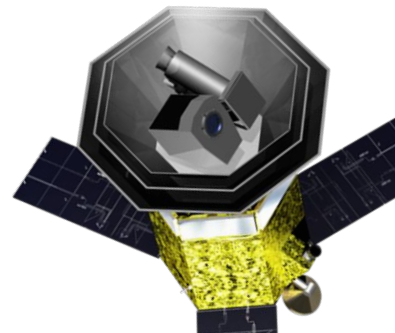




Setting Instrumental Requirements for the gain calibration of LiteBIRD

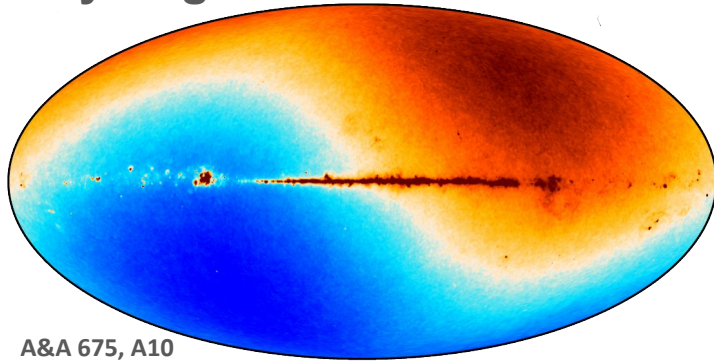
Alessandro Novelli

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



What is gain calibration?

Sky brightness

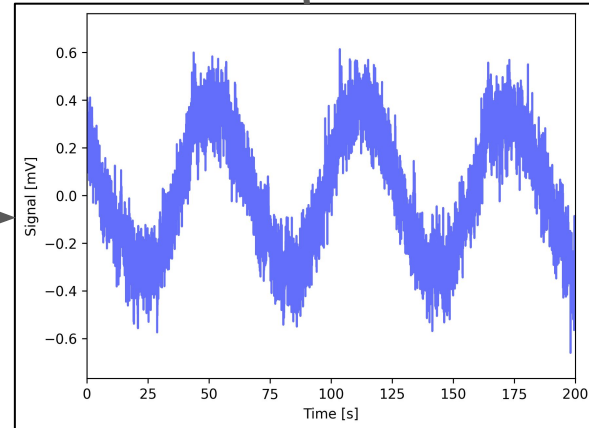


Consists in finding the conversion factor between sky-brightness and detector output

g

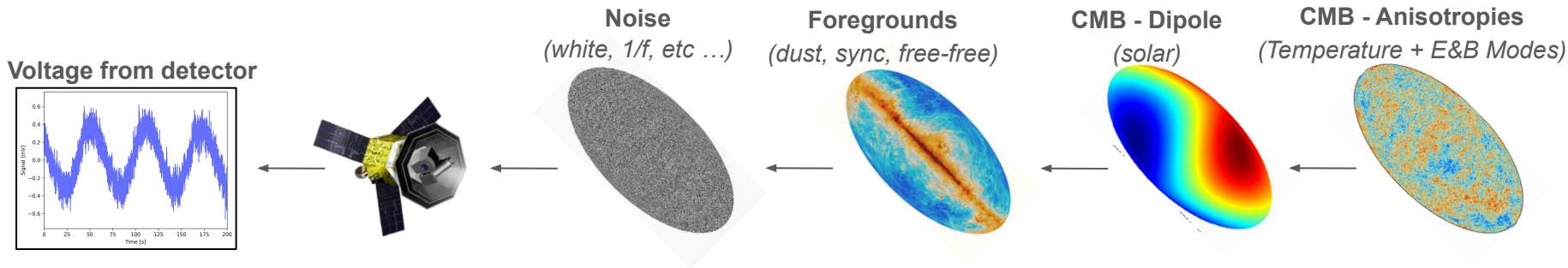
Current from detector

g^{-1}



How is it performed?

