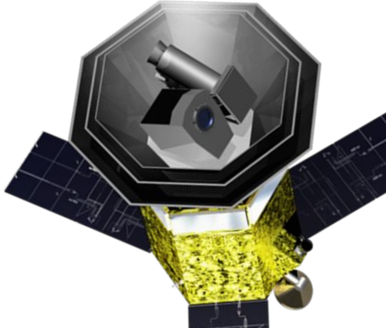
Setting Instrumental Requirements for the gain calibration of LiteBIRD

Alessandro Novelli

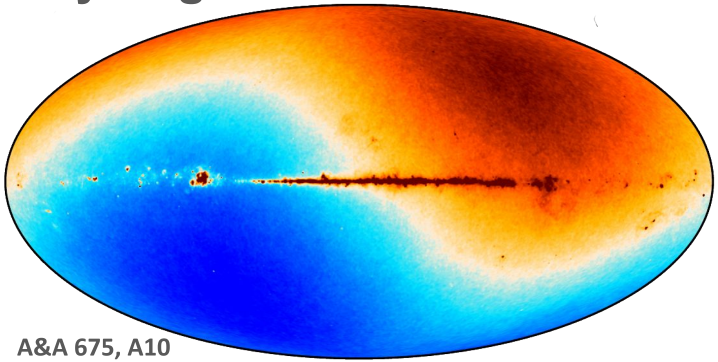
CMB-CAL @ Univ. Bicocca, 04/11/2024



What is gain calibration?

Consists in finding the conversion factor between sky-brightness and detector output

Sky brightness

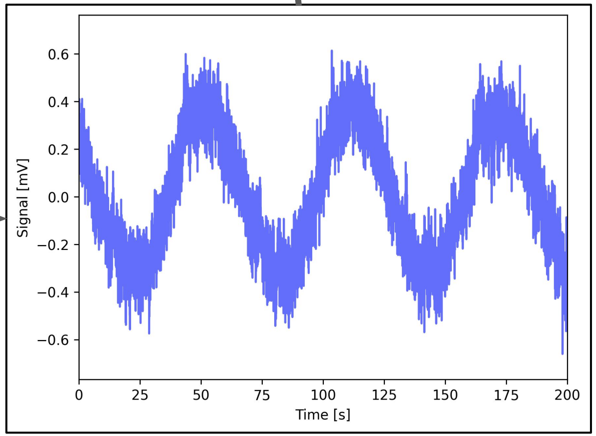


A&A 675, A10

g

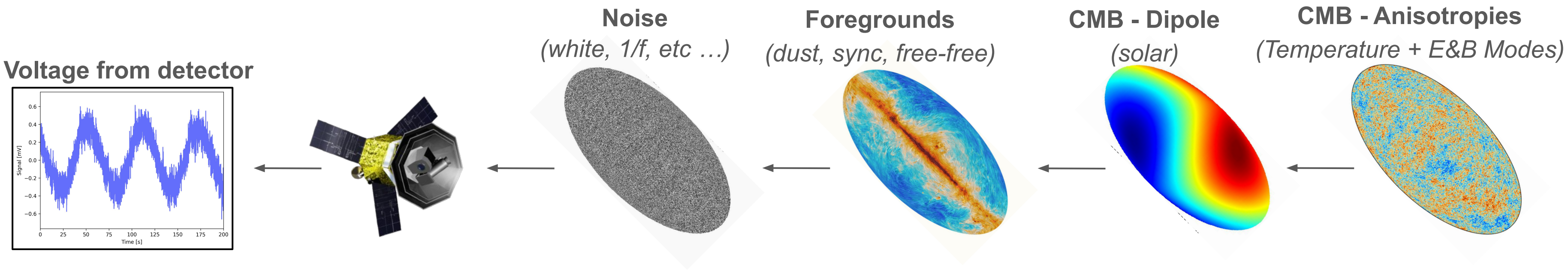
g^{-1}

Current from detector



How is it performed?

- To find ***g*** one usually compares the output signal with an expected **reference signal** (usually the CMB dipole)
- This, however, is usually mixed in with many other sources



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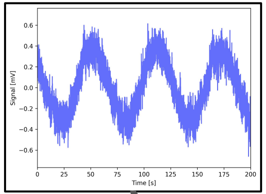
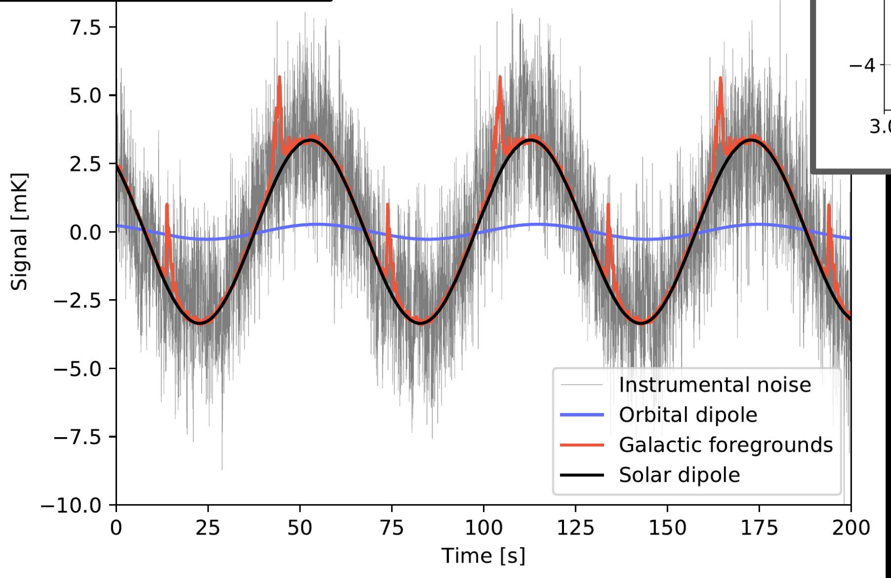
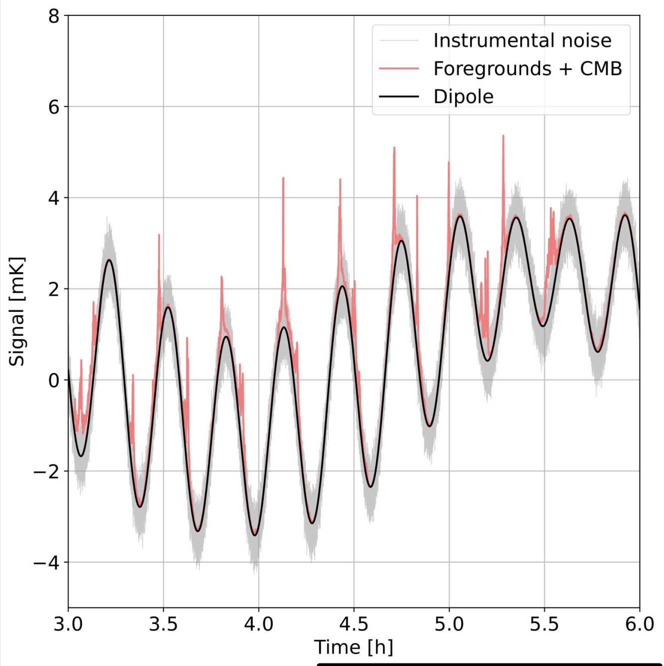
Voltage from detector



Planck:
(E. Gjerløw, A&A 675, A7)

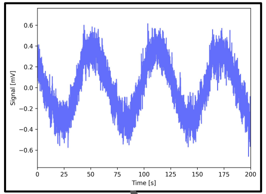




LiteBIRD:
(litebird_sim)

What level of noise can we accept and still calibrate with sufficient precision?

Voltage from detector



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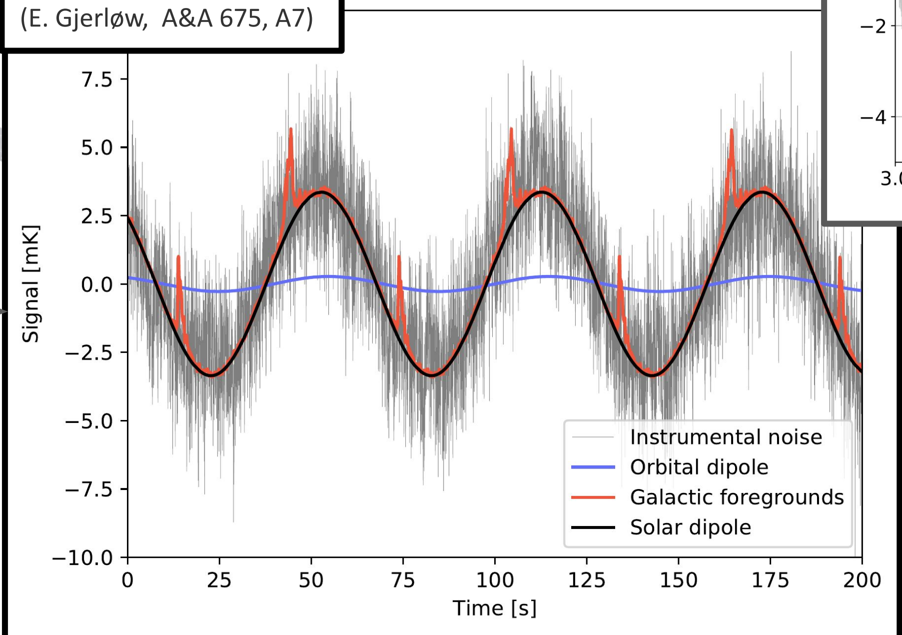

