An Overview of Methods for REACH Calibration

Christian Kirkham[1,2] and the REACH Collaboration

[1]Cavendish Astrophysics, University of Cambridge
[2]Kavli Institute for Cosmology, University of Cambridge

8th Global 21-cm Workshop, California Institute of Technology, 23 Sep 2025

Table of Contents

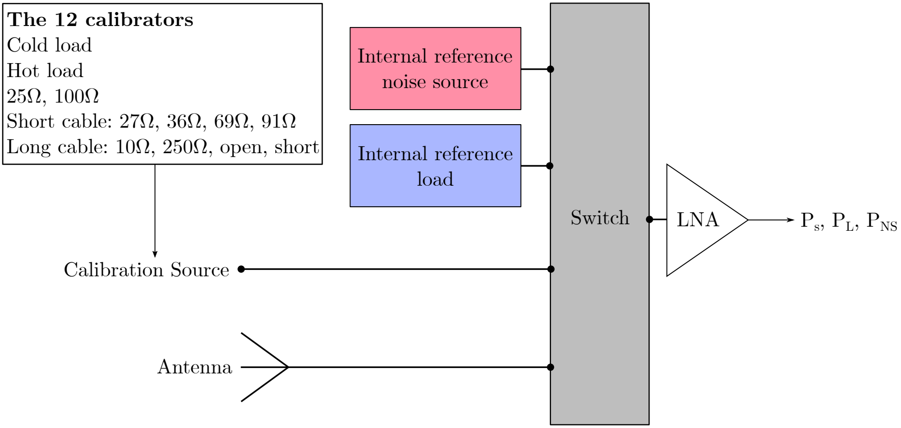
Table of Contents

Calibrating REACH

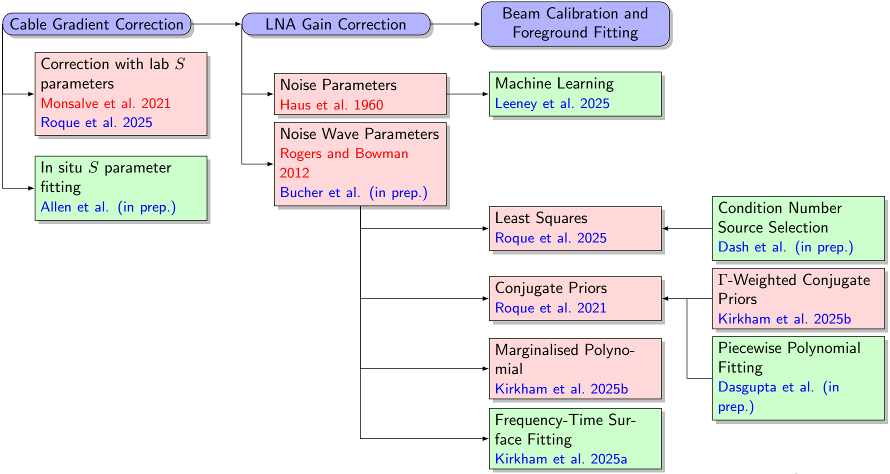
- We want to find the relation of output power spectral density (PSD) from the low noise ampliifier to physical temperature
- In general this relation can be written as

$$P_{\text{source}} = kBgM(T_{\text{source}} + T_{\text{rec}}) \tag{1}$$

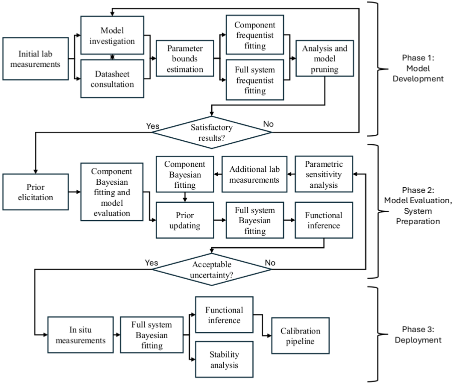
REACH Receiver

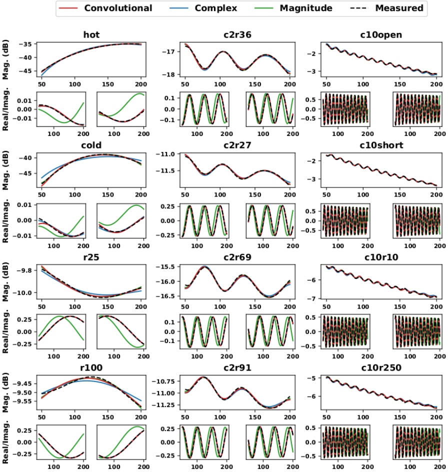


Overview of REACH Calibration

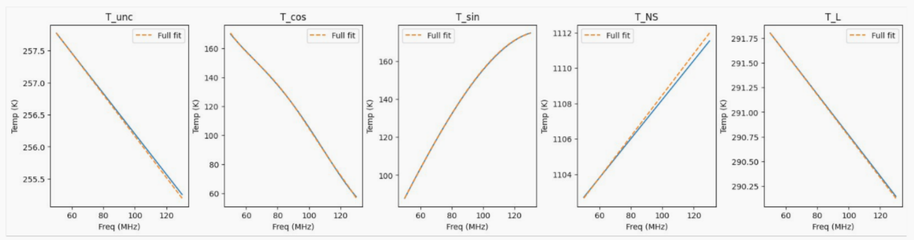


In-situ S parameter fitting (Allen et al. in prep.)





