中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

Calibration of a Two-way Differential Receiver for Global Spectrum Experiments

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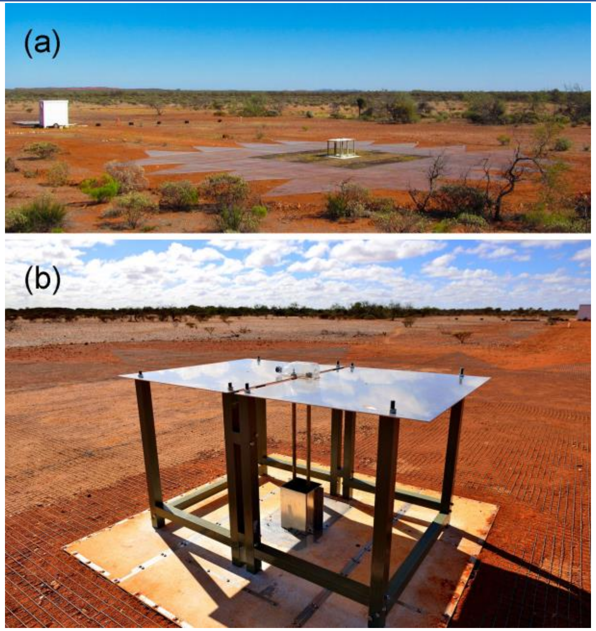
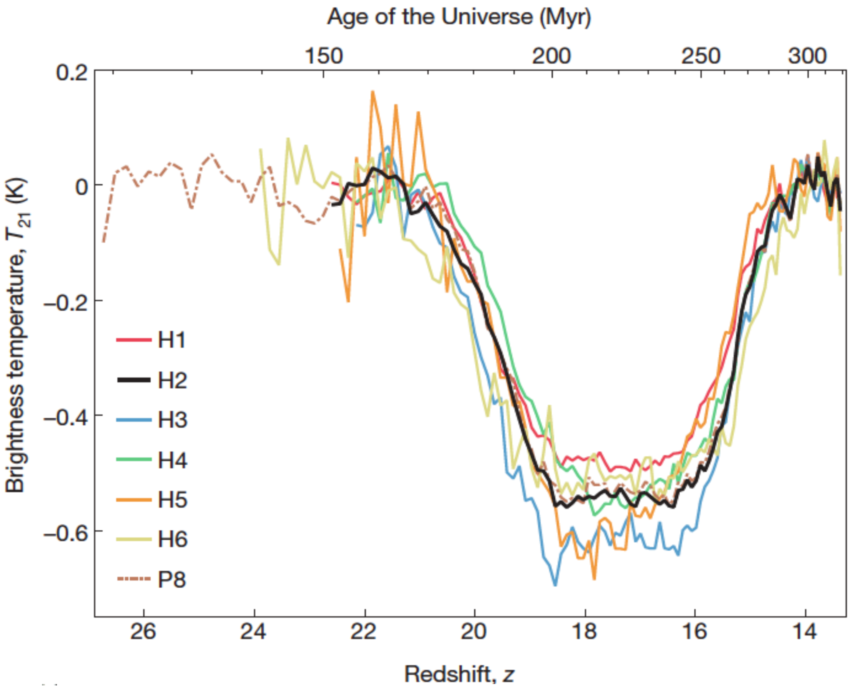
Introduction

EDGES





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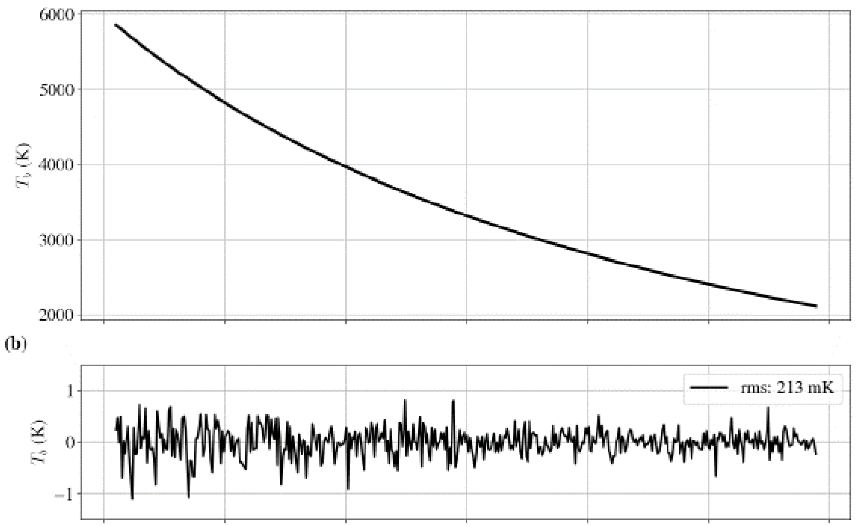
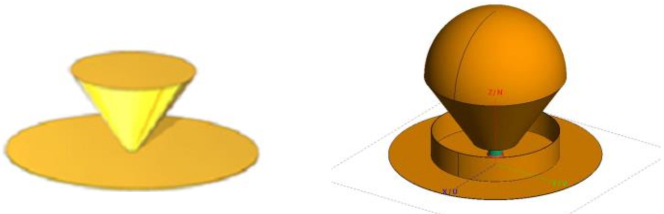