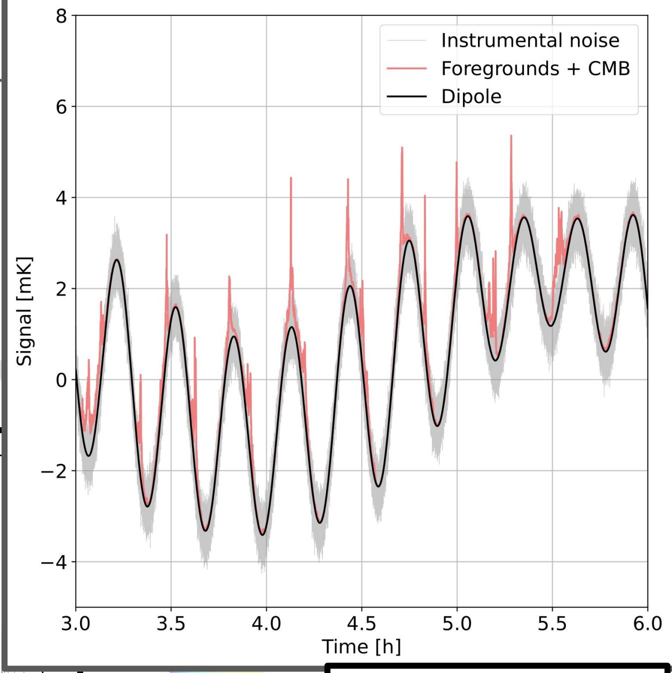

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What level of noise can we accept and still calibrate with sufficient precision?

Step 1: What precision is needed?

Step 2: What is our requirement on the instrument?

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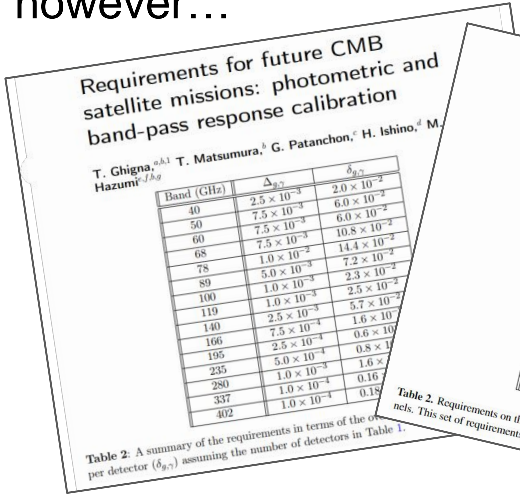
Step 1: What precision is needed in the gain calibration?

There are papers discussing this, however…

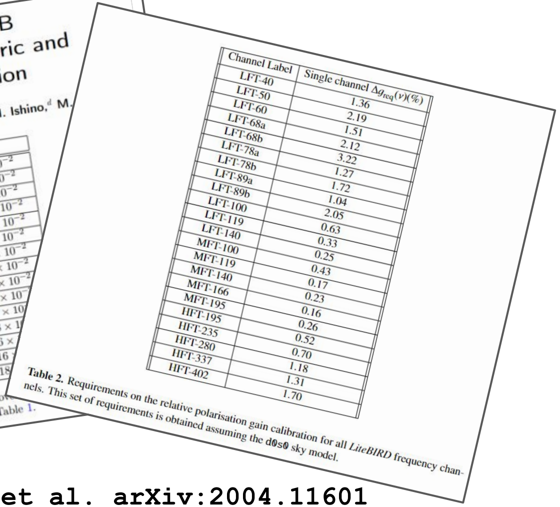


Requirements for future CMB satellite missions: photometric and band-pass response calibration

T. Ghigna,[a,b,1] T. Matsumura,[b] G. Patanchon,[c] H. Ishino,[d] M. Hazumi[e,f,b,g]

Band (GHz)	$\Delta_{g,\gamma}$	$\delta_{g,\gamma}$
40	2.5×10^{-3}	2.0×10^{-2}
50	7.5×10^{-3}	6.0×10^{-2}
60	7.5×10^{-3}	6.0×10^{-2}
68	7.5×10^{-3}	10.8×10^{-2}
78	1.0×10^{-2}	14.4×10^{-2}
89	5.0×10^{-3}	7.2×10^{-2}
100	1.0×10^{-3}	2.3×10^{-2}
119	1.0×10^{-3}	2.5×10^{-2}
140	2.5×10^{-3}	5.7×10^{-2}
166	7.5×10^{-4}	1.6 × 10
195	2.5×10^{-4}	0.6 × 10
235	5.0×10^{-4}	0.8 × 1
280	1.0×10^{-3}	1.6 ×
337	1.0×10^{-4}	0.16
402	1.0×10^{-4}	0.18

Table 2: A summary of the requirements in terms of the ov… per detector ($\delta_{g,\gamma}$) assuming the number of detectors in Table 1.



Channel Label	Single channel $\Delta g_{req}(\nu)(\%)$
LFT-40	1.36
LFT-50	2.19
LFT-60	1.51
LFT-68a	2.12
LFT-68b	3.22
LFT-78a	1.27
LFT-78b	1.72
LFT-89a	1.04
LFT-89b	2.05
LFT-100	0.63
LFT-119	0.33
LFT-140	0.25
MFT-100	0.43
MFT-119	0.17
MFT-140	0.23
MFT-166	0.16
MFT-195	0.26
HFT-195	0.52
HFT-235	0.70
HFT-280	1.18
HFT-337	1.31
HFT-402	1.70

Table 2. Requirements on the relative polarisation gain calibration for all *LiteBIRD* frequency channels. This set of requirements is obtained assuming the d0s0 sky model.

- Ghigna et al. arXiv:2004.11601
- Carralot et al. in prep.

Step 1: What precision is needed in the gain calibration?

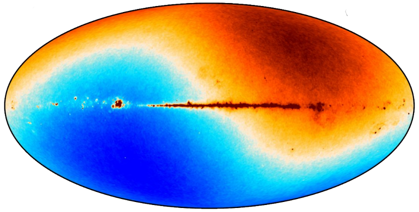
There are papers discussing this, however… they assume a constant gain

Quick Overview:

(Carralot talk on friday for more)

- Apply a random gain miscalibration Δg to a full sky map

$$MAP_{INPUT} = (1 + \Delta g) \times$$



- Separate the CMB from the rest of the sky (comp-sep) and see how the miscalibration biases the results
  (Credits: Carralot et al, Ghigna et al.)

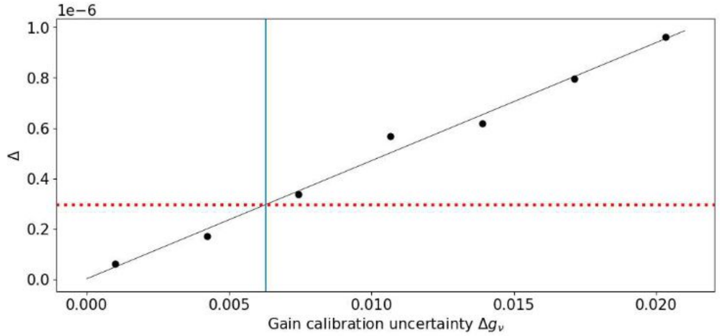


Figure 4. Black dots: $\Delta = \sqrt{\mu^2 + \sigma^2}$ as a function of the gain calibration uncertainty Δg_ν for the LFT 100 GHz channel. Red dashed line: the single channel gain systematic budget $\delta_r^{req} = 6.5 \cdot 10^{-6}/22$. The blue solid line corresponds to the requirement on the gain calibration accuracy obtained for the LFT 100 GHz ≈ 0.63%.

