SARAS 2 constraints on global 21-cm signal

Saurabh Singh
On behalf of SARAS team

Raman Research Institute
McGill University

McGill

RRI

Members

SARAS team

- Ravi Subrahmanyan (RRI)
- N. Udaya Shankar (RRI)
- Jishnu Nambissan T. (RRI)
- Saurabh Singh (RRI/McGill)
- Mayuri Sathyanarayana Rao (RRI/LBNL)
- B. S. Girish (RRI)
- A. Raghunathan (RRI)
- R. Somashekar (RRI)
- K. S. Srivani (RRI)

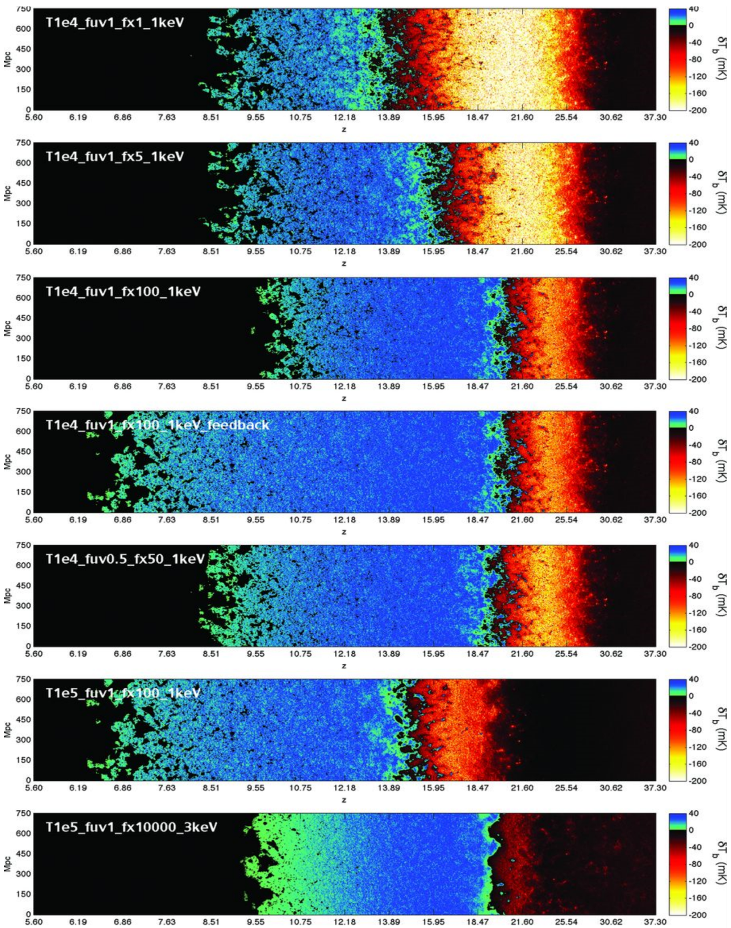
Collaborators

- Anastasia Fialkov (U. of Sussex)
- Aviad Cohen
- Rennan Barkana (Tel Aviv U.)

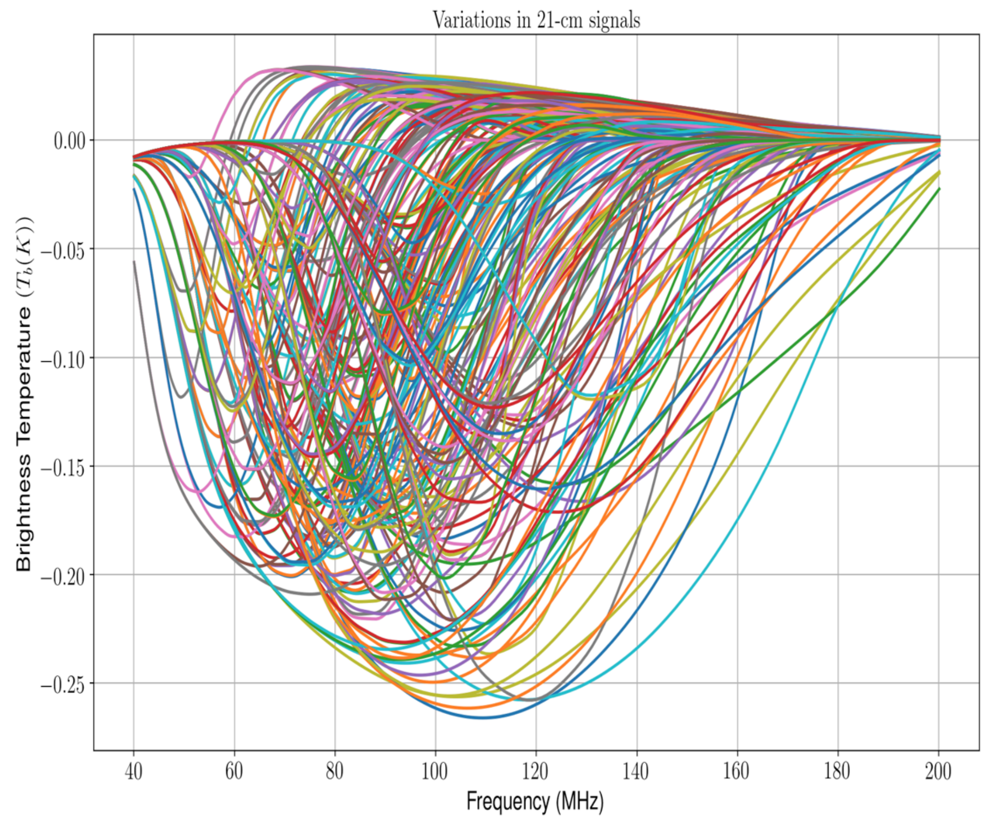
Logistical and Technical Support

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

Theoretical possibilities within “standard cosmology”

