MUSIC Readout
Update on Measured Performance

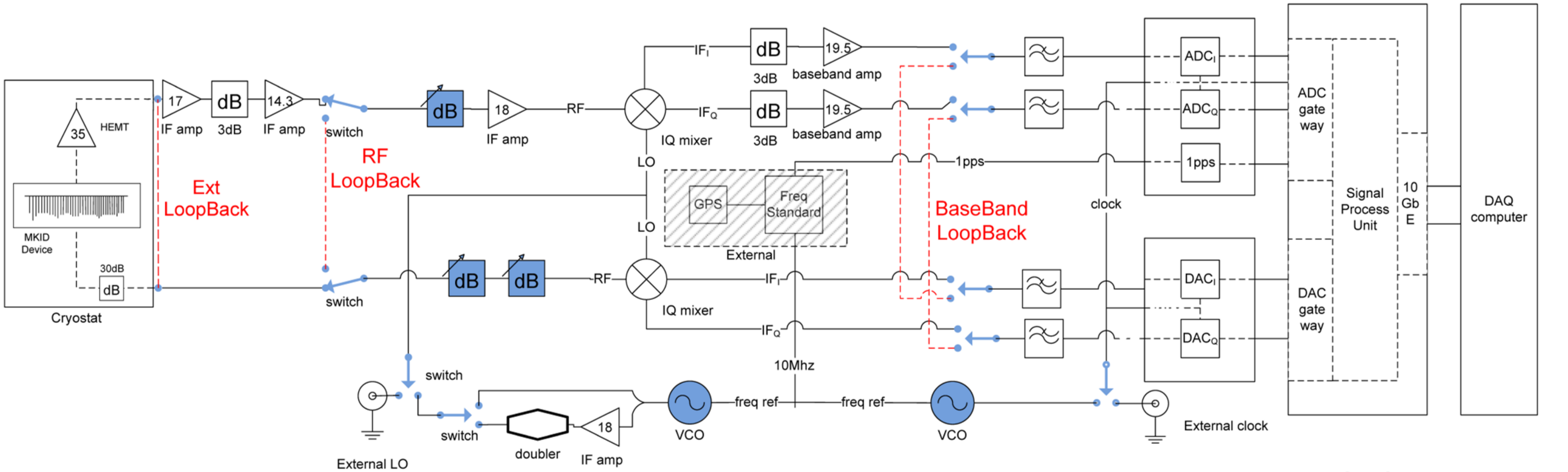
Seth Siegel

Outline

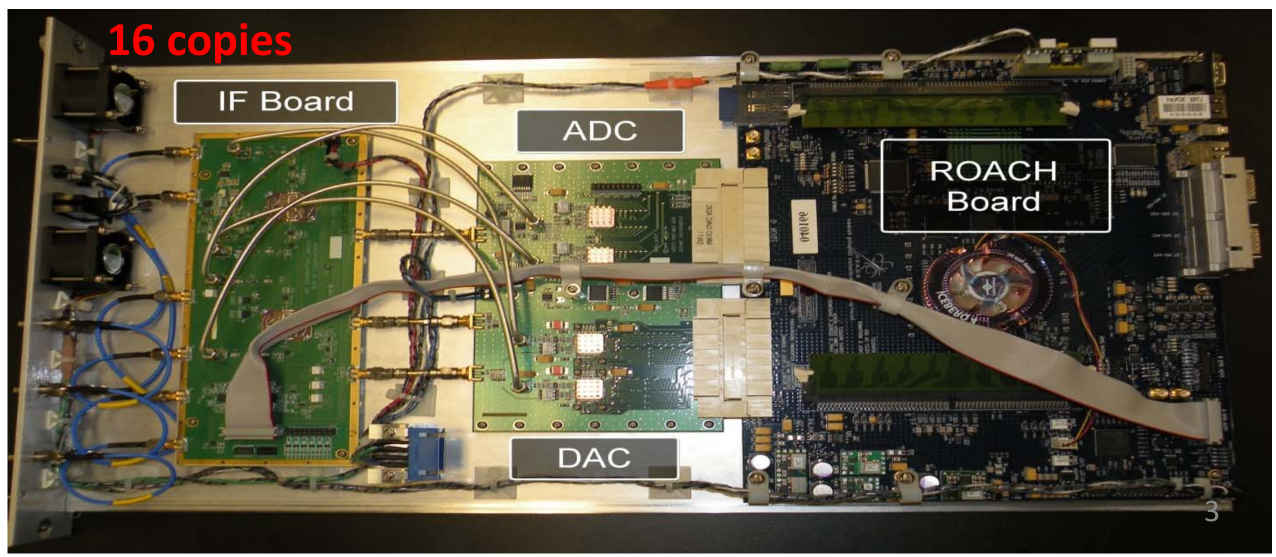
- MKID noise expectations
- Measured electronics noise
- Measured resonator noise
- Removal
- Sensitivities

Readout

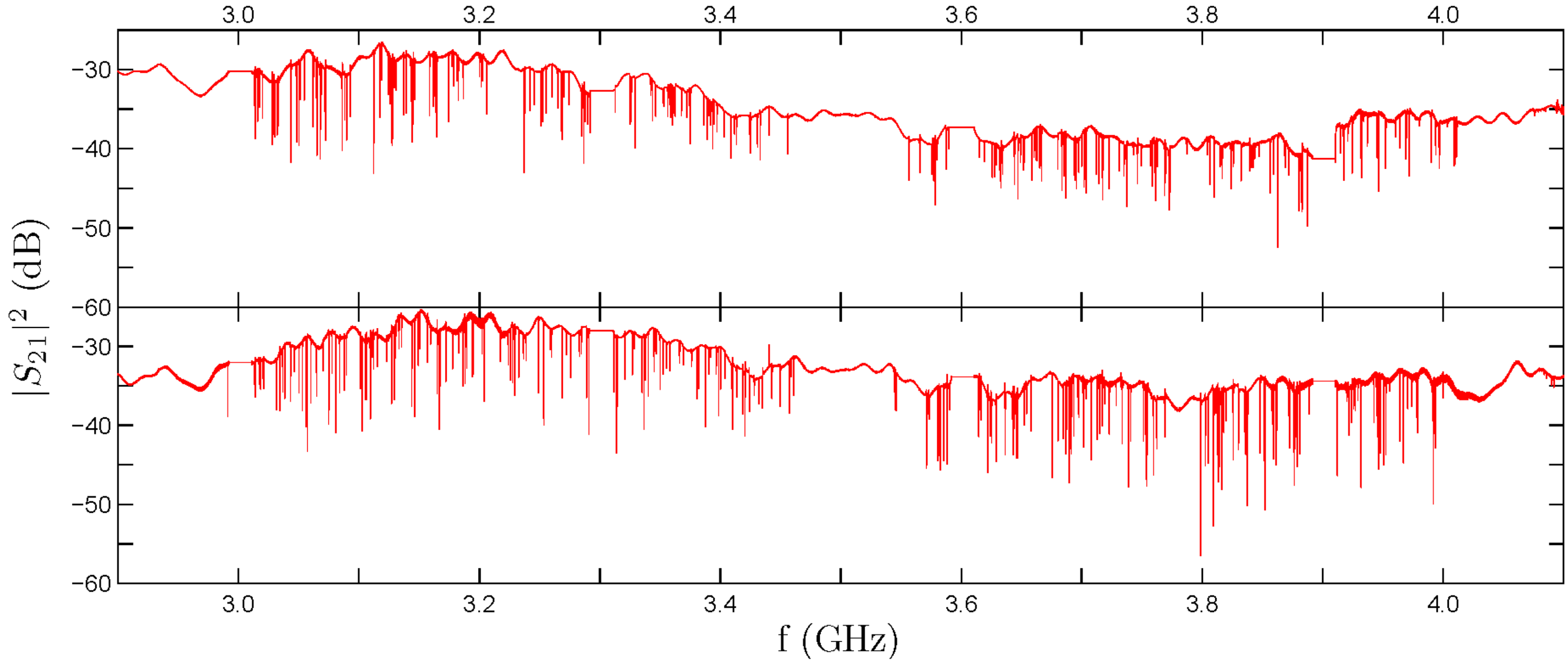
Schematic courtesy of Ran Duan

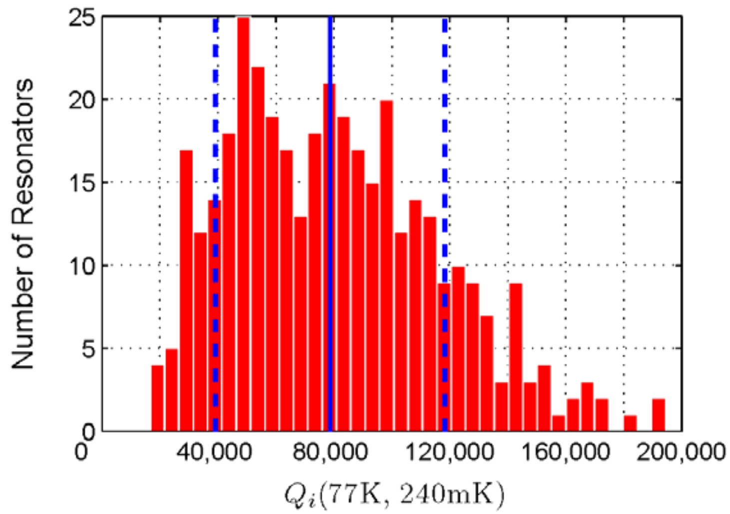


Dewar | **MKID IF Board** | **MKID ADC/DAC Board** | **ROACH Board** | **DAQ Computer**



Detector Yield

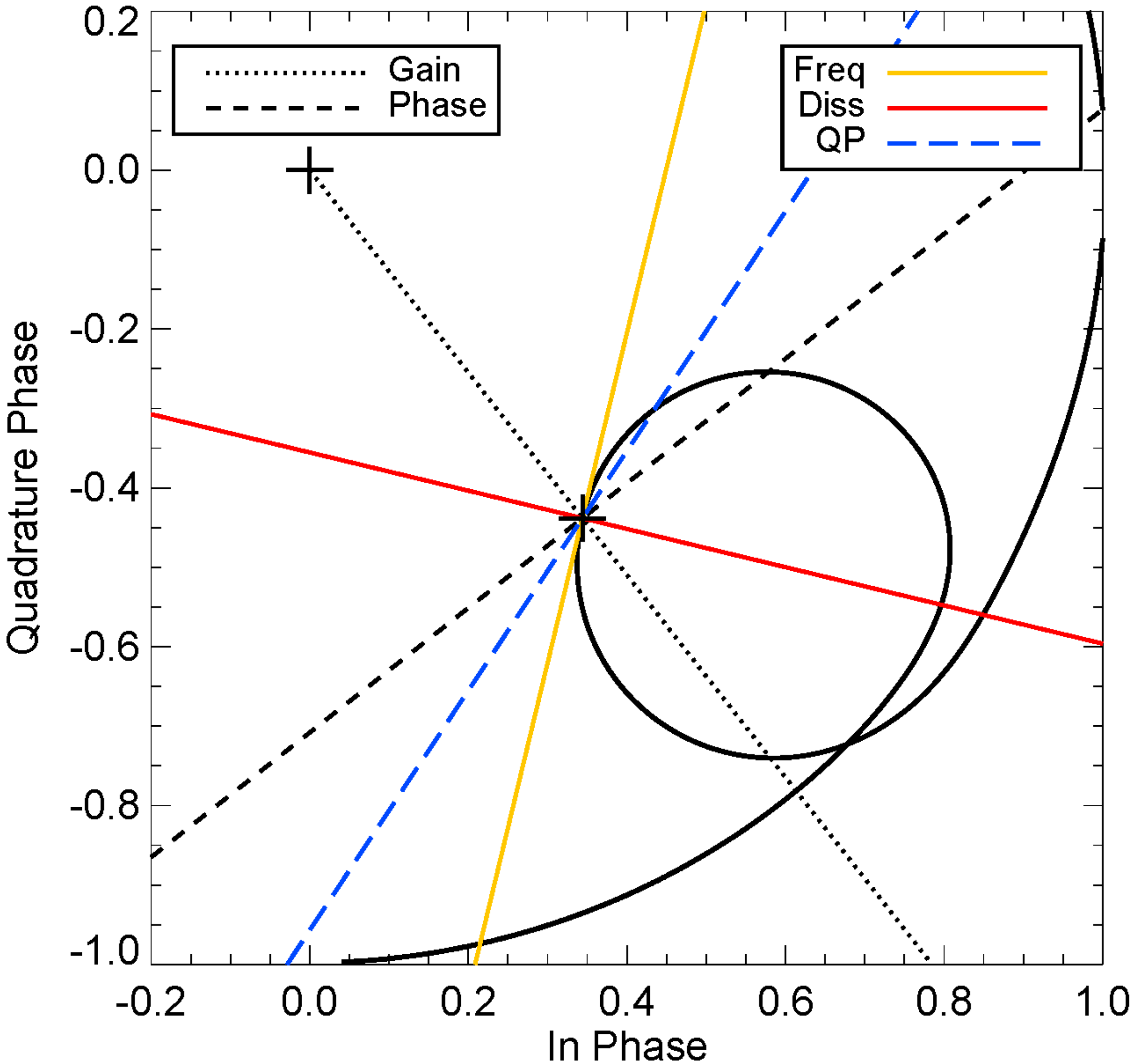




During engineering runs in May and July, employed **two** 6x12 arrays populating ¼ of the full focal plane

- Found **96%** of designed resonators **(551 resonators)**
- Final yield **66%** **(382 resonators)**
- Sources of loss
  - Resonator collisions **(22%)**
  - Low quality factor or bifurcation at low readout power **(8%)**