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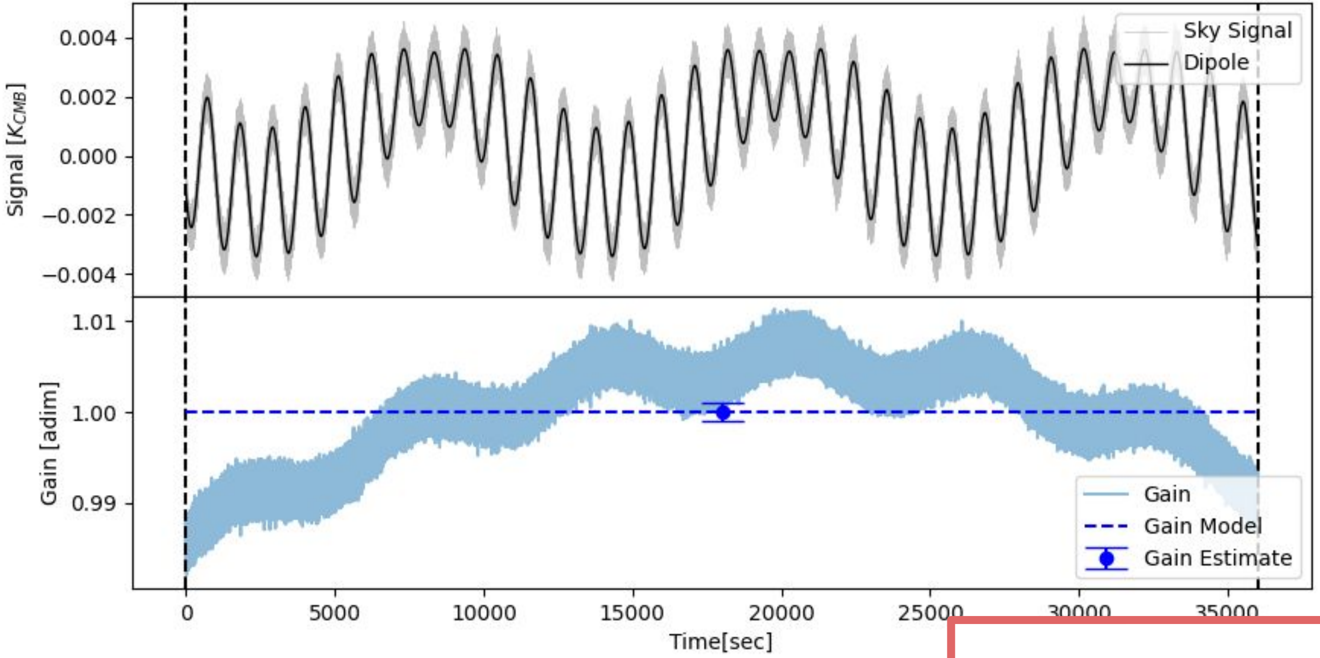

This can introduce a **significant mismatch** if the gain is not actually stable for the whole 3 years

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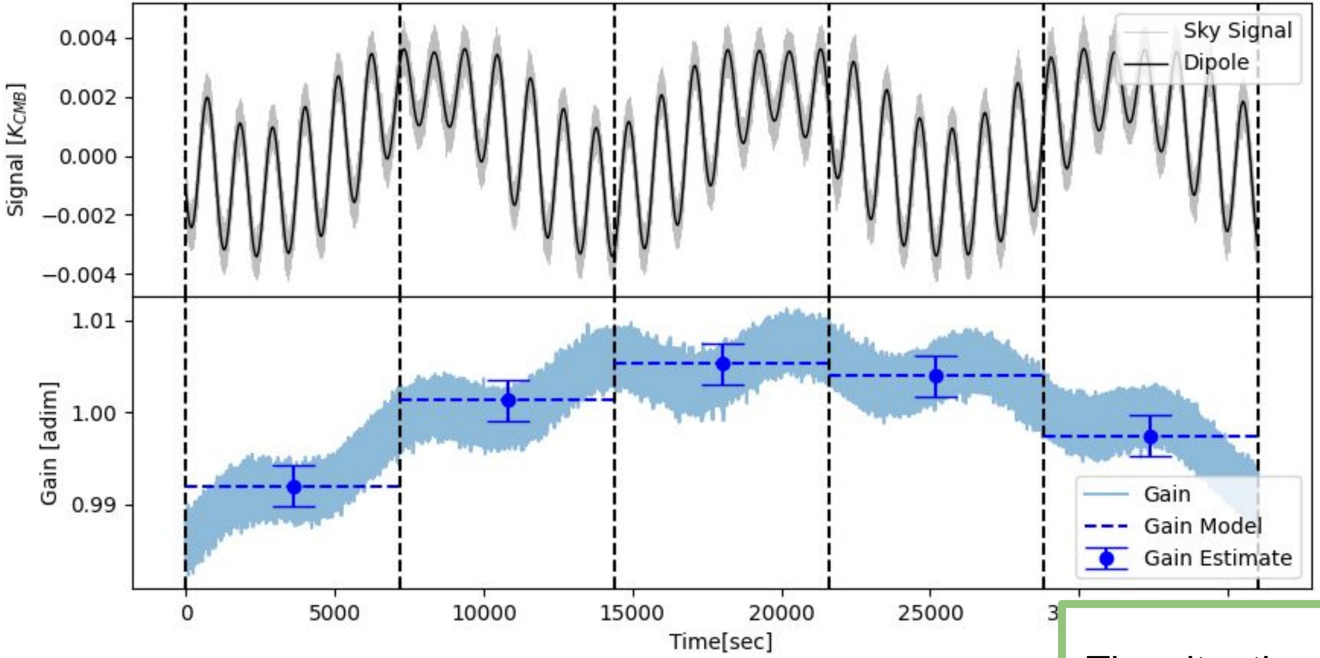

The situation improves if we chunk the tod
(However the uncertainty increases)

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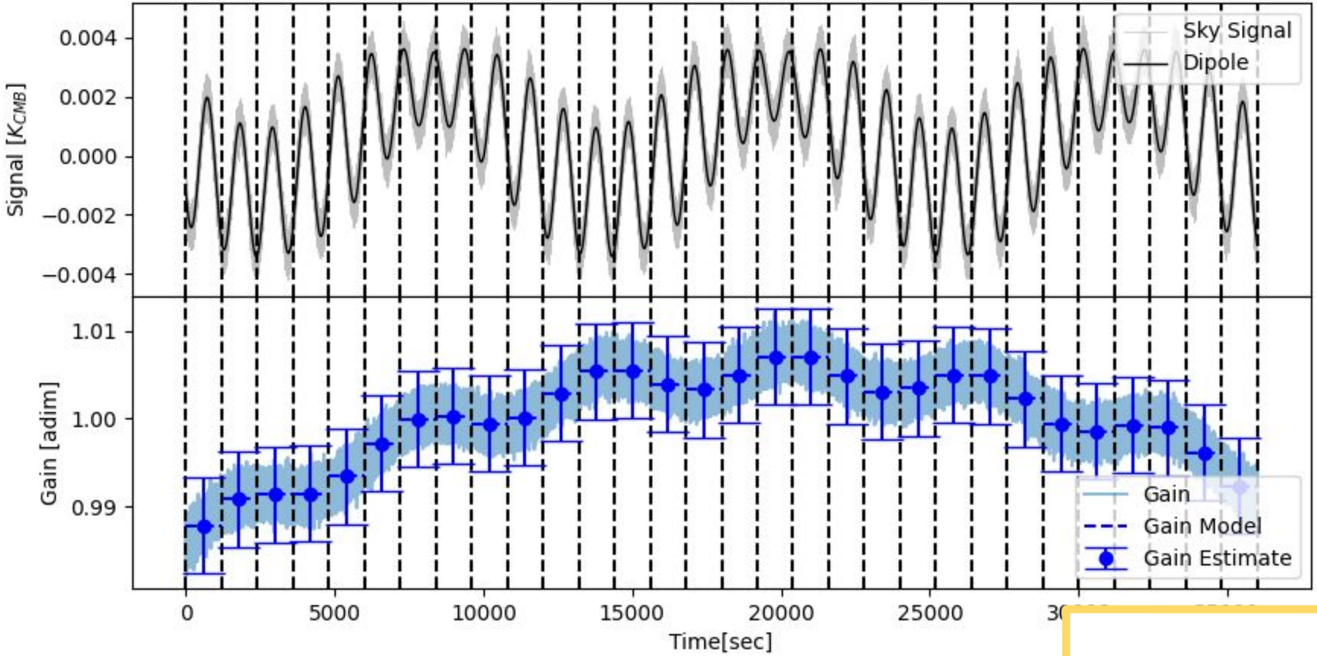
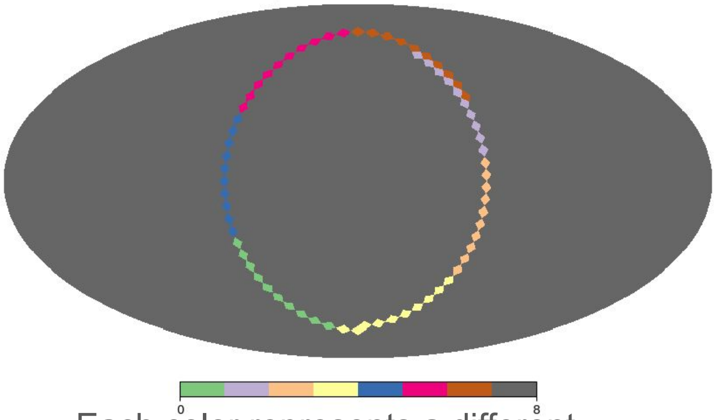


The limit on the smallest chunk is given by the period of the dipole (20 min)

Step 1: What precision is needed in the gain calibration?

