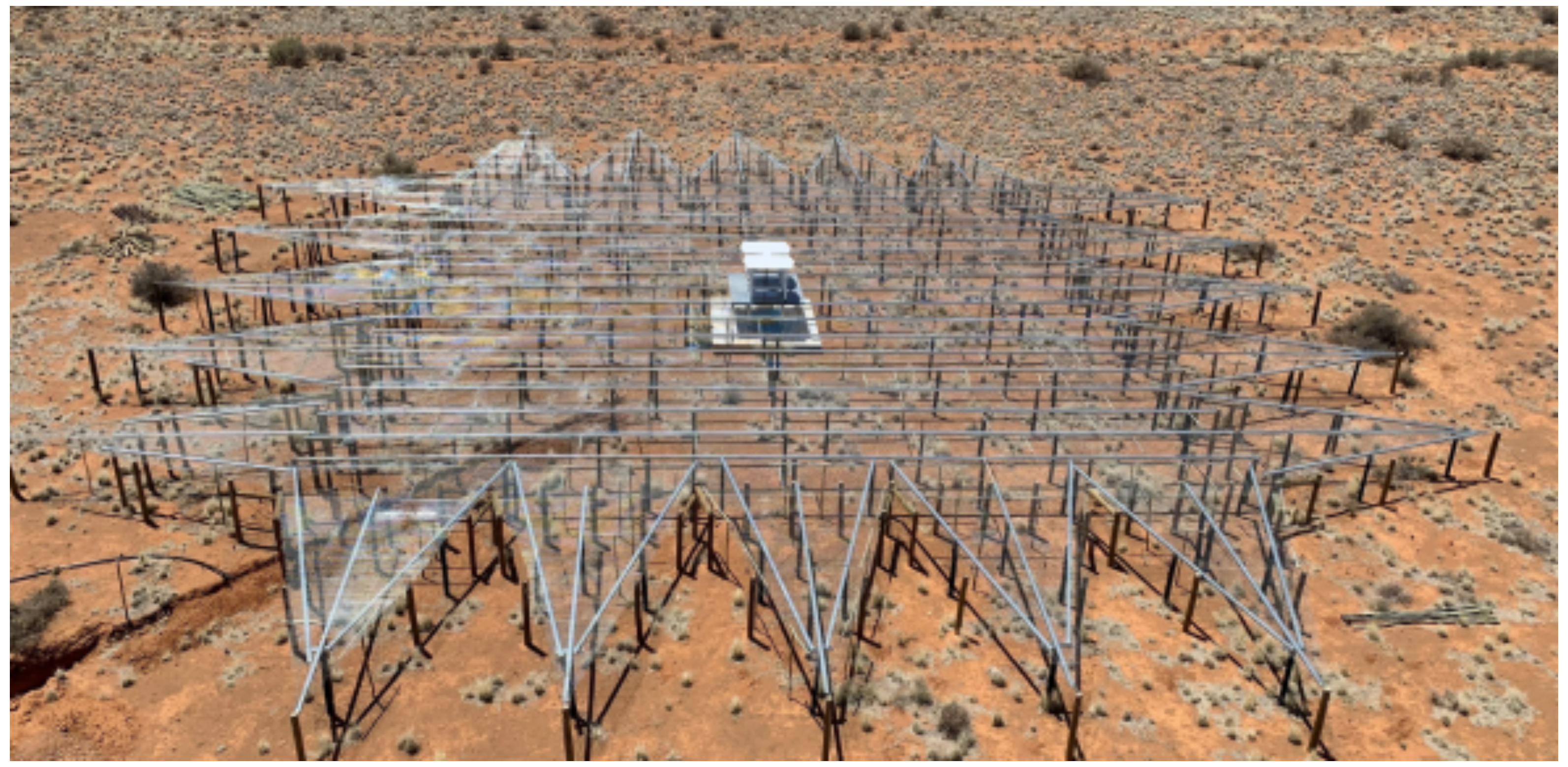
Calibration for 21cm Cosmology

Harry Bevins
And REACH collaboration

Contents

- Calibrating 21cm experiments
- Calibrating REACH
- Calibrating CosmoCube?



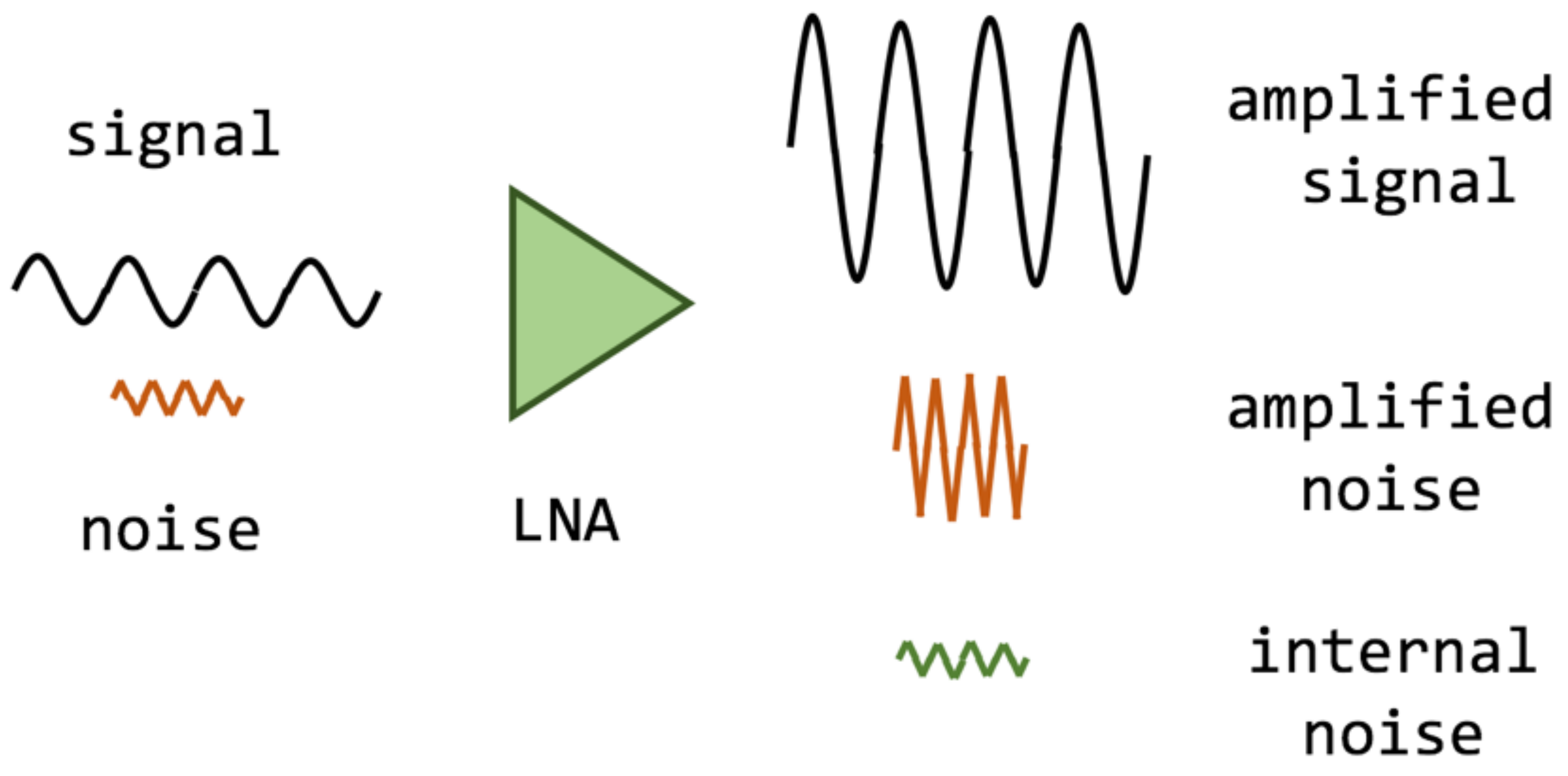
How do we calibrate a sky-averaged 21cm experiment?

What do we measure?

- Stick a metal antenna in a remote location
- Radio waves make the electrons in the metal wiggle around
- Sets up a current on the blades and we measure a voltage that oscillates at the frequency of the incoming waves
- But this signal is very weak, a function of time not frequency and we really want the sky temperature in Kelvin

Low Noise Amplifier

- We need to amplify the signal in a way that does not degrade the signal-to-noise
- Place the LNA before the spectrometer
- LNAs have a high gain but a low noise figure
- They amplify input noise and signal and introduce very little additional noise

