SARAS: EVOLUTION OF SYSTEM DESIGN AND RELATED CHALLENGES

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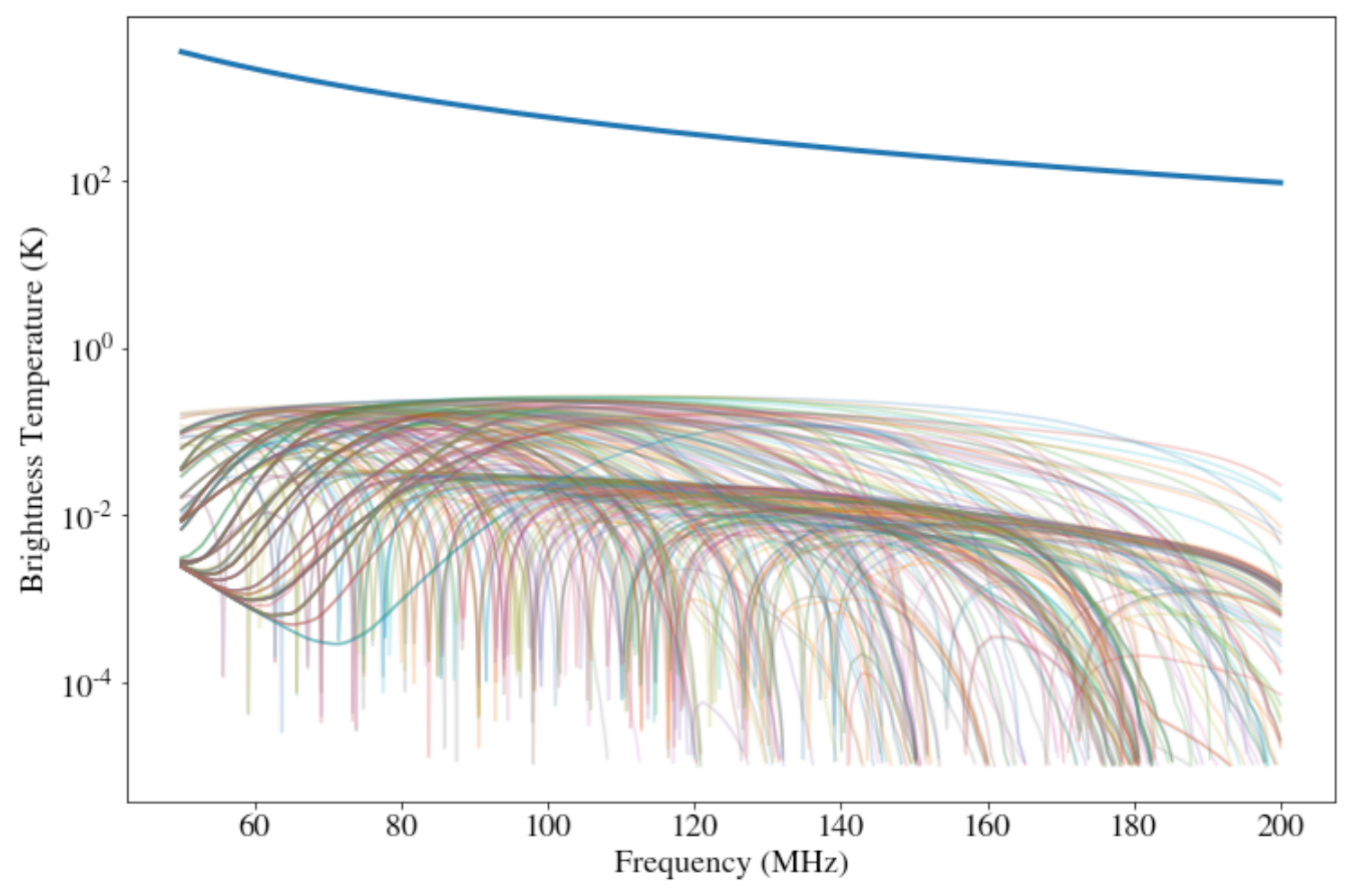
CHALLENGES

- Sensitivity is not a big concern!
- Thermal noise levels at 80 MHz, for 1 MHz channel bandwidth and 10 hours of integration ~ 10 mK per frequency channel
- Systematics are far bigger challenges



Preserving the spectral smoothness of the foreground is the key!

Can spatial information be exploited?

CHALLENGES IN MODELING THE INSTRUMENT RESPONSE

- Antenna beam
- Antenna transfer function

} Often not calibratable
Needs to be
modeled externally

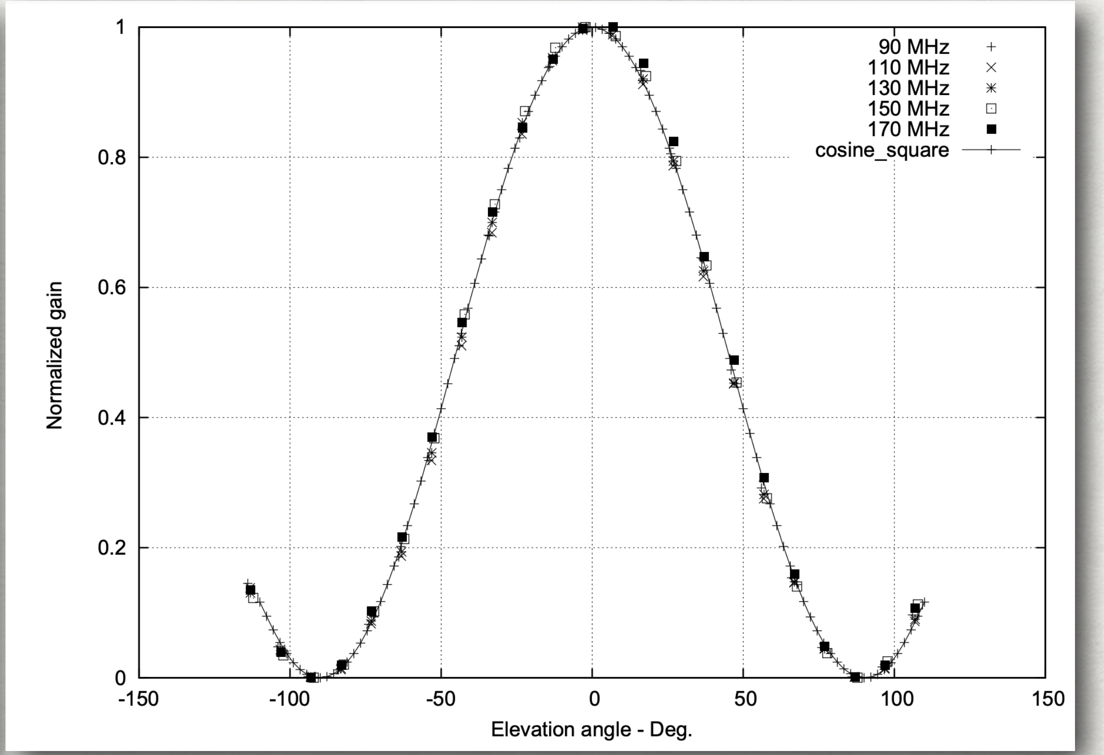
- Bandpass transfer function (analog + digital chain) → Mostly corrected with noise source injection