MKID Expected Noise



HEMT White Noise

$$\hat{V}(t) = Ae^{i\phi} + \delta w_{\text{hemt}}$$

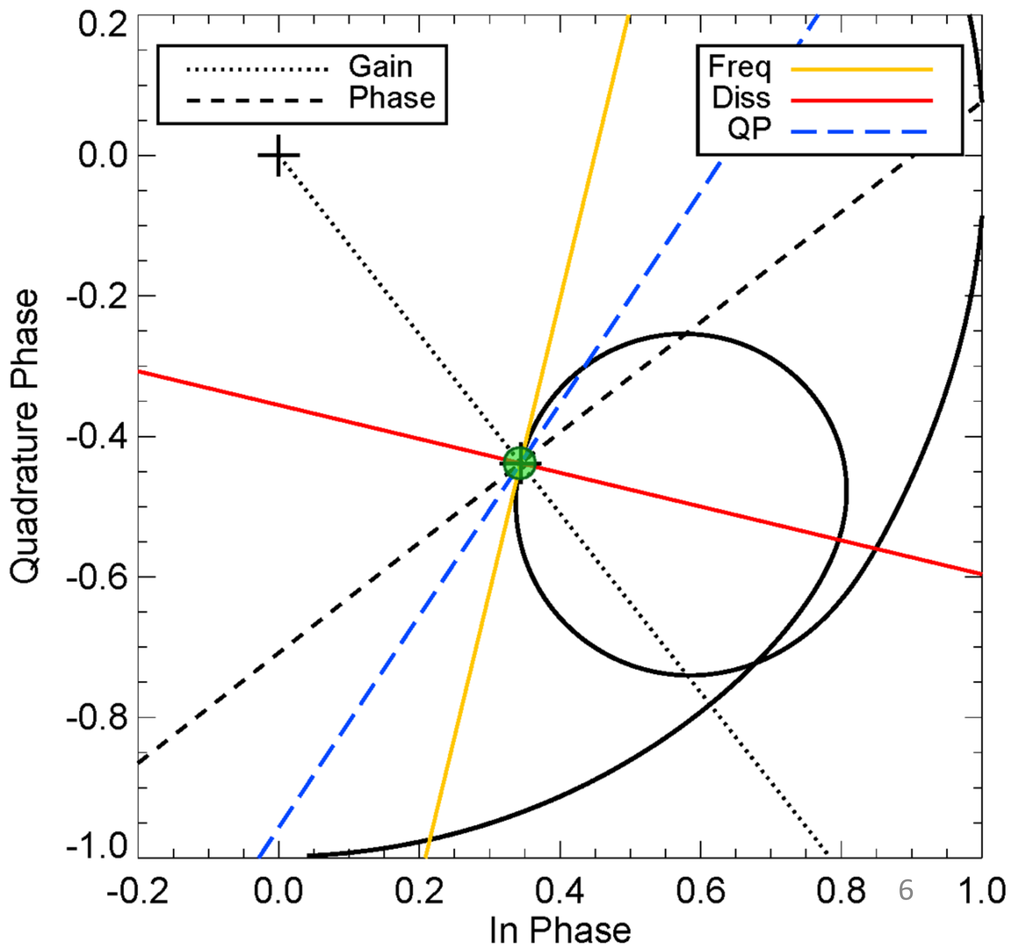
- Additive noise
  - Scales as P_{read}^{-1} relative to signal
- Parameterize the power spectral density with a noise temperature

$$S_{\delta w} = G_{\text{post-hemt}}\ k_{\text{B}} T_{\text{N}}$$

- Have measured noise temperature as a function of bias settings for the 8 HEMTs used in MUSIC. Operate at bias settings that achieve a reasonable compromise between low noise temperature and long-timescale stability.

$$\min\left(T_{\text{N}}\right) = 2.4\ \text{K}$$

$$\max\left(T_{\text{N}}\right) = 5.5\ \text{K}$$



Electronics Noise

$$\hat{V}(t) = A(1+\delta A)e^{i(\phi+\delta\phi)} + \delta w_{\mathrm{hemt}}$$
$$= Ae^{i\phi}(1+\delta A + i\delta\phi) + \delta w_{\mathrm{hemt}}$$

The various electronic components suffer from gain and phase type noise

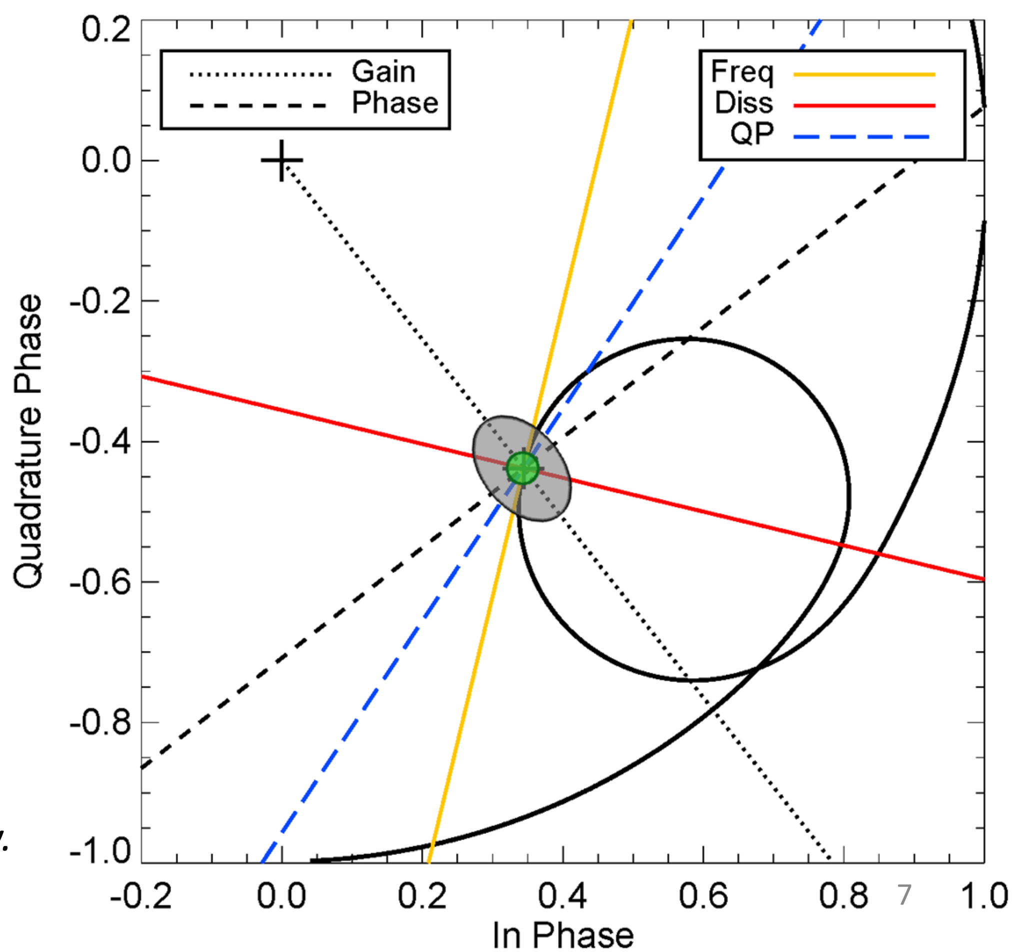
- Fluctuations in amplifier gain
- Fluctuations in DAC/ADC reference voltage
- Jitter in the DAC/ADC clock
- Drift in cable delays

Multiplicative in nature, this noise appear in the **gain** (radial) and **phase** (angular) direction.

Power spectral density is a combination of **1/f** and **drift** $(\propto f^{-2})$ type noise

Correlated among carrier tones.

Not necessarily independent of carrier frequency.



On-Resonance Noise

The **HEMT white noise** and **electronics gain and phase fluctuations** affect carriers centered on-resonance and carriers centered off-resonance in the same way.

Our strategy has been to construct templates of the gain and phase fluctuations (possibly as a function of frequency) by averaging over off-resonance timestreams and then subtracting these templates from the on-resonance data.

The resonators have **additional sources of noise** that all appear as

$$\hat{V}(t) = S_{21}(S_{21}^{\mathrm{res}} + \delta S_{21}^{\mathrm{res}})\hat{V}_0$$

$$= S_{21} S_{21}^{\mathrm{res}} \hat{V}_0 \left(1 + |S_{21}^{\mathrm{res}}|^{-1} e^{-i\phi_{\mathrm{res}}} \delta S_{21}^{\mathrm{res}}\right)$$

$$= A e^{i\phi} \left(1 + |S_{21}^{\mathrm{res}}|^{-1} e^{-i\phi_{\mathrm{res}}} \delta S_{21}^{\mathrm{res}}\right)$$

Two Level System Noise

$$\hat{V}(t) = Ae^{i\phi}\left[1 + \delta A + i\delta\phi + \frac{2Q^2}{|S_{21}^{\mathrm{res}}|Q_c}\left(\frac{\delta f}{f}\right)_{\mathrm{TLS}} e^{-i(\frac{\pi}{2}+\phi_{\mathrm{res}})}\right] + \delta w_{\mathrm{hemt}}$$

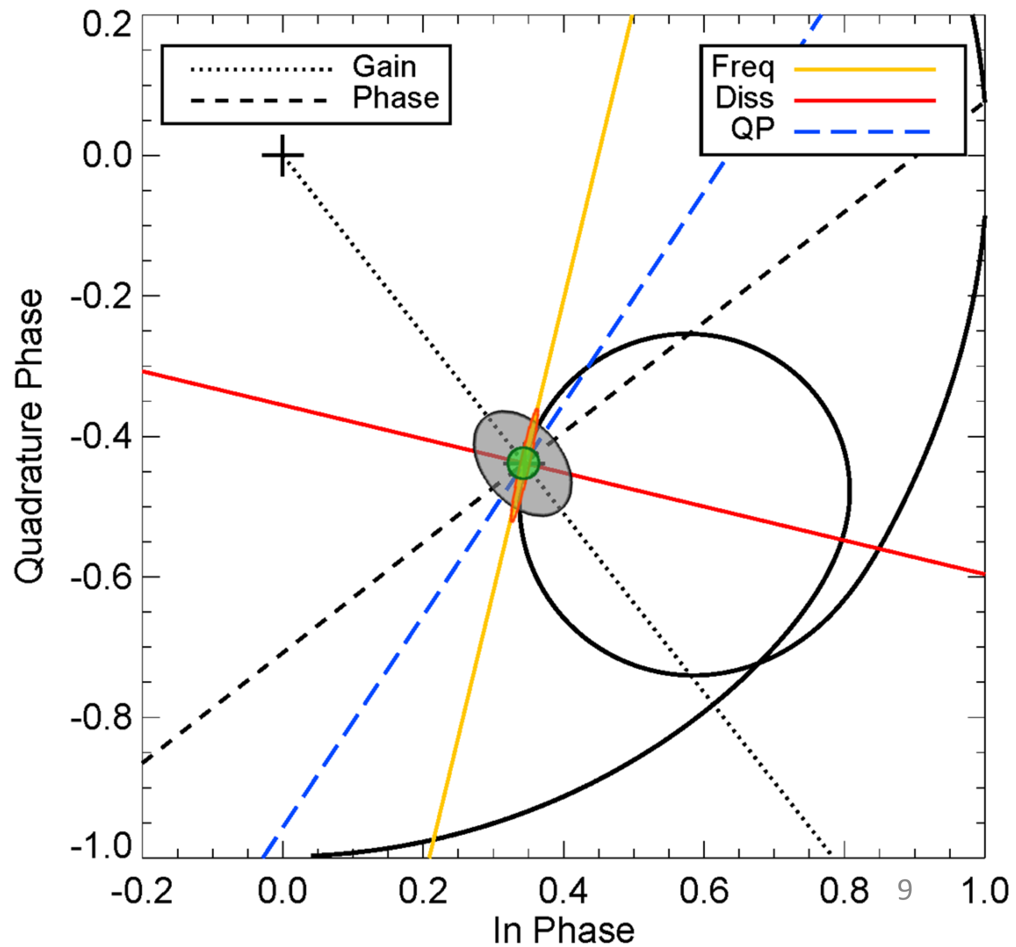
Results in fluctuations in the capacitance of the resonator

$$\delta S_{21} = -2i\,\frac{Q^2}{Q_c}\left(\frac{\delta f}{f}\right)_{\mathrm{TLS}}$$

PSD of the TLS induced frequency fluctuations predicted by a semi-empirical model. Normalization has been measured for resonators of the same geometry as those in MUSIC:

$$S_{\delta f/f}^{\mathrm{TLS}} = 2.1\times10^{-17}\left(\frac{f_{\mathrm{audio}}}{1\ \mathrm{Hz}}\right)^{-1/2}\left(\frac{P_{\mathrm{int}}}{1\ \mathrm{pW}}\right)^{-1/2}\left(\frac{T}{250\ \mathrm{mK}}\right)^{-1.7}\ \mathrm{Hz}^{-1}$$