- I want to be able to simulate the effect of multiple calibrations on the sky to introduce them in the analysis
  - I need to know how the gain uncertainty scales with the calibration time ( as a function of )



Each color represents a different calibration chunk

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I can use a **tod-based minimum variance approach**

- matches the TOD to a dipole + fg template
- NO strong assumptions on calib strategy
- easy to simulate

Data model — sky emission (all sources) — noise

$$d_i(t) = g_i \left(m(t) + n^{tot}(t)\right)$$

gain estimate — **noise term**

$$\tilde{g} = \frac{\int d(t)\, m_0(t)\, dt}{\int m_0(t)^2\, dt} \approx g \left(1 + \frac{\int n(t)\, m_0(t)\, dt}{\int m_0(t)^2\, dt}\right)$$

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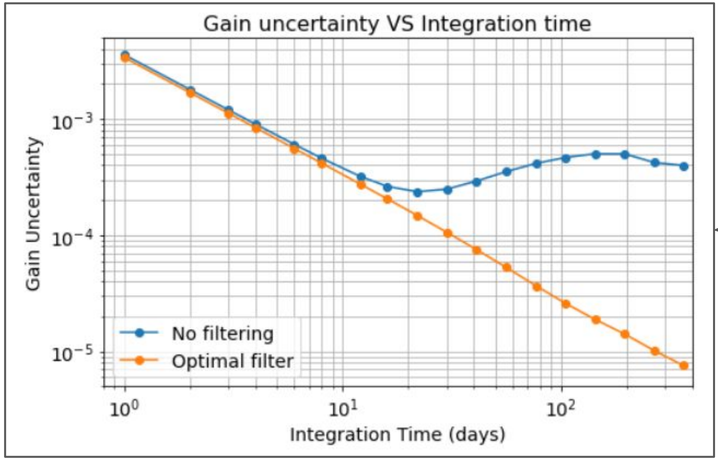

We can extract a relationship between gain uncertainty and calibration time (orange line)

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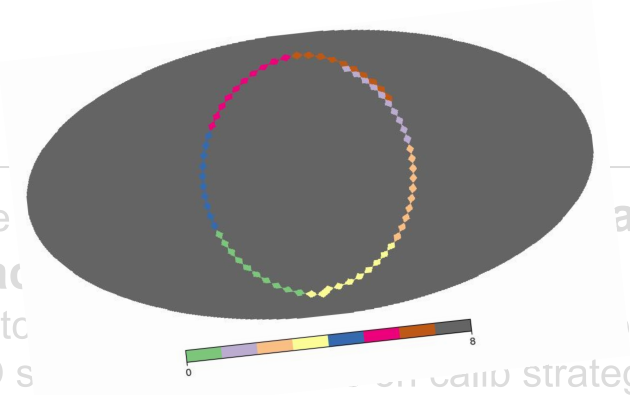

I can use ... ance

approac

- matc ... late
- NO s ... calib strategy
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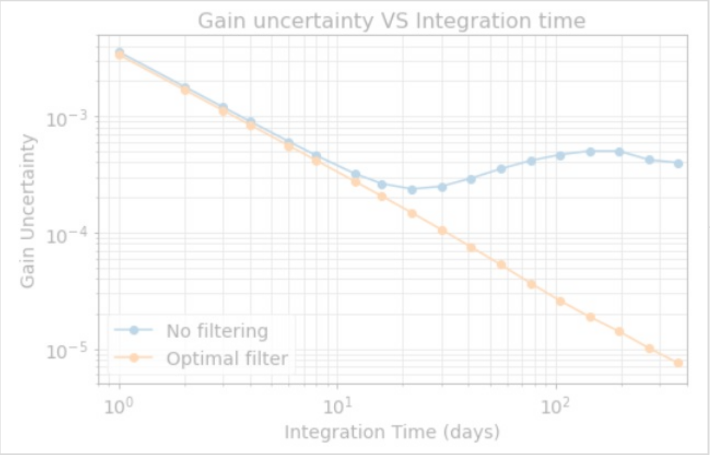

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Step 1: What precision is needed in the gain calibration?

Here are the results!

- Longer integration times produce larger features

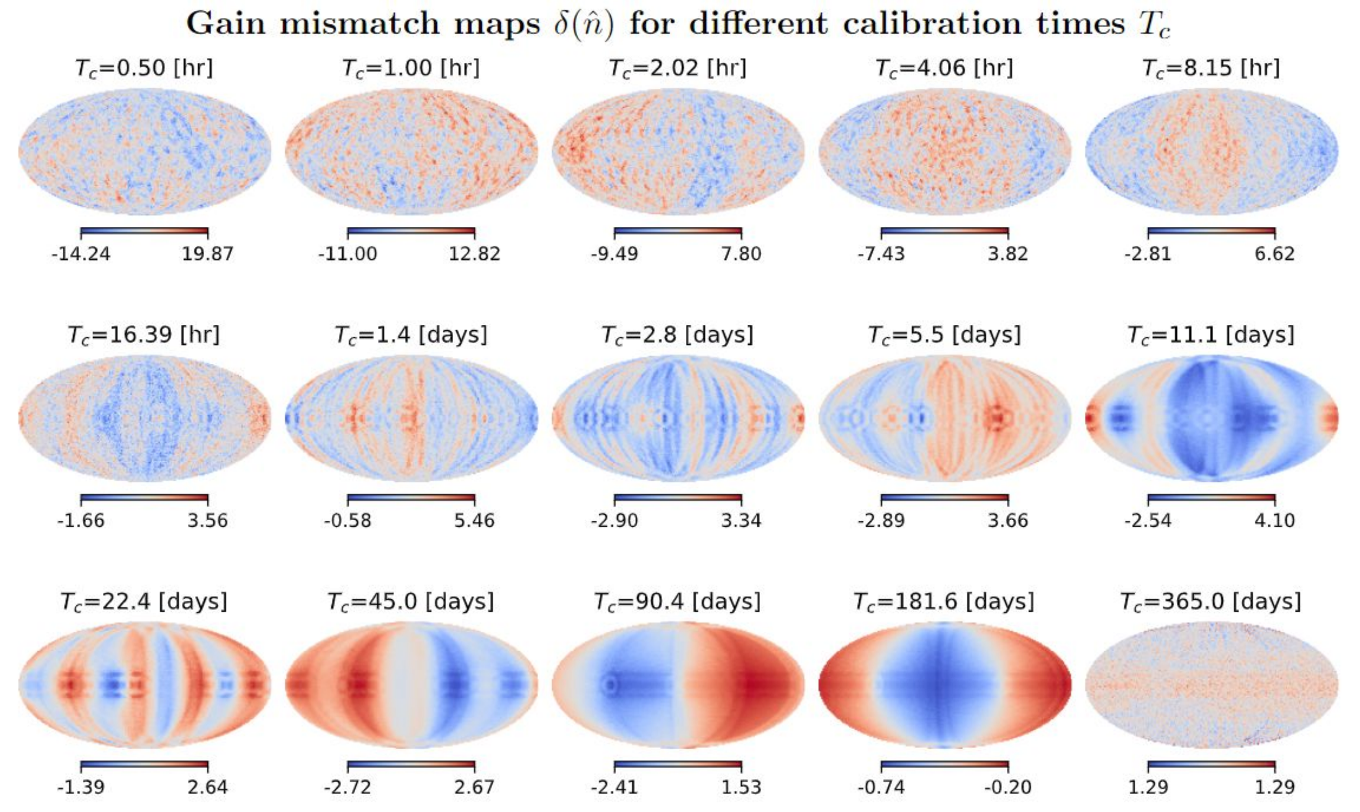
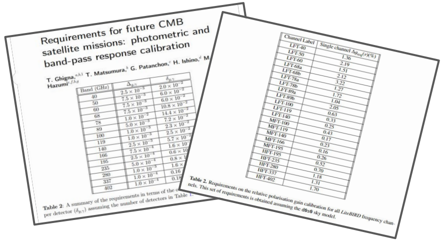


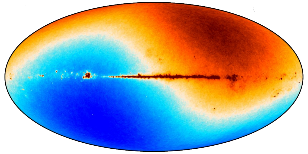
Figure 4: Gain miscalibration maps obtained computing Eq. 4.1 with different re-calibration times and a reference value for $\sigma_{\tilde{g},m} = 1$.

Step 1: What precision is needed in the gain calibration?