- Additives from amplifiers + ground coupling → Often not calibratable
Needs to be
modeled externally

All these characteristics are frequency and (more or less) time/temperature dependent

SARAS 1

- SARAS carried out first round of observations in 2012-2013
- It employed a fat-dipole antenna over absorber tiles



Return loss better than 15 dB across the band

Image Courtesy:
Patra et al. 2012, Raghunathan et al. 2012

SARAS 1 RECEIVER

- SARAS 1 and 2 have similar analog receiver architecture and calibration schemes

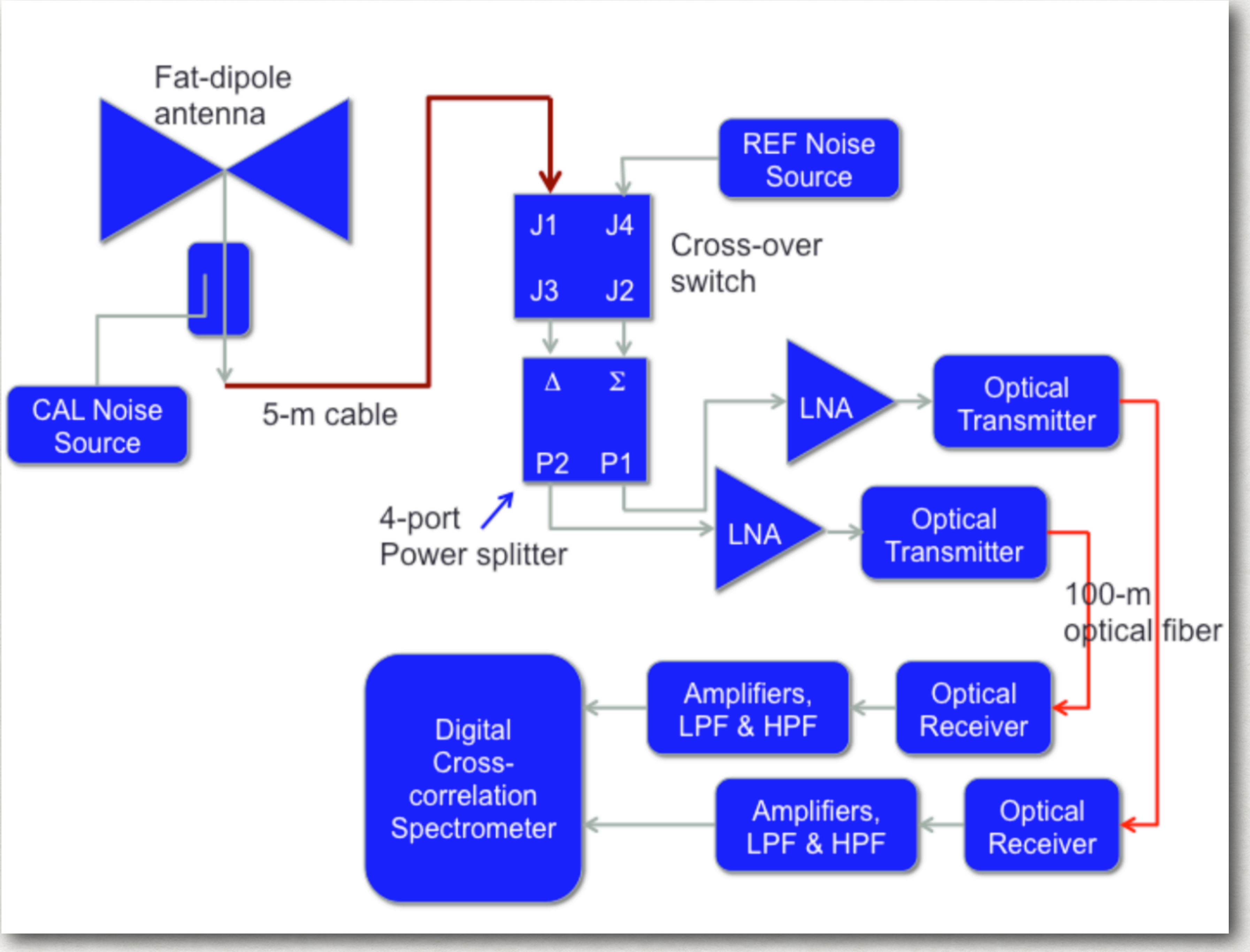


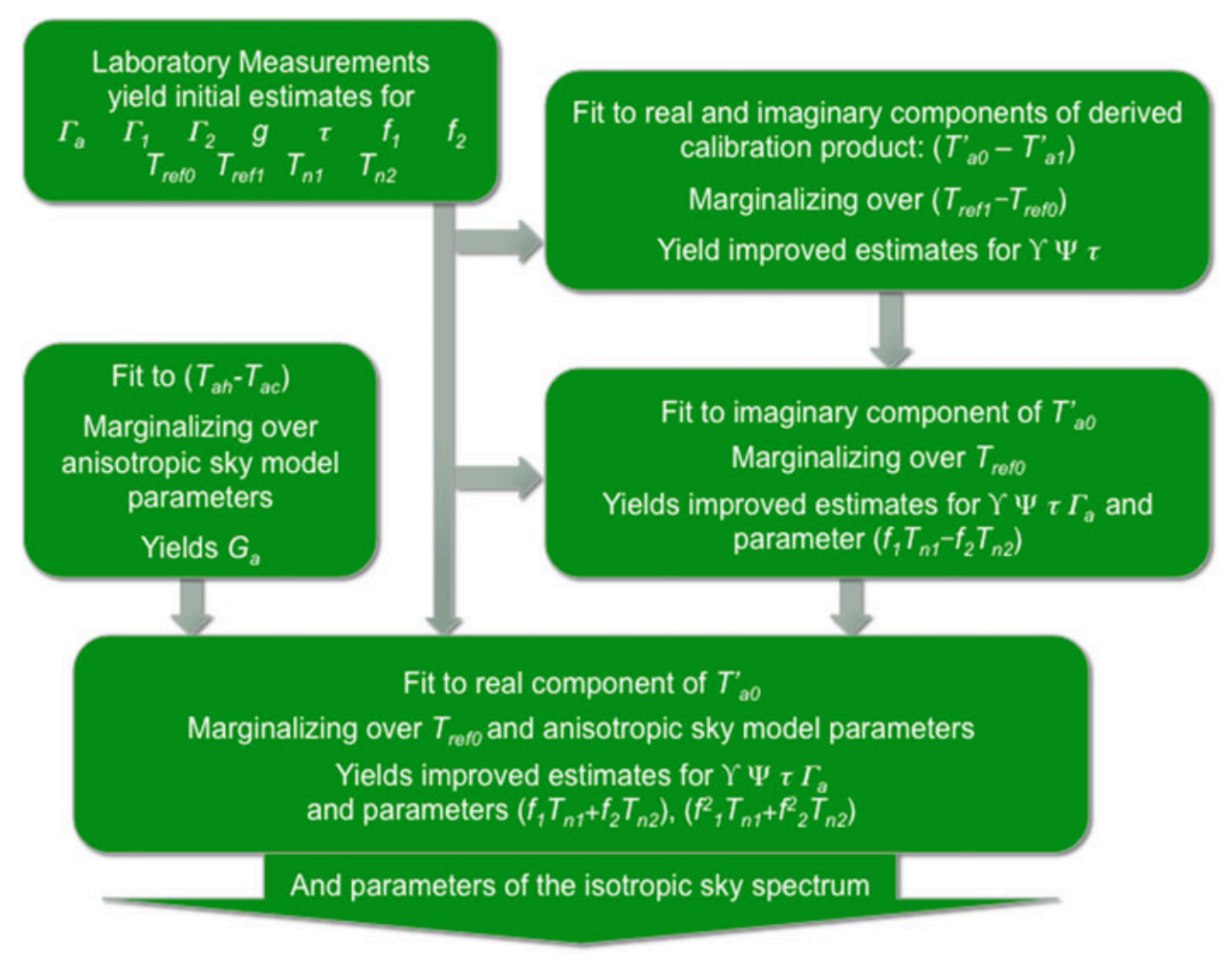
Image Courtesy: Patra et al. 2015

SARAS (1&2) CALIBRATION

- **Bandpass calibration:** toggling between antenna and noise source every second
- **Absolute calibration**: tracking temperature of hot/cold loads via temperature loggers and radiometer measurements
- **Pseudo cross-correlation**: the signal path is split into two analog channels, phase-switched, and cross-correlated
  - Imaginary part of the cross-correlation contains systematics plus noise, which can be used to model them in the real component
