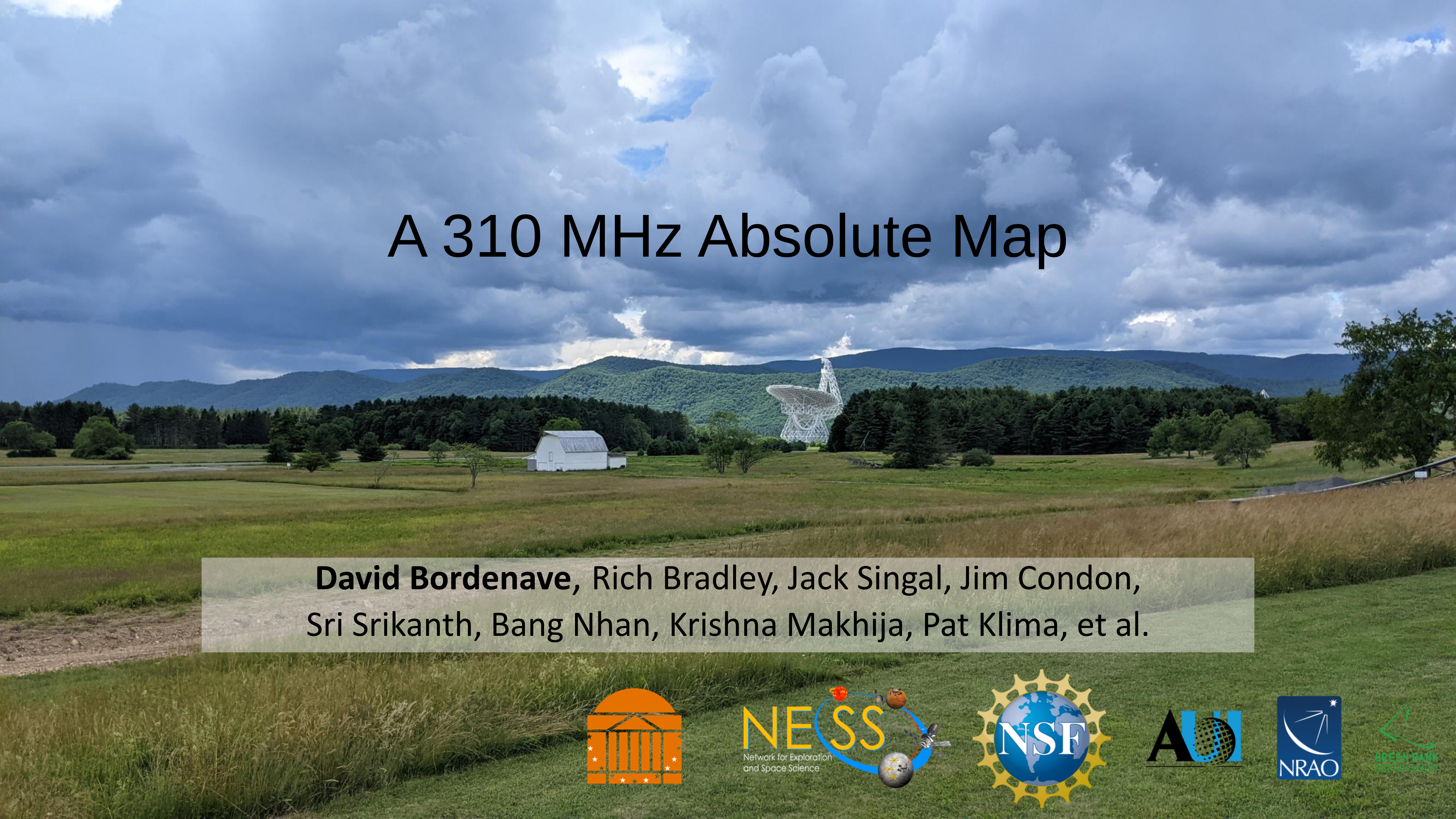
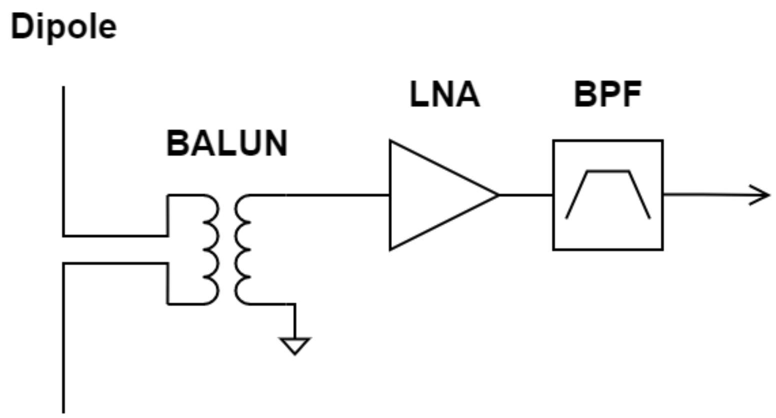


A 310 MHz Absolute Map

David Bordenave, Rich Bradley, Jack Singal, Jim Condon,
Sri Srikanth, Bang Nhan, Krishna Makhija, Pat Klima, et al.

What is a Balanced Correlation Receiver?

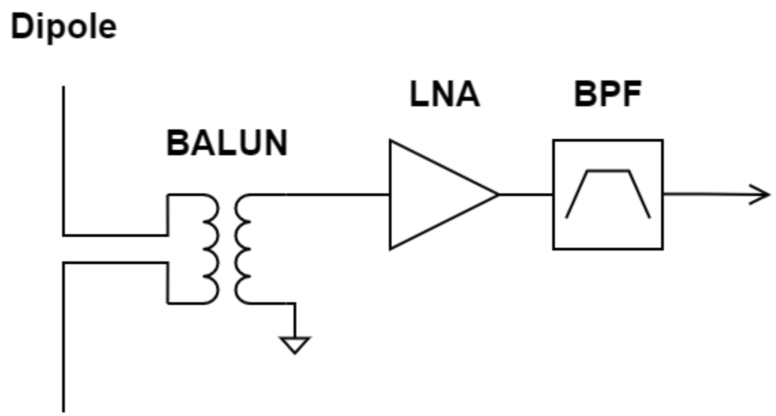
Single-Ended Receiver



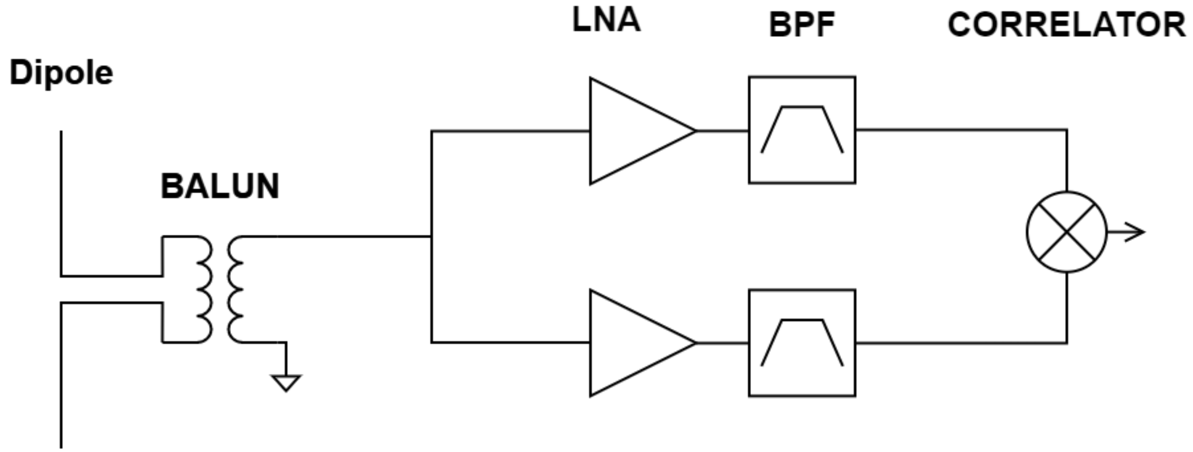
Problem: Noise (random fluctuations) in the gain of the amplifier and response of the other components makes it so the relation of power input to voltage output keeps changing in an unknown way

What is a Balanced Correlation Receiver?

Single-Ended Receiver



(Conventional) Correlation Receiver

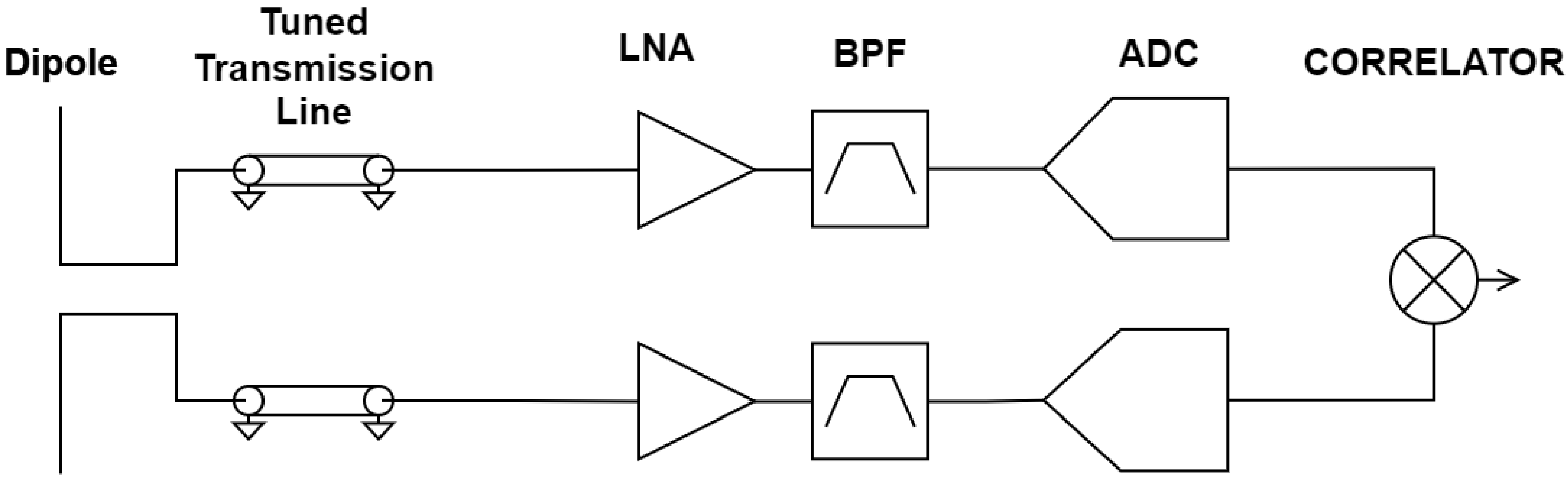


Problem: Noise (random fluctuations) in the gain of the amplifier and response of the other components makes it so the relation of power input to voltage output keeps changing in an unknown way

Solution: Split antenna signal into two signal-chains, each having their own <u>independent</u> noise and gain fluctuations. After cross correlation, non-common-mode contributions are surpressed (e.g. the Receiver noise temperature)

What is a Balanced Correlation Receiver?

(Balanced) Correlation Receiver



Improved Solution: Remove all direct common signal paths and synthesize beam digitally! This approach further minimizes the additive noise/fluctuations compared to the conventional correlation receiver by removing the need for a common balun and power splitters/combiners.

GBT310 Instrument Properties

The Green Bank Telescope:

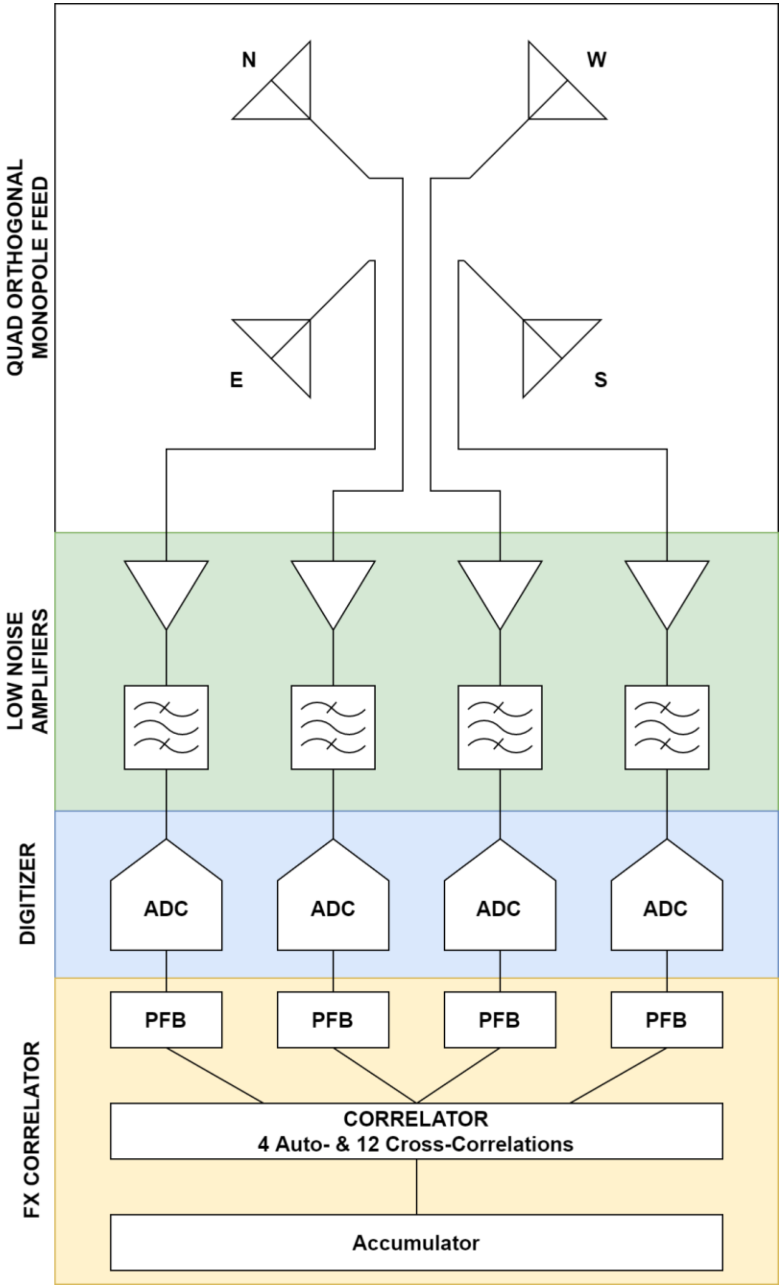
- Unblocked aperture
  -> Best efficiency & Less scattering
- Largest fully steerable radio telescope
  -> High angular resolution (~30 arcmin)

Custom Narrow Band Feed:

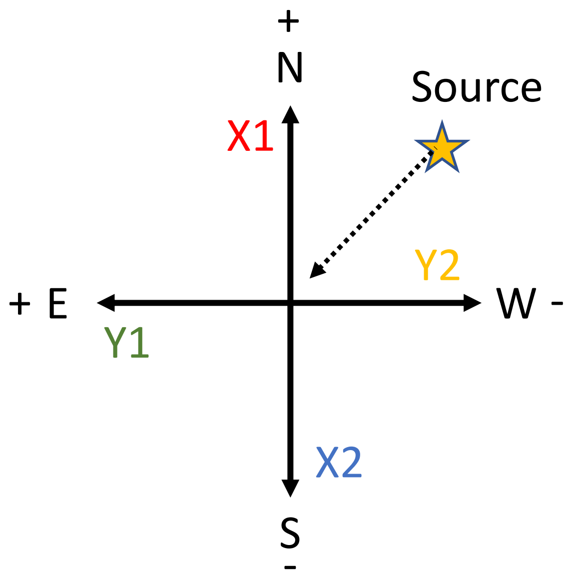
- High Gain: ~15dB (~30˚ FWHM)
  -> Minimizes thermal ground pick up by under-illumination of GBT
- Optimized for narrow bandwith: ~20 MHz
  -> Impedance well matched to 50Ω; low loss

The Balanced Correlation Receiver:

- Independent treatment of monopoles and amplifiers allows for only cross-correlations in output data
  -> Near zero receiver noise & High-stability
- Built-in phase coherent hot/cold calibrators
- Component level circuit model characterization
- Digitization at the Frontend



Full Stokes with a Balanced Correlation Receiver



Four orthogonal antenna E-field pairs:

$$e^+_{NE} = \binom{\mathrm{X1}}{\mathrm{Y1}} \qquad e^+_{SE} = \binom{-\mathrm{X2}}{\mathrm{Y1}}$$

$$e^+_{SW} = \binom{-\mathrm{X2}}{-\mathrm{Y2}} \qquad e^+_{NW} = \binom{\mathrm{X1}}{-\mathrm{Y2}}$$

