SARAS: Science and Challenges

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SARAS team

SARAS team

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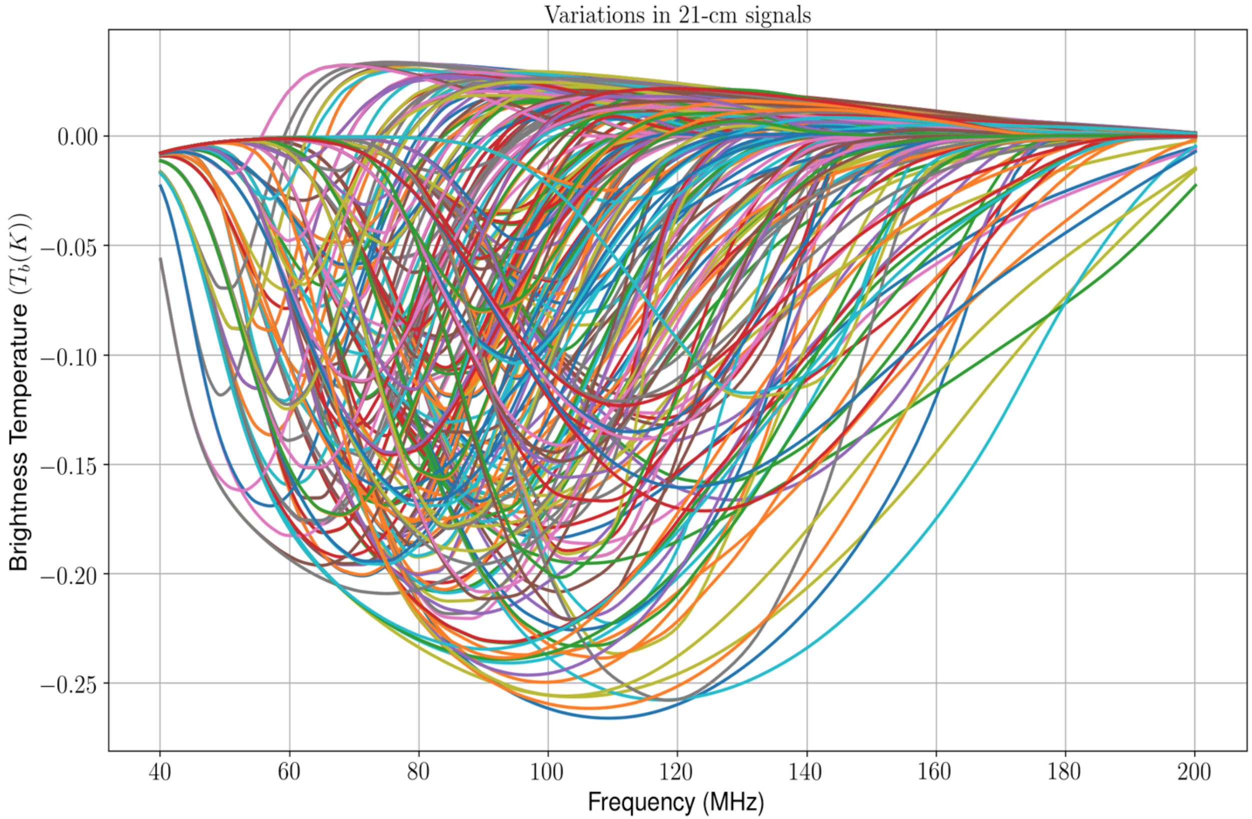
Logistics and Technical Support

- Gauribidanur Field Station
- Mechanical Engineering Services, RRI
- Electronics Engineering Group, RRI
- Indian Astronomical Observatory, Leh, Indian Institute of Astrophysics
- Timbaktu Collective

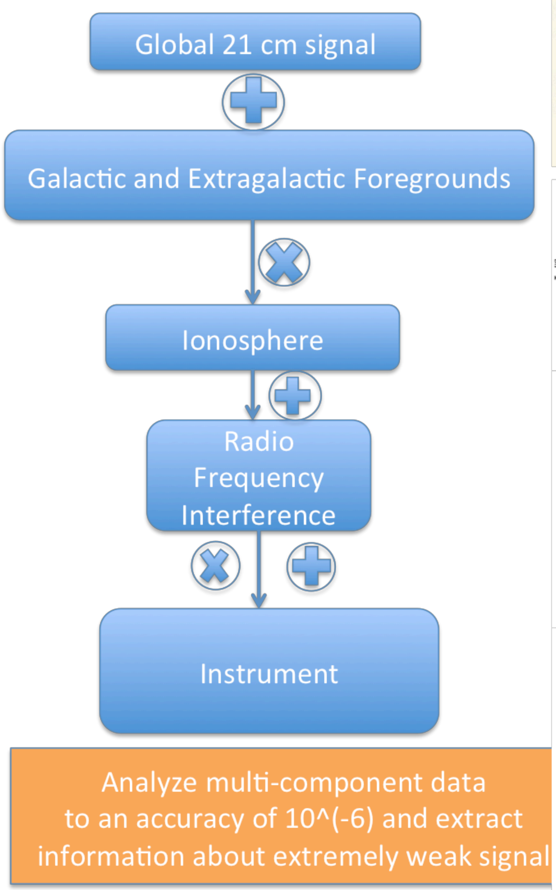
Theoretical possibilities within "standard cosmology"

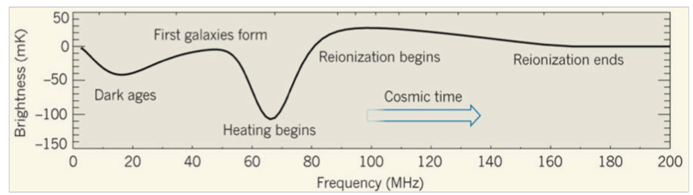


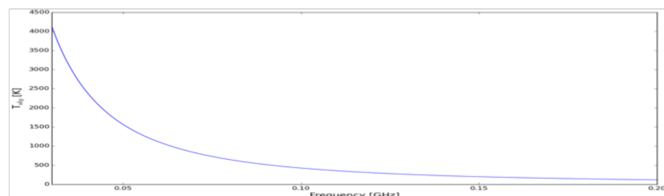
- Minimum mass of halos for star formation
- Star formation efficiency
- SED
- X-ray efficiency
- Optical depth to reionization

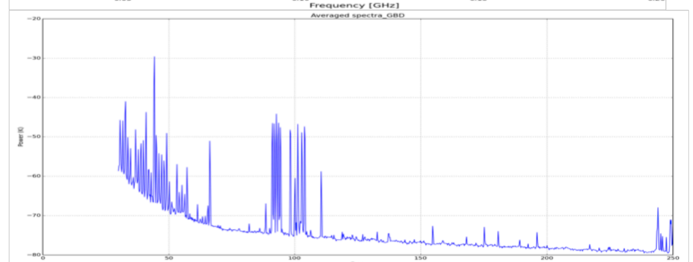
Cohen, A., Fialkov, A., Barkana, R. et al., M. 2017b, MNRAS, 472, 1915