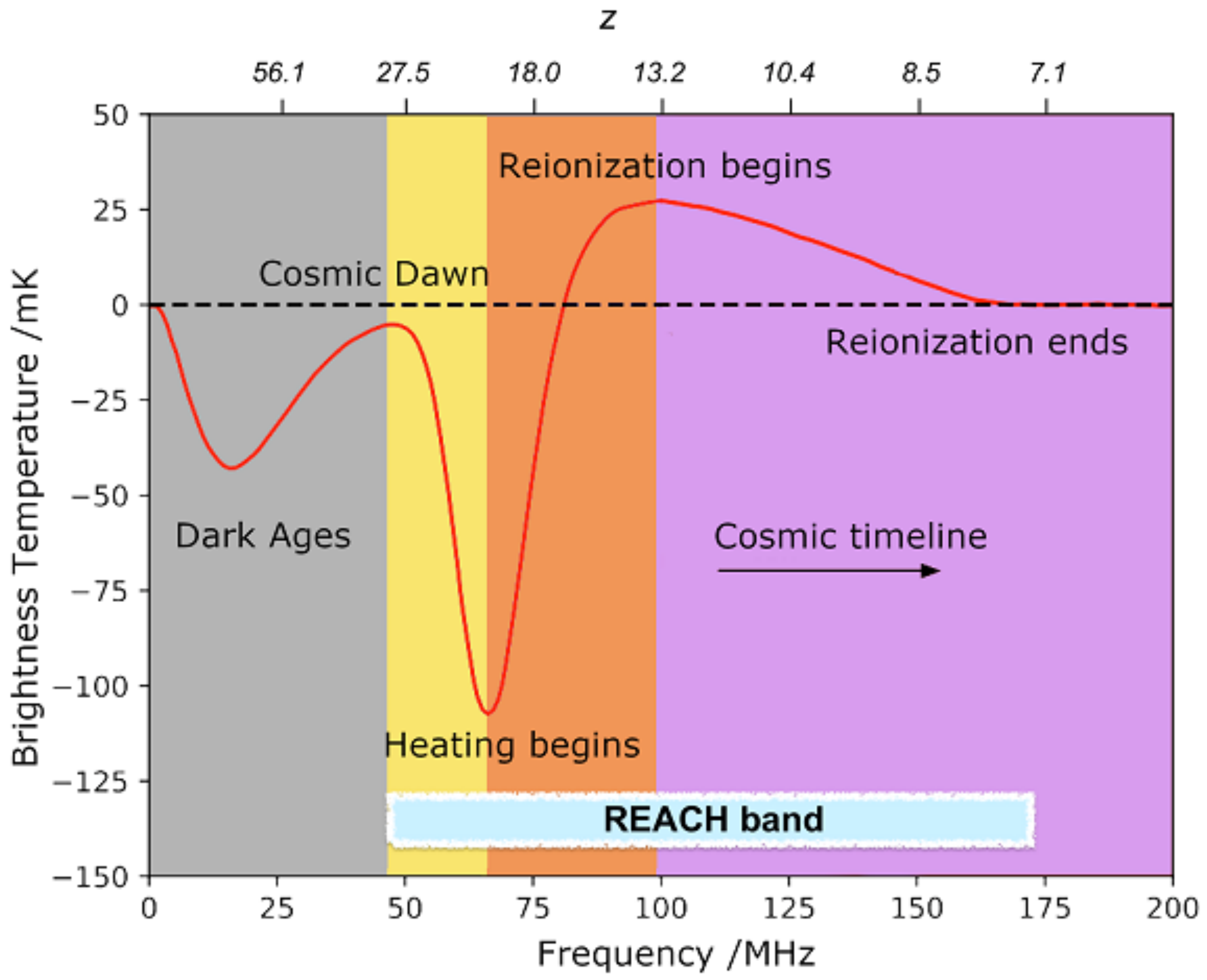


Spectrometer and Power

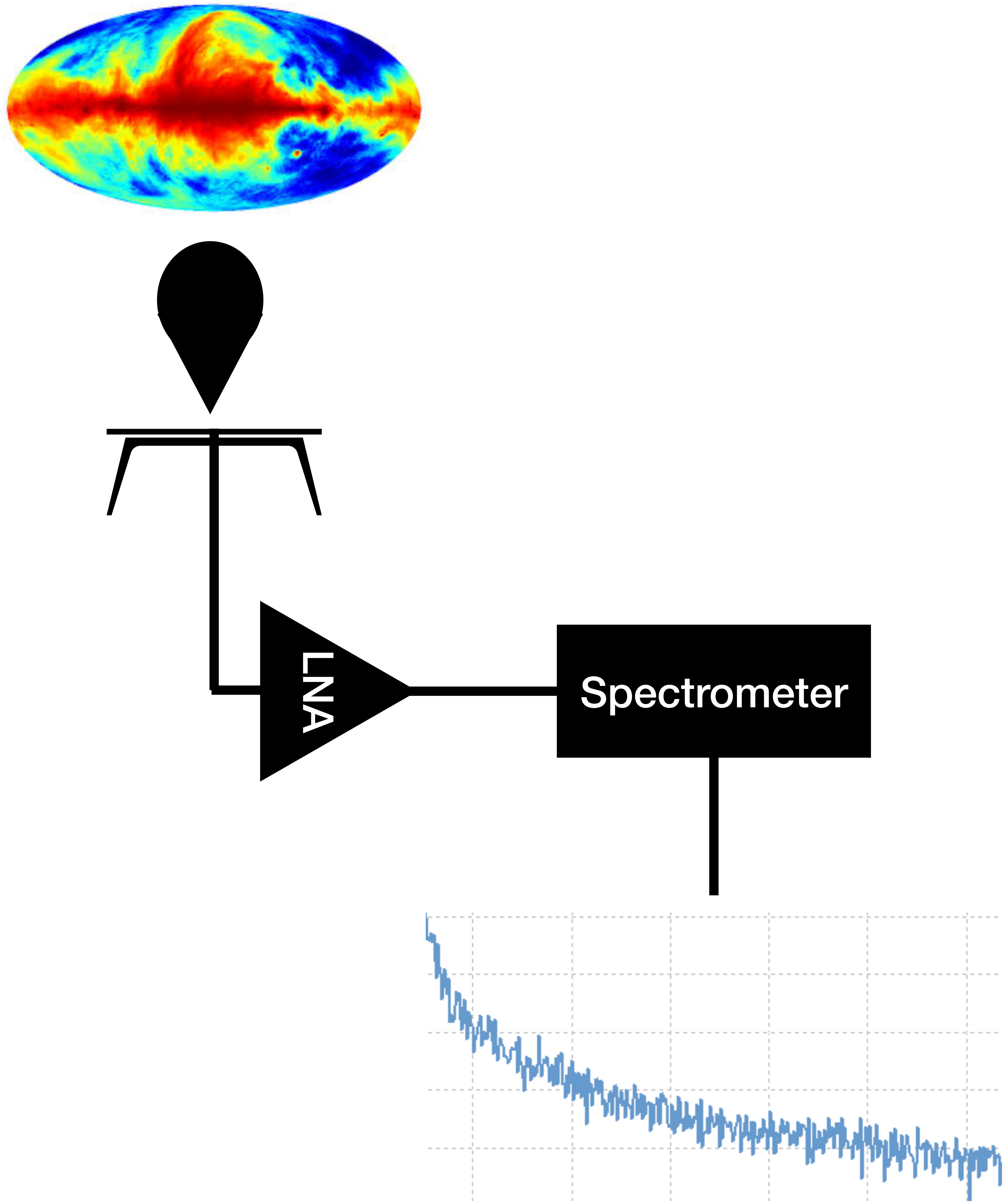
- We measure an amplified voltage as a function of time
- We want temperature as a function of frequency so that we can extract redshift information
- Fourier transform the signal and convert into a power spectral density

$$V(\nu) = \int v(t) e^{-i2\pi\nu t} dt$$

$$P(\nu) \propto |V(\nu)|^2$$



The issue?



- We want T_{sky} what we get is

$$P_{\text{ant}} = gM(T_{\text{ant}} + T_{\text{rec}})$$

- T_{sky} and T_{ant} are related by the beam of the antenna (see Dominic's talk)

- g is the frequency dependent gain of the receiver chain

- M includes measured information about the reflection coefficients of the antenna

- T_{rec} is power added by the LNA and other components in the receiver chain

- Need references to solve for g and T_{rec}

The issue?

Measured

$$P_{\text{ant}} = gM(T_{\text{ant}} + T_{\text{rec}})$$

Unknowns?

What we want

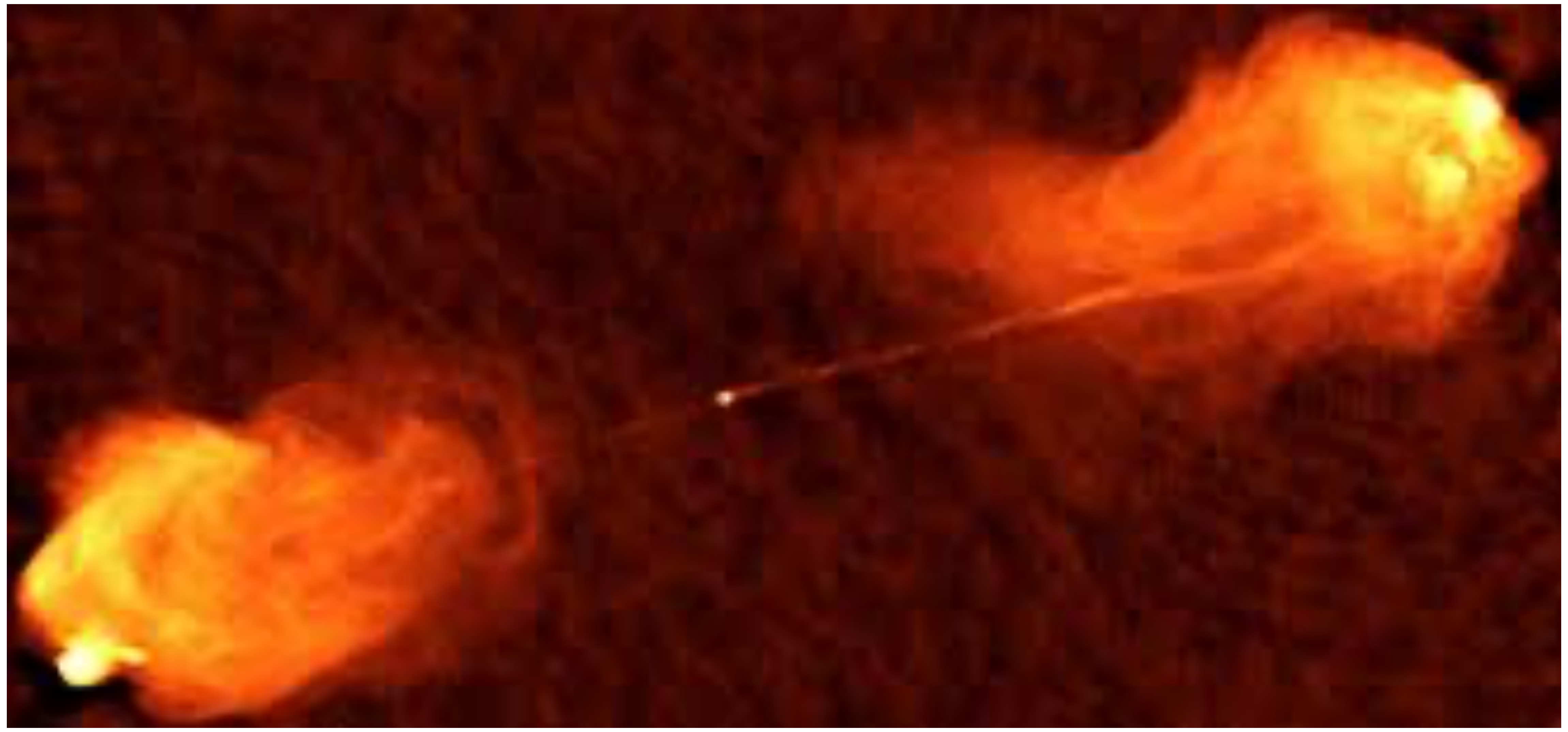
Known sources?