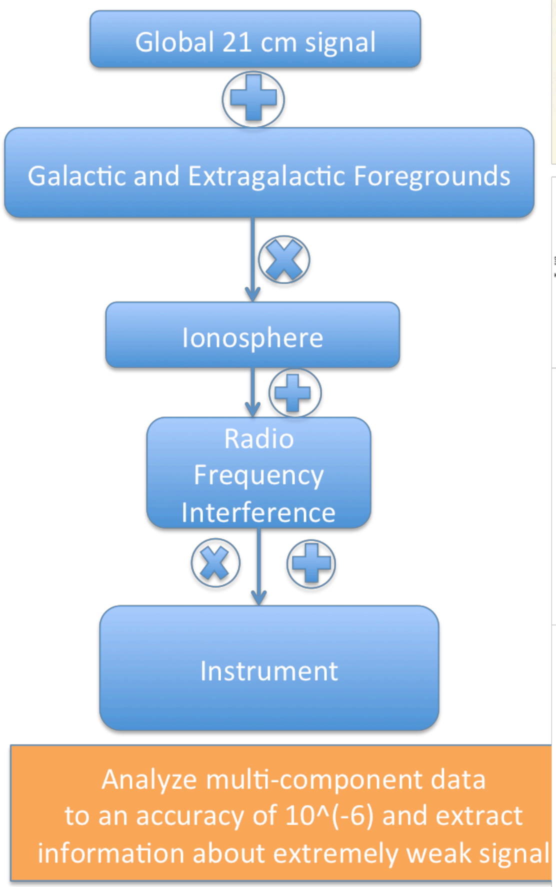


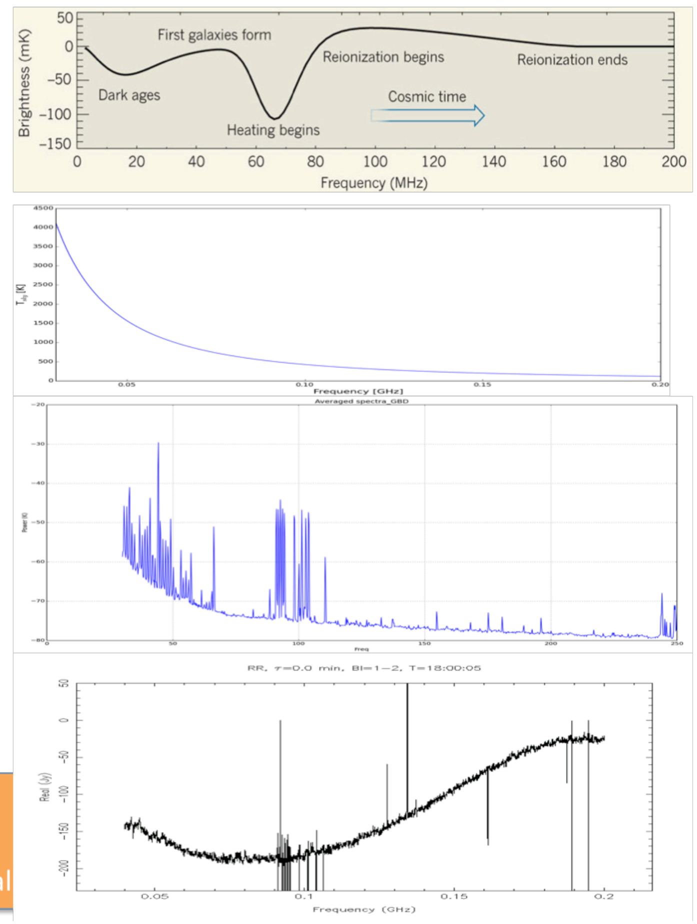
Mesigner et al. 2013



Cohen et al. 2017b

Challenges in the detection





21-cm signal
< 100s of mK

Foregrounds
100-10,000 K

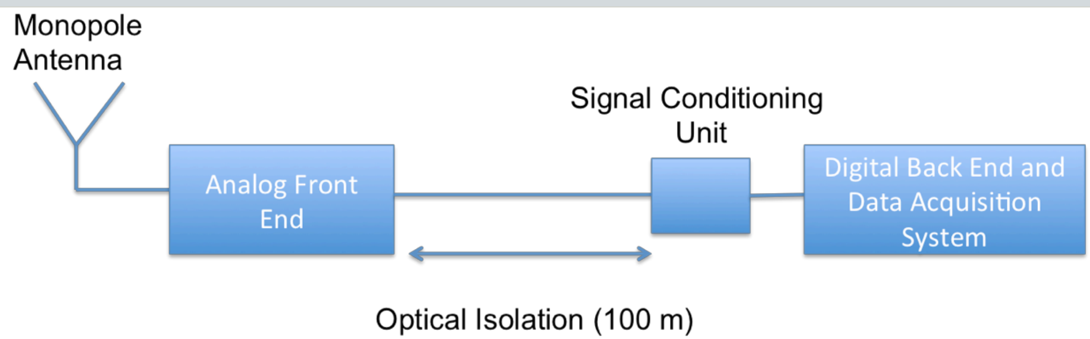
RFI
A few mK to 10,000 K and more

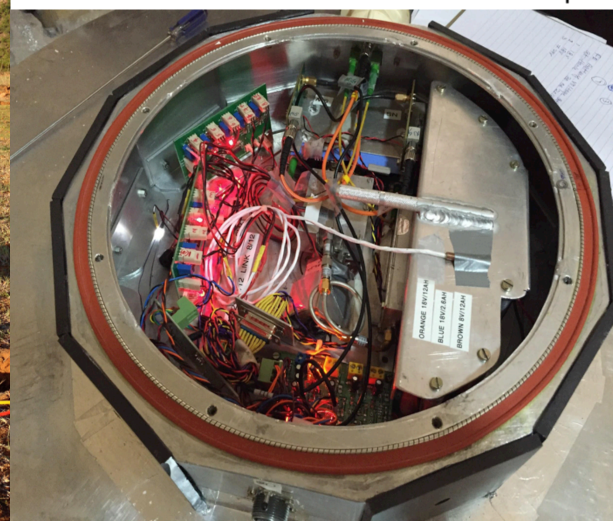
Receiver Noise
10-20 K

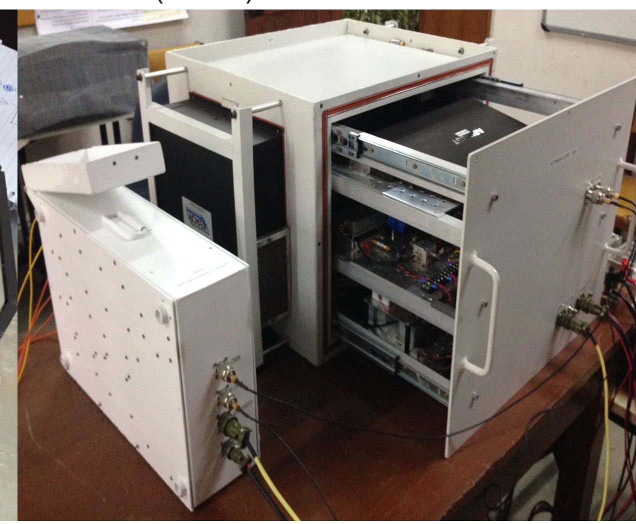
Design philosophy for the radiometer

- 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 that may mimic the signal
- We measure smoothness using 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





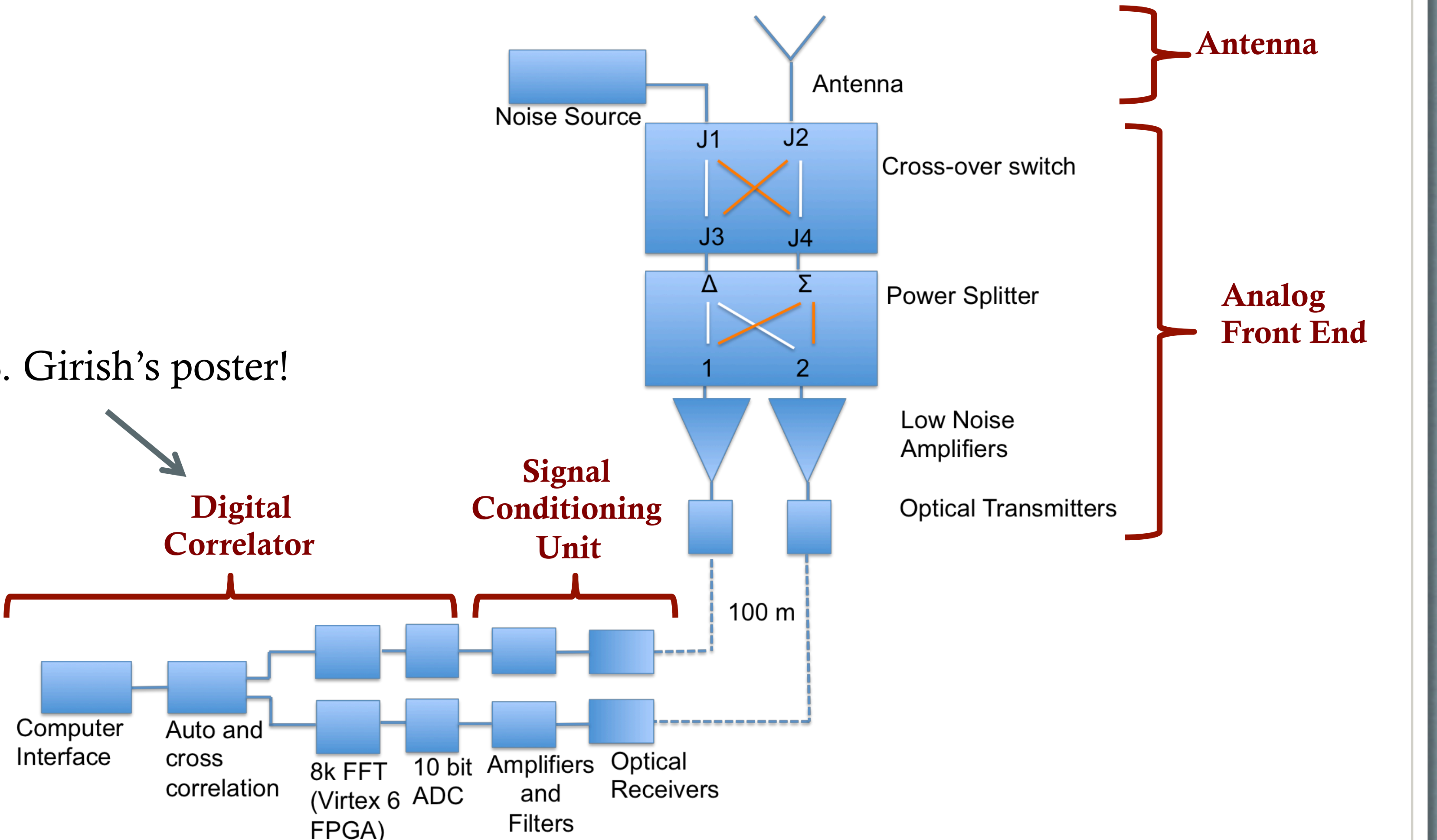


SARAS: **S**haped **A**ntenna measurement of the background **RA**dio **S**pectrum

Singh et al. 2018a

SARAS 2 radiometer

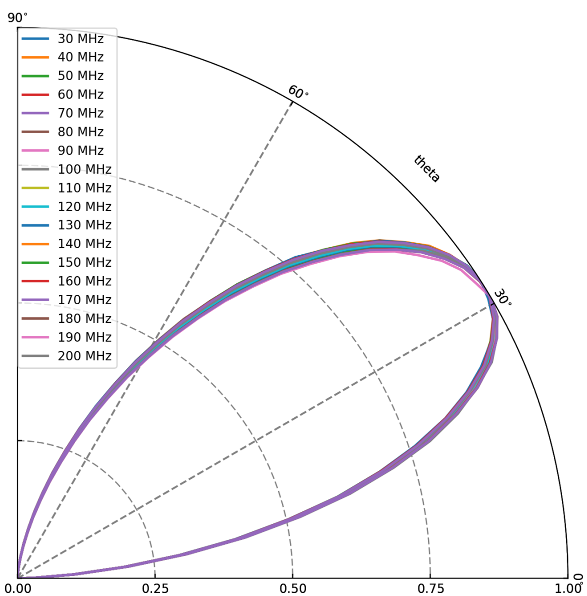
See B.S. Girish's poster!