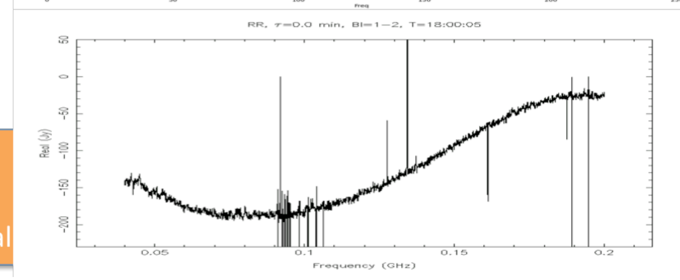
Challenges in the detection











21-cm signal
< 100s of mK

Foregrounds
100-10,000 K

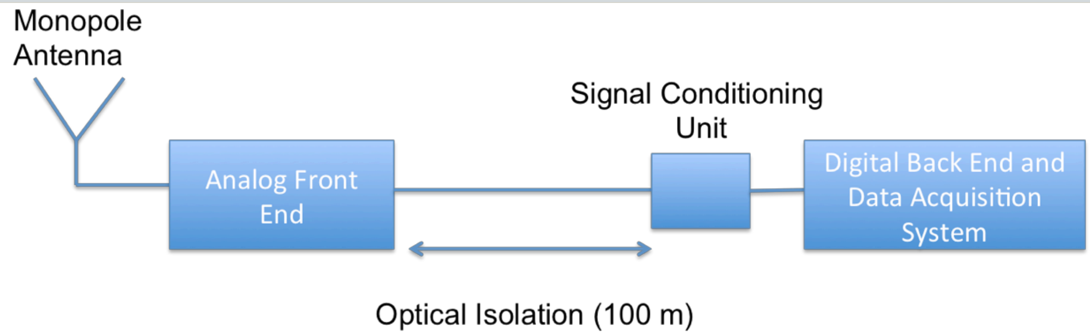
RFI
A few mK to 10,000 K and more

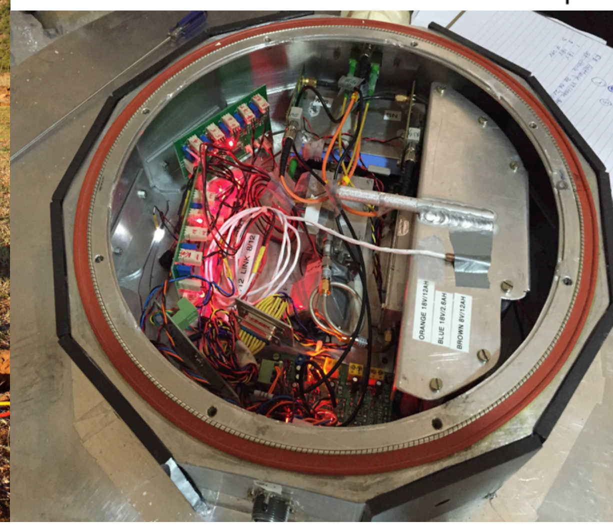
Receiver Noise
10-20 K

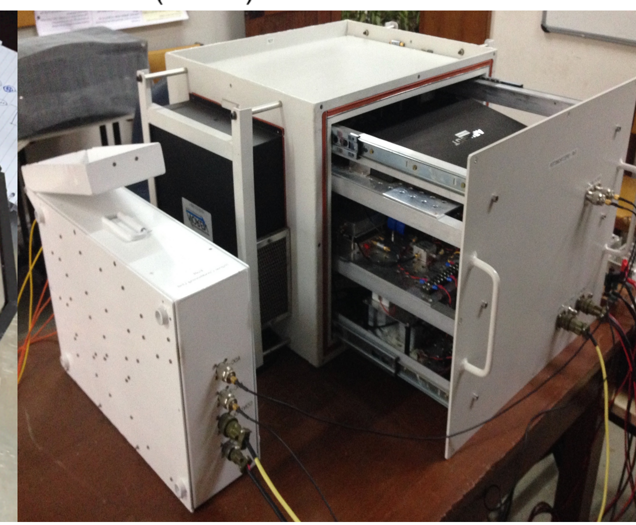
Design philosophy for the radiometer

- Foregrounds have smooth spectrum while the 21-cm signal is predicted to have various spectral features
- Thus the design of the instrument is focused towards avoiding any spectral features from the system itself to avoid confusing it with the signal
- We measure smoothness using the concept of maximally smooth function
- It is a constrained polynomial approach in which coefficients are optimized such that there is no zero crossing in any second and higher order derivatives (i.e. there is no inflection point in the fit)
- Such functions fit only to the smooth part of the curve and preserve the spectral structures

SARAS 2 radiometer

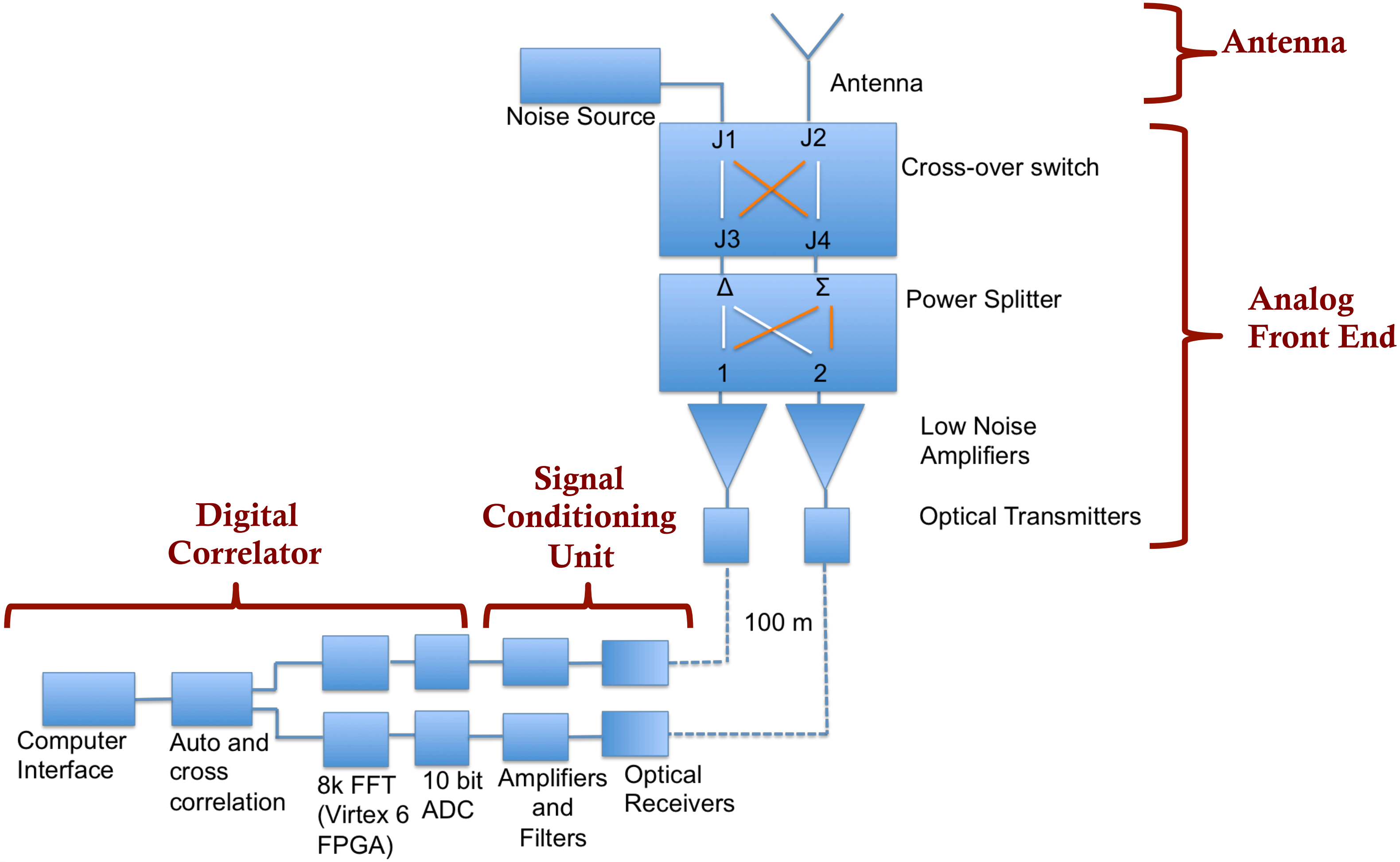






SS, Ravi Subrahmanyan, N. Udaya Shankar et al., 2018, Exp. Ast., 45, 269

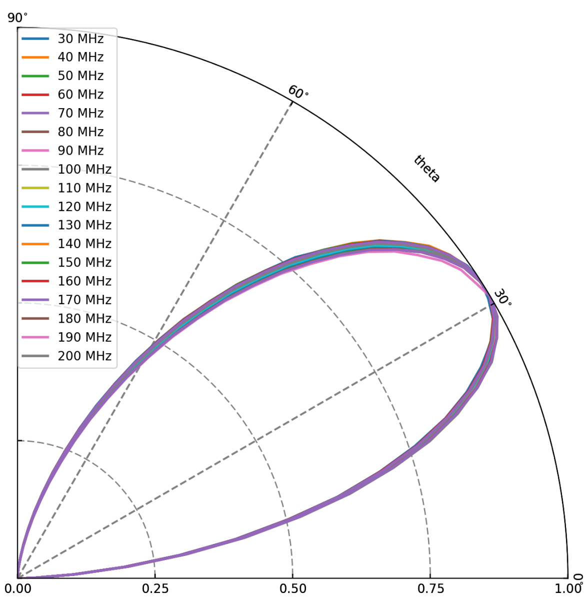
SARAS 2 radiometer

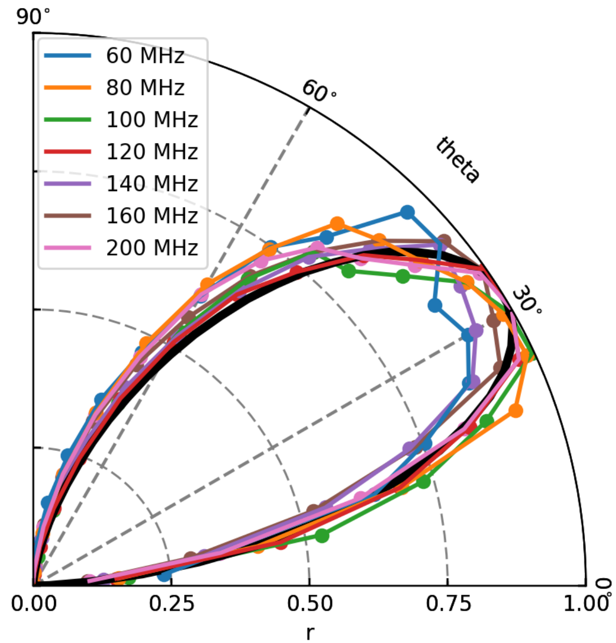


SARAS 2: control of systematics for 21-cm measurements

Antenna power pattern

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



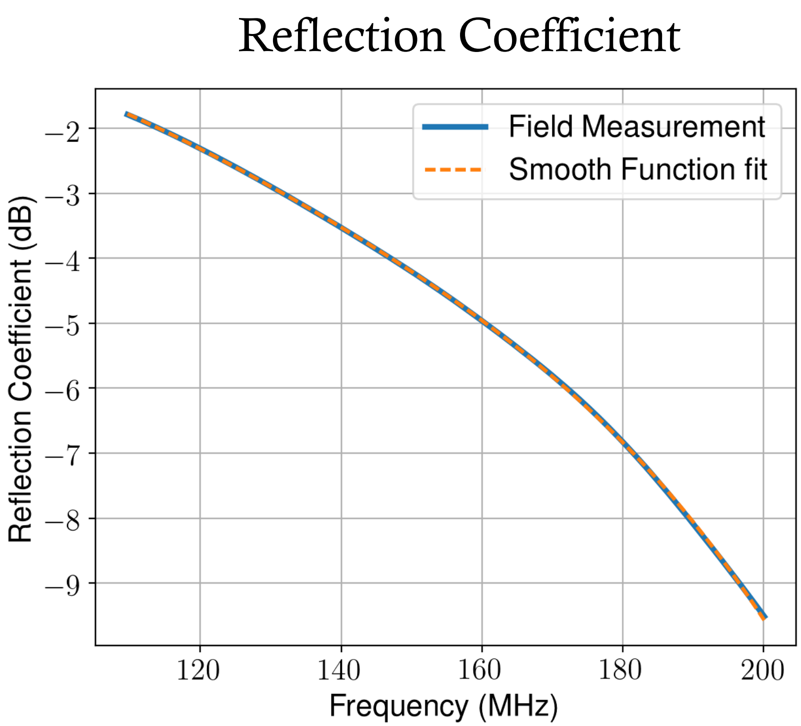


- Foreground spatial sky structure appears as frequency structure if beam is frequency dependent.
- SARAS 2 antenna has been made electrically small to achieve achromatic beam