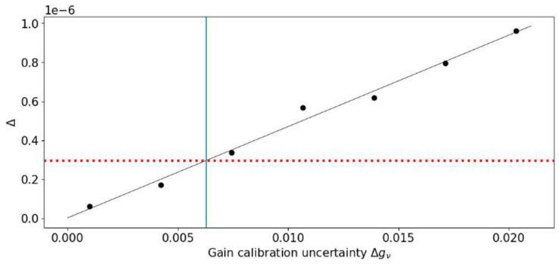
Now that I have these maps I can expand the results found in the papers



From:

$MAP_{INPUT} = (1 + \Delta g) \times$ 

Results:



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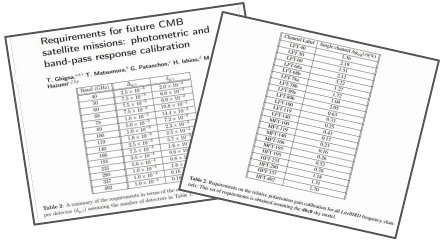
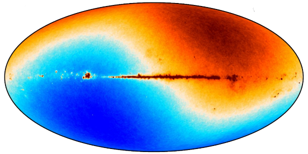


From:

MAP_{INPUT} = (1 + Δg) ×



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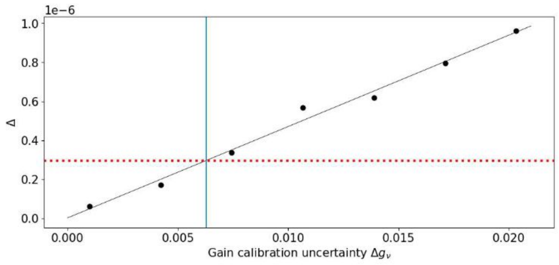

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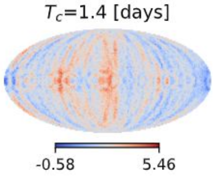
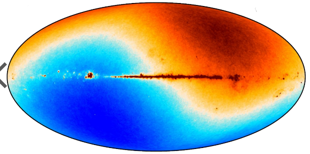
To:

MAP_{INPUT} = (1 + Δg



) ×



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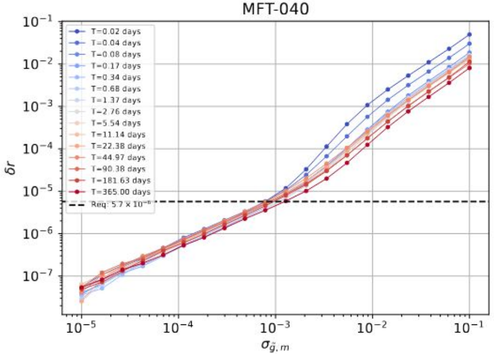

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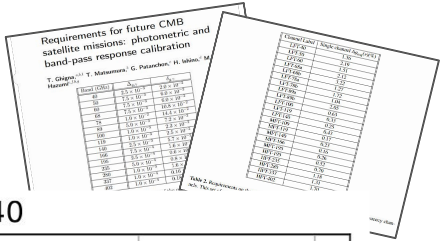
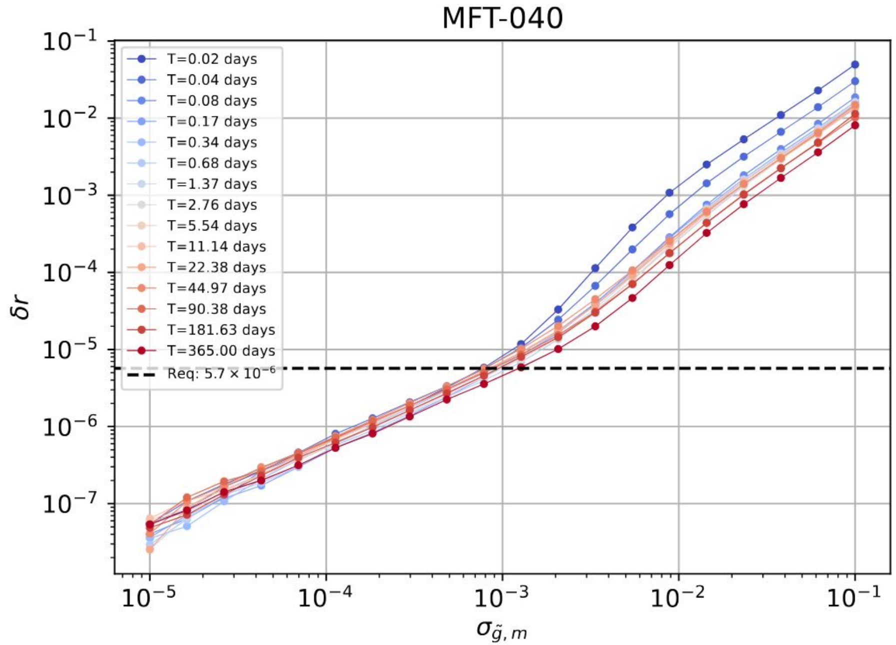


RESULTS:

- At LiteBIRD's systematics threshold the relationship between gain uncertainty and measurement bias is independent of T_C



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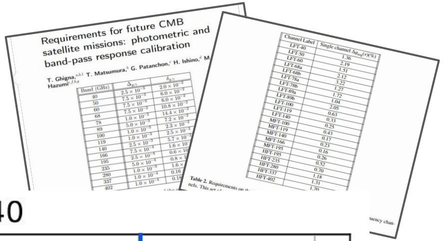
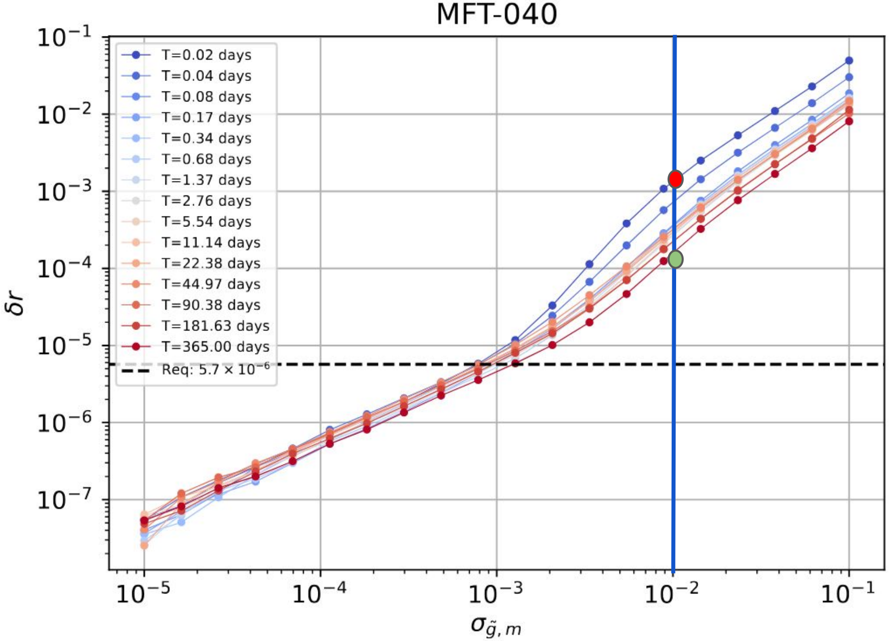


RESULTS:

- At LiteBIRD's systematics threshold the relationship between gain uncertainty and measurement bias is independent of T_C
- If the threshold would have been higher it would been convenient to calibrate on longer timescales (lower bias on r)



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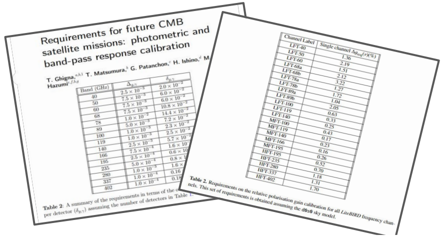
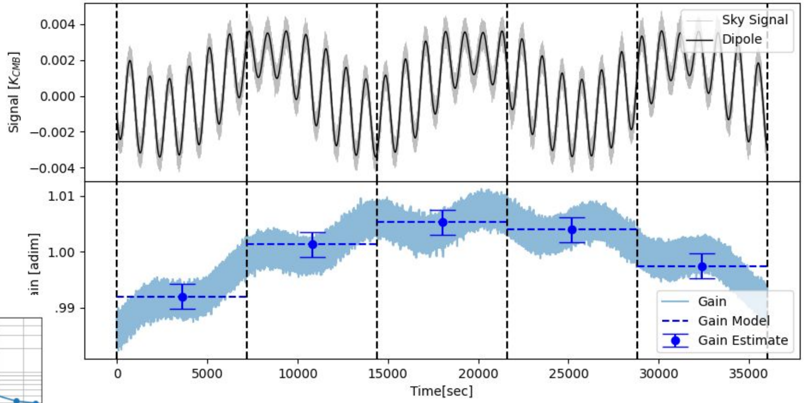


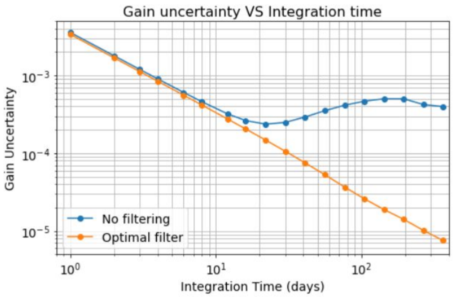
RESULTS:

Since there is no significant effect depending on T_c we prefer to calibrate on shorter timescales and track gain fluctuations

This gives us:

- The optimal calibration time: 20~30 min
- The maximum calibration error that is acceptable in each calibration chunk