- Typically we do this by observing a known bright source like Cygnus A

- Then comparing the output of the spectrometer to our expectations

- But REACH and experiments like it have no resolution on the sky so we cannot do this

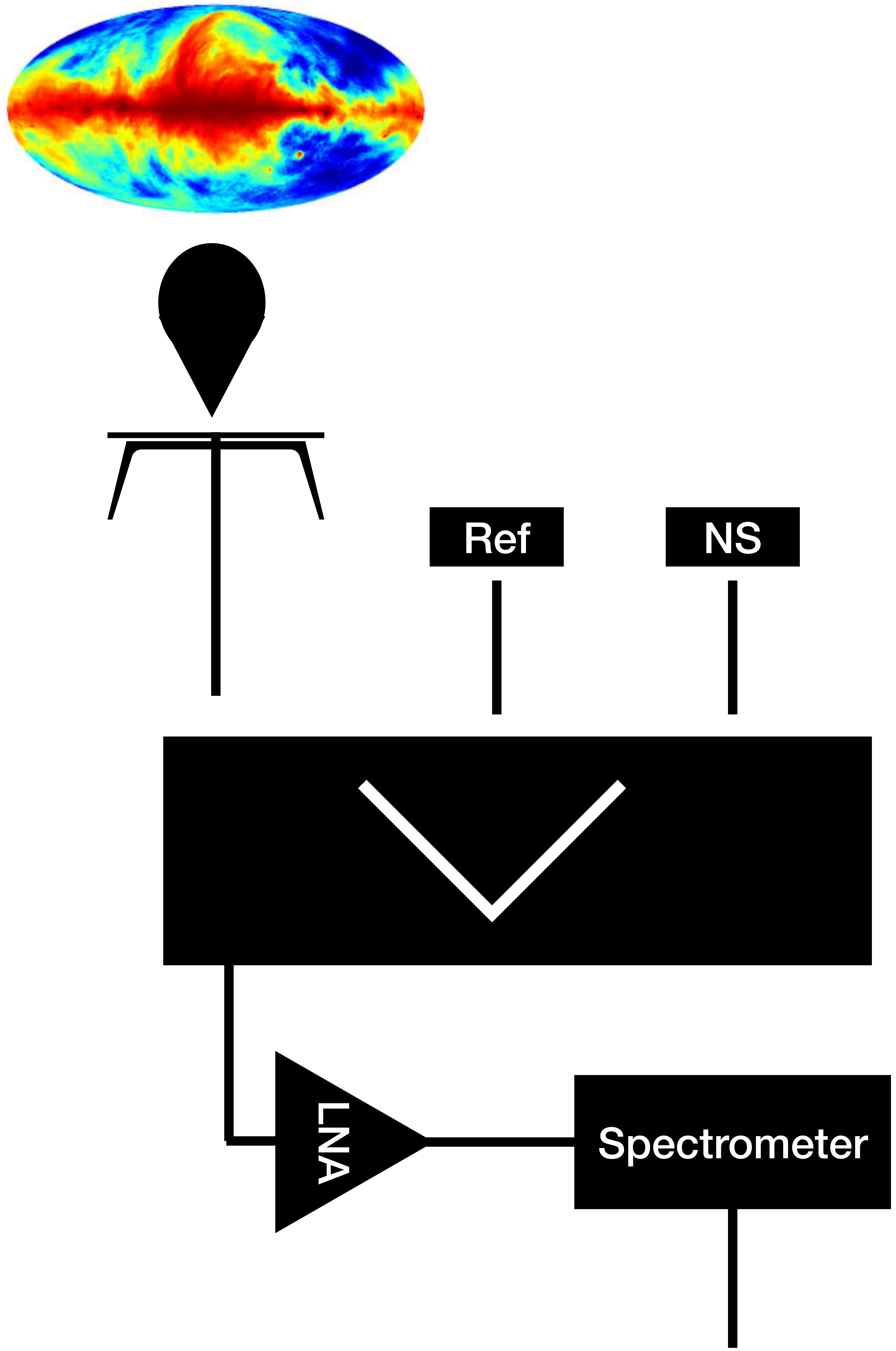
- Instead we can use reference loads and noise diodes to do Dickie Switching



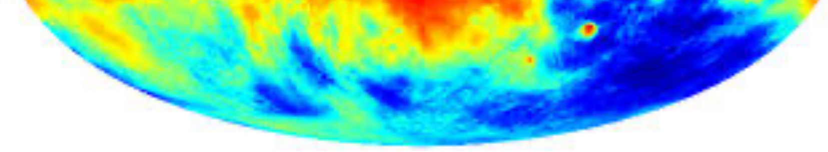
Dickie Switching

- The idea behind Dickie switching is to cancel the gain
- We have a reference load which has an impedance matched to the receiver with power P_L and temperature T_L
- And a matched noise source with power P_{NS} and an effective temperature T_{NS}
- Then the temperature of our unknown is given by

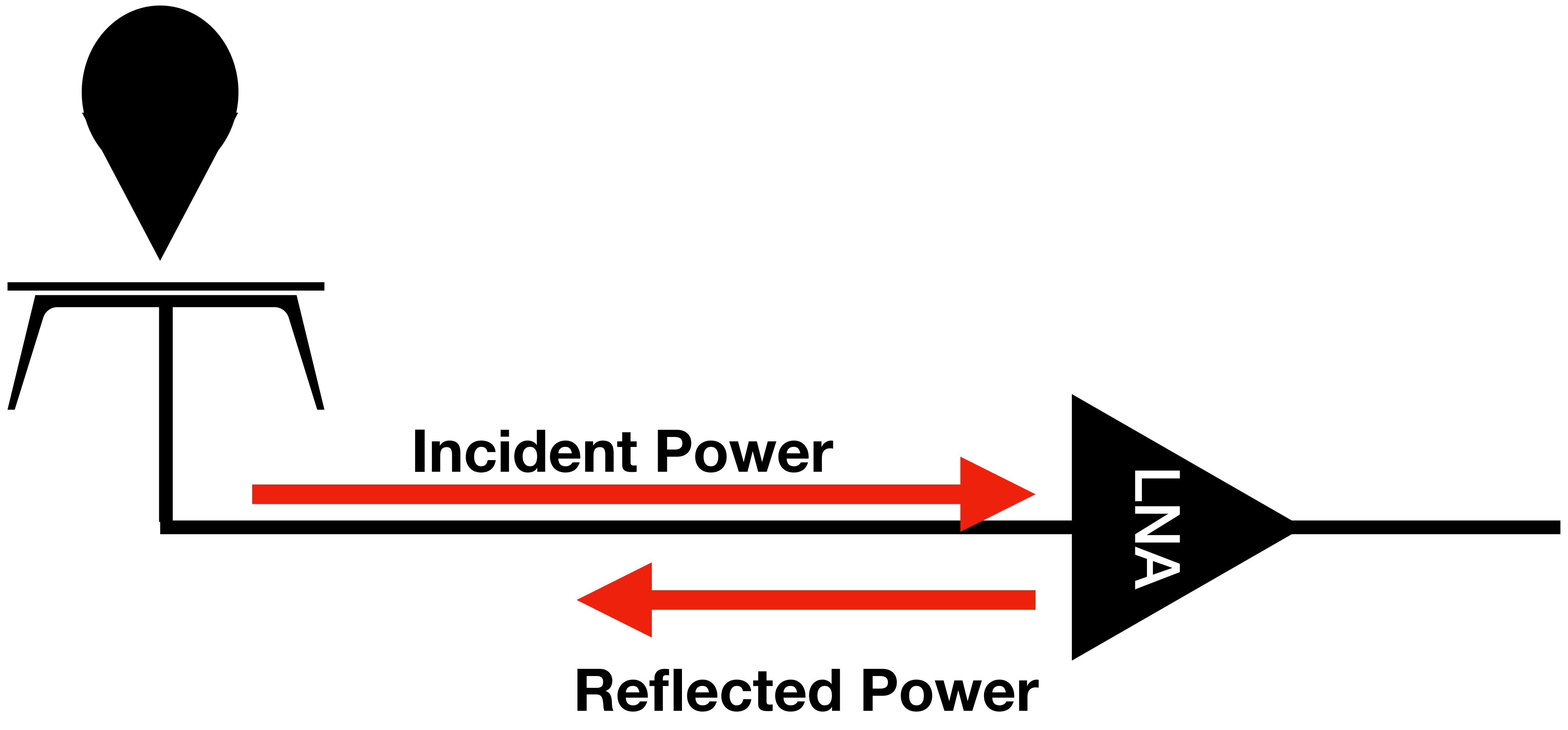
$$T^*_{\text{ant}} = T_{NS}\left(\frac{P_{\text{ant}} - P_L}{P_{NS} - P_L}\right) + T_L$$



Calibrating REACH



Why Dickie Switching is not enough?