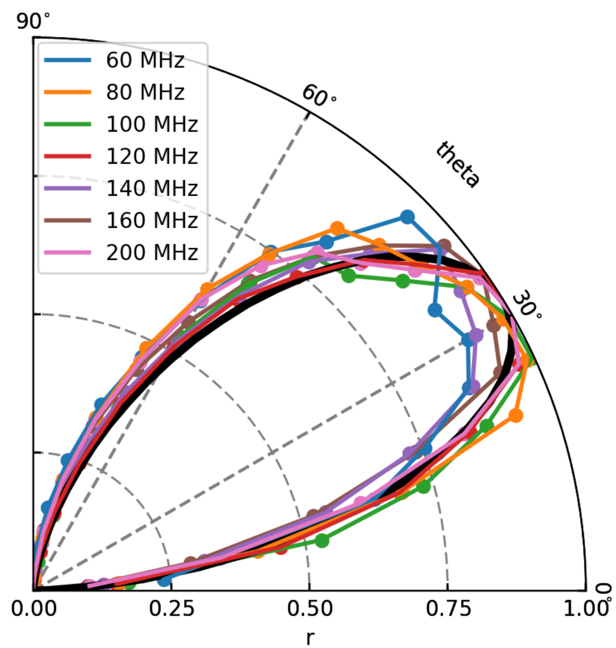


SARAS 2: control of systematics (antenna)

Antenna power pattern

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



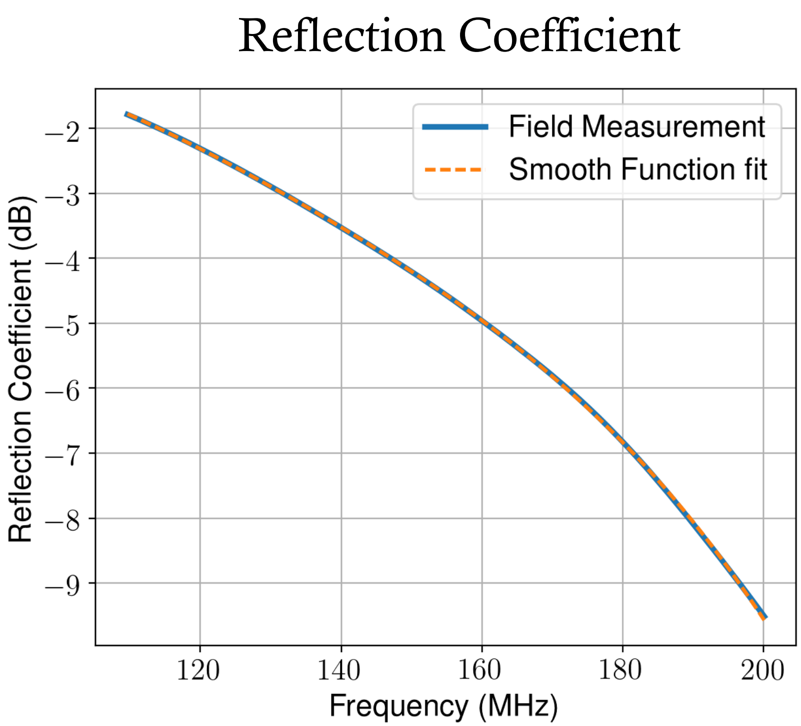


- Foreground spatial sky structure appears as frequency structure if beam is frequency dependent
- SARAS 2 antenna has been made electrically small to achieve achromatic beam

SARAS 2: control of systematics (antenna)

Antenna transfer functions

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



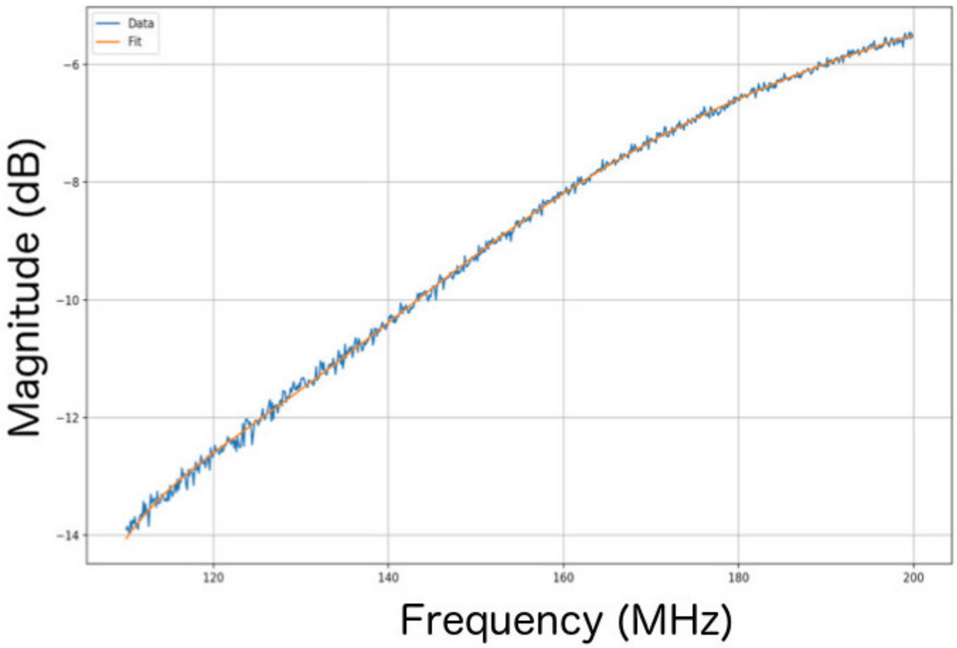
- Smoothness of reflection coefficient has been measured to 1 part in 10^4
- Since no balun is used, we do not have resistive loss in the antenna and hence no unwanted frequency characteristics

SARAS 2: control of systematics (antenna)