Piecewise Polynomial Fitting (Dasgupta et al. in prep.)



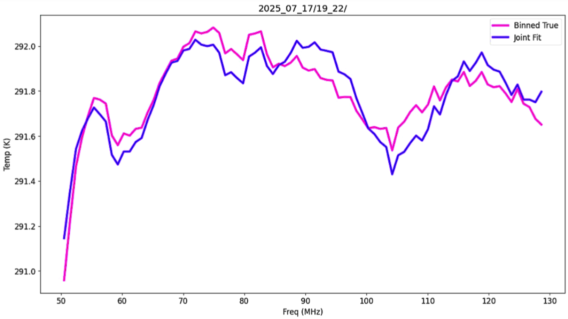


Table of Contents

Characterising the LNA with Noise Waves

- One way to characterise the LNA is using 'noise waves' (Meys, 1978; Monsalve et al., 2017)

$$T'_{\mathrm{NS}}\left(\frac{P_{\mathrm{s}}-P_{\mathrm{L}}}{P_{\mathrm{NS}}-P_{\mathrm{L}}}\right)+T'_{\mathrm{L}}=T_{\mathrm{s}}\left[\frac{1-|\Gamma_{\mathrm{s}}|^2}{|1-\Gamma_{\mathrm{s}}\Gamma_{\mathrm{r}}|^2}\right]+T_{\mathrm{unc}}\left[\frac{|\Gamma_{\mathrm{s}}|^2}{|1-\Gamma_{\mathrm{s}}\Gamma_{\mathrm{r}}|^2}\right]$$
$$+T_{\mathrm{cos}}\left[\frac{\mathrm{Re}\left(\frac{\Gamma_{\mathrm{s}}}{1-\Gamma_{\mathrm{s}}\Gamma_{\mathrm{r}}}\right)}{\sqrt{1-|\Gamma_{\mathrm{r}}|^2}}\right]+T_{\mathrm{sin}}\left[\frac{\mathrm{Im}\left(\frac{\Gamma_{\mathrm{s}}}{1-\Gamma_{\mathrm{s}}\Gamma_{\mathrm{r}}}\right)}{\sqrt{1-|\Gamma_{\mathrm{r}}|^2}}\right] \tag{2}$$

- "Calibration equation" - three noise wave parameters: T_{unc}, T_{cos}, T_{sin}
- We also fit for T'_{NS}, T'_{L} (Roque et al., 2021)

Degeneracies in the Noise Wave Parameters

- Fitting for T'_{NS} and T'_{L} fits for the mismatch in reflection coefficients, however introduces degeneracies

$$\begin{aligned} T'_{\mathrm{NS}} = & \frac{1}{1-|\Gamma_{\mathrm{rec}}|^2}\Big[T_{\mathrm{NS}}\left(1-\left|\Gamma_{\mathrm{NS}}\right|^2\right)|F_{\mathrm{NS}}|^2 - T_{\mathrm{L}}\left(1-\left|\Gamma_{\mathrm{L}}\right|^2\right)|F_{\mathrm{L}}|^2 \\ & + T_{\mathrm{unc}}\left(\left|\Gamma_{\mathrm{NS}}\right|^2|F_{\mathrm{NS}}|^2 - \left|\Gamma_{\mathrm{L}}\right|^2|F_{\mathrm{L}}|^2\right) \\ & + T_{\cos}\left(\left|\Gamma_{\mathrm{NS}}\right||F_{\mathrm{NS}}|\cos\alpha_{\mathrm{NS}} - \left|\Gamma_{\mathrm{L}}\right||F_{\mathrm{L}}|\cos\alpha_{\mathrm{L}}\right) \\ & + T_{\sin}\left(\left|\Gamma_{\mathrm{NS}}\right||F_{\mathrm{NS}}|\sin\alpha_{\mathrm{NS}} - \left|\Gamma_{\mathrm{L}}\right||F_{\mathrm{L}}|\sin\alpha_{\mathrm{L}}\right)\Big] \end{aligned} \tag{3}$$

and

$$\begin{aligned} T'_{\mathrm{L}} = & \frac{1}{1-|\Gamma_{\mathrm{rec}}|^2}\Big[T_{\mathrm{L}}\left(1-\left|\Gamma_{\mathrm{L}}\right|^2\right)|F_{\mathrm{L}}|^2 + T_{\mathrm{unc}}\left|\Gamma_{\mathrm{L}}\right|^2|F_{\mathrm{L}}|^2 \\ & + T_{\cos}\left|\Gamma_{\mathrm{L}}\right||F_{\mathrm{L}}|\cos\alpha_{\mathrm{L}} + T_{\sin}\left|\Gamma_{\mathrm{L}}\right||F_{\mathrm{L}}|\sin\alpha_{\mathrm{L}}\Big] \end{aligned} \tag{4}$$