- Dickie switching cancels the gain
- But it assumes all of your sources are impedance matched including the antenna

$$P_{\text{ant}} = gM(T_{\text{ant}} + \cancel{T_{\text{rec}}})$$

- Virtually impossible to build an antenna thats matched and do 21cm with it
- So we have to solve for T_{rec} which is a function of the mismatch between the source and the receiver
- Need additional references in the system that have different mismatches covering the properties of the antenna

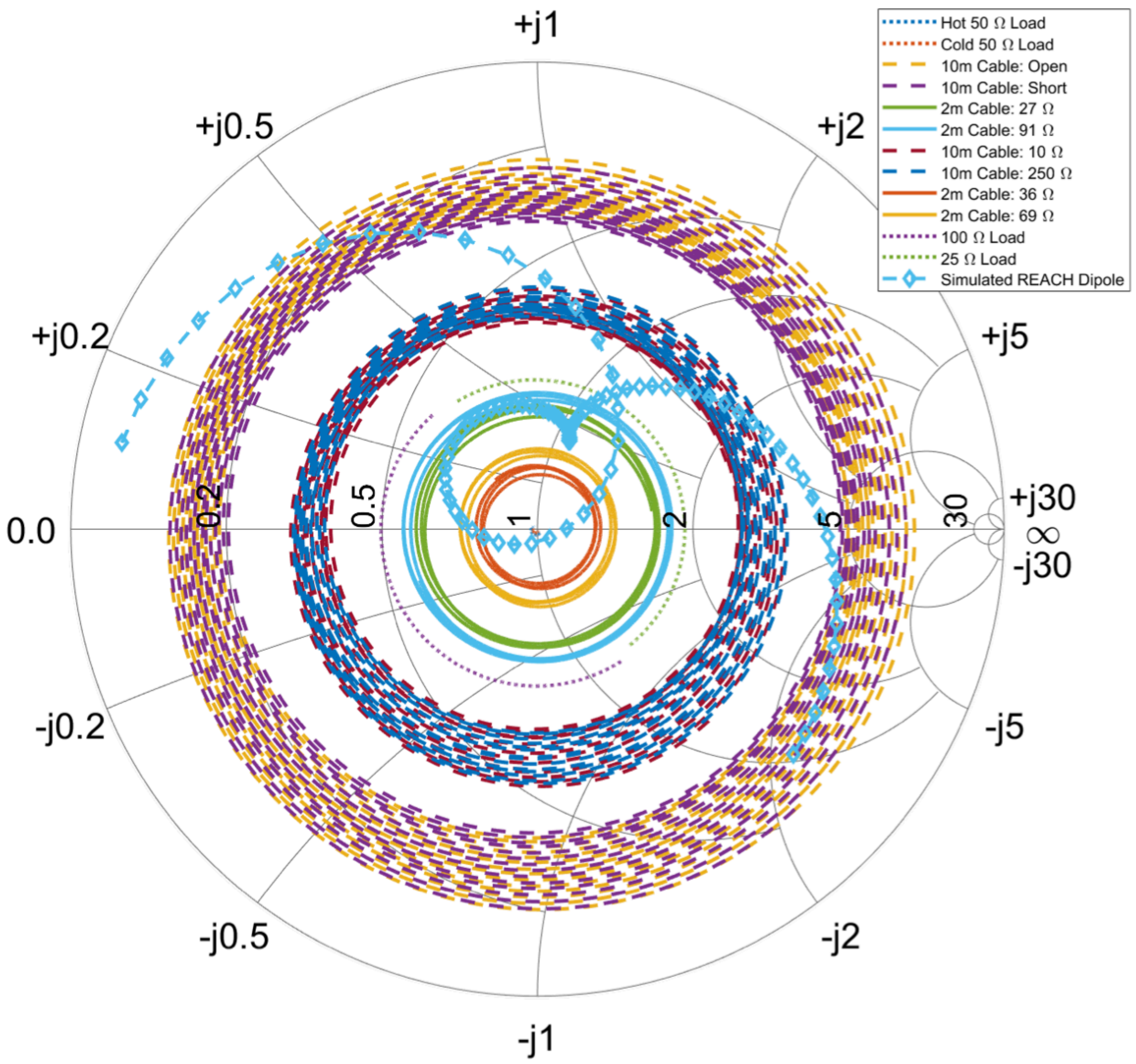
$$T_{\text{NS}}\left(\frac{P_{\text{source}} - P_{\text{L}}}{P_{\text{NS}} - P_{\text{L}}}\right) + T_{\text{L}} = T_{\text{source}}\left[\frac{1 - |\Gamma_{\text{source}}|^2}{|1 - \Gamma_{\text{source}}\Gamma_{\text{rec}}|^2}\right] + T_{\text{unc}}\left[\frac{|\Gamma_{\text{source}}|^2}{|1 - \Gamma_{\text{source}}\Gamma_{\text{rec}}|^2}\right] + T_{\text{cos}}\left[\frac{\text{Re}\left(\frac{\Gamma_{\text{source}}}{1-\Gamma_{\text{source}}\Gamma_{\text{rec}}}\right)}{\sqrt{1 - |\Gamma_{\text{rec}}|^2}}\right] + T_{\text{sin}}\left[\frac{\text{Im}\left(\frac{\Gamma_{\text{source}}}{1-\Gamma_{\text{source}}\Gamma_{\text{rec}}}\right)}{\sqrt{1 - |\Gamma_{\text{rec}}|^2}}\right].$$

The minimum set?

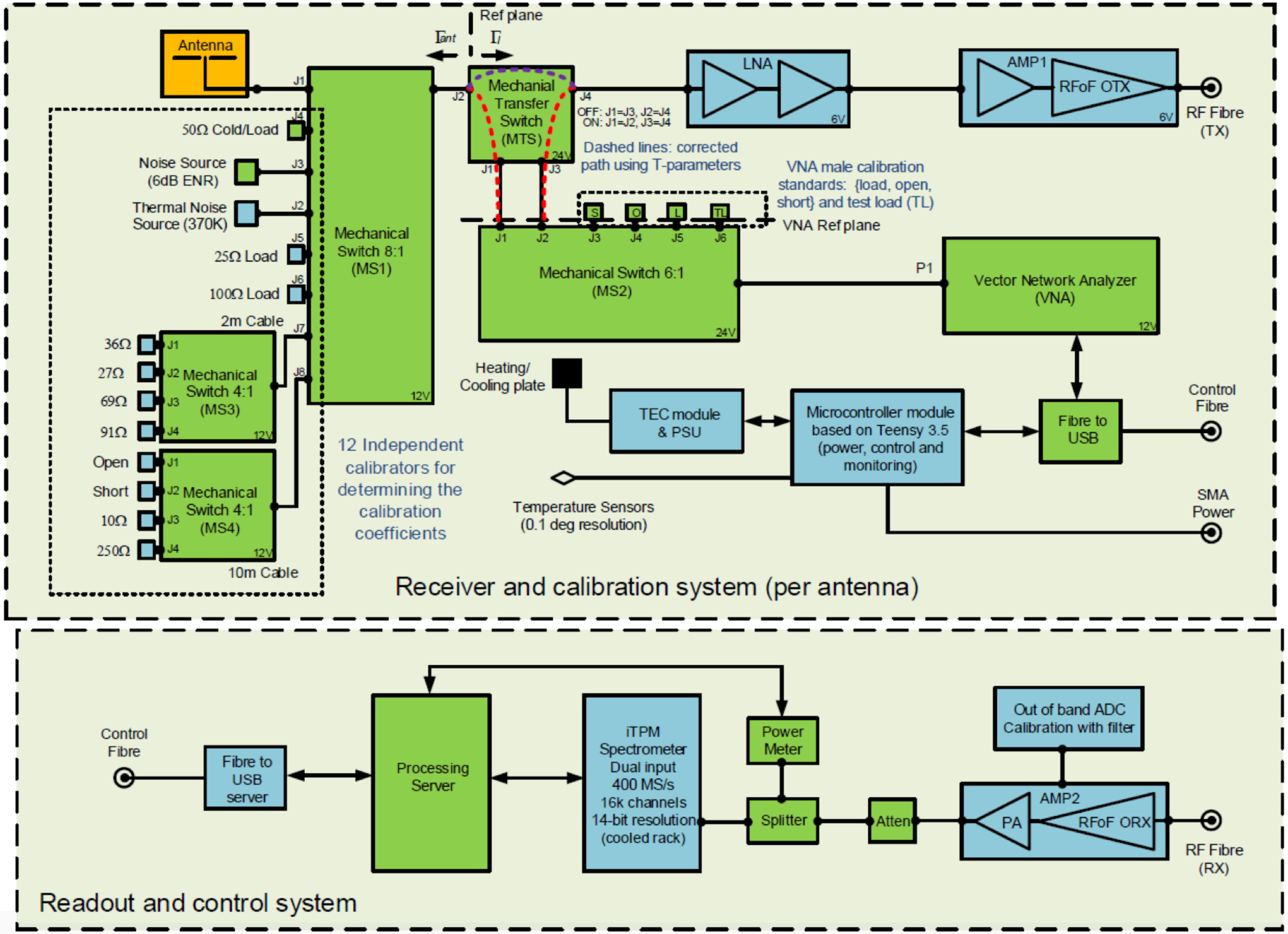
- In practice we should be able to calibrate with just four different calibrators
    - Cold load: This is at ambient temperature (same as LNA) and should be matched with the LNA (i.e. have the same impedance)
    - Hot load: Heated above ambient with same resistance as LNA
    - Short: Zero (in theory) impedance source
    - Open: Infinite (in theory) impedance source

Why REACH has more?