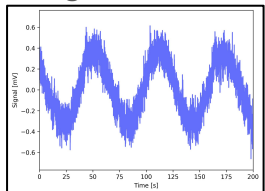
- To find **g** one usually compares the output signal with an expected **reference signal** (usually the CMB dipole)
- This, however, is usually mixed in with many other sources



How is it performed?

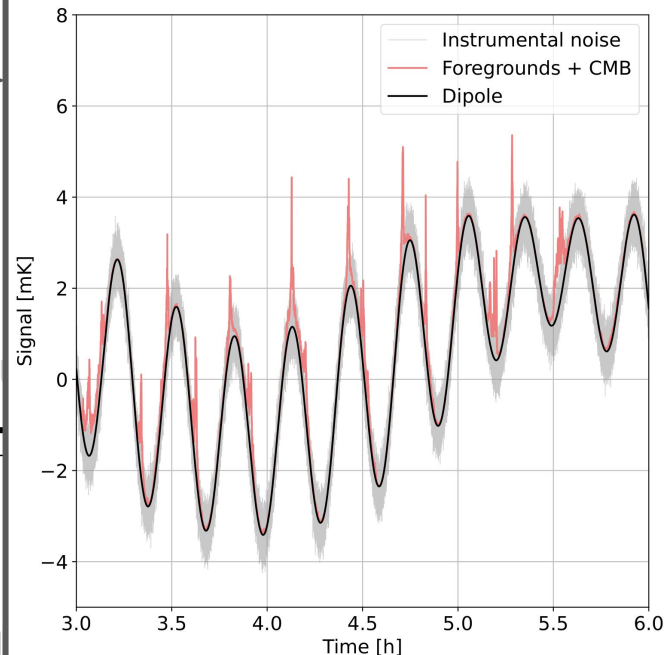
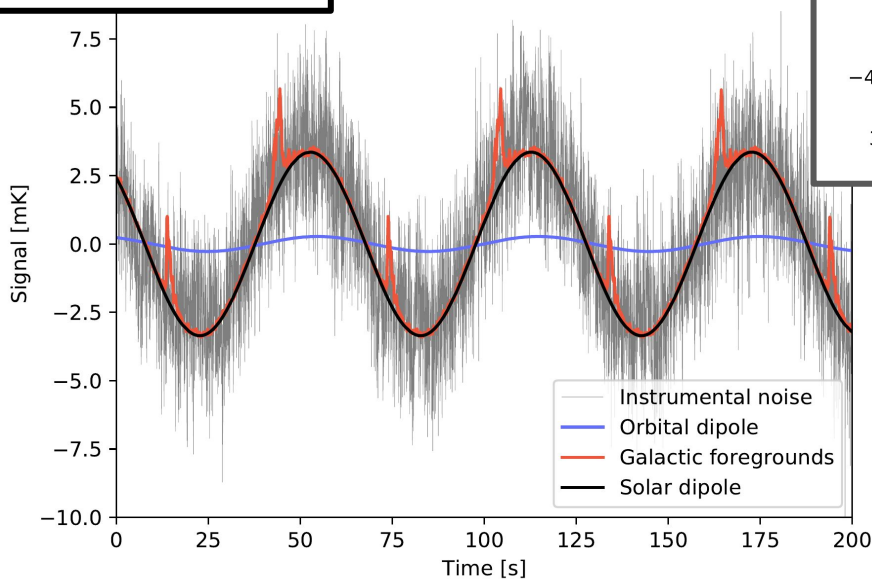
- To find α one usually compares the output signal with **signal** (usually the CMB dipole)
- This, however, is usually mixed in with many other so

Voltage from detector



Planck:

(E. Gjerløw, A&A 675, A7)



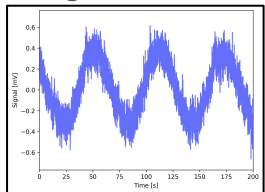
LiteBIRD:

(litebird_sim)

How much noise can we accept and still calibrate with sufficient precision?