  - Differencing of the data acquired in different system 'states' cancels out common-mode additives after splitting
  - Real part contains the sky signal that can be used for modeling EoR

SARAS 1 MODELING

- Based on hierarchal modeling:
- The terms defining the instrument model are solved in the imaginary component of the measurement set and in calibration products
- Final stages of modeling involve sky terms



Laboratory Measurements yield initial estimates for
Γ_a Γ_1 Γ_2 g τ f_1 f_2
T_{ref0} T_{ref1} T_{n1} T_{n2}

Fit to real and imaginary components of derived calibration product: $(T'_{a0} - T'_{a1})$
Marginalizing over $(T_{ref1} - T_{ref0})$
Yield improved estimates for Υ Ψ τ

Fit to $(T_{ah}$-$T_{ac})$
Marginalizing over anisotropic sky model parameters
Yields G_a

Fit to imaginary component of T'_{a0}
Marginalizing over T_{ref0}
Yields improved estimates for Υ Ψ τ Γ_a and parameter $(f_1 T_{n1} - f_2 T_{n2})$

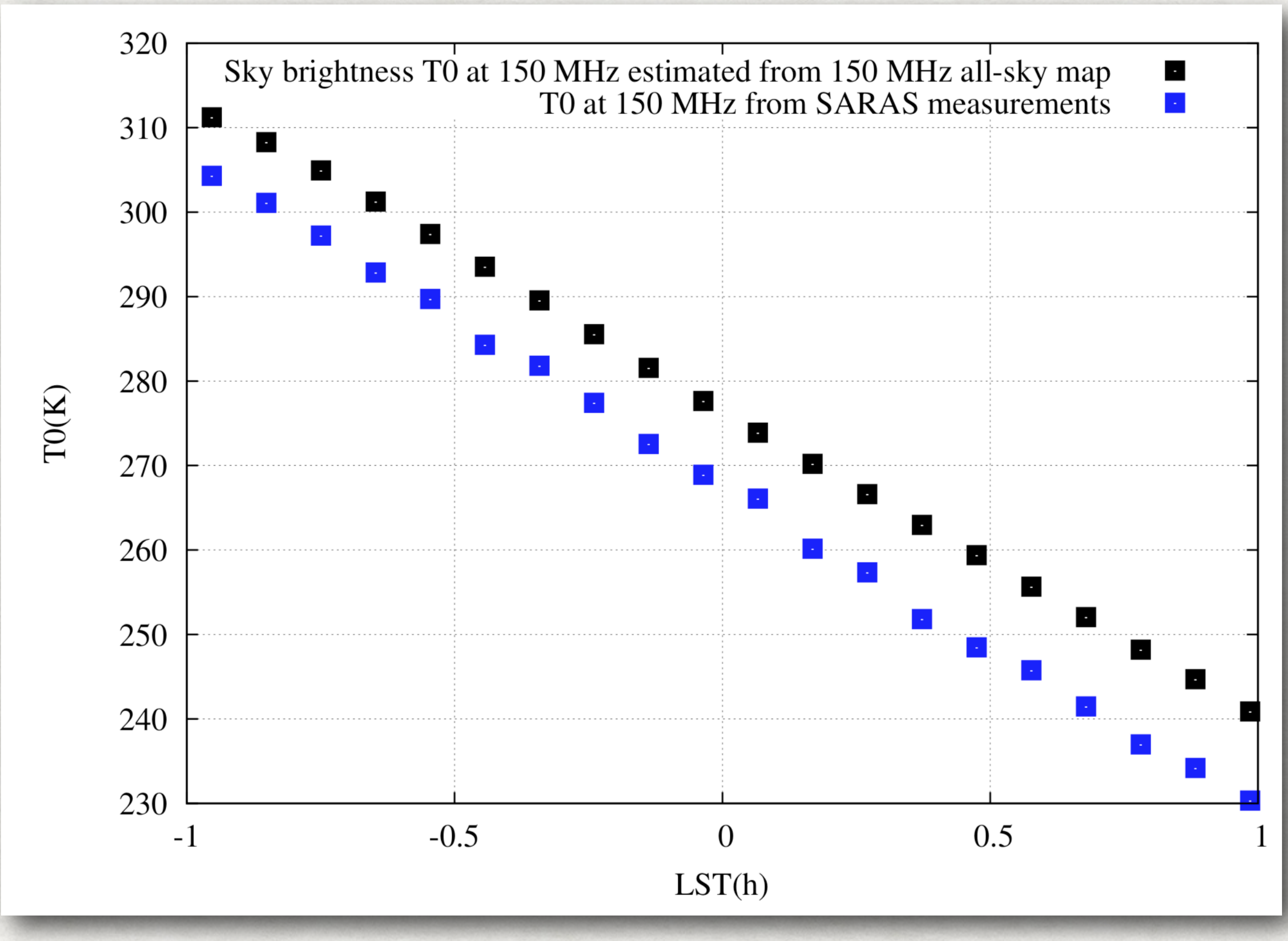
Fit to real component of T'_{a0}
Marginalizing over T_{ref0} and anisotropic sky model parameters
Yields improved estimates for Υ Ψ τ Γ_a
and parameters $(f_1 T_{n1} + f_2 T_{n2})$, $(f^2{}_1 T_{n1} + f^2{}_2 T_{n2})$

