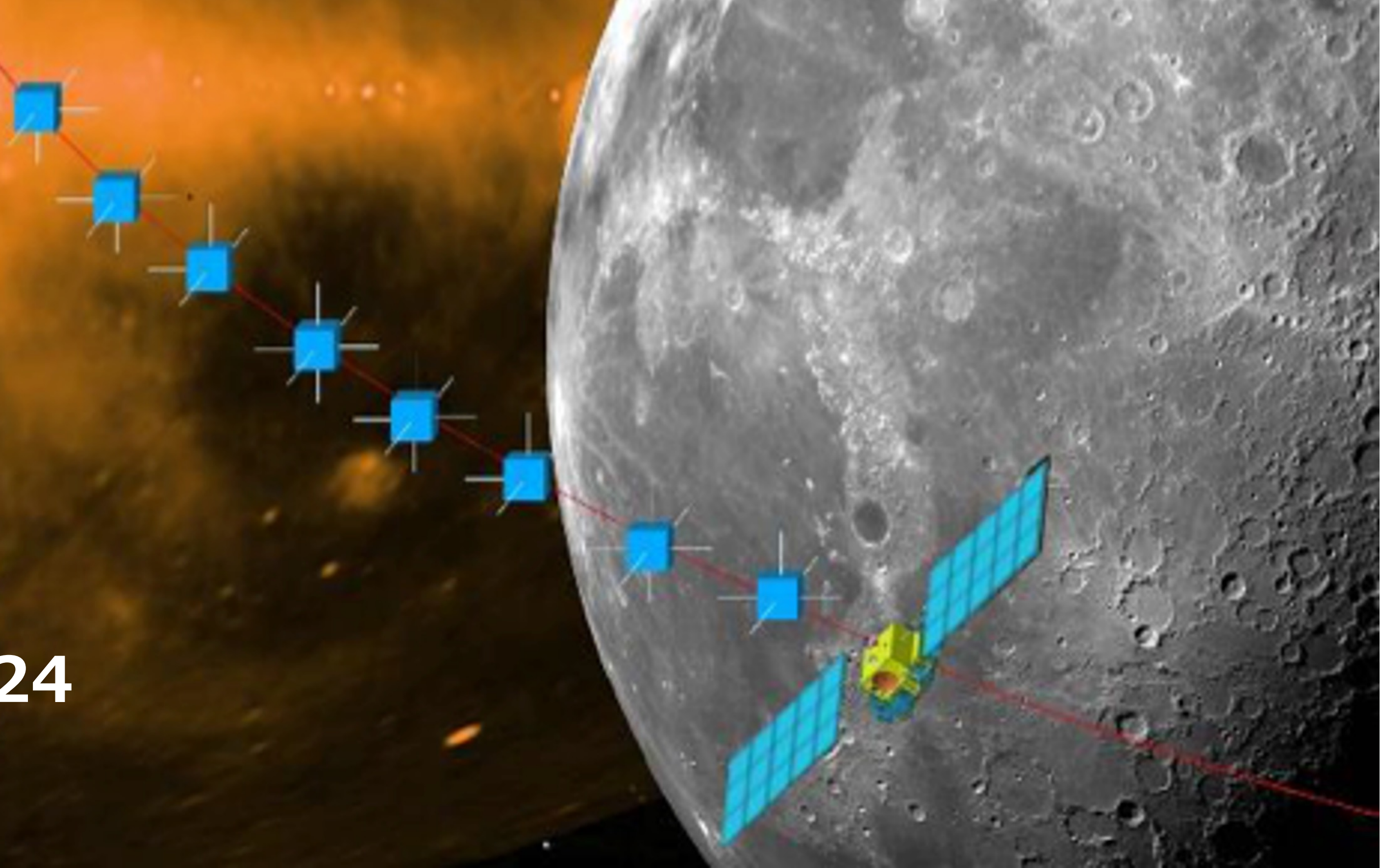
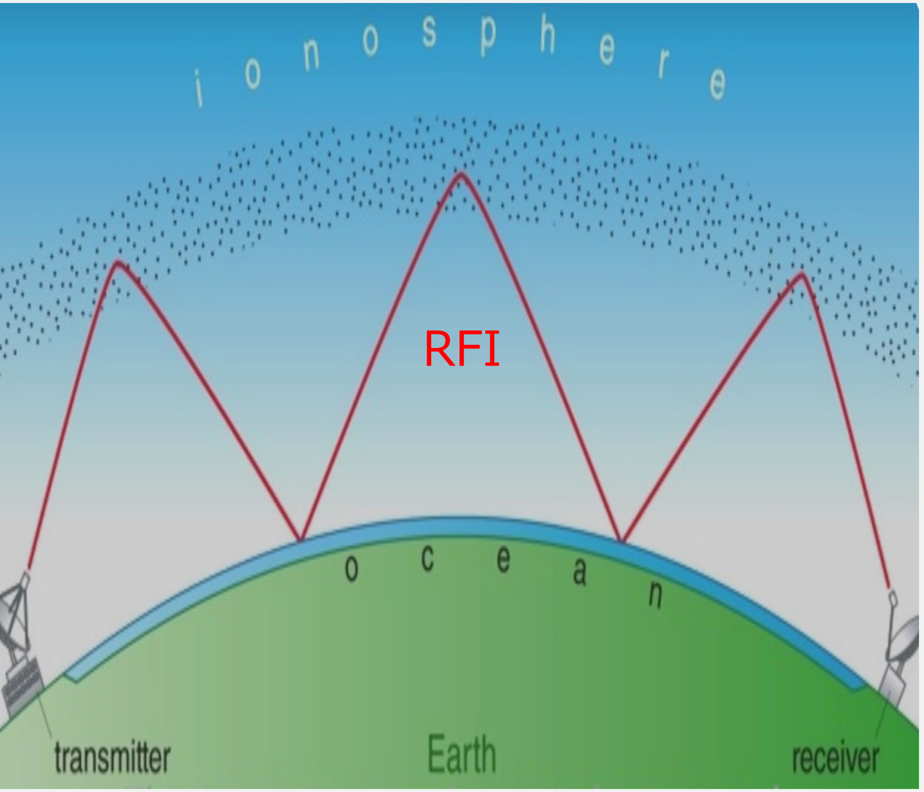
Measuring 21cm global spectrum on the lunar orbit
---High-frequency payload in Hongmeng project

Fengquan Wu
Payload development team
NAOC

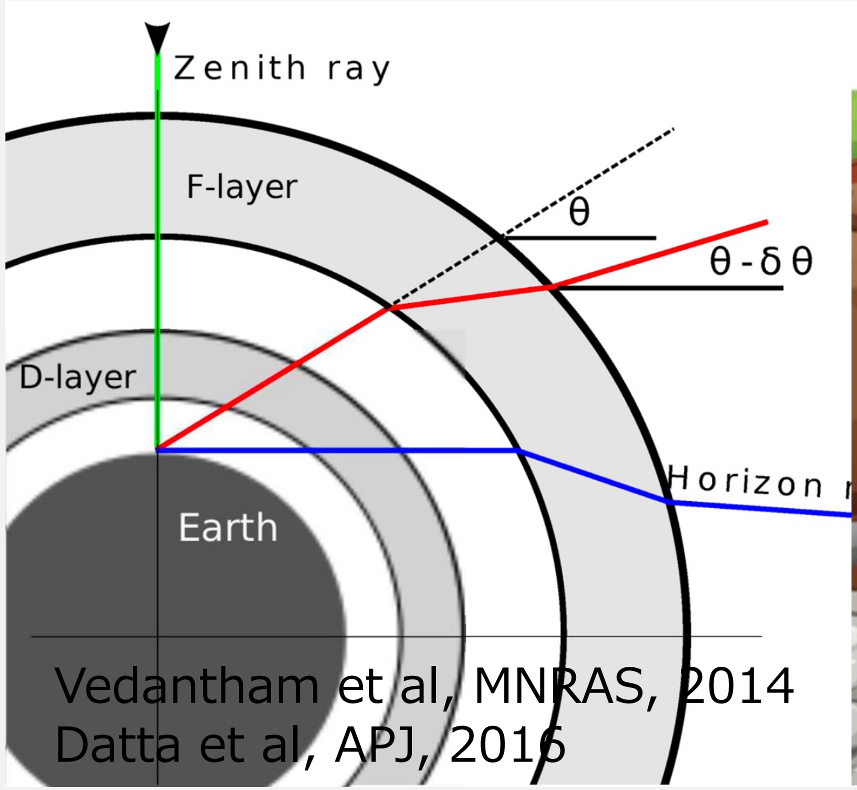


21 cm Cosmology Workshop 2024
Hangzhou July 23

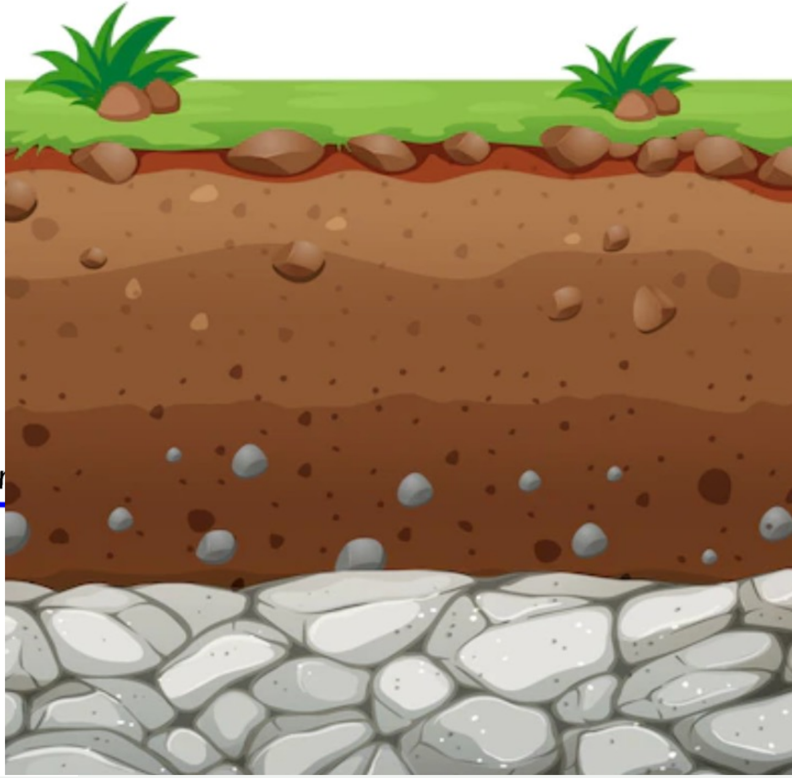
21cm global spectrum — Environment effect



RFI contamination



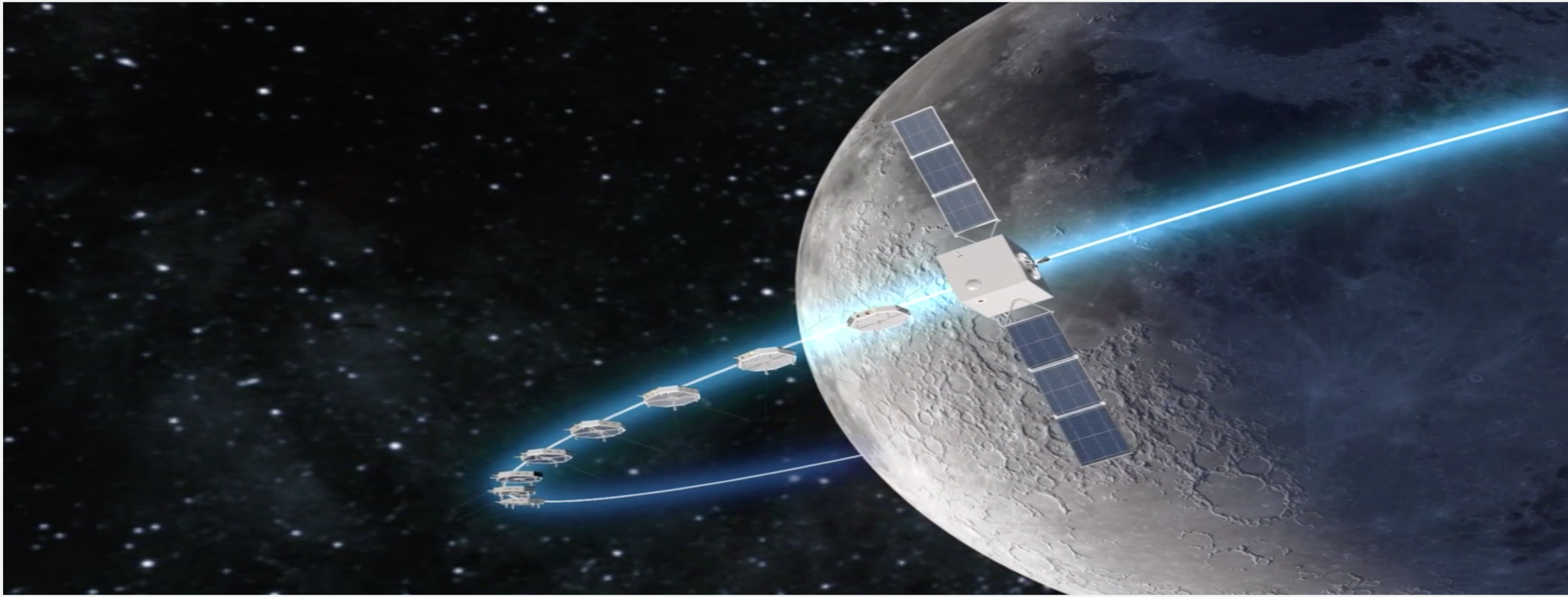
Ionosphere effect



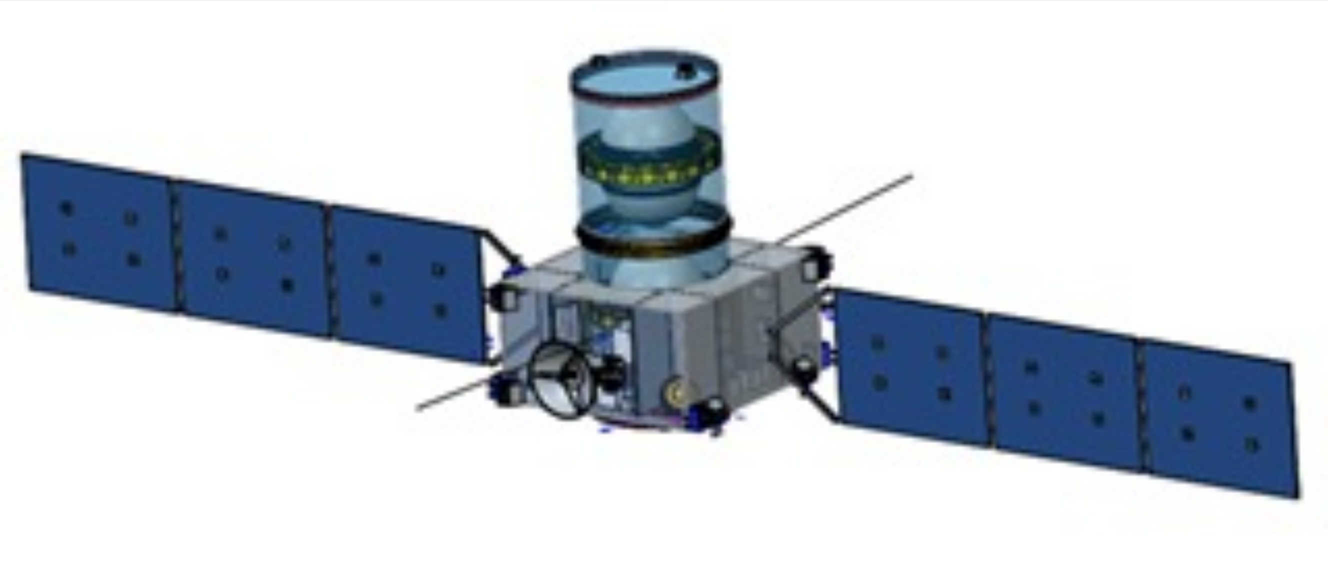
Ground effect

Overview of Hongmeng （鸿蒙）project(PI: Xuelei Chen)

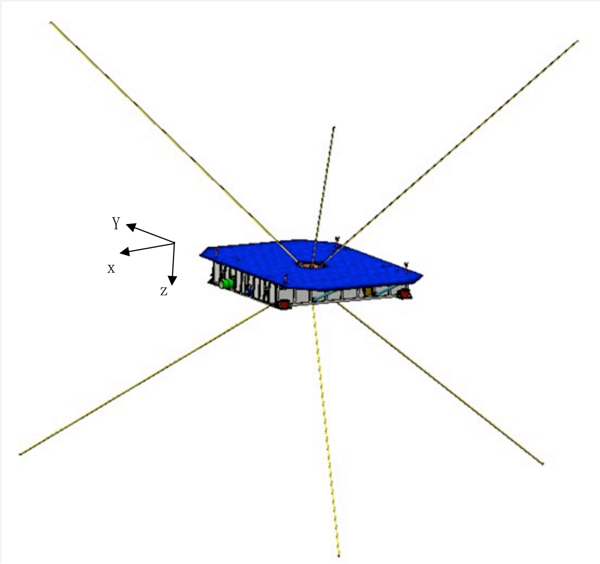
Long wavelength array on lunar orbit（Pre-study project in CAS）



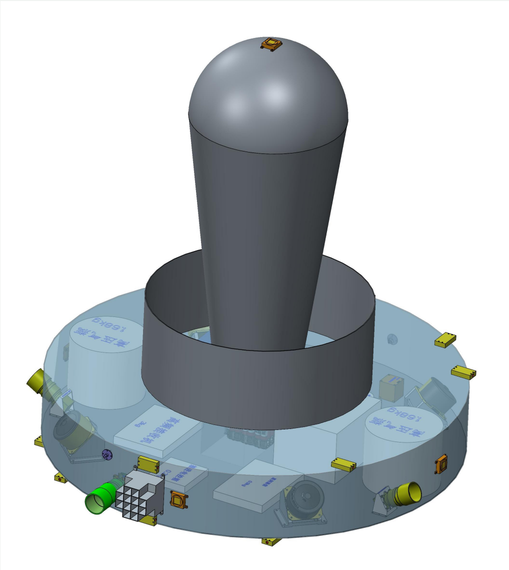
- Whole sky imaging at frequency below 30MHz
- Global spectrum measurement at frequency below 120MHz