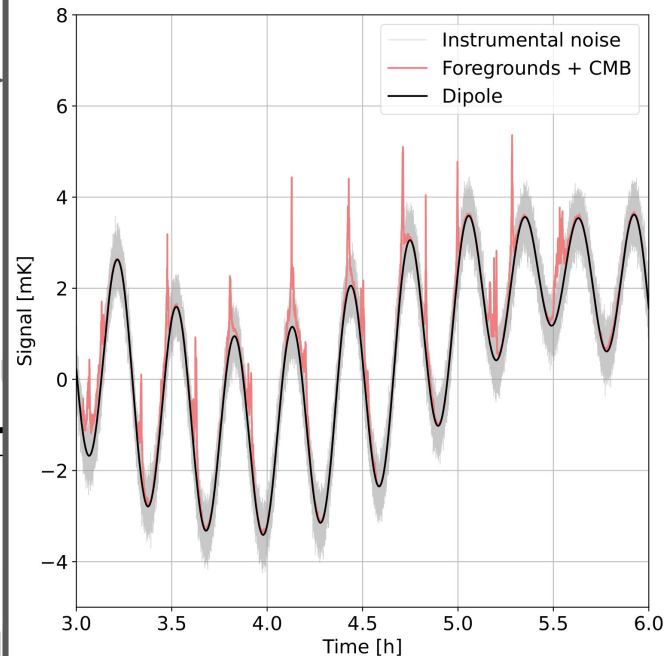
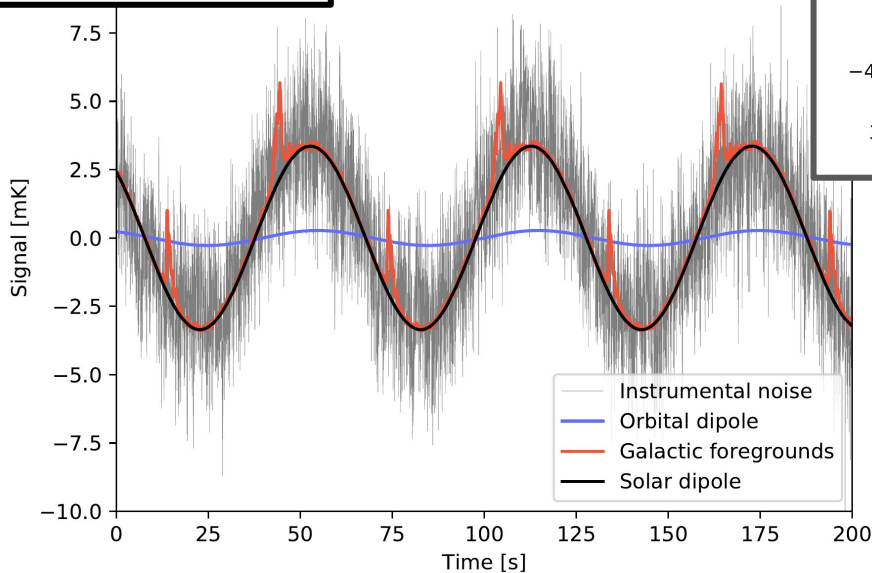
- To get a signal with sufficient precision
- This, however, is usually mixed in with many other so

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?

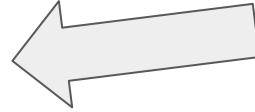
→ Step 1: What precision is needed?

→ Step 2: What is our requirement on the instrument?

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?



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,d,1} T. Matsumura,^a G. Patanchon,^c H. Ishino,^d M. Hazumi^{a,b}

Band (GHz)	$\Delta_{B,\gamma}$	$\delta_{B,\gamma}$
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^{-1}
195	2.5×10^{-4}	0.6×10^{-1}
235	5.0×10^{-4}	0.8×10^{-1}
280	1.0×10^{-3}	1.6×10^{-1}
337	1.0×10^{-4}	0.16×10^{-1}
402	1.0×10^{-4}	0.18×10^{-1}

Table 2: A summary of the requirements in terms of the channels. This set of requirements is obtained assuming the *LiteBIRD* sky model.