SARAS 2: control of systematics for 21-cm measurements

Antenna transfer functions

$$T_A = \alpha(1 - |\Gamma|^2)T'_A$$



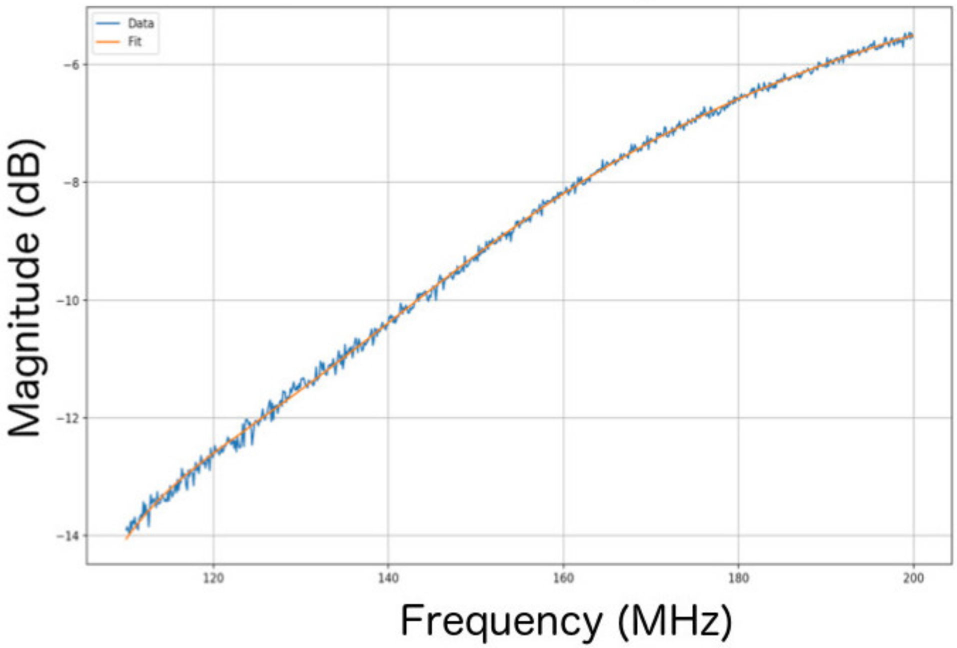
- Smoothness of reflection coefficient has been measured to 1 part in 10,000
- Since no balun is used, we do not have resistive loss in the antenna and hence no unwanted frequency characteristics

SARAS 2: control of systematics for 21-cm measurements

Antenna transfer functions

$$T_A = \alpha(1 - |\Gamma|^2)T'_A$$

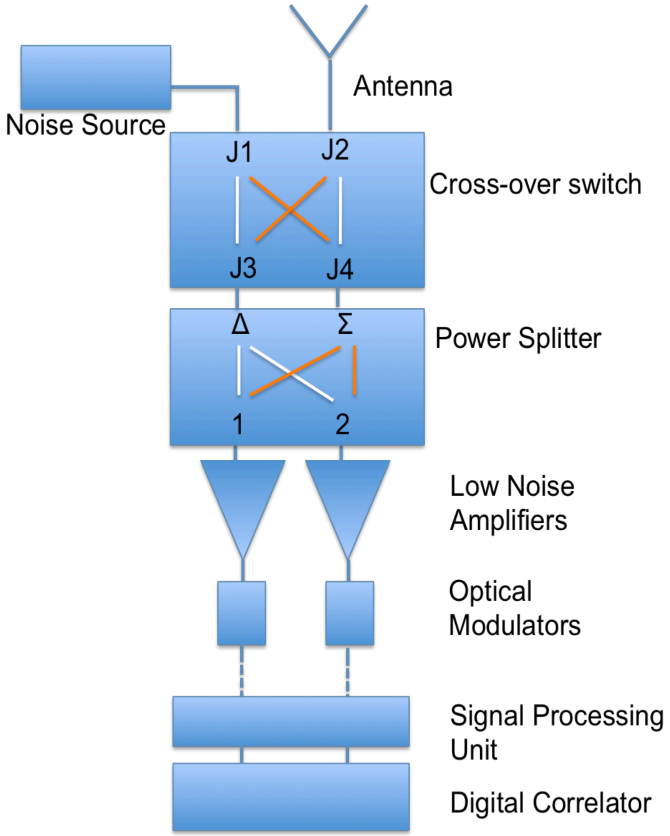
Total Efficiency



- There is a trade-off between sensitivity and smoothness of the transfer function
- SARAS 2 prefers smoothness and hence has comparatively low efficiency

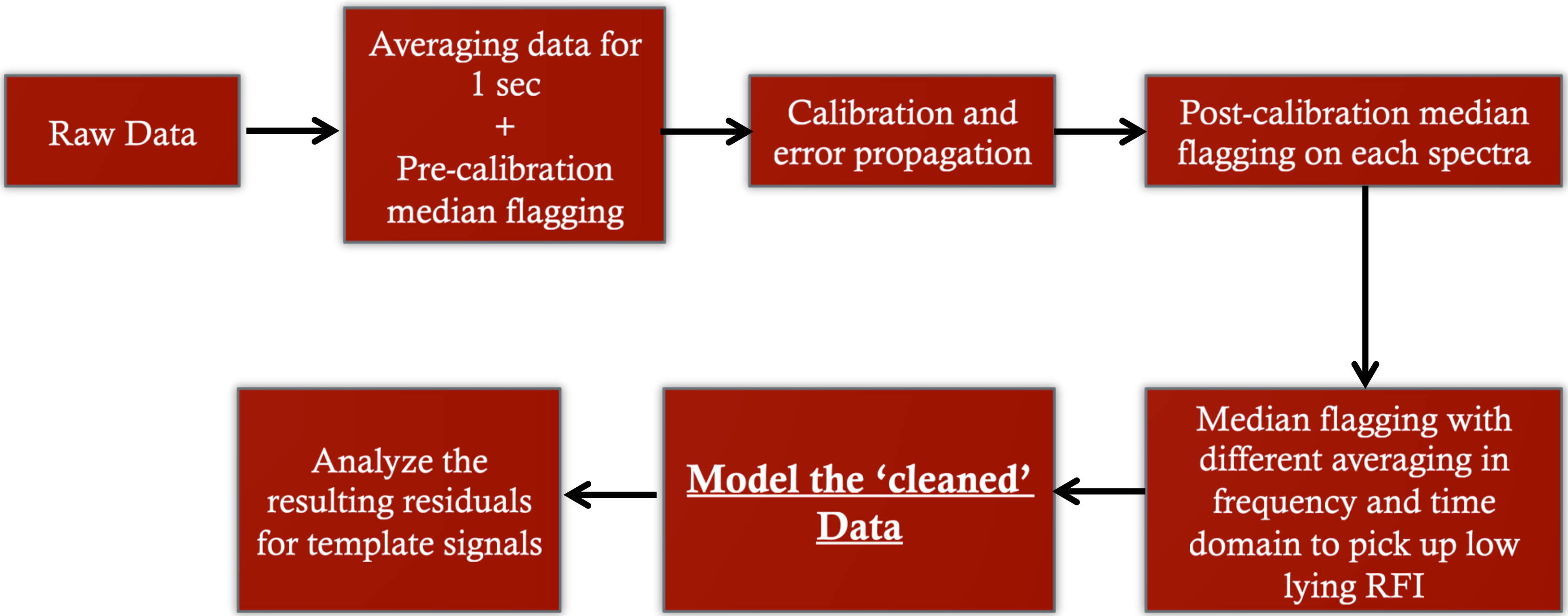
SARAS 2: control of systematics for 21-cm measurements

Receiver architecture



- Noise source injection calibrates the multiplicative gain of the system
- Phase switching cancels the internal additives that may arise due to cross-talk between receiver arms
- Signals due to multipath propagation only result in a spectrally smooth component