From Noroozian et al., LTD 13 proceedings



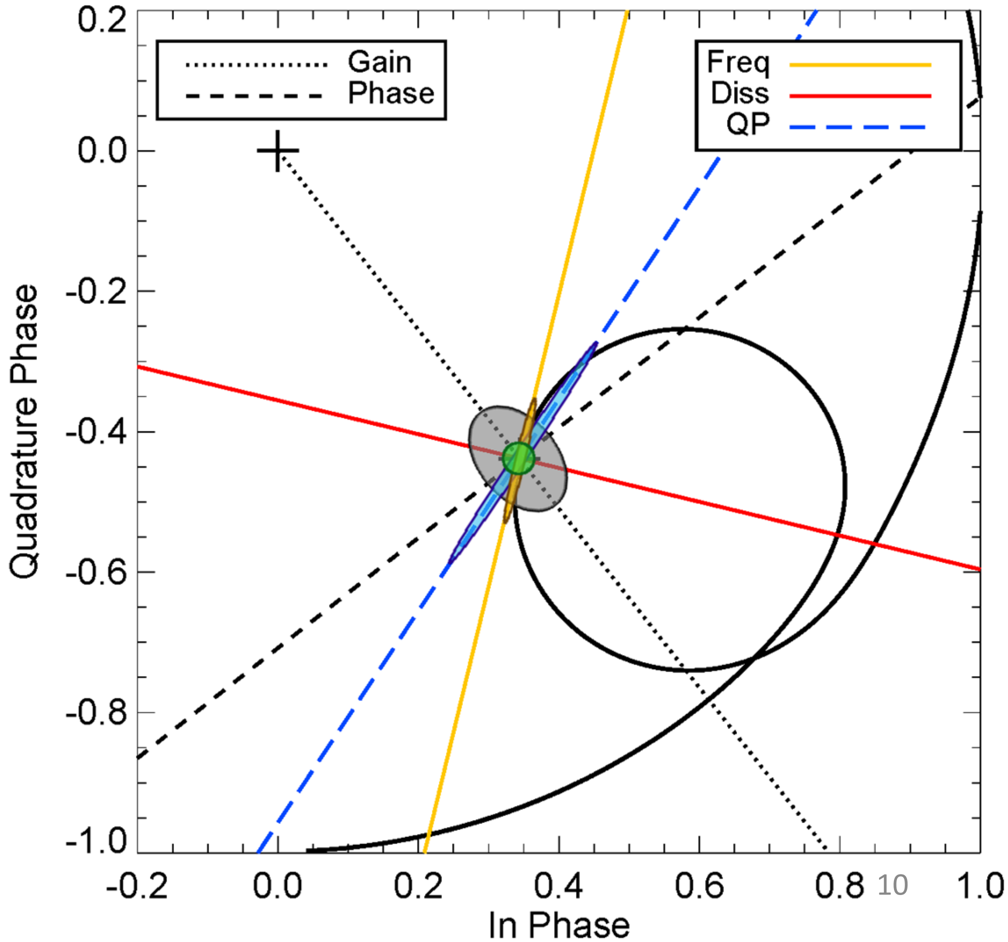
Quasi-particle Noise

$$\hat{V}(t) = Ae^{i\phi}\left[1 + \delta A + i\delta\phi + \frac{2Q^2}{|S_{21}^{\rm res}|Q_c}\left(\frac{\delta f}{f}\right)_{TLS} e^{-i(\frac{\pi}{2}+\phi_{\rm res})} + \frac{Q^2\beta}{|S_{21}^{\rm res}|Q_c}\delta n_{qp}e^{i(\Psi-\phi_{\rm res})}\right] + \delta w_{\rm hemt}$$

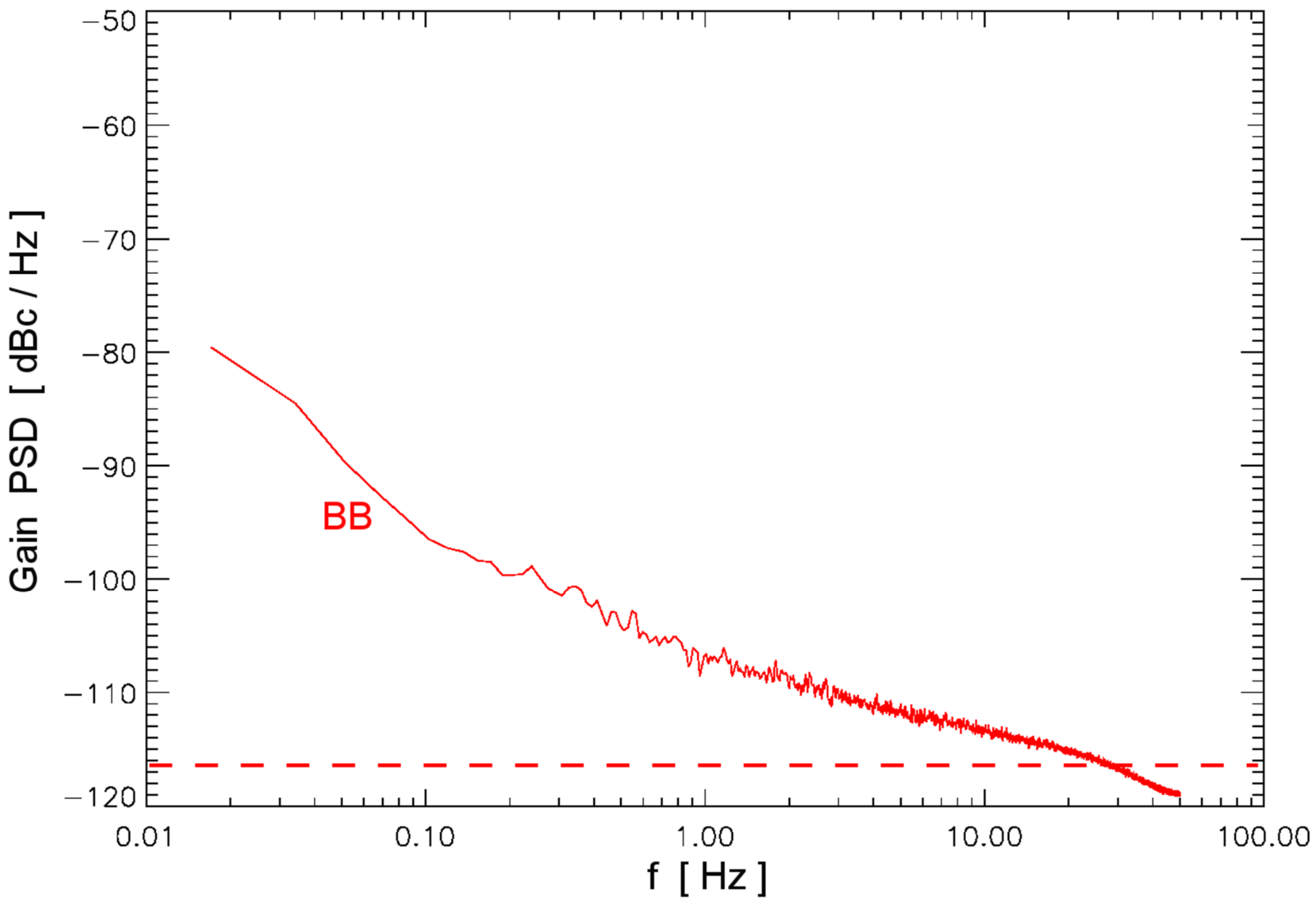
1. Fluctuations in atmospheric emission **(sky noise)**
   - Power spectral density scales as

     $$\propto f^{-8/3}$$

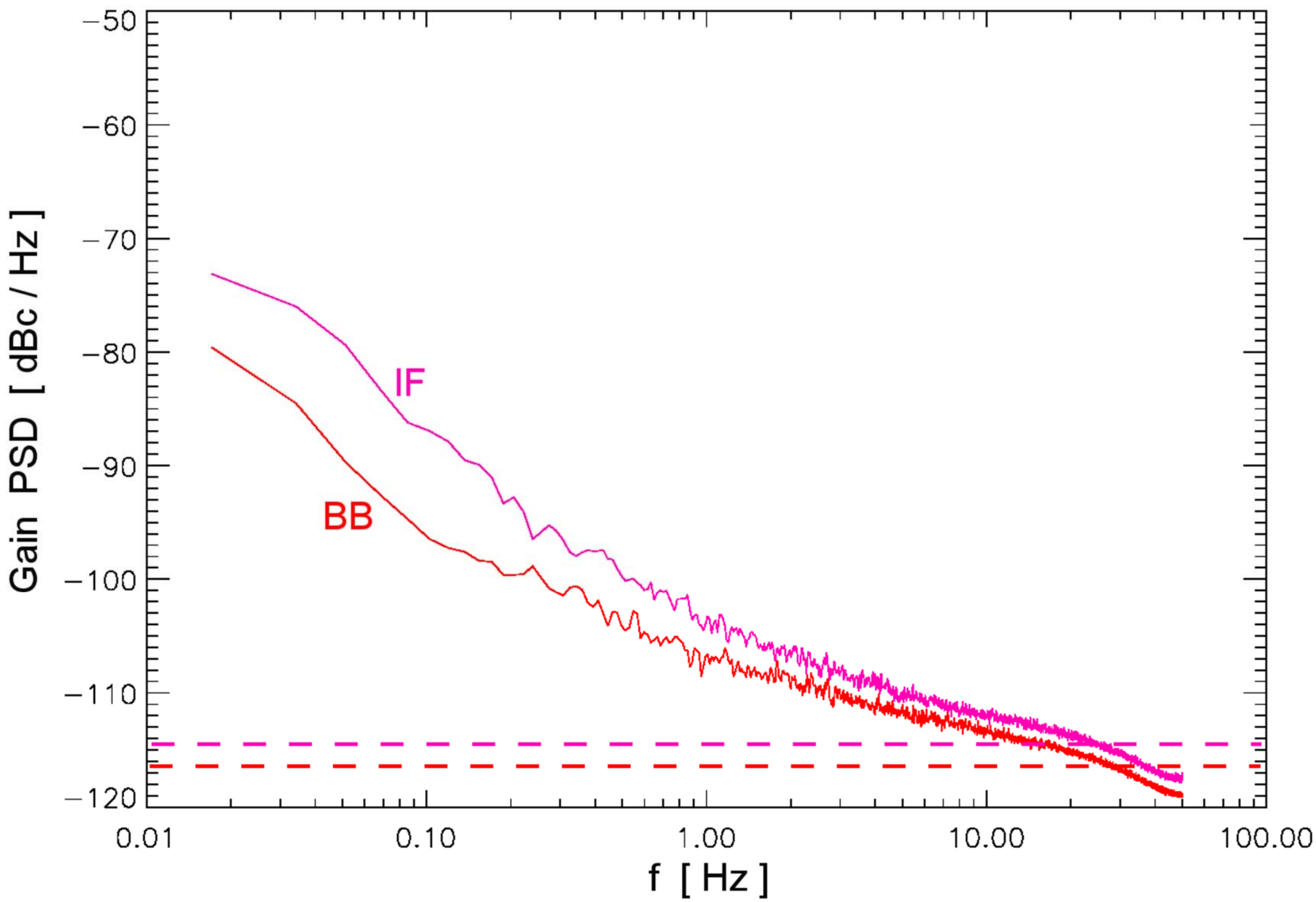
   - Correlated among detectors
   - Described in depth in *Sayers et al. 2009*
2. Photon noise (shot and Bose)
3. Thermal generation noise
4. Recombination noise