Channel Label	Simple channel $\Delta_{B,\gamma}(\%)$
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
MFT-100	0.25
MFT-119	0.43
MFT-140	0.17
MFT-166	0.23
MFT-195	0.16
HFT-195	0.26
HFT-235	0.52
HFT-280	0.70
HFT-337	1.18
HFT-402	1.31
	1.70

Table 2: Requirements on the relative polarisation gain calibration for all *LiteBIRD* frequency channels. This set of requirements is obtained assuming the *dB90* sky model.

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

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

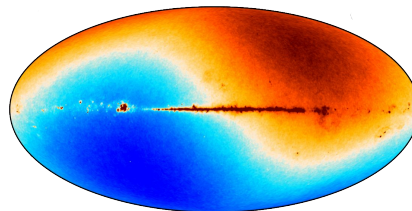
There are papers discussing this, however... they assume a constant gain

Quick Overview:

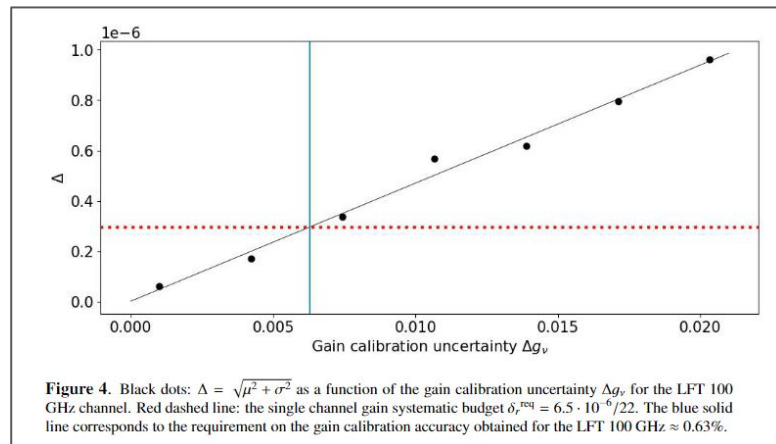
(Carralot talk on friday for more)