Algorithms developed for data reduction and analysis



Dual Approach to Data modeling

Measurement Equation

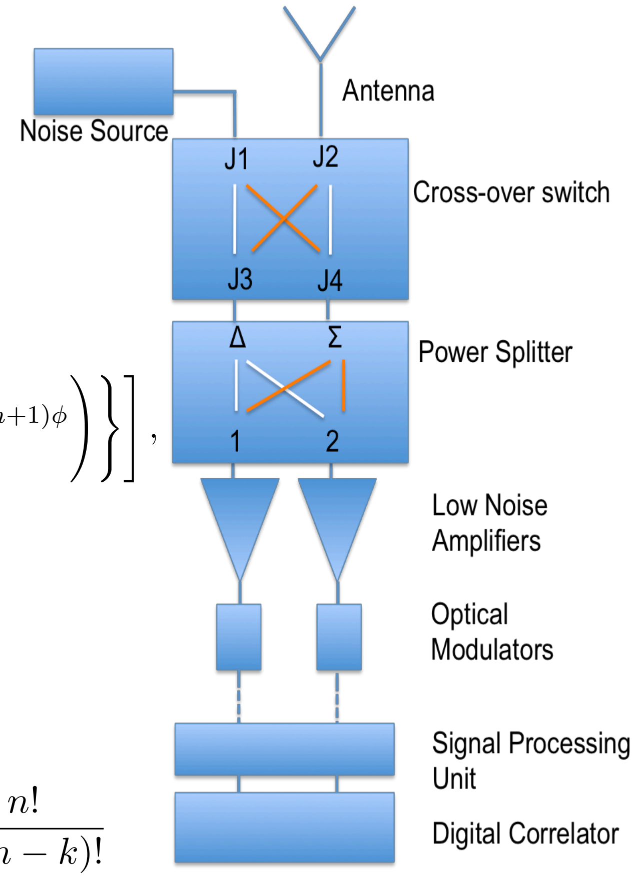
$$T_{\mathrm{meas}} = \left[\left(\frac{C_1}{C_2}\right) T_A - T_{\mathrm{REF}} + \left(\frac{C_{n1}}{C_2}\right) T_{\mathrm{N}_1} + \left(\frac{C_{n2}}{C_2}\right) T_{\mathrm{N}_2}\right], \quad \text{where}$$

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

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

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

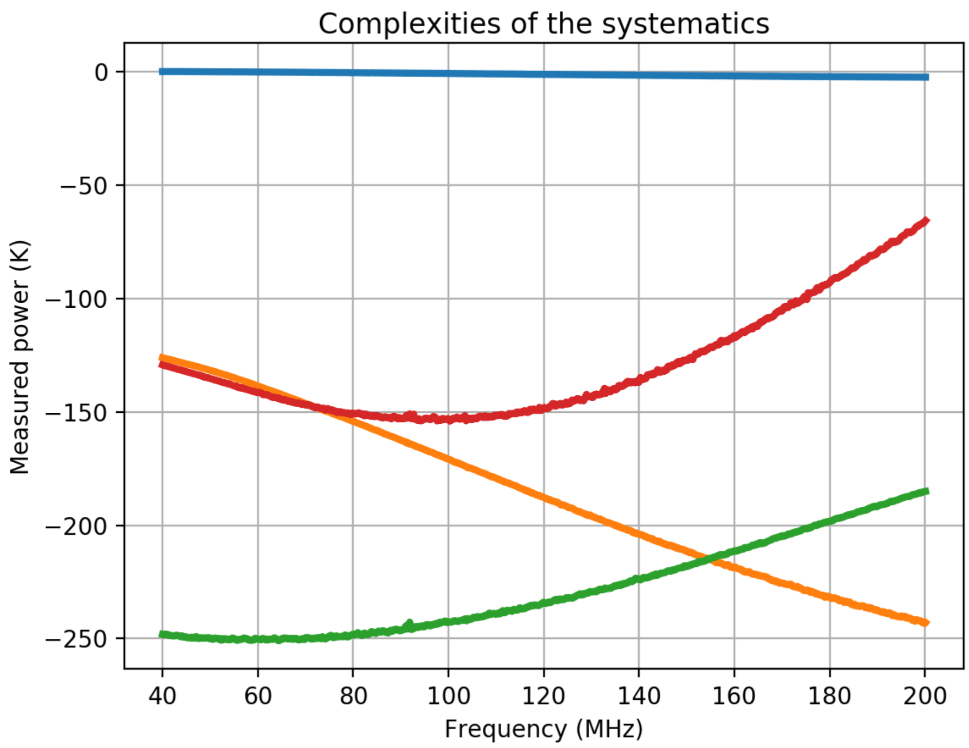
$$C_{n2} = f_2\chi + f_2^2|\chi|^2.$$



Maximally Smooth Functions

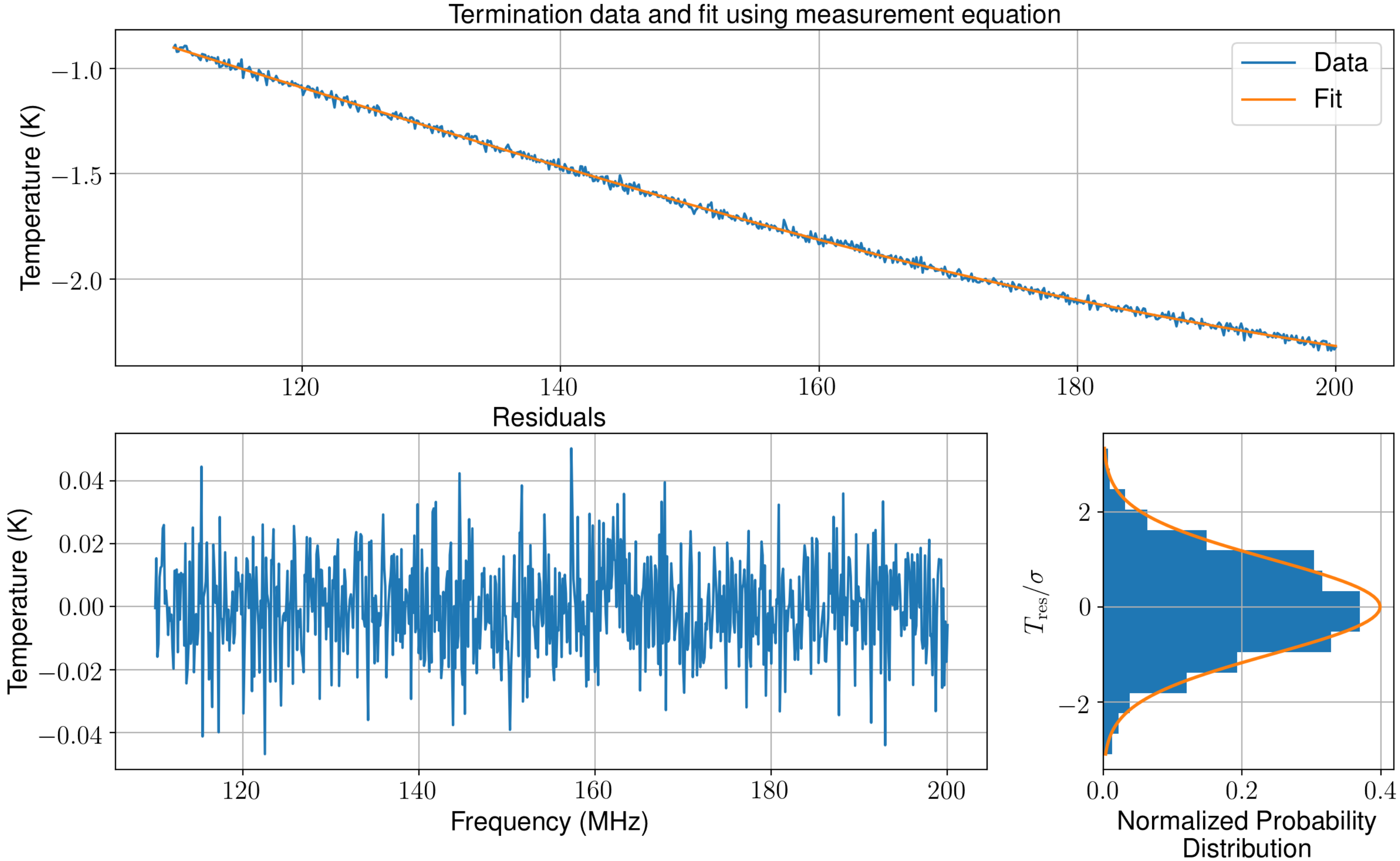
$$f(x) = a_0 + \sum_{i=1}^{n} (-1)^i (x - x_0)^i \{\sum_{j=0}^{n-i} a_{i+j} C_j^{i+j} (x_m - x_0)^j\}, \quad C_k^n = \frac{n!}{k!(n-k)!}$$