And parameters of the isotropic sky spectrum

Image Courtesy:
Patra et al. 2012

SARAS 1 RESULTS

- Provided an improved absolute calibration for 150 MHz map all-sky map of Landecker & Wielebinski (1970)*



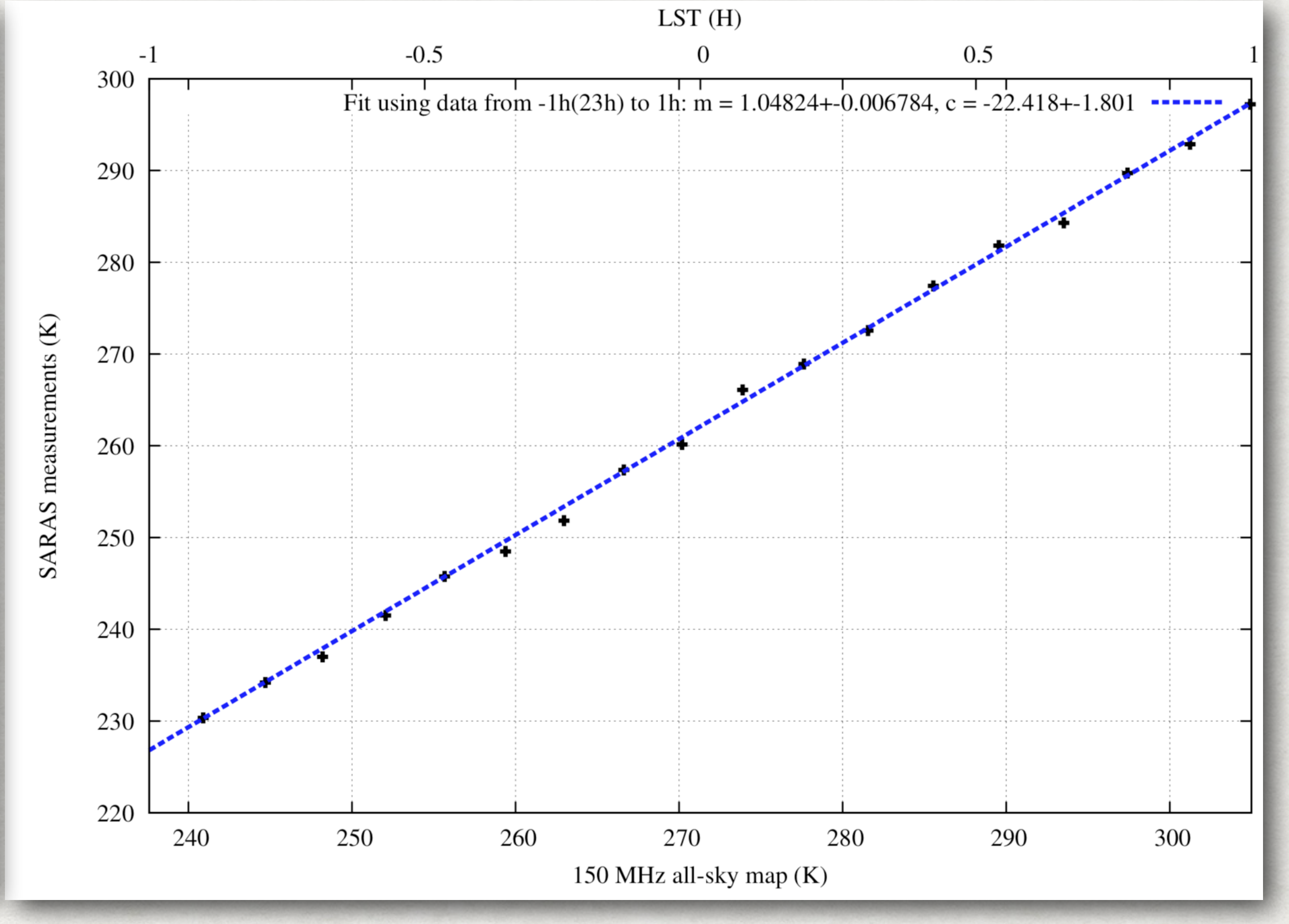


Image Courtesy:
Patra et al. 2015

*updated map available at:
https://lambda.gsfc.nasa.gov/product/foreground/fg_all_sky150_mhzmap_get.cfm

SARAS 1 CHALLENGES

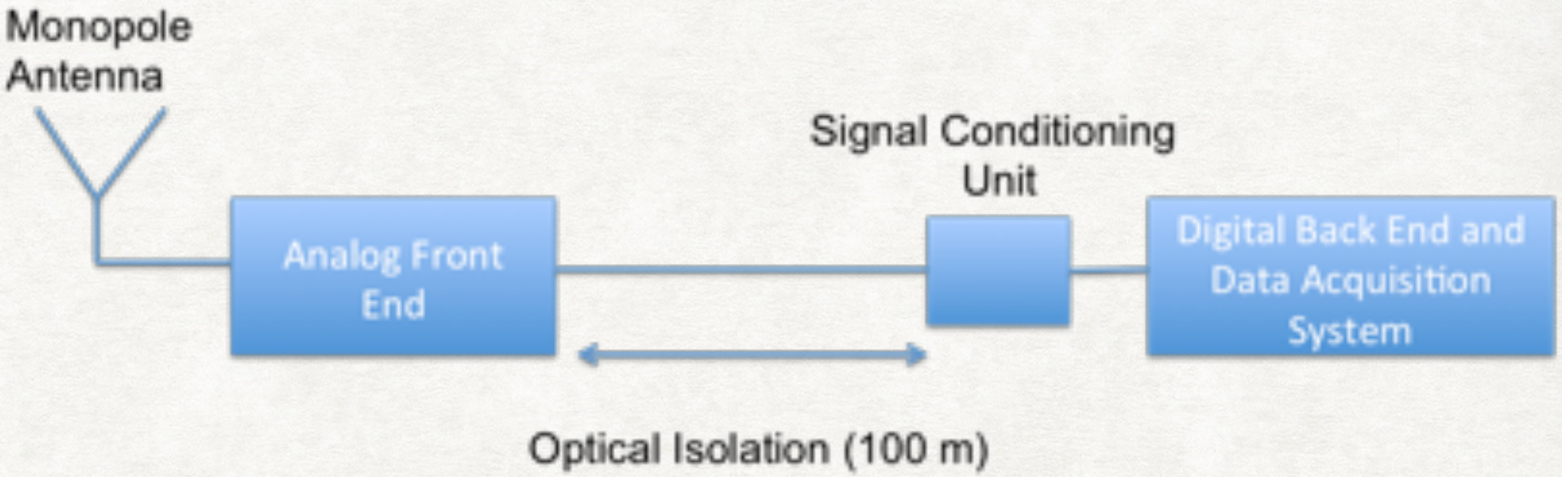
- Radio Frequency Interference!
- Cable reflections (direct and multi-path), which were difficult to model to mK accuracy
- Absorbers, which had finite absorption, introduced another length scale corresponding to height between antenna and ground