Two effective cross-dipoles can be formed:

$$e^+_A = \langle e^+_{NE} \otimes e^+_{SW} \rangle \qquad e^+_B = \langle e^+_{NW} \otimes e^+_{SE} \rangle$$

Two combinations are possible to reconstruct Stokes parameters

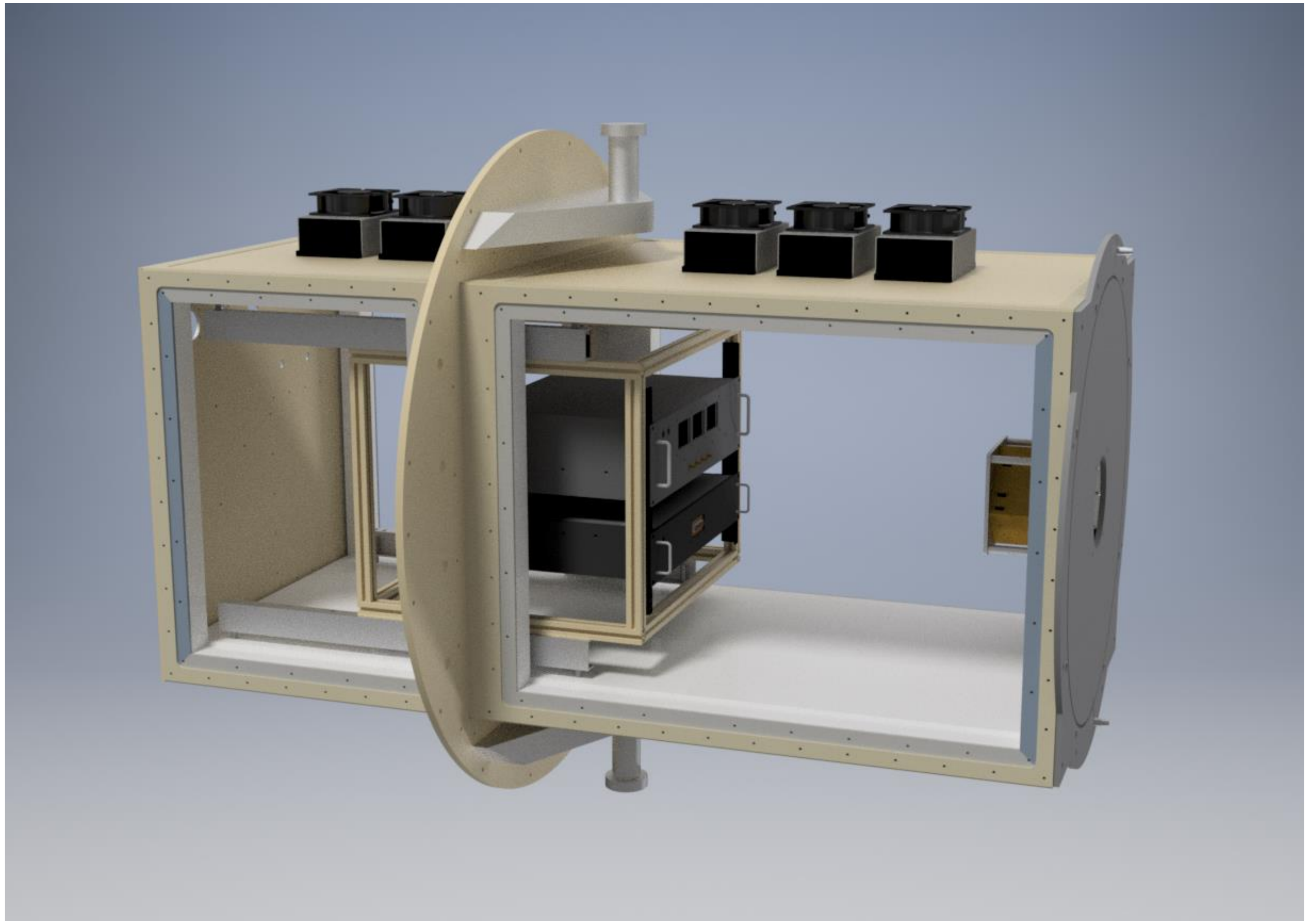
$$S_A = \mathbf{T}e^+_A = -\begin{bmatrix} \mathrm{X1X2}^* + \mathrm{Y1Y2}^* \\ \mathrm{X1X2}^* - \mathrm{Y1Y2}^* \\ \mathrm{X1Y2}^* + \mathrm{Y1X2}^* \\ i(-\mathrm{X1Y2}^* + \mathrm{Y1X2}^*) \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

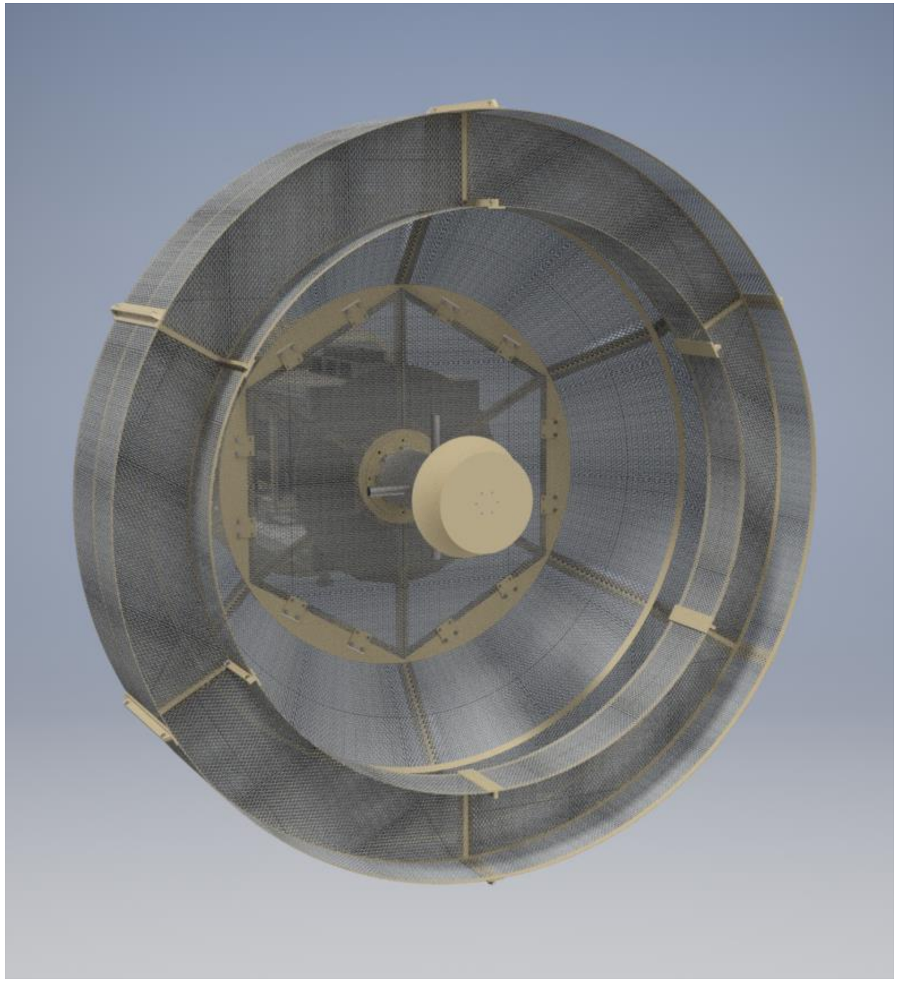
Cartesian to Stokes
Basis Transform Matrix

6 unique cross-power spectra

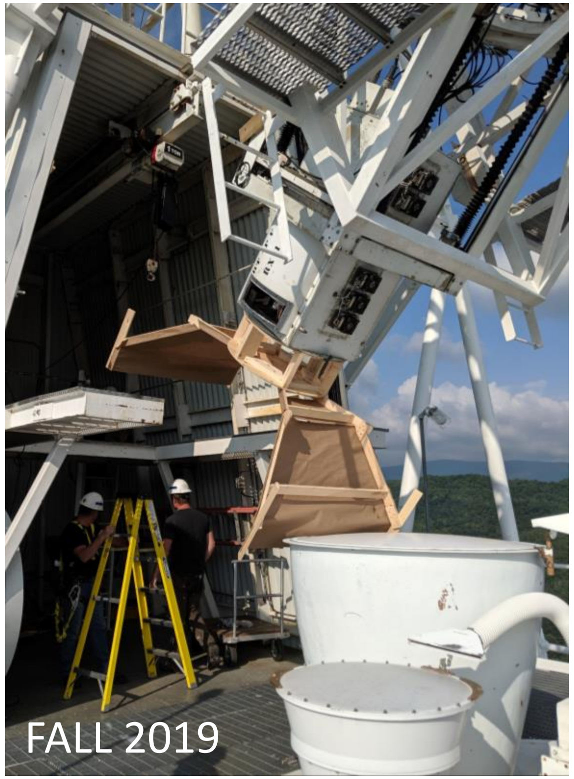
$$S_B = \mathbf{T}e^+_B = -\begin{bmatrix} \mathrm{X1X2}^* + \mathrm{Y2Y1}^* \\ \mathrm{X1X2}^* - \mathrm{Y2Y1}^* \\ -\mathrm{X1Y1}^* - \mathrm{Y2X2}^* \\ i(\mathrm{X1Y1}^* - \mathrm{Y2X2}^*) \end{bmatrix}$$