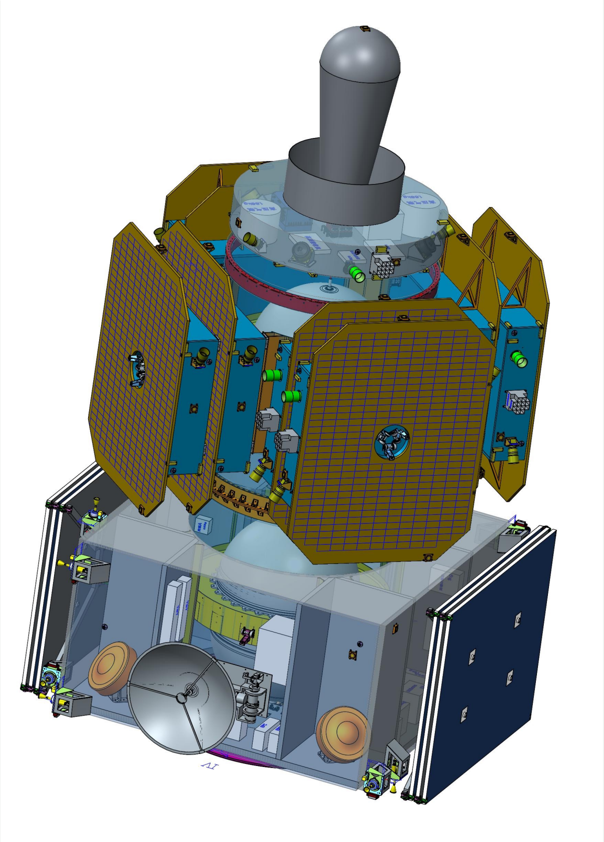
600kg



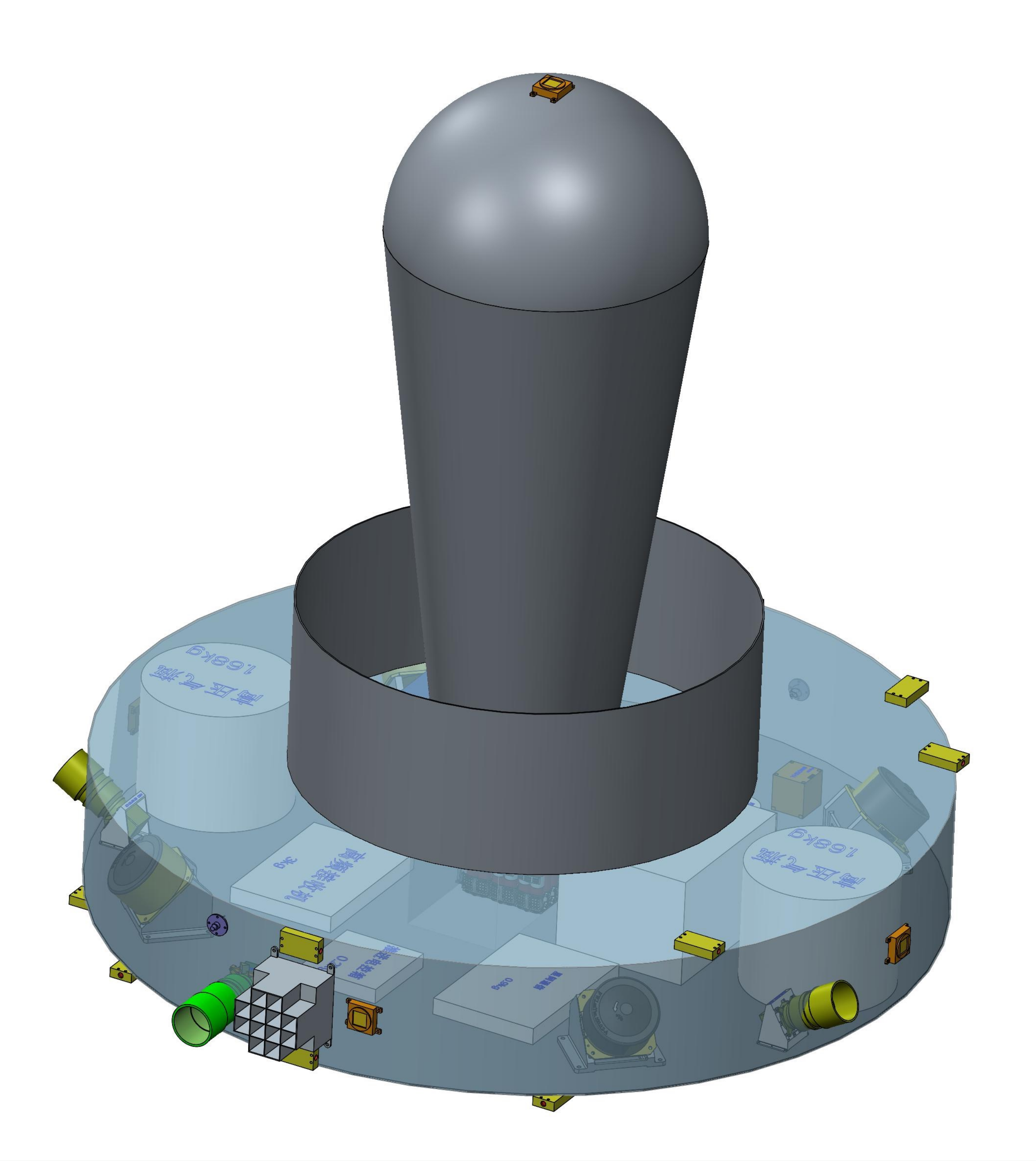
80kg



90kg



1300kg



Antenna

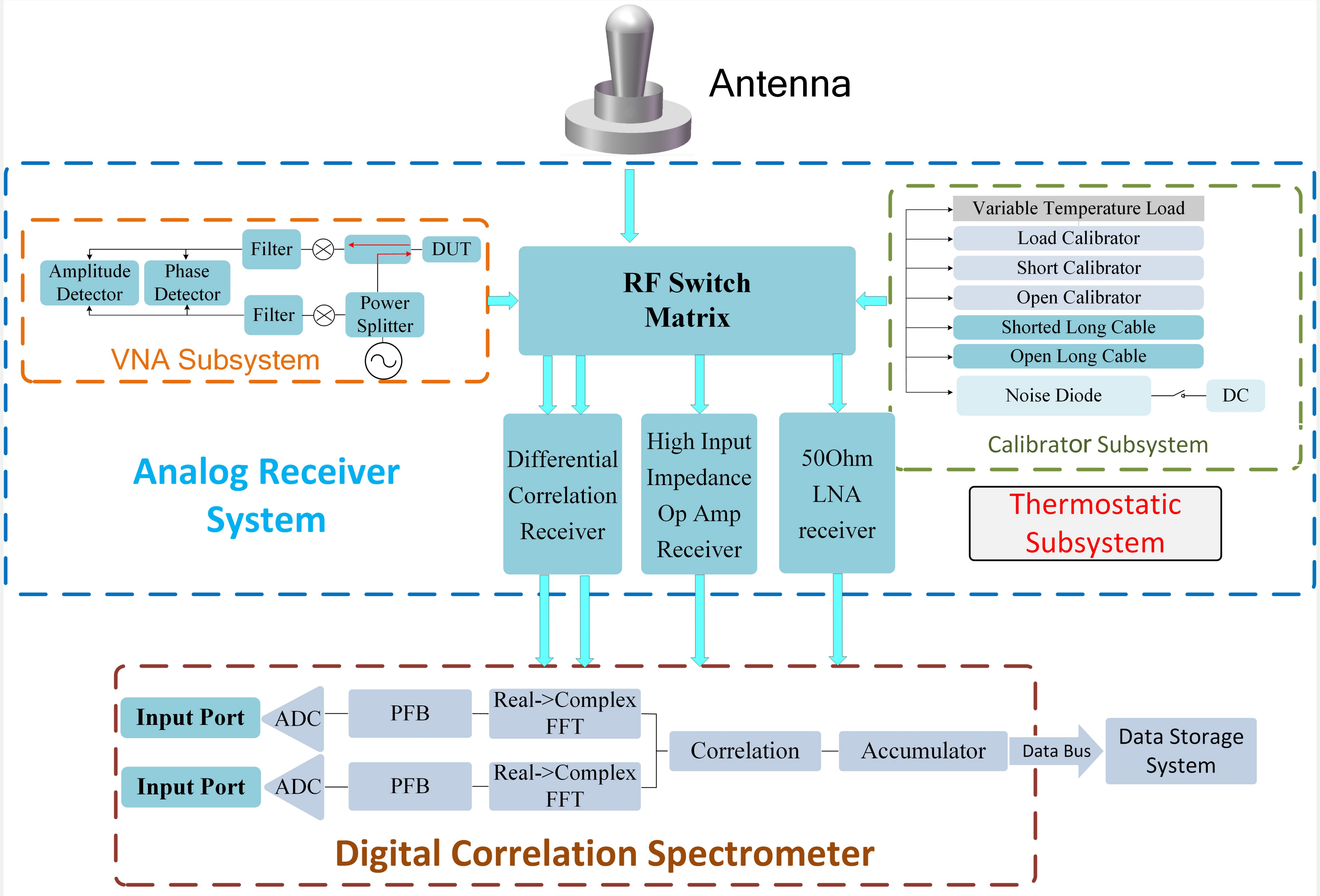
Loaded ring

Satellite body

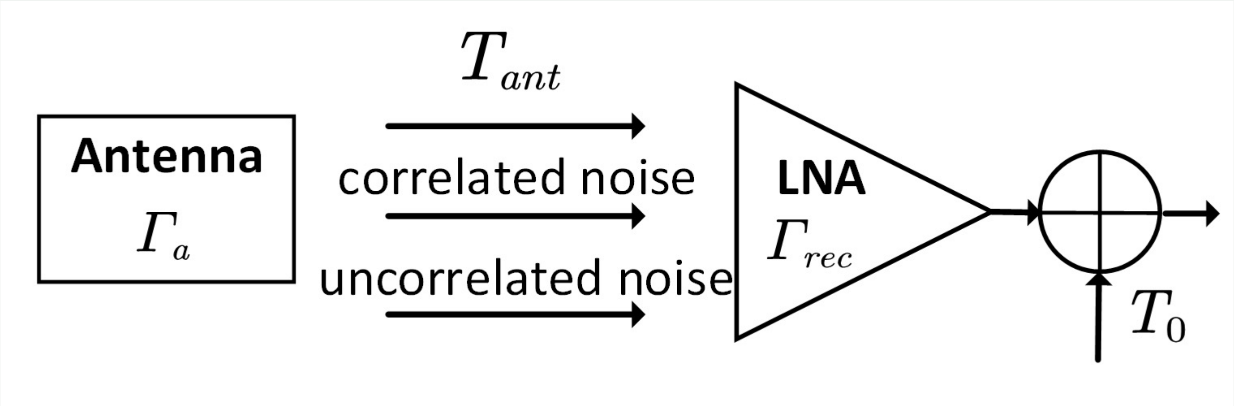
System design of global spectrum satellite

Multi-receiver design：

Cross check the system effect and signal



Two-port noise wave for 50 Ohm LNA receiver



$$X_{\mathrm{unc}} = -\frac{|\Gamma_{\mathrm{cal}}|^2}{1-|\Gamma_{\mathrm{cal}}|^2},$$

$$X_{\mathrm{L}} = \frac{|1-\Gamma_{\mathrm{cal}}\Gamma_{\mathrm{rec}}|^2}{1-|\Gamma_{\mathrm{cal}}|^2},$$

$$X_{\cos} = -\,\mathrm{Re}\left(\frac{\Gamma_{\mathrm{cal}}}{1-\Gamma_{\mathrm{cal}}\Gamma_{\mathrm{rec}}} \times \frac{X_{\mathrm{L}}}{\sqrt{1-|\Gamma_{\mathrm{rec}}|^2}}\right),$$

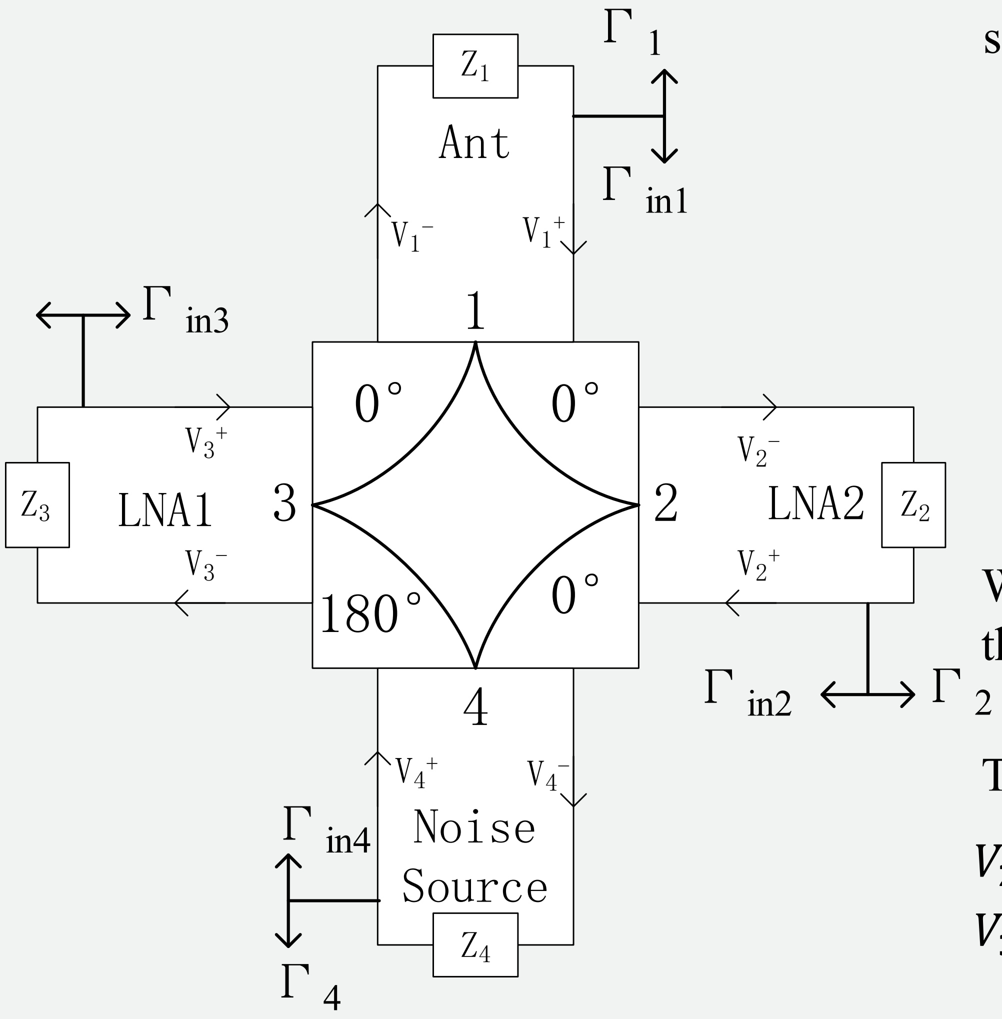
$$X_{\sin} = -\,\mathrm{Im}\left(\frac{\Gamma_{\mathrm{cal}}}{1-\Gamma_{\mathrm{cal}}\Gamma_{\mathrm{rec}}} \times \frac{X_{\mathrm{L}}}{\sqrt{1-|\Gamma_{\mathrm{rec}}|^2}}\right),$$

$$X_{\mathrm{NS}} = \left(\frac{P_{\mathrm{cal}}-P_{\mathrm{L}}}{P_{\mathrm{NS}}-P_{\mathrm{L}}}\right) X_{\mathrm{L}},$$

$$X_{\mathrm{unc}}T_{\mathrm{unc}} + X_{\cos}T_{\cos} + X_{\sin}T_{\sin} + X_{\mathrm{NS}}T_{\mathrm{NS}} + X_{\mathrm{L}}T_{\mathrm{L}} = T_{\mathrm{cal}}$$

Use 5 calibrators to solve for noise parameters at each frequency point

Four-port noise wave for differential receiver



The whole system can be modelled as a four-port microwave network

Consider the case where the antenna connected to port 1 is a temperature source and the other ports are only involved in signal reflection.

$$T_1(V_1) = \frac{|V_1|^2}{8Z_0}\frac{|1-\Gamma_1|^2}{(1-|\Gamma_1|^2)} \qquad V_1^+(V_1) = \frac{V_1(1-\Gamma_1)}{2(1-\Gamma_1\Gamma_{in1})} \qquad \Gamma_{in1} = V_1^-/V_1^+$$

$$\begin{bmatrix} V_1^- \\ V_2^- \\ V_3^- \\ V_4^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ V_3^+ \\ V_4^+ \end{bmatrix} \qquad \begin{aligned} \Gamma_2 &= V_2^+/V_2^- \\ \Gamma_3 &= V_3^+/V_3^- \\ \Gamma_4 &= V_4^+/V_4^- \end{aligned}$$

With the equation above, we can obtain all V_i^- and V_i^+ with respect to T_1, the equivalent temperature of antenna.

The cross-correlation power is $P_c = \frac{V_{2o}^* V_{3o}}{2Z_0}$, with

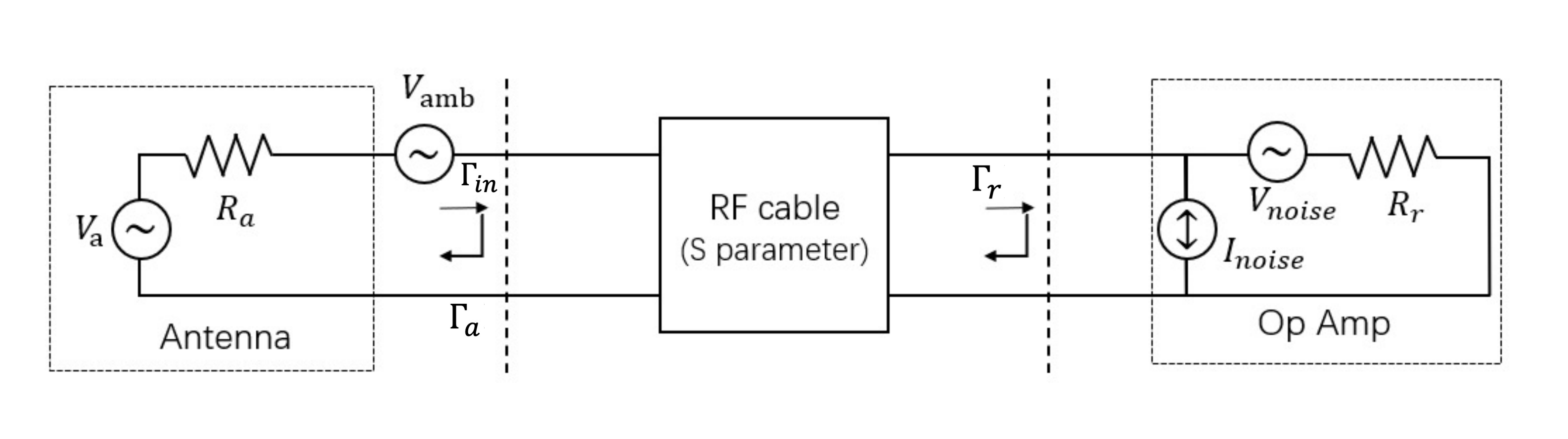
$$V_{2o} = G_2 V_2^- \sqrt{(1-|\Gamma_2|^2)}$$
$$V_{3o} = G_3 V_3^- \sqrt{(1-|\Gamma_3|^2)}$$

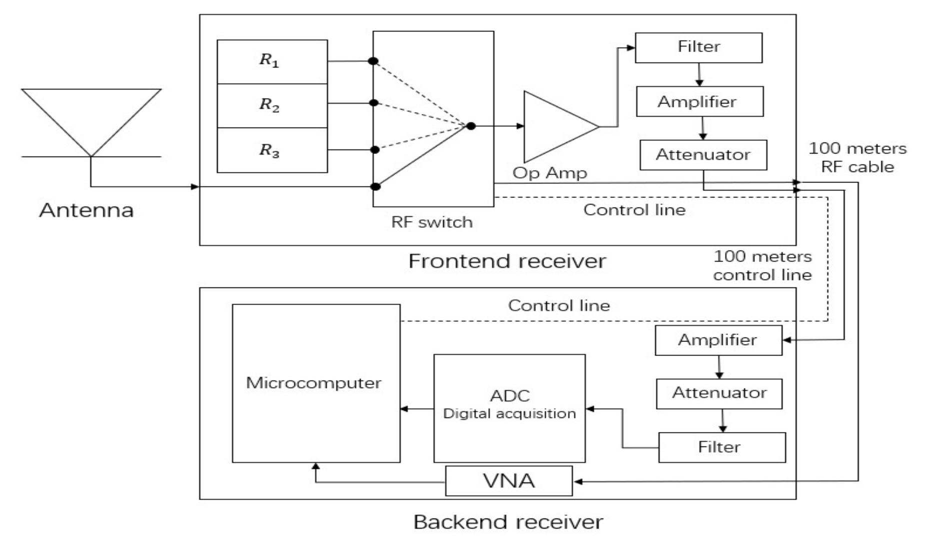
Similarly, we can calculate cross-correlation power generated by noise source and uncorrelated part of two LNAs noise.