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

$$\text{MAP}_{\text{INPUT}} = (1 + \Delta g) \times$$

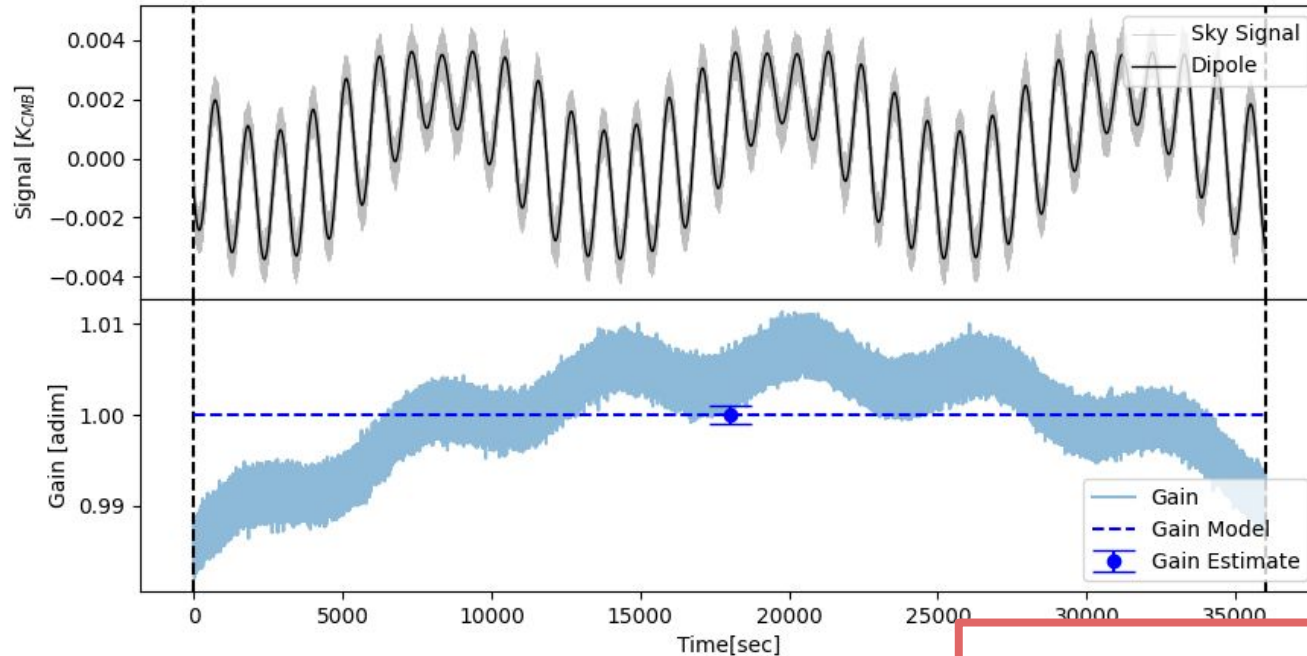


- Separate the CMB from the rest of the sky (comp-sep) and see how the miscalibration biases the results
(Credits: Carralot et al, Ghigna et al.)



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

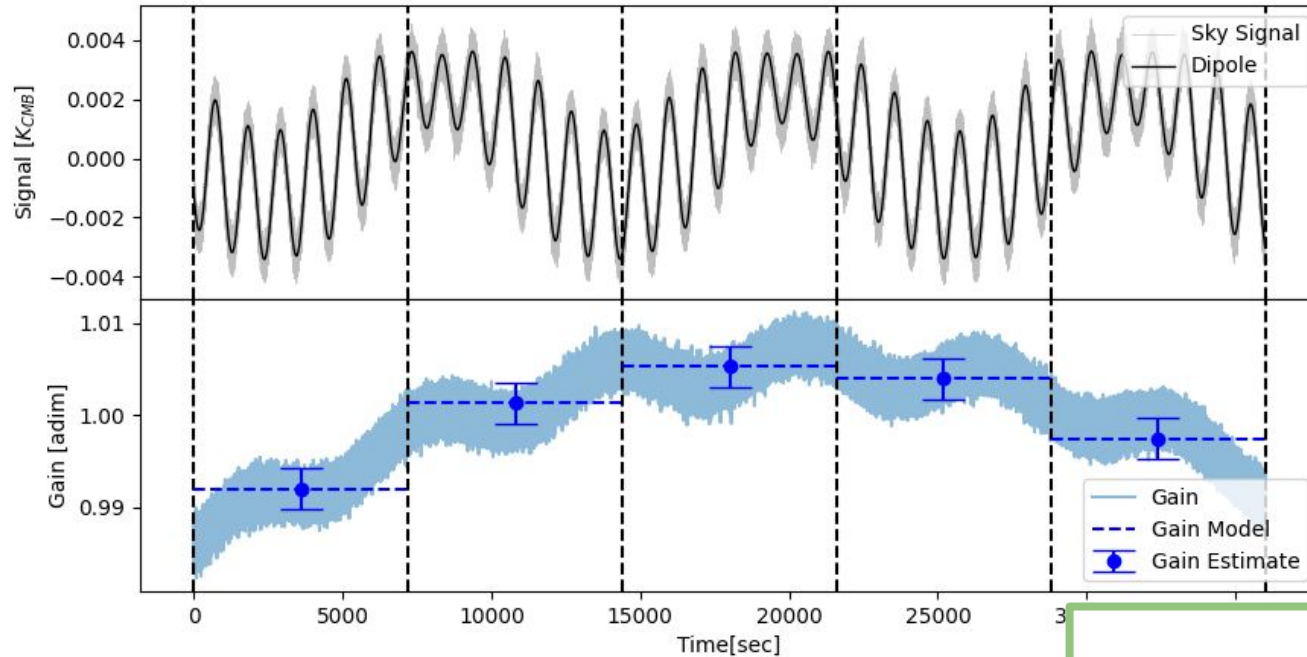
There are papers discussing this, however... they assume a constant gain