Antenna transfer functions

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

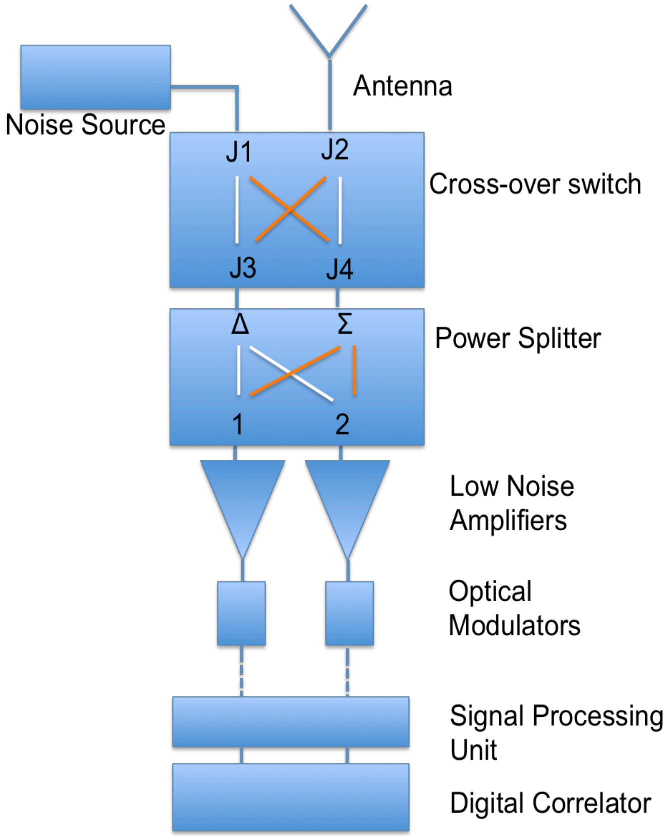
Total Efficiency



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

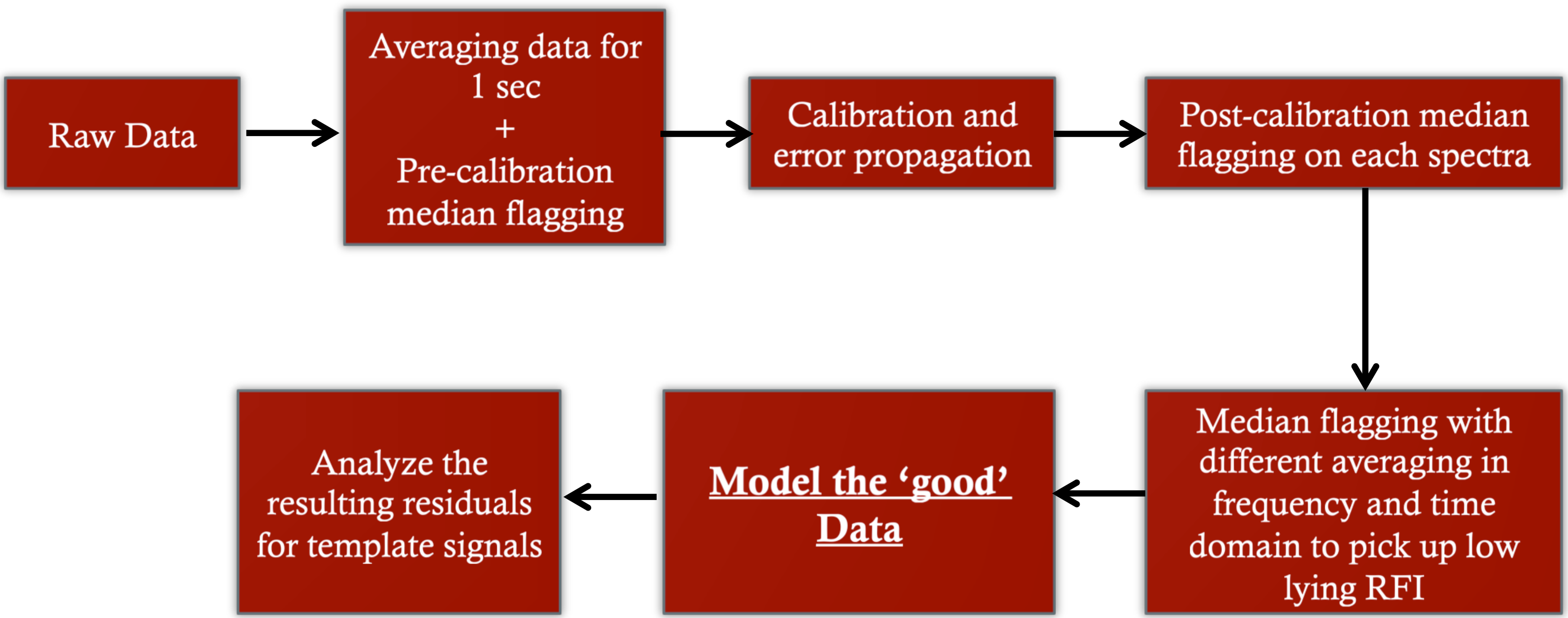
SARAS 2: control of systematics (receiver)

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, owing to extreme miniaturization

Algorithms developed for data reduction and analysis



Dual Approach to Data modeling

Measurement Equation

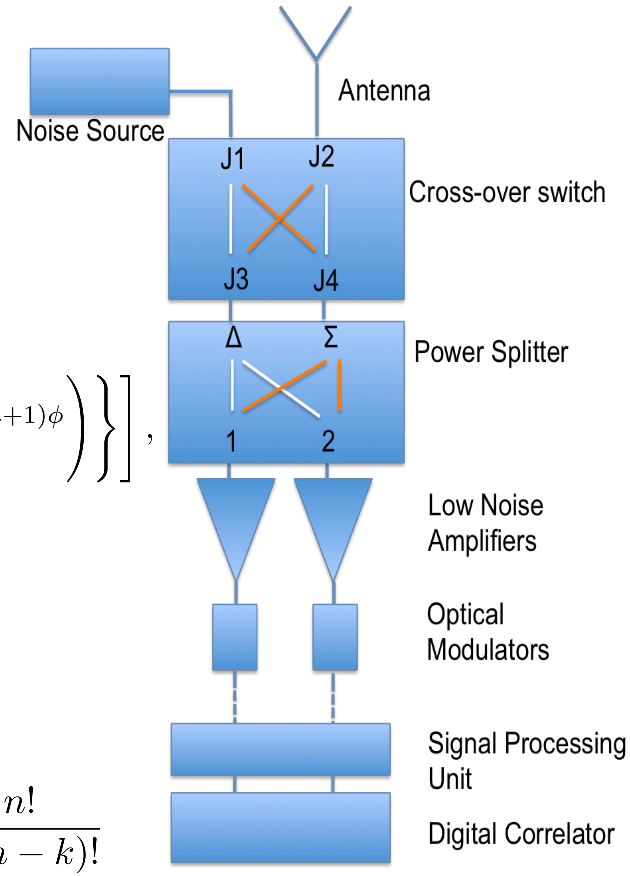
$$T_{\text{meas}} = \left[\left(\frac{C_1}{C_2} \right) T_A - T_{\text{REF}} + \left(\frac{C_{n1}}{C_2} \right) T_{\text{N}_1} + \left(\frac{C_{n2}}{C_2} \right) T_{\text{N}_2} \right], \quad \text{where}$$