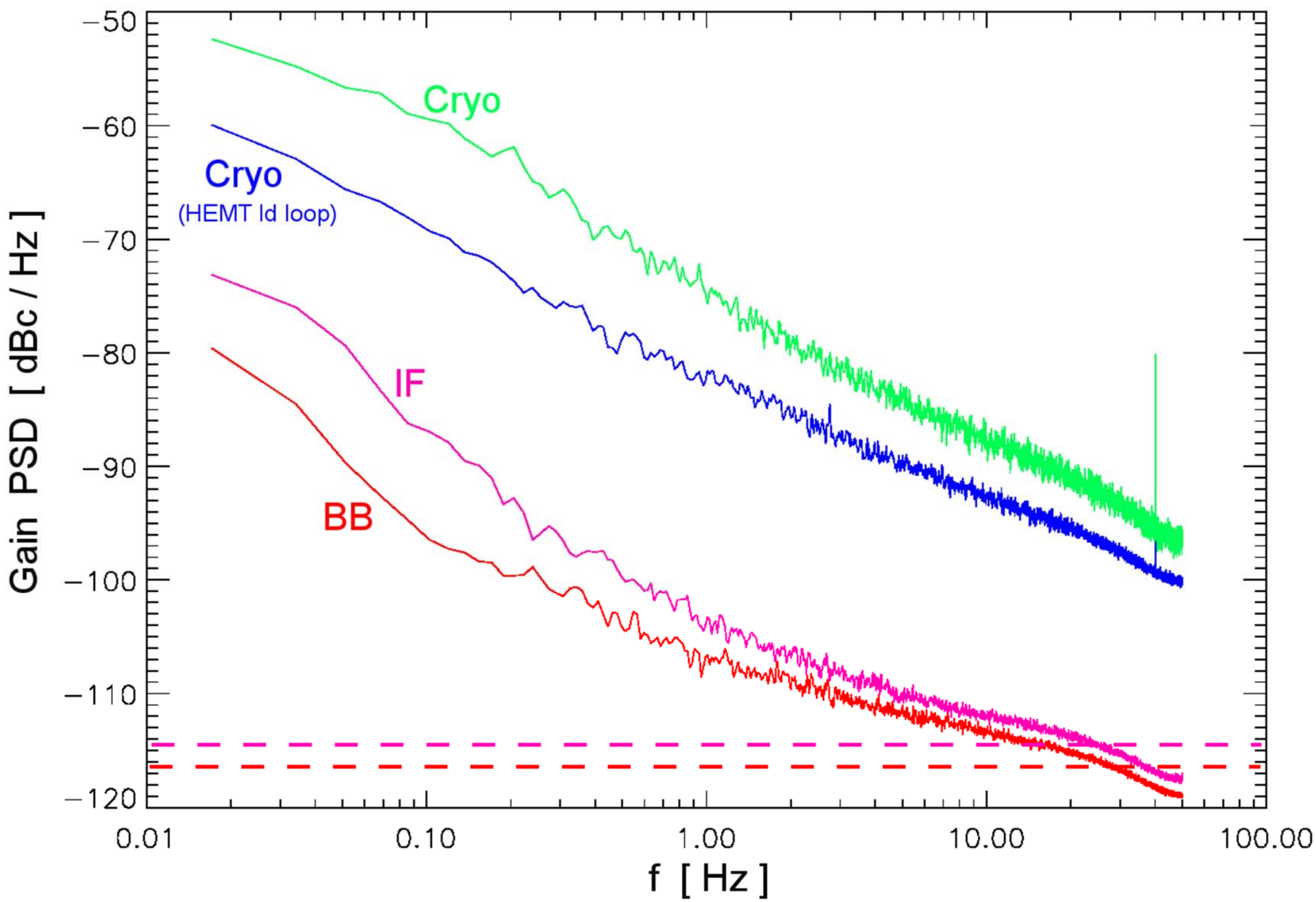
Electronics Stability - Gain Direction



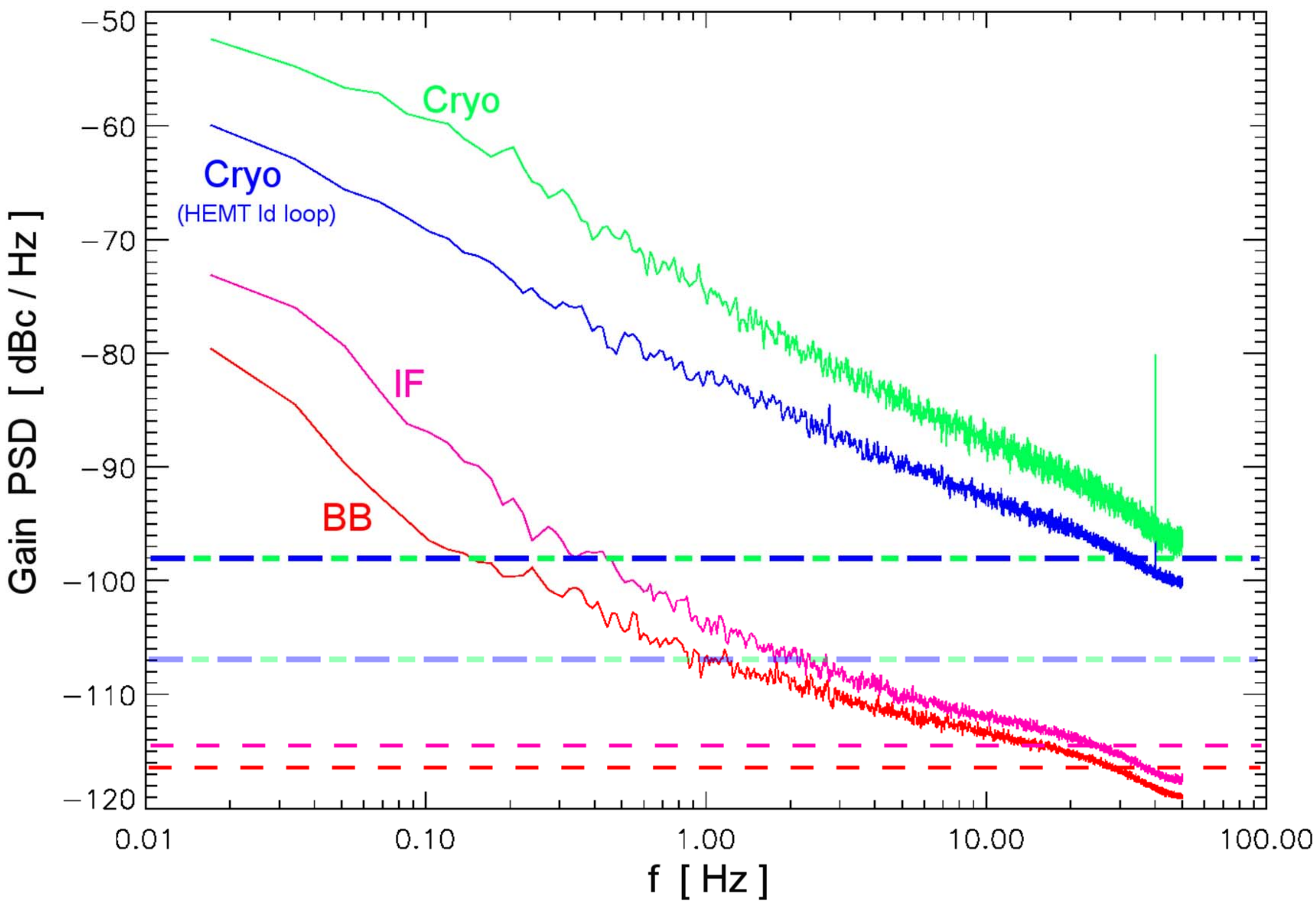
Electronics Stability - Gain Direction



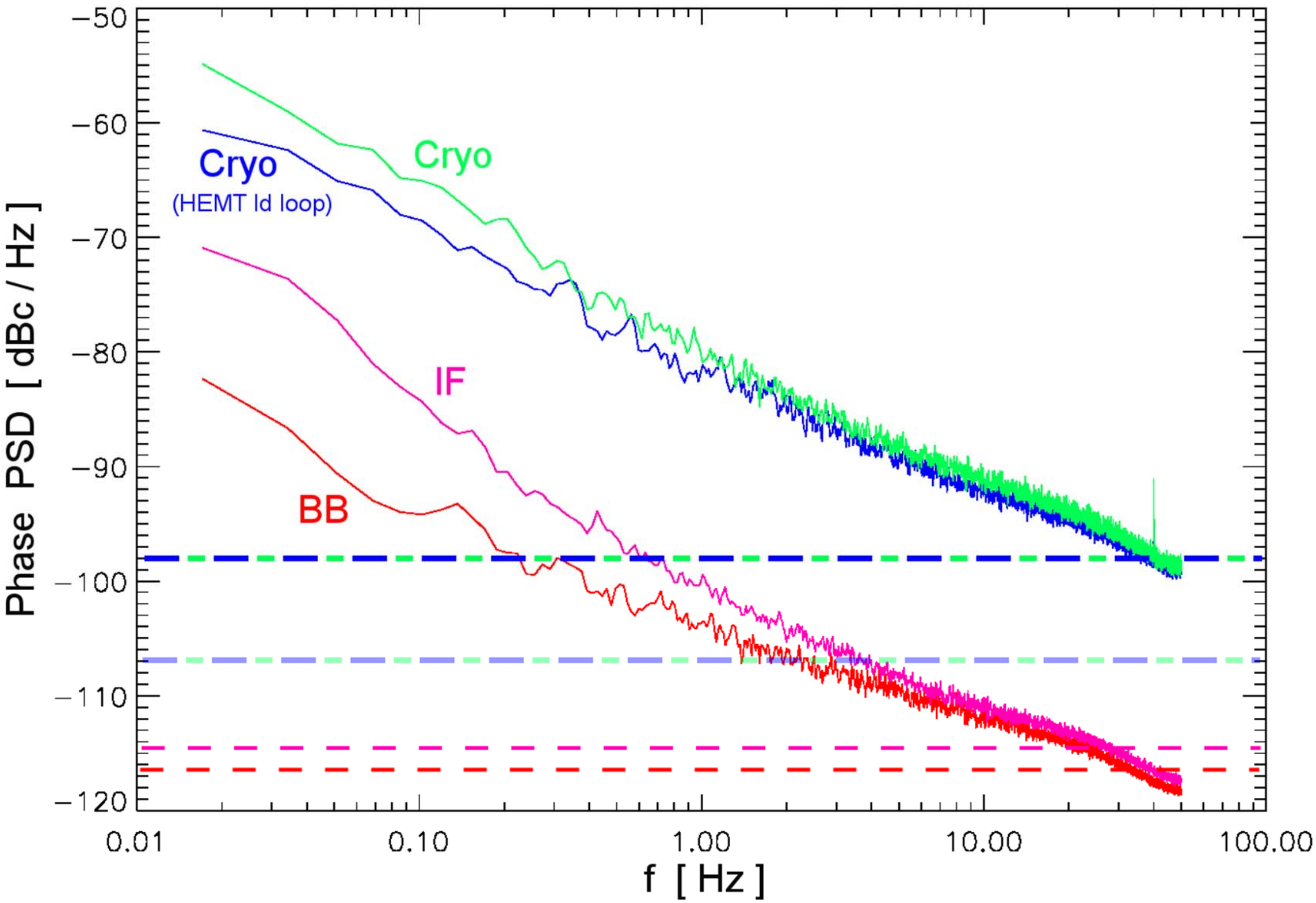
Electronics Stability - Gain Direction



Electronics Stability - Gain Direction

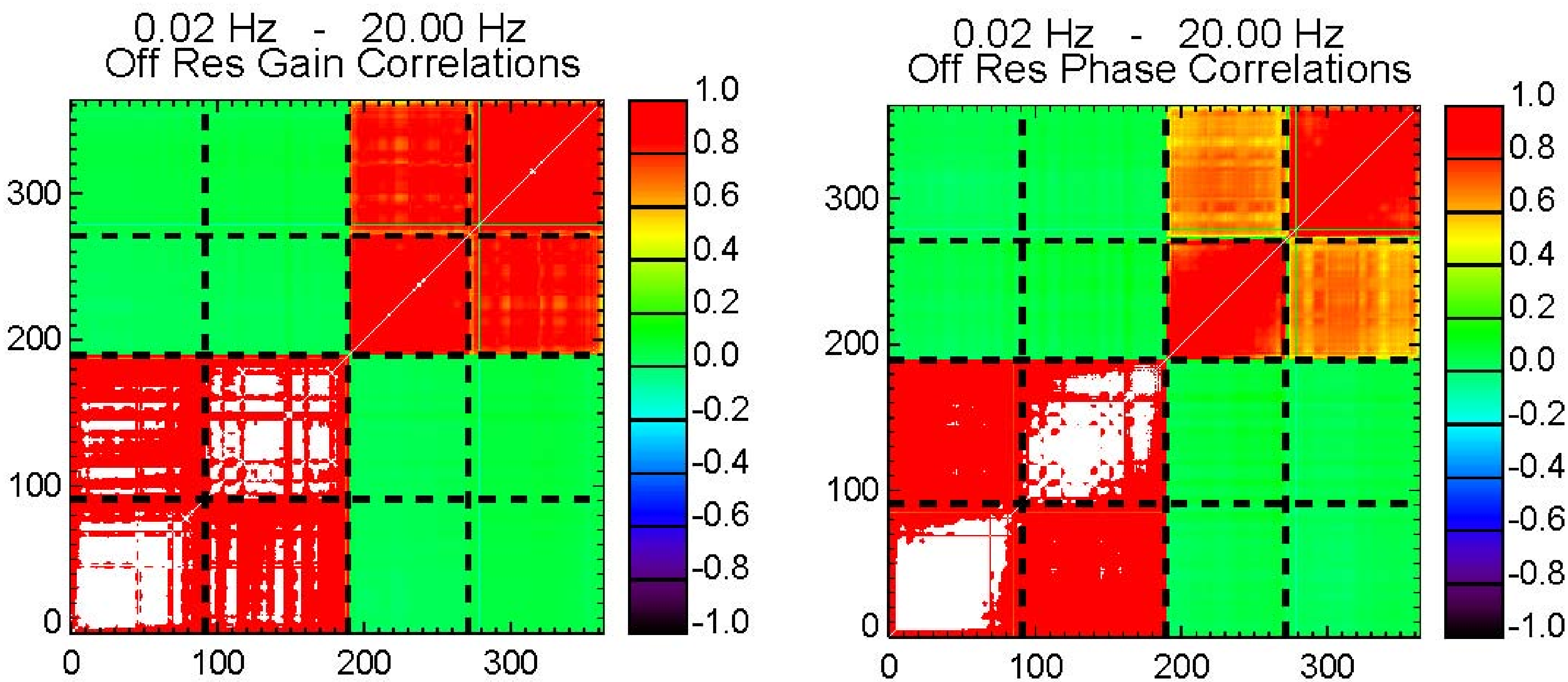


Electronics Stability - Phase Direction



Electronics Noise Removal

Pearson correlation coefficients between all off-resonance carriers:
(Black dashed lines denote the different read-out boards)



- Noise is **correlated** among the carriers and therefore **removable**. Treat the gain and phase fluctuations as a common signal and determine the least squares estimate of this signal in the presence of HEMT white noise.

Electronics Noise Removal

- Assume the following model for **carrier** i at **time** j

$$I_{ij} = A_i \left[(1 + \delta A_j) \cos\phi_i - \delta\phi_j \sin\phi_i\right] + \delta w_{\text{hemt}}$$

$$Q_{ij} = A_i \left[(1 + \delta A_j) \sin\phi_i + \delta\phi_j \cos\phi_i\right] + \delta w_{\text{hemt}}$$