System Block Diagram

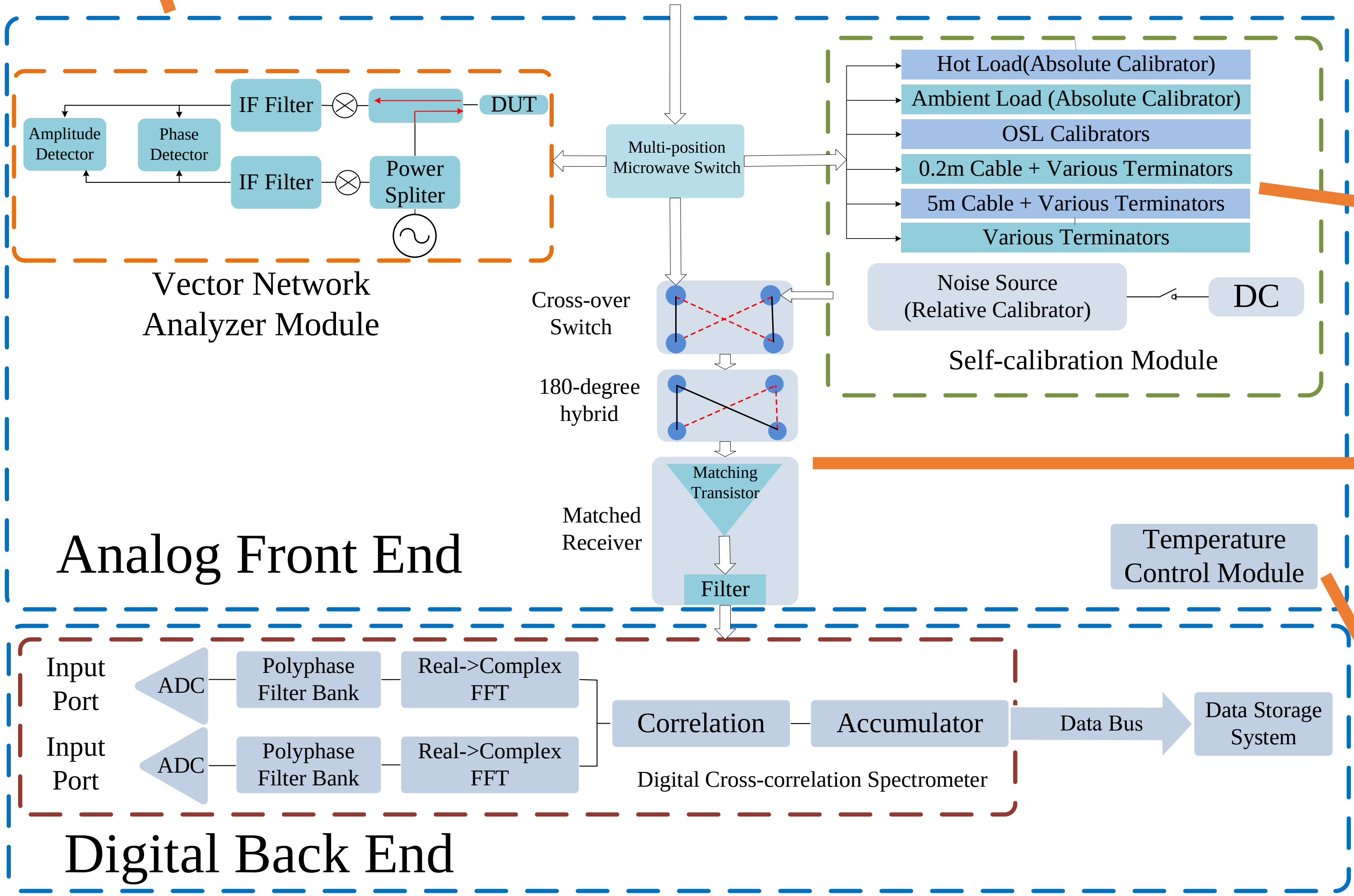
Frequency range: 30-200 MHz

Real-time VNA measurement



Antenna

- Smooth reflection coefficient
- Frequency-independent beam

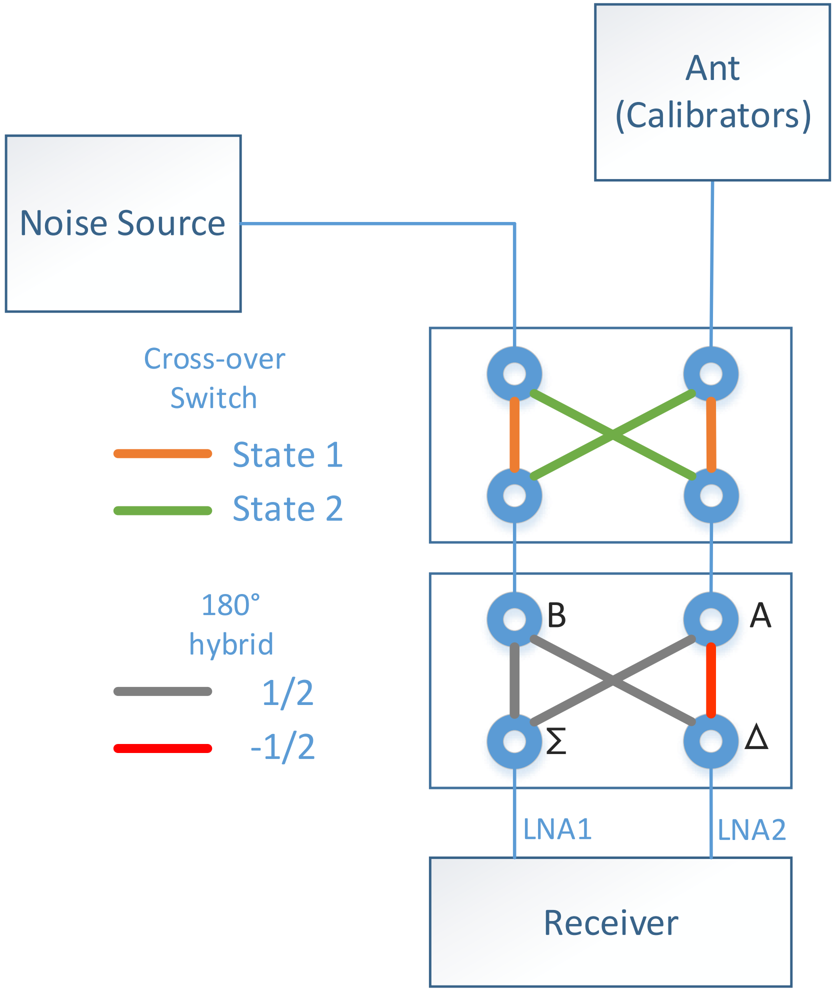


Multiple Calibrators

Two-way differential cross-correlation: Keep noise source always connecting to the receiver .

Keep LNA temperature constant

Calibration Model



Ideally...