SITES OF OBSERVATIONS

SITES OF OBSERVATIONS

SARAS 2

- SARAS 2 carried out observations over 2016-17 using a spherical monopole antenna



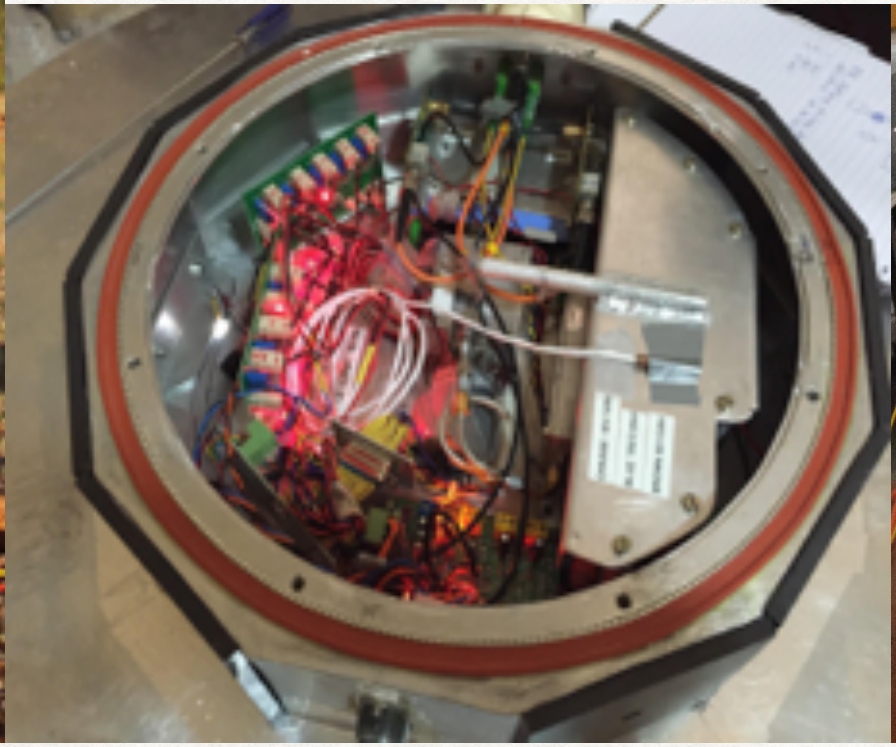
Monopole Antenna

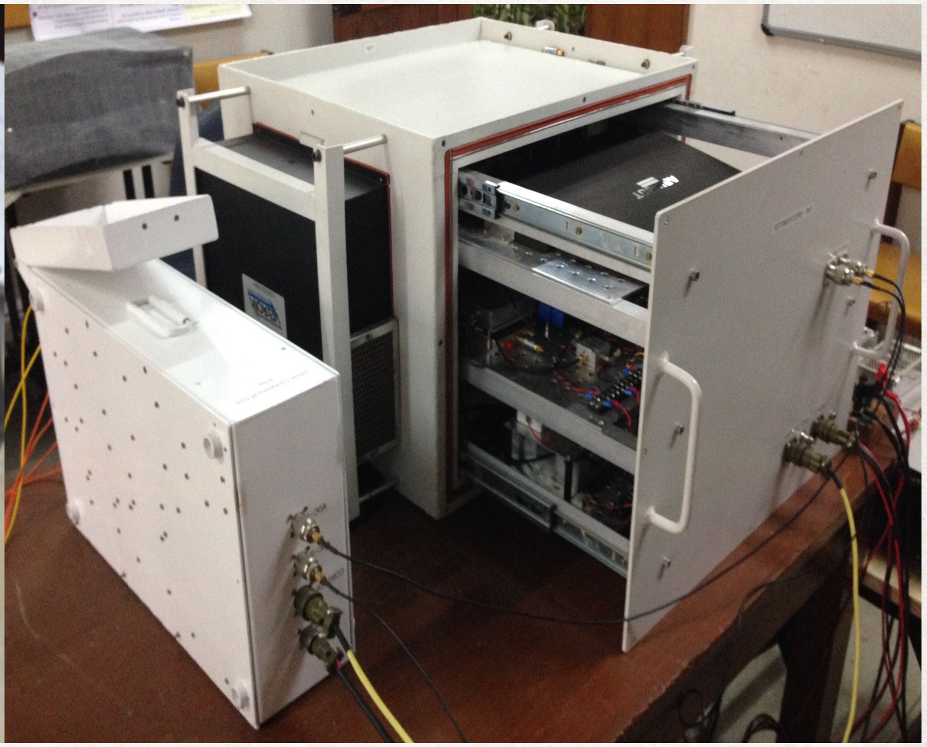
Analog Front End

Signal Conditioning Unit

Digital Back End and Data Acquisition System

Optical Isolation (100 m)





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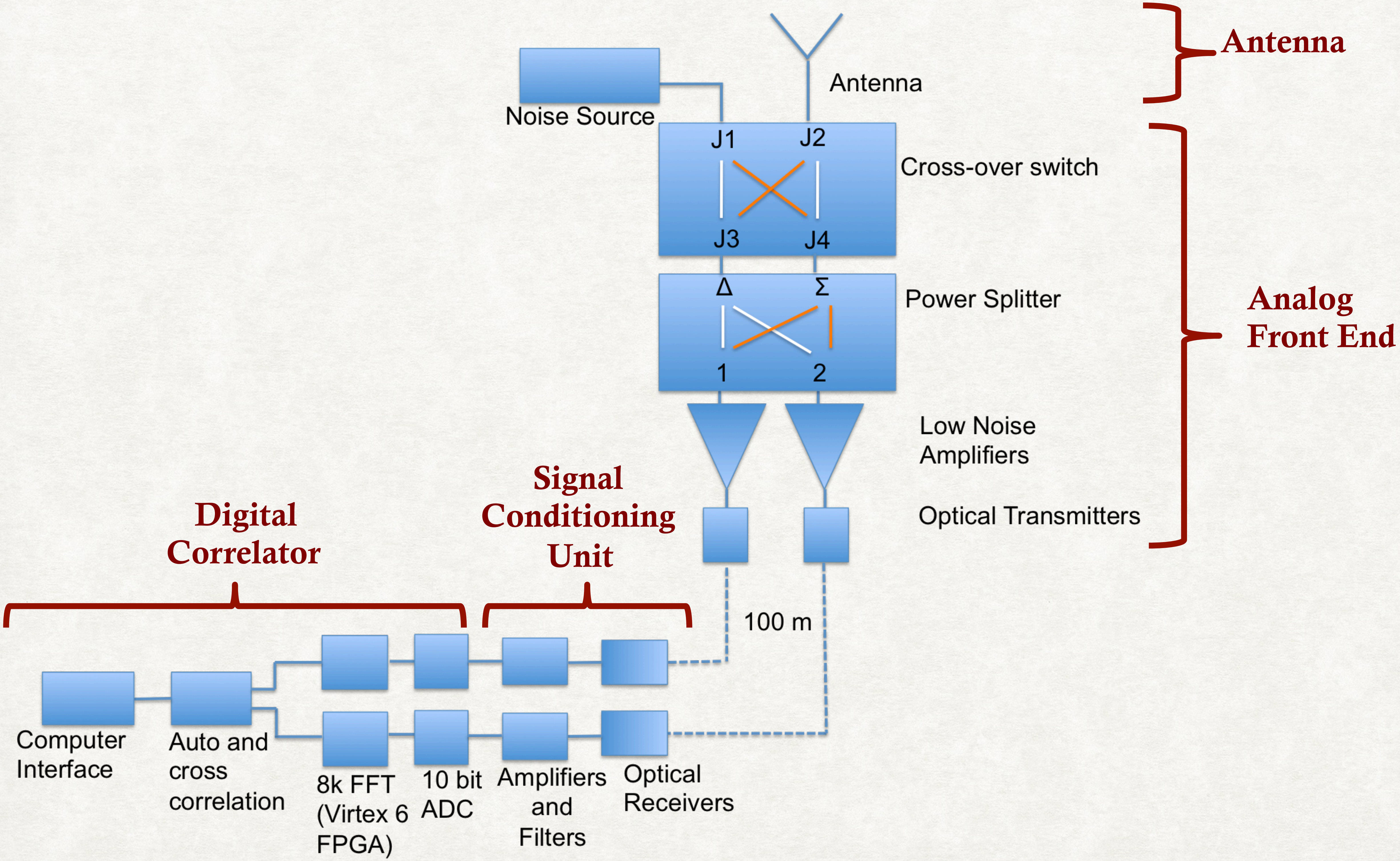
SARAS 2 RECEIVER