- Iteratively re-calculate the OLS estimate of the templates

$$\boldsymbol{\delta A} \qquad \boldsymbol{\delta\phi}$$

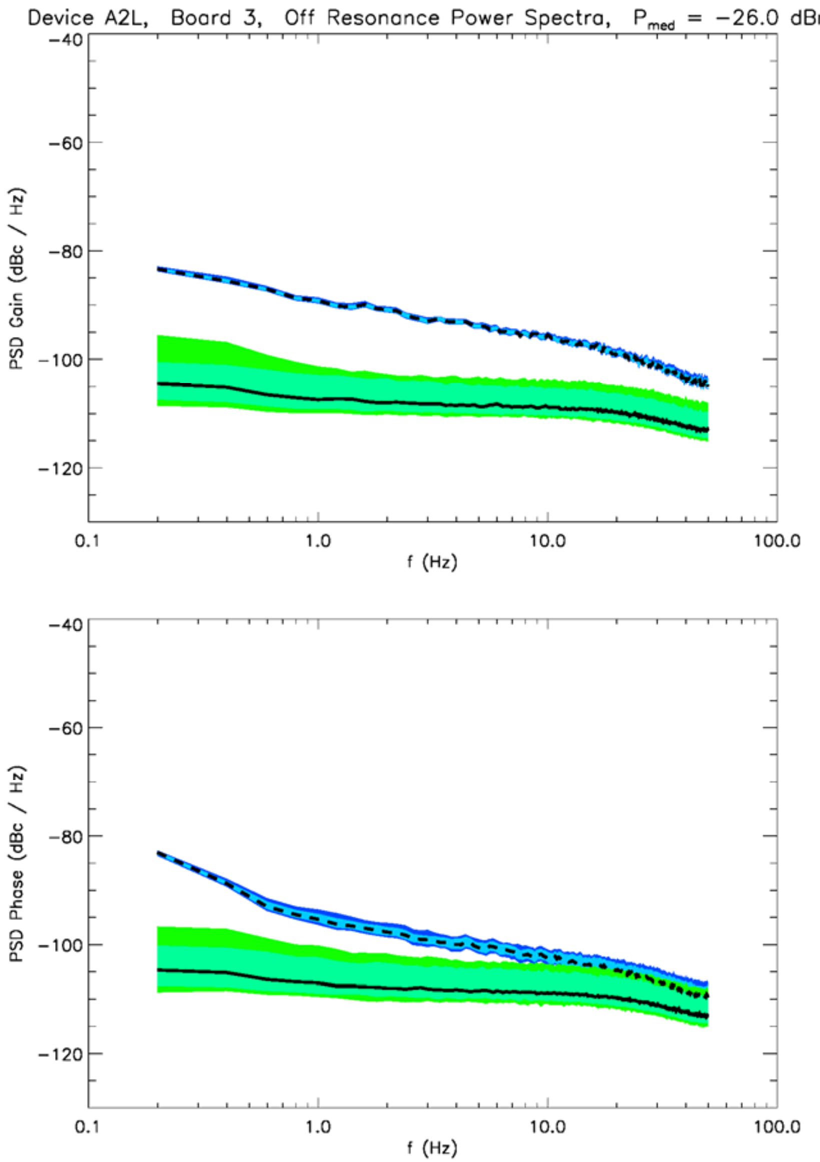
and then the coefficients

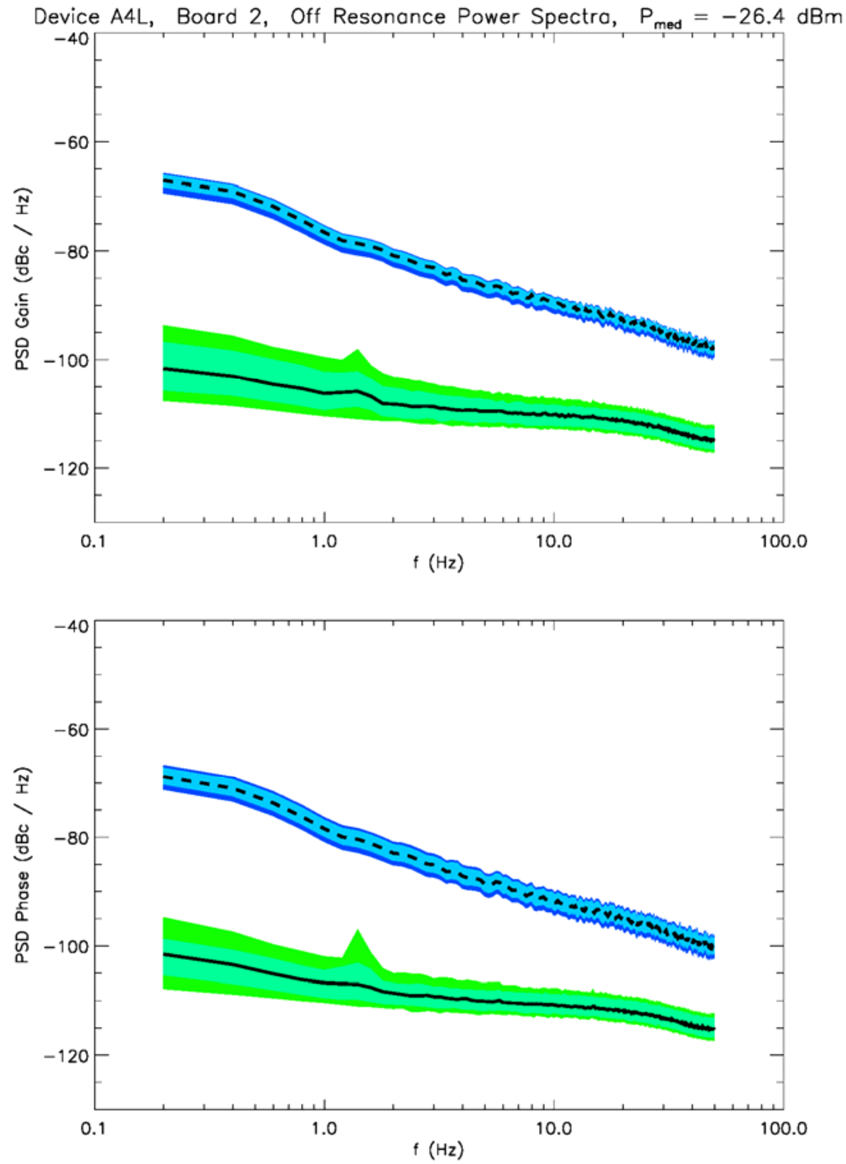
$$\boldsymbol{A} \qquad \boldsymbol{\phi}$$

- May allow templates that are dependent on carrier frequency

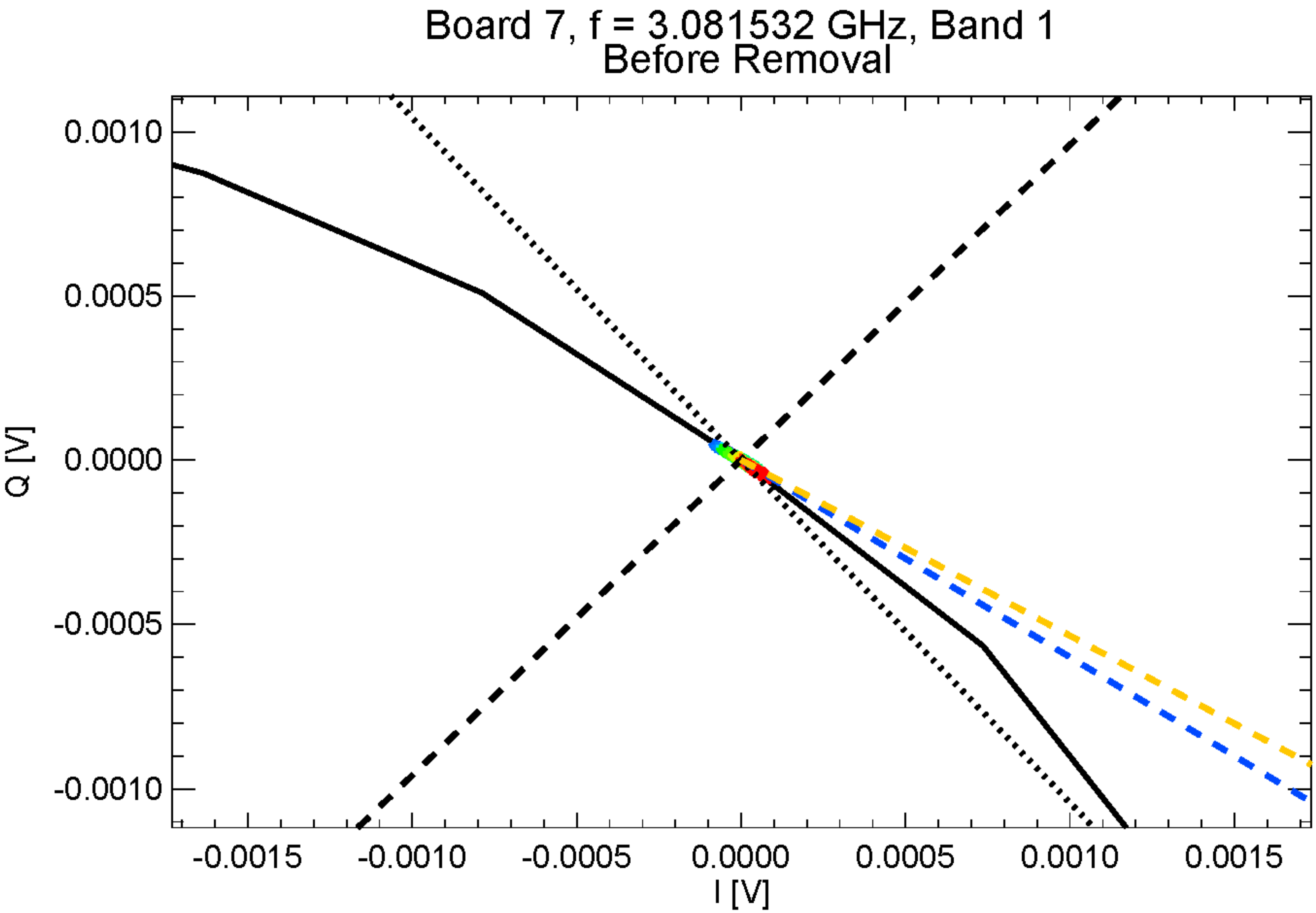
$$\delta\phi_j(\omega_i) \equiv \delta\phi_j + \omega_i \delta\tau_j$$

Electronics Noise Removal (Off-Resonance)

