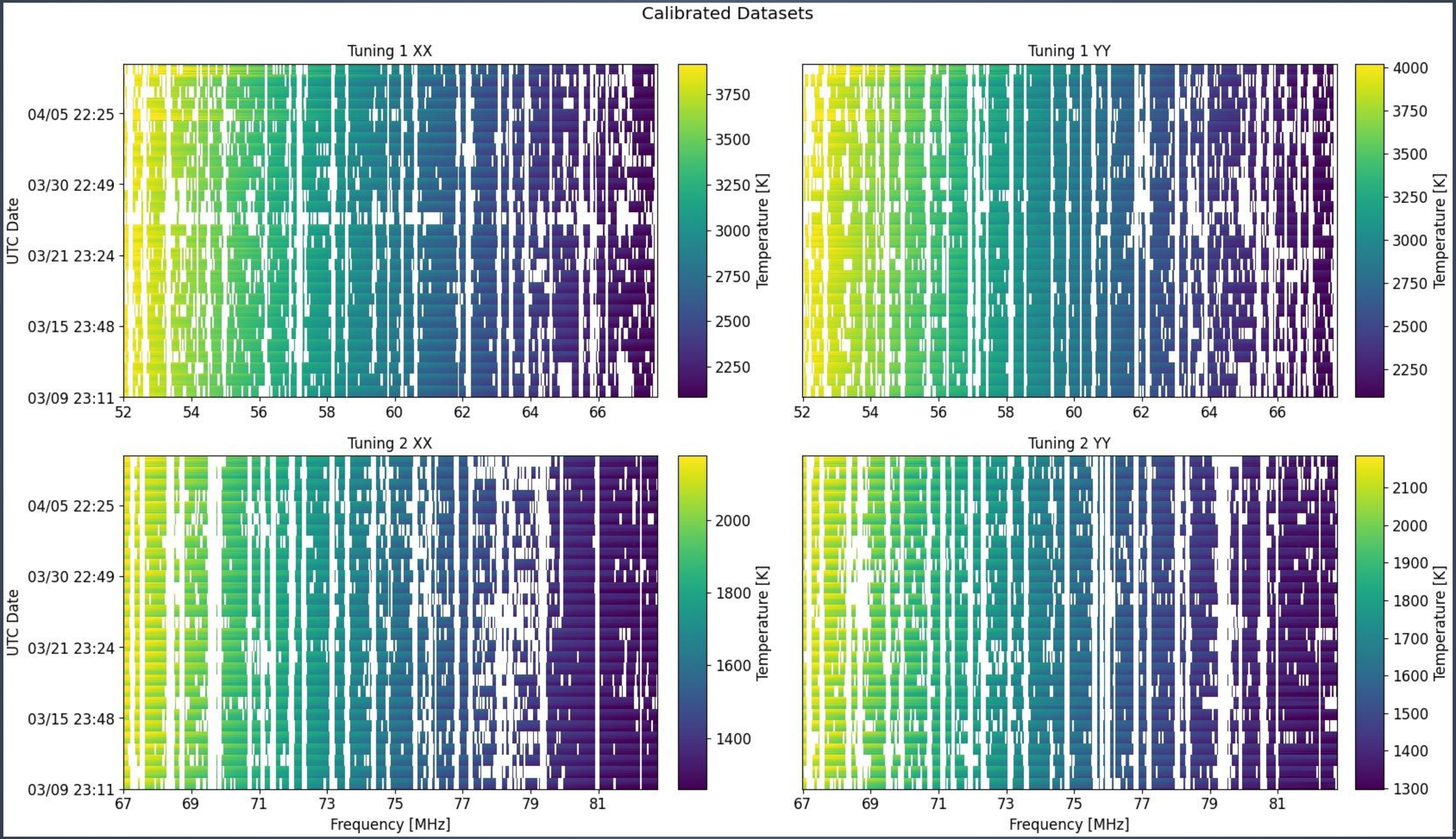
Calibrated Dynamic Spectra



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Foreground Modelling: Bayesian Framework