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

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

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

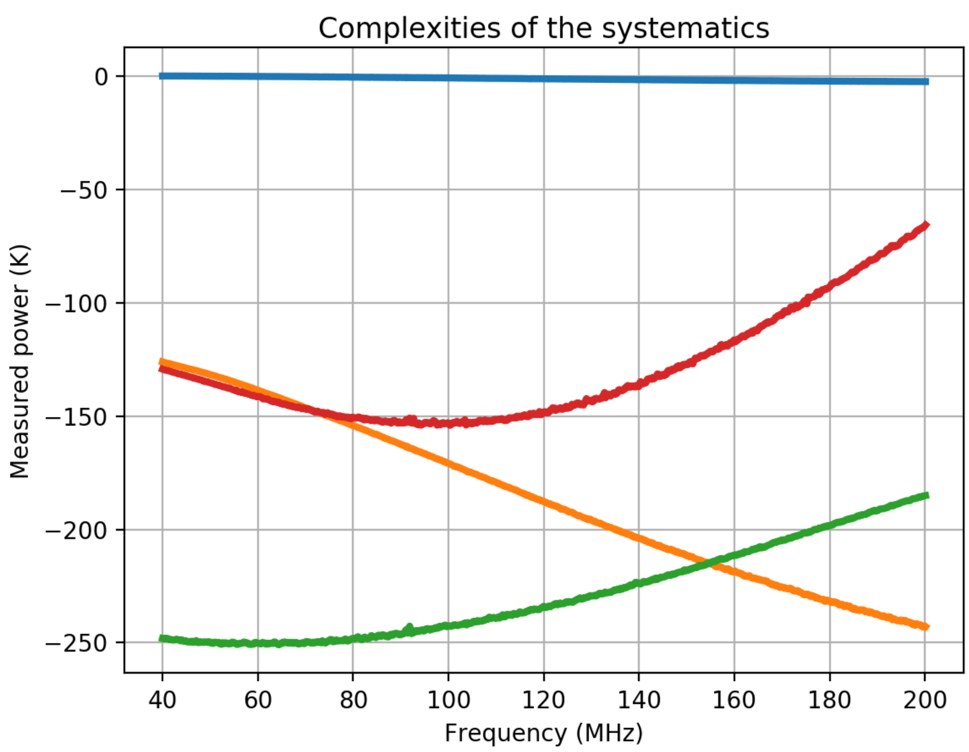
$$C_{n2} = f_2 \chi + f_2^2 |\chi|^2.$$



Maximally Smooth Functions

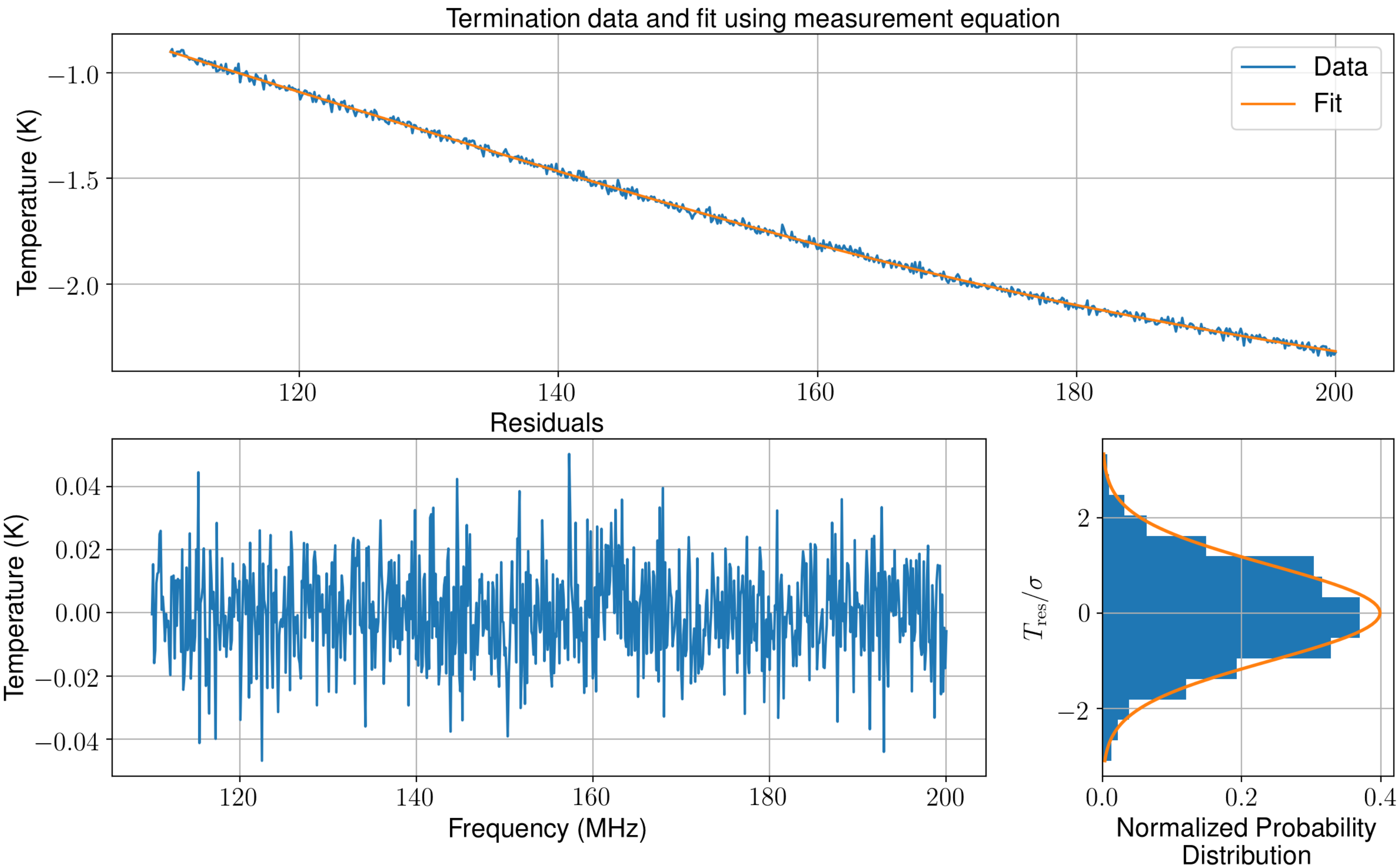
$$f(x) = a_0 + \sum_{i=1}^{n} (-1)^i (x - x_0)^i \{ \sum_{j=0}^{n-i} a_{i+j} C_j^{i+j} (x_m - x_0)^j \}, \quad C_k^n = \frac{n!}{k!(n-k)!}$$

Performance measure of SARAS 2

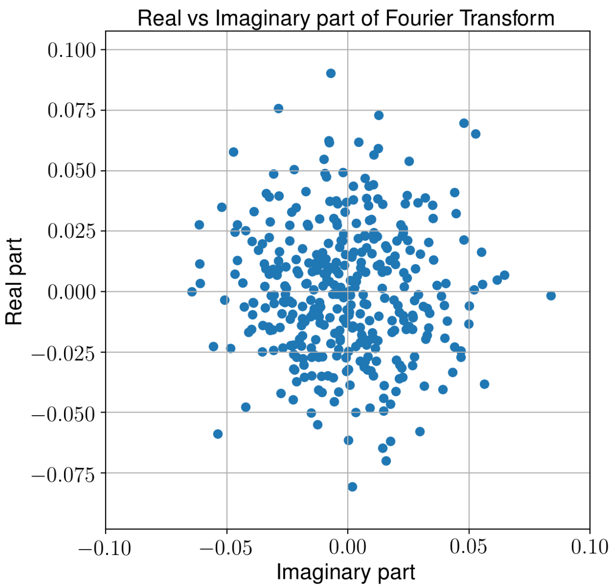


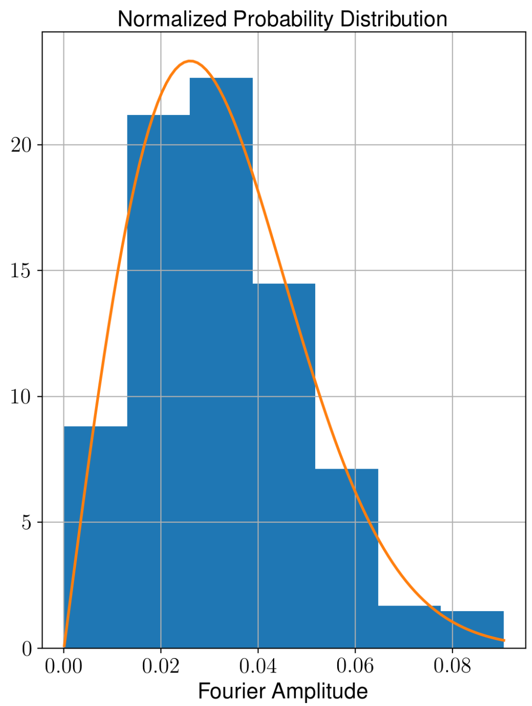
- The system was run for different terminations that replaced the antenna
- The motive of the exercise was to be able to model the internal systematics, from the most ideal case to the one closely resembling in impedance of antenna

Performance measure of SARAS 2



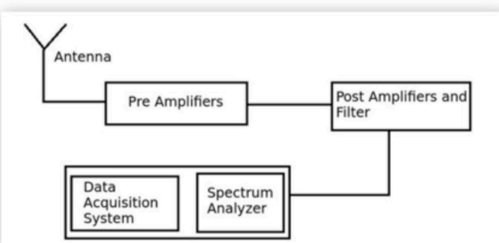
Performance measure of SARAS 2

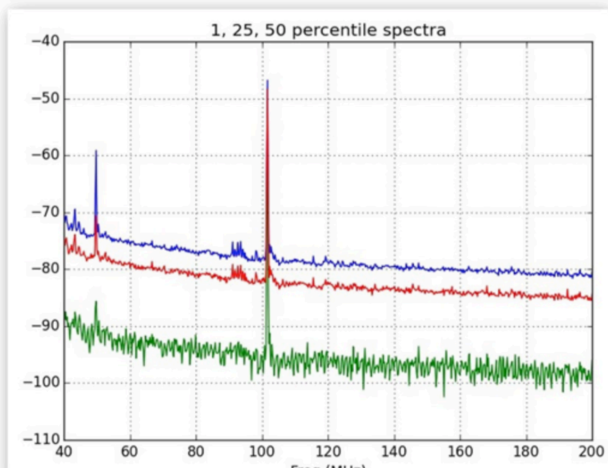




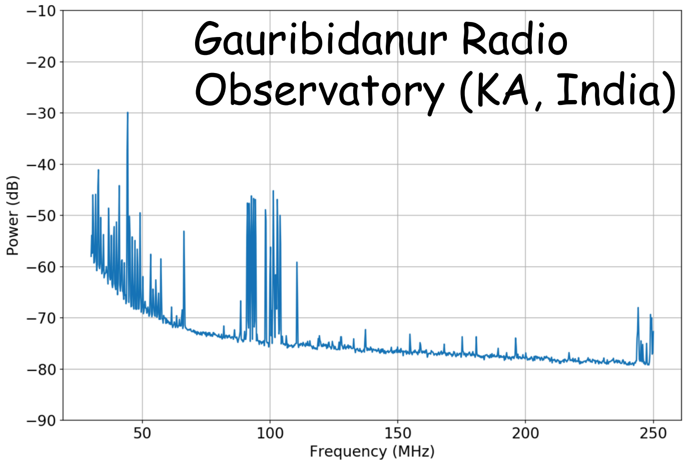
- Modeling of internal additives leave no residuals with Fourier amplitudes exceeding 2 mK
- Thus SARAS 2 system is capable of detection of complex 21-cm profiles