Performance measure of SARAS 2

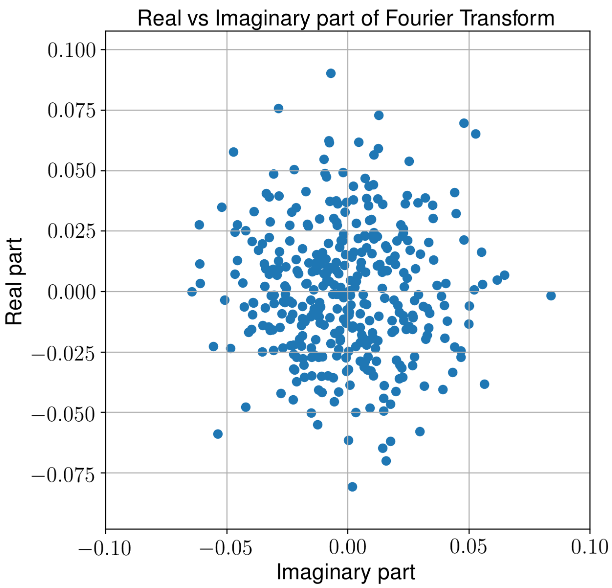


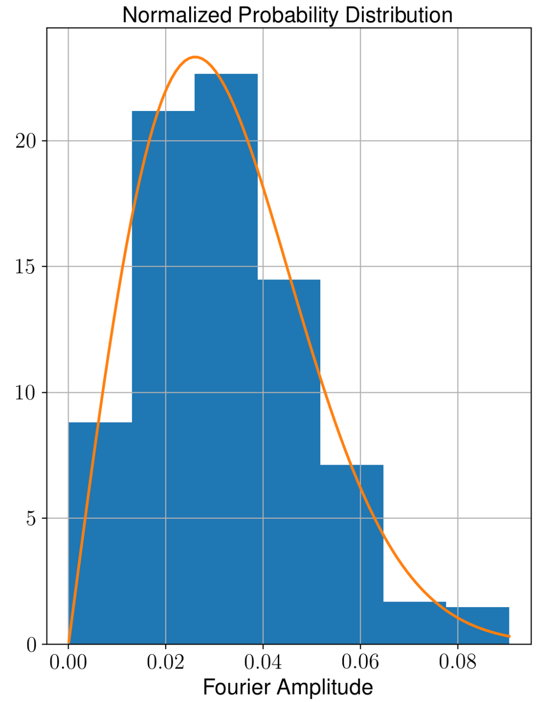
- The system was run overnight for different terminations that replaced the antenna
- The motive of the exercise was to be able to model the internal systematics, from the most ideal case to the one closely resembling in impedance of antenna

Performance measure of SARAS 2



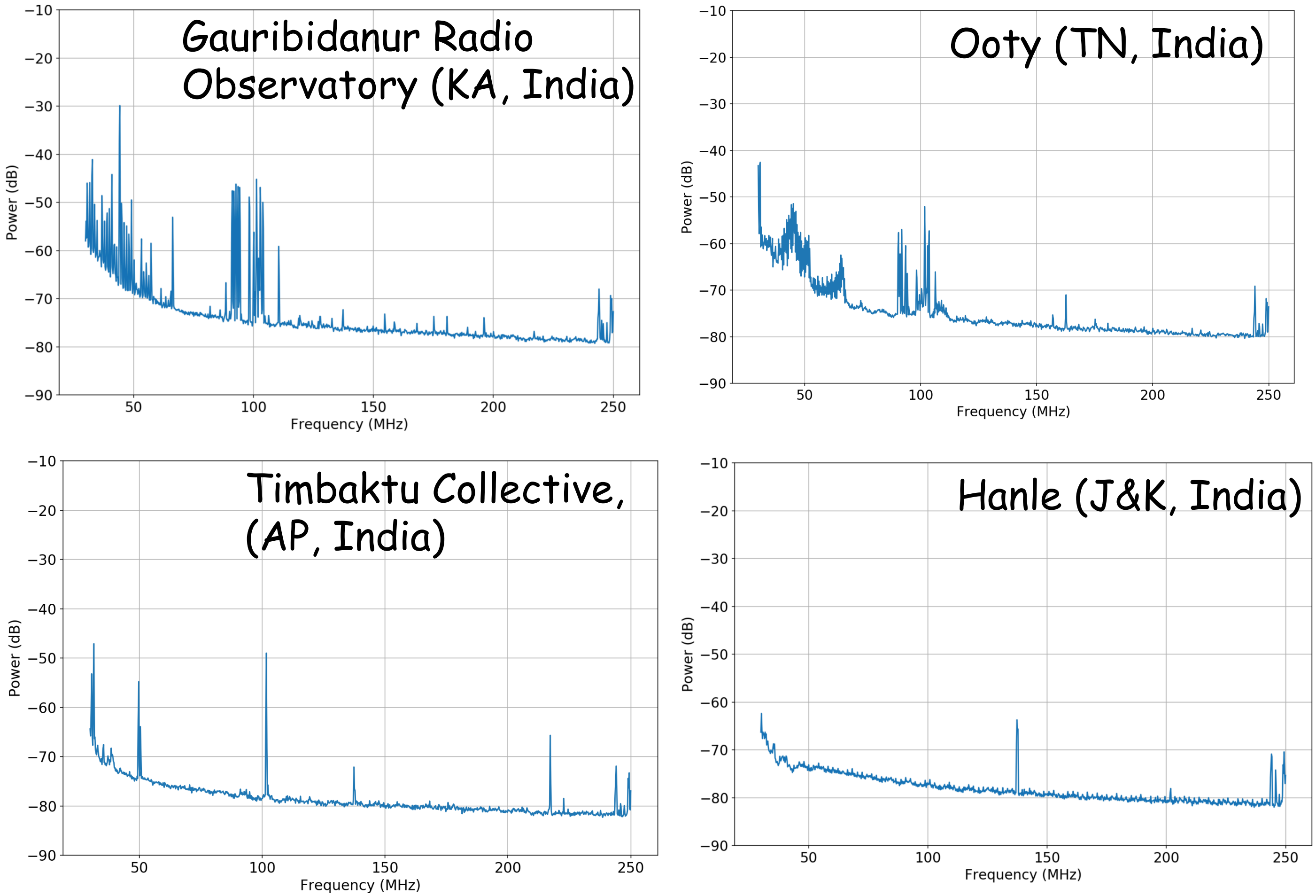
Performance measure of SARAS 2





- Modeling of internal additives leave no residuals with Fourier amplitudes exceeding 2 mK
- Thus SARAS 2 system is capable of detection of complex 21-cm profiles

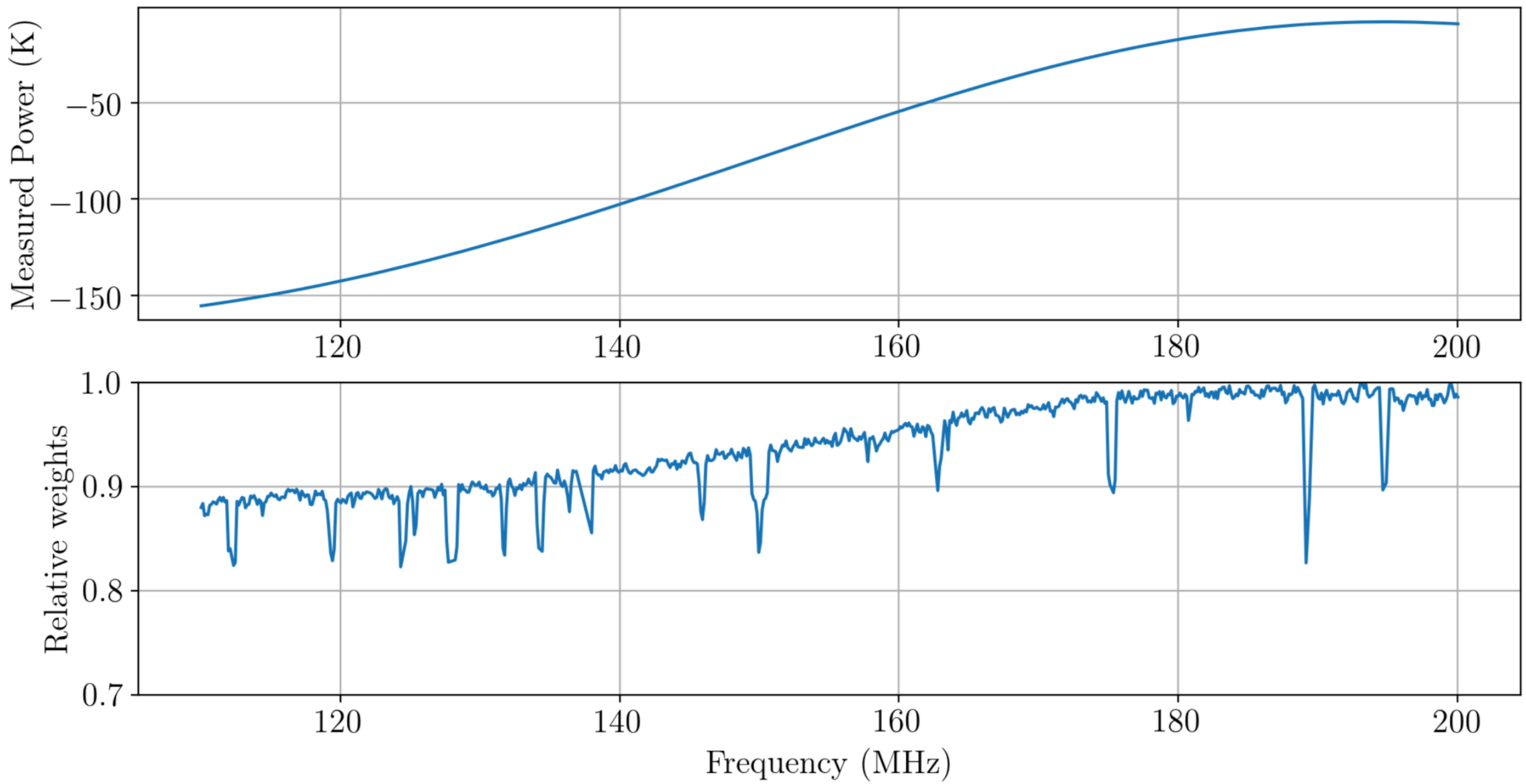
Locating an observing site



SARAS 2 ready to watch the sky!