Multi-resistor calibration for high impedance receiver

$$P = g[(4R_aKT + |V_{amb}|^2)\ |S_0|^2 + I_{noise}^2 Z^2 + V_{noise}^2]$$

$$S_0 = \frac{Z_0}{Z_a + Z_0} \frac{e^{-\gamma l}(1+\Gamma_r)}{(1 - S_{22}\Gamma_r)(1 - \Gamma_a \Gamma_{in})}$$





Simulation & Error propagation analysis

Calibration Error in 21-centimeter Global Spectrum Experiments

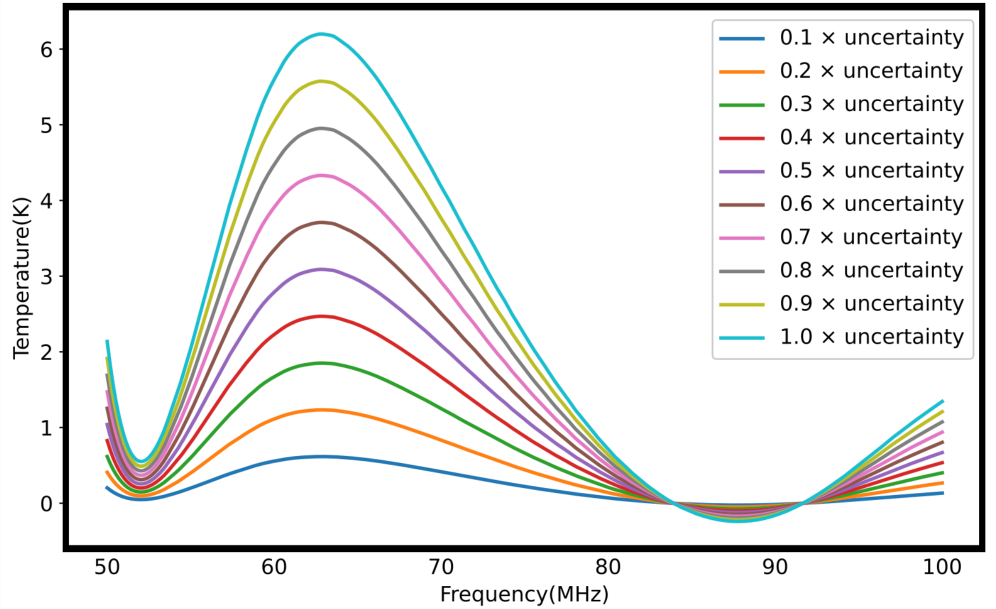
Shijie Sun et.al. Universe **2024**, *10*(6), 236

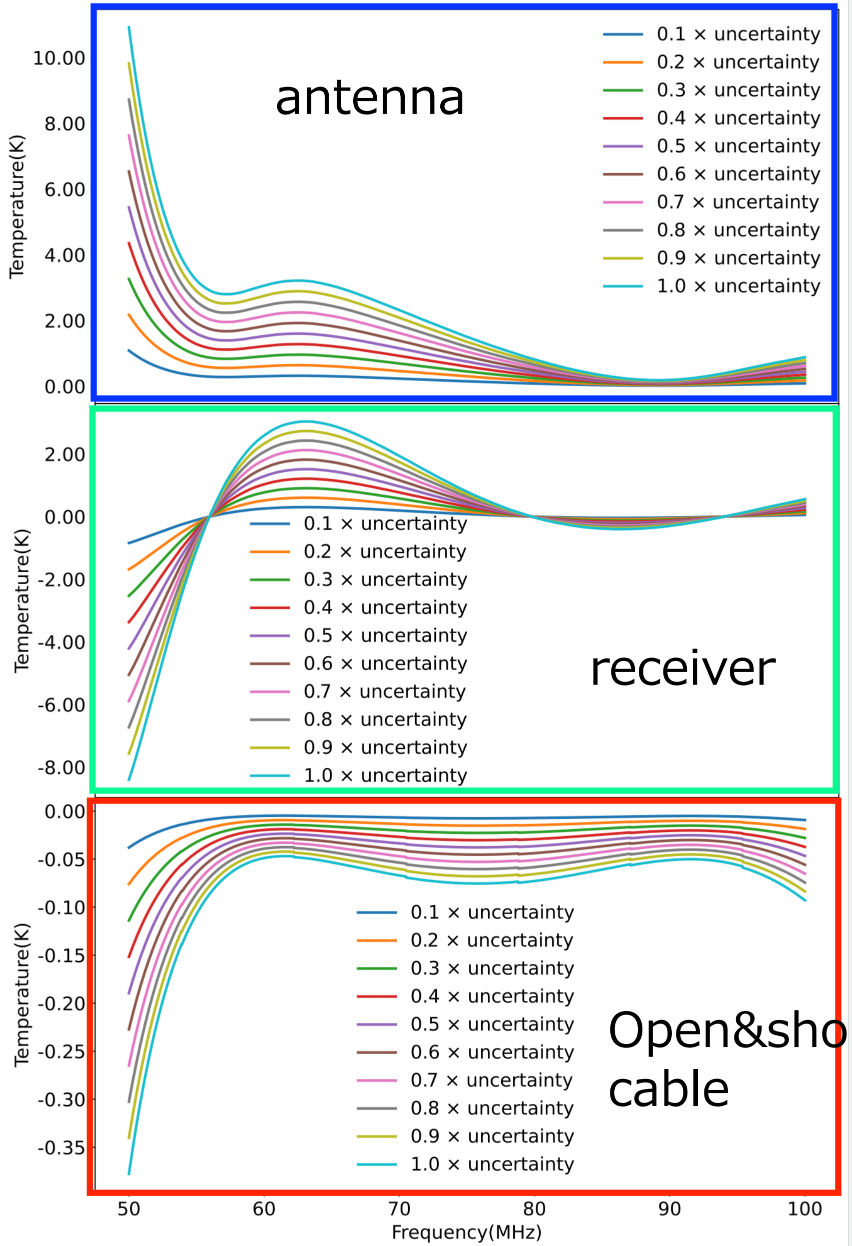
$$T_{\text{sky}} = \frac{T_{\text{ant}} - T_0}{(1 - |\Gamma_{\text{ant}}|^2)|F_{\text{ant}}|^2} - \frac{T_u |\Gamma_{\text{ant}}|^2}{1 - |\Gamma_{\text{ant}}|^2} - \frac{(T_c \cos(\phi) + T_s \sin(\phi))|\Gamma_{\text{ant}}|}{(1 - |\Gamma_{\text{ant}}|^2)|F_{\text{ant}}|} \qquad F_{\text{ant}} = \frac{(1 - |\Gamma_{\text{rec}}|^2)^{\frac{1}{2}}}{1 - \Gamma_{\text{ant}}\Gamma_{\text{rec}}}$$

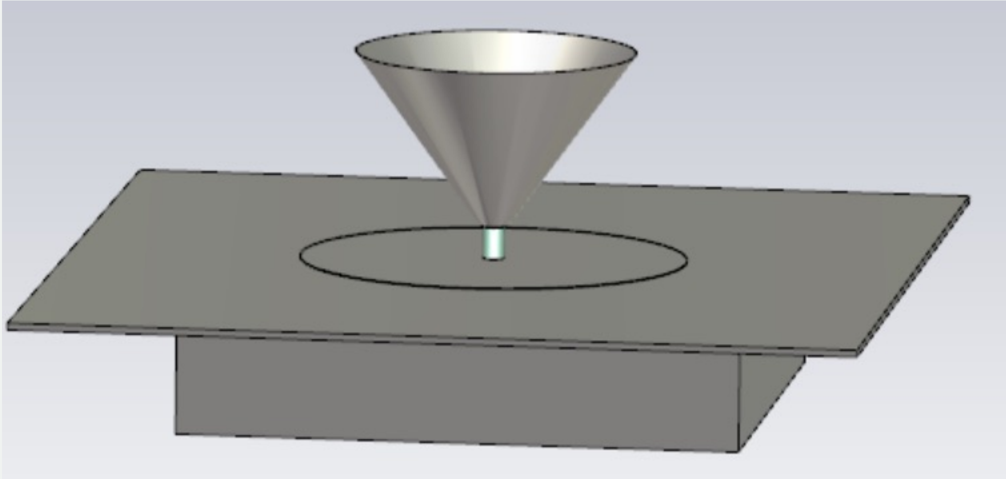
$$\delta T_{\text{sky}} = \frac{\partial T_{\text{sky}}}{\partial \Gamma_{\text{ant}}}\delta\Gamma_{\text{ant}} + \frac{\partial T_{\text{sky}}}{\partial \Gamma_{\text{rec}}}\delta\Gamma_{\text{rec}} + \frac{\partial T_{\text{sky}}}{\partial \Gamma_{\text{open}}}\delta\Gamma_{\text{open}}$$

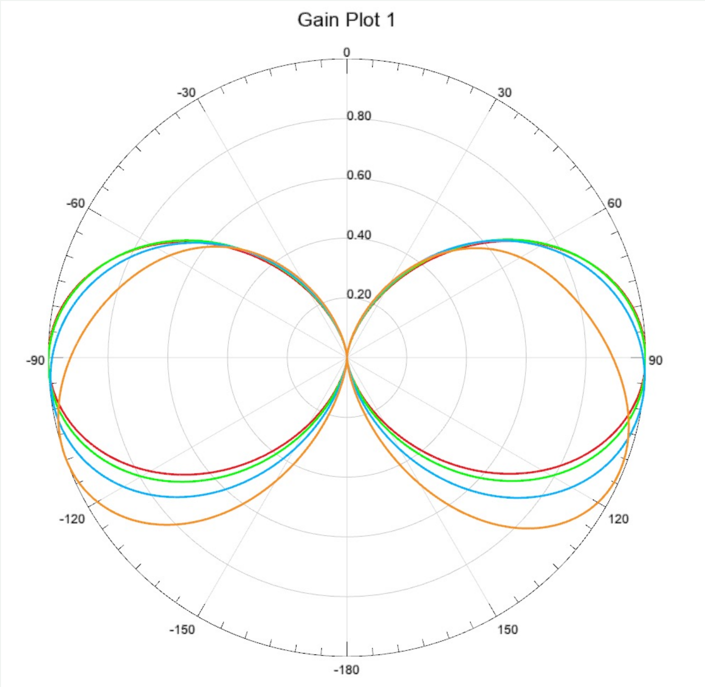
$$\frac{\partial T_{\text{sky}}}{\partial \Gamma_{\text{open}}} = \frac{\partial T_{\text{sky}}}{\partial T_u}\frac{\partial T_u}{\partial \Gamma_{\text{open}}} + \frac{\partial T_{\text{sky}}}{\partial T_c}\frac{\partial T_c}{\partial \Gamma_{\text{open}}} + \frac{\partial T_{\text{sky}}}{\partial T_s}\frac{\partial T_s}{\partial \Gamma_{\text{open}}}$$

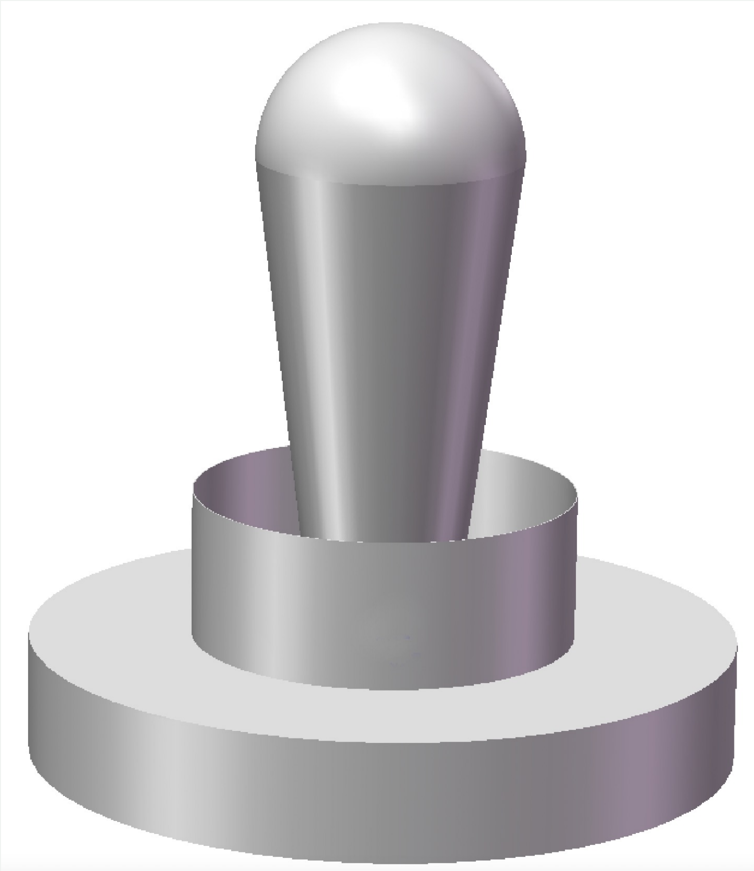
$$\frac{\partial T_{\text{sky}}}{\partial \Gamma_{\text{rec}}} = \left.\frac{\partial T_{\text{sky}}}{\partial \Gamma_{\text{rec}}}\right|_{\text{direct}} + \frac{\partial T_{\text{sky}}}{\partial T_u}\frac{\partial T_u}{\partial \Gamma_{\text{rec}}} + \frac{\partial T_{\text{sky}}}{\partial T_c}\frac{\partial T_c}{\partial \Gamma_{\text{rec}}} + \frac{\partial T_{\text{sky}}}{\partial T_s}\frac{\partial T_s}{\partial \Gamma_{\text{rec}}} + \frac{\partial T_{\text{sky}}}{\partial T_0}\frac{\partial T_0}{\partial \Gamma_{\text{rec}}}$$