- REACH has a whole host of calibration sources to get better coverage of the Smith chart
- Different resistances move you along with real axis
- Different cable lengths give you wrap around the imaginary axis
- However this increases the complexity of the system!
- Note that the properties change in different environments



- Key Points:
  - Number of calibrators
  - Presence of switches and cables
  - In situ measurements of reflection coefficients



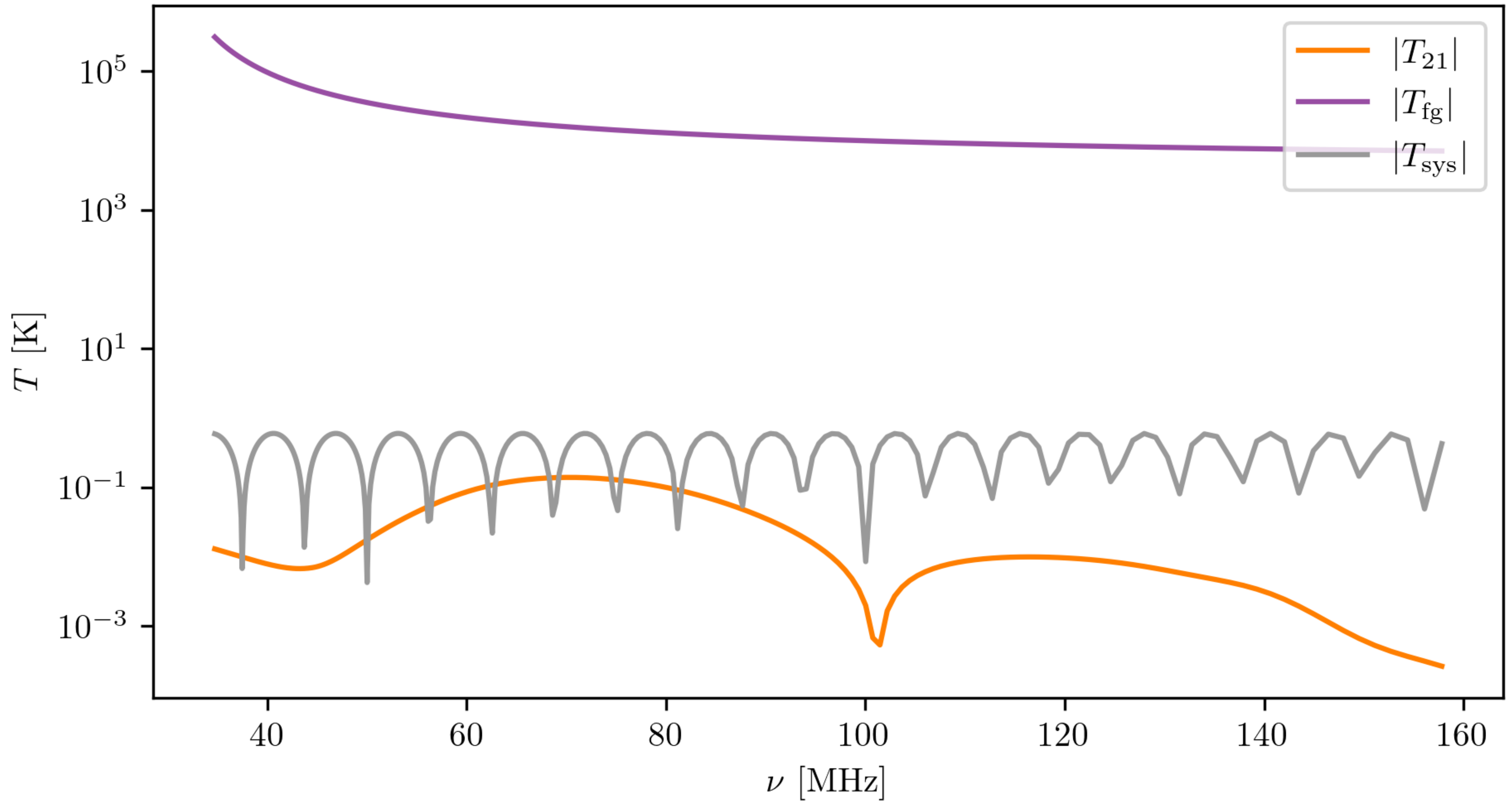
Okay so now what?

- In practice we observe the calibrators, a matched load (cold source) and a noise diode with a large excess temperature one after the other

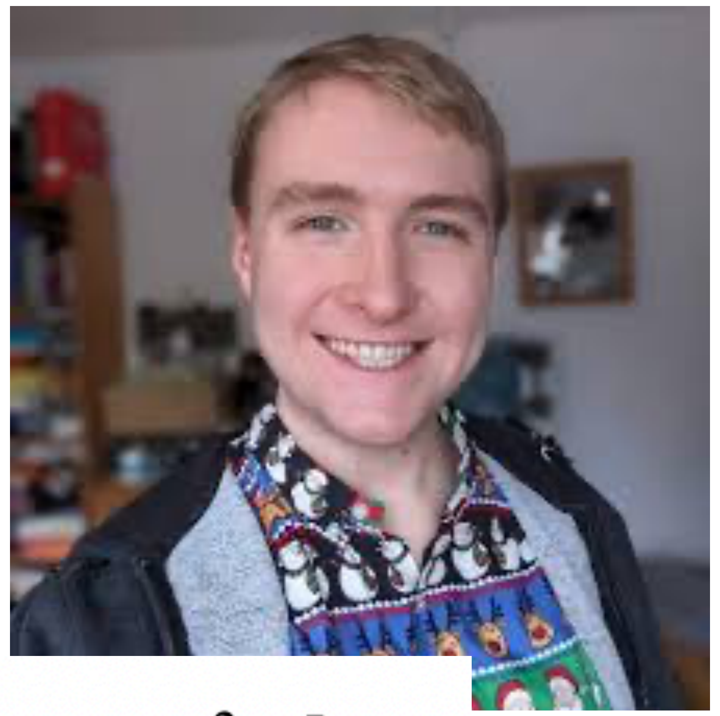
- Formulate our solutions around dickie switching but account for mismatch

- Solve for the properties of the system and learn how the system deals with mismatched sources like the antenna

- Once we have solved for the system we can apply the solution to the antenna



Solving the equations - Analytic Methods



- Two commonly used formalisms for T_{rec} known as noise waves ($T_{\mathrm{sin}}, T_{\mathrm{cos}}, T_{\mathrm{unc}}$; Meys 1978) and noise parameters ($R_n, \Gamma_{\mathrm{opt}}, T_{\mathrm{min}}$; Price+ 2023)

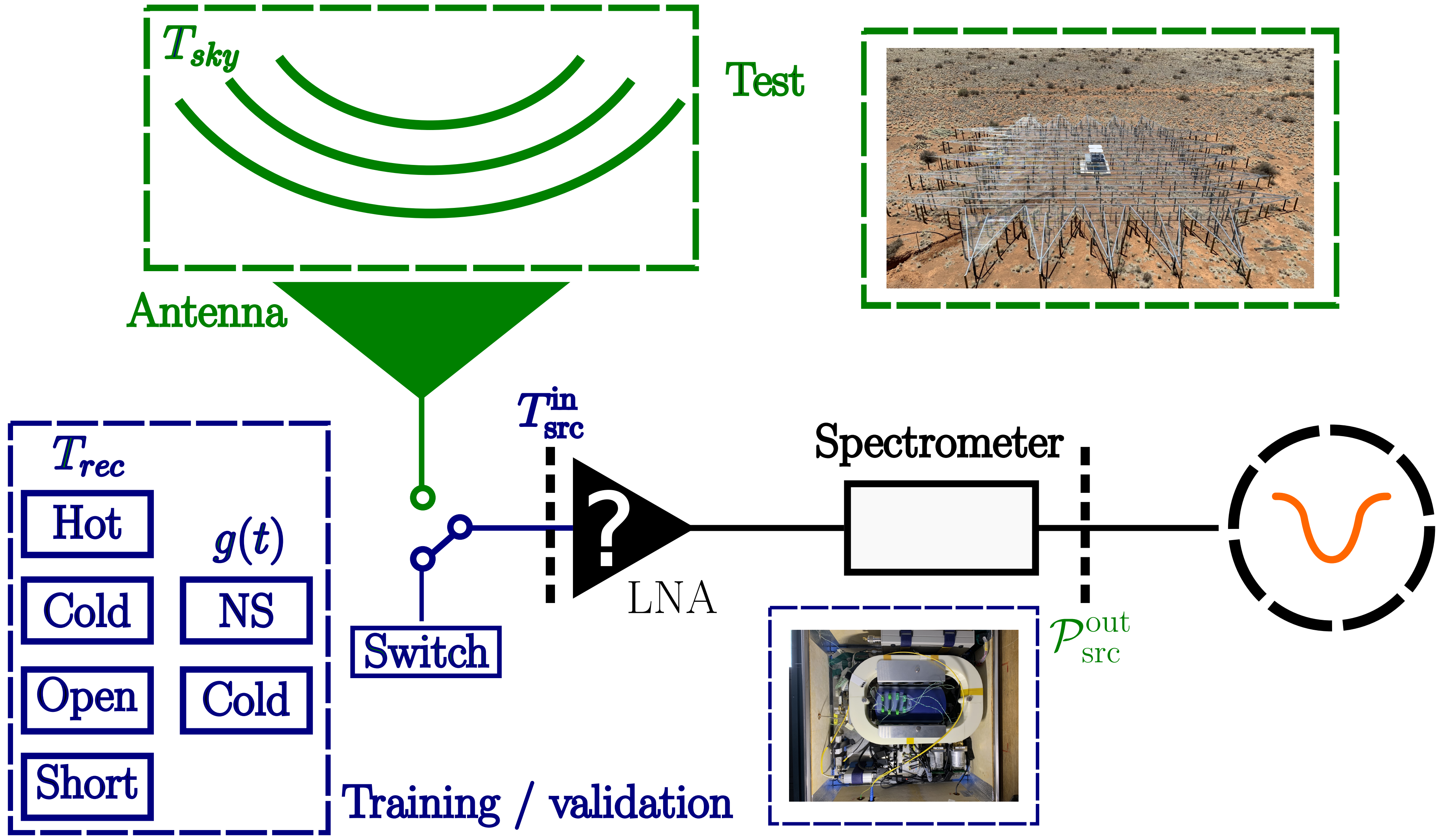
- Least squares frequency by frequency methods