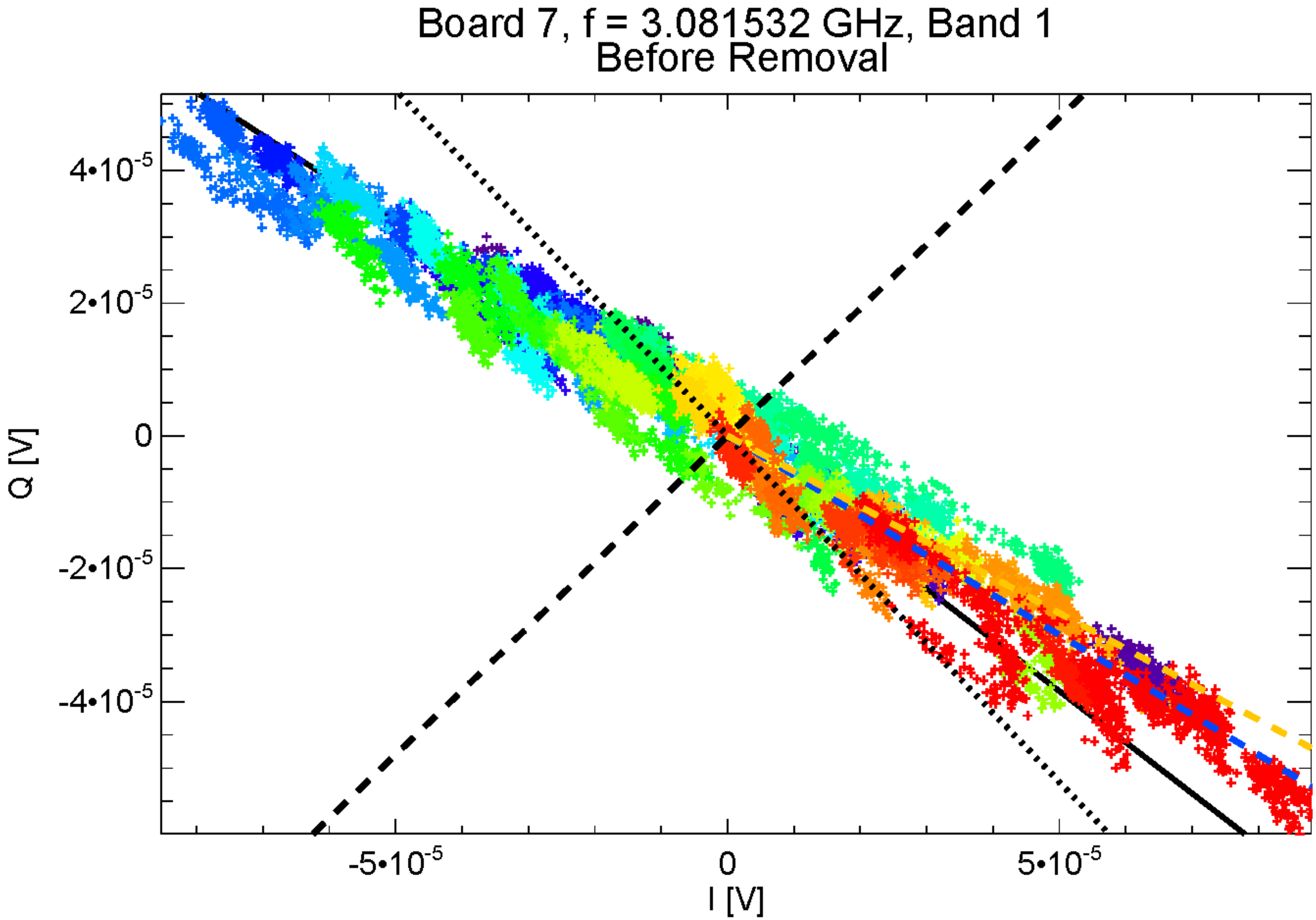




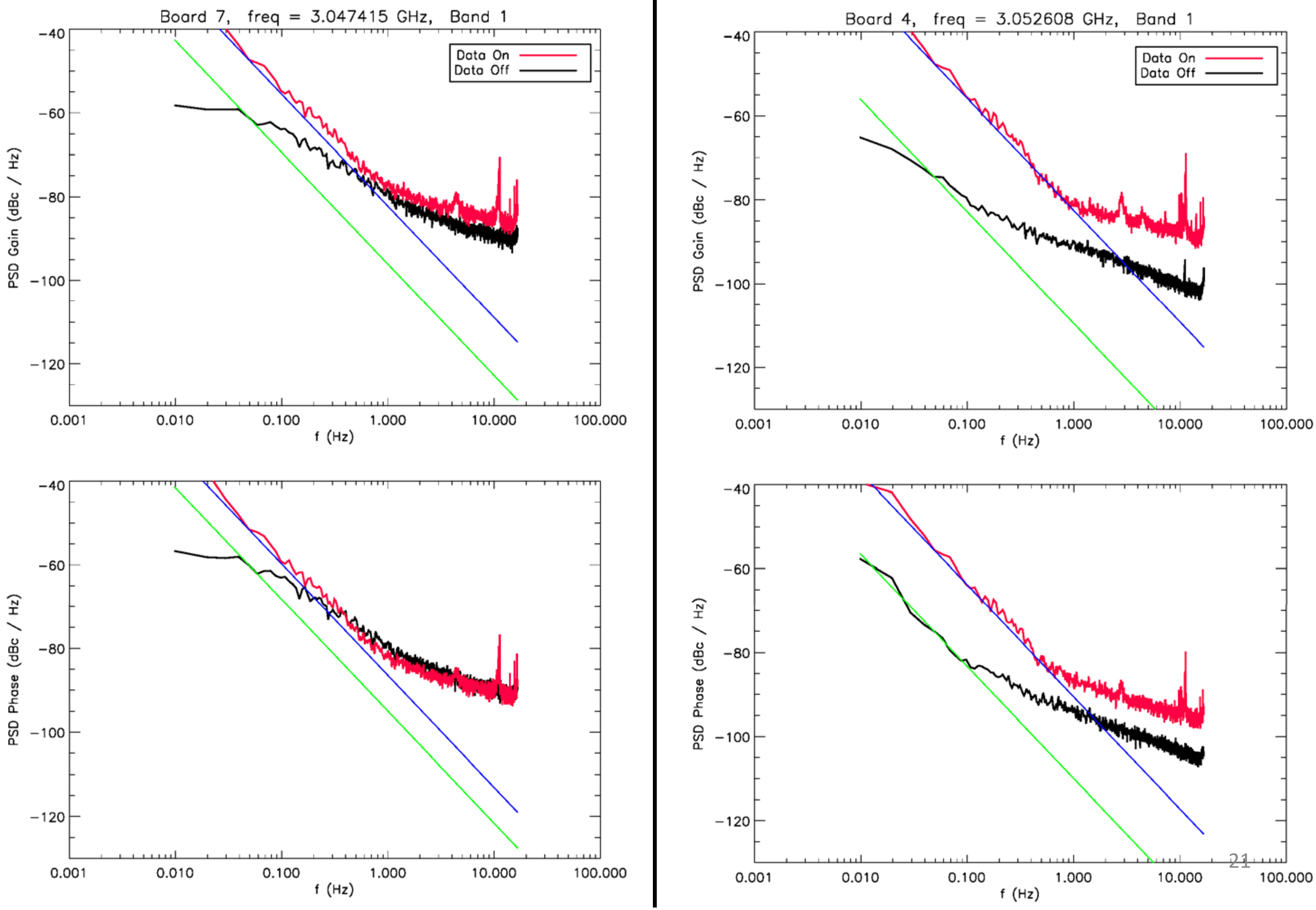
Measured On-Resonance Noise



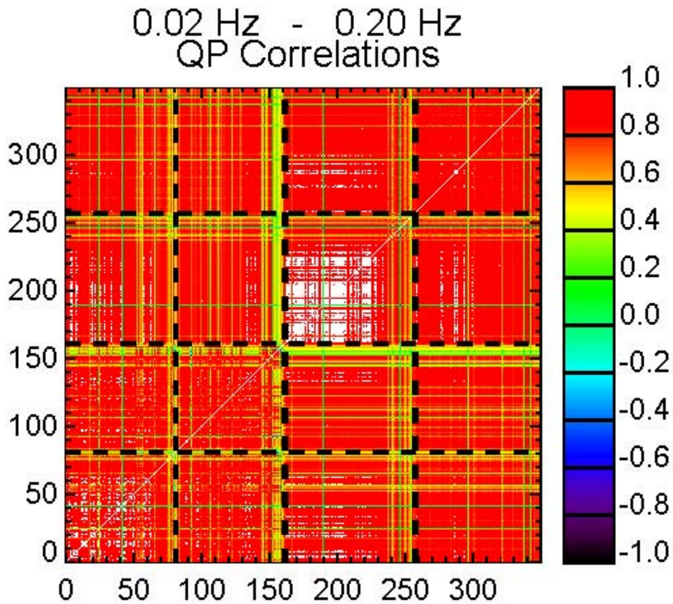
Measured On-Resonance Noise

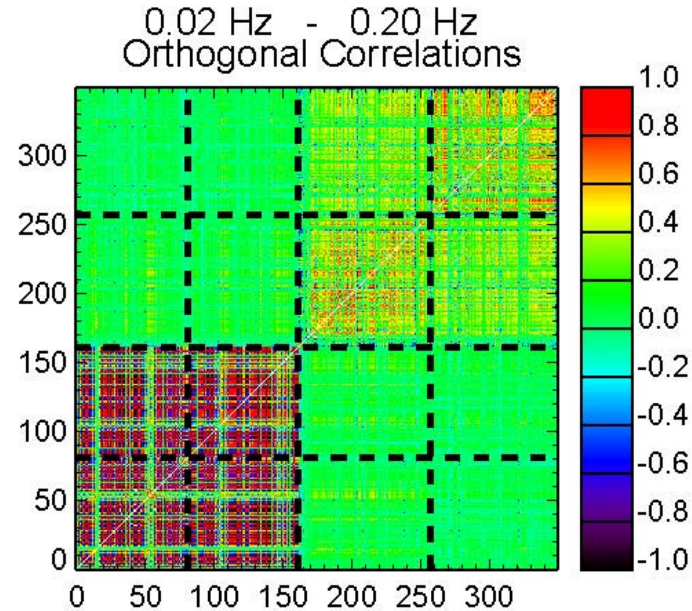


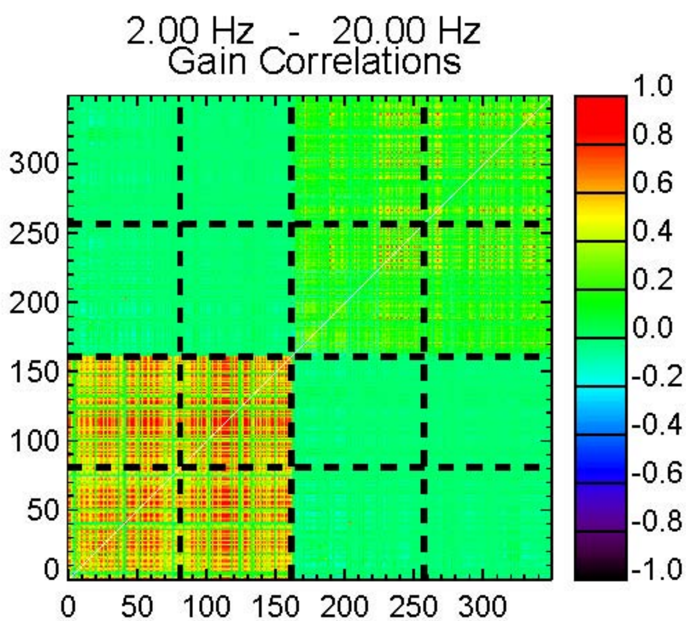
Measured On-Resonance Noise

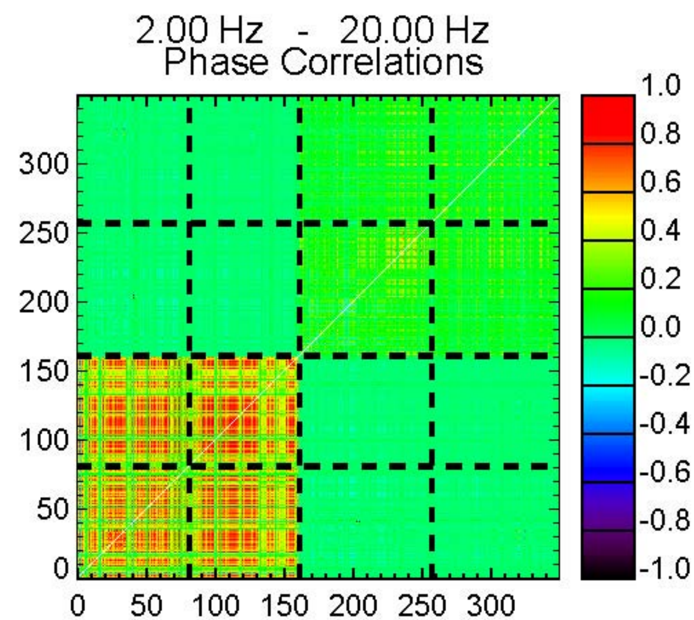


On-Resonance Correlations









Removal

- Determine the quasi-particle direction for each resonator by diagonalizing $CPSD_{IQ}$ at frequencies **10 – 100 mHz**.

- Create a template for the sky noise by averaging the timestreams of resonators of a given band (in the quasi-particle direction). Iteratively recalculate the coefficients that scale this template to the individual resonators using frequencies **10 – 100 mHz**.

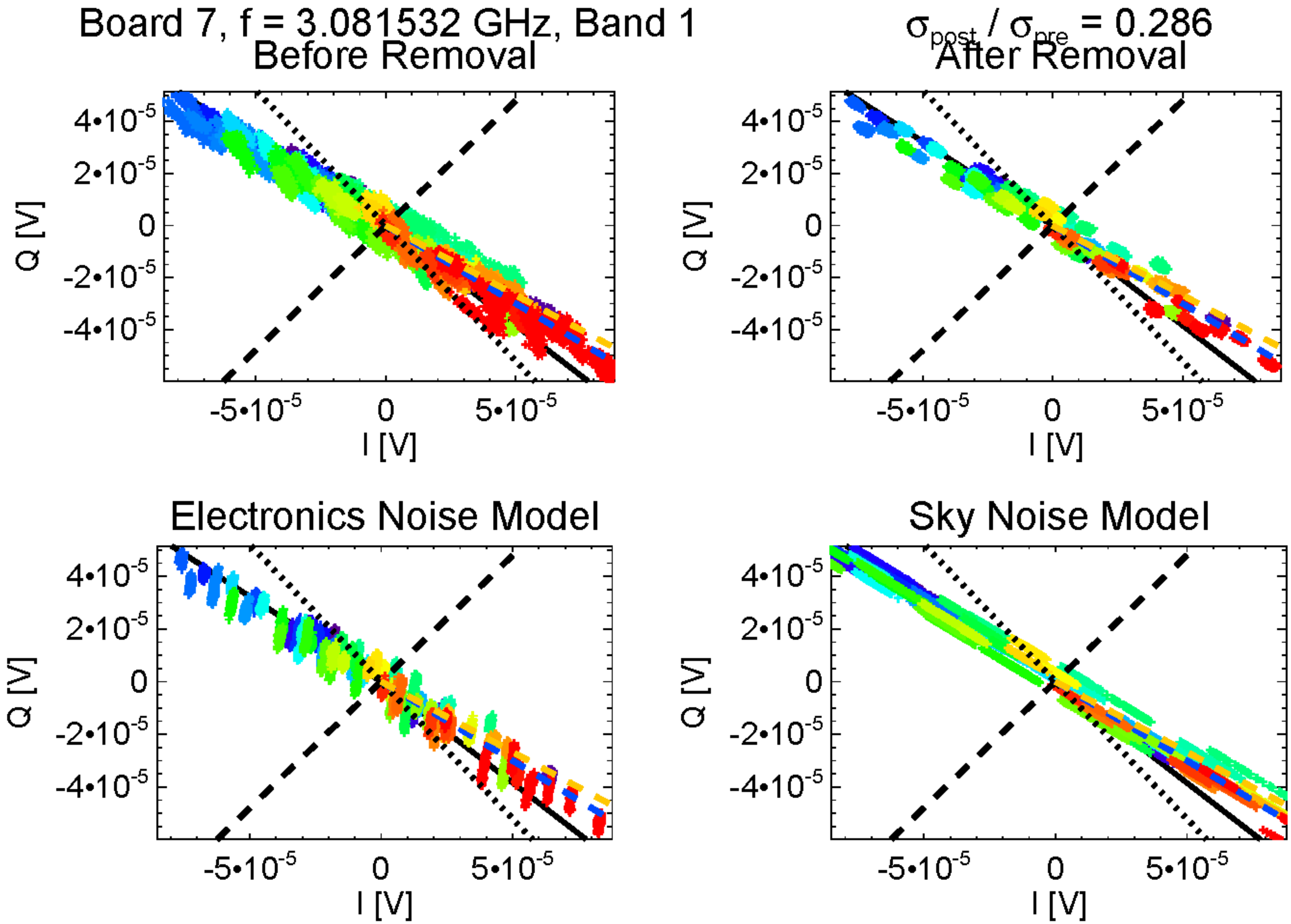
- Subtract the sky noise template.