- Cross-over Switch State 1:

$$P_{\mathrm{on1}} = \frac{1}{2} G_1 G_2^* (T_{\mathrm{ant}} - T_{\mathrm{Non}}) + P_{\mathrm{cor}}$$

$$P_{\mathrm{off1}} = \frac{1}{2} G_1 G_2^* (T_{\mathrm{ant}} - T_{\mathrm{Noff}}) + P_{\mathrm{cor}}$$

- Cross-over Switch State 2:

$$P_{on2} = \frac{1}{2} G_1 G_2^* (T_{\mathrm{Non}} - T_{\mathrm{ant}}) + P_{\mathrm{cor}}$$

$$P_{off2} = \frac{1}{2} G_1 G_2^* (T_{\mathrm{Noff}} - T_{\mathrm{ant}}) + P_{\mathrm{cor}}$$

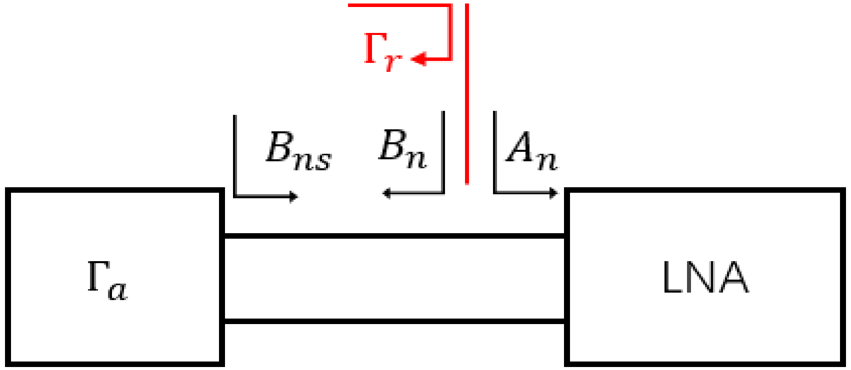
$$P_{\mathrm{on}} = P_{\mathrm{on1}} - P_{\mathrm{on2}} = G_1 G_2^* (T_{\mathrm{ant}} - T_{\mathrm{Non}})$$

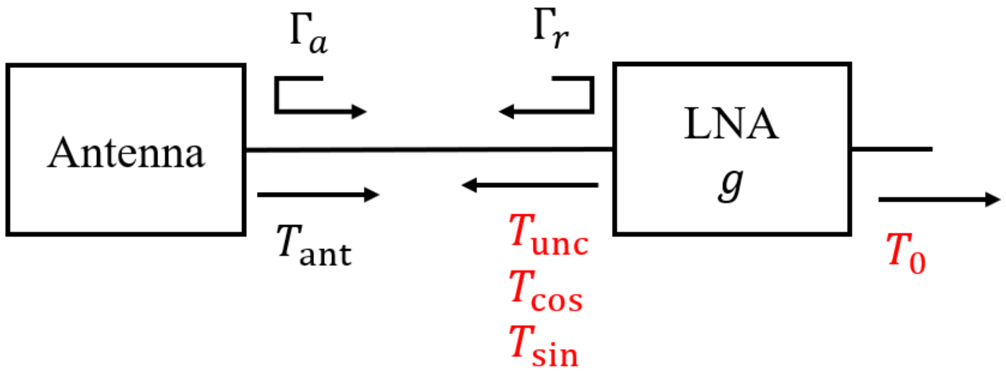
$$P_{\mathrm{off}} = P_{\mathrm{off1}} - P_{\mathrm{off2}} = G_1 G_2^* (T_{\mathrm{ant}} - T_{\mathrm{Noff}})$$

$$T'_{\mathrm{ant}} = -\frac{P_{\mathrm{off}}}{P_{\mathrm{on}} - P_{\mathrm{off}}} (\mathrm{T}_{\mathrm{Non}} - \mathrm{T}_{\mathrm{Noff}}) + T_{\mathrm{Noff}}$$

Calibration Model

LNA noise wave model





$$P = \overline{|A_n + \Gamma_a F B_n + F B_{ns}|^2}$$

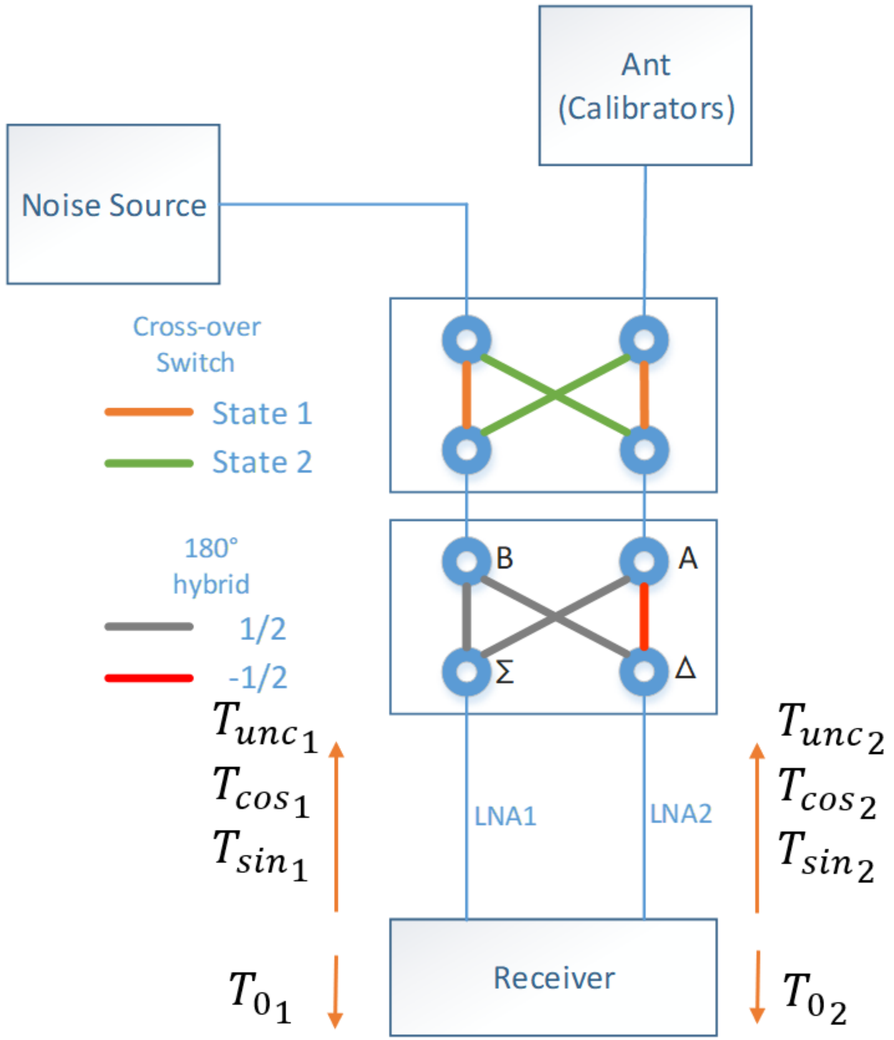
$$F = \frac{\sqrt{1 - |\Gamma_\mathrm{r}|^2}}{1 - \Gamma_a \Gamma_\mathrm{r}}$$