- Bernardi et al 2016
- Likelihood of measuring some T for a single ν

$$\mathcal{L}_j\left(T_{\mathrm{ant}}(\nu_j)|\mathbf{\Theta}\right) = \frac{1}{\sqrt{2\pi\sigma^2(\nu_j)}}\mathrm{e}^{-\frac{[T_{\mathrm{ant}}(\nu_j) - T_m(\nu_j,\mathbf{\Theta})]^2}{2\sigma^2(\nu_j)}}$$

where

$$\sigma(\nu_j) = \frac{T_{\mathrm{ant}}(\nu_j)}{\sqrt{\Delta\nu\Delta t}},$$

- Likelihood for the full spectrum

$$\ln\mathcal{L}\left(\mathbf{T}_{\mathrm{ant}}|\mathbf{\Theta}\right) = \sum_{j=1}^{M}\ln\mathcal{L}_j\left(T_{\mathrm{ant}}(\nu_j)|\mathbf{\Theta}\right)$$

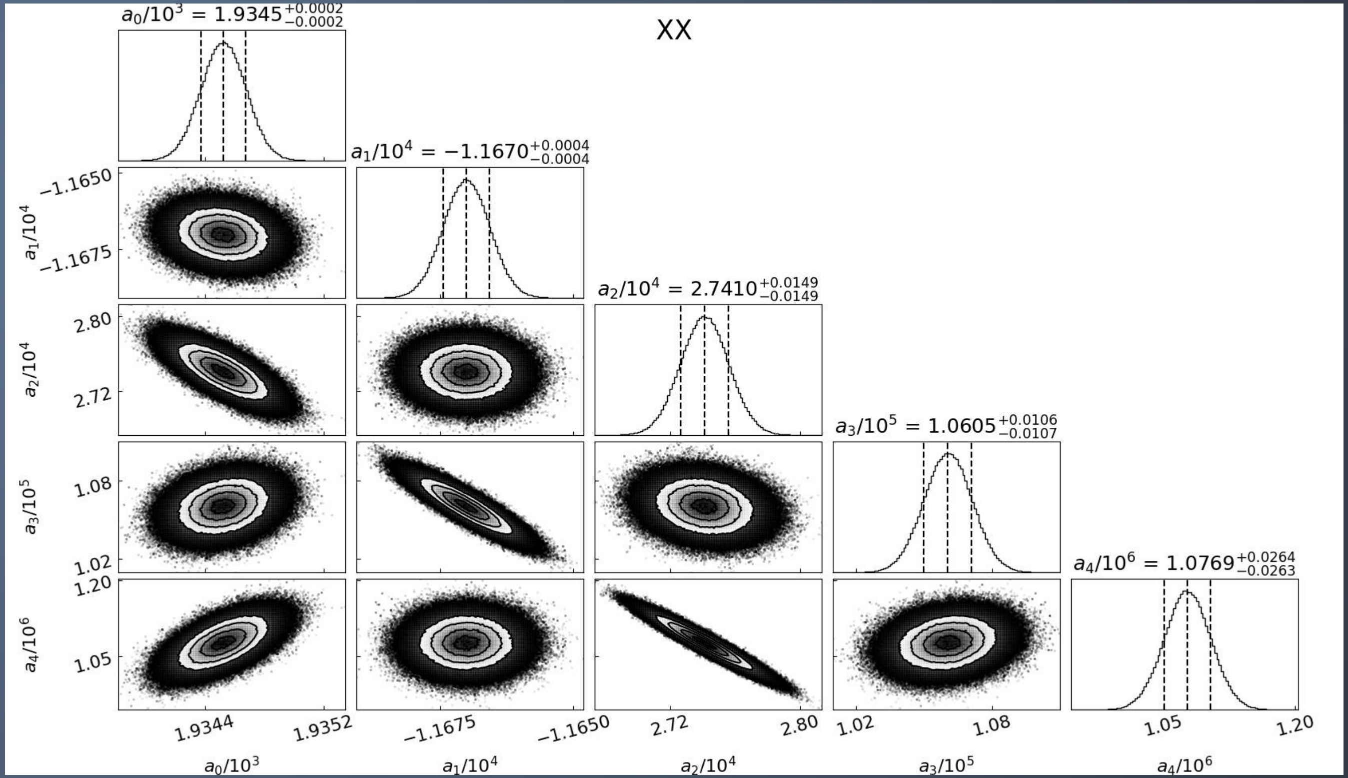
- Model temperature spectrum

$$T_m(\nu_j) = T_f(\nu_j) + T_{\mathrm{HI}}(\nu_j).$$

- Uninformative prior, $\{p_n \in \mathbb{R}\}$

Foreground Modelling

- Log Polynomial used: $$T_f(\nu_i) = \sum_{n=0}^{N} p_n \left[\log_{10}\left(\frac{\nu_i}{\nu_0}\right)\right]^n$$
- Two modelling methods
  - MCMC fitting via *emcee*
  - Maximally Smooth Functions
    - $$\frac{d^m y}{dx^m} \geq 0 \text{ or } \frac{d^m y}{dx^m} \leq 0,$$ (m ≥ 2)