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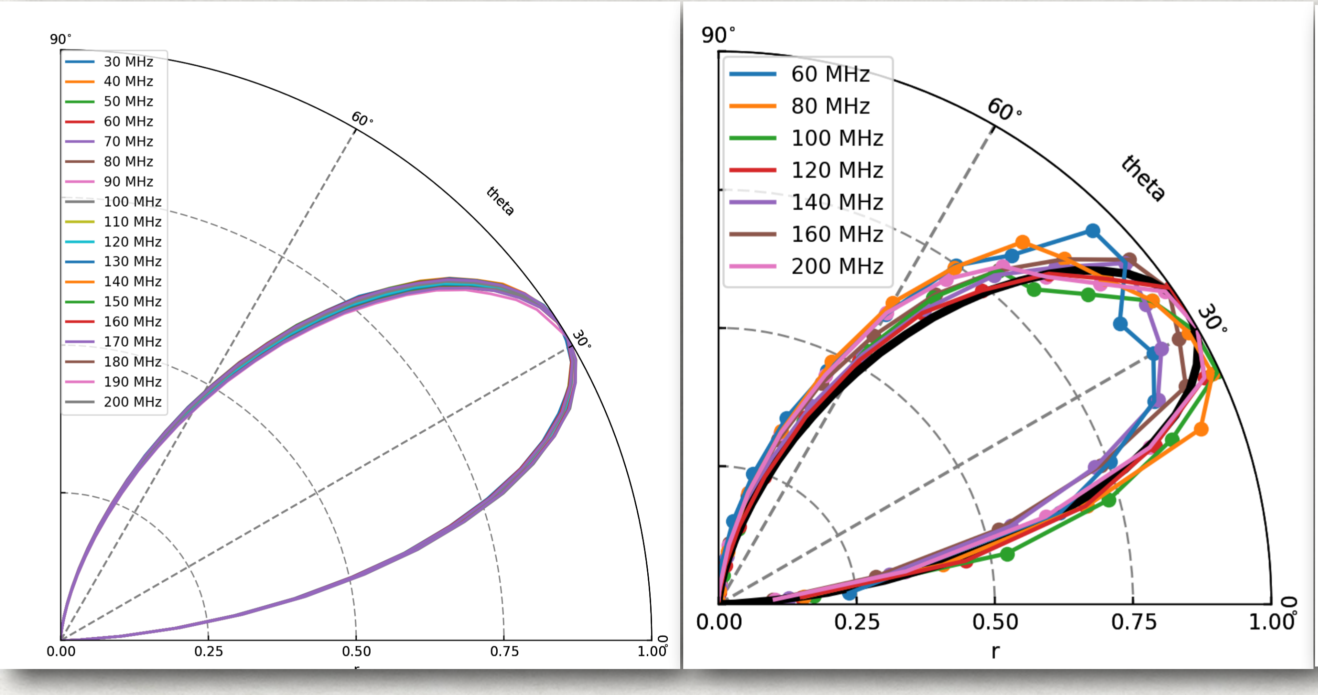
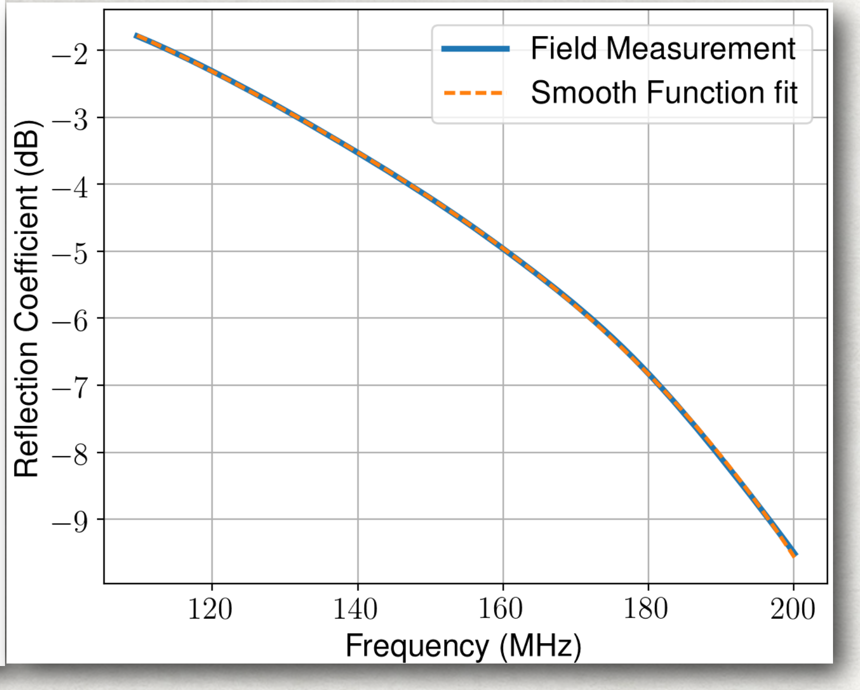
CONTROL OF SYSTEMATICS

$$T'_A = \frac{\int_\Omega T_B(\theta,\phi)G(\theta,\phi)d\Omega}{\int_\Omega G(\theta,\phi)d\Omega}$$