$$\begin{aligned}
\overline{|A_n|^2} &= T_0 \\
\overline{|B_n|^2} &= T_{\mathrm{unc}} \\
\overline{2A_n^* B_n} &= T_{\cos} \cos\alpha + T_{\sin} \sin\alpha \\
\overline{|B_{ns}|^2} &= (1 - |\Gamma_a|^2) T_{\mathrm{ant}} \\
\alpha &= \arg(\Gamma_a F)
\end{aligned}$$

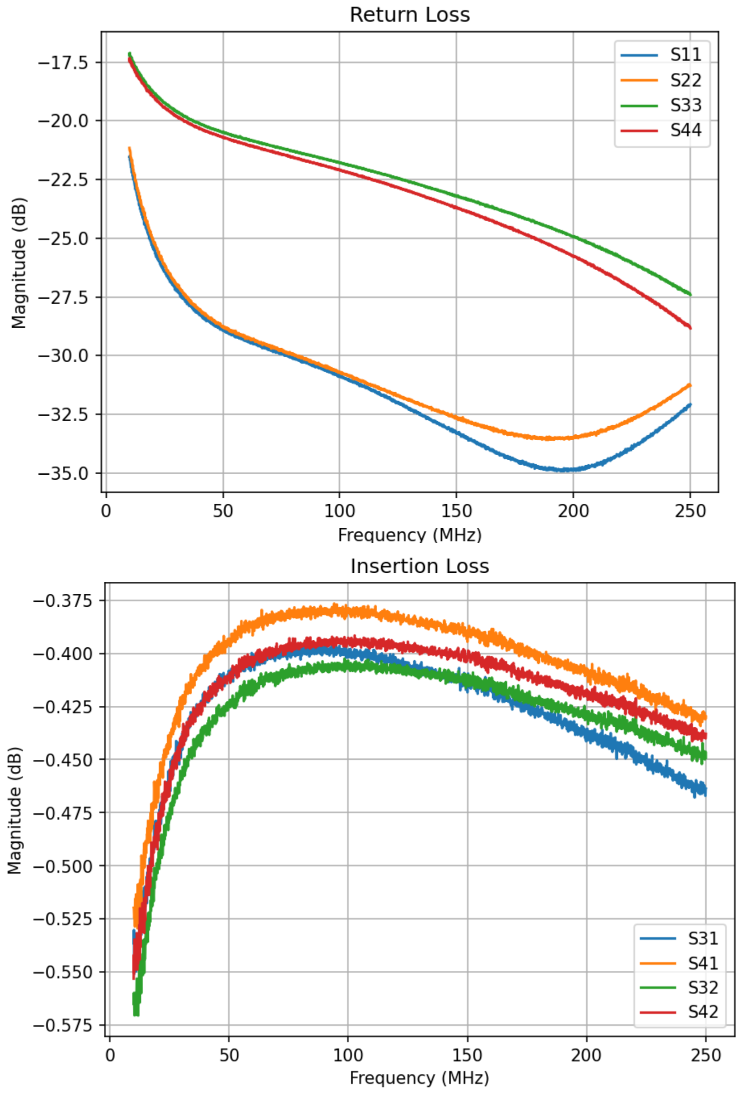
$$\begin{aligned}
P = g\big[&T_{\mathrm{ant}}(1 - |\Gamma_a|^2)|F|^2 \\
&+ T_{\mathrm{unc}} |\Gamma_a|^2 |F|^2 \\
&+ T_{\cos} |\Gamma_a||F| \cos\alpha \\
&+ T_{\sin} |\Gamma_a||F| \sin\alpha \\
&+ T_0\big]
\end{aligned}$$