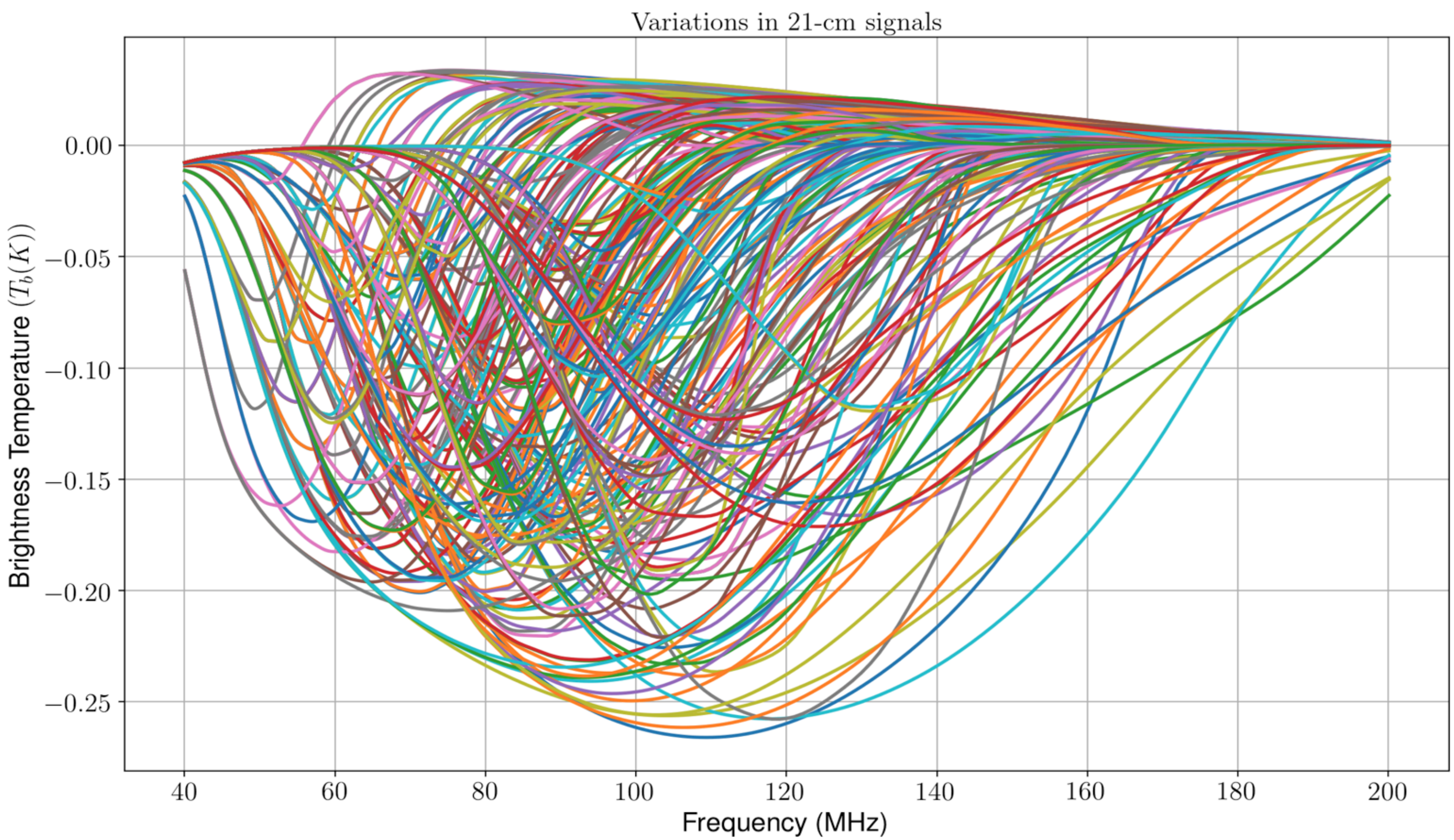



SARAS 2 data modeling



- 12 mK RMS noise, demonstrating a dynamic range better than 1 part in 65,000
- We do not see evidence of any limiting systematics at this level

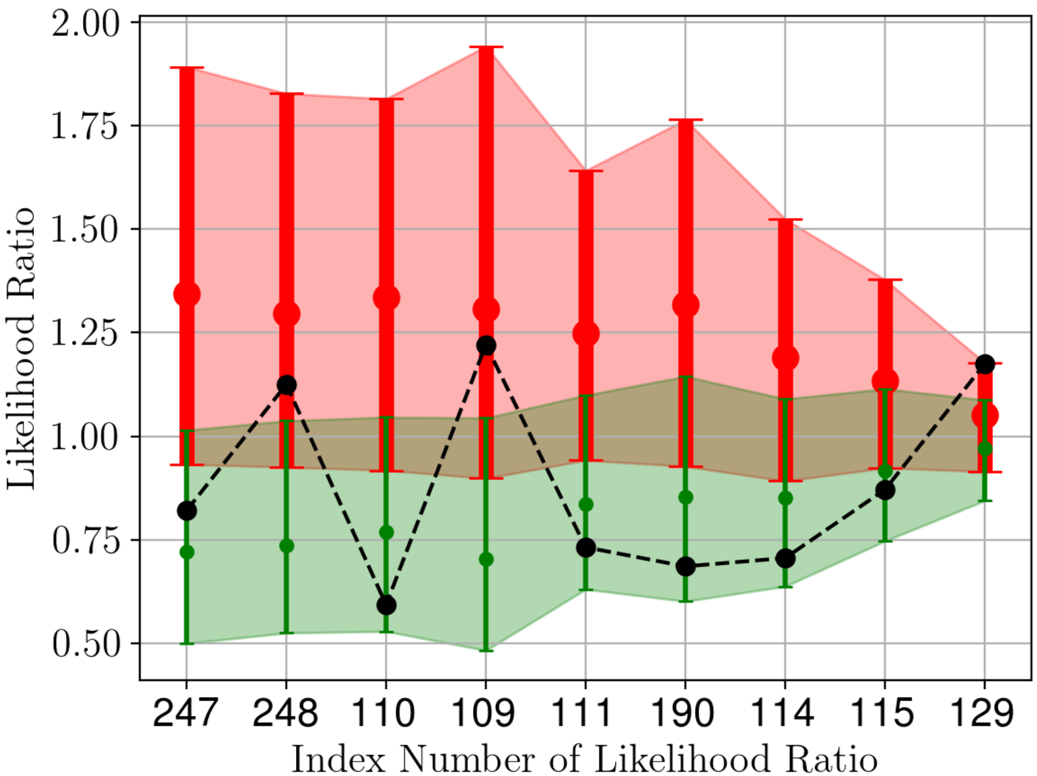
Constraining EoR



Bayes Factor Test

Joint forward modeling

Bayes Factor Approach



$$\mathrm{LR} = \prod_{i=1}^{N} \frac{e^{\frac{-(y_i - M_i)^2}{2\sigma_i^2}}}{e^{\frac{-y_i^2}{2\sigma_i^2}}}$$

- Likelihood Ratio less than unity suggests that the data is more consistent with noise than model, Likelihood Ratio more than unity suggests the data favours the model
- The significance is computed by performing same analysis on mock data with different noise realizations

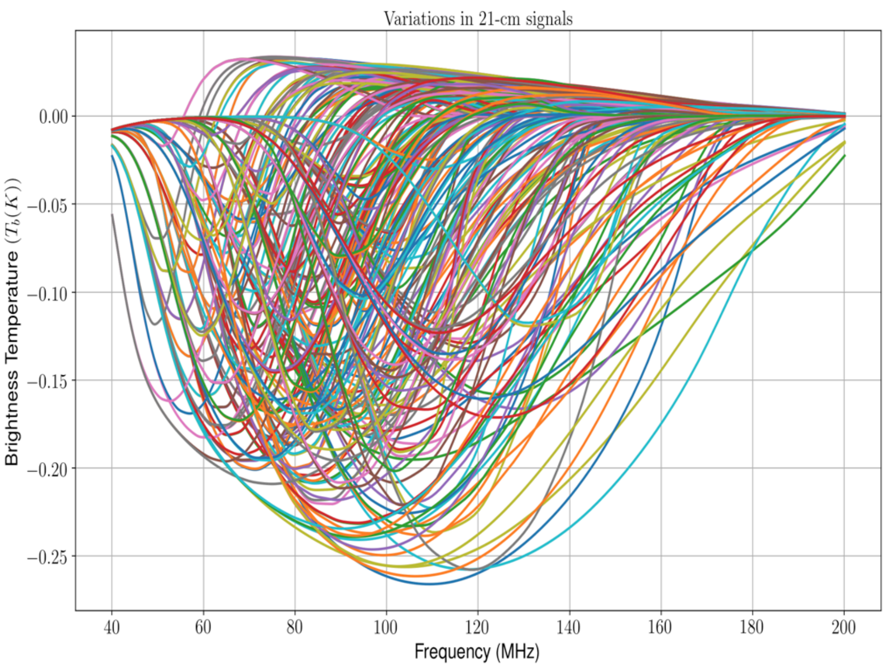
Foreword modeling approach

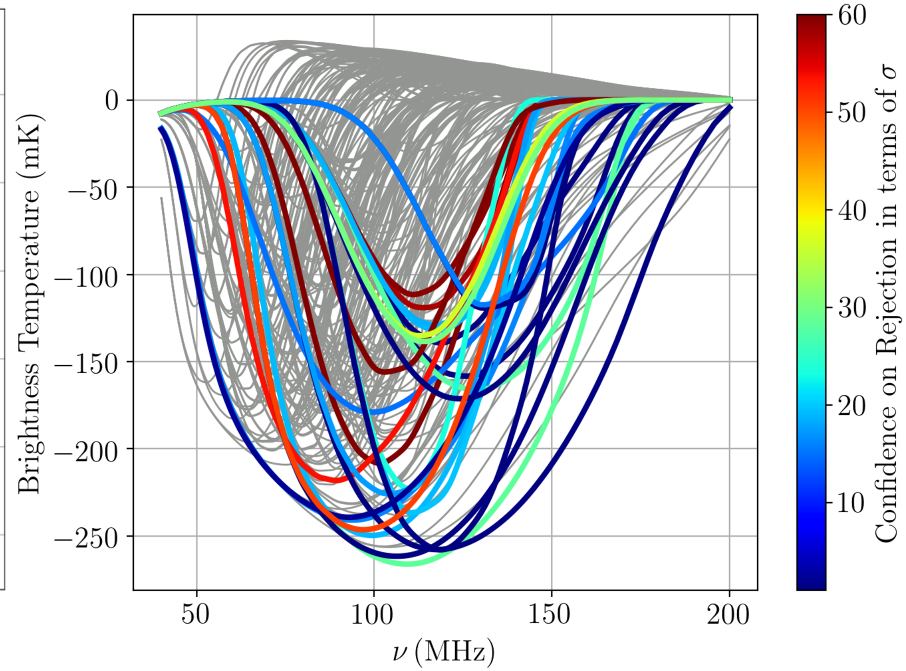
- We carry out a sensitivity test for each signal
- The data is jointly fit for foreground plus systematics with scale factor times the model