- Bayesian methods modelling noise waves as polynomials (Ian Roque, Christian Kirkham+)
  - Conjugate priors (very fast)
  - Analytically marginalising over the polynomial order
  - Weighting temperatures by reflection coefficients

$$
\begin{aligned}
T_{\mathrm{NS}}\left(\frac{P_{\mathrm{source}}-P_{\mathrm{L}}}{P_{\mathrm{NS}}-P_{\mathrm{L}}}\right)+T_{\mathrm{L}} = T_{\mathrm{source}} & \left[\frac{1-|\Gamma_{\mathrm{source}}|^2}{|1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}|^2}\right] \\
&+ T_{\mathrm{unc}}\left[\frac{|\Gamma_{\mathrm{source}}|^2}{|1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}|^2}\right] \\
&+ T_{\mathrm{cos}}\left[\frac{\mathrm{Re}\left(\frac{\Gamma_{\mathrm{source}}}{1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}}\right)}{\sqrt{1-|\Gamma_{\mathrm{rec}}|^2}}\right] \\
&+ T_{\mathrm{sin}}\left[\frac{\mathrm{Im}\left(\frac{\Gamma_{\mathrm{source}}}{1-\Gamma_{\mathrm{source}}\Gamma_{\mathrm{rec}}}\right)}{\sqrt{1-|\Gamma_{\mathrm{rec}}|^2}}\right].
\end{aligned}
$$

Solving the equations - Machine Learning

- And machine learning tools (Sam Leeney+)
- Difficult to do because the temperature of our calibrator sources is so different from the antenna sky
- Regressing on the power measurements
- Fitting the noise parameters i.e. quantities that are independent of the calibrators
- Goal is to account for higher order effects not captured by the analytic models



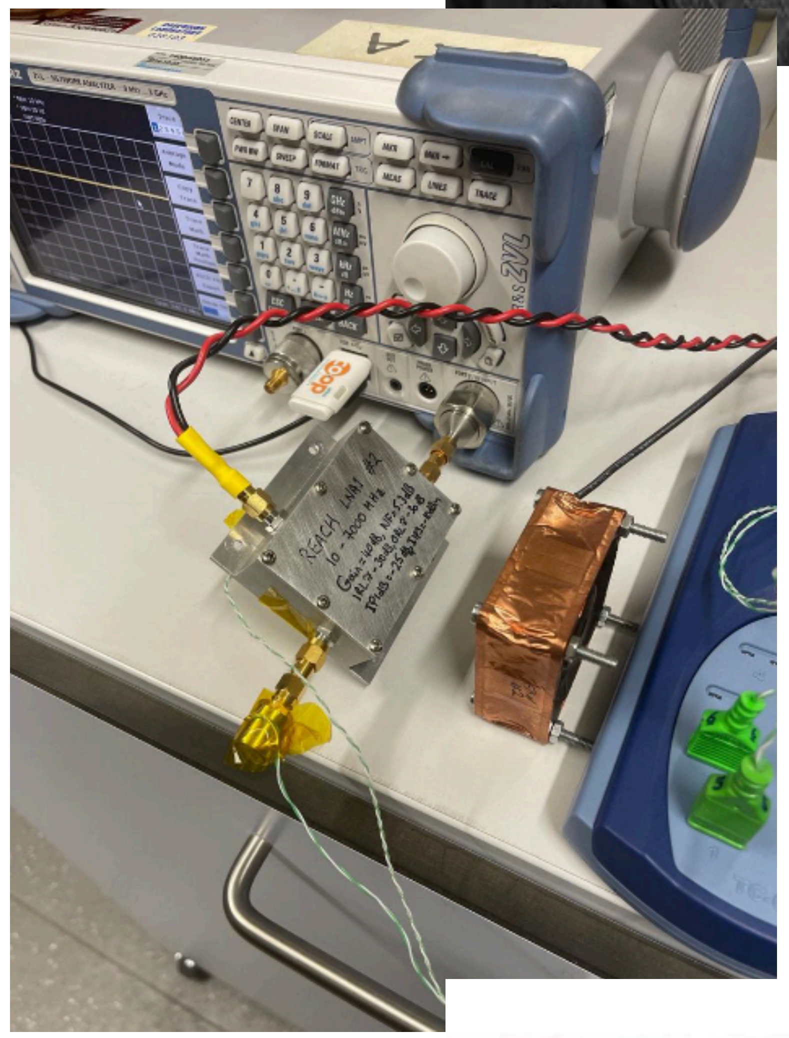
Adjacent activities

- Understanding observations and calibration techniques by building mock data sets (Kaan Artuc, Jiacong Zhu)
  - Increasing complexity and lab based observations

- Working on understanding how our calibration solutions change with bandwidth (Saswata Dasgupta)
  - Utilising data in the presence of systematics

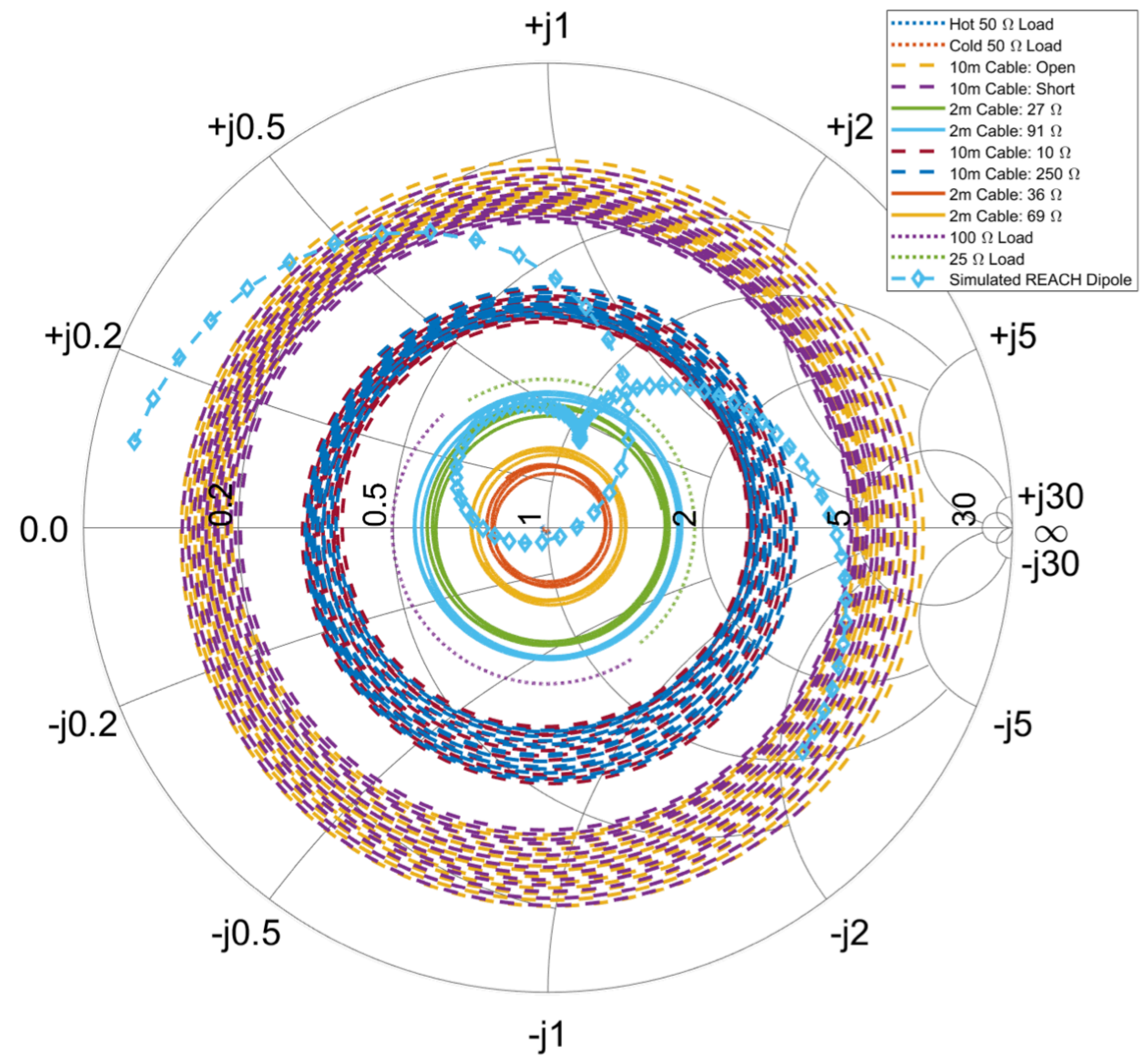
- De embedding measurements of the components in the system with detailed modelling (Saurabh Pegwal and Dirk de Villiers)