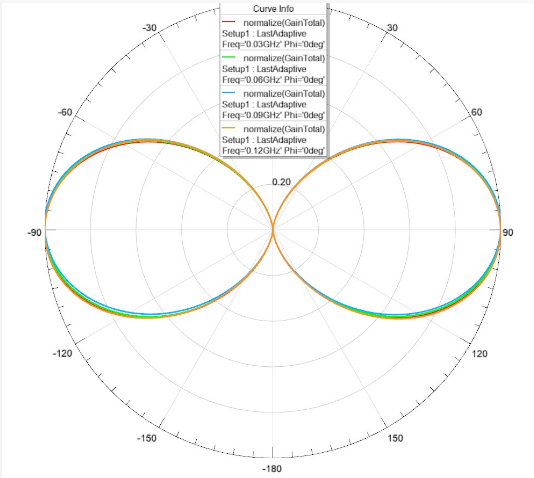


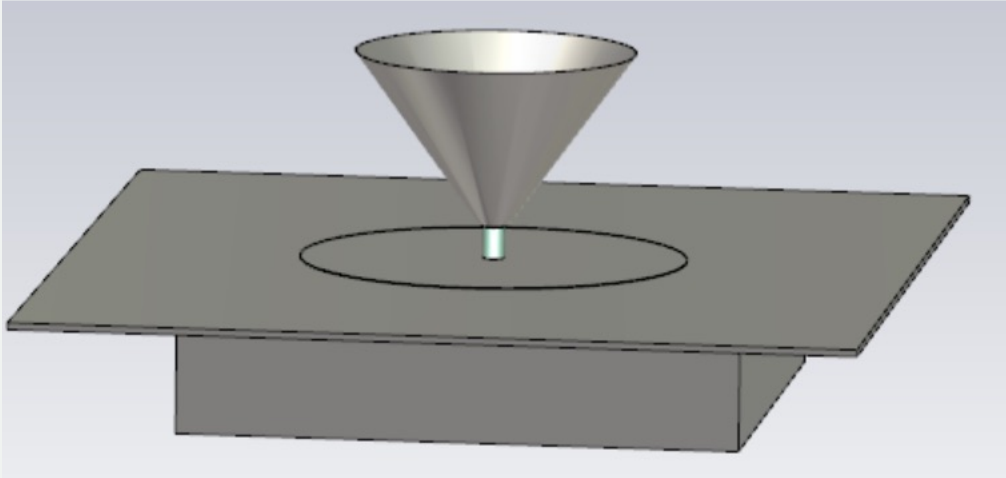


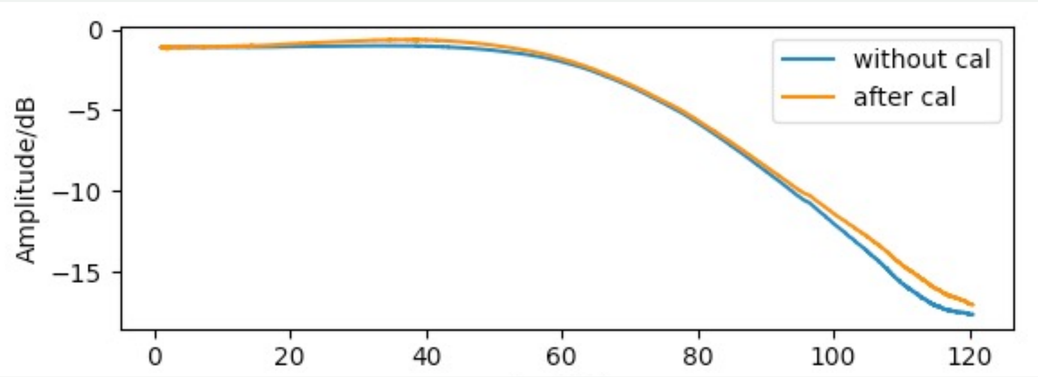



Gain Plot 1
0
-30
30
-60
60
-90
90
-120
120
-150
150
-180
0.80
0.60
0.40
0.20

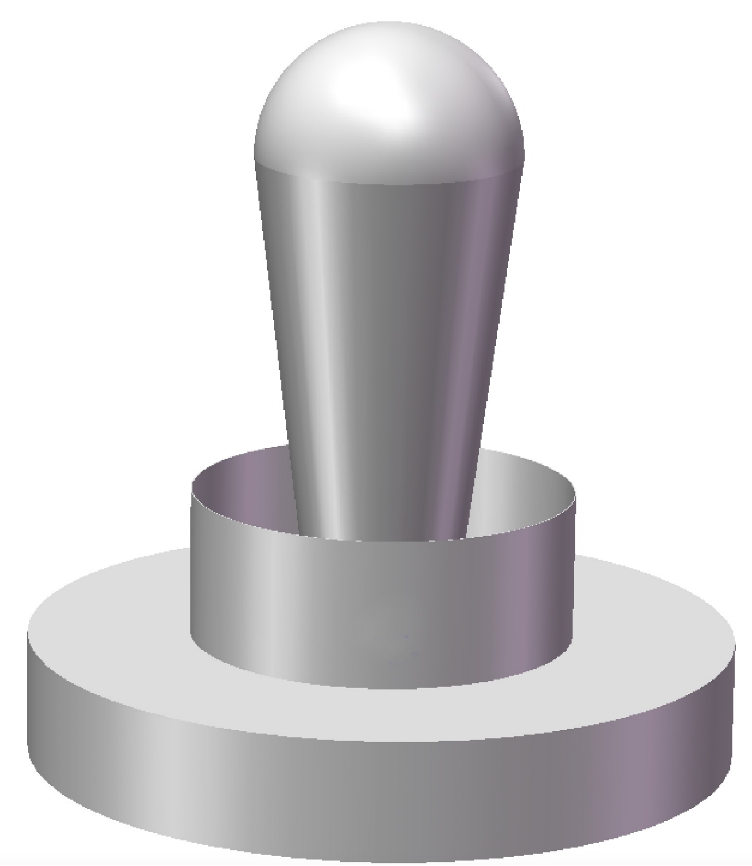


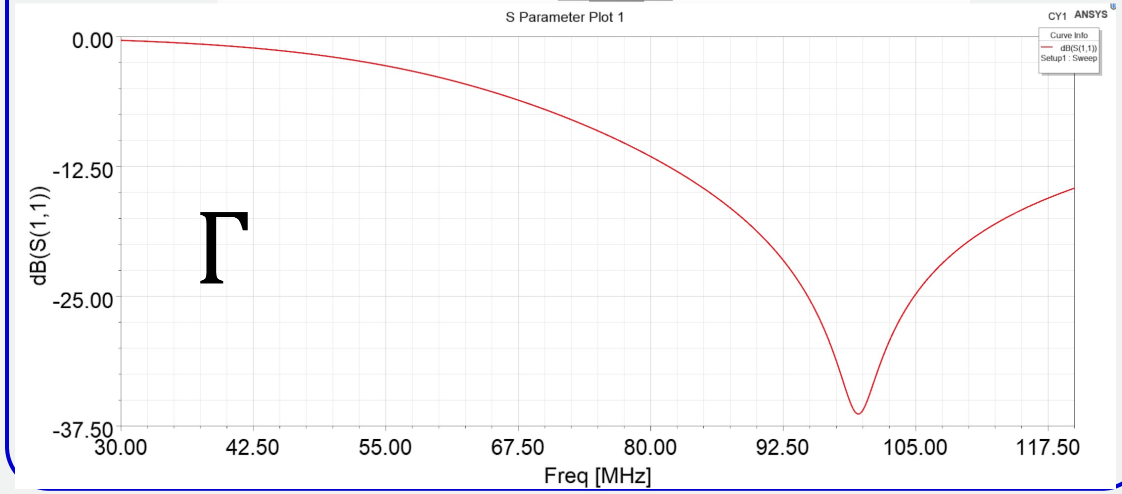

Curve Info
normalize(GainTotal)
Setup1 : LastAdaptive
Freq='0.03GHz' Phi='0deg'
normalize(GainTotal)
Setup1 : LastAdaptive
Freq='0.06GHz' Phi='0deg'
normalize(GainTotal)
Setup1 : LastAdaptive
Freq='0.09GHz' Phi='0deg'
normalize(GainTotal)
Setup1 : LastAdaptive
Freq='0.12GHz' Phi='0deg'
-30
30
-60
60
-90
90
-120
120
-150
150
-180
0.20



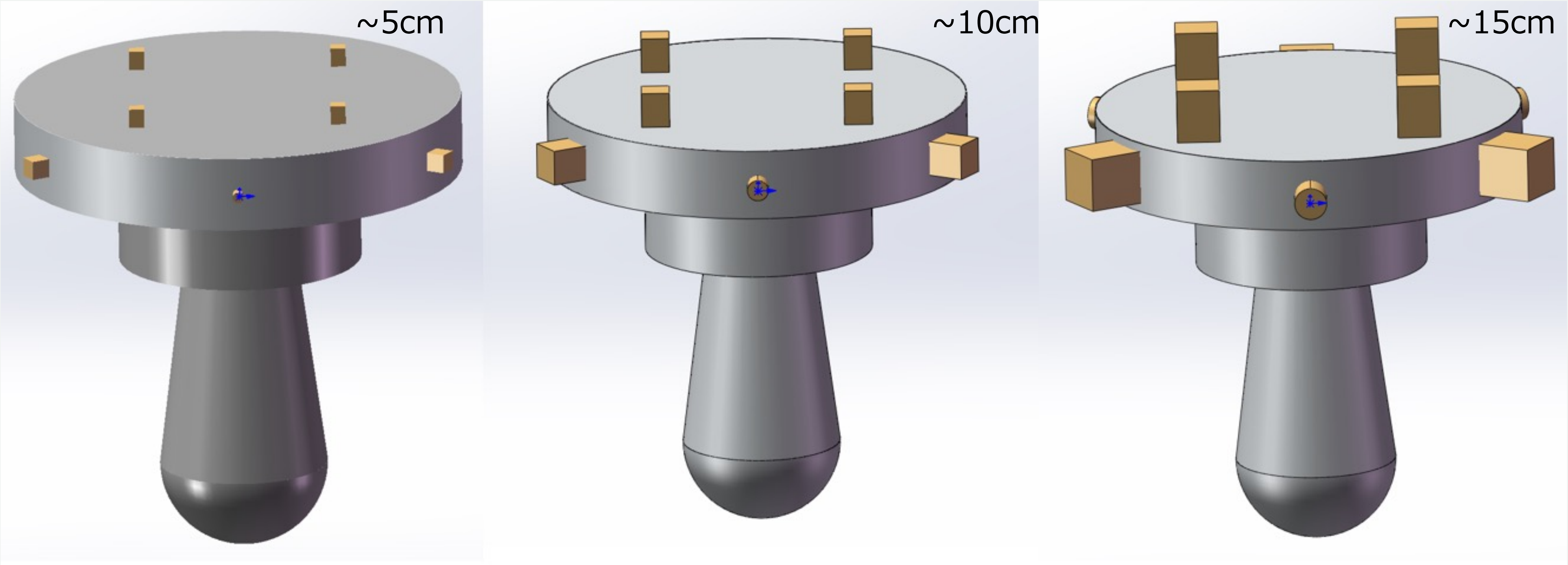


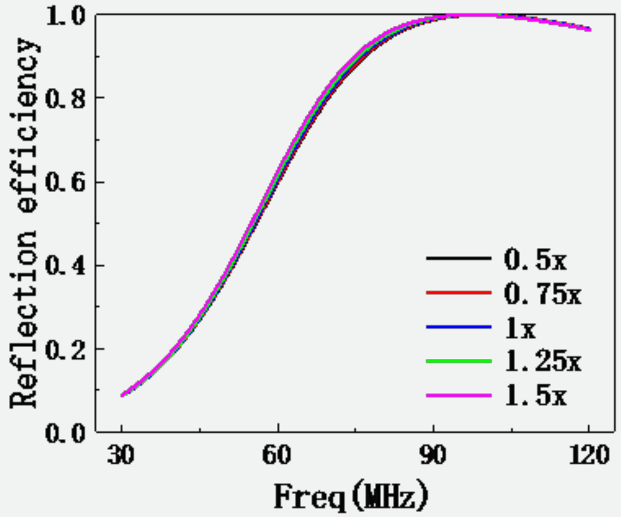
0
−5
−10
−15
Amplitude/dB
0
20
40
60
80
100
120
without cal
after cal

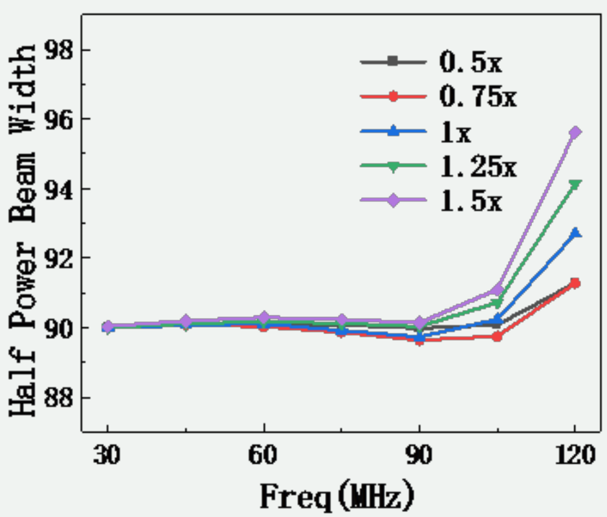




S Parameter Plot 1
CY1
ANSYS
Curve Info
dB(S(1,1))
Setup1 : Sweep
0.00
-12.50
-25.00
-37.50
dB(S(1,1))
30.00
42.50
55.00
67.50
80.00
92.50
105.00
117.50
Freq [MHz]
Γ

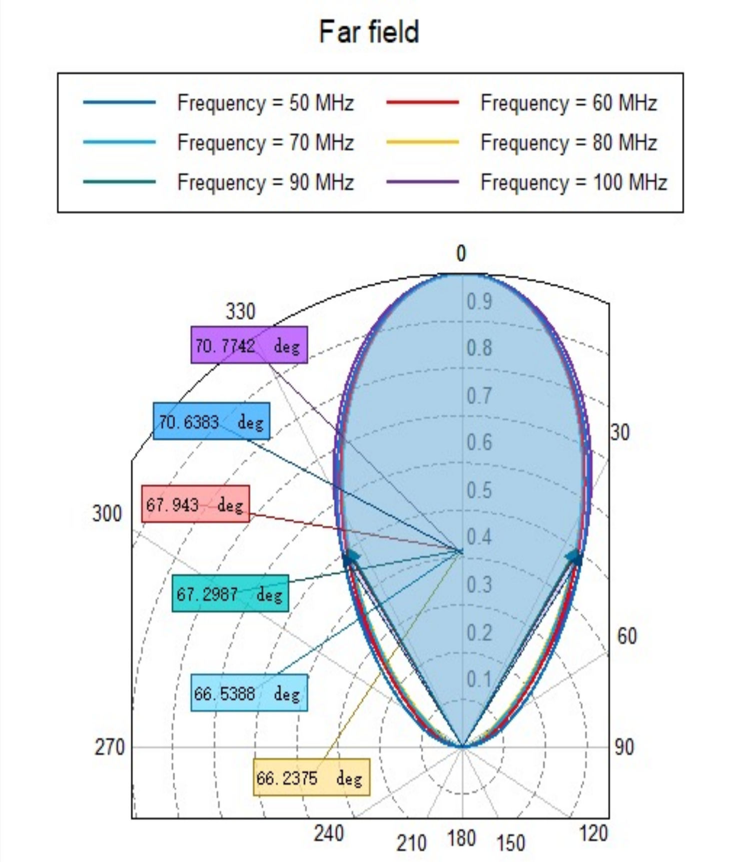

~5cm
~10cm
~15cm

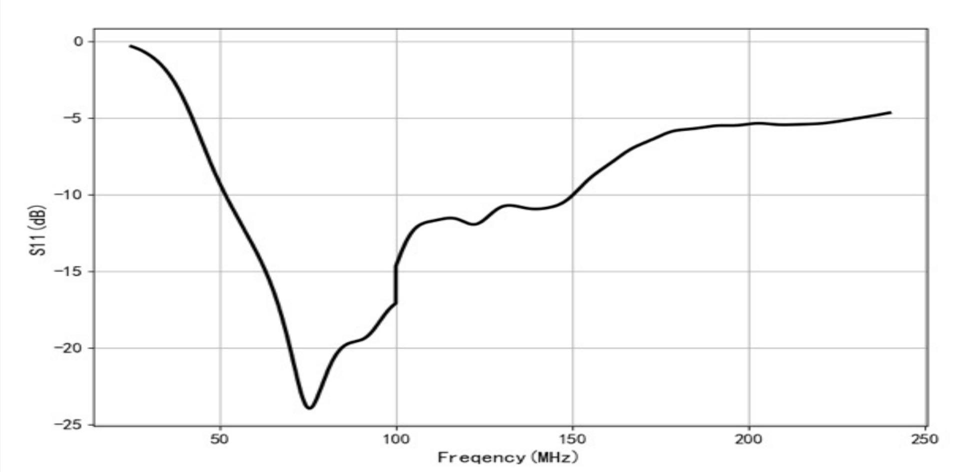

Reflection efficiency
Freq (MHz)
0.5x
0.75x
1x
1.25x
1.5x


Half Power Beam Width
Freq (MHz)
0.5x
0.75x
1x
1.25x
1.5x

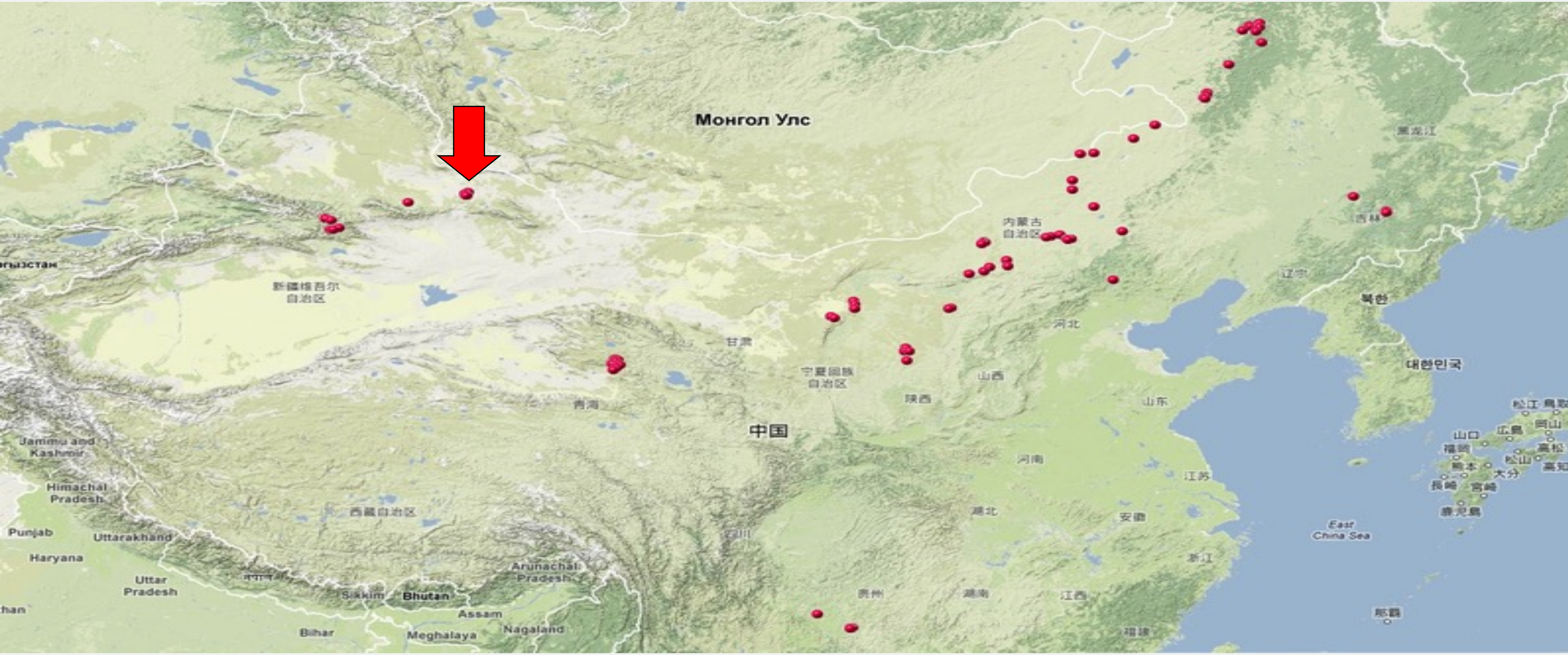

Testing of 50 Ohm LNA receiver channel


Φ2010mm
200mm
Φ1050mm
840mm


Far field
Frequency = 50 MHz
Frequency = 60 MHz
Frequency = 70 MHz
Frequency = 80 MHz
Frequency = 90 MHz
Frequency = 100 MHz
70.7742 deg
70.6383 deg
67.943 deg
67.2987 deg
66.5388 deg
66.2375 deg

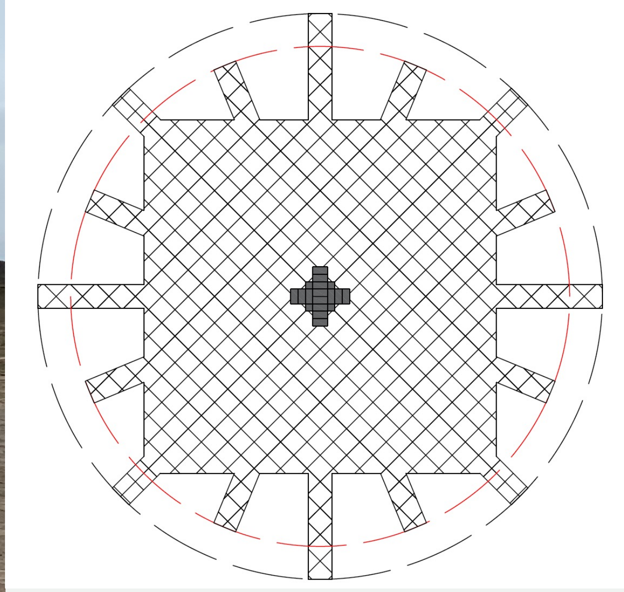

S11 (dB)
Freqency (MHz)

Field Testing Site in Xinjiang



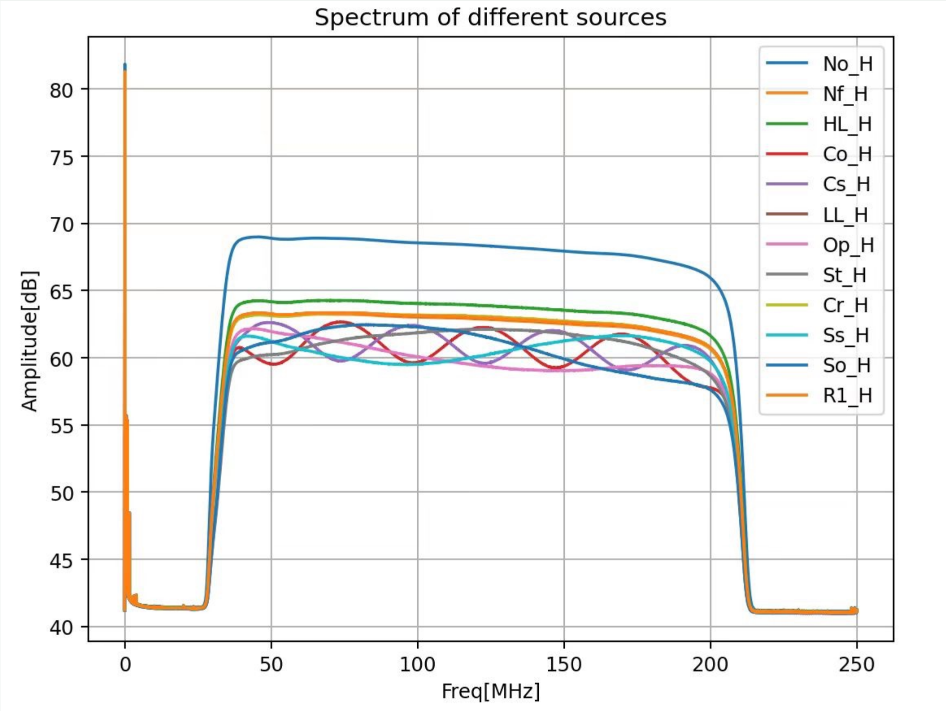
Tianlai array（天籁阵列）---Radio interferometer array for dark energy