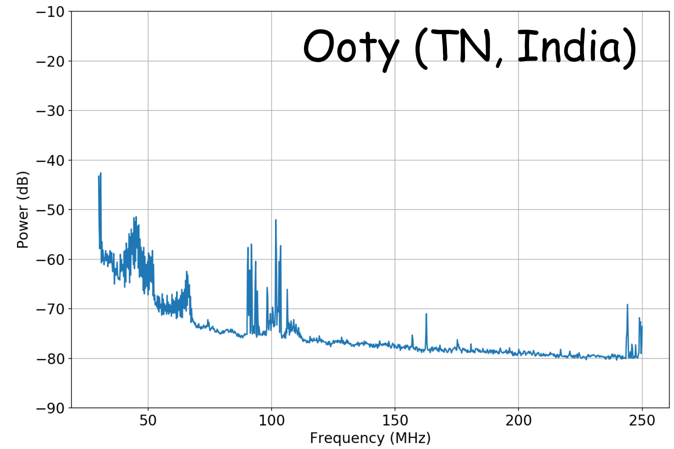
Locating an observing site

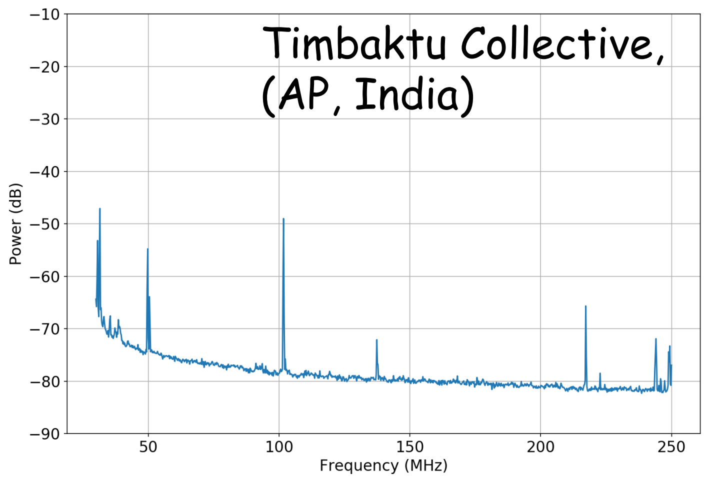


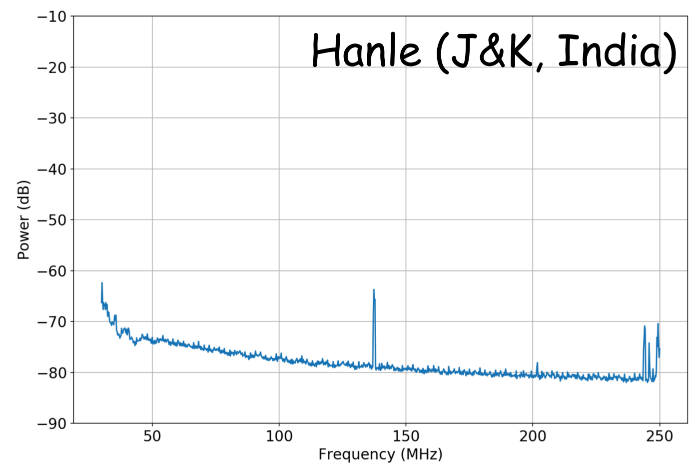


Locating an observing site



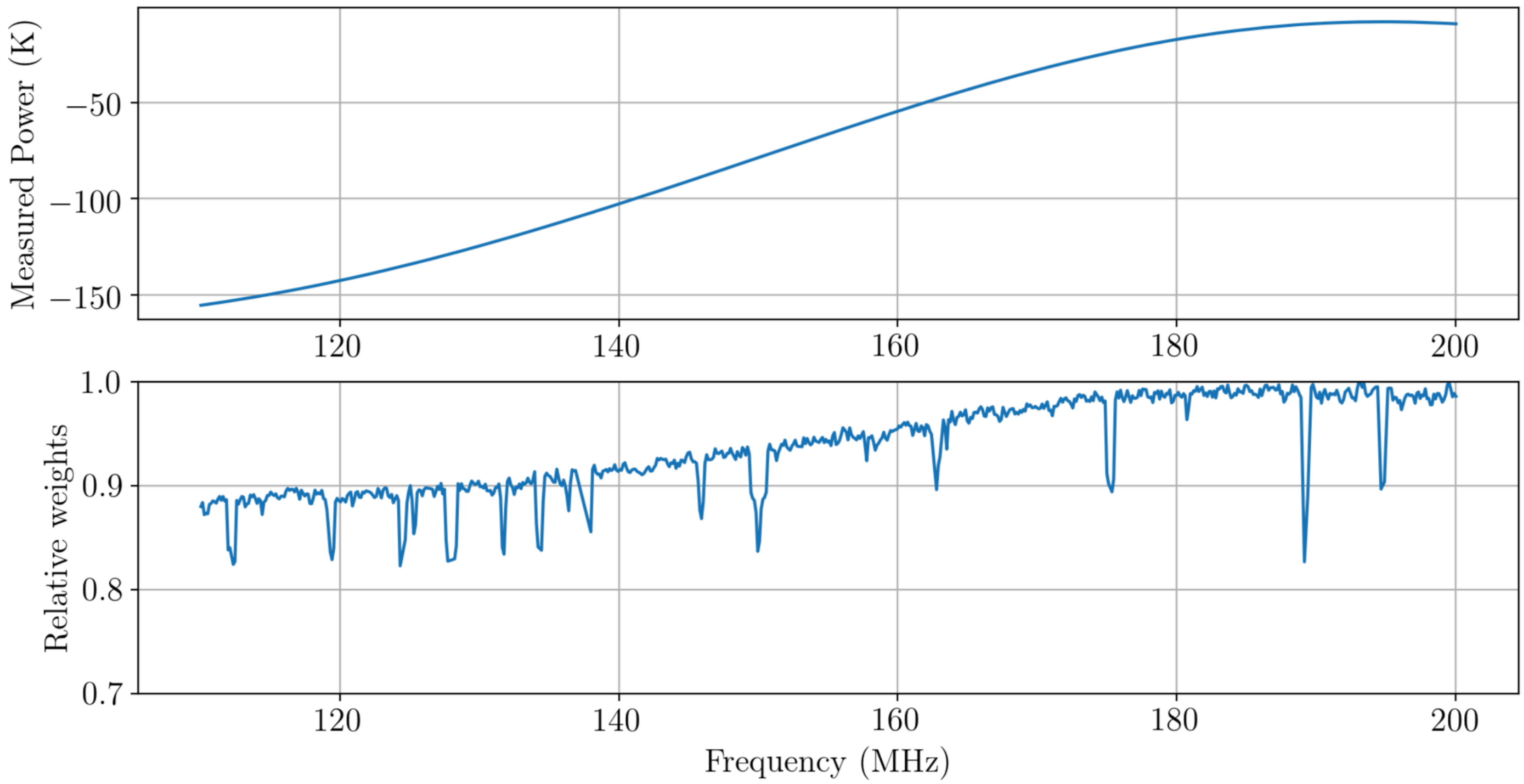






SARAS 2 ready to watch the sky!

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

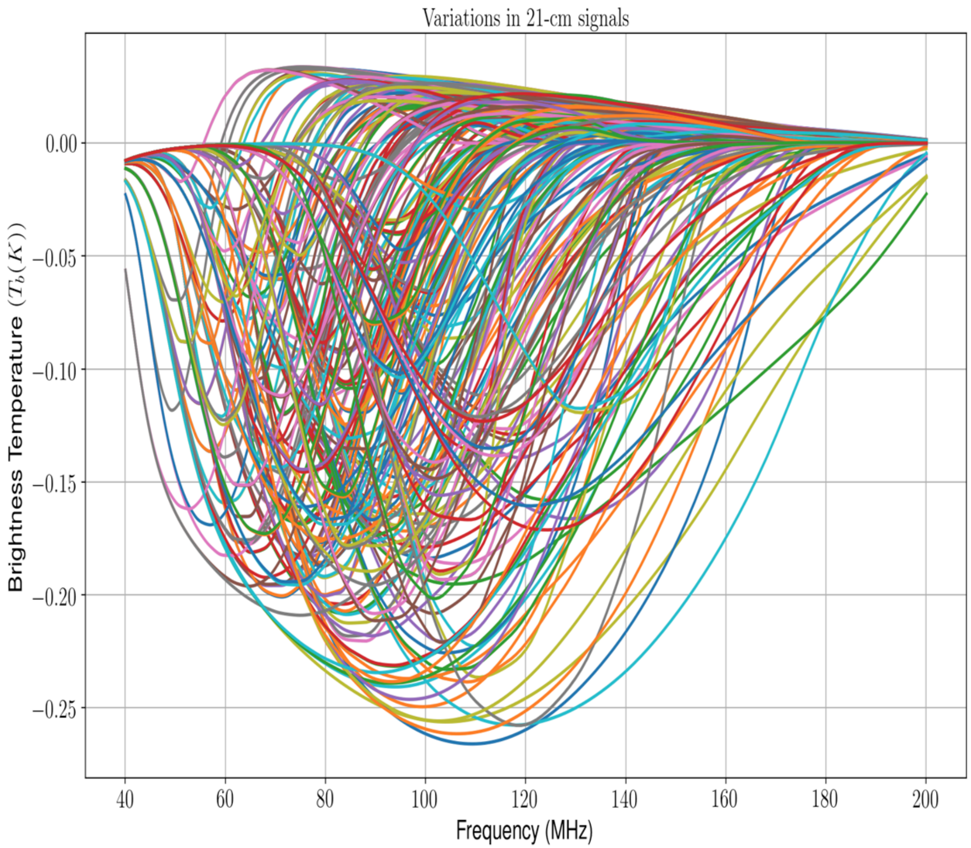
Constraining EoR through SARAS 2 data

Parameters varied:

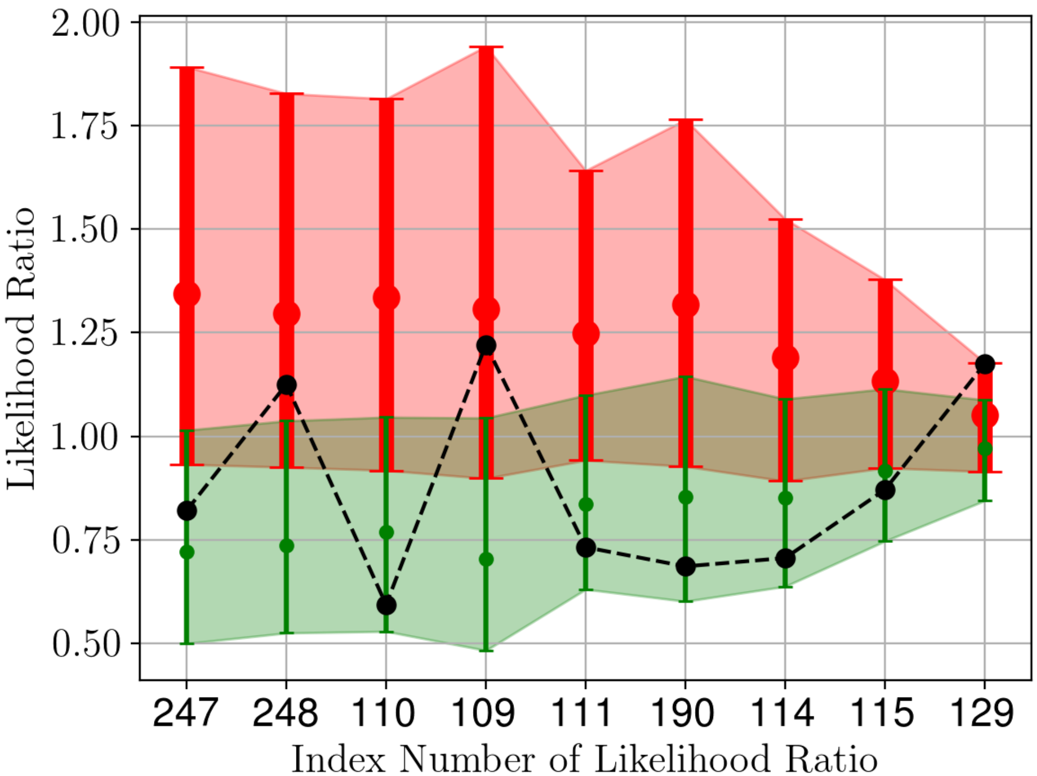
- Minimum mass of halos for star formation
- Star formation efficiency
- SED
- X-ray efficiency
- Optical depth to reionization

Examining data for templates

- 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

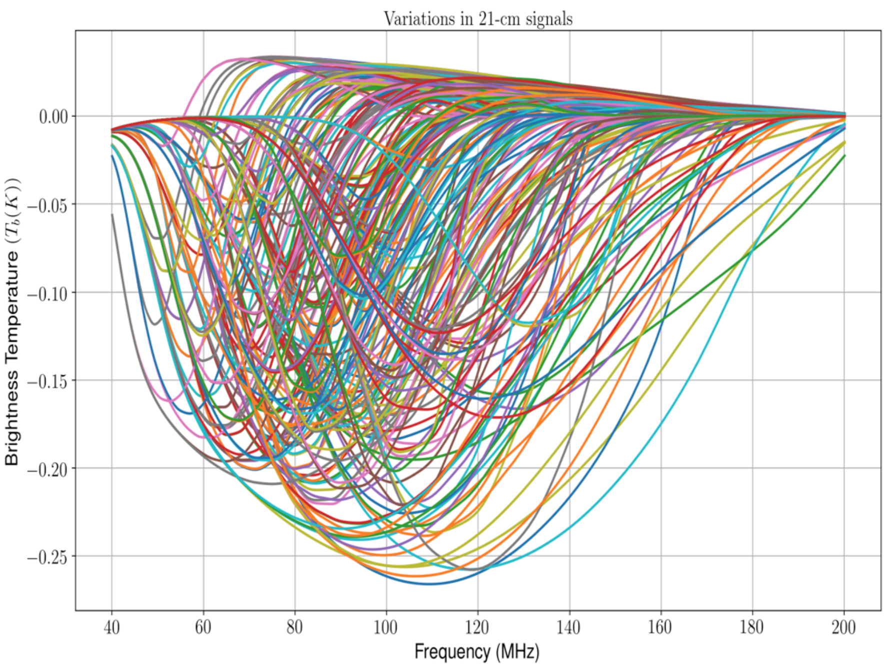
Foreword modeling approach

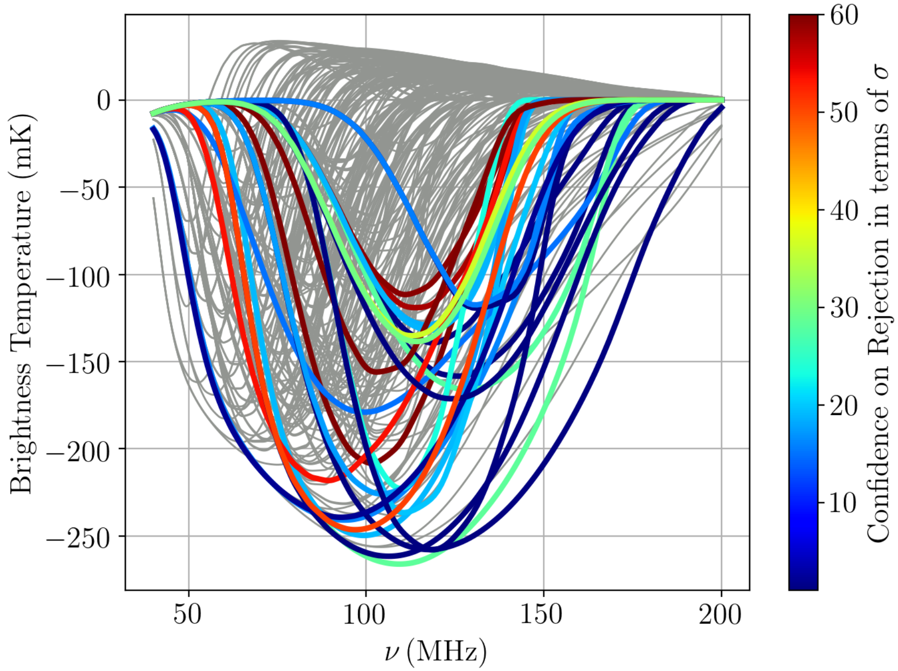
- We carry out a sensitivity test for each signal
- The data is jointly fit for foreground plus systematics with scale factor times the model

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

- 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 ~10% of the theoretically predicted 21-cm signals