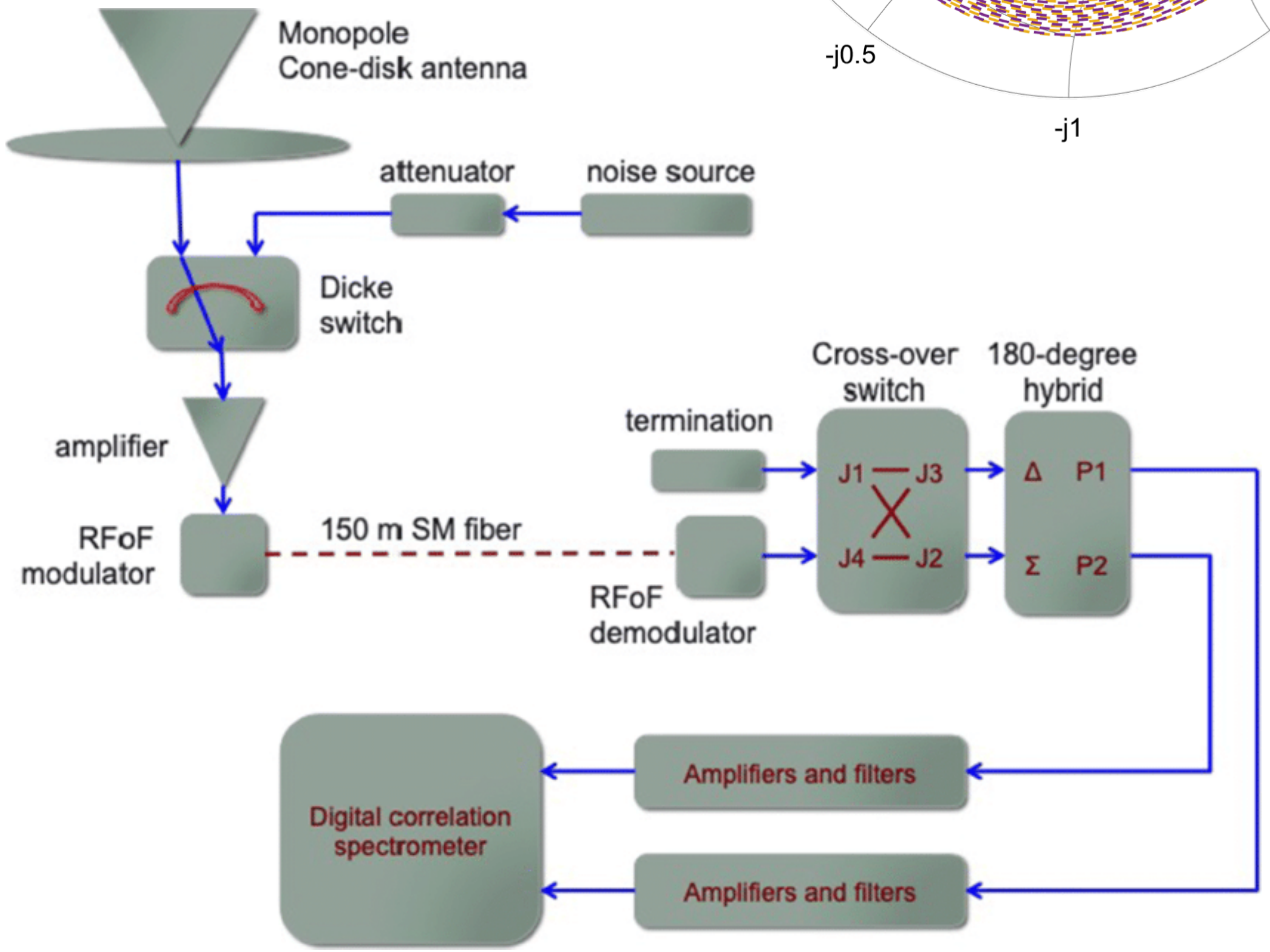





Adjacent activities

- Maths from first principles (Dominic Anstey+)
- Theoretical modelling of expected noise (Christian Kirkham, Sam Leeney+)
- Optimum set of calibrators?
- Other calibration approaches?
  - Noise injection
  - Cross correlator (e.g. SARAS3)

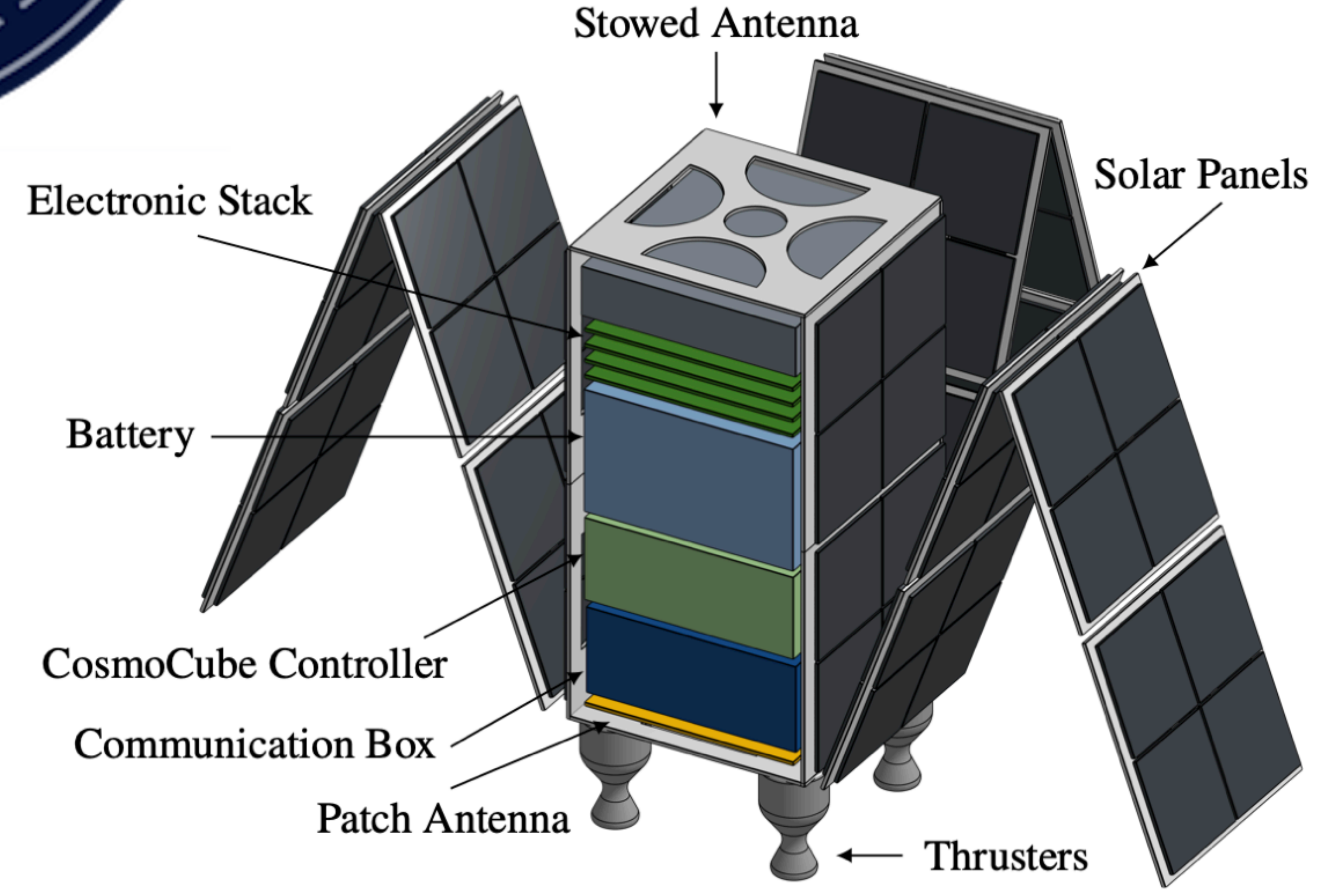




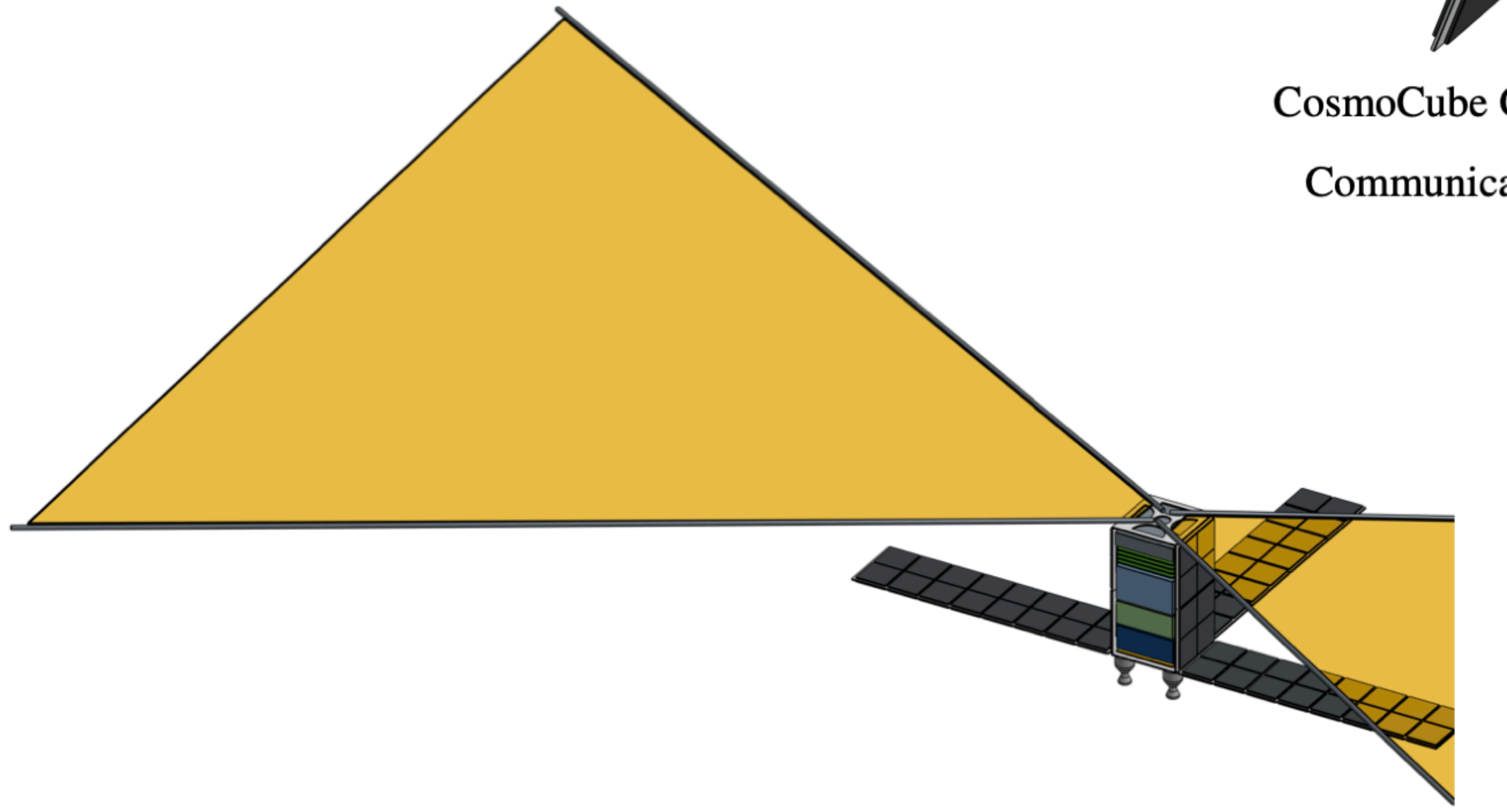
Calibrating CosmoCube?