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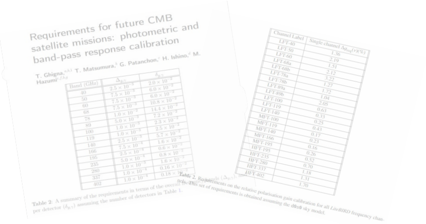

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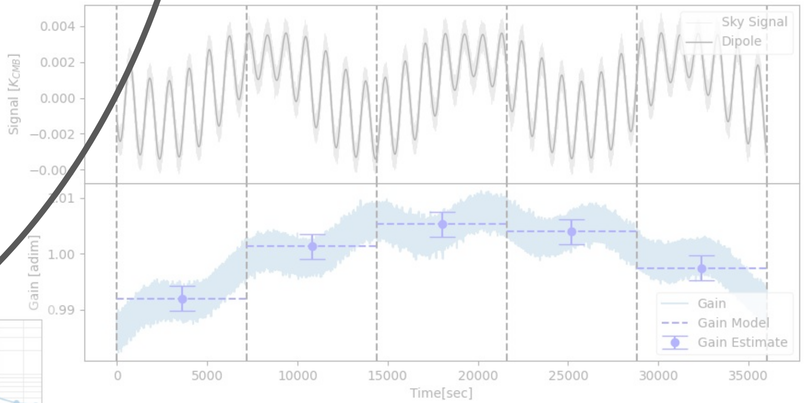

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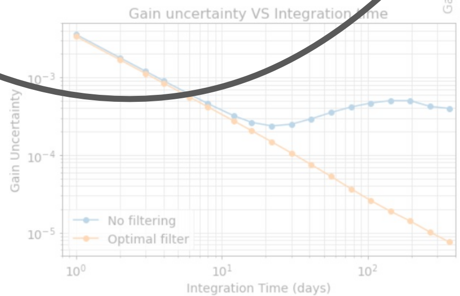

What level of noise can we accept and still calibrate with sufficient precision?

- Step 1: What precision is needed?
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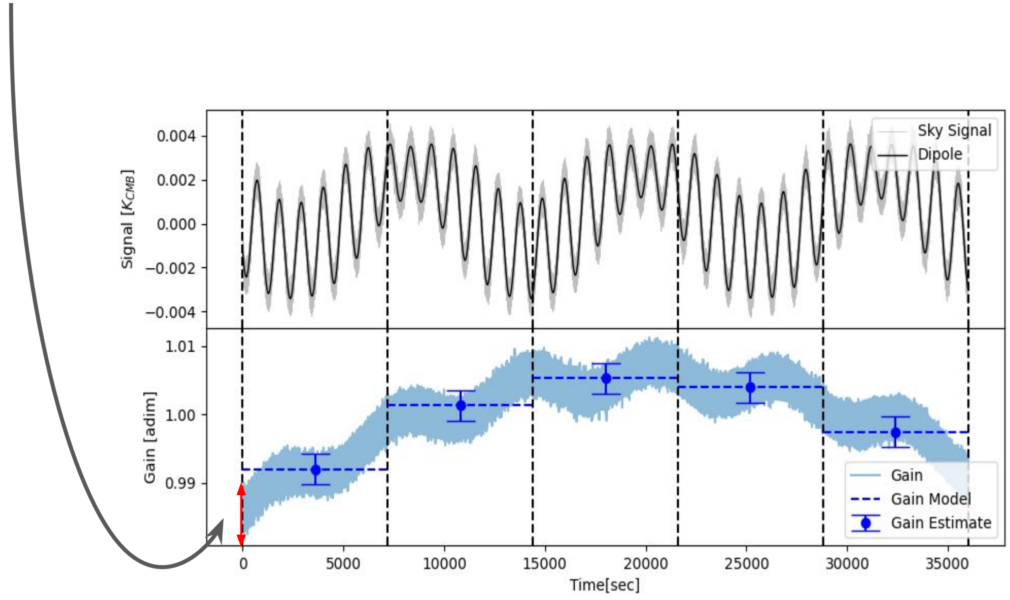
GAIN STABILITY

We can set requirements on:

- The amplitude of noise-like gain fluctuations $\mathbf{P_G}$



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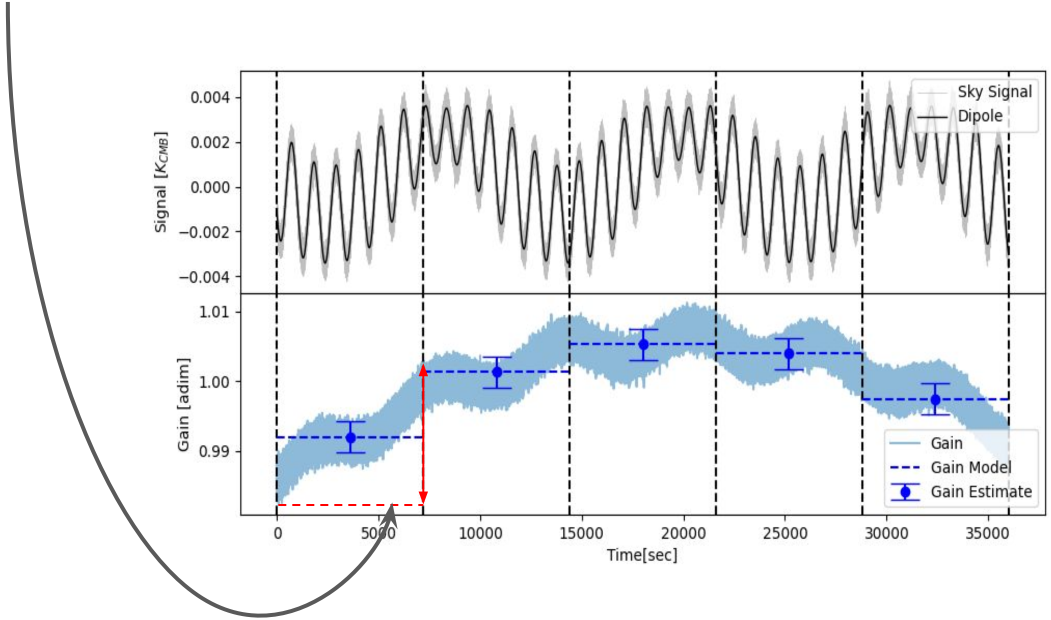
- Systematic gain fluctuations on a 20-min timescale $\boldsymbol{\delta}_{\mathbf{MAX}}$



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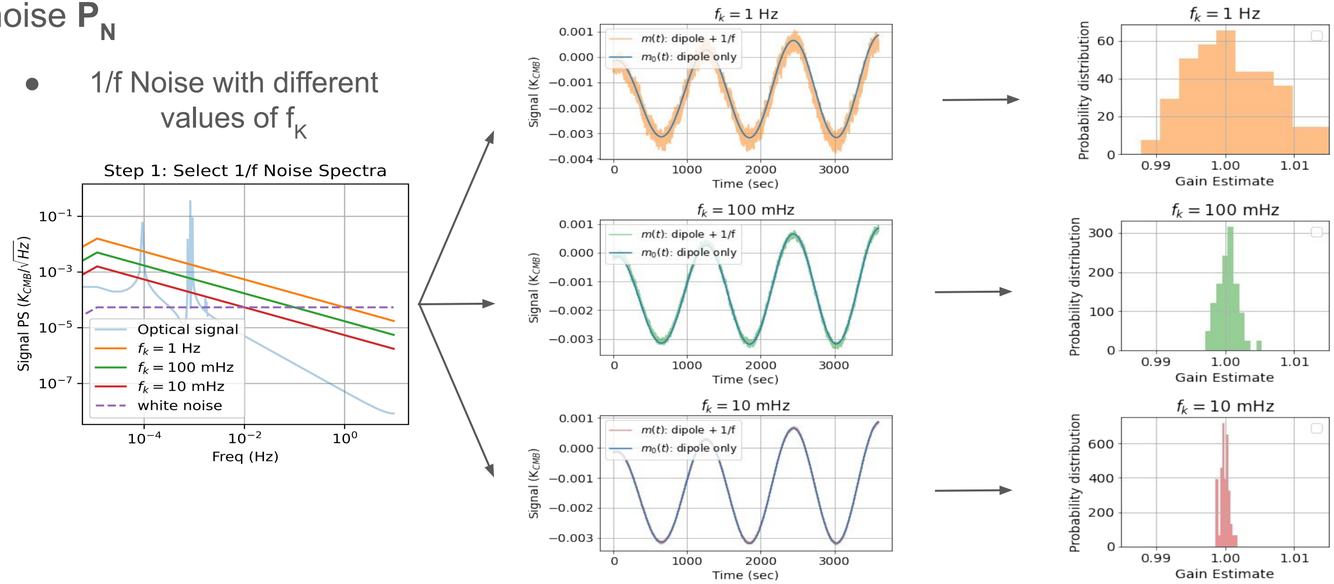
INSTRUMENT NOISE

We can set requirements on:

- The amplitude of 1/f noise $\mathbf{P_N}$

- 1/f Noise with different values of f_K
- Simulate TOD
- Calculate Uncertainty on our gain estimate