- Create a template of the electronics gain and phase fluctuations (as a function of microwave frequency) using the off-resonance data. **This is done separately for each scan.**

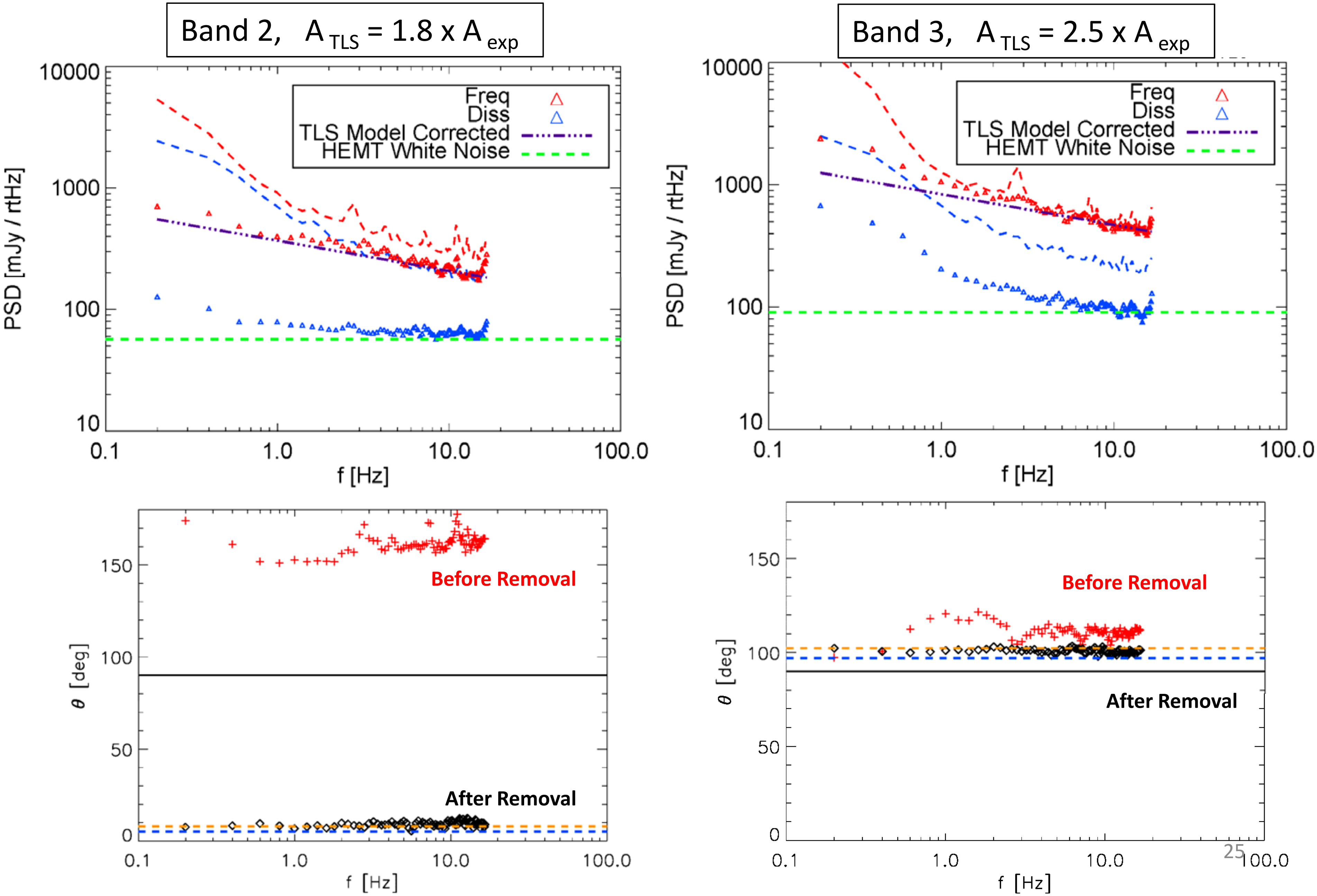
- Calculate the coefficients that scale the electronics template to each resonator using frequencies **2.0 – 16.667 Hz**, avoiding spectral lines.

- Subtract the gain and phase electronics template.

Removal


Board 7, f = 3.081532 GHz, Band 1
Before Removal
σpost / σpre = 0.286
After Removal
Electronics Noise Model
Sky Noise Model
Q [V]
I [V]
4•10-5
2•10-5
0
-2•10-5
-4•10-5
-5•10-5
5•10-5

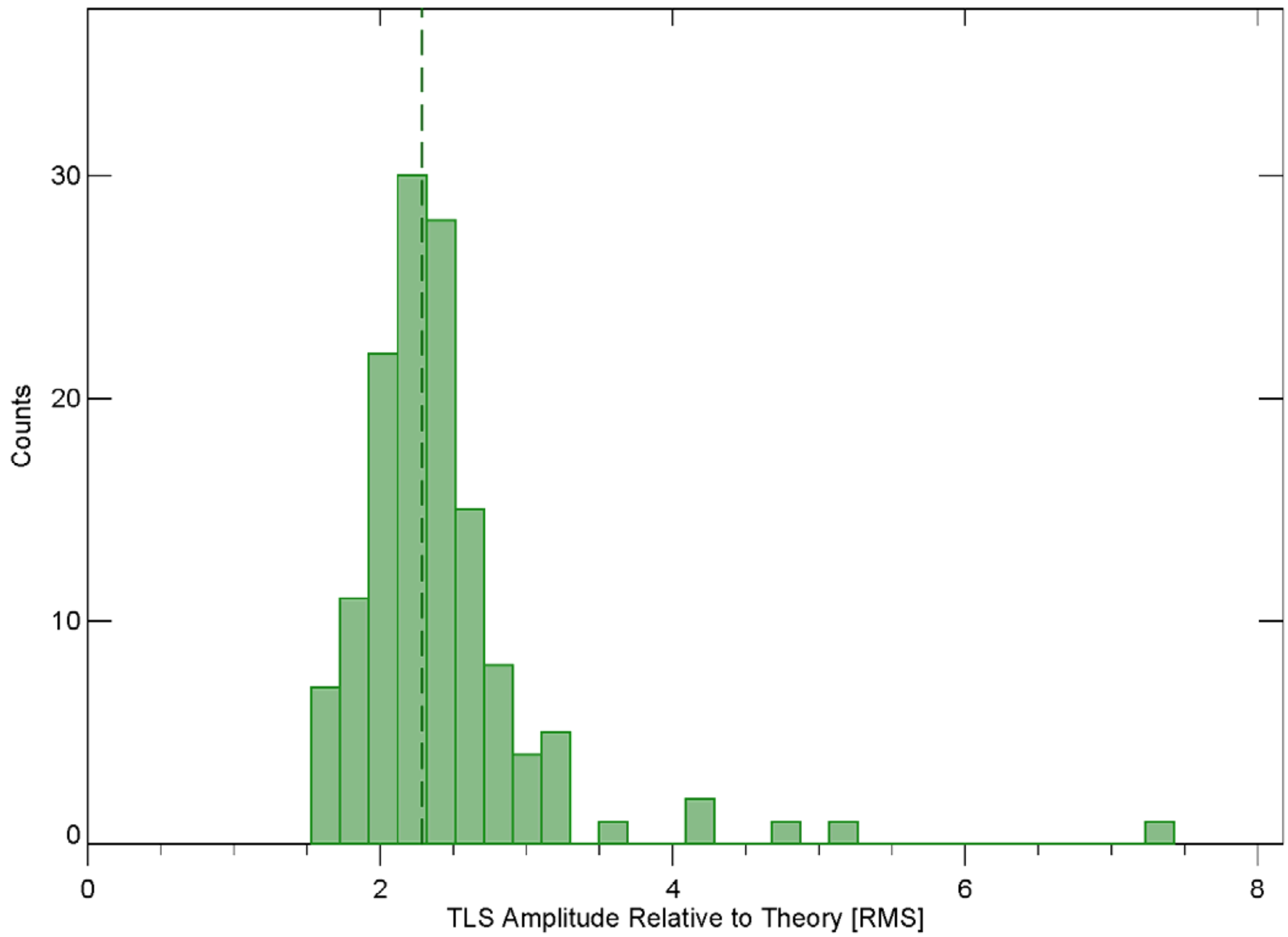
Removal



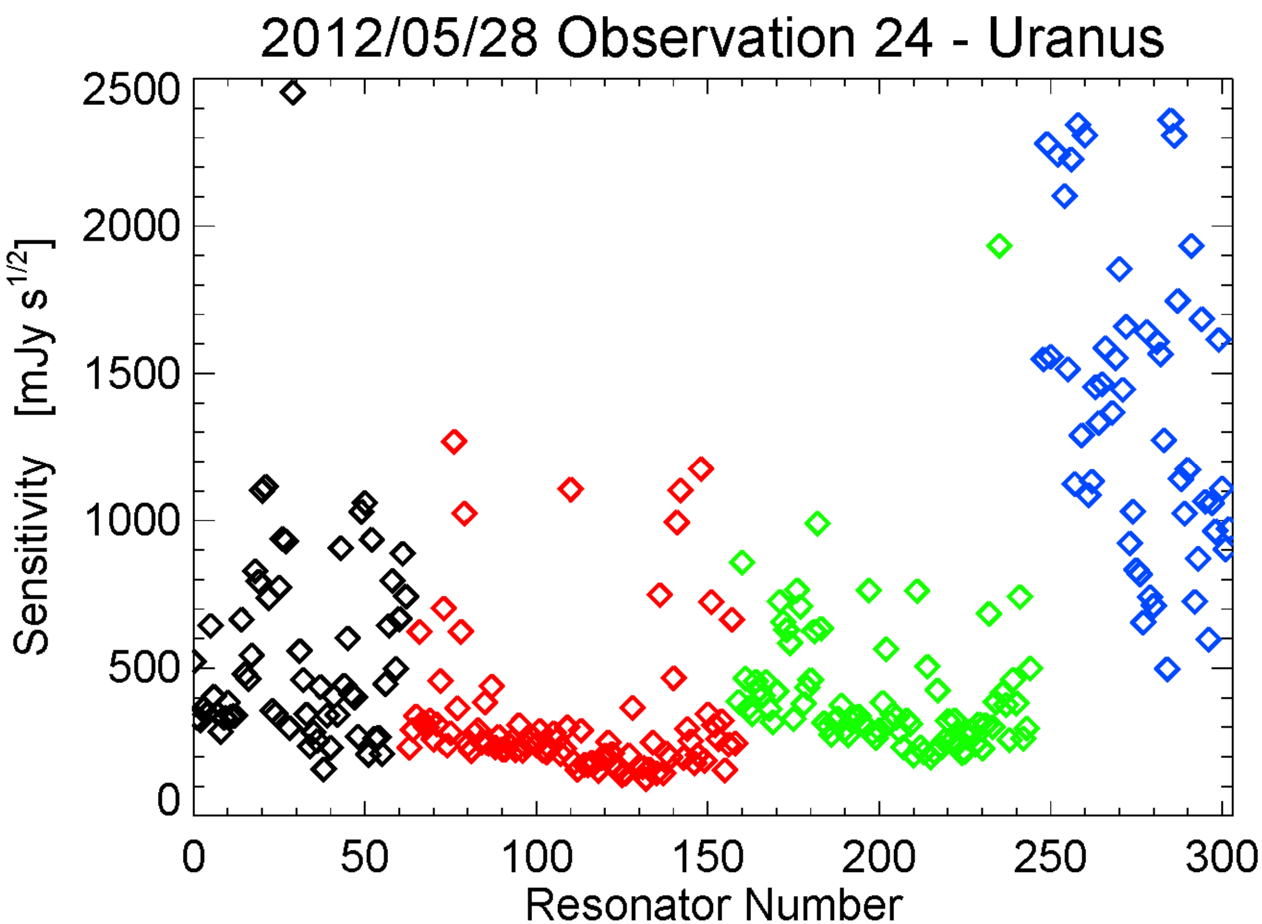
Band 2, A_{TLS} = 1.8 x A_{exp}
Band 3, A_{TLS} = 2.5 x A_{exp}
Freq
Diss
TLS Model Corrected
HEMT White Noise
PSD [mJy / rtHz]
10000
1000
100
10
0.1
1.0
10.0
100.0
f [Hz]
Before Removal
After Removal
θ [deg]
150
100
50
0

Measured TLS

- Measure larger TLS than expected: x 2.25 in RMS
- Histogram below produced using resonators whose residual noise has its major component aligned with frequency direction, and has an approximately f $^{-1/2}$ power spectra between 5.0 -16.667 Hz



Measured Sensitivities



150 GHz	442 mJy $s^{1/2}$
230 GHz	248 mJy $s^{1/2}$
290 GHz	333 mJy $s^{1/2}$
350 GHz	1465 mJy $s^{1/2}$

- Getting down to 150-200 mJy $s^{1/2}$ for some resonators in the 230 and 290 GHz bands
- Flux calibration consistent between observations to 5-10%.

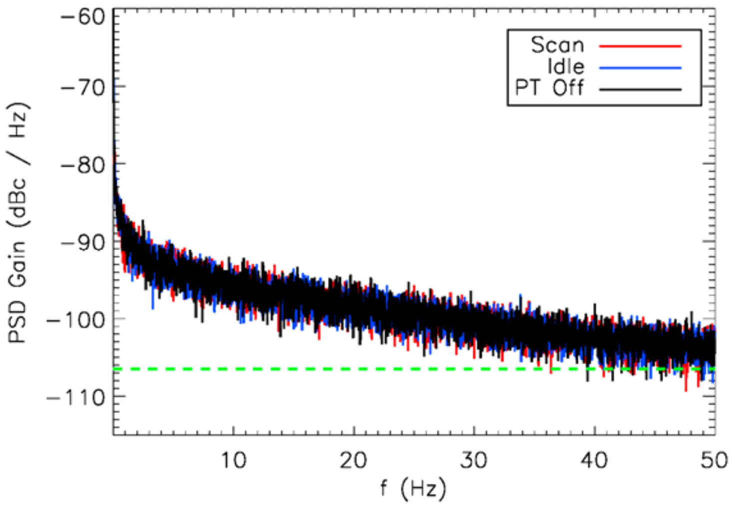
Additional Slides

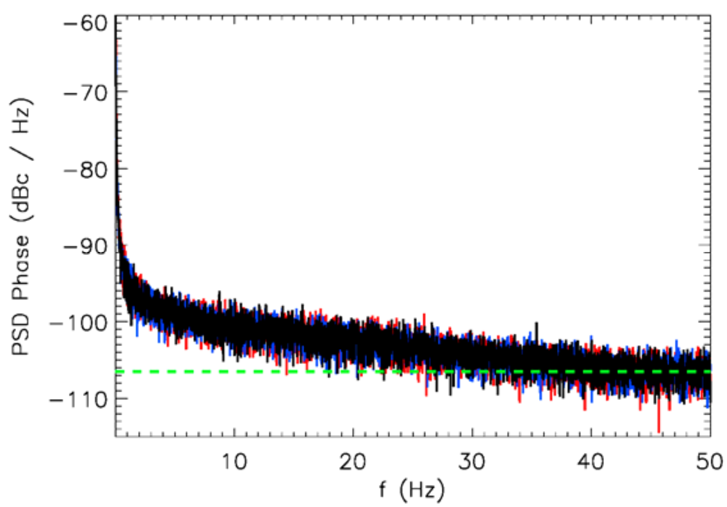
Spectral Lines

Collected noise data with:

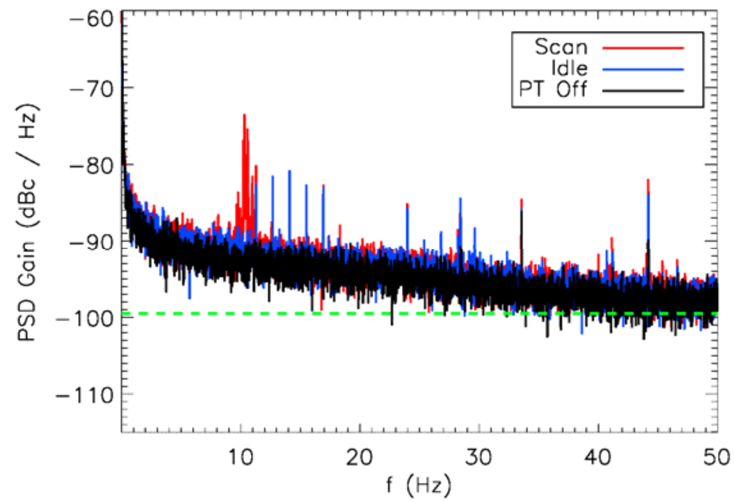
1. Telescope doing AZ raster scans
2. Telescope idle
3. Telescope idle with pulse tube off

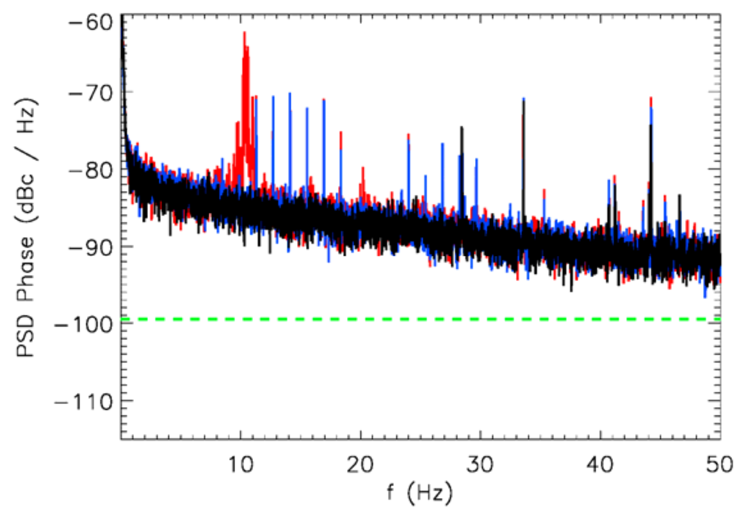
Off Resonance





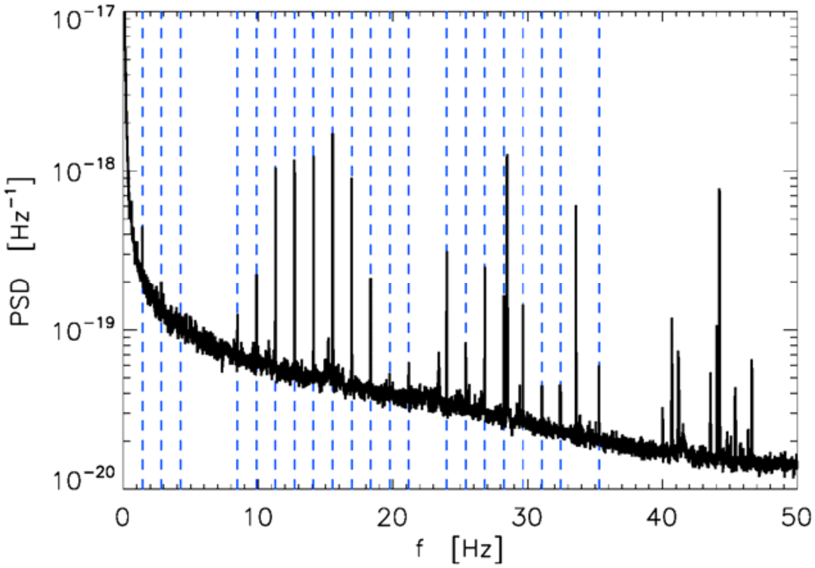
On Resonance

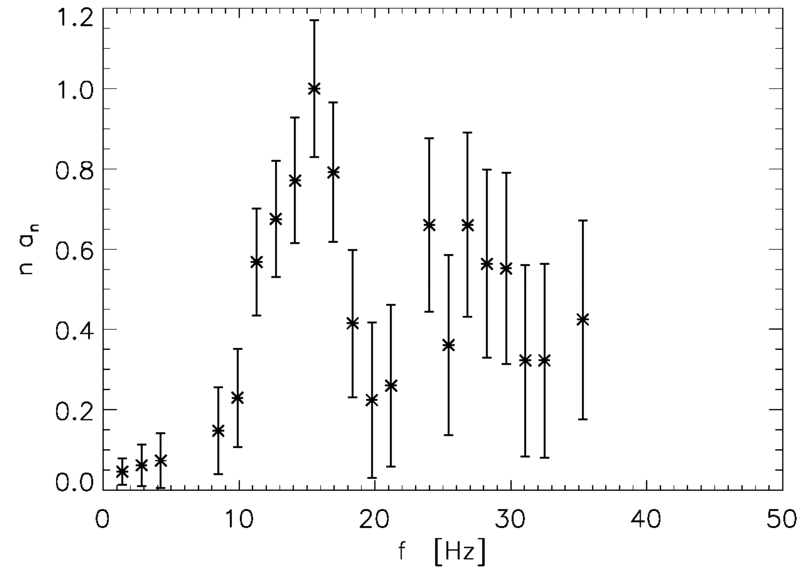




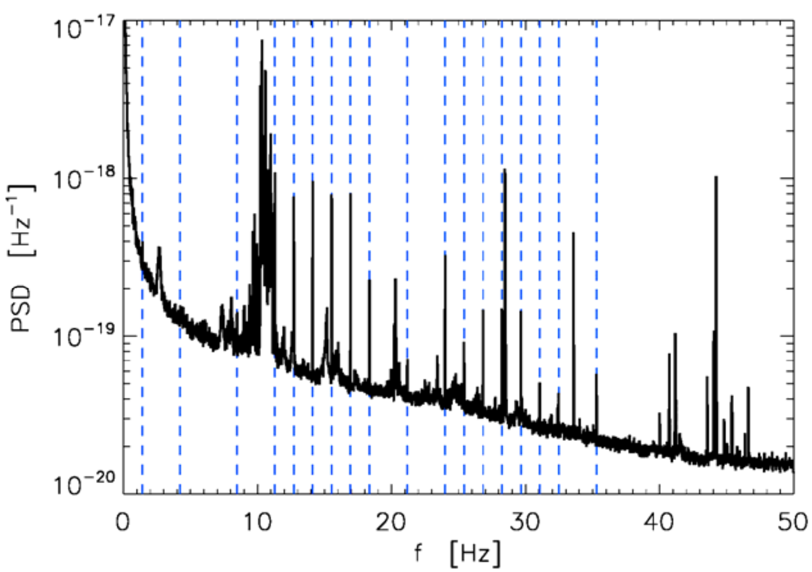
Spectral Lines

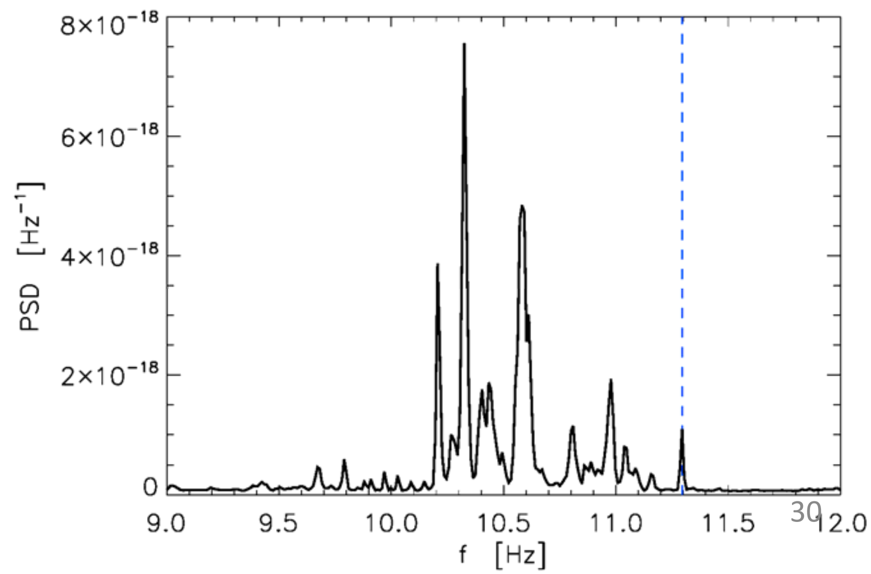
Telescope idle, pulse tube on -- pulse tube frequency $f_{\rm pt} = 1.41\ {\rm Hz}$





Telescope AZ raster, pulse tube on





Spectral Lines

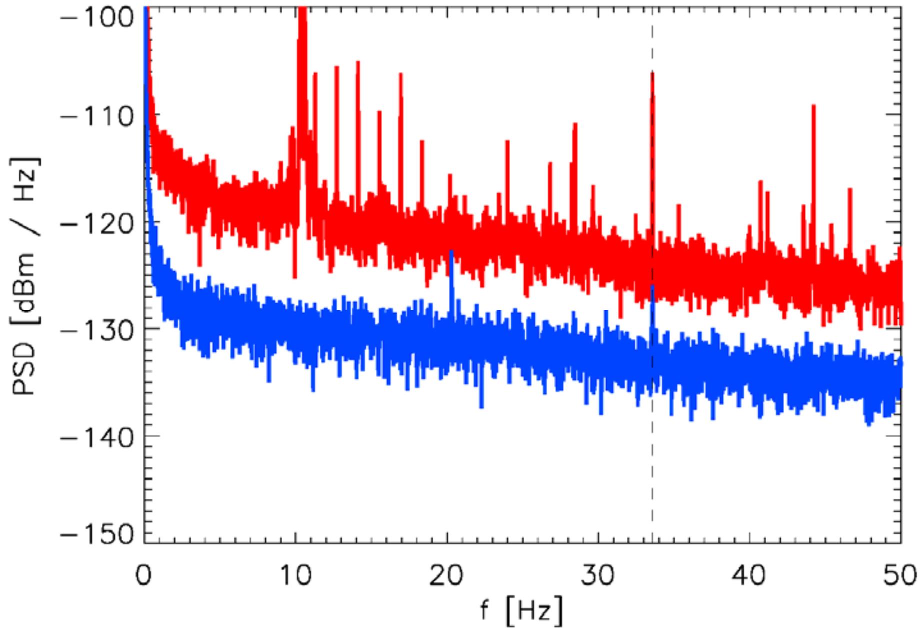
Both the pulse tube lines and the peak at 10 Hz appear in a common direction in the complex plane.

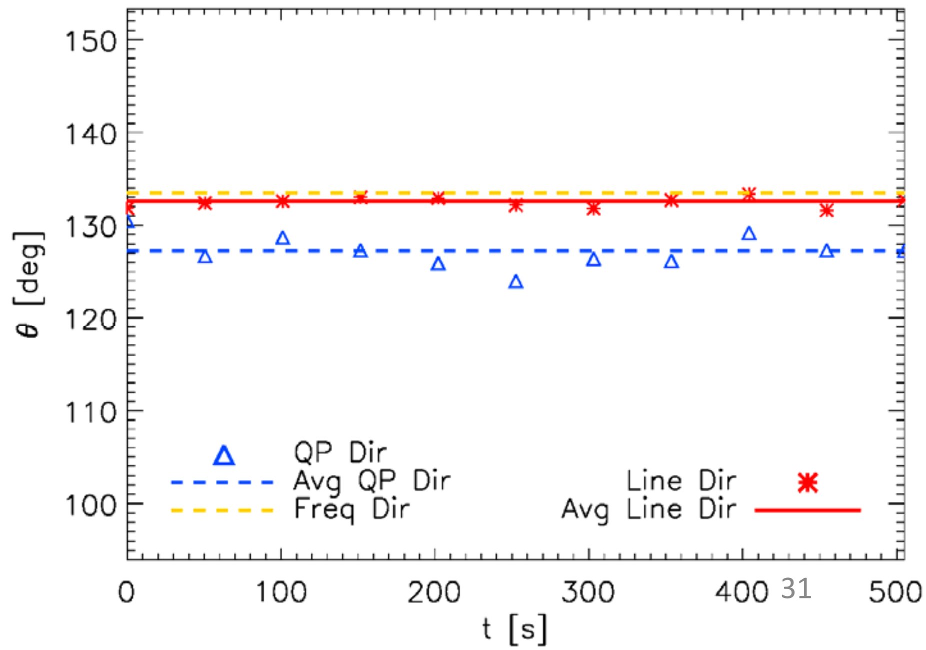
Most mechanisms by which the pulse tube cooler might influence the resonators are either thermal or optical in nature

- Temperature of filter stack could fluctuate at f_{pt} changing resonator loading
- Mechanical vibrations in the cryostat could produce thermal fluctuations in the UC stage and change resonator bath temperature

Both thermal and optical mechanisms would place the spectral lines in the **quasi-particle direction**. We calibrate this direction with a Black body source chopped at 33.58 Hz (black dashed line). We find evidence that the spectral features instead occur in the **frequency direction**.

- **Could the cause be magnetic?** Previous work showed that MKIDs sensitive to magnetic field in the direction perpendicular to the plane of the array, and that a changing magnetic field produces response in the frequency direction. *See Czakon et al., LTD13 proceedings.*





Quasi-Particle Angle