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

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

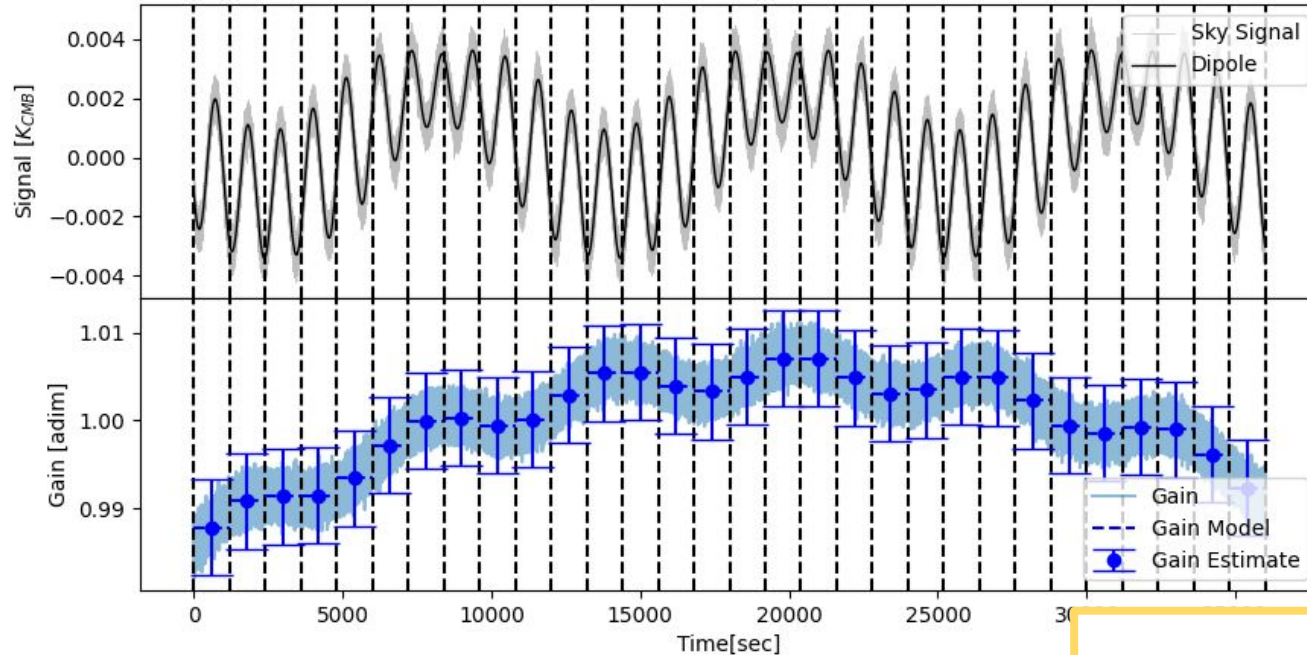
There are papers discussing this, however... they assume a constant gain