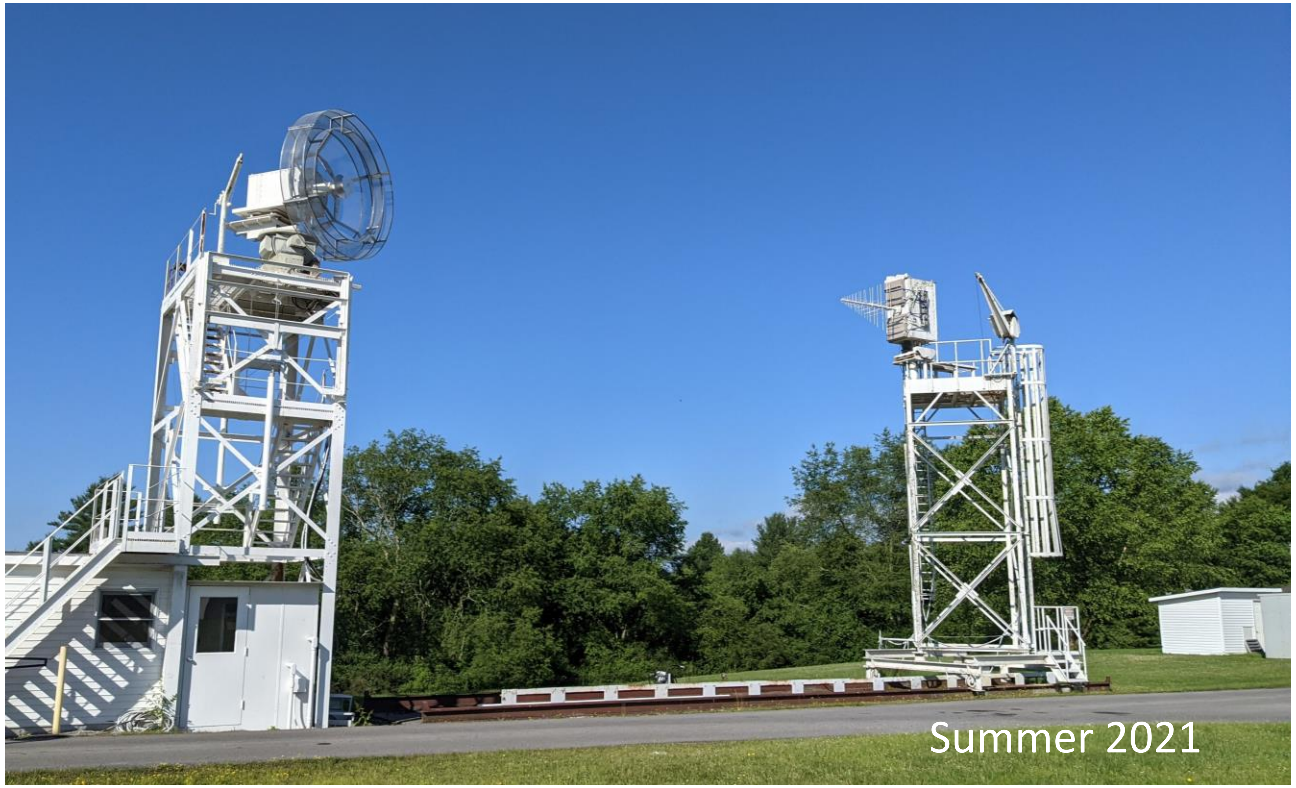
The GBT310 Prime Focus Receiver



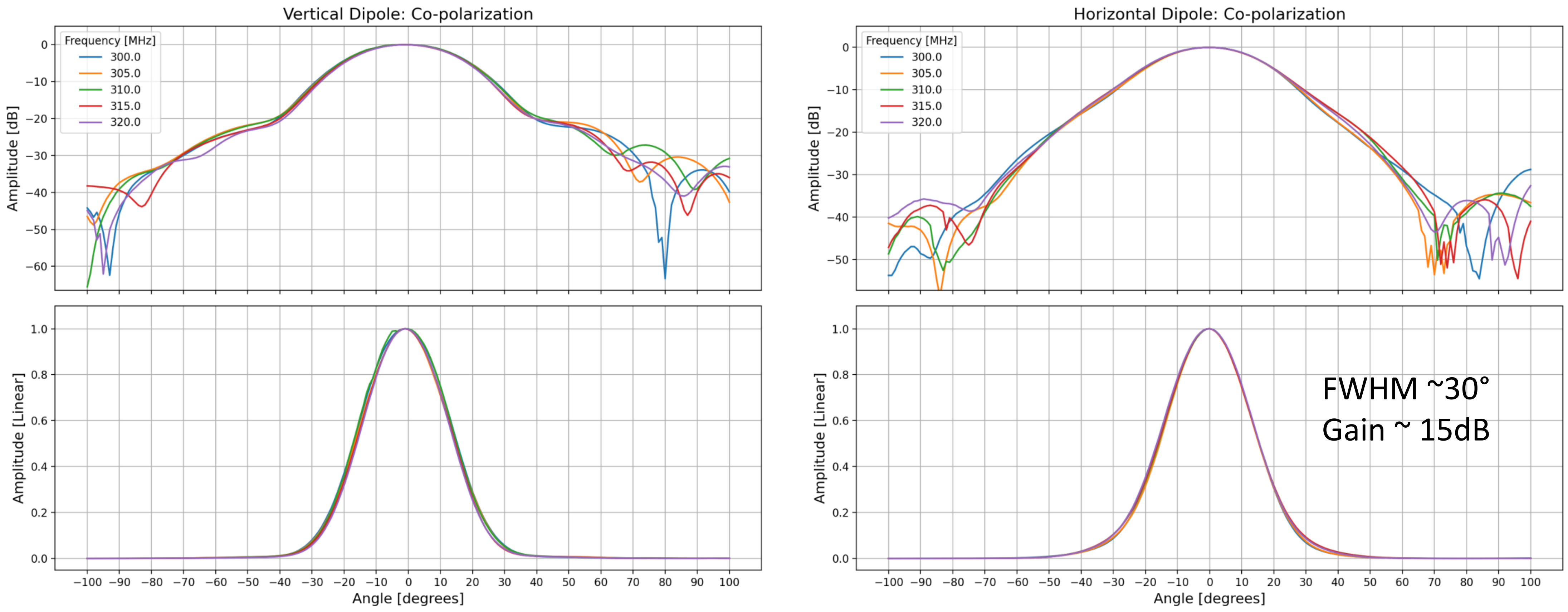


Feed Testing

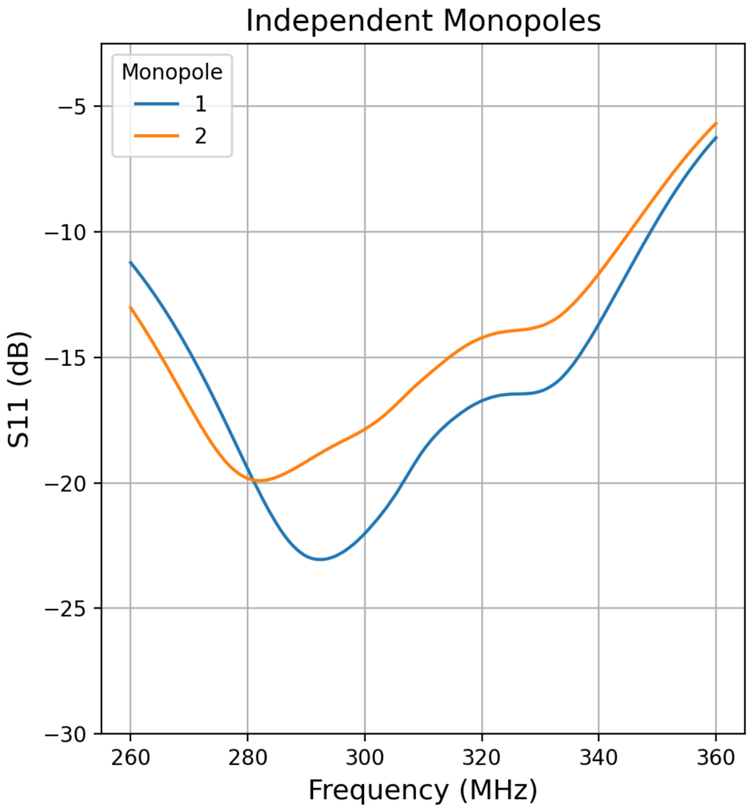


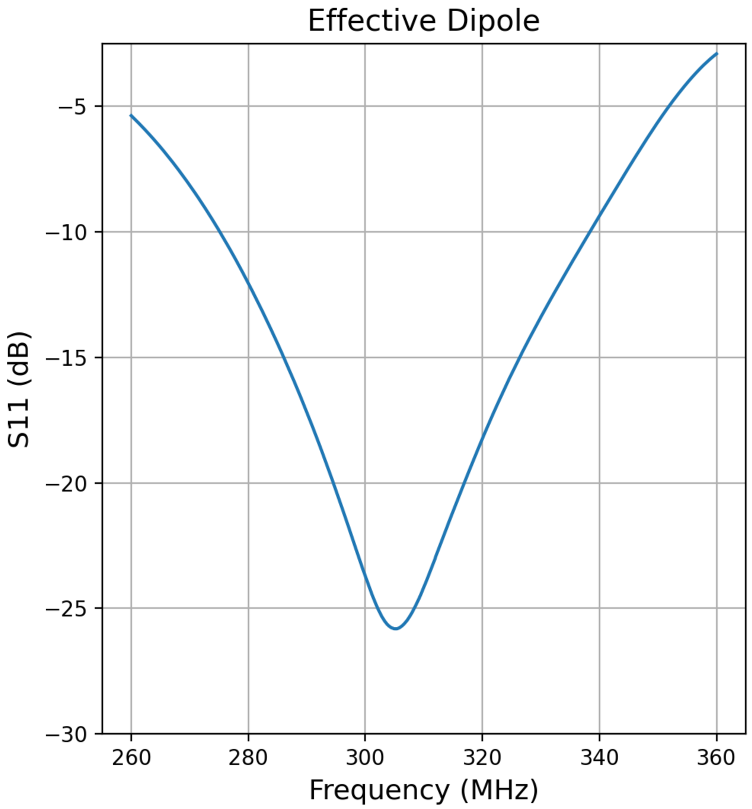


Beam Pattern Measurements

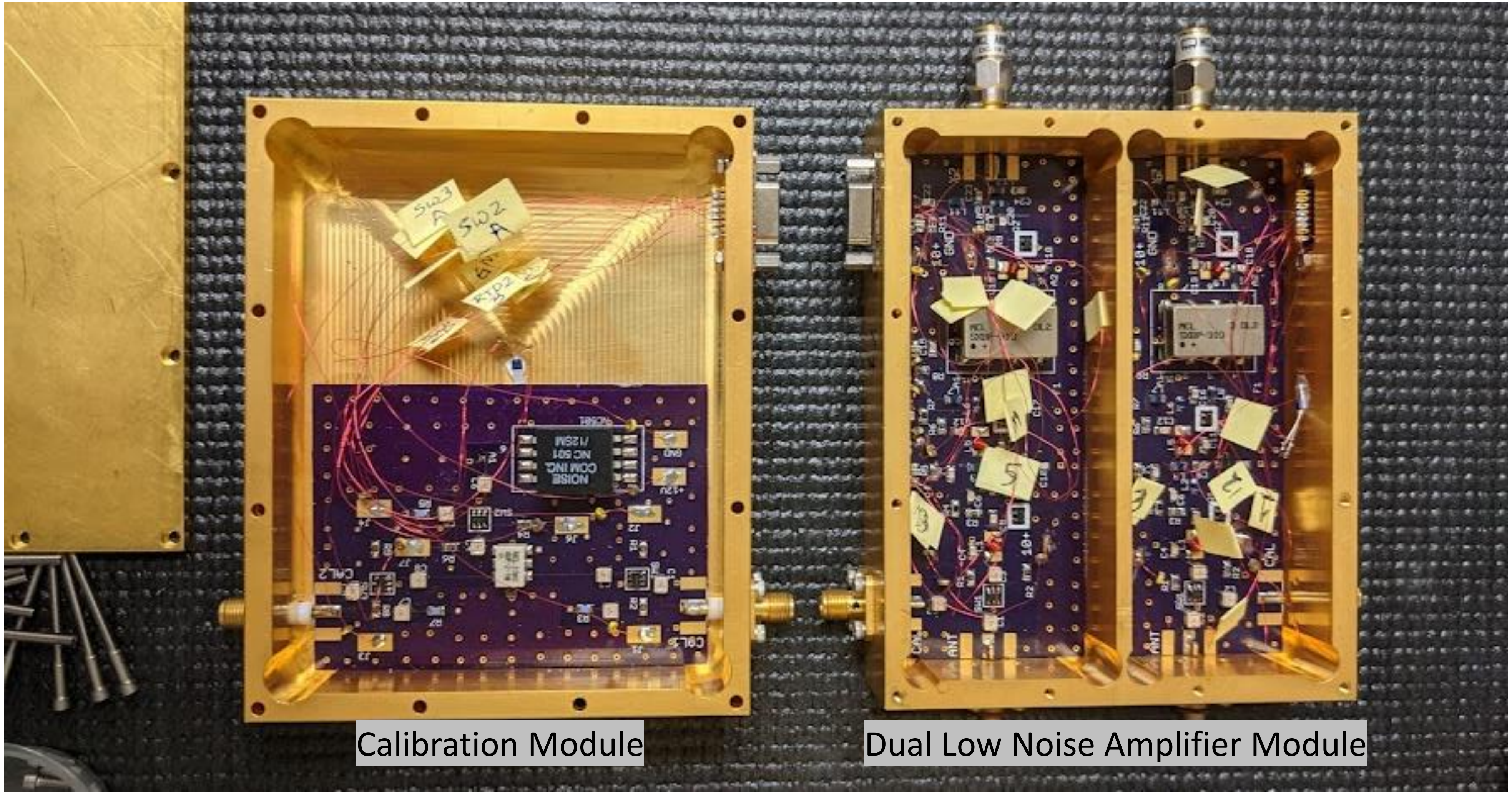


Beam S-Parameters Measurements



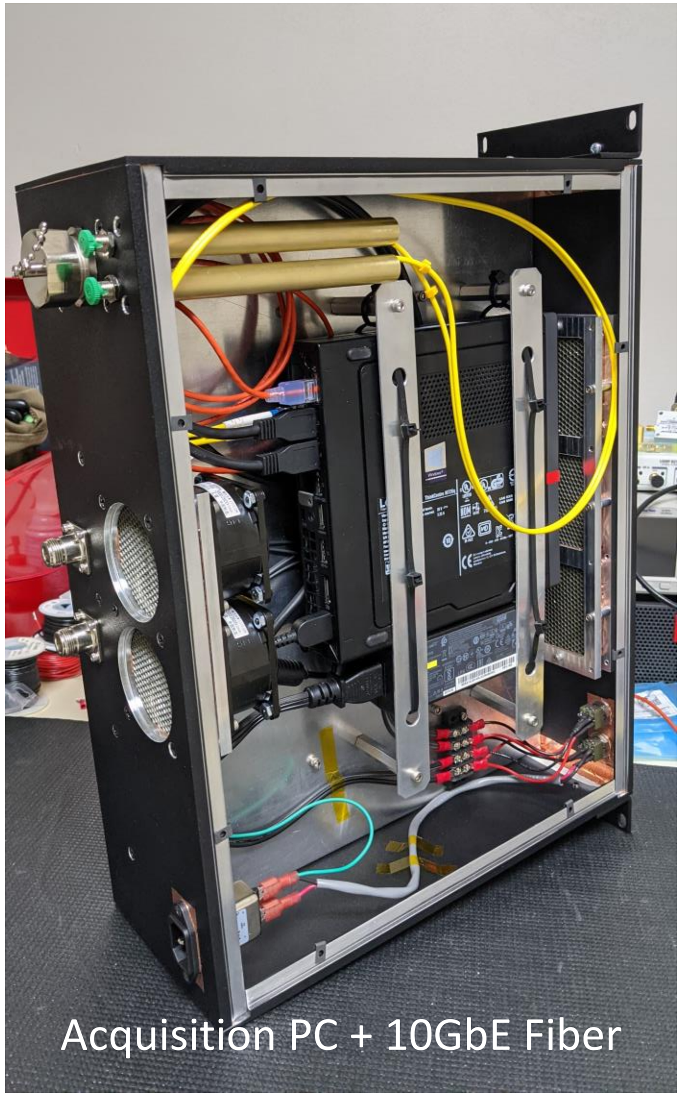


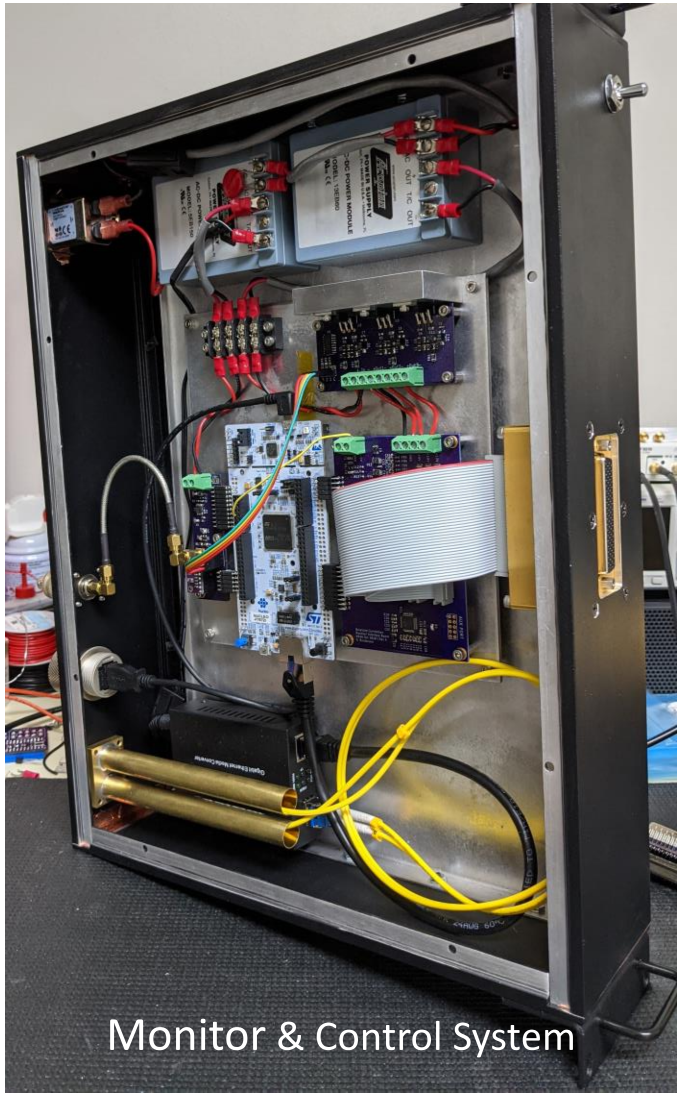
Frontend RF Modules



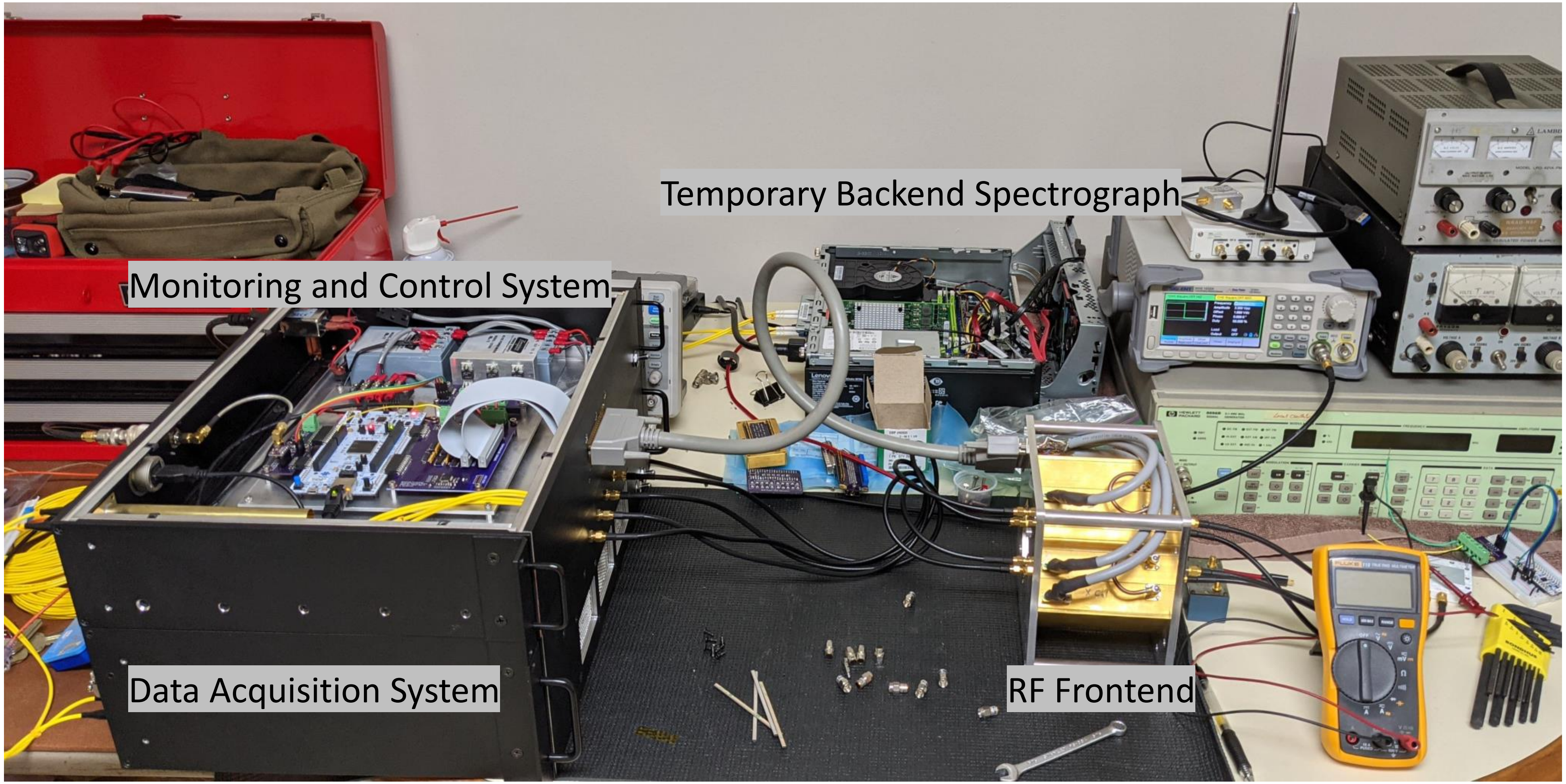