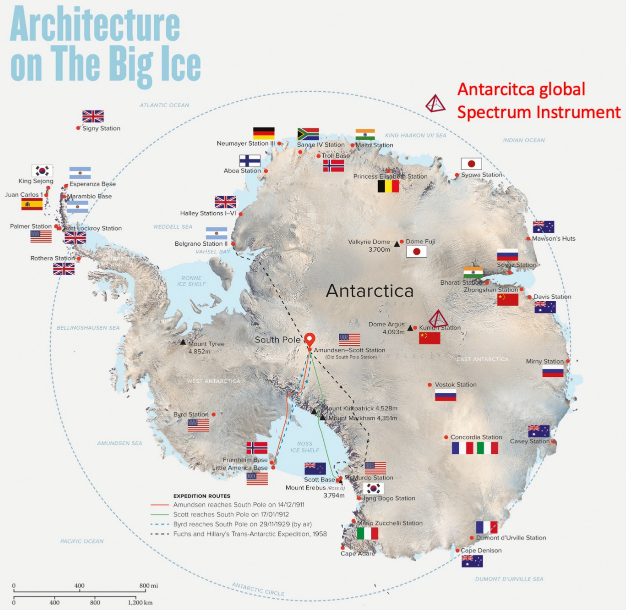
Field Testing in Xinjiang

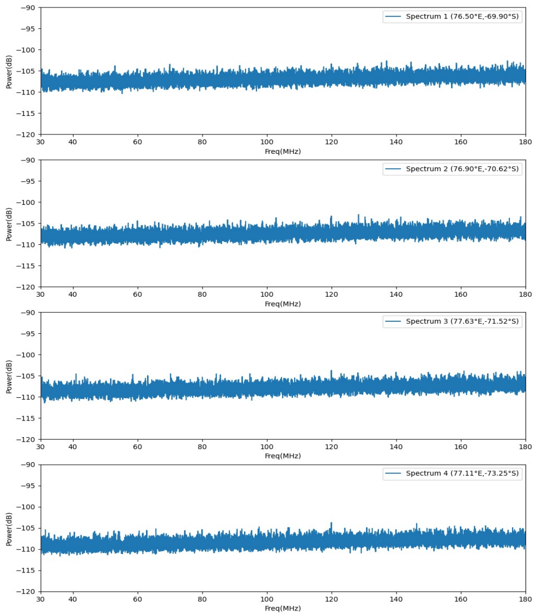


Ground plate

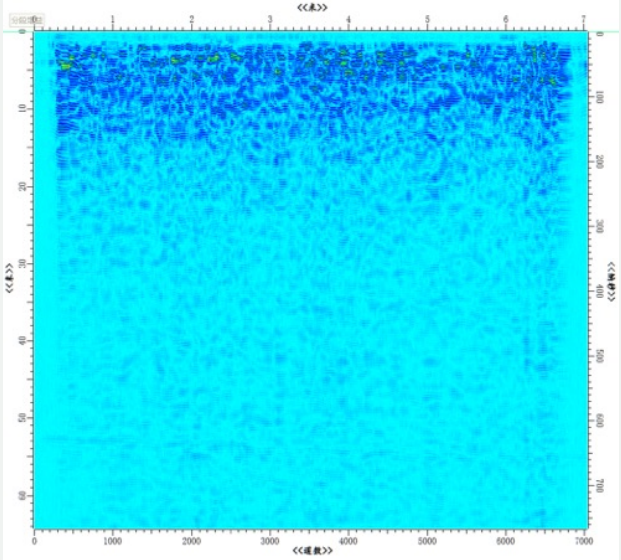
Field Testing in Antarctica





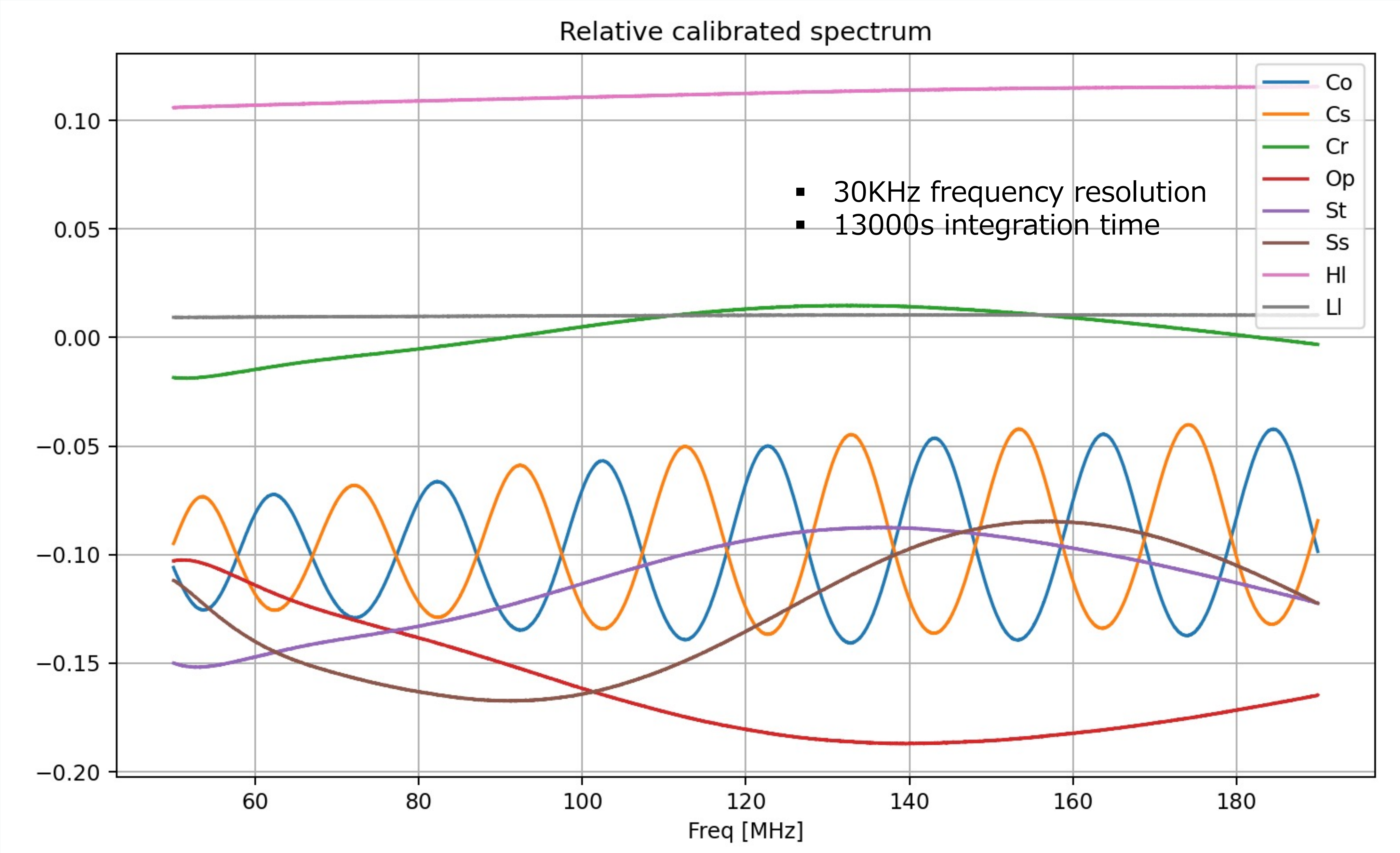


RF enviroment

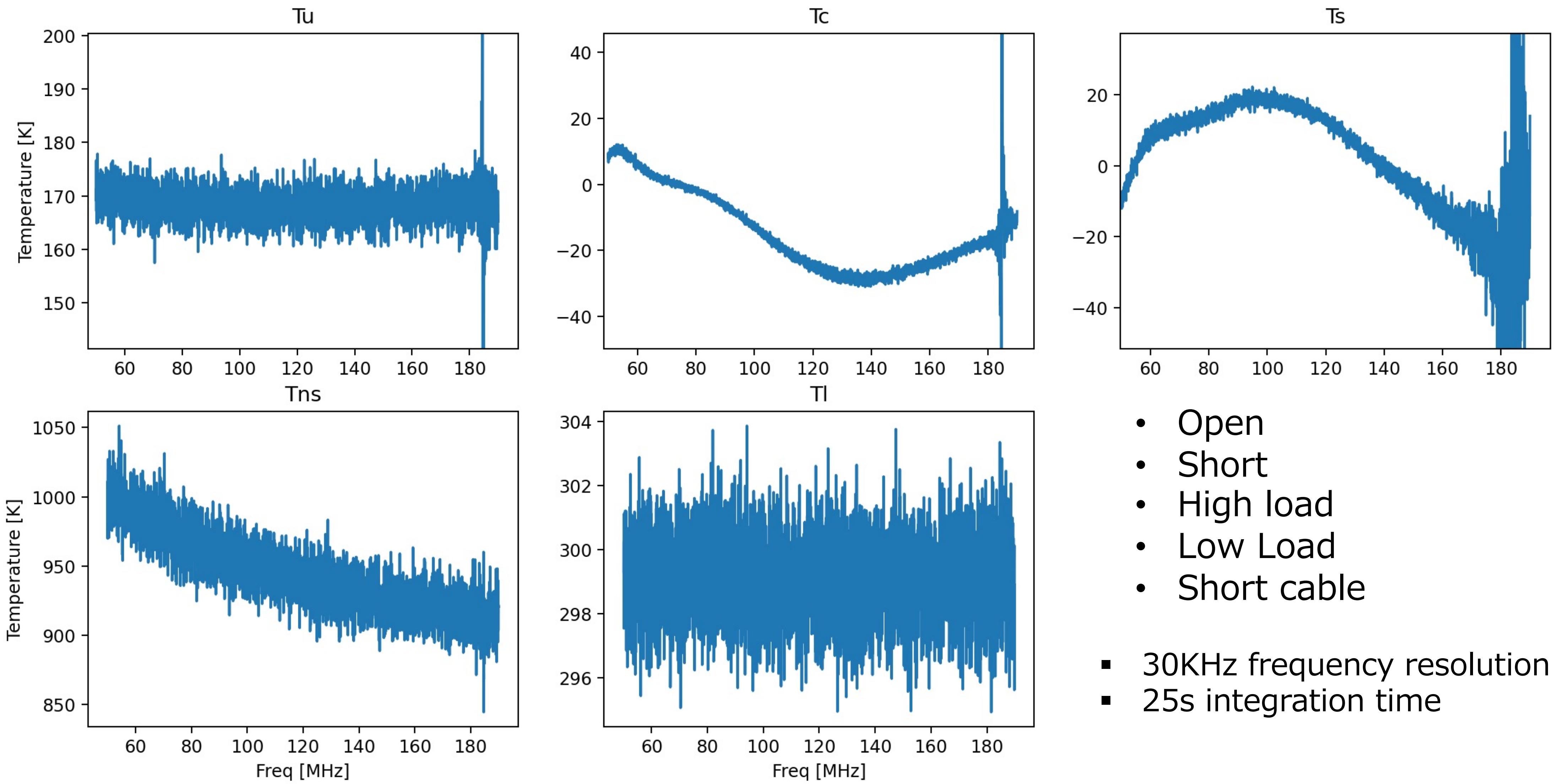


Ground penetrating radar

Spectra after Relative calibration



Noise wave parameters

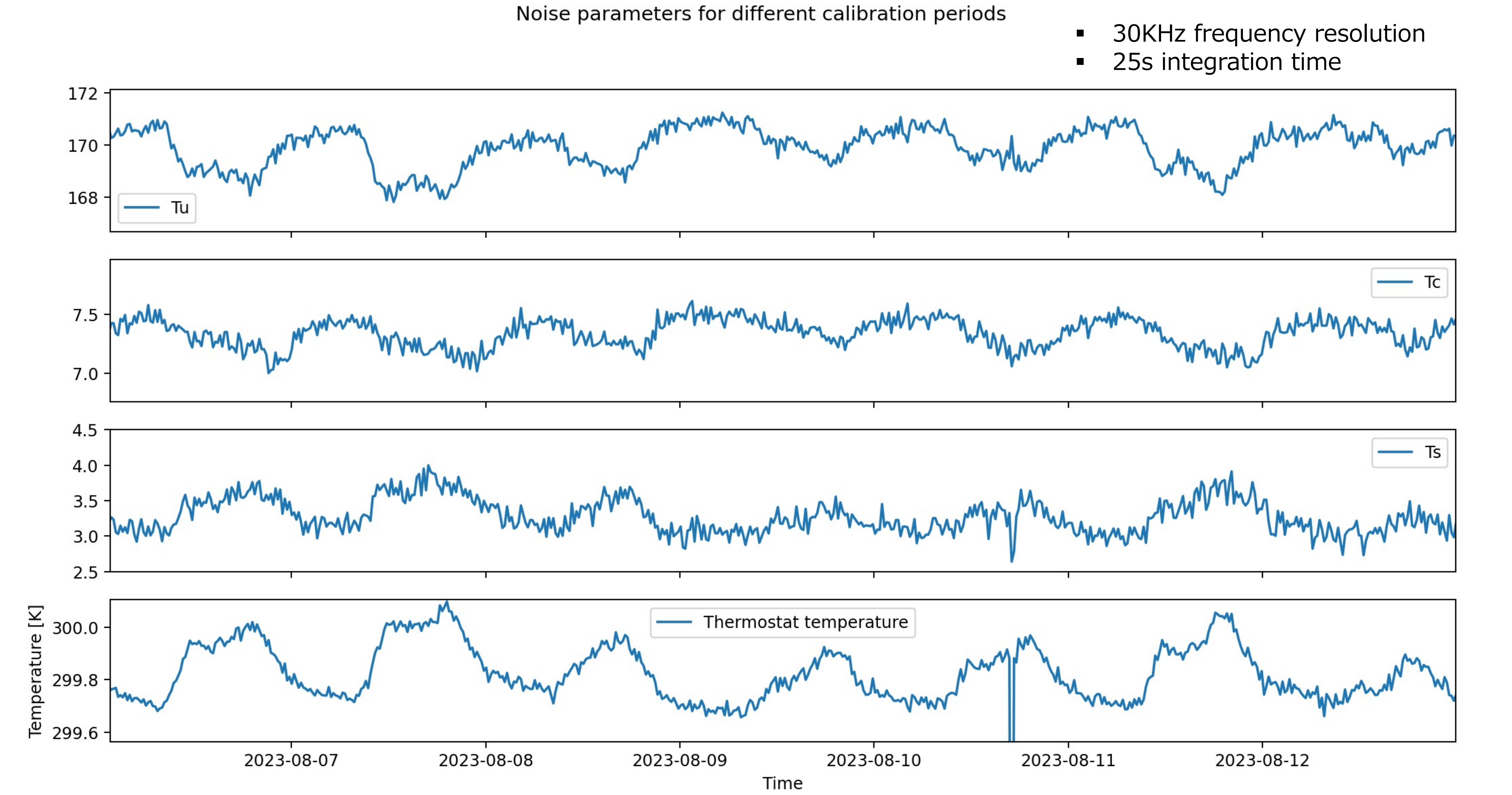


- Open
- Short
- High load
- Low Load
- Short cable

- 30KHz frequency resolution
- 25s integration time

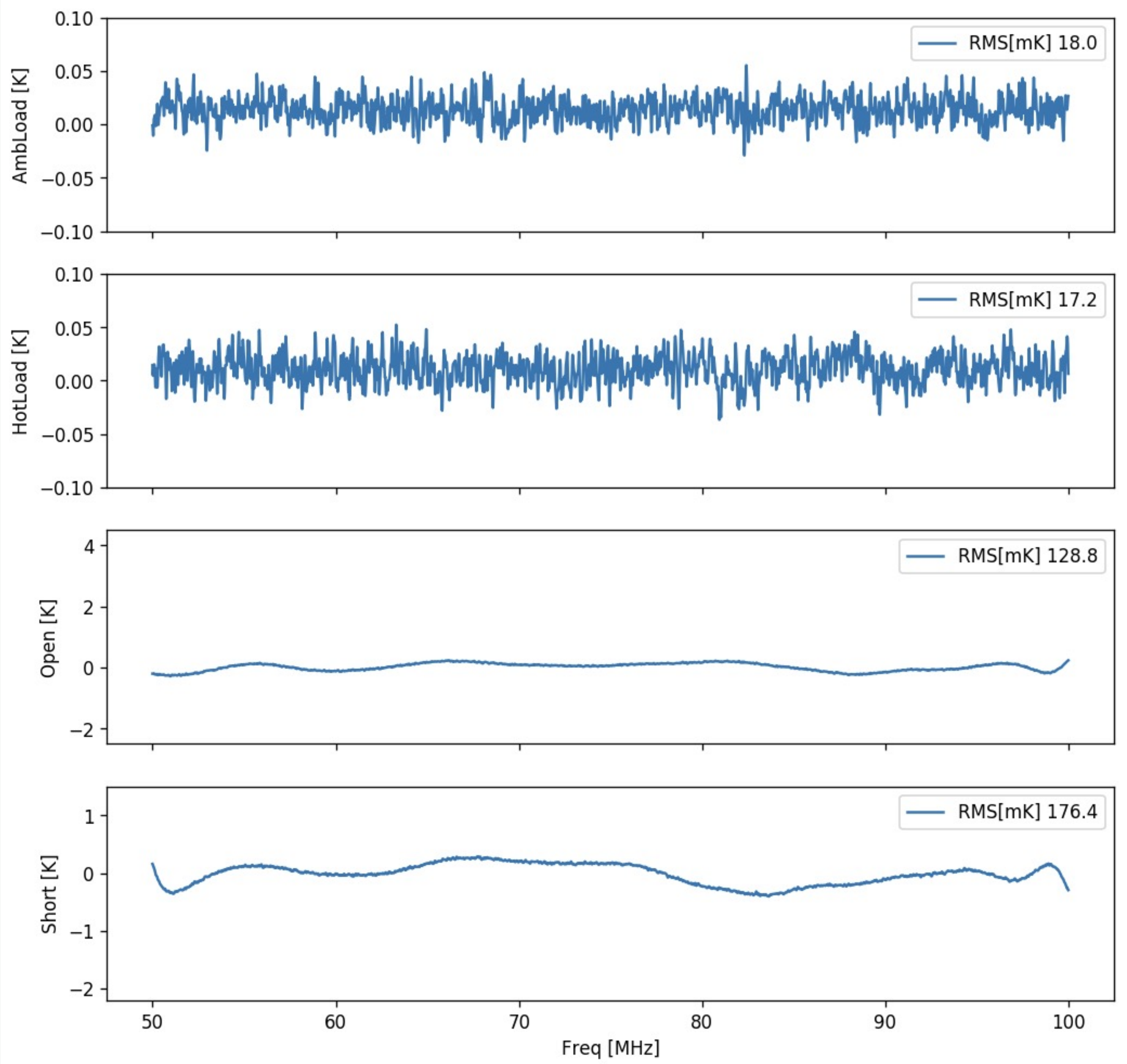
Noise wave parameters evolution

- 30KHz frequency resolution
- 25s integration time



Self-calibration precision

- 30KHz frequency resolution
- 13000s integration time



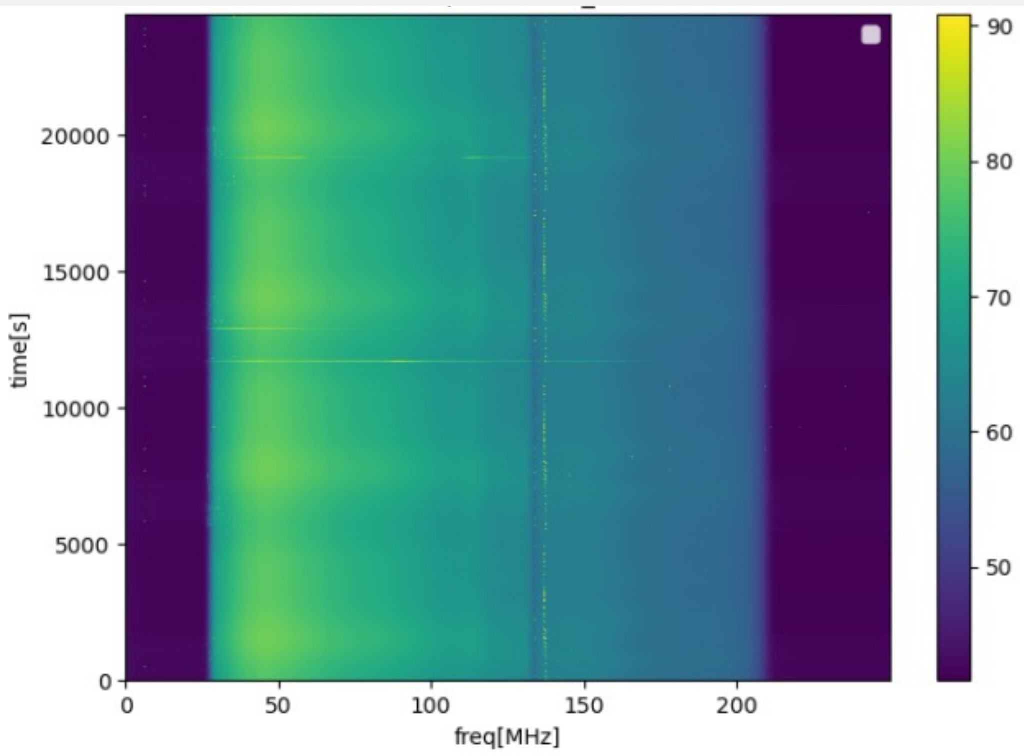
Load

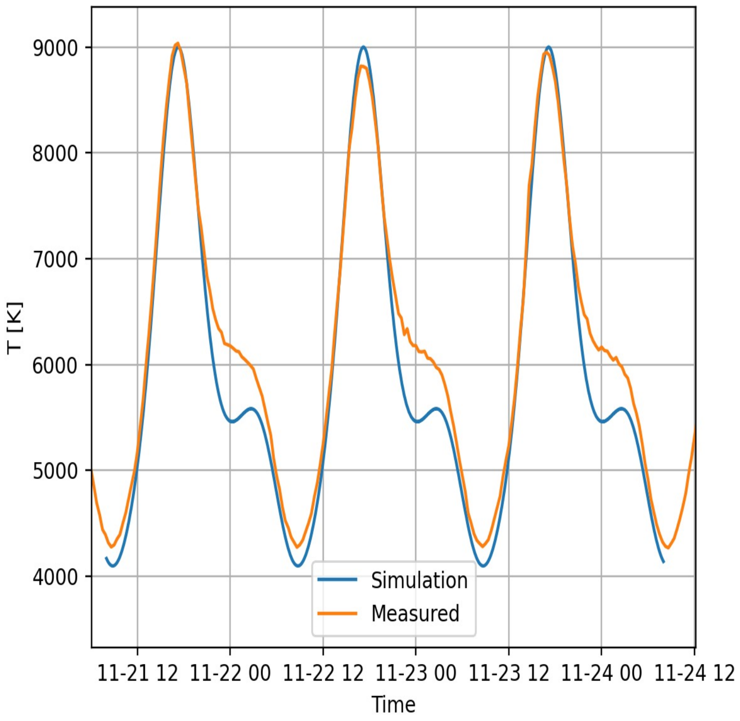
Open

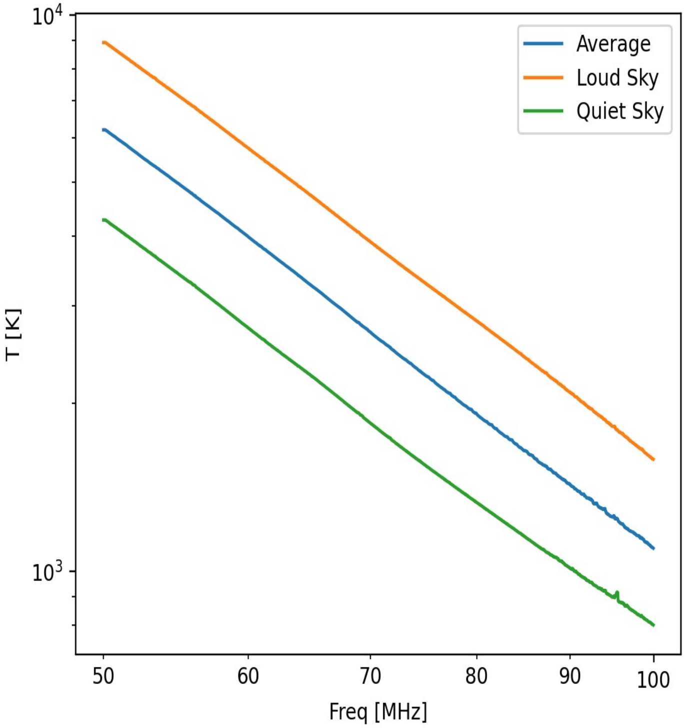
Short

Load : ± 0.018K Open Short : ±0.13K

Sky observation

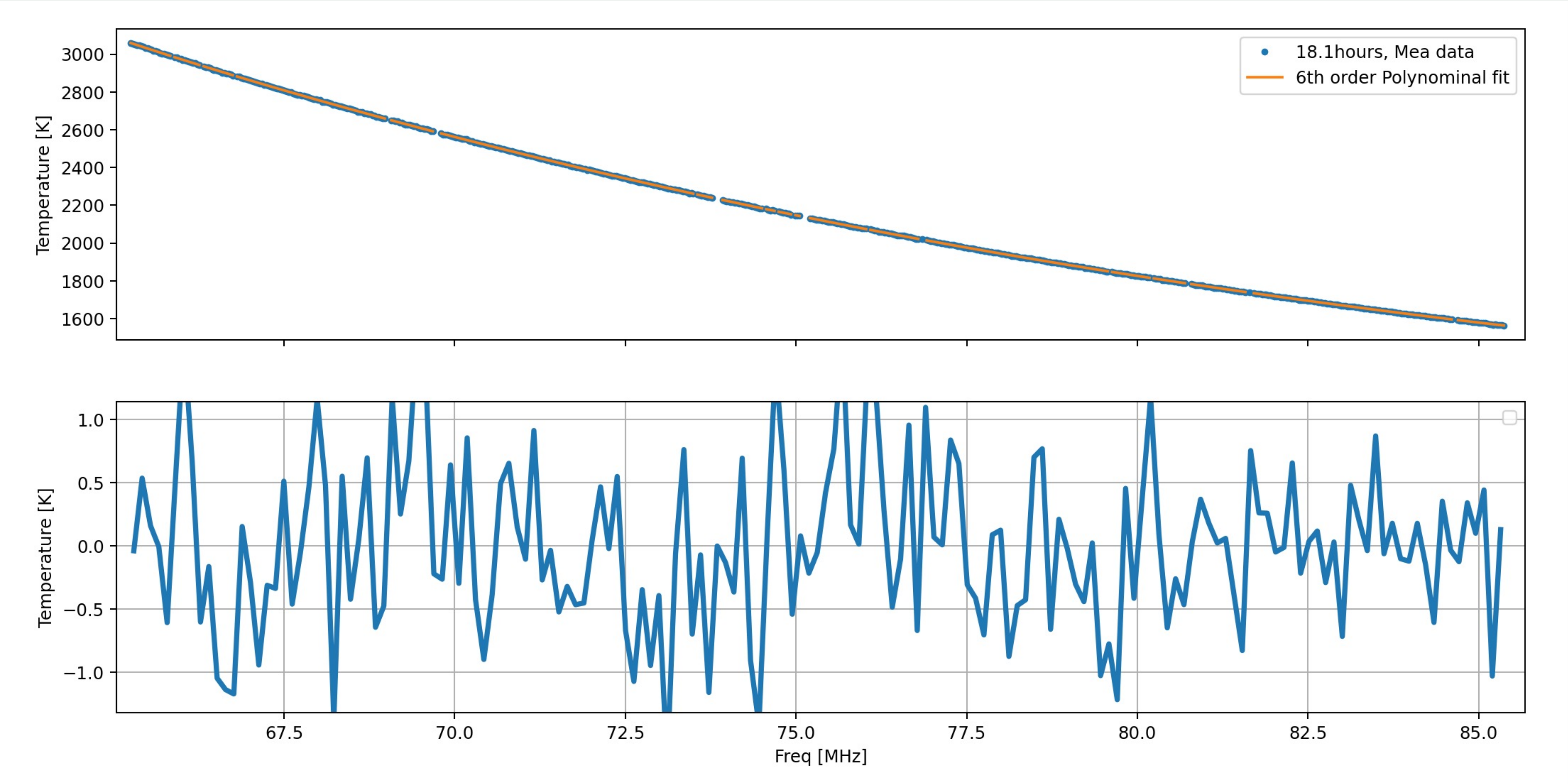






30KHz frequency resolution

Sky average spectrum (18 hours)