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INSTRUMENT NOISE

We can set requirements on:

- The amplitude of 1/f noise $\mathbf{P_N}$
    - It is best summarized by the amplitude of 1/f noise at the dipole frequency $\mathbf{P_N(f_{DIP})}$
    - Can be converted into maximum thermal fluctuations of the focal plane $\mathbf{P_T(f_{DIP})}$

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Requirements using FgBuster

	Gain stability		Detectors' noise	
Band [GHz]	P_G [$1/\sqrt{\text{Hz}}$]	δ_{MAX} [adim]	$P_N(f_{dip})$ [$\mu\text{K}_{\text{CMB}}/\sqrt{\text{Hz}}$]	$A_T(f_{dip})$ [$\text{mK}/\sqrt{\text{Hz}}$]
L1-40	$8.8 \times 10^{+0}$	7.5×10^{-1}	4.8×10^{-2}	4.4×10^{-1}
L2-50	$2.6 \times 10^{+1}$	$2.2 \times 10^{+0}$	1.4×10^{-1}	$1.7 \times 10^{+0}$
L1-60	$2.6 \times 10^{+1}$	$2.2 \times 10^{+0}$	1.4×10^{-1}	$2.5 \times 10^{+0}$
L3-68	$2.2 \times 10^{+1}$	$2.3 \times 10^{+0}$	1.4×10^{-1}	$1.4 \times 10^{+0}$
L2-68	$2.6 \times 10^{+1}$	$2.2 \times 10^{+0}$	1.4×10^{-1}	$2.4 \times 10^{+0}$
L4-78	$3.0 \times 10^{+1}$	$3.1 \times 10^{+0}$	1.8×10^{-1}	$2.7 \times 10^{+0}$
L1-78	$3.5 \times 10^{+1}$	$3.0 \times 10^{+0}$	1.9×10^{-1}	$3.6 \times 10^{+0}$
L3-89	$1.5 \times 10^{+1}$	$1.6 \times 10^{+0}$	9.1×10^{-2}	$1.6 \times 10^{+0}$
L2-89	$1.7 \times 10^{+1}$	$1.5 \times 10^{+0}$	9.6×10^{-2}	$1.8 \times 10^{+0}$
L4-100	$2.9 \times 10^{+0}$	3.1×10^{-1}	1.8×10^{-2}	3.8×10^{-1}
L3-119	$2.9 \times 10^{+0}$	3.1×10^{-1}	1.8×10^{-2}	5.1×10^{-1}
L4-140	$7.1 \times 10^{+0}$	7.8×10^{-1}	4.6×10^{-2}	$1.9 \times 10^{+0}$
M1-100	$1.6 \times 10^{+0}$	3.1×10^{-1}	1.6×10^{-2}	3.2×10^{-1}
M2-119	$1.4 \times 10^{+0}$	3.1×10^{-1}	1.4×10^{-2}	3.7×10^{-1}
M1-140	$3.9 \times 10^{+0}$	7.6×10^{-1}	3.9×10^{-2}	$1.2 \times 10^{+0}$
M2-166	9.7×10^{-1}	2.3×10^{-1}	1.1×10^{-2}	2.9×10^{-1}
M1-195	3.6×10^{-1}	7.6×10^{-2}	3.9×10^{-3}	9.3×10^{-2}
H1-195	3.3×10^{-1}	7.7×10^{-2}	3.6×10^{-3}	9.5×10^{-2}
H2-235	7.1×10^{-1}	1.6×10^{-1}	8.1×10^{-3}	2.0×10^{-1}
H1-280	$1.2 \times 10^{+0}$	3.1×10^{-1}	1.5×10^{-2}	2.6×10^{-1}
H2-337	1.1×10^{-1}	2.9×10^{-2}	1.5×10^{-3}	1.5×10^{-2}
H3-402	1.2×10^{-1}	2.9×10^{-2}	1.4×10^{-3}	5.8×10^{-3}

Table 2: Gain calibration requirements for the LiteBIRD satellite using parametric methods for component separation. The requirements have been derived for:

- P_G: maximum Amplitude Spectral density of noise fluctuations.
- δ_{MAX}: maximum fluctuation of the gain in 20 min.
- $P_N(f_{dip})$: maximum noise of the detectors at the dipole frequency.
- $A_T(f_{dip})$: maximum thermal fluctuations of the focal plane at the dipole frequency.

Thank you for the attention!

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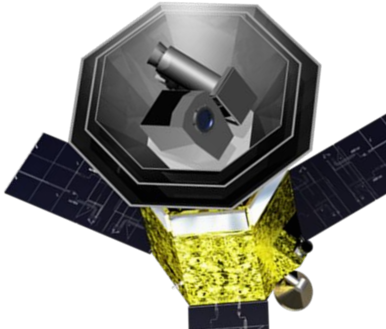


BACKUP SLIDES

Full mission requirements

Band [GHz]	w. fgbuster	w. NILC
LFT-40	2.5×10^{-3}	1.4×10^{-2}
LFT-50	7.5×10^{-3}	2.2×10^{-2}
LFT-60	7.5×10^{-3}	1.5×10^{-2}
LFT-68a	7.5×10^{-3}	2.1×10^{-2}
LFT-68b	7.5×10^{-3}	3.2×10^{-2}
LFT-78a	1.0×10^{-2}	1.3×10^{-2}
LFT-78b	1.0×10^{-2}	1.7×10^{-2}
LFT-89a	5.0×10^{-3}	1.0×10^{-2}
LFT-89b	5.0×10^{-3}	2.1×10^{-2}
LFT-100	1.0×10^{-3}	6.3×10^{-3}
LFT-119	1.0×10^{-3}	3.3×10^{-3}
LFT-140	2.5×10^{-3}	2.5×10^{-3}
MFT-100	1.0×10^{-3}	4.3×10^{-3}
MFT-119	1.0×10^{-3}	1.7×10^{-3}
MFT-140	2.5×10^{-3}	2.3×10^{-3}
MFT-166	7.5×10^{-4}	1.6×10^{-3}
MFT-195	2.5×10^{-4}	2.6×10^{-3}
HFT-195	2.5×10^{-4}	5.2×10^{-3}
HFT-235	5.0×10^{-4}	7.0×10^{-3}
HFT-280	1.0×10^{-3}	1.2×10^{-2}
HFT-337	1.0×10^{-4}	1.3×10^{-2}
HFT-402	1.0×10^{-4}	1.7×10^{-2}

Table 1: Summary of the gain calibration requirements obtained in [1] (obtained using `fgbuster`) and in [2] (obtained using `NILC`). In both cases the requirements have been obtained assuming a uniform miscalibration of the gain across the sky.

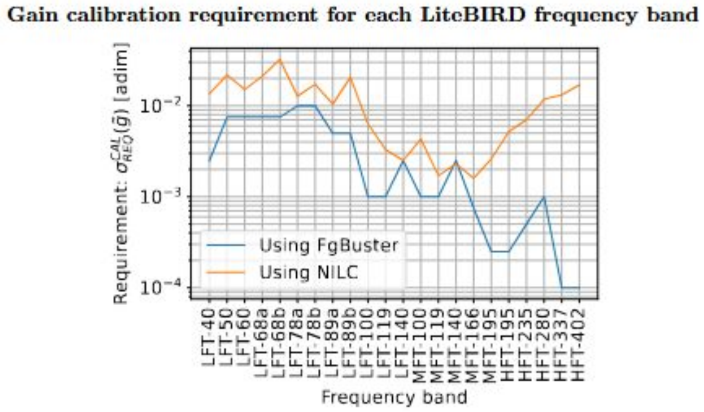


Figure 1: Gain calibration requirements for each LiteBIRD frequency band. The blue line shows the results obtained in [1] performing the component separation with `fgbuster` while the orange line shows the results obtained in [2] using `NILC`.