Calibration Model

Two-way LNA noise wave model

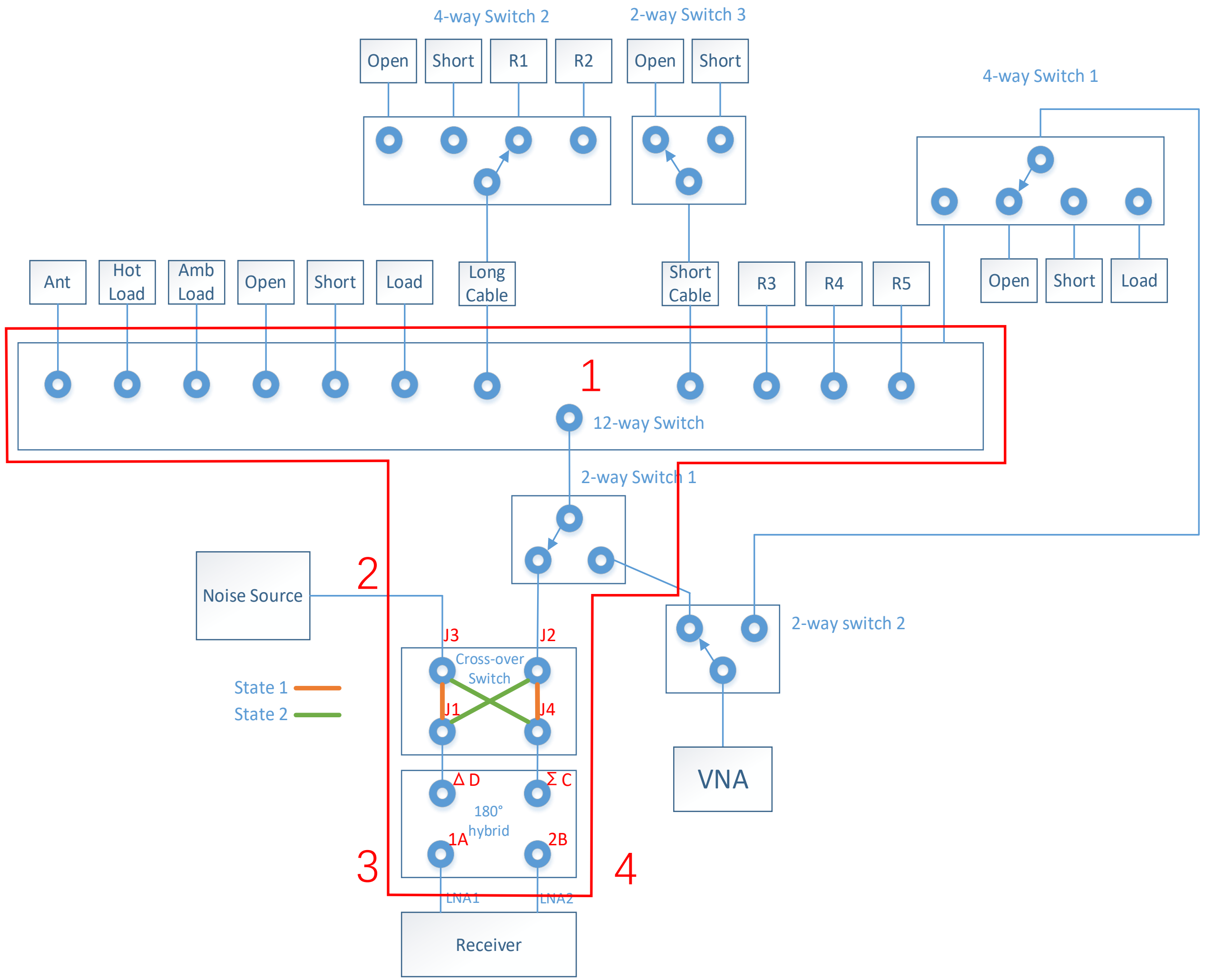


Non-ideal 180° Hybrid



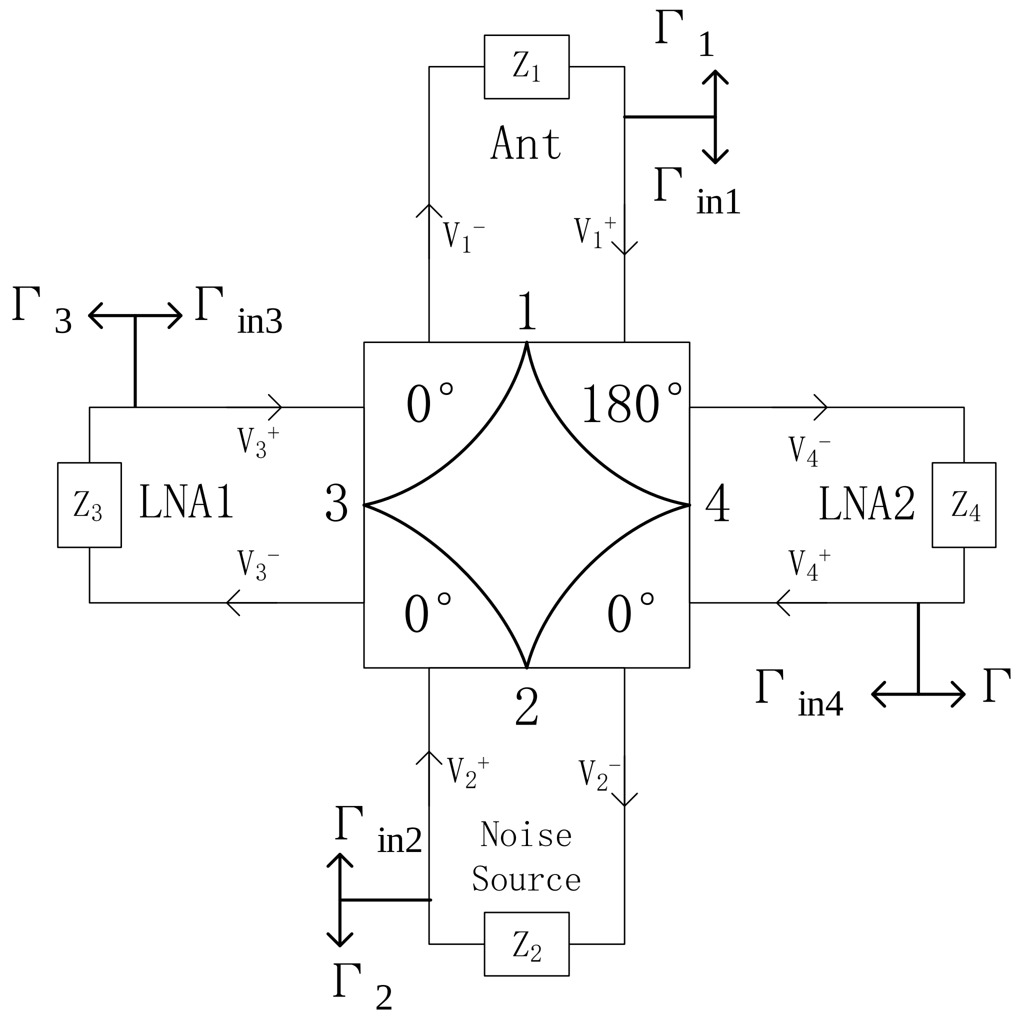
Calibration Model

Two-way LNA noise wave model



Calibration Model

Two-way LNA noise wave model



T_{ant}:
Antenna / Calibrator temperature

T_{NS}:
Noise Source on / off temperature

T_{nw}:
T_{u1}: Uncorrelated noise of LNA1, real value
T_{u2}: Uncorrelated noise of LNA2, real value
T_{c1}: Correlated noise of LNA1, complex value
T_{c2}: Correlated noise of LNA2, complex value

T_{amb}:
Ambient temperature leakage

$[S], Z_1, Z_2, Z_3, Z_4 \Rightarrow K_{\mathrm{ant}}, K_{\mathrm{NS}}, K_{\mathrm{nw}}, K_{\mathrm{amb}}$

$$P = g(K_{\mathrm{ant}}T_{\mathrm{ant}} - K_{\mathrm{NS}}T_{\mathrm{NS}} + \Sigma K_{\mathrm{nw}}T_{\mathrm{nw}} + K_{\mathrm{amb}}T_{\mathrm{amb}})$$