CosmoCube?

- Environment stability? And thermal control?
- Space restrictions?
- Optimal set of calibrators?
- Signal even smaller and foregrounds brighter!
- Unable to go and fix it! Need more redundancy



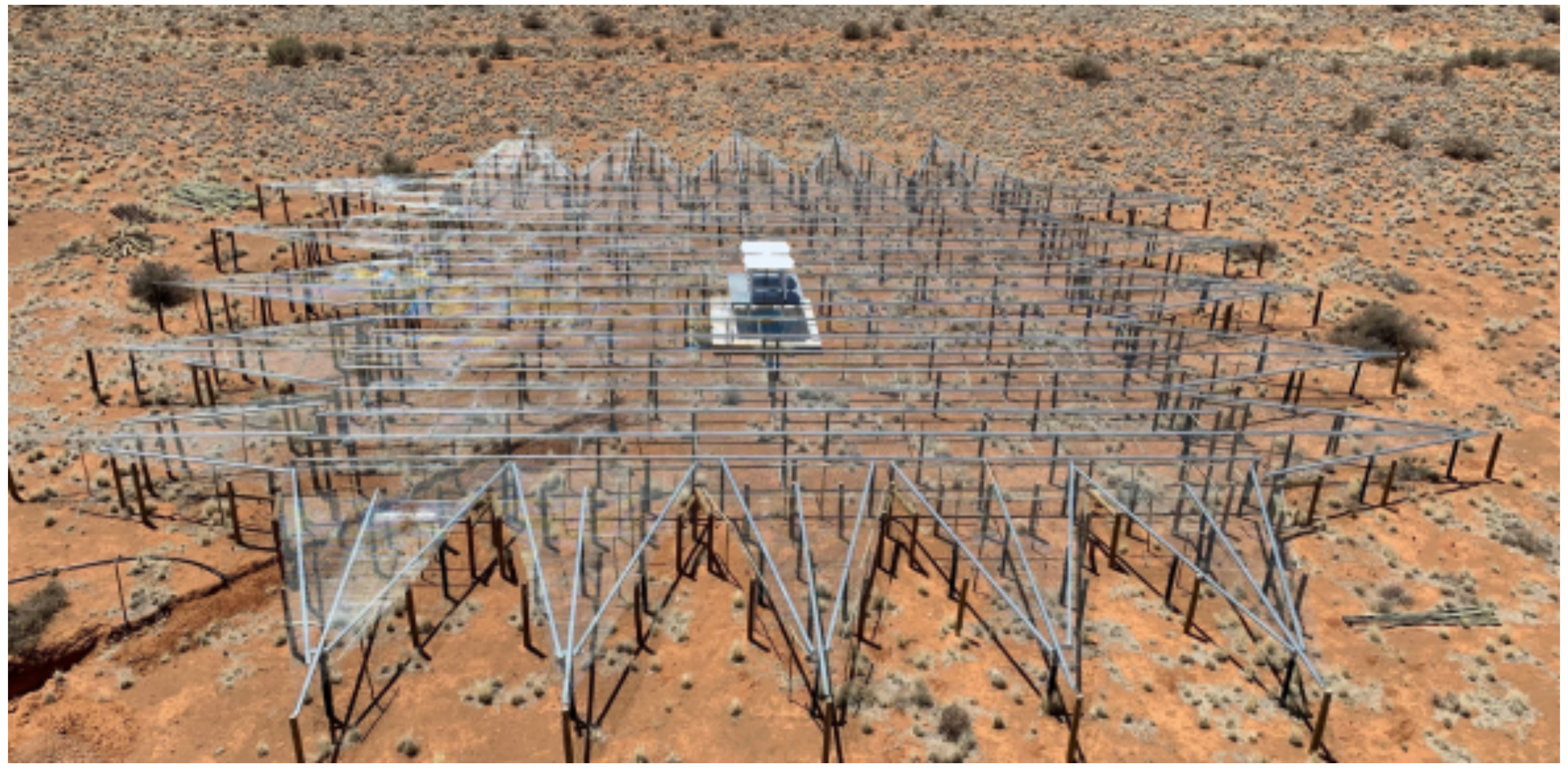
(b) CosmoCube in stowed configuration

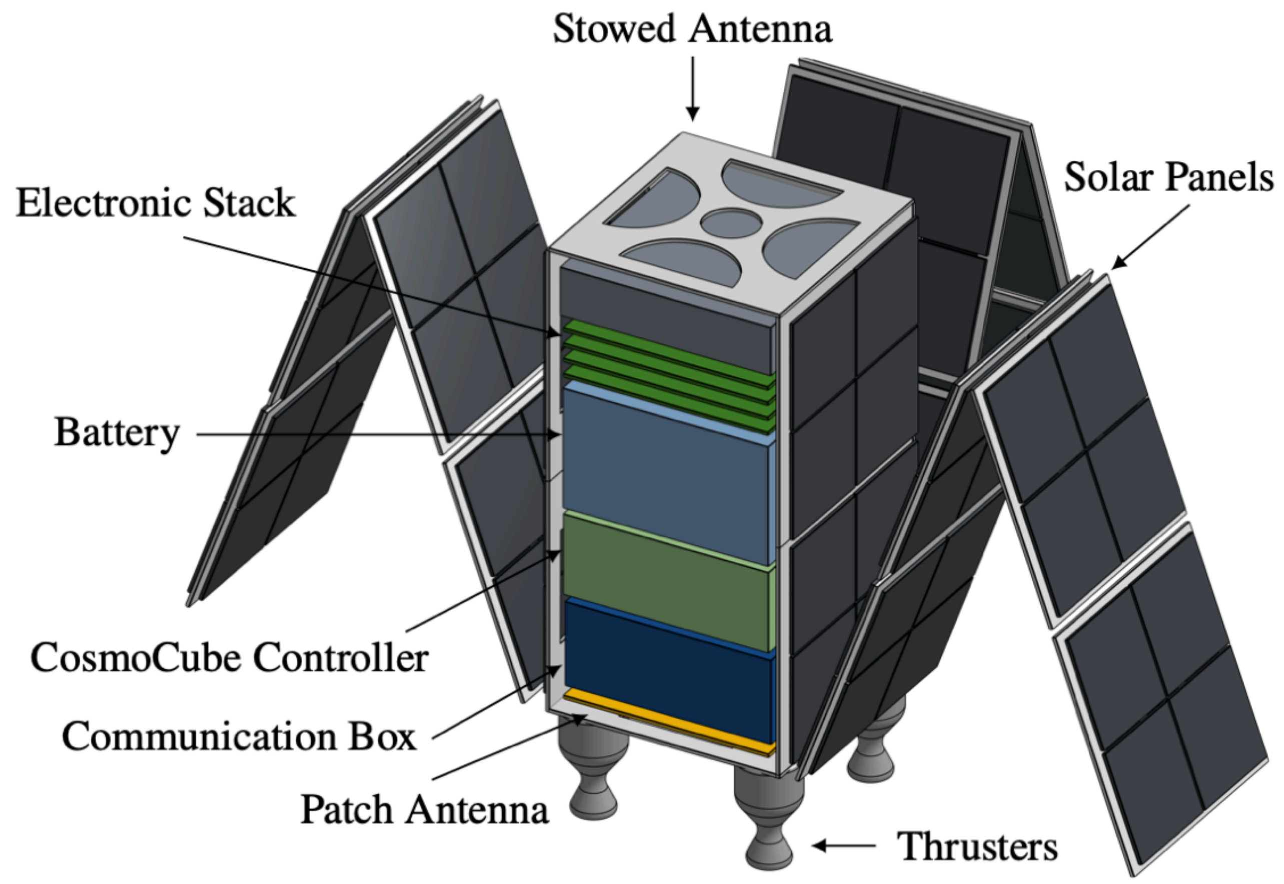

(a) CosmoCube with deployed antenna **[2406.10096]**

Conclusions

Conclusions

- Accurate calibration of our instruments is crucial for 21cm Cosmology
- We have a lot of expertise in REACH both on designing receivers and developing calibration algorithms
- Work being driven by PhD students and postdocs
- Space brings a whole host of new challenges that have to be addressed





(b) CosmoCube in stowed configuration