Requirements using NILC

	Gain stability		Detectors' noise	
Band [GHz]	P_G $[1/\sqrt{\mathrm{Hz}}]$	δ_{MAX} [adim]	$P_N(f_{dip})$ $[\mu\mathrm{K_{CMB}}/\sqrt{\mathrm{Hz}}]$	$P_T(f_{dip})$ $[\mathrm{mK}/\sqrt{\mathrm{Hz}}]$
L1-40	$4.8 \times 10^{+1}$	$4.1 \times 10^{+0}$	2.6×10^{-1}	$2.4 \times 10^{+0}$
L2-50	$7.7 \times 10^{+1}$	$6.5 \times 10^{+0}$	4.2×10^{-1}	$5.2 \times 10^{+0}$
L1-60	$5.3 \times 10^{+1}$	$4.5 \times 10^{+0}$	2.9×10^{-1}	$4.3 \times 10^{+0}$
L3-68	$6.3 \times 10^{+1}$	$6.6 \times 10^{+0}$	3.9×10^{-1}	$4.3 \times 10^{+0}$
L2-68	$1.1 \times 10^{+2}$	$9.6 \times 10^{+0}$	6.1×10^{-1}	$1.0 \times 10^{+1}$
L4-78	$3.8 \times 10^{+1}$	$4.0 \times 10^{+0}$	2.3×10^{-1}	$3.5 \times 10^{+0}$
L1-78	$6.0 \times 10^{+1}$	$5.1 \times 10^{+0}$	3.3×10^{-1}	$6.3 \times 10^{+0}$
L3-89	$3.1 \times 10^{+1}$	$3.2 \times 10^{+0}$	1.9×10^{-1}	$3.7 \times 10^{+0}$
L2-89	$7.2 \times 10^{+1}$	$6.1 \times 10^{+0}$	3.9×10^{-1}	$7.5 \times 10^{+0}$
L4-100	$1.9 \times 10^{+1}$	$2.0 \times 10^{+0}$	1.1×10^{-1}	$2.8 \times 10^{+0}$
L3-119	$9.5 \times 10^{+0}$	$1.0 \times 10^{+0}$	6.0×10^{-2}	$1.6 \times 10^{+0}$
L4-140	$7.1 \times 10^{+0}$	7.8×10^{-1}	4.6×10^{-2}	$1.9 \times 10^{+0}$
M1-100	$7.0 \times 10^{+0}$	$1.3 \times 10^{+0}$	6.7×10^{-2}	$1.3 \times 10^{+0}$
M2-119	$2.4 \times 10^{+0}$	5.3×10^{-1}	2.4×10^{-2}	6.4×10^{-1}
M1-140	$3.6 \times 10^{+0}$	7.0×10^{-1}	3.6×10^{-2}	$1.2 \times 10^{+0}$
M2-166	$2.1 \times 10^{+0}$	4.9×10^{-1}	2.3×10^{-2}	6.7×10^{-1}
M1-195	$3.7 \times 10^{+0}$	7.9×10^{-1}	4.1×10^{-2}	$1.2 \times 10^{+0}$
H1-195	$6.8 \times 10^{+0}$	$1.6 \times 10^{+0}$	7.6×10^{-2}	$2.1 \times 10^{+0}$
H2-235	$1.0 \times 10^{+1}$	$2.2 \times 10^{+0}$	1.1×10^{-1}	$2.6 \times 10^{+0}$
H1-280	$1.4 \times 10^{+1}$	$3.6 \times 10^{+0}$	1.7×10^{-1}	$3.2 \times 10^{+0}$
H2-337	$1.4 \times 10^{+1}$	$3.8 \times 10^{+0}$	2.1×10^{-1}	$2.3 \times 10^{+0}$
H3-402	$2.0 \times 10^{+1}$	$4.9 \times 10^{+0}$	3.0×10^{-1}	$1.2 \times 10^{+0}$

Table 3: Gain calibration requirements for the LiteBIRD satellite using minimum-variance methods for component separation. The requirements have been derived for:

- P_G: maximum amplitude spectral density of noise fluctuations.
- δ_{MAX}: maximum fluctuation of the gain in 20 min.
- $P_N(f_{dip})$: maximum noise of the detectors at the dipole frequency.
- $P_T(f_{dip})$: maximum thermal fluctuations of the focal plane at the dipole frequency.

I want to be able to simulate the effect of multiple calibrations on the sky

- To make realistic simulations I need
  - to know how the gain uncertainty scales with the calibration time

To estimate our ability to determine *g* we can take a simplified data model

Data model — sky emission (all sources) — noise

$$d_i(t) = g_i \left(m(t) + n^{tot}(t)\right)$$

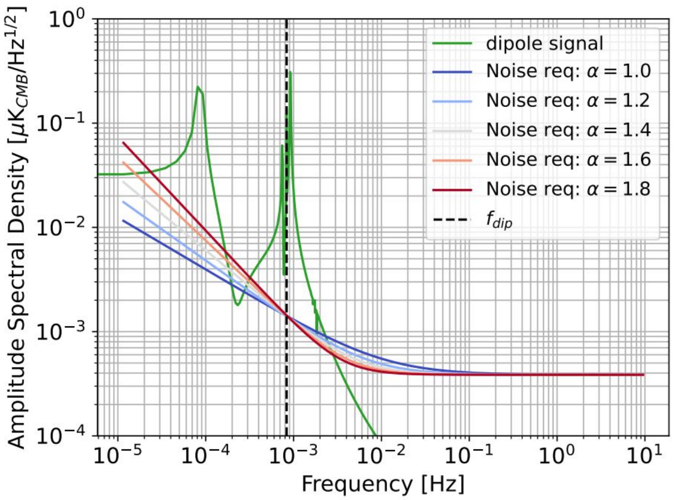
And convolve it with a reference signal:

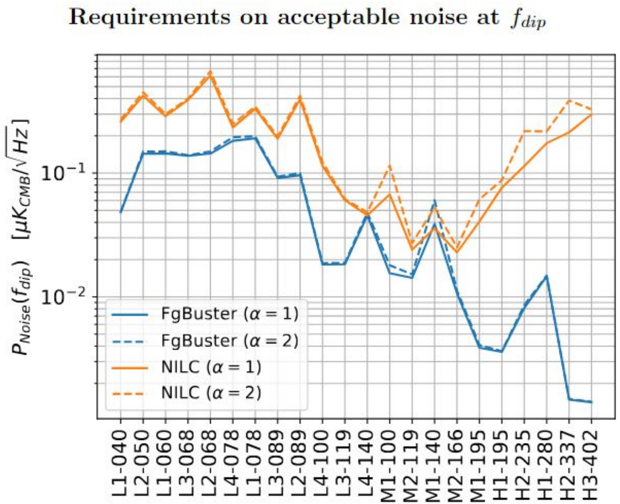
gain estimate — noise term

$$\tilde{g} = \frac{\int d(t)\, m_0(t)\, dt}{\int m_0(t)^2\, dt} = \frac{\int g\,(m(t) + n(t))\, m_0(t)\, dt}{\int m_0(t)^2\, dt} \approx g\left(1 + \frac{\int n(t)\, m_0(t)\, dt}{\int m_0(t)^2\, dt}\right)$$

Results:

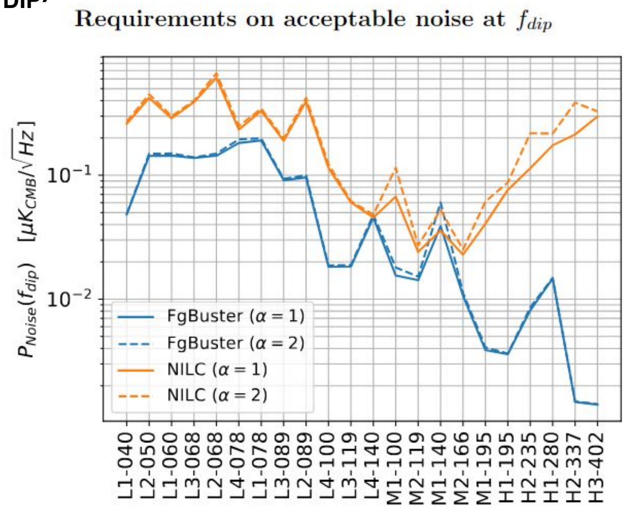
- The requirements on the noise level can be summarized into a requirement on the noise at the dipole frequency: $\mathbf{P_N(f_{DIP})}$
    - (removes any dependency from the noise power spectrum shape)

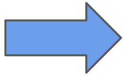


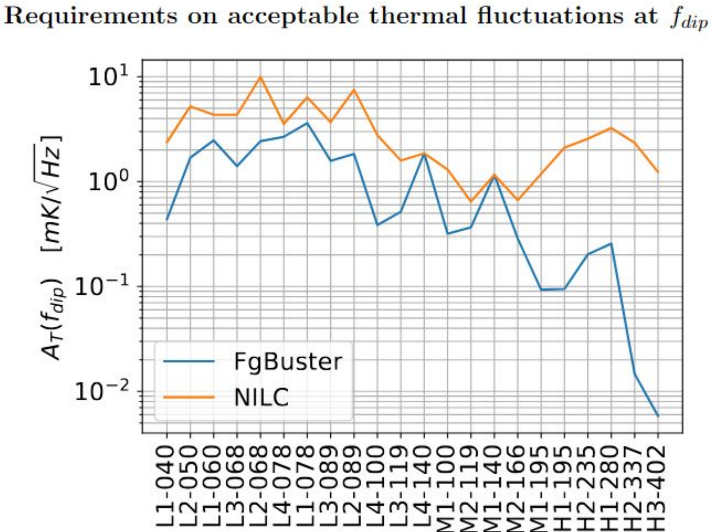


Results:

- The requirements on the noise level can be summarized into a requirement on the noise at the dipole frequency: $\mathbf{P_N(f_{DIP})}$
  - (removes any dependency from the shape of the noise)
- Under the assumption that the 1/f noise is mainly produced by thermal fluctuation of the focal plane we can convert this into a requirement on the fluctuations of the focal plane at the dipole frequency: $\mathbf{A_T(f_{DIP})}$







Thank you for the attention