Table of Contents

Surface Fitting

- We fit a polynomial frequency-time surface to capture system drifts

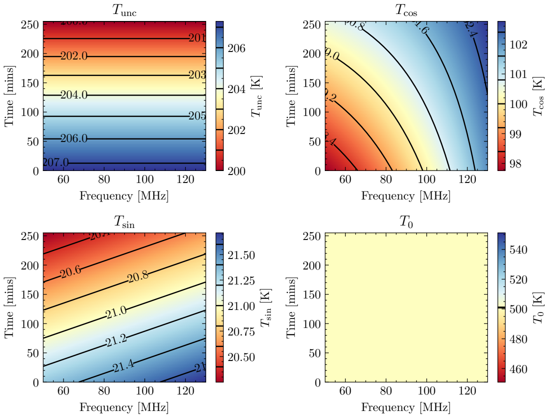
$$T_{\mathrm{NWP}}(\nu, t) = \sum_i \sum_j A_{ij} \cdot \nu^i t^j \tag{5}$$

- Which can be written linearly as

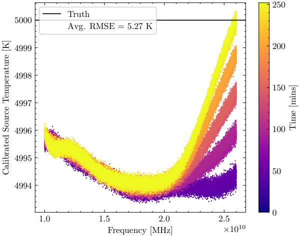
$$\mathbf{T} = \mathbf{XB\Theta} \tag{6}$$

- Can be integrated with previous calibration methods e.g. conjugate priors

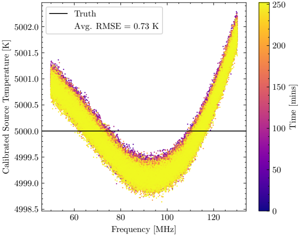
Data Simulation



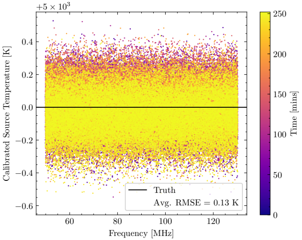
Simulated Data Results



1-D Polynomial

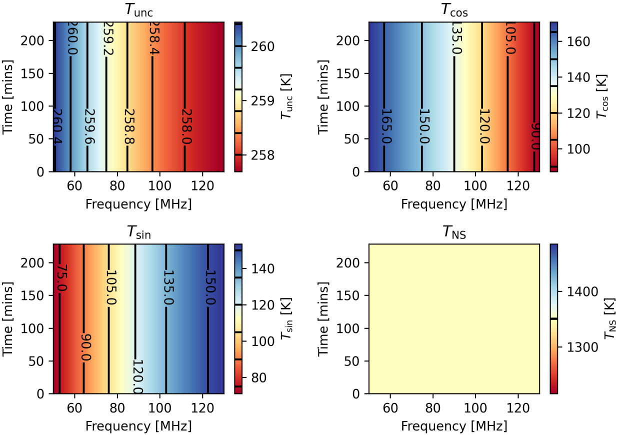


Surface Fit

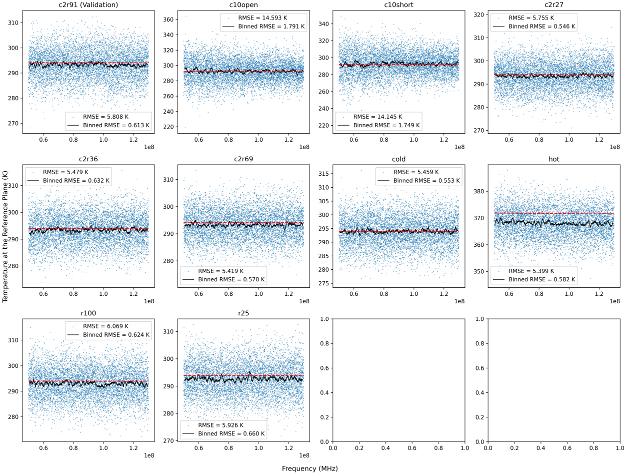


Γ_L, Γ_{NS} Surface Fit

Fitting REACH Data



Fitting REACH Data



Summary

- There is a lot of exciting work on REACH calibration coming out soon!
- If the state of the receiver is drifting over the course of an observation it is necessary to consider this time change
- Degeneracies can have a large impact on your result
- Tests on data from the REACH instrument indicate that the REACH receiver is not drifting significantly over an observation

arXiv:2509.13010