Calibration Steps

Hot load

Cold load

Assume $T_{nw} = 0$

Noise Source Temperature → **Relative Calibration** → **Noise Wave Parameters Calculation**

Other calibrators

Polynomials fitting

Frequency by frequency

$$P_{\text{hot\_on}} = g_1(K_{\text{ant}} T_{\text{hot}} - K_{\text{NS}} T_{\text{Non}} + K_{\text{amb}} T_{\text{amb}})$$
$$P_{\text{hot\_off}} = g_1(K_{\text{ant}} T_{\text{hot}} - K_{\text{NS}} T_{\text{Noff}} + K_{\text{amb}} T_{\text{amb}})$$
$$P_{\text{cold\_on}} = g_2(K_{\text{ant}} T_{\text{cold}} - K_{\text{NS}} T_{\text{Non}} + K_{\text{amb}} T_{\text{amb}})$$
$$P_{\text{cold\_off}} = g_2(K_{\text{ant}} T_{\text{cold}} - K_{\text{NS}} T_{\text{Noff}} + K_{\text{amb}} T_{\text{amb}})$$

$$T'_{\text{ant}} = -\frac{P_{\text{off}}}{P_{\text{on}} - P_{\text{off}}} K_{NS}(\mathrm{T}_{\text{Non}} - \mathrm{T}_{\text{Noff}}) + K_{NS} T_{\text{Noff}}$$

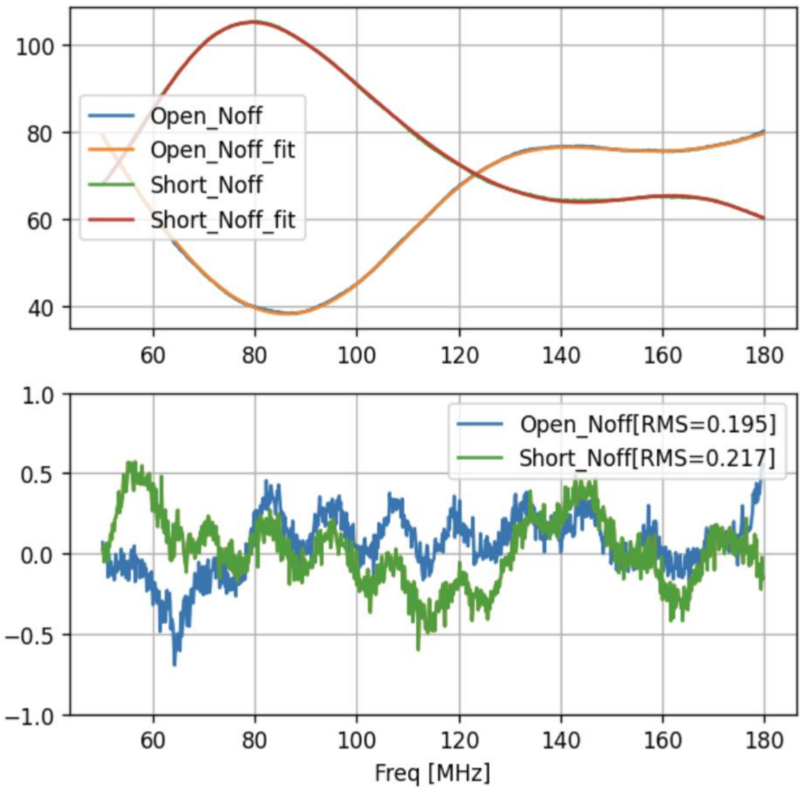
$$T'_{\text{ant}} = K_{\text{ant}} T_{\text{ant}} + \Sigma K_{\text{nw}} T_{\text{nw}} + K_{\text{amb}} T_{\text{amb}}$$