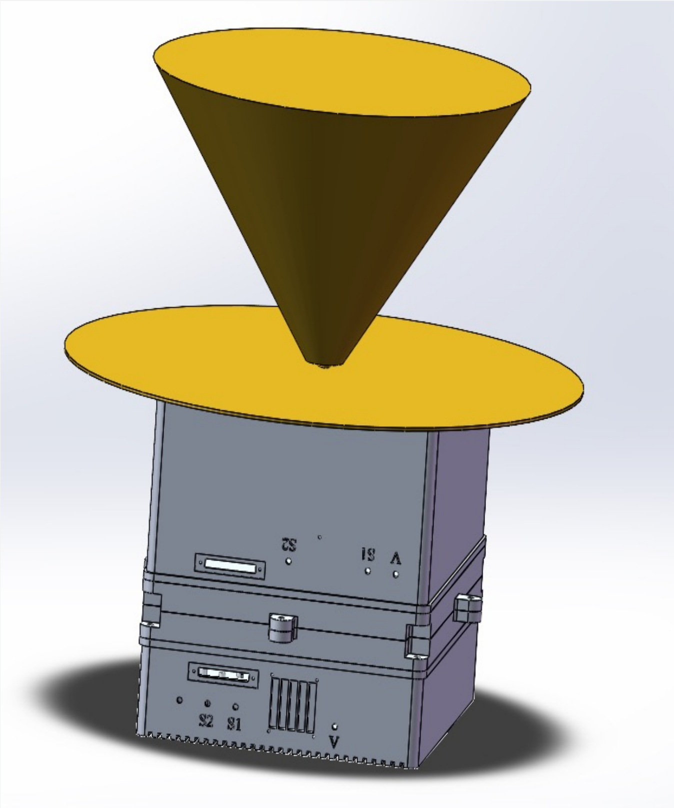
Spectrum

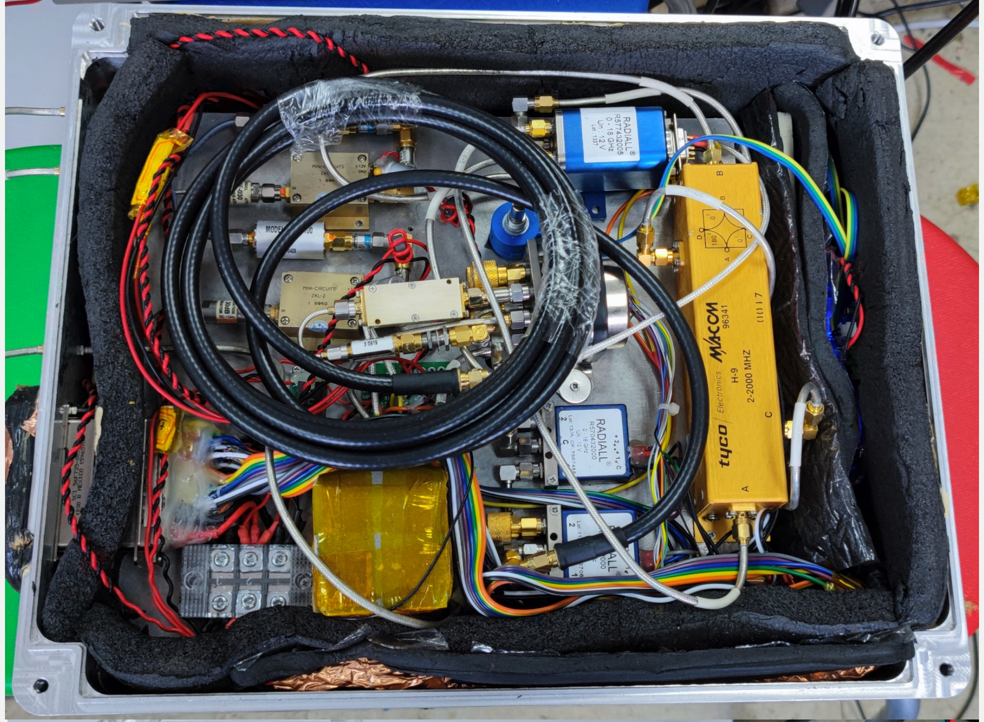
Residuals

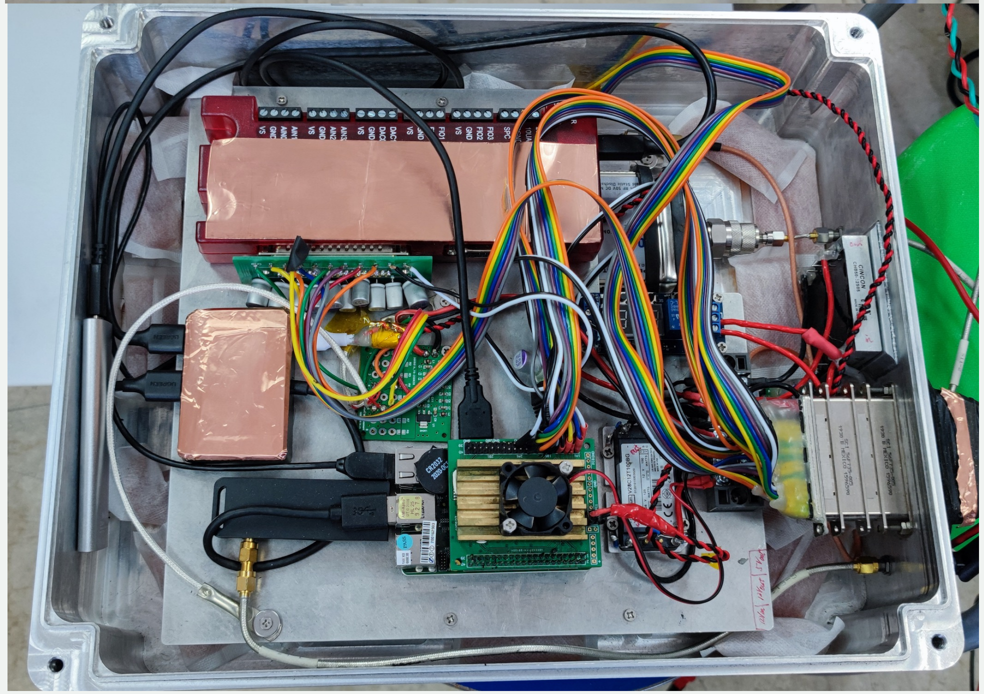
120KHz resolution

Testing of other receiver channel

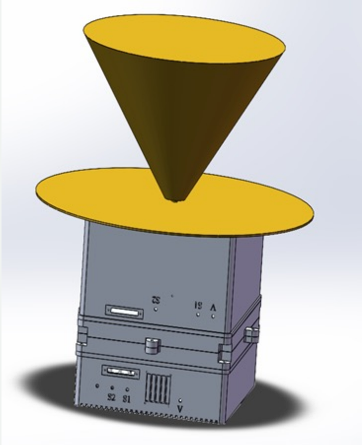
- **Prototype**

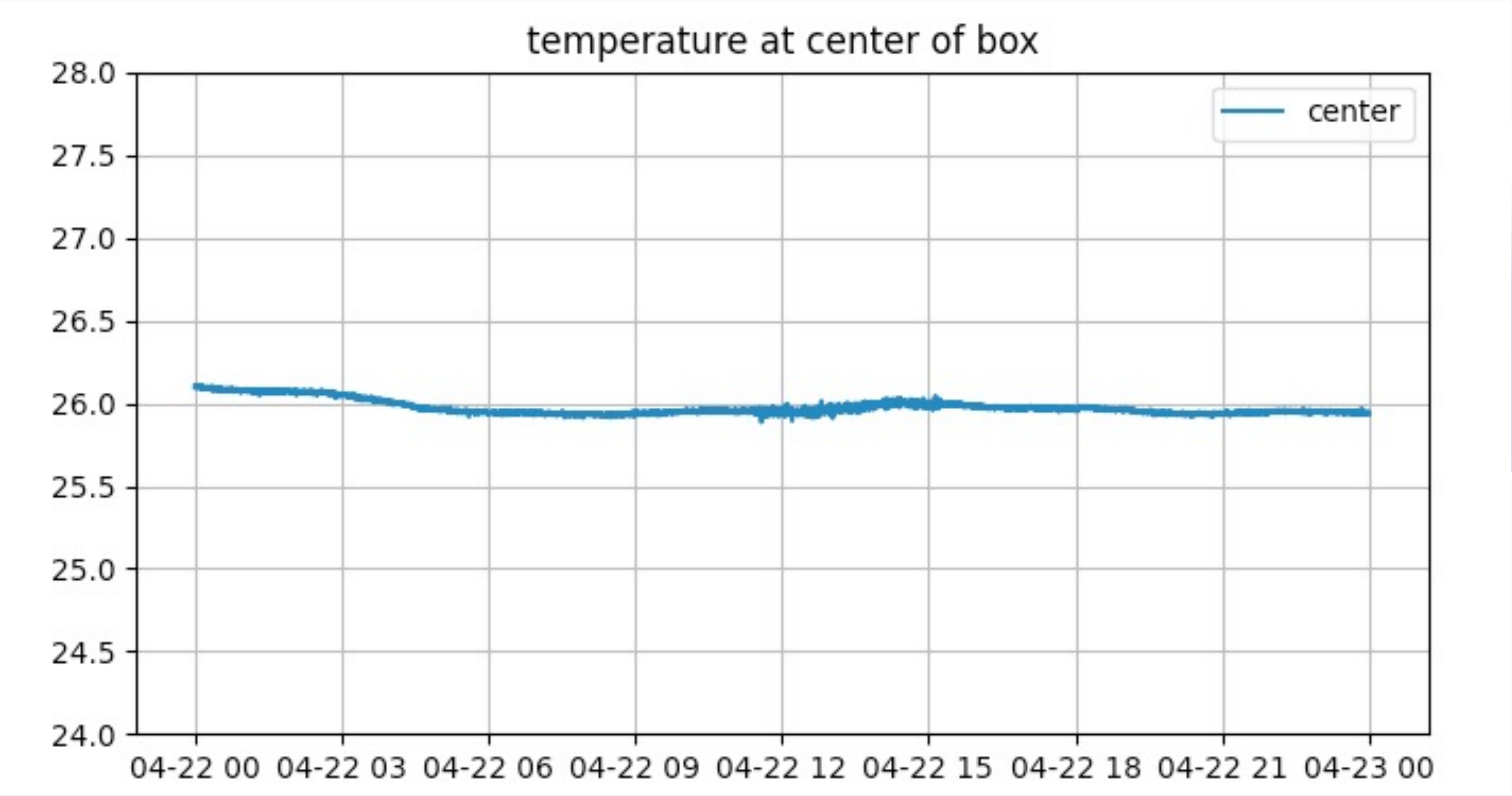


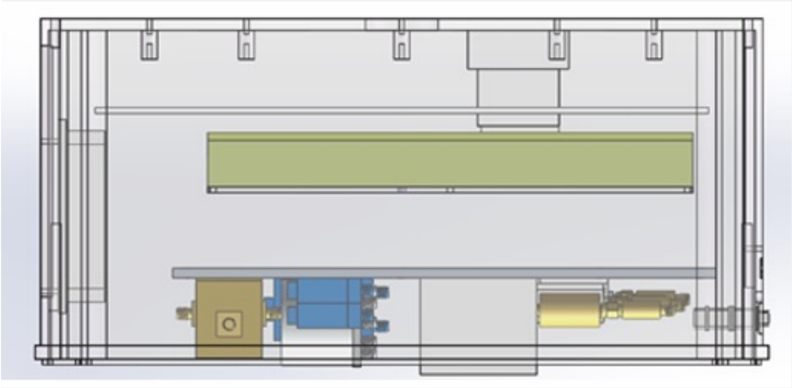


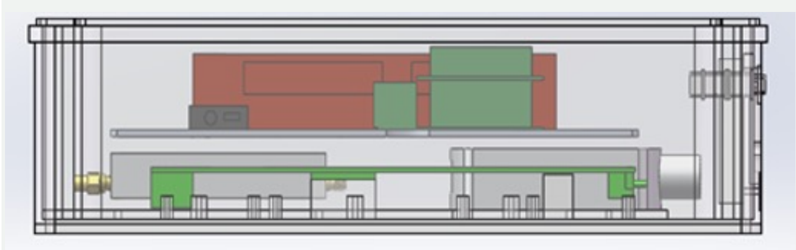


Temperature variation of key components