Custom Receiver Boxes


RF/Software Defined Radios


Acquisition PC + 10GbE Fiber

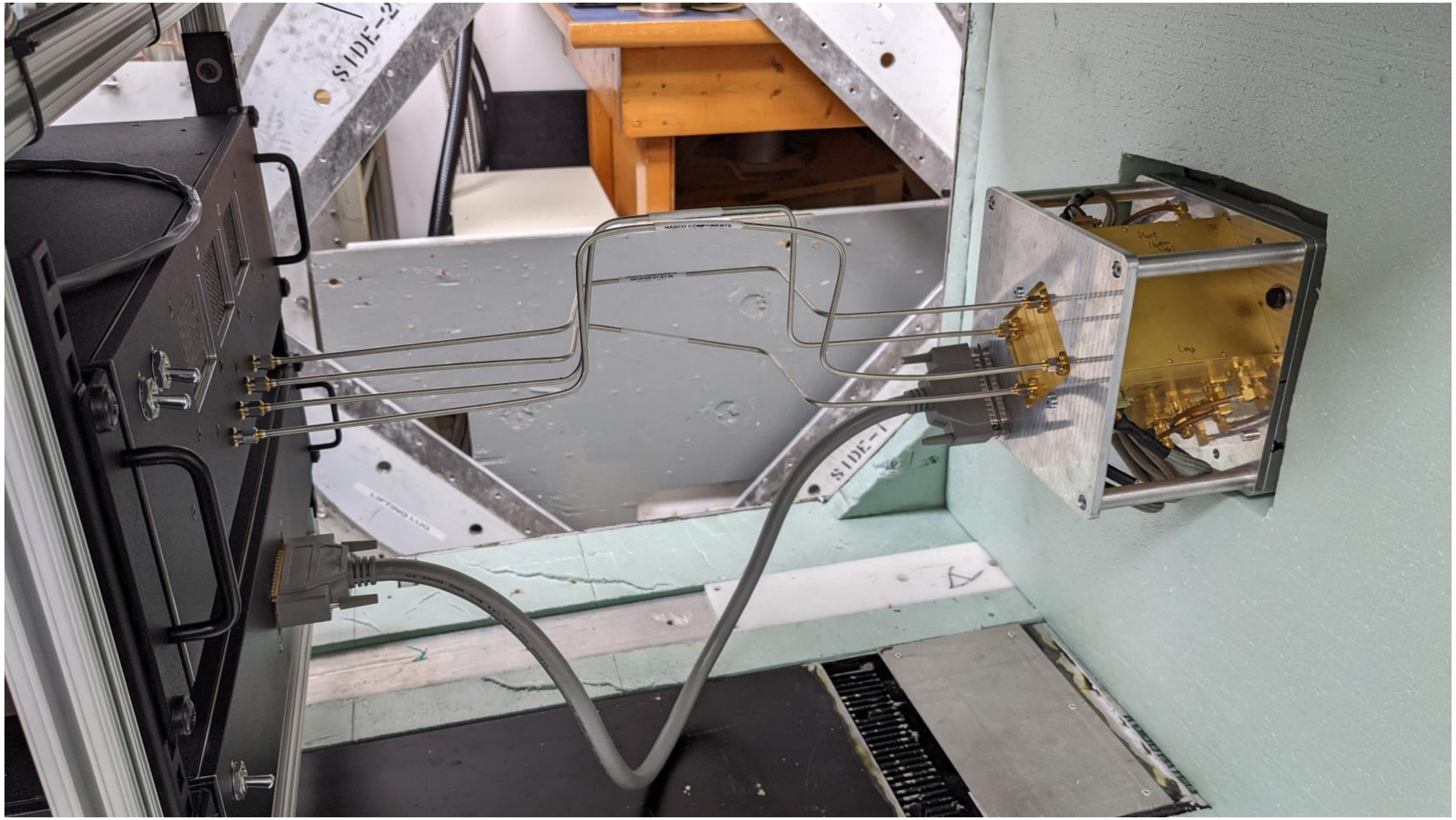

Monitor & Control System

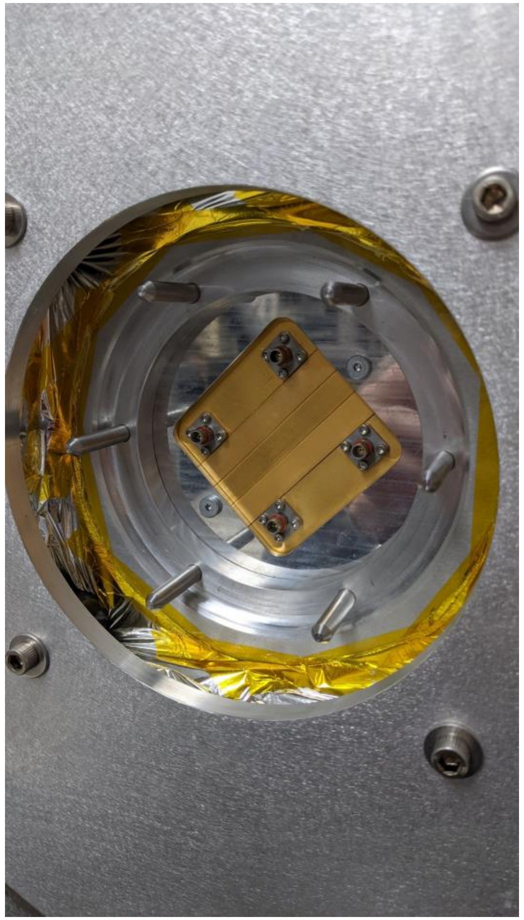
Frontend on the Bench/Kitchen Table



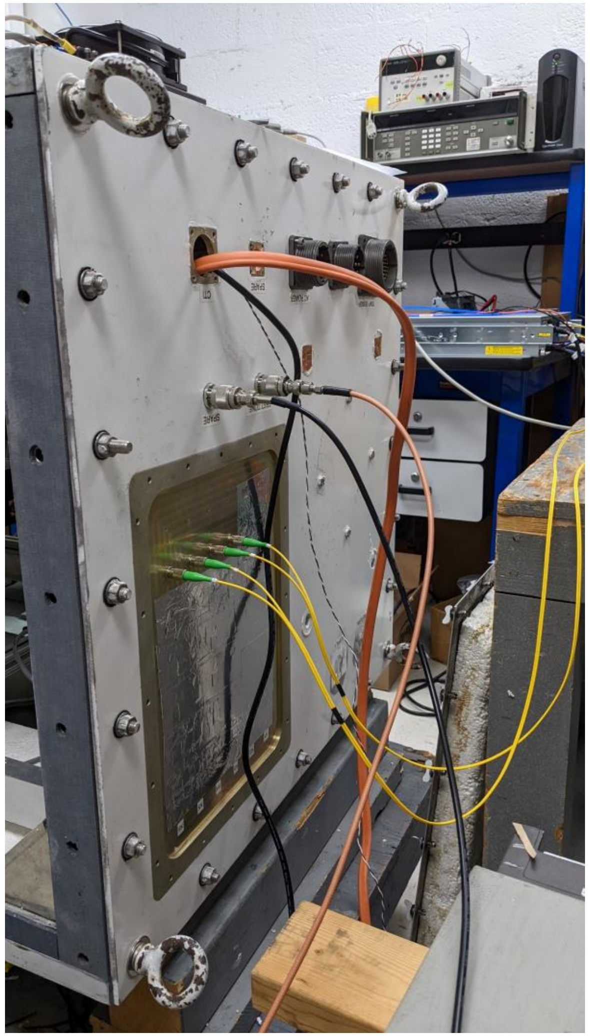
Integrated Prime Focus Receiver

RF Frontend

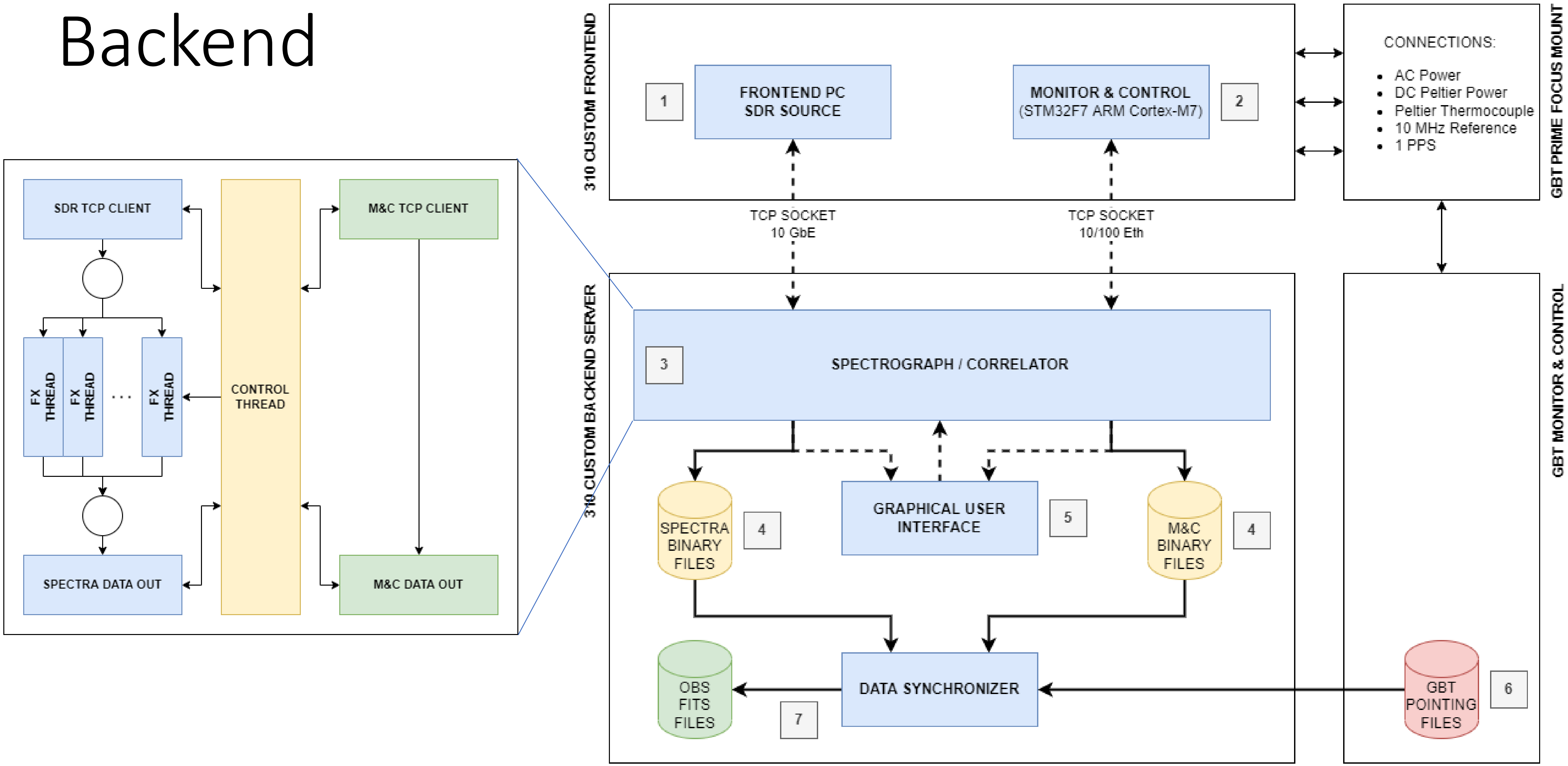




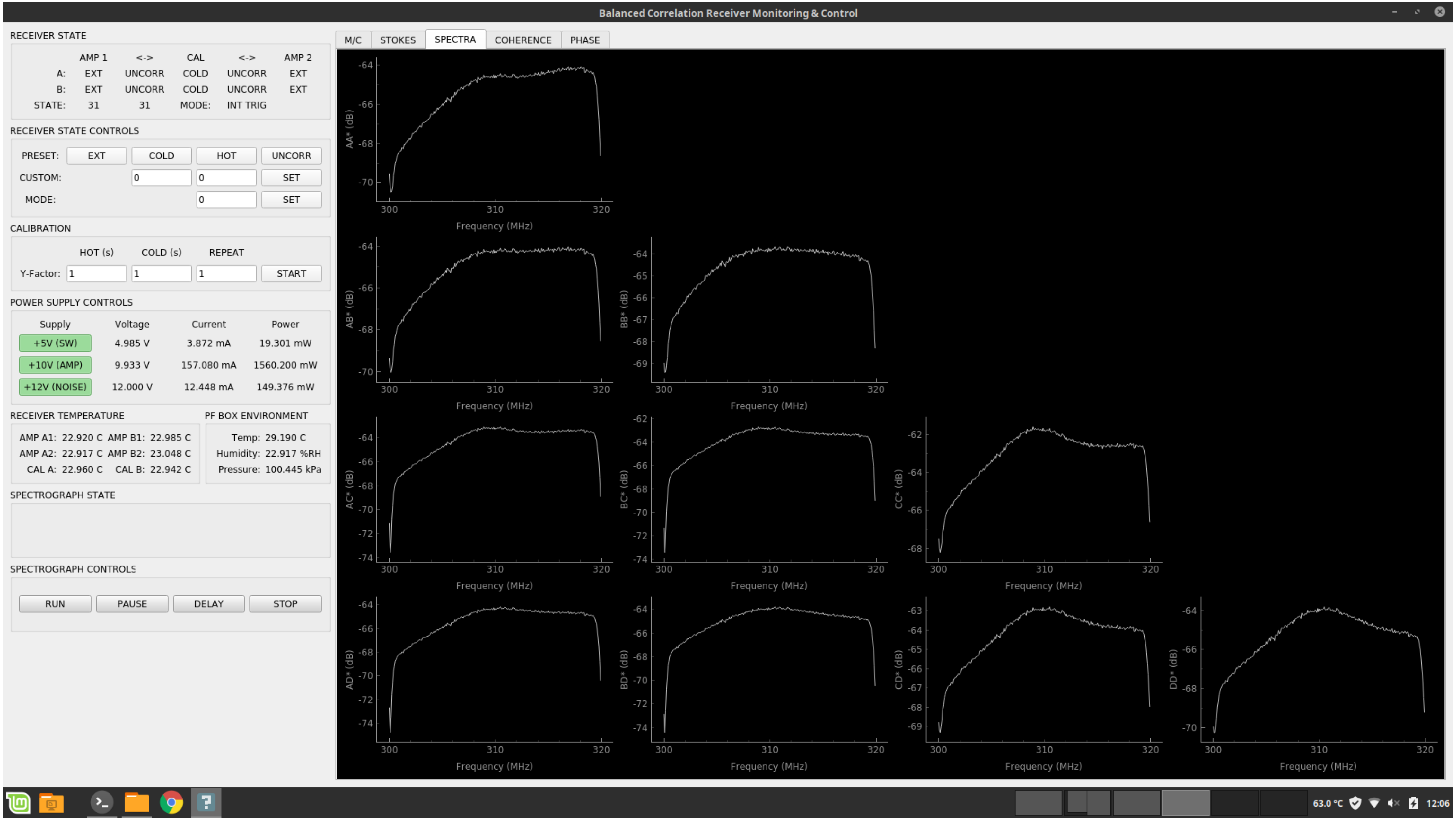
Power Distribution and Bulkhead Connections