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

- We then compute coefficients for foregrounds, systematics and the scale factor along with their uncertainties
- The fitting uncertainties are used to deduce significance on the rejection, $\zeta = \left|\frac{1-\tilde{a}}{\sigma_{\tilde{a}}}\right|$

Signals disfavored





We reject roughly 10% of the theoretically predicted 21-cm signals

SS, Ravi Subrahmanyan, N. Udaya Shankar et al. 2018, ApJ, 858, 54
SS, Ravi Subrahmanyan, N. Udaya Shankar et al. 2017, ApJL, 845, L12

Scenarios disfavored by the SARAS 2

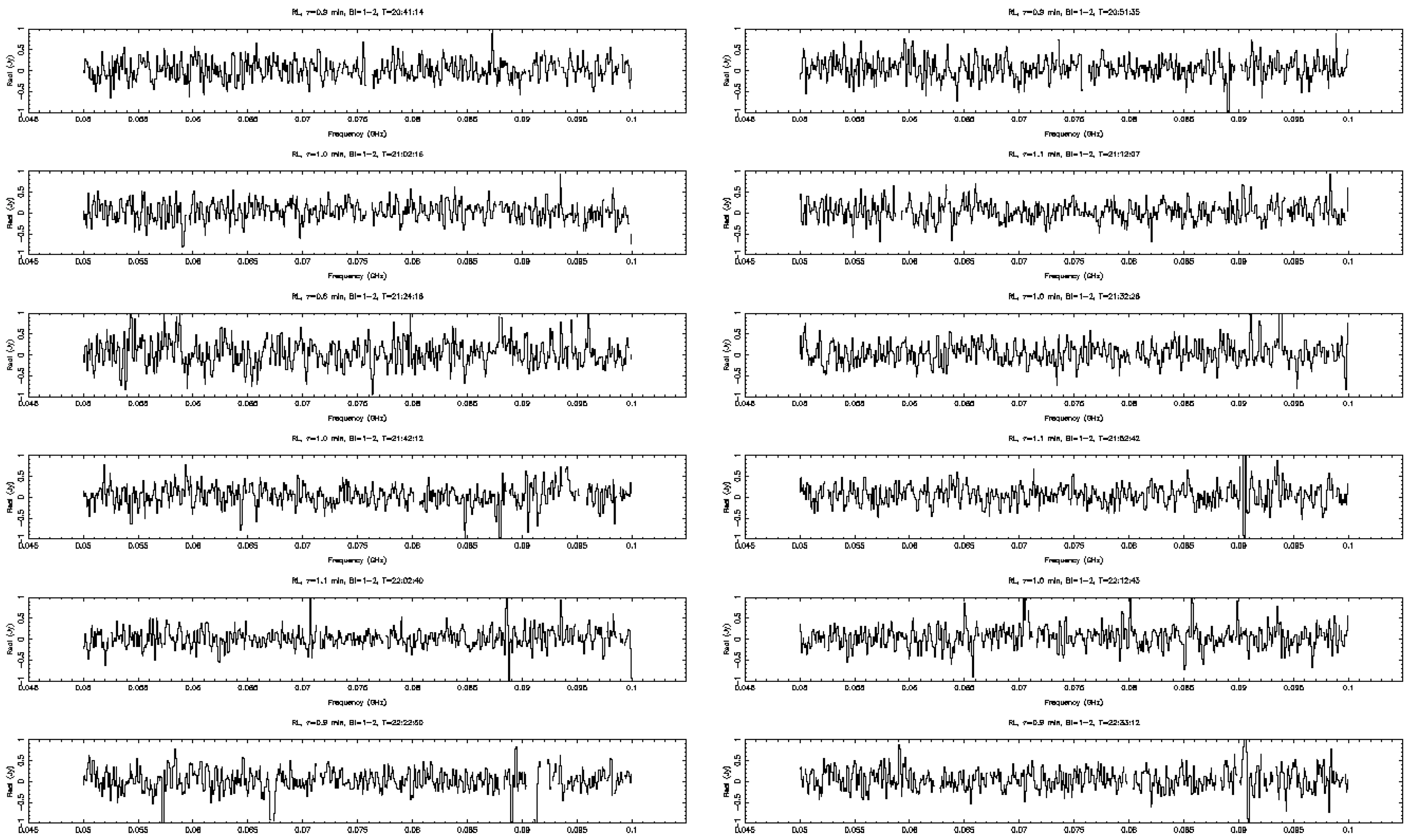
- SARAS 2 rejects the scenario of **Rapid Reionization** in tandem with either **late X-ray heating**
- Poor X-ray heating can be attributed to low X-ray efficiency f_X, defined as: $\frac{L_X}{\mathrm{SFR}} = 3 \times 10^{40} f_X \ \mathrm{erg\ s^{-1} M_\odot^{-1}\ yr.}$
- Rapid Reionization can be caused either by large mean free path of the ionizing photons, high star formation and ionizing efficiencies of the sources. The data disfavors large mean free paths (~70 Mpc)
- Data allows $f_{\mathrm{X}} > 0.1$ and $\frac{dT_b}{dz} < 120$ mK

Pathway to SARAS 3

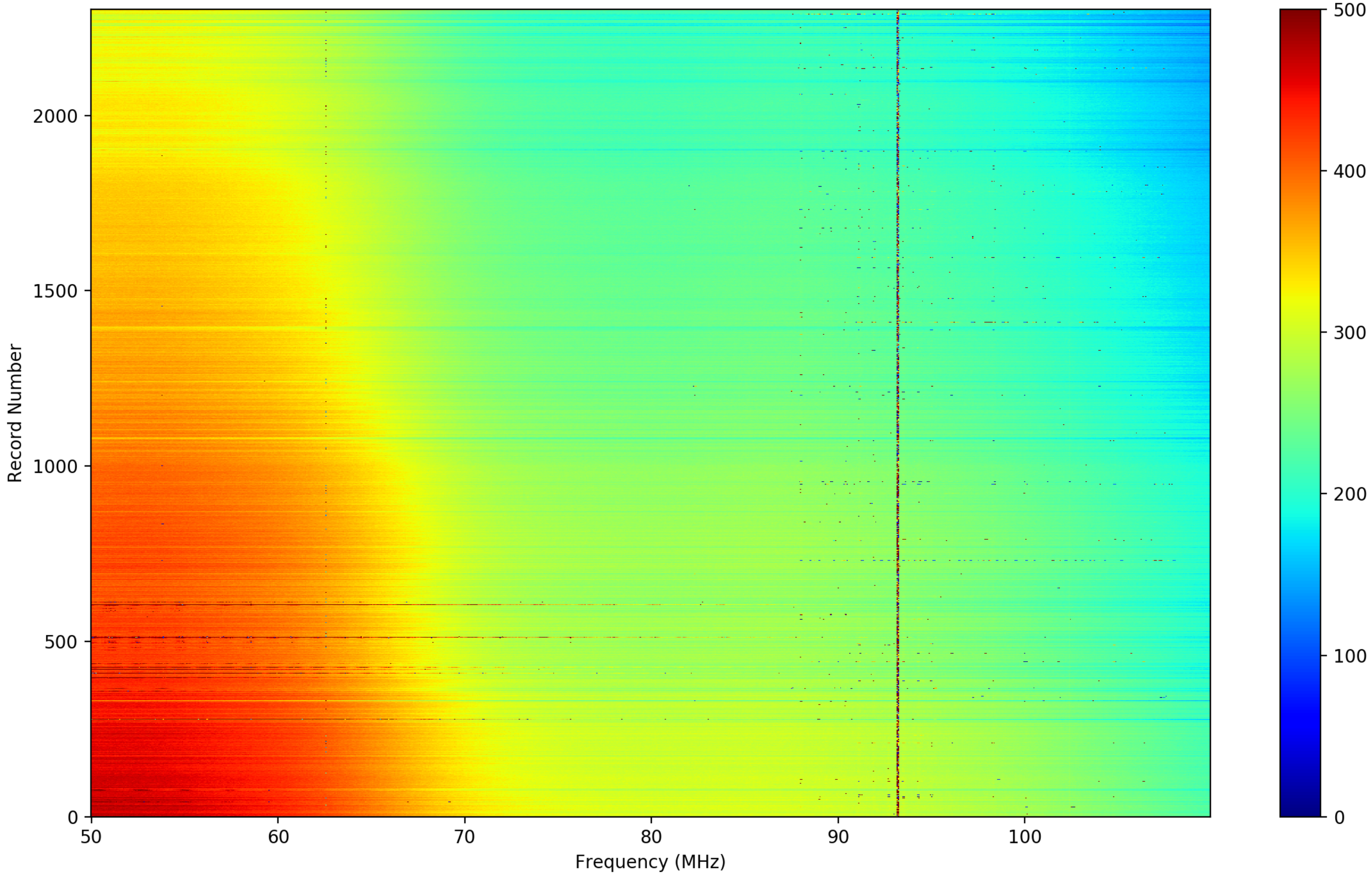
- Following up on EDGES detection, we have upgraded to SARAS 3 focusing on 50-100 MHz.
- Currently we are using two antennas: spherical monopole and discone, where the dimensions are scaled from SARAS 2
- We recently conducted observations with SARAS 3 in radio quiet location of Trans-Himalayan regions and the analysis is under progress