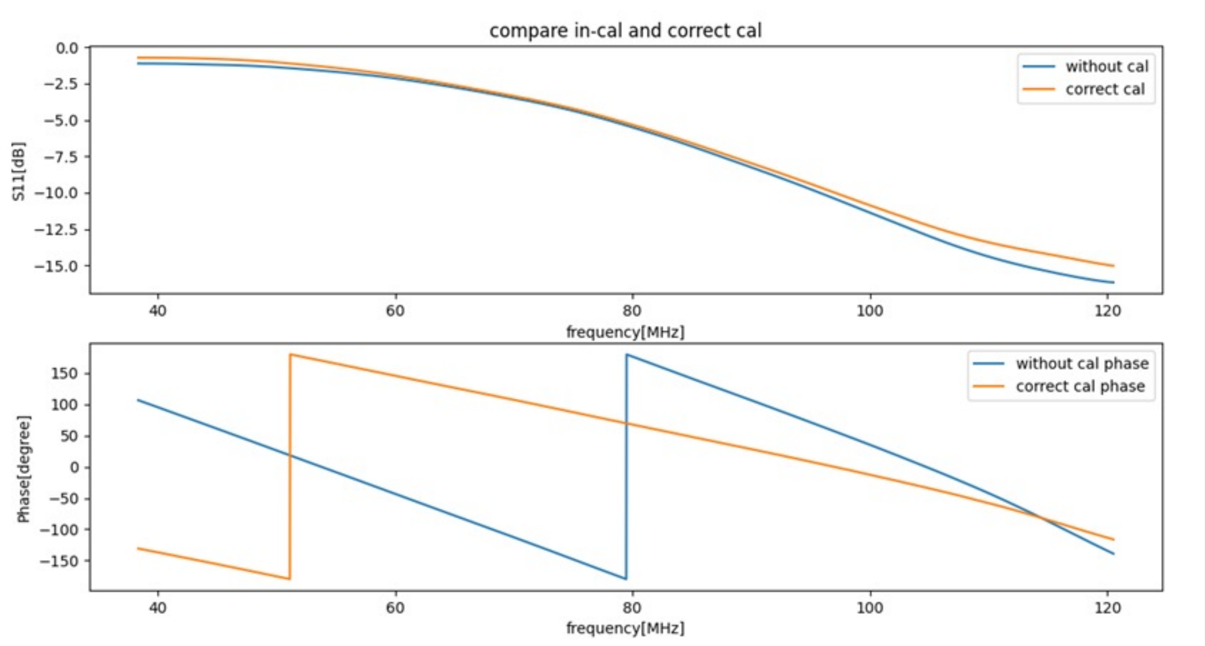




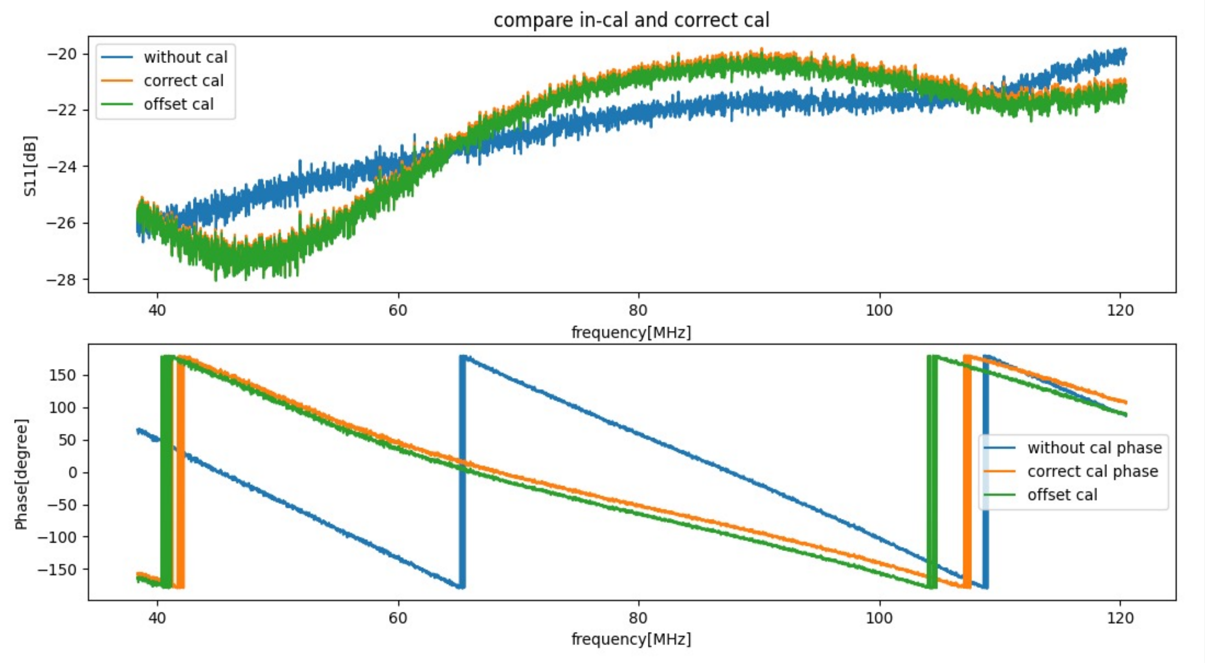


S11 of antenna and receiver

Antenna

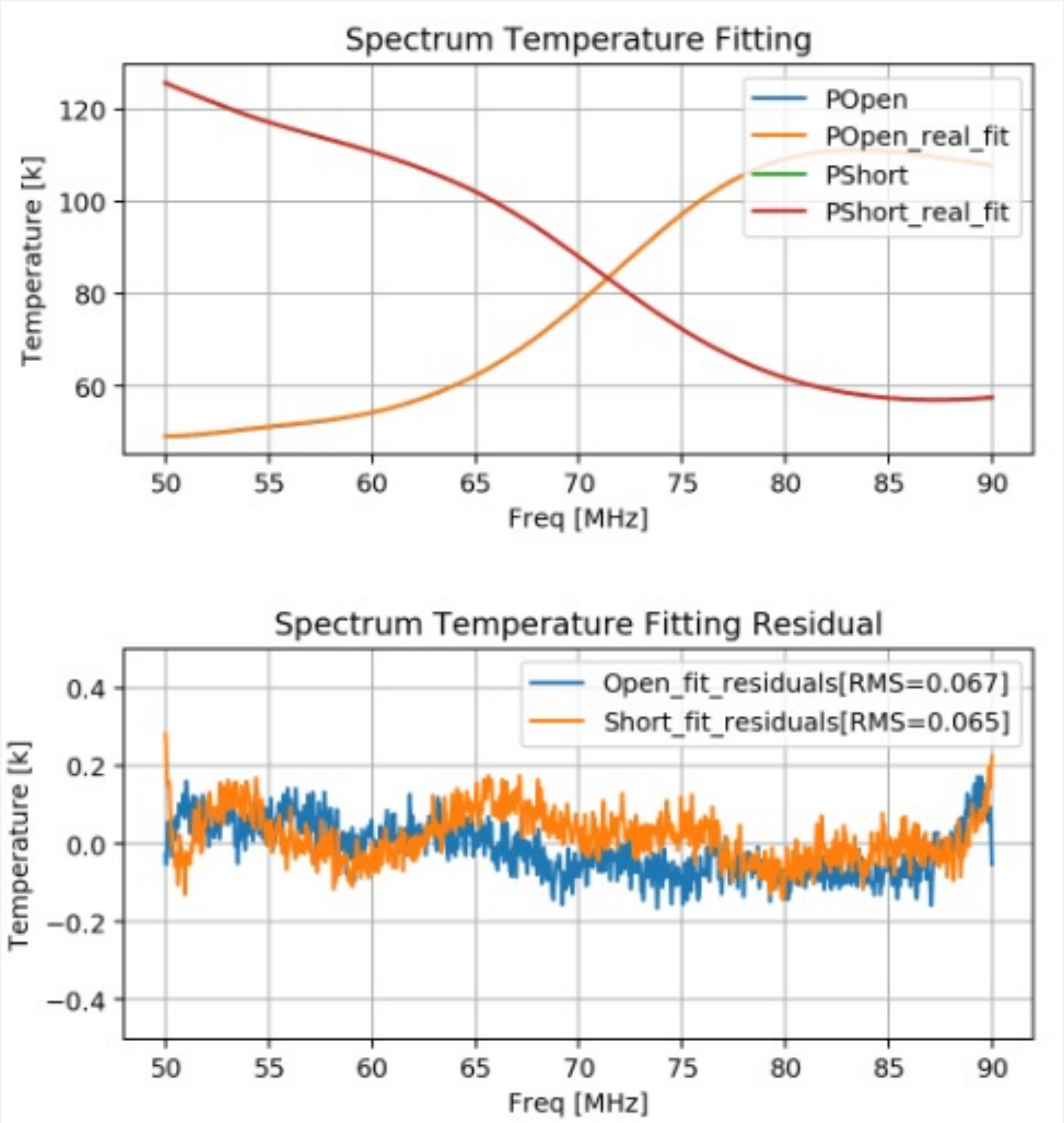


Receiver

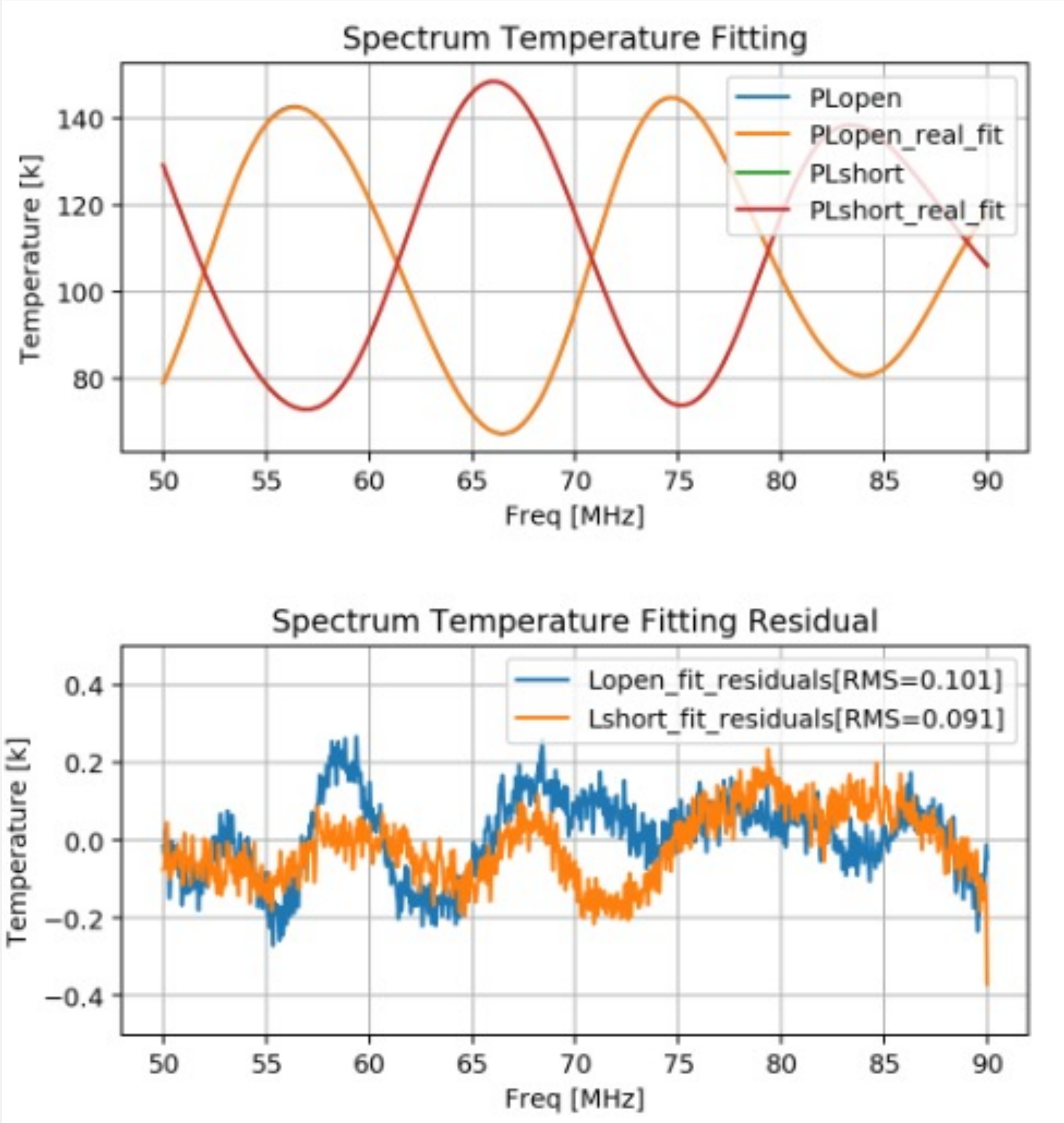


Noise wave parameters calculation

Open, Short Spectrum and fitting residual



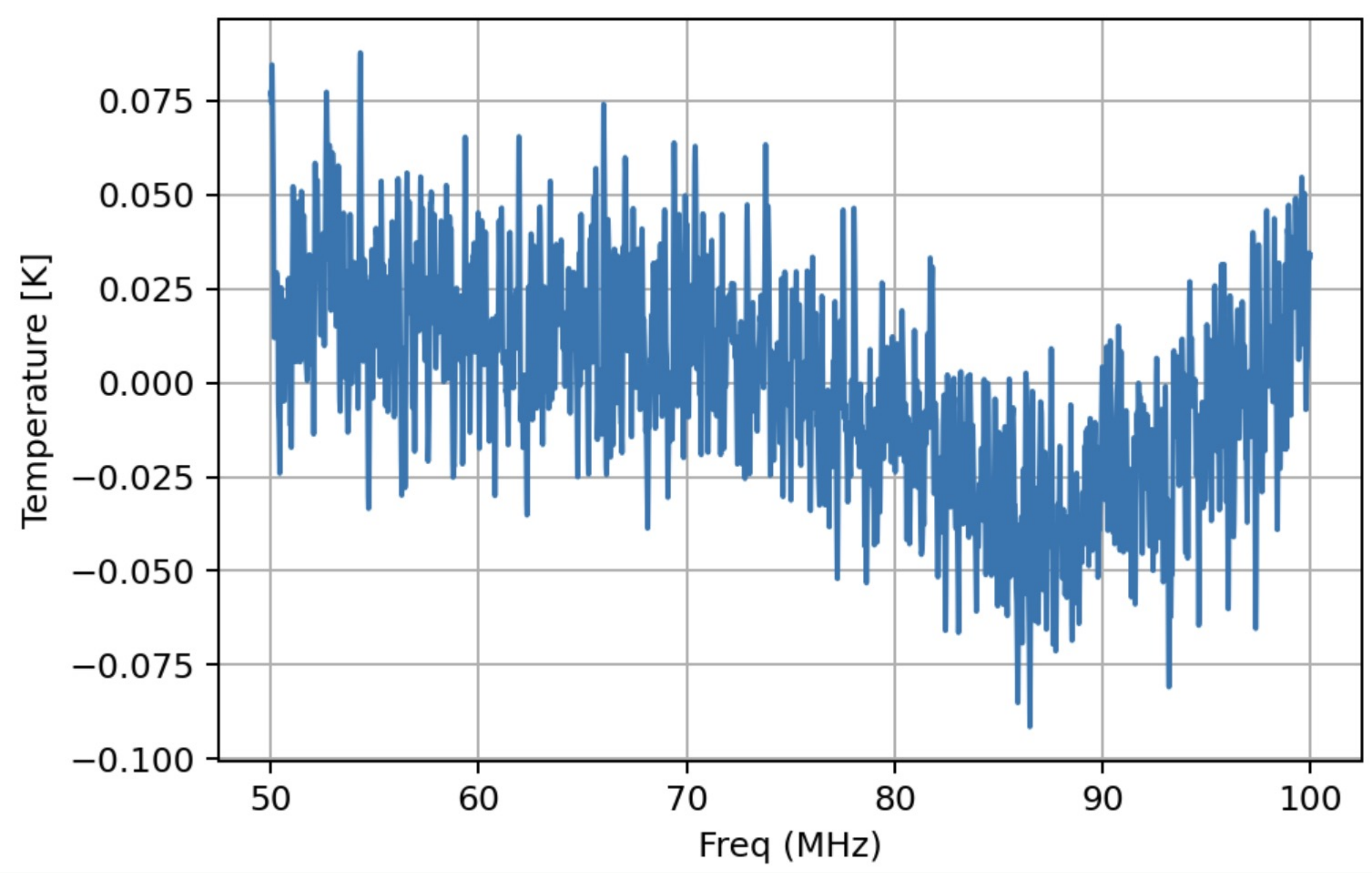
5m + Open, 5m + Short Spectrum and fitting residual