Backend



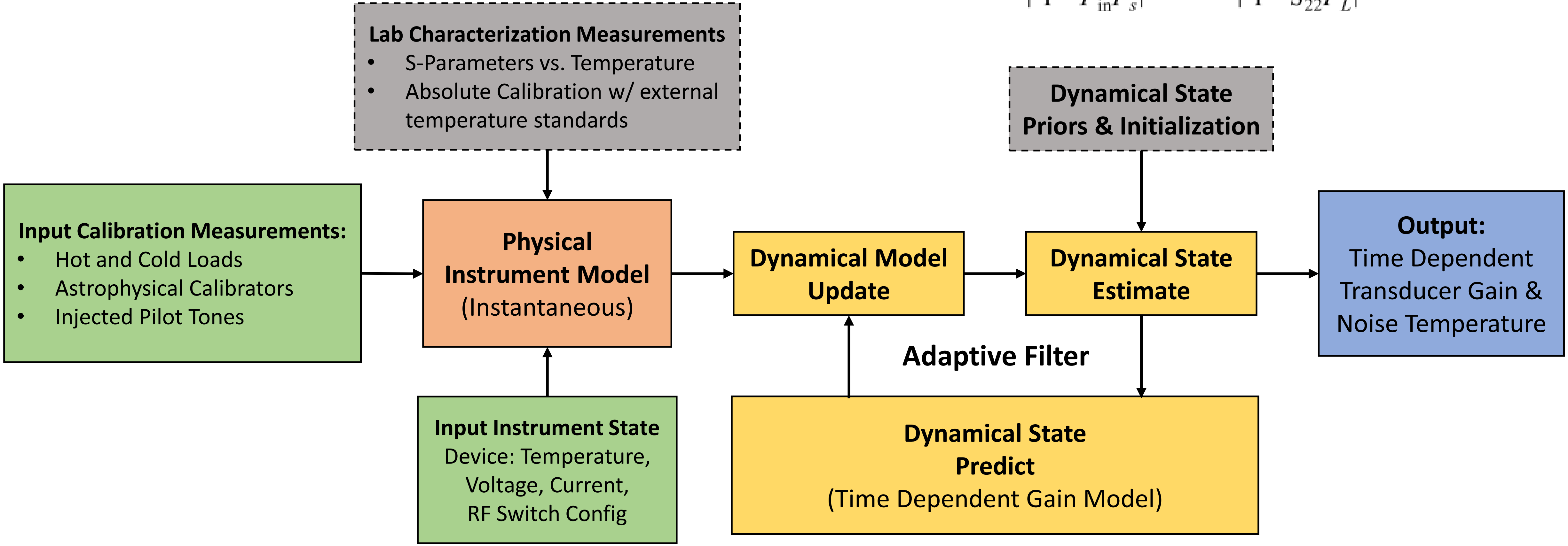
SDR TCP CLIENT
CONTROL THREAD
M&C TCP CLIENT
FX THREAD
FX THREAD
. . .
FX THREAD
SPECTRA DATA OUT
M&C DATA OUT
310 CUSTOM FRONTEND
1
FRONTEND PC
SDR SOURCE
MONITOR & CONTROL
(STM32F7 ARM Cortex-M7)
2
CONNECTIONS:
AC Power
DC Peltier Power
Peltier Thermocouple
10 MHz Reference
1 PPS
GBT PRIME FOCUS MOUNT
TCP SOCKET
10 GbE
TCP SOCKET
10/100 Eth
310 CUSTOM BACKEND SERVER
3
SPECTROGRAPH / CORRELATOR
SPECTRA BINARY FILES
4
GRAPHICAL USER INTERFACE
5
M&C BINARY FILES
4
OBS FITS FILES
7
DATA SYNCHRONIZER
GBT POINTING FILES
6
GBT MONITOR & CONTROL


Balanced Correlation Receiver Monitoring & Control
RECEIVER STATE
AMP 1 <-> CAL <-> AMP 2
A: EXT UNCORR COLD UNCORR EXT
B: EXT UNCORR COLD UNCORR EXT
STATE: 31 31 MODE: INT TRIG
RECEIVER STATE CONTROLS
PRESET: EXT COLD HOT UNCORR
CUSTOM: 0 0 SET
MODE: 0 SET
CALIBRATION
HOT (s) COLD (s) REPEAT
Y-Factor: 1 1 1 START
POWER SUPPLY CONTROLS
Supply Voltage Current Power
+5V (SW) 4.985 V 3.872 mA 19.301 mW
+10V (AMP) 9.933 V 157.080 mA 1560.200 mW
+12V (NOISE) 12.000 V 12.448 mA 149.376 mW
RECEIVER TEMPERATURE
AMP A1: 22.920 C AMP B1: 22.985 C
AMP A2: 22.917 C AMP B2: 23.048 C
CAL A: 22.960 C CAL B: 22.942 C
PF BOX ENVIRONMENT
Temp: 29.190 C
Humidity: 22.917 %RH
Pressure: 100.445 kPa
SPECTROGRAPH STATE
SPECTROGRAPH CONTROLS
RUN PAUSE DELAY STOP
M/C STOKES SPECTRA COHERENCE PHASE
AA* (dB)
AB* (dB)
BB* (dB)
AC* (dB)
BC* (dB)
CC* (dB)
AD* (dB)
BD* (dB)
CD* (dB)
DD* (dB)
Frequency (MHz)
300 310 320
63.0 °C 12:06

Calibration Pipeline

Transducer Gain eqn:

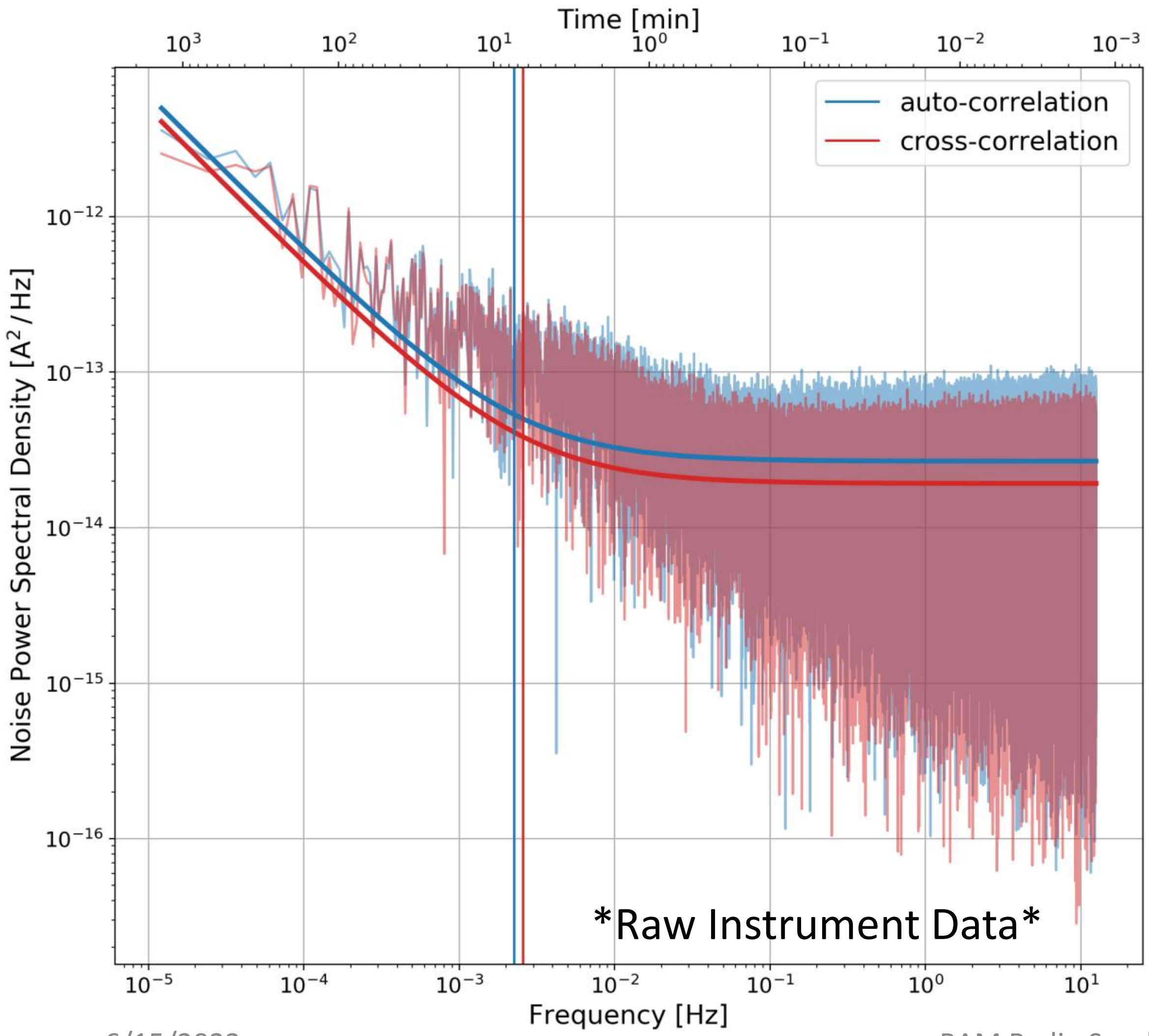
$$G_T = \frac{1 - |\Gamma_s|^2}{|1 - \Gamma_{\text{in}}\Gamma_s|^2} |S_{21}|^2 \frac{1 - |\Gamma_L^2|^2}{|1 - S_{22}\Gamma_L|^2}$$



$$x_k = [G_\nu, \dot{G}_\nu, \ddot{G}_\nu, T_\nu, \dot{T}_\nu, \ddot{T}_\nu]$$

+ covariances

1/f Noise – A Metric for System Stability

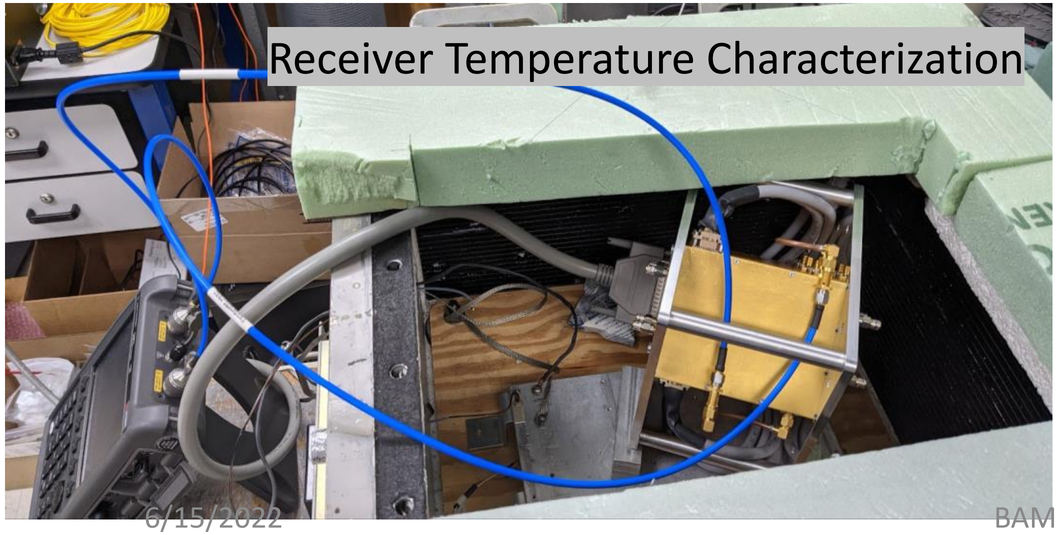


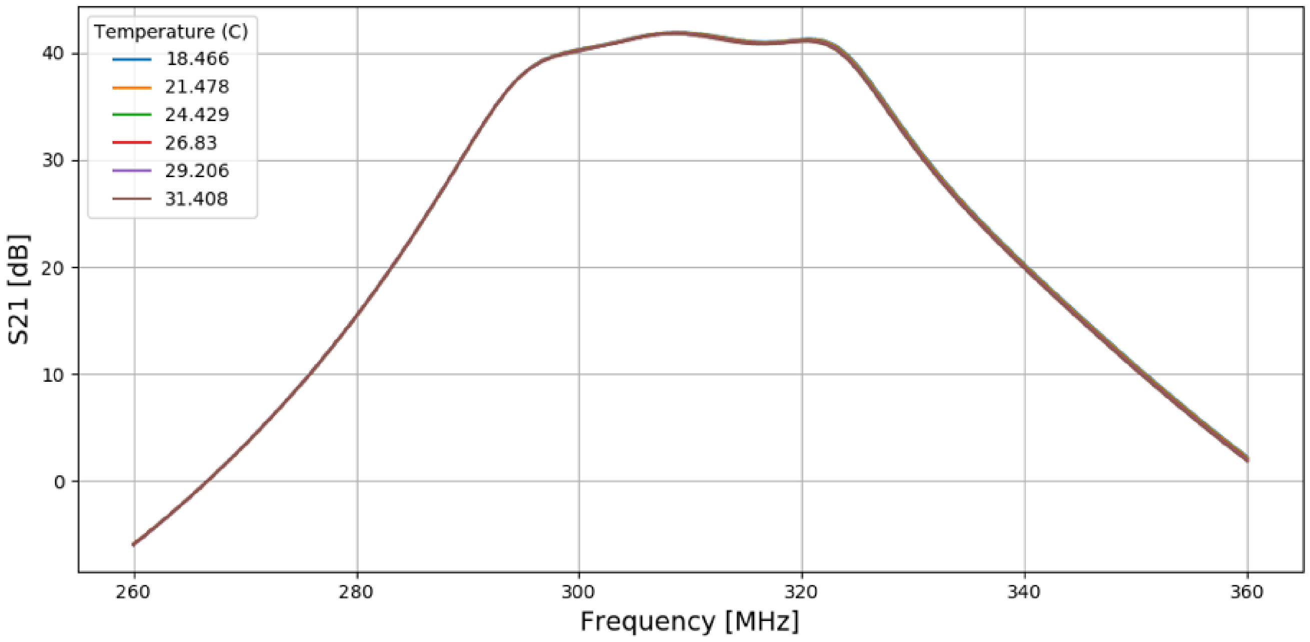
- 1/f noise is widely found in nature and electronic devices
- The correlated behavior in time manifests as a drift
- System calibration must be performed sufficiently faster than the 1/f corner frequency

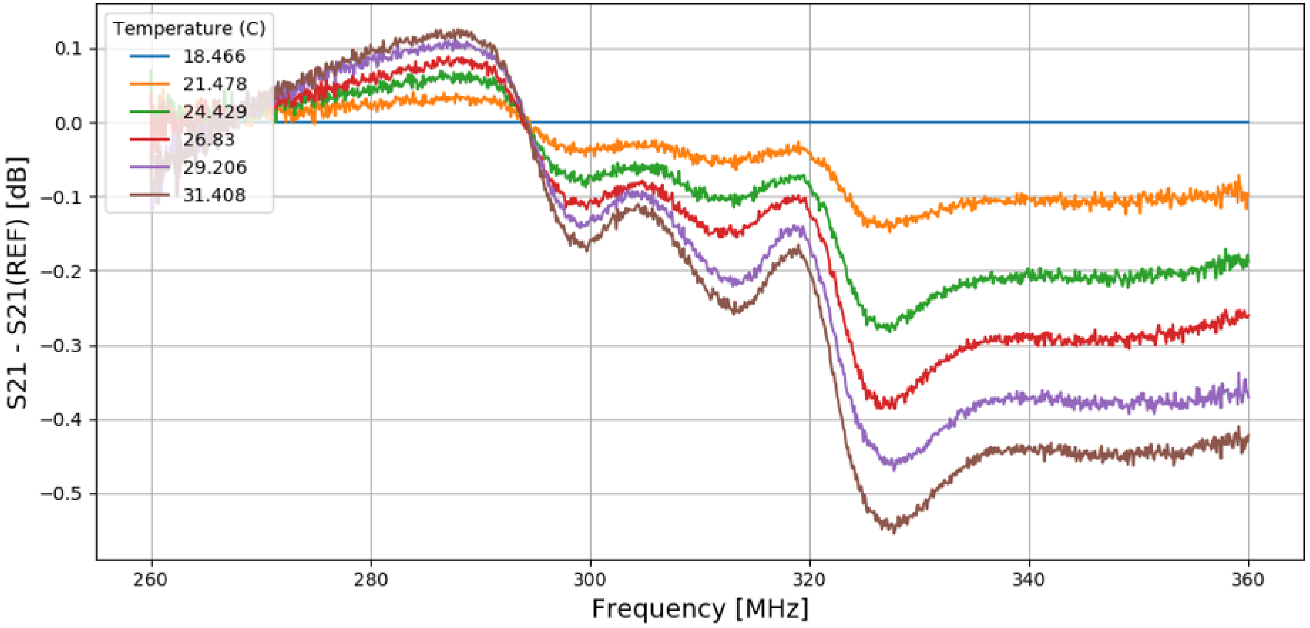
Lab Characterization

Physical Circuit Models are Calibrated using:

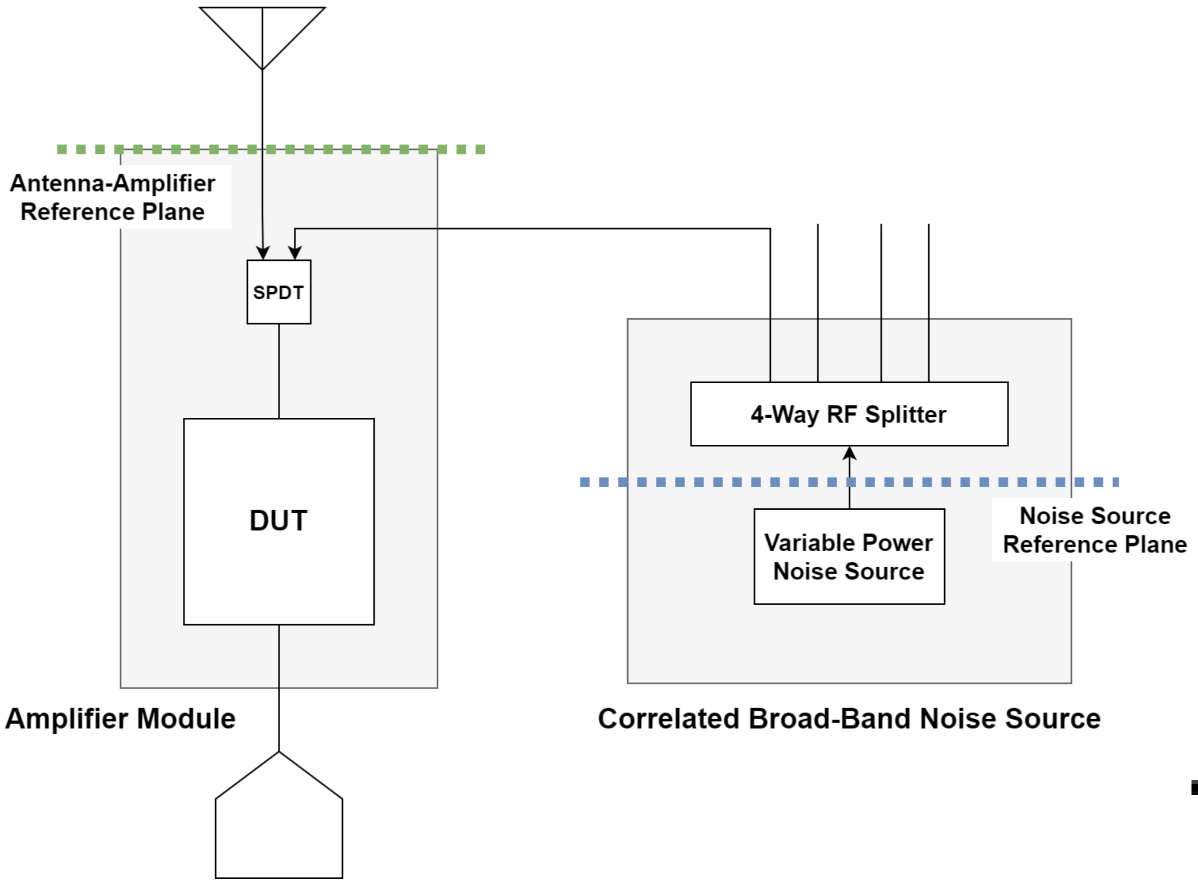
- S-Parameters vs Device Temperature
- Lab Temperature Standards
- Arbitrary Impedance Loads

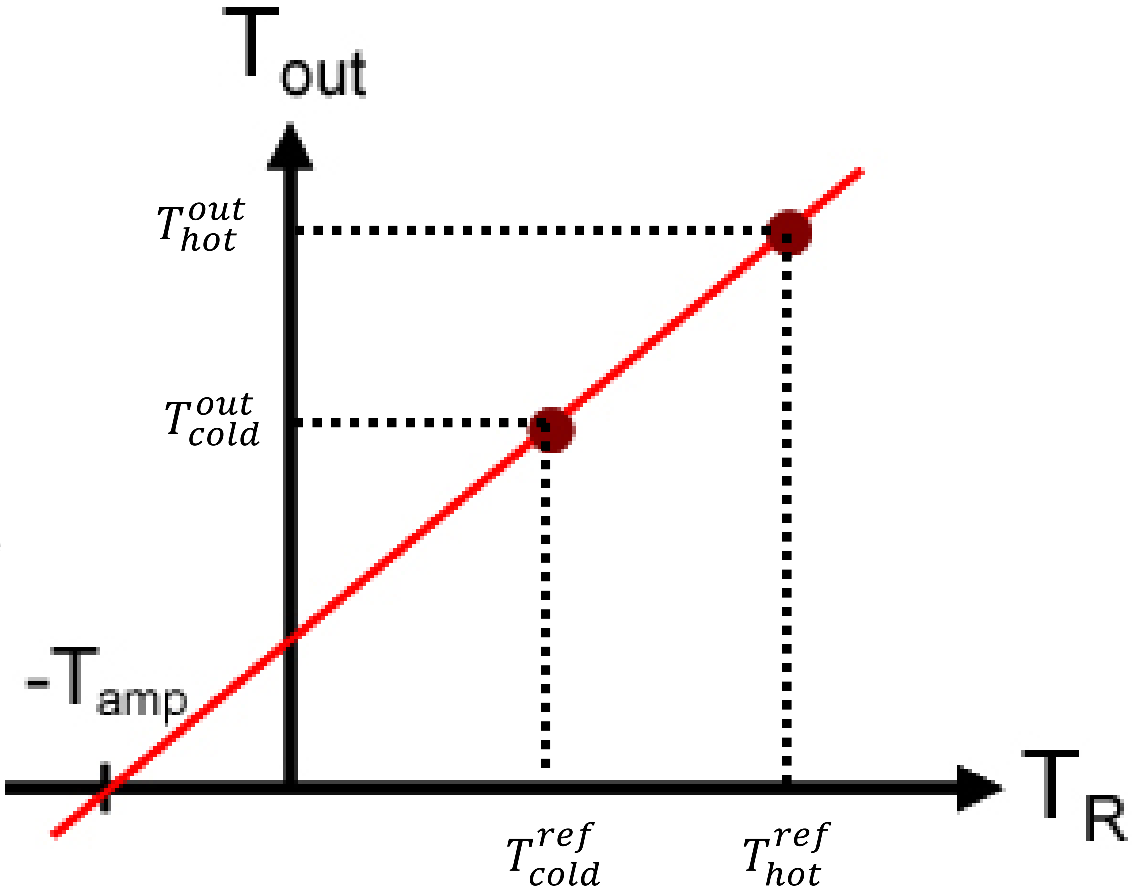




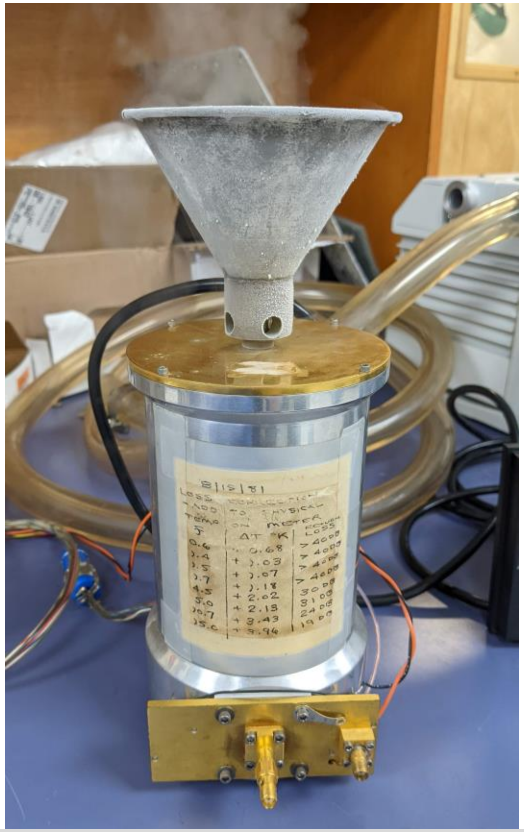


Y-Factor: Broadband Noise Calibration

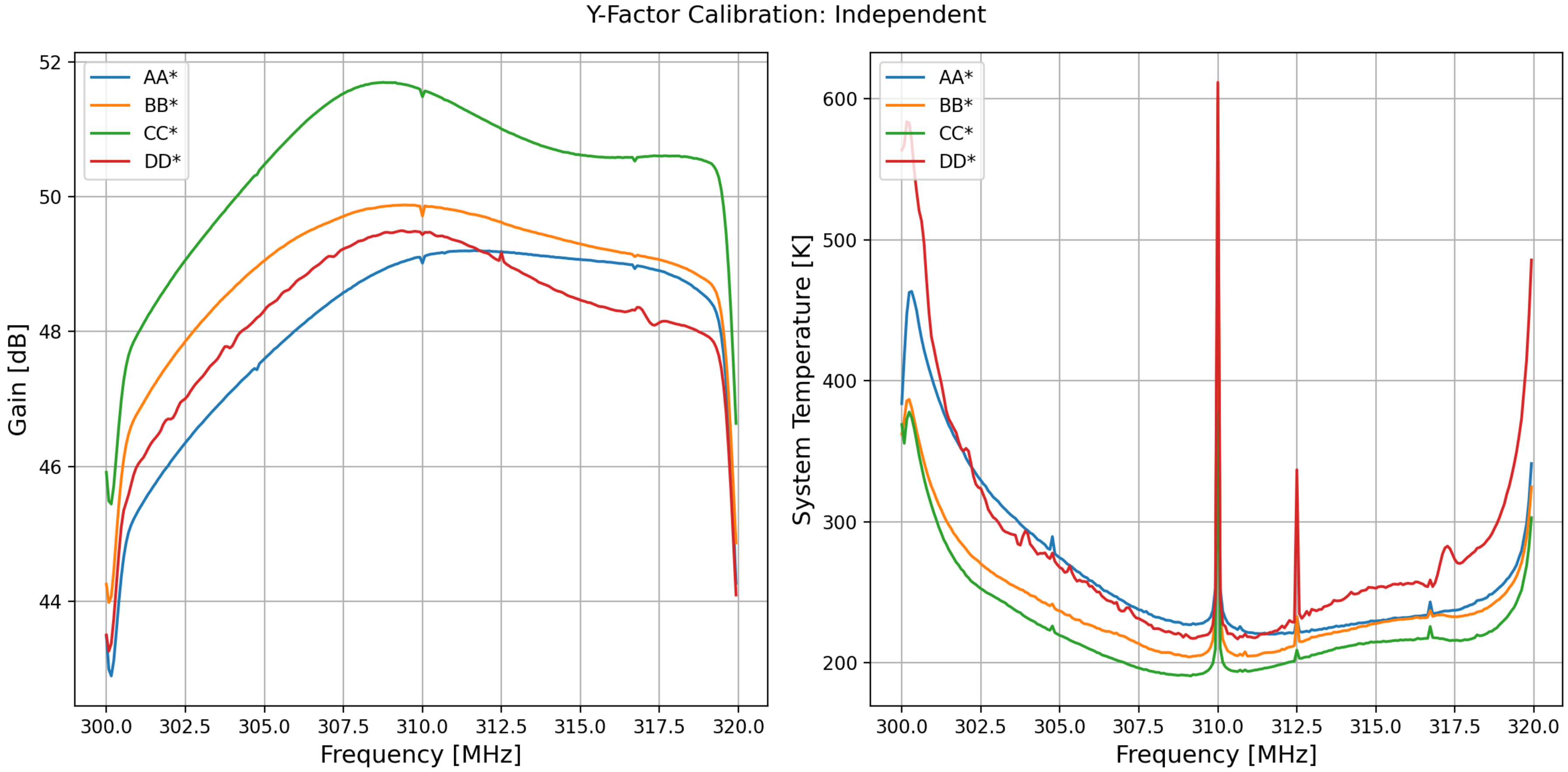




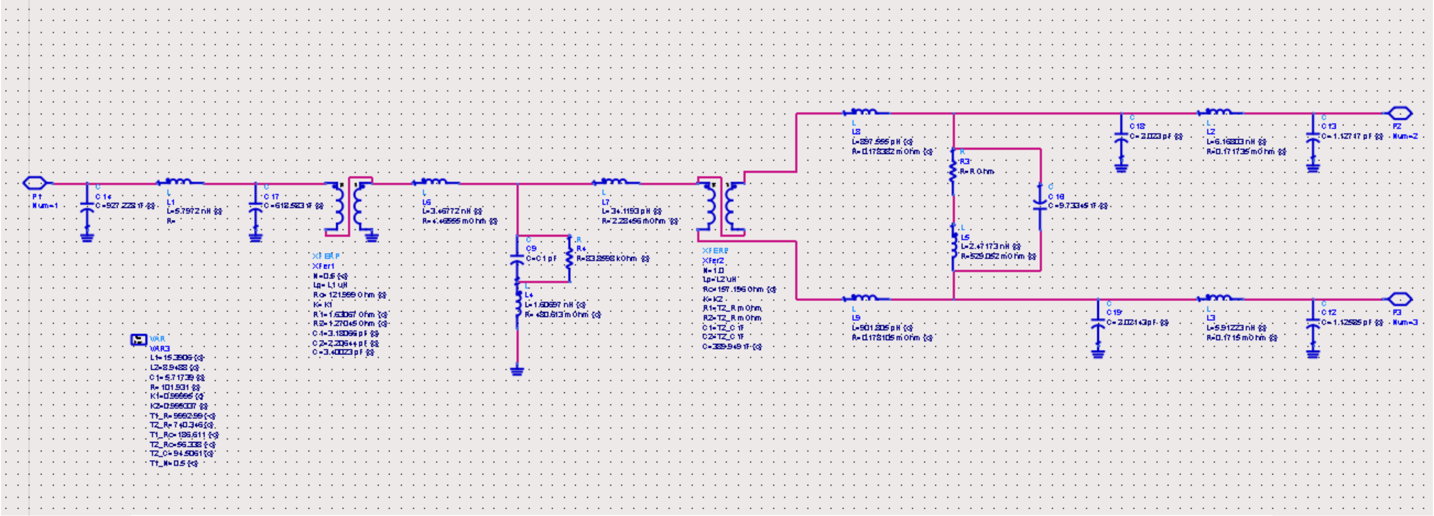
Cryogenic Y-Factor (Hot/Cold) Reference Calibrations

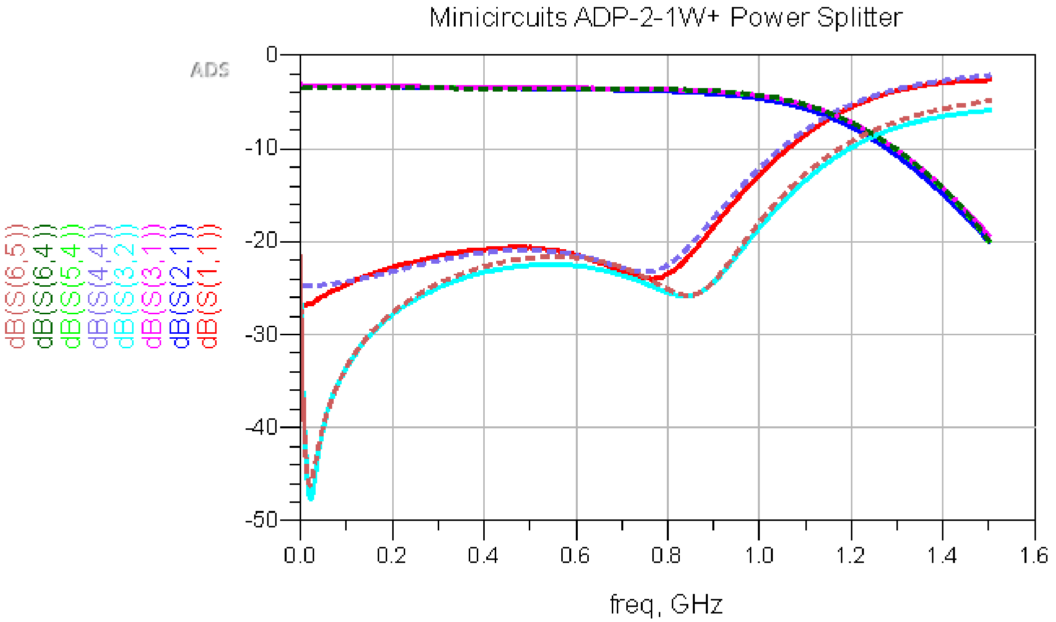


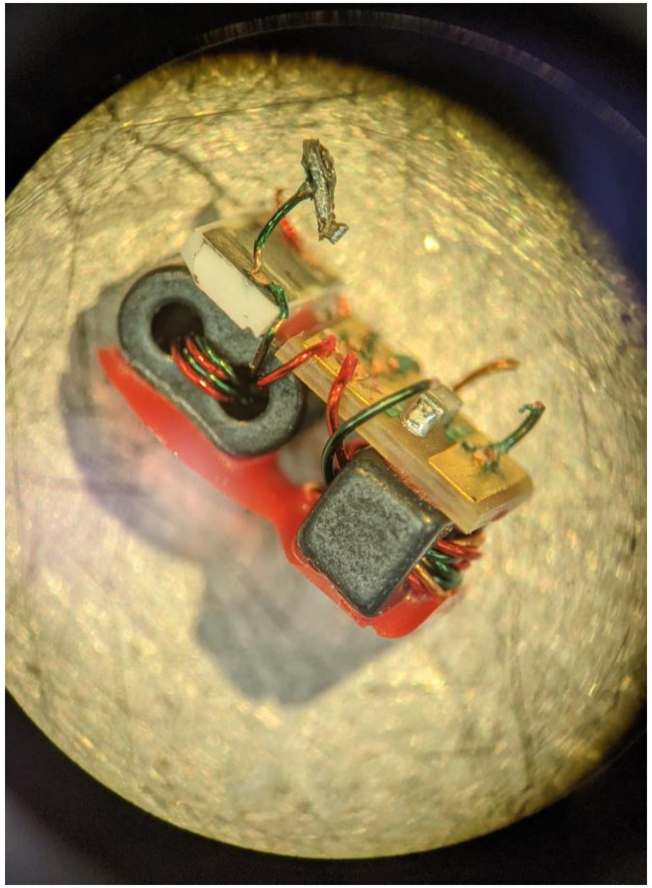
80’s Vintage Liquid Nitrogen Temperature Standard