Beam Pattern



Reflection Coefficient



- Beam is achromatic
- Antenna transfer function is a smooth function of frequency, with no spectral wiggles
- Signals due to multipath propagation only result in a spectrally smooth component, owing to extreme miniaturization

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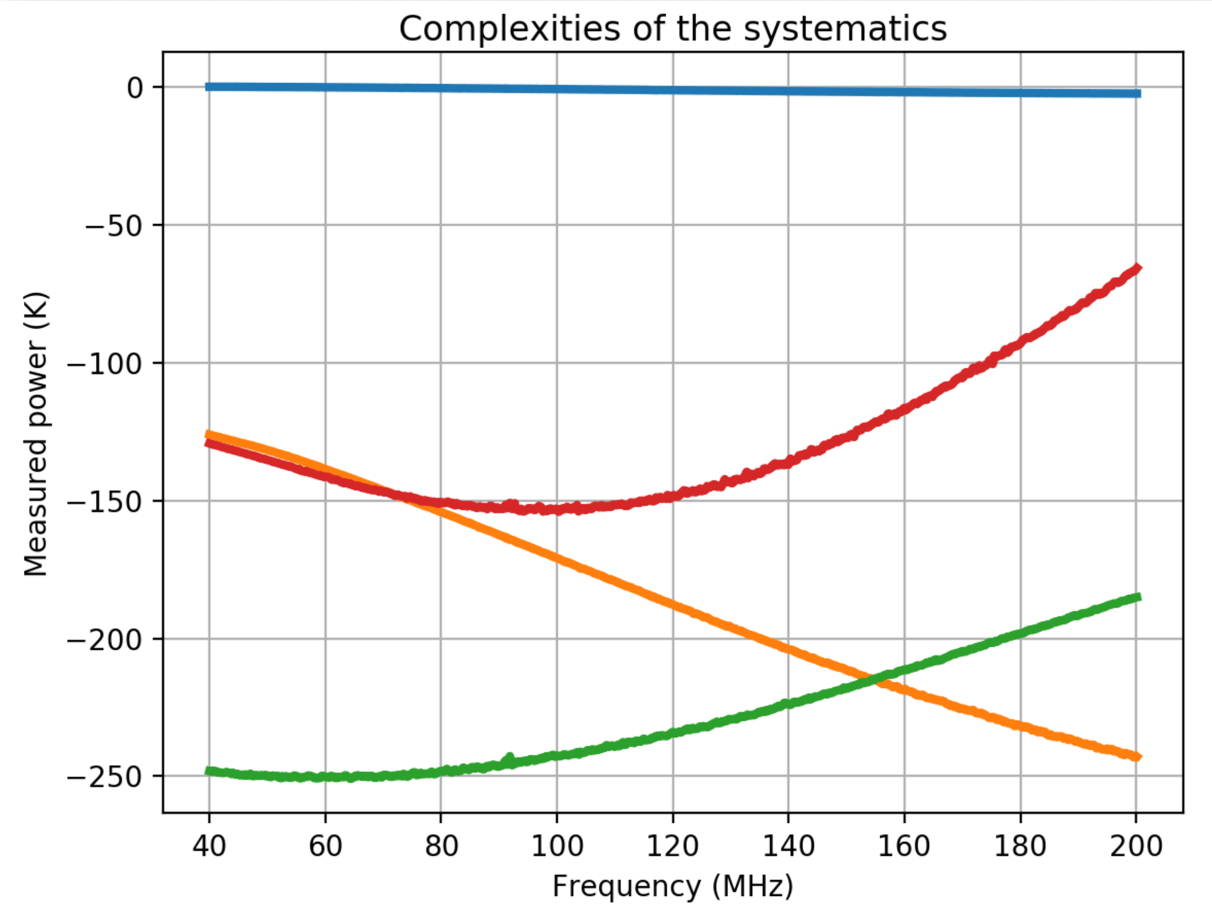
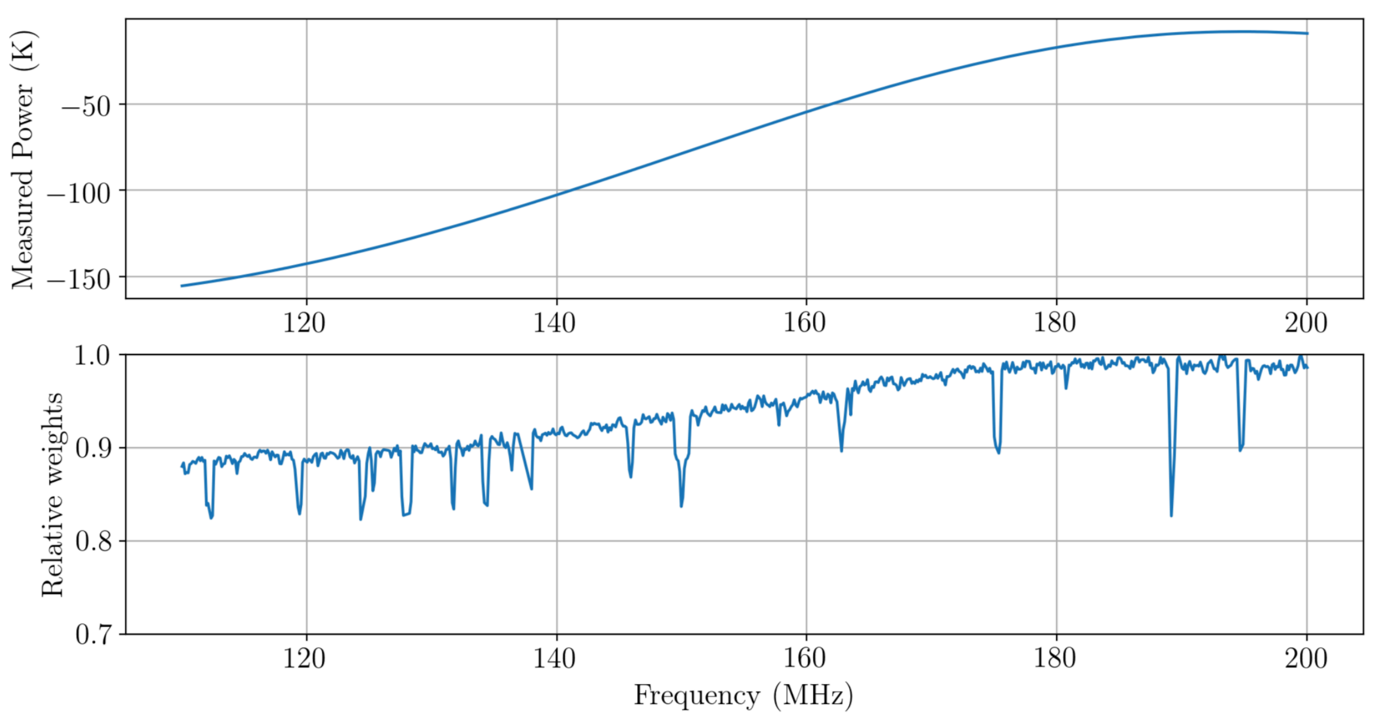
LAB AND FIELD RUNS