Iteration

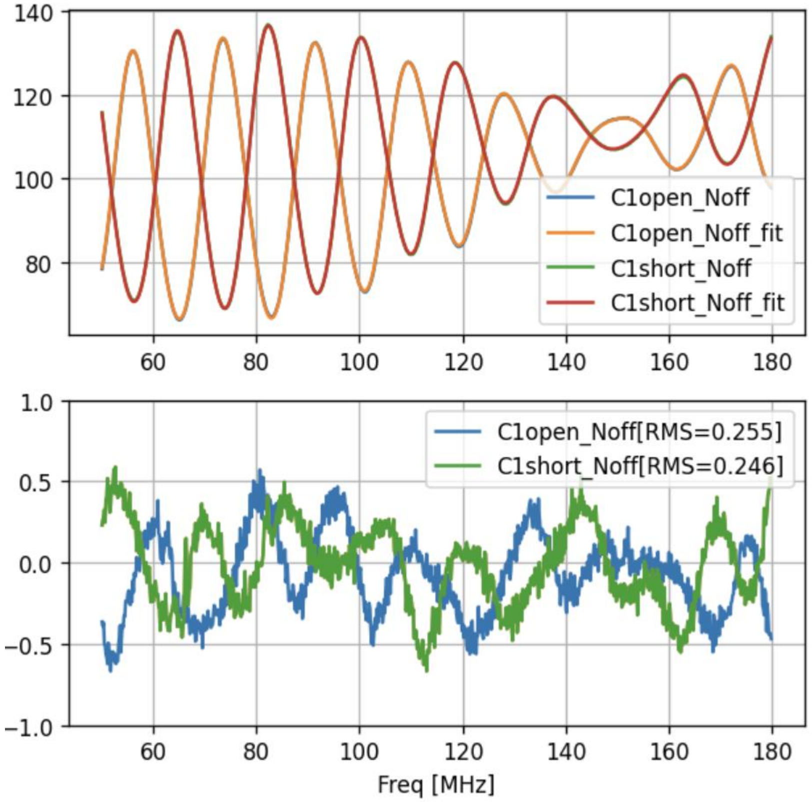
Calibration Results

Spectrum and fitting residuals T'_{ant}

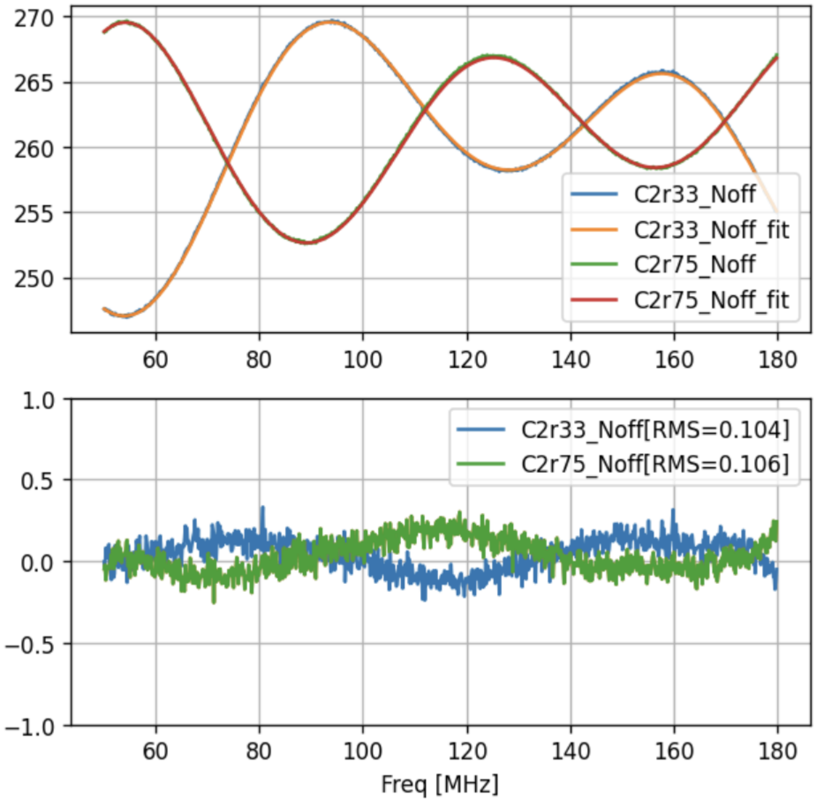
Open, Short



5m + Open, 5m + Short



0.2m + 33Ω, 0.2m+75Ω



Calibration Results

Noise wave parameters

T_{nw}:

T_{u1}: Uncorrelated noise of LNA1, real value

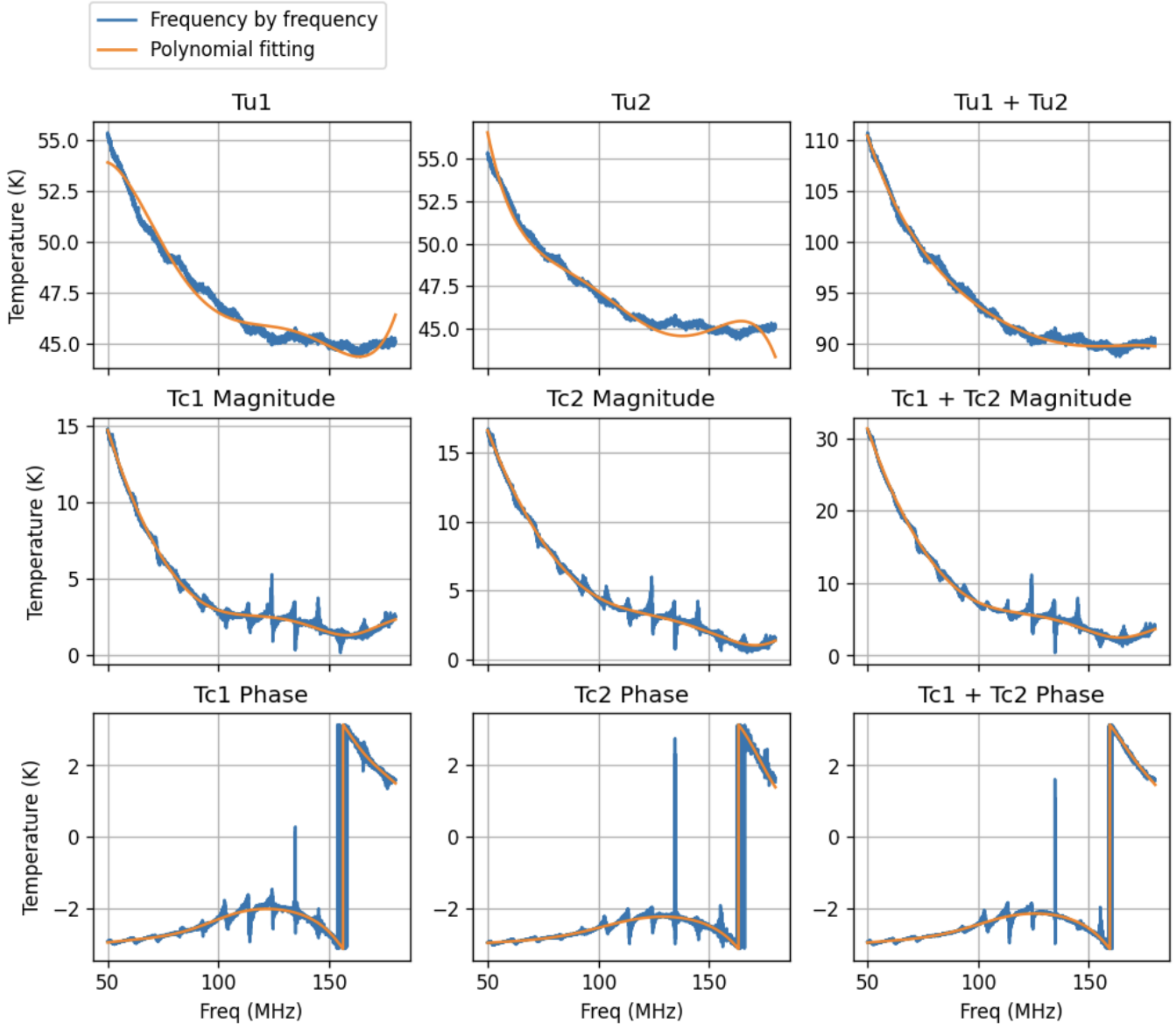
T_{u2}: Uncorrelated noise of LNA2, real value