Circuit Modeling

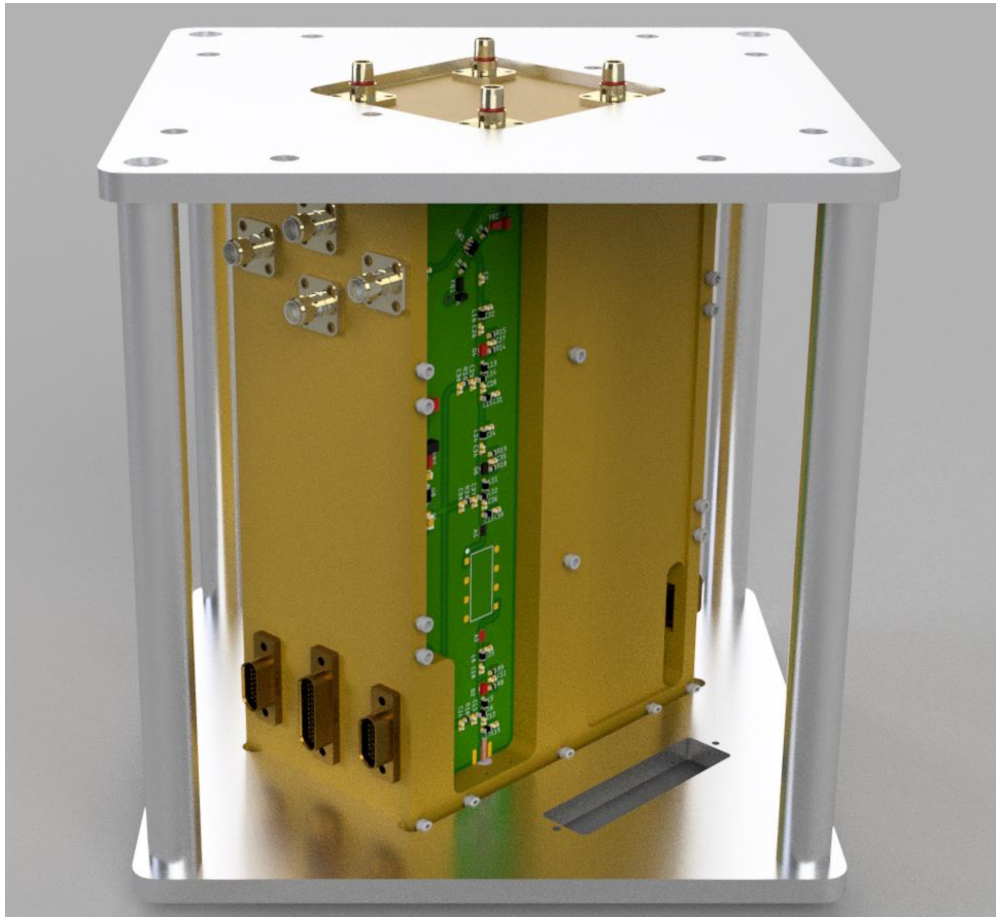




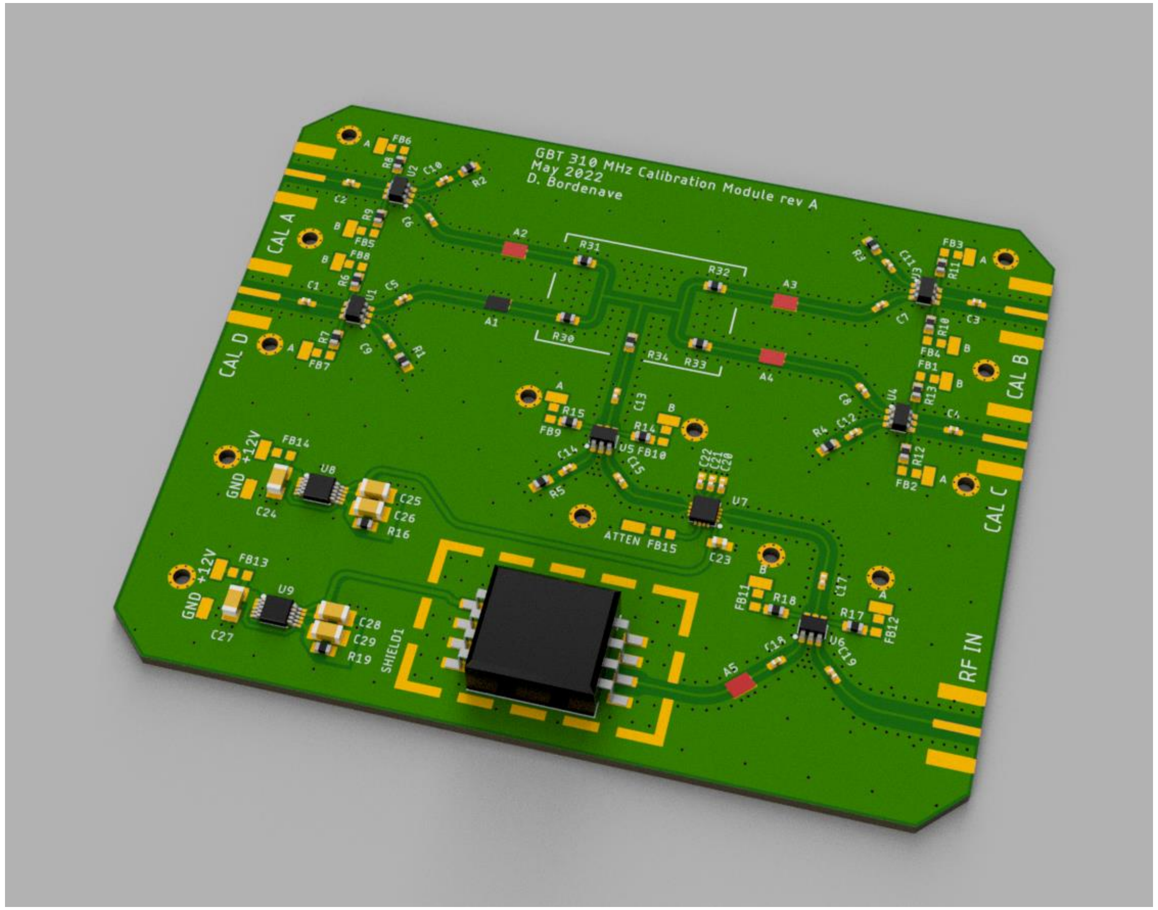


Improved Frontend Receiver

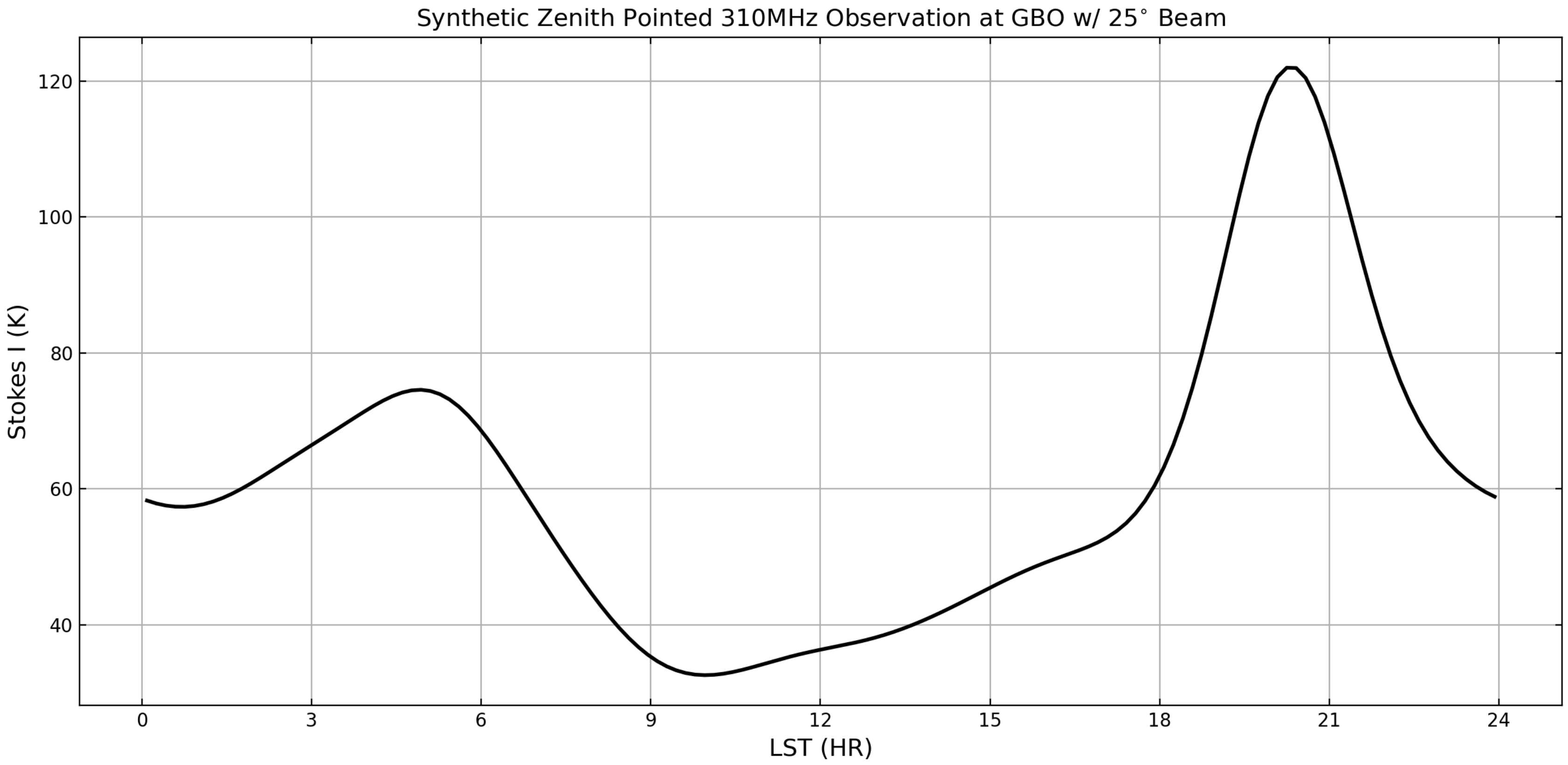
Complete RF frontend Assembly w/ AMPS and Cals

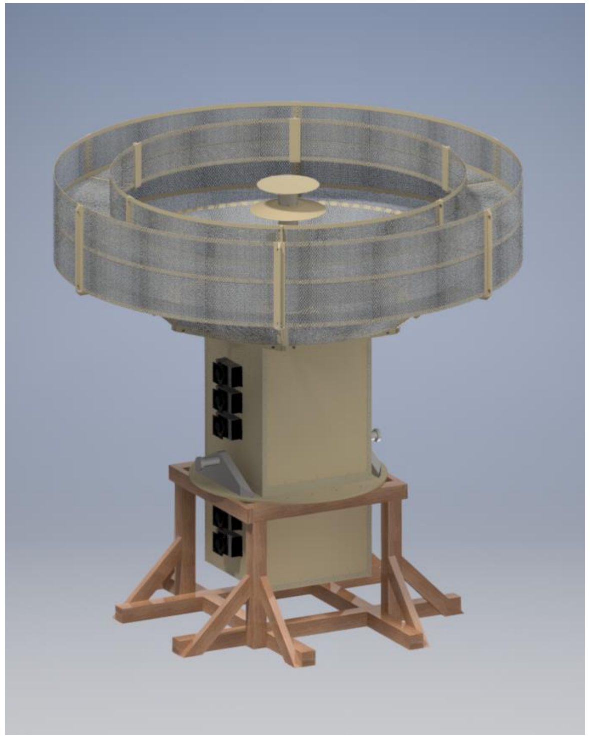


4-channel Coherent Noise source

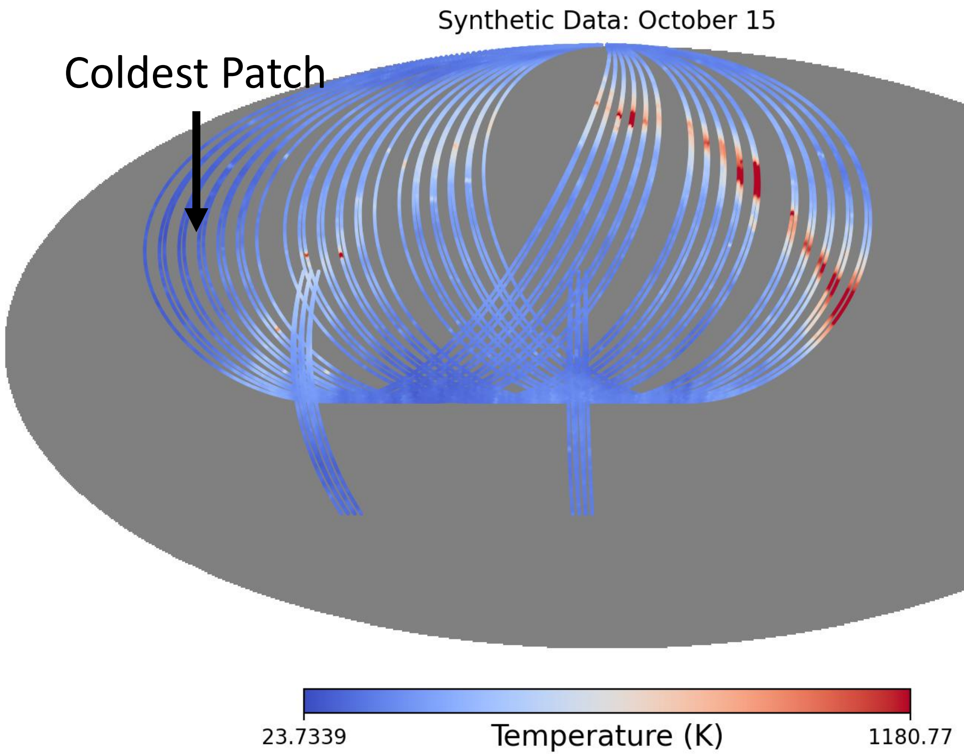


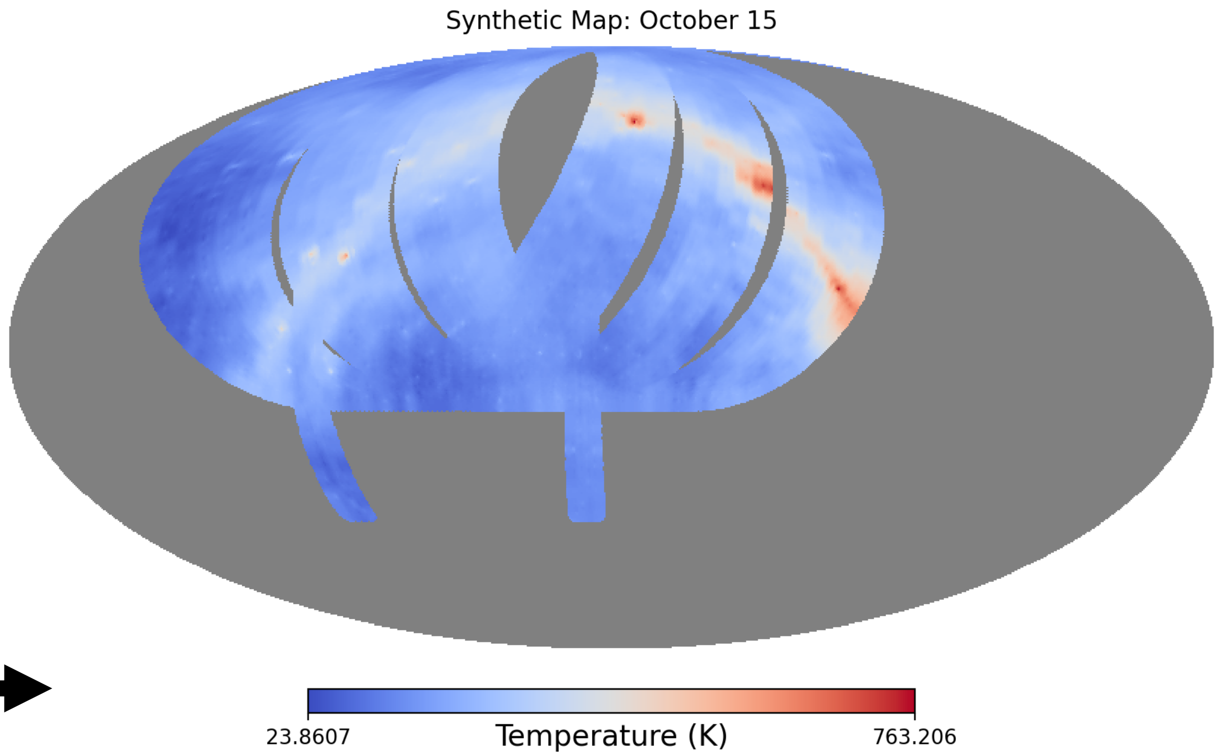
Ground Commissioning (Late August)