7.63KHz frequency resolution, 12000s integration time

calibration residuals of antenna simulator

50 Ohm Load as antenna simulator

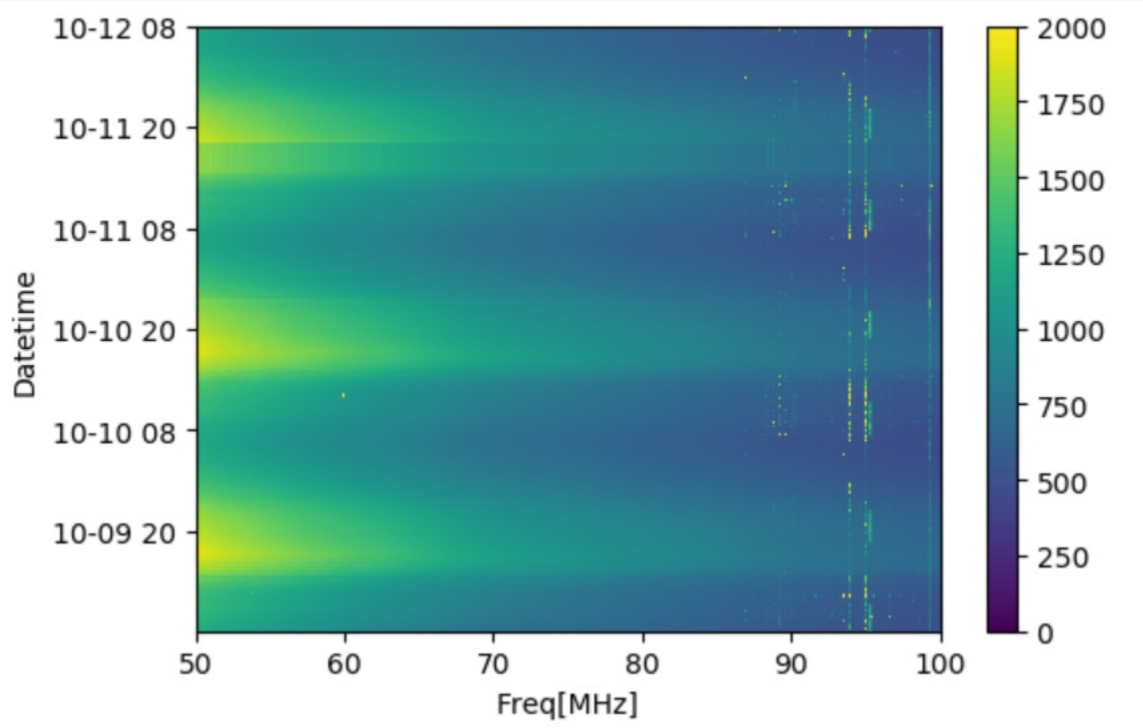


7.63KHz frequency resolution, 12000s integration time

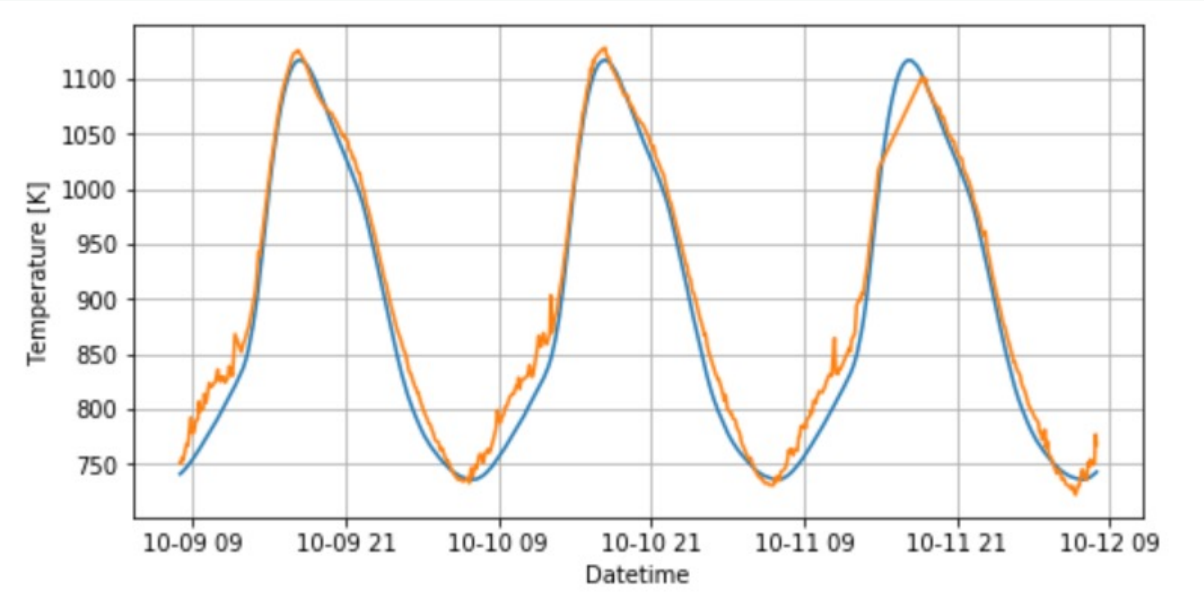
Sky observation

Sky temperature measured from
10-09 8:00 to 10-12 8:00

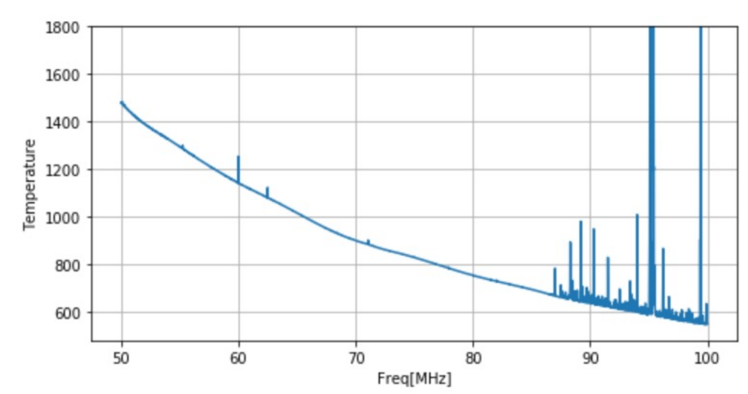
(Here we didn't consider the radiation loss caused by soil.)

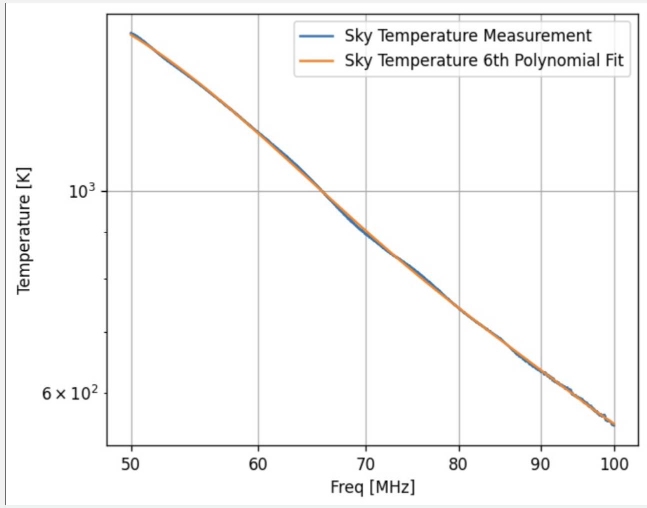


Sky temperature varies over time averaged over 50-100MHz

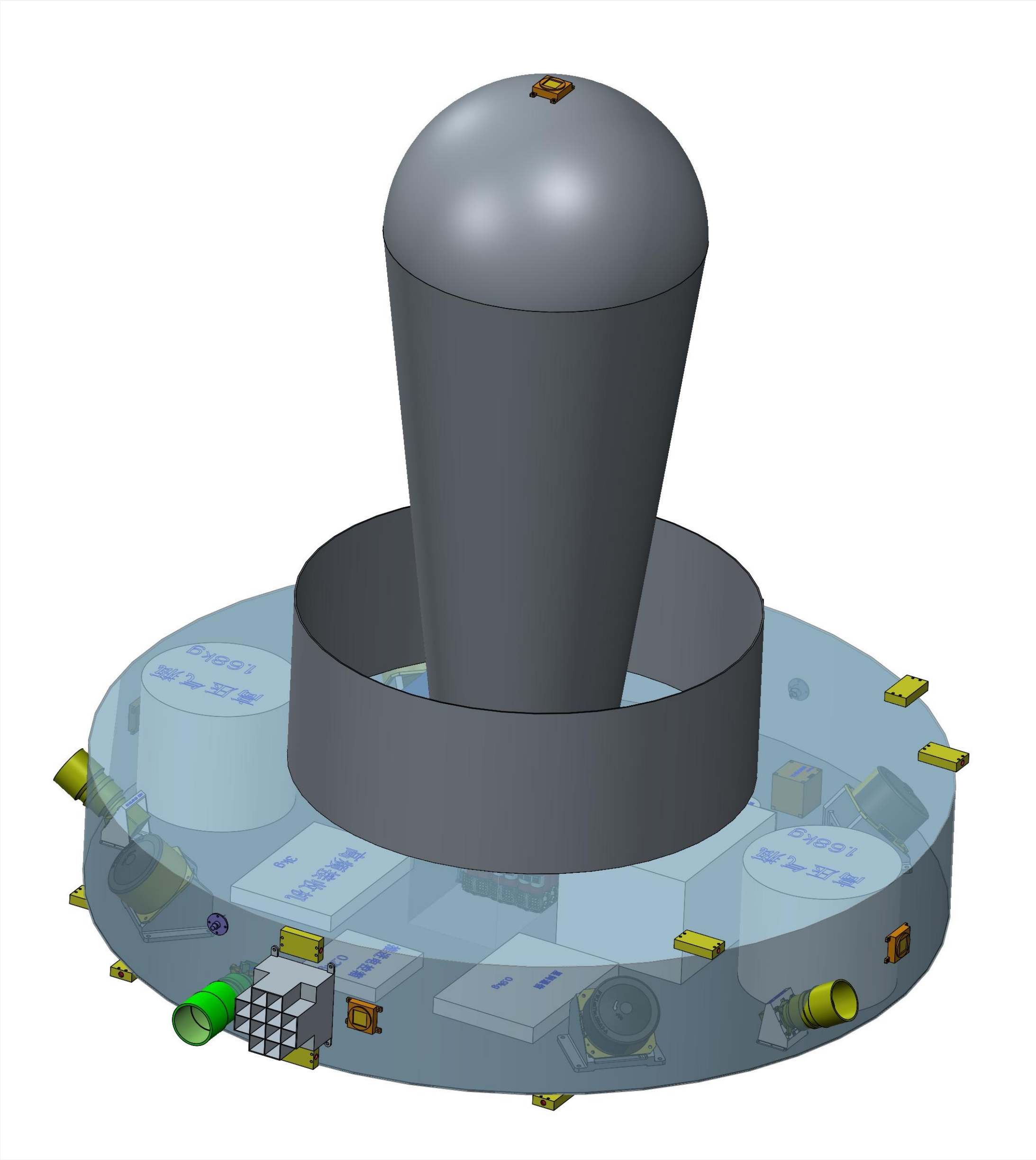


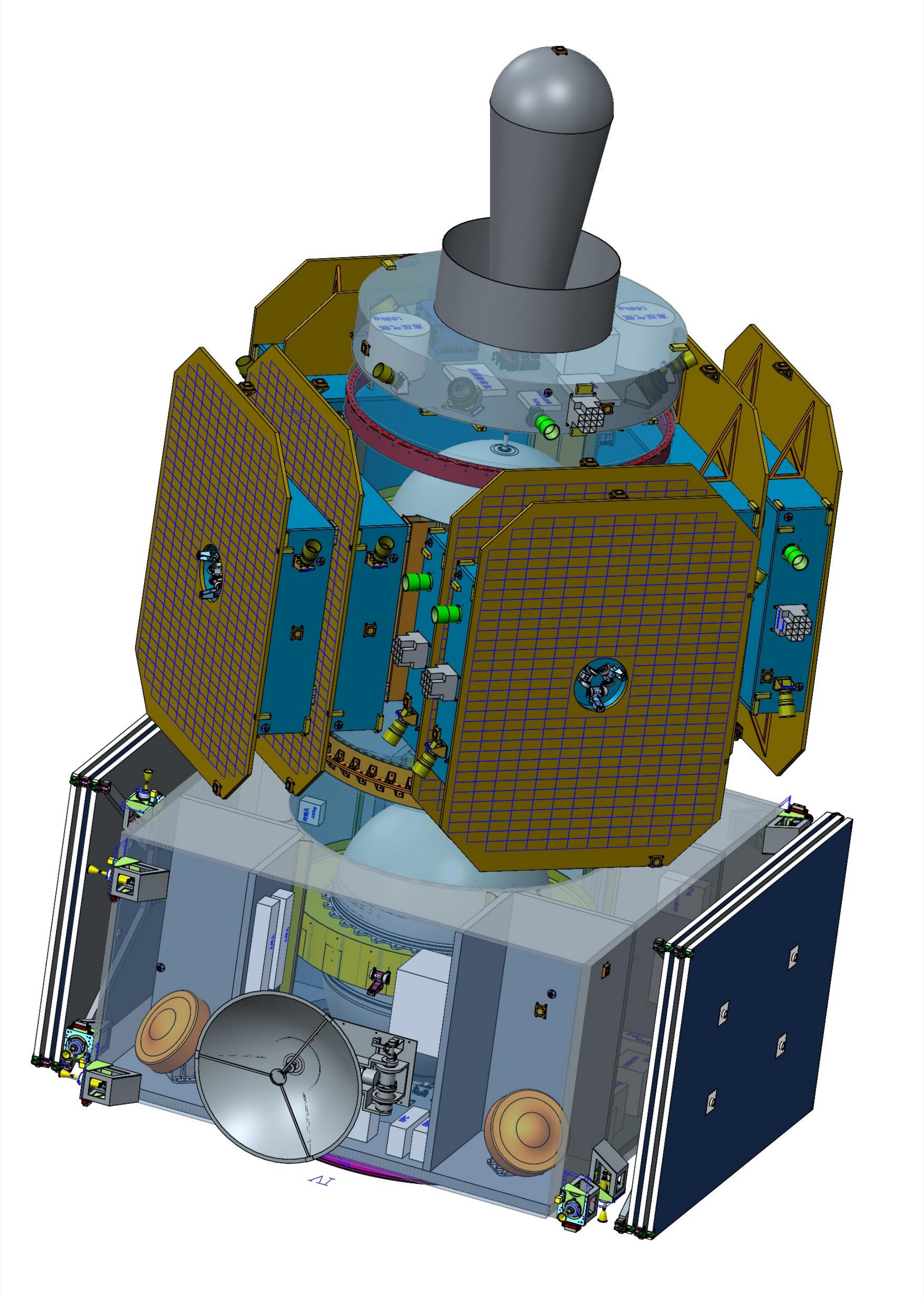
Sky temperature varies over time averaged over time





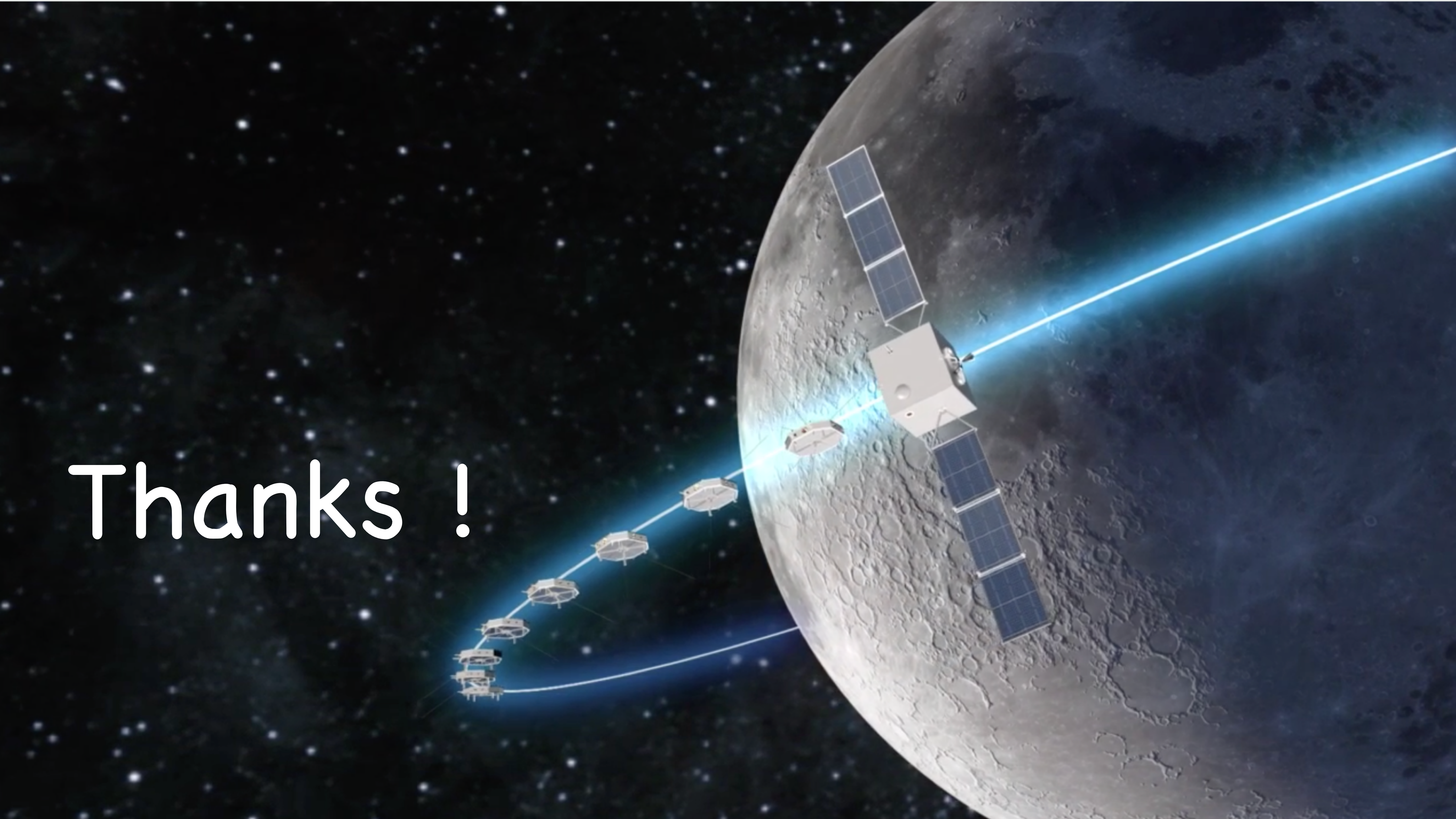
7.63KHz frequency resolution,16600s observation time


高压气瓶
1.68kg
高频接收机
3kg
高压气瓶
1.68kg



Summary

- Multi-receiver design
- Antenna simulator residuals < 0.2K
- Field testing is still going on
- Collaboration is welcome


Thanks !