T_{c1}: Correlated noise of LNA1, complex value

T_{c2}: Correlated noise of LNA2, complex value

Obvious degeneracy between T_{u1} and T_{u2}

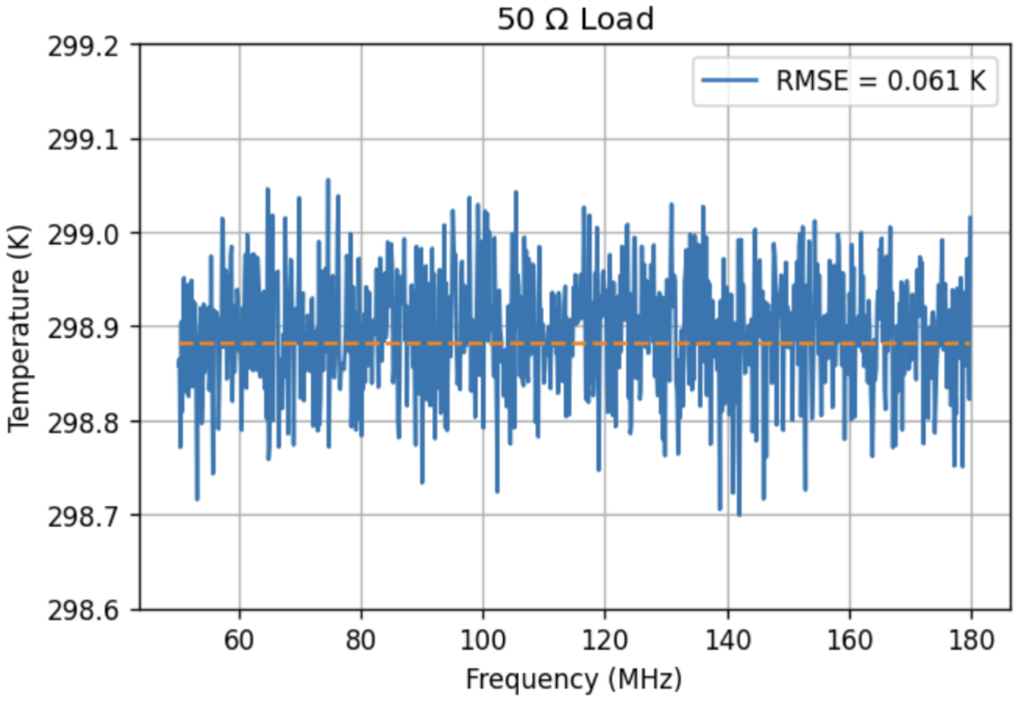
Huge spikes and noise in frequency by frequency method.

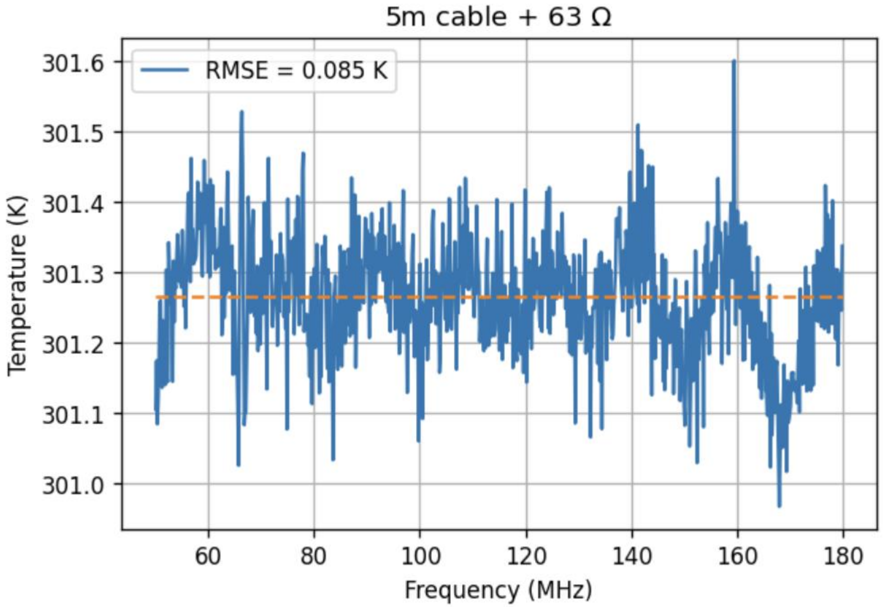


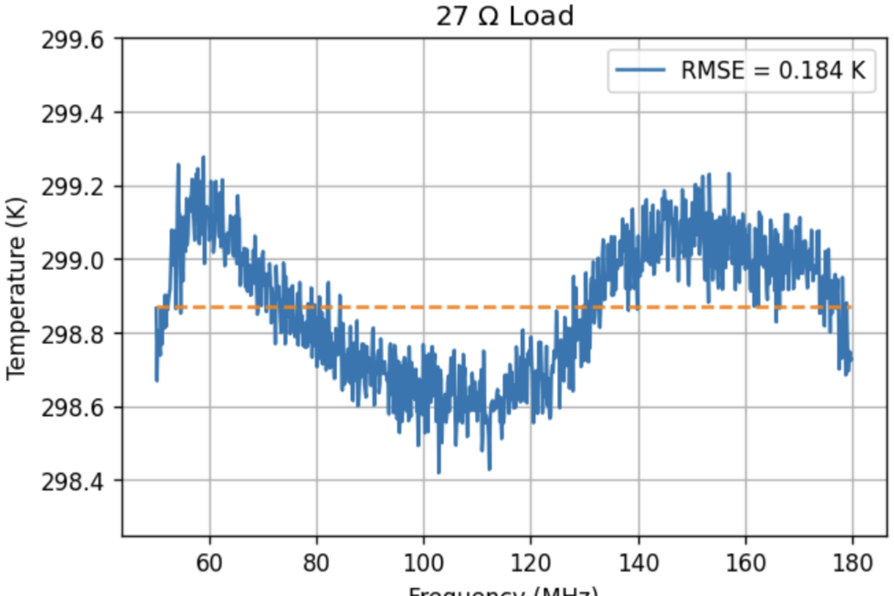
Calibration Results

Physical temperature recovery

$$T_{\text{ant}}$$







Conclusions & Future questions

- Construct a calibration method for two-way differential receiver.
- Use polynomial fittings and frequency by frequency method to do cross-checking
- The physical temperature recovery error is less then ±0.05K for 50Ω load and ±0.25K for 27Ω load. Residuals are wide band structures, can be partly subtracted during foreground remove.

- Obvious structures still exist in recovery residuals.
- VNA measurement error? Real-time and in-lab.
- LNA design, trade off between low reflection coefficient and low noise.
- Selection of cable length and terminator impedance.

Thank you!