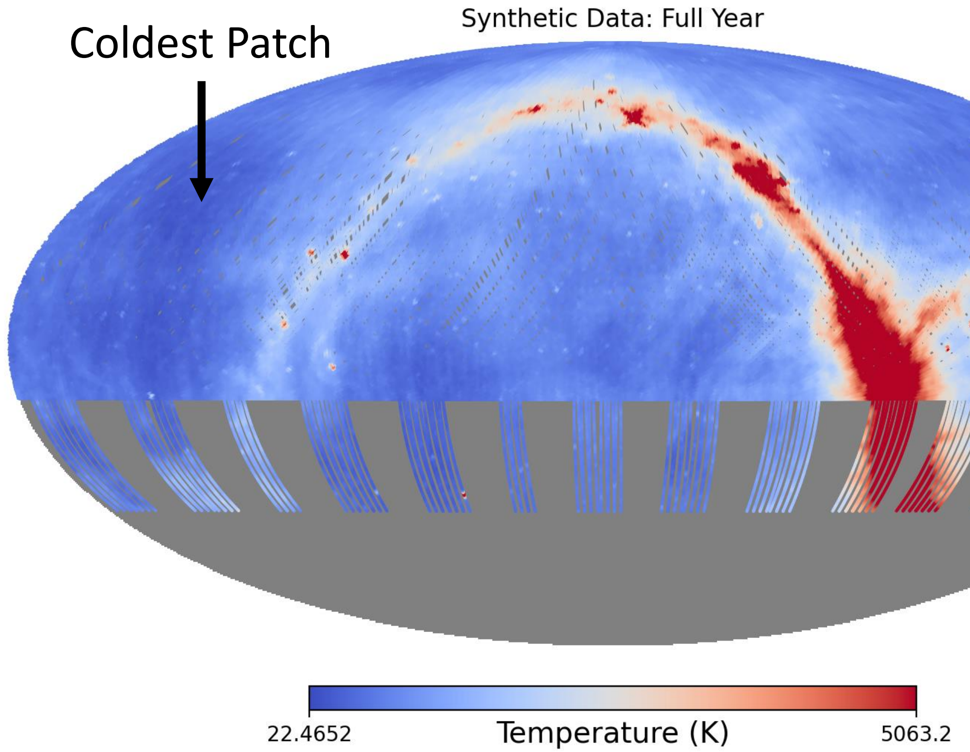
Observation Simulations (mid Oct)

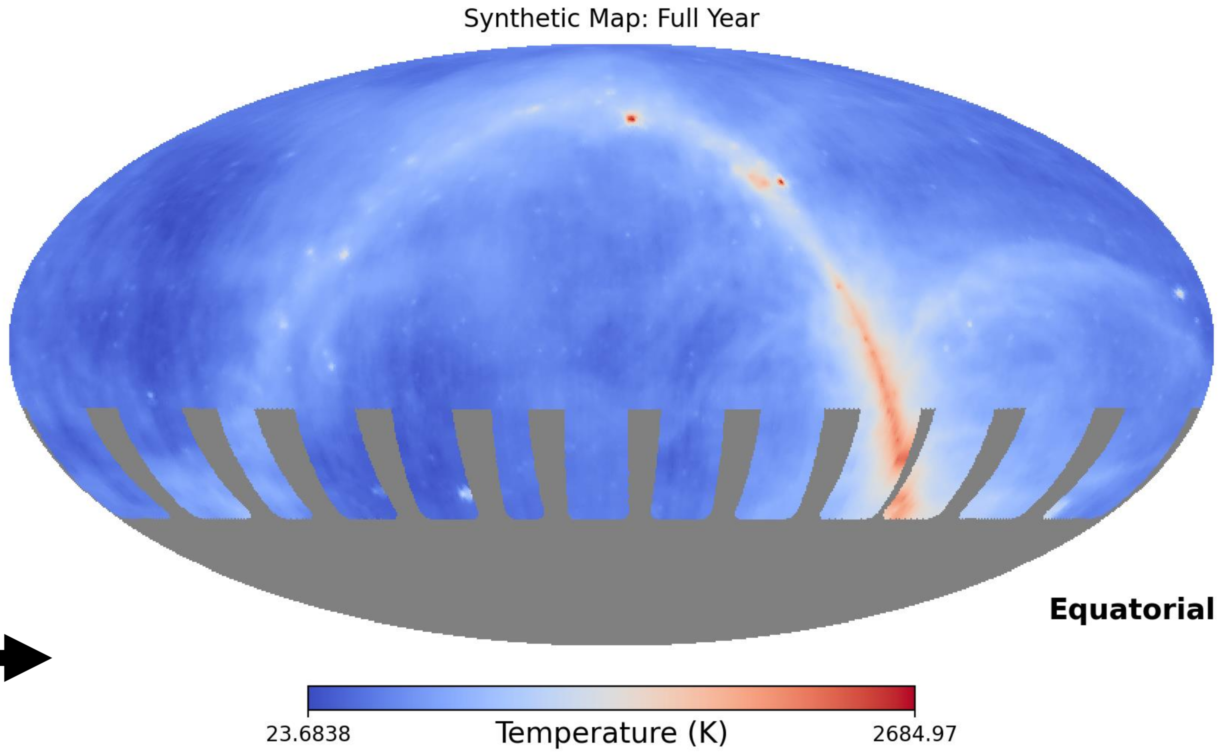




Inverse Distance Weighting diminishes peak surface brightness

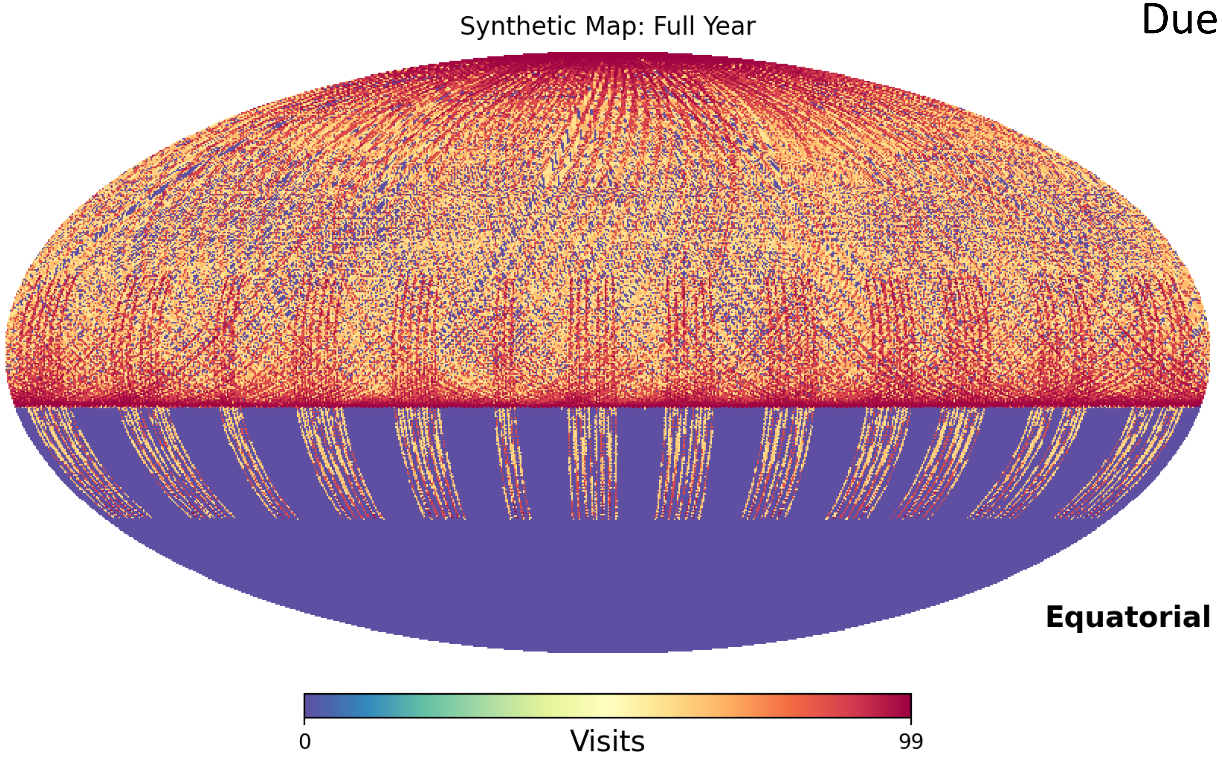
Observation Simulations (Full Year)



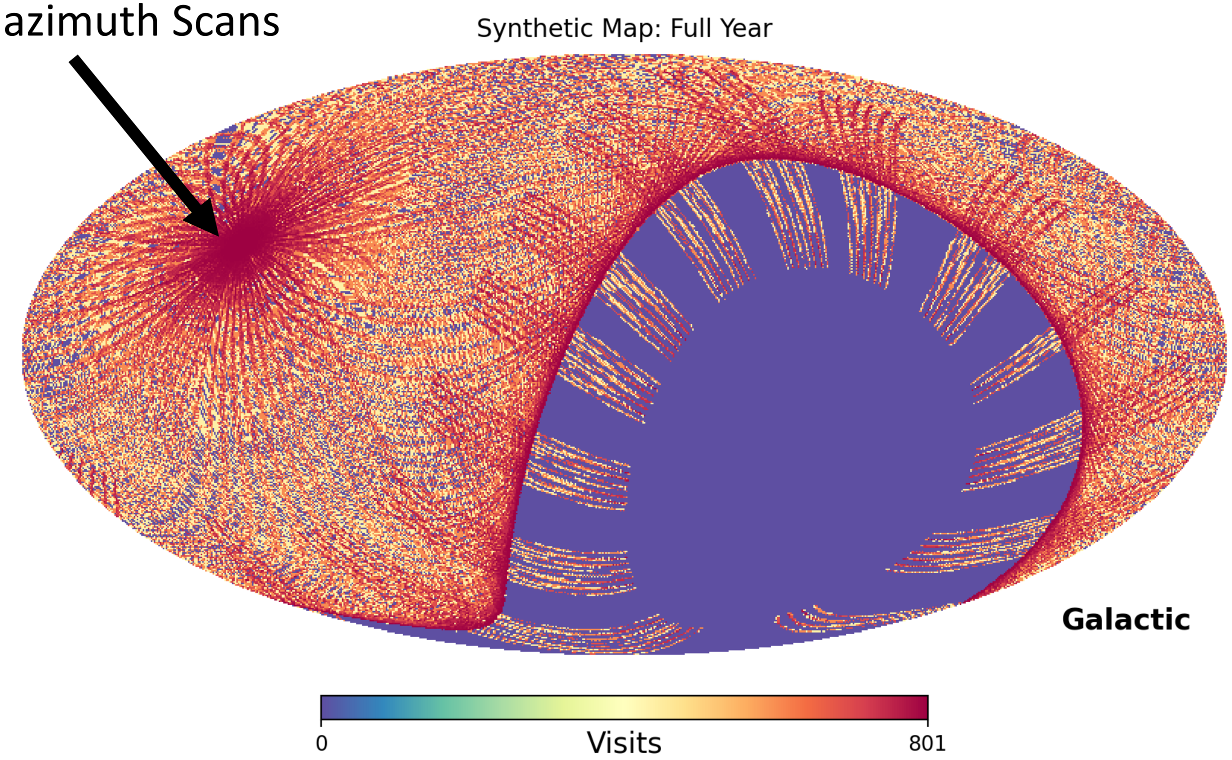


Inverse Distance Weighting diminishes peak surface brightness

Observation Coverage



Oversampled NCP
Due to azimuth Scans



#TODO:

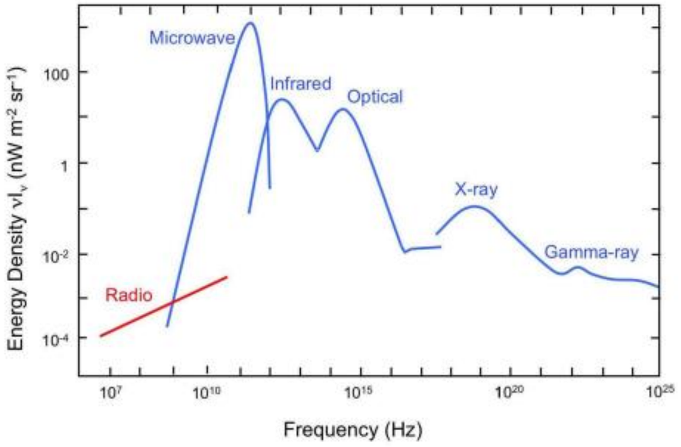
- Finish fabrication/characterization of improved RF Frontend (on-going)
- Ground Commissioning of Receiver at Green Bank in late Summer
- First observation on GBT in October
- Full Northern Sky Map (Pending Proposals)

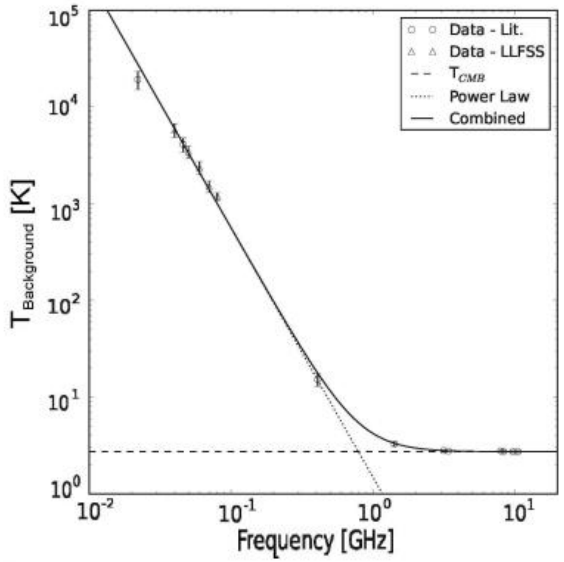
Scientific Motivation

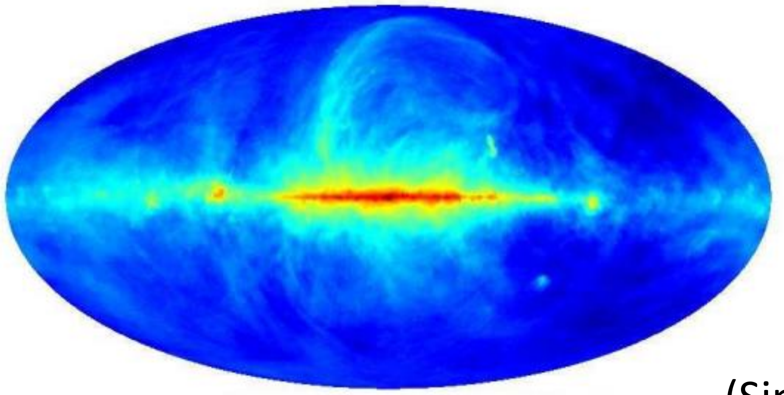
$$T_{\rm B}({\rm K}) = 24.1 \pm 2.1 \left(\frac{\nu}{310\ {\rm MHz}}\right)^{-2.6\pm0.04}$$

Resolving the Excess
"Radio Synchrotron Background"
Mystery

- Current known source populations and emission mechanisms cannot account for the observed total radio surface brightness
- Measurements below 3 GHz do not prioritize absolute zero-level calibration
- High-quality large area maps of the sky are indispensable in nearly all fields of astronomy







(Singal 2019)