SARAS 3 deployed

A first look



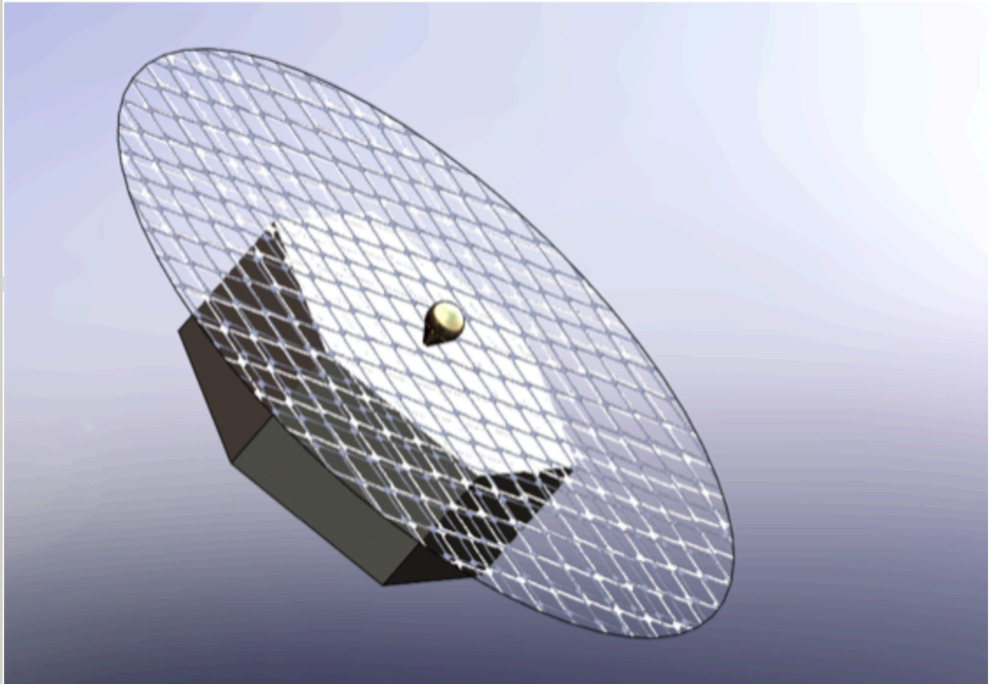
A first look

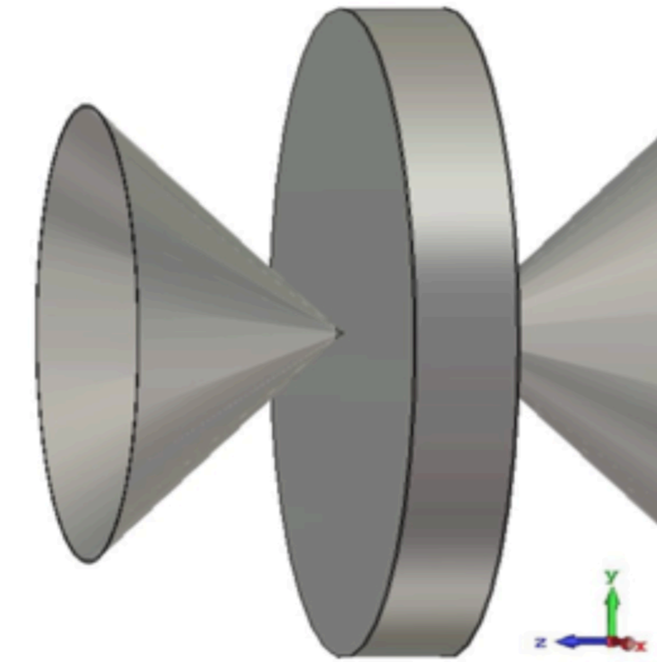


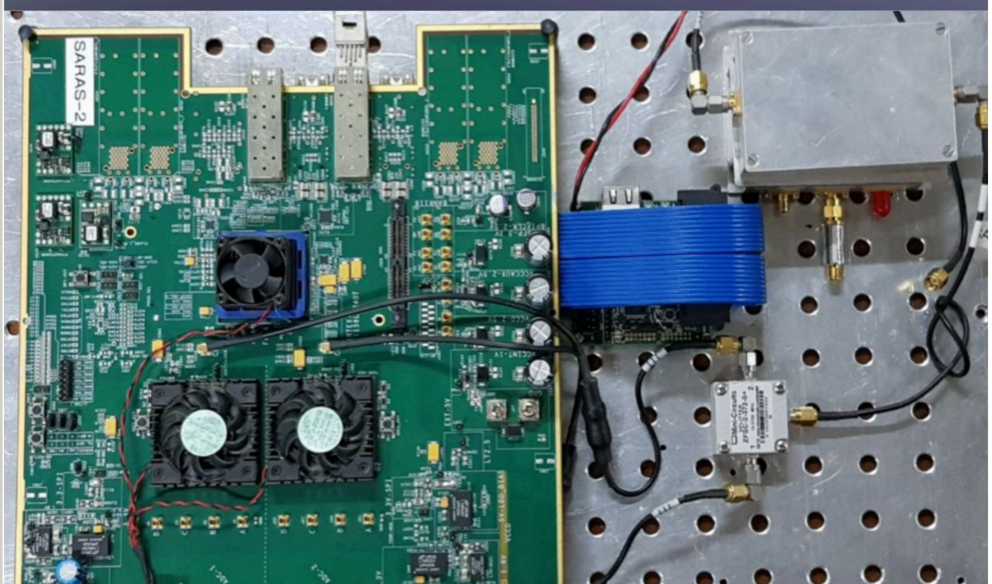
Record Number
0
500
1000
1500
2000
50
60
70
80
90
100
Frequency (MHz)
0
100
200
300
400
500

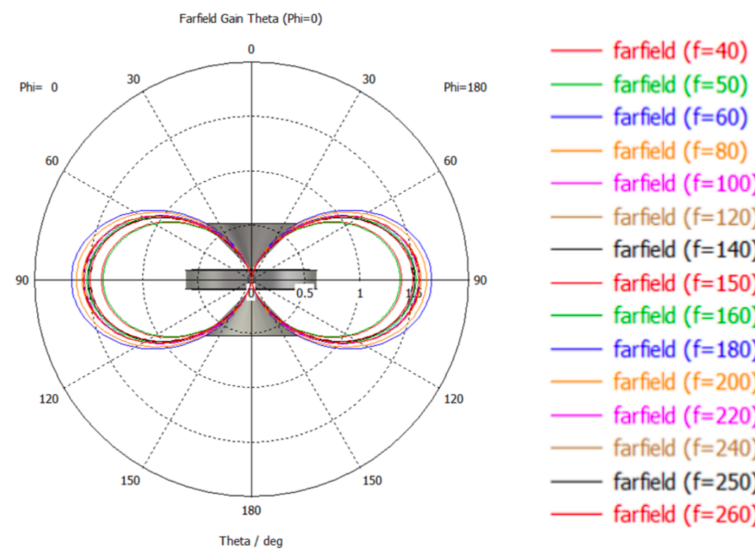
Towards space-based mission

- A space-based mission avoids many problems that are intrinsic to ground based experiments:
  - Ionospheric effects
  - Ground coupling to the antenna
  - Radio Frequency Interference (subject to orbit)
- We have proposed PRATUSH, a space based radiometer in lunar orbit for 21-cm global signal to Indian Space Research Organization (ISRO)
- It has been approved for Phase A (detailed design)
- MoU with Satellite Applications Centre to translate a lab model to a space qualified system






SARAS-2


Farfield Gain Theta (Phi=0)
Phi= 0
Phi=180
0
30
30
60
60
90
90
0.5
1
120
120
150
150
180
Theta / deg
farfield (f=40)
farfield (f=50)
farfield (f=60)
farfield (f=80)
farfield (f=100)
farfield (f=120)
farfield (f=140)
farfield (f=150)
farfield (f=160)
farfield (f=180)
farfield (f=200)
farfield (f=220)
farfield (f=240)
farfield (f=250)
farfield (f=260)

Conclusion

- SARAS 2 data has ruled out a class of theoretically predicted models of Epoch of Reionization, disfavoring scenarios of late X-ray heating and rate of reionization
- SARAS 3 has carried out observations in 50-100 MHz in light of EDGES result. Analysis in progress.
- We are also working towards building a wide-band 40-200 MHz system that is efficient over the band 40-200 MHz, preserving the spectral properties of the SARAS 2 system
- We would shortly begin development activities towards first prototype for space based radiometer