- Laboratory tests using loads with different spectral signatures
- Deployment in 2016-17 in Trans-Himalayan range, and Timbaktu Collective led to useful data ~60 hours
- Antenna Efficiency derived using observed data and sky model
- Efficiency enables analysis in 110-200 MHz

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SARAS 2 DATA MODELING

$$M(\nu) = F(\nu) + a \times S(\nu) \longrightarrow$$

- Scale factor test
- Likelihood ratio test

Measurement Equation

Low order polynomials/
smooth functions

$$T_{\mathrm{meas}} = \left[\left(\frac{C_1}{C_2}\right) T_A - T_{\mathrm{REF}} + \left(\frac{C_{n1}}{C_2}\right) T_{\mathrm{N}_1} + \left(\frac{C_{n2}}{C_2}\right) T_{\mathrm{N}_2} \right], \quad \text{where}$$

$$C_1 = \left[\sum_{l=0}^{\infty} |\gamma^{2l}| \sum_{m=0}^{\infty} \Re(\gamma^m \mathrm{e}^{im\phi}) \right],$$

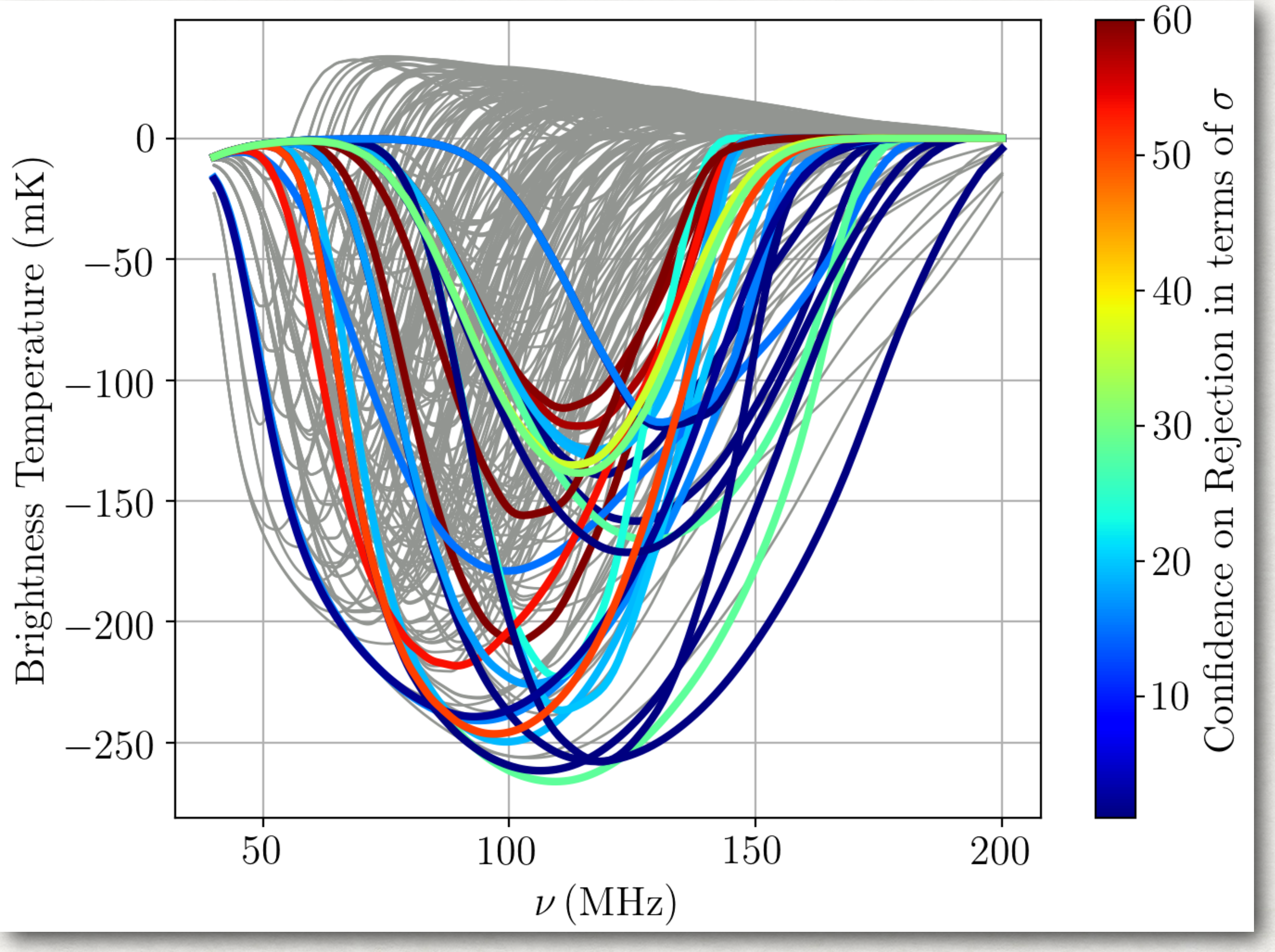
$$C_2 = \left[1 - |\psi|^2 \left(\sum_{l=0}^{\infty} \gamma^l \mathrm{e}^{i(l+1)\phi} \right) \left(\sum_{m=0}^{\infty} \gamma^m \mathrm{e}^{i(m+1)\phi} \right)^* + 2i\Im \left\{ \psi \left(\sum_{n=0}^{\infty} \gamma^n \mathrm{e}^{i(n+1)\phi} \right) \right\} \right],$$

$$C_{n1} = f_1\chi^* + f_1^2|\chi|^2, \text{ and}$$

$$C_{n2} = f_2\chi + f_2^2|\chi|^2.$$

SARAS 2 RESULTS

- SARAS 2 rejects the scenario of Rapid Reionization in tandem with either late X-ray heating or no heating



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SARAS 2 CHALLENGES

- The radiometer was system dominated over 50-100 MHz
- Low efficiency was not favorable to analyze data in 50-100 MHz
- It also implied larger coupling of ground radiation with the system

TOWARDS LOW BAND UPGRADE…

- We upgraded the radiometer in 50-100 MHz band using scaled version of the antenna
- We conducted test observations with the upgraded system in Timbaktu Collective and near Indian Astronomical Observatory, Hanle (Leh-Ladakh, J&K) in 2018
- Currently, the analysis of ~100 hours of observations is limited by our ability to correct for ground radiation coupling to the antenna

SUMMARY

- SARAS 1 provided an improved absolute calibration to 150 MHz sky map
- SARAS 2, with miniaturised design and no large length-scales, ruled out a class of theoretically predicted global 21-cm signatures
- Reduced sensitivity could not enable analysis in 50-100 MHz band
- Upgraded radiometer optimized for 50-100 MHz
- Next presentation would focus on our attempts at observing in this band