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Results

MSF

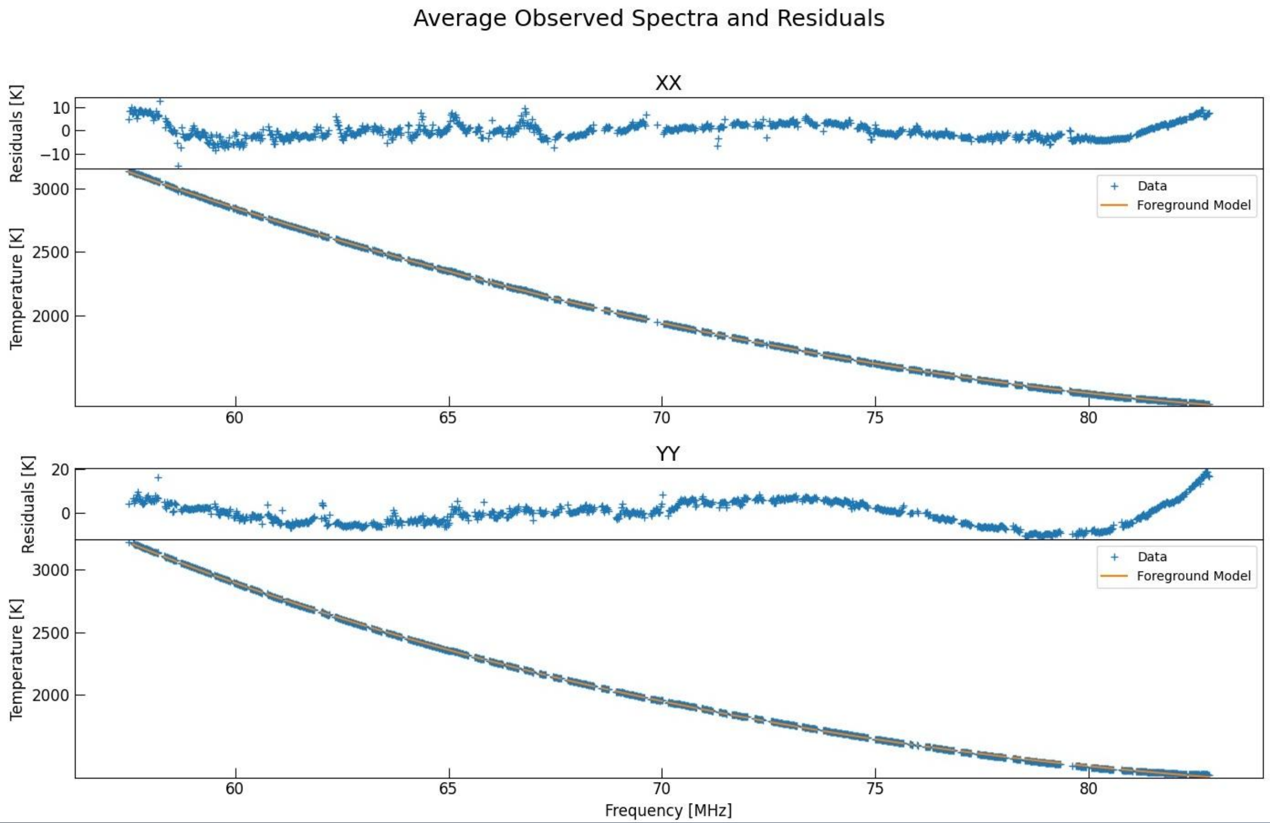
XX: 3.29 K

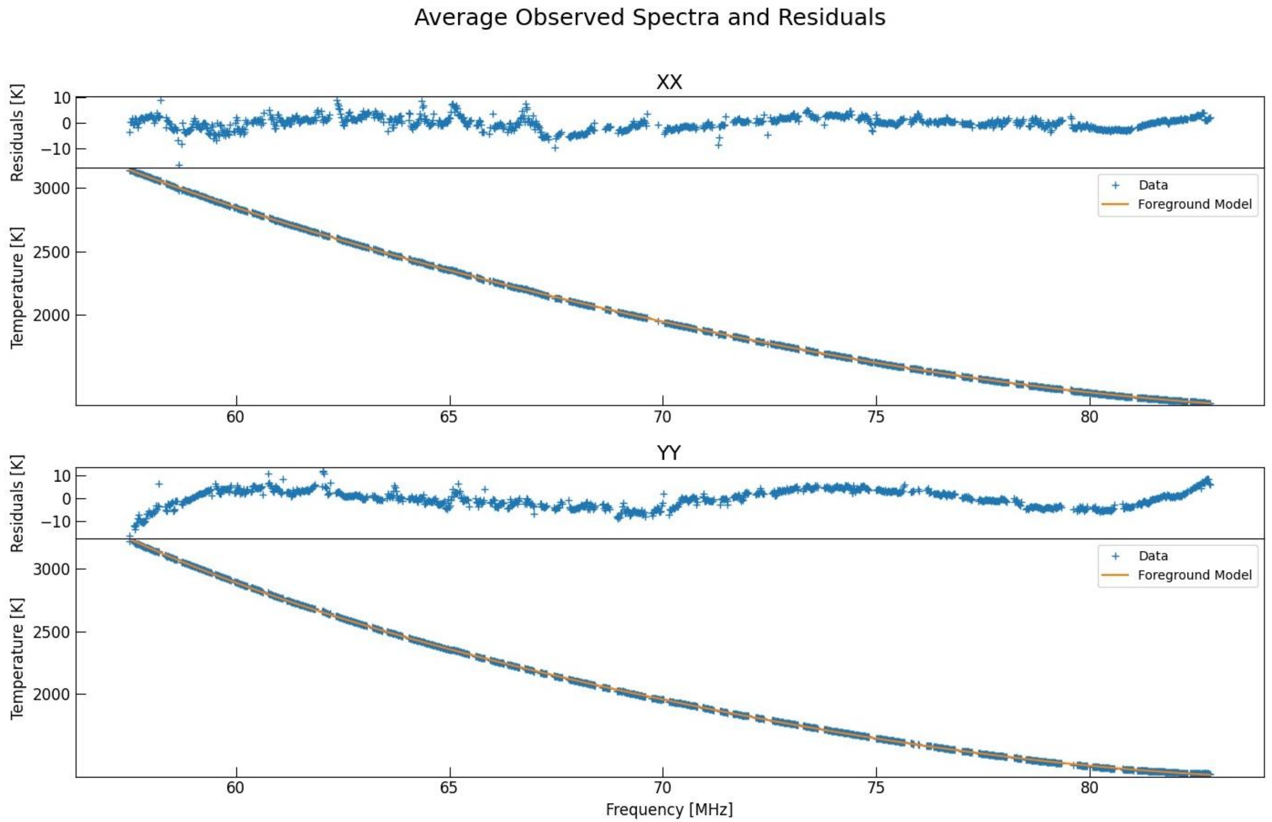
YY: 5.26 K

MCMC

XX: 2.47 K

YY: 3.81 K





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Future Work

- Robust flagging algorithm for low-level RFI
  - Machine learning?
- Better understanding of the LWA dipole gain pattern
  - ECHO collaboration
- Alternative achromatic beamforming frameworks?
  - Detune beam via phase modulation?
- Explore other sky models for calibration
  - GSM 2016, SSM, GMOSS, LFSM?

Summary

- Current residual RMS limits are $\sim$ 3 K, want $\sim$ 50 mK
- Future efforts must focus on constraining uncertainties in the LWA beam pattern (dipole gain pattern, mutual coupling effects, etc) and calibration
- Work will be continued at NASA's Goddard Space Flight Center