Singh et al. 2018b
Singh et al. 2017

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

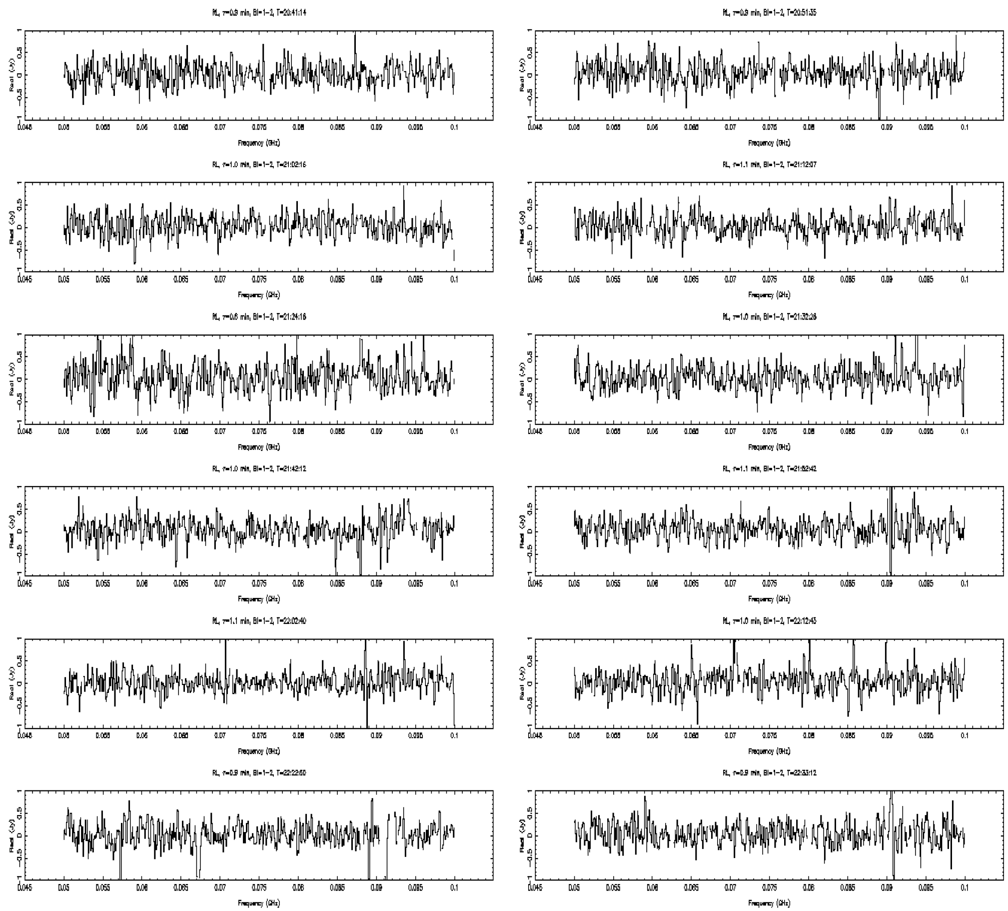
Pathway to SARAS 3

- 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 test observations with SARAS 3 in Timbaktu Collective and radio quiet location near Indian Astronomical Observatory, Hanle (Leh-Ladakh, J&K)

SARAS 3 test deployment

SARAS 3 test deployment

- The test observations were carried out with two antennas sequentially, spanning over 14 days
- Based on the analysis, we have upgraded the system, and plan to re-deploy this summer, when the site becomes accessible again

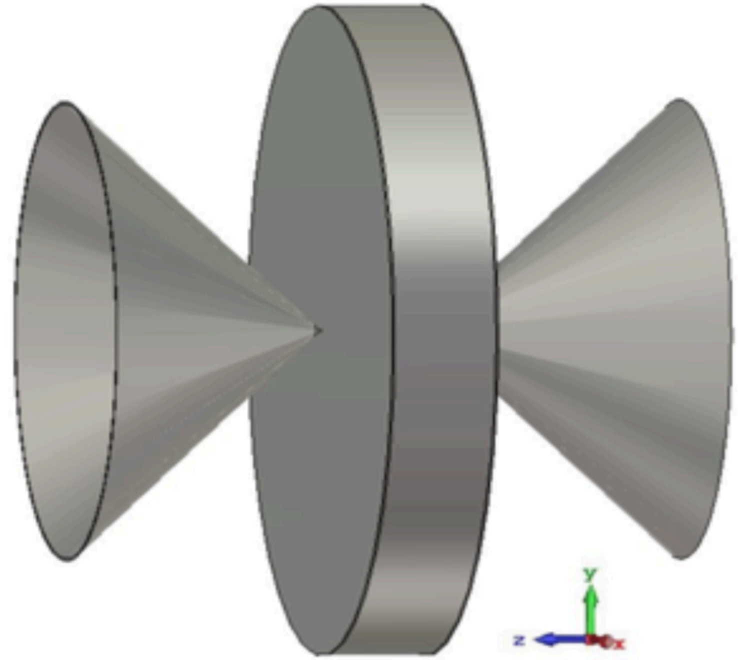


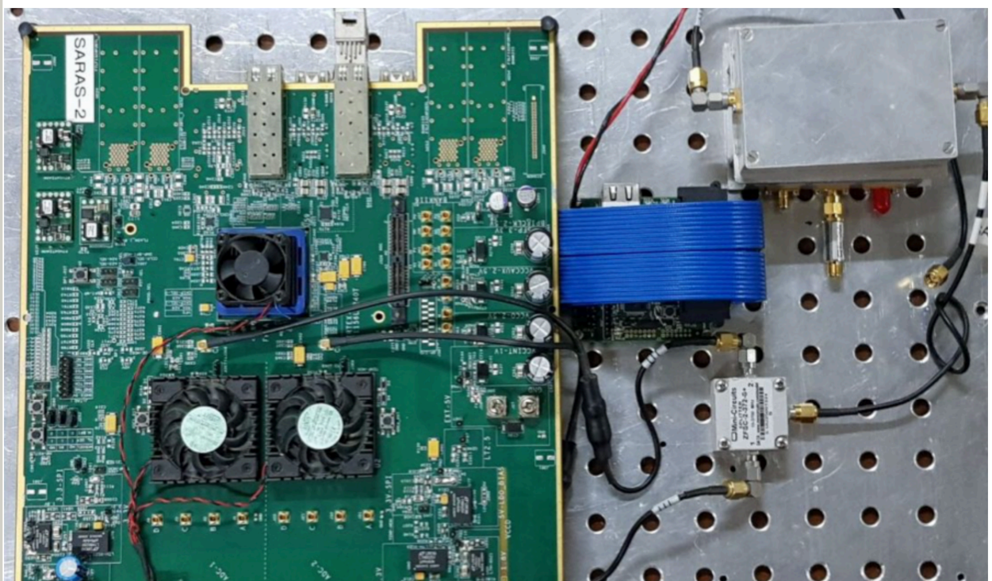
Towards a space-based mission

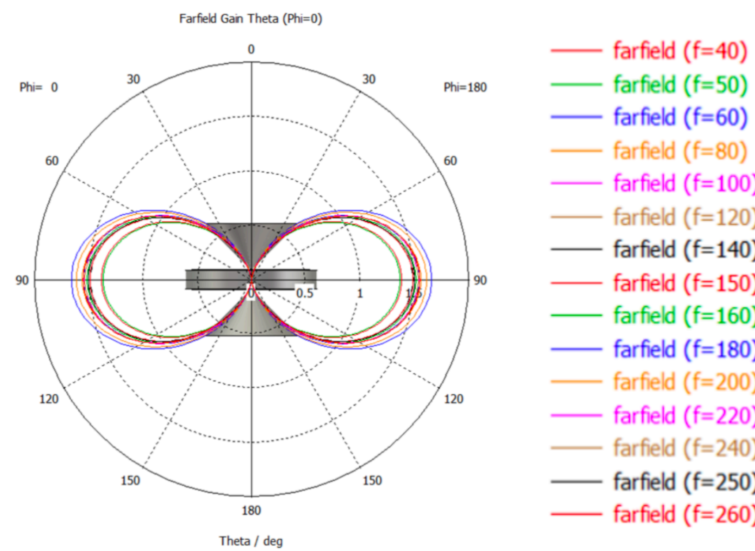
- A space-based mission avoids many problems that are intrinsic to ground based experiments:
  - Ionospheric effects
  - Ground coupling to the antenna
  - Radio Frequency Interference (subject to orbit)
- We have proposed PRATUSH*, a space based radiometer, operating in 50-200 MHz band, in lunar orbit for detection of 21-cm global signal to Indian Space Research Organization (ISRO),
- Seed funding has been awarded for Phase A (pre-project activities)
- MoU with Satellite Applications Centre (ISRO) has been signed to translate a lab model to a space qualified system

*__P__robing __R__eioniz__AT__ion of the __U__niverse using __S__ignal from __H__ydrogen
Proposers: Jishnu N., Mayuri S., Saurabh S.

- We are refining antenna design, and planning modifications in the existing digital system for PRATUSH







Conclusion

- SARAS 2 data (110-200 MHz) has ruled out a class of theoretically predicted models of Epoch of Reionization, disfavoring scenarios of late X-ray heating and rapid reionization.
- SARAS 3 has carried out test observations in 50-100 MHz. Based on analysis, we have improved the system and plan the science deployment in summer 2019.
- We would soon begin development activities towards first prototype for space based radiometer, operating in 50-200 MHz.