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



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

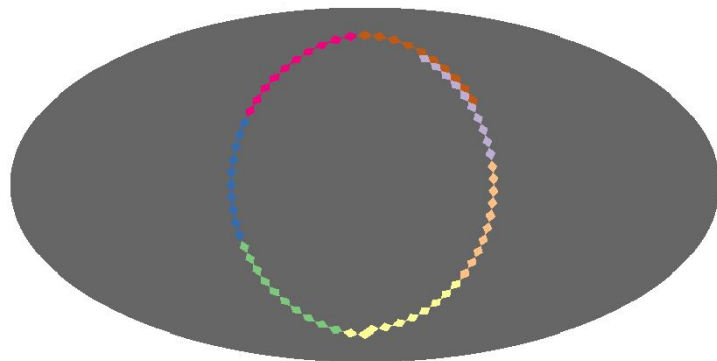
There are papers discussing this, however... they assume a constant gain




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

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 )



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

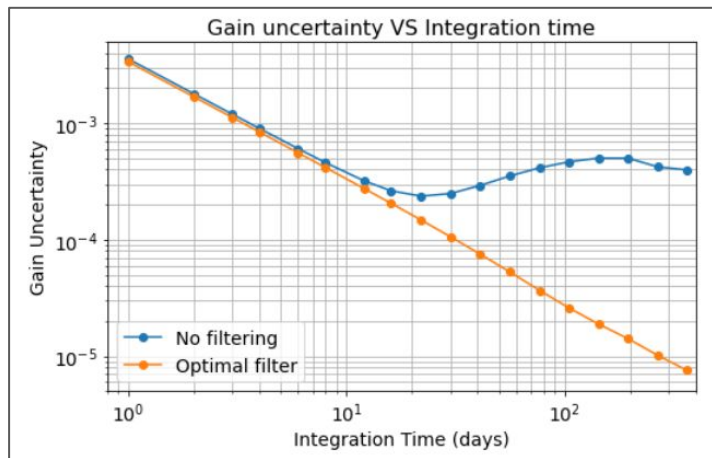
- matches the TOD to a dipole + fg template
- NO strong assumptions on calib strategy
- easy to simulate

$$\overset{\text{Data model}}{d_i(t)} = \overset{\text{sky emission (all sources)}}{g_i} \left(\overset{\text{noise}}{m(t) + n^{tot}(t)} \right)$$

$$\overset{\text{gain estimate}}{\tilde{g}} = \frac{\int d(t) m_0(t) dt}{\int m_0(t)^2 dt} \approx g \left(1 + \overset{\text{noise term}}{\frac{\int n(t) m_0(t) dt}{\int m_0(t)^2 dt}} \right)$$

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 )



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


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

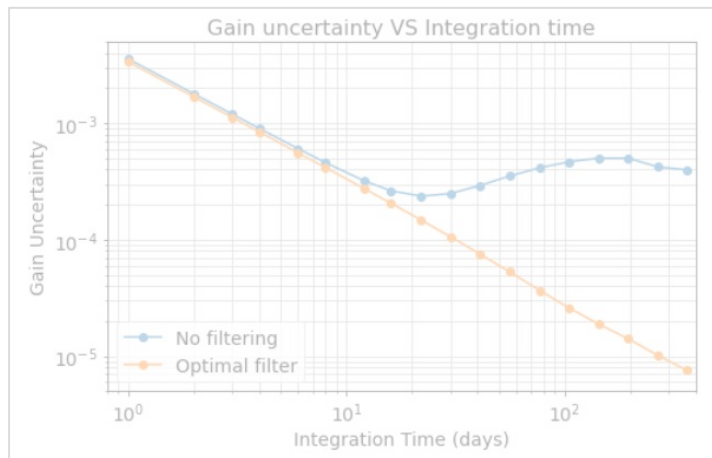
- matches the TOD to a dipole + fg template
- NO strong assumptions on calib strategy
- easy to simulate

$$\overset{\text{Data model}}{d_i(t)} = \overset{\text{sky emission (all sources)}}{g_i} \left(\overset{\text{noise}}{m(t) + n^{\text{tot}}(t)} \right)$$

$$\overset{\text{gain estimate}}{\tilde{g}} = \frac{\int d(t) m_0(t) dt}{\int m_0(t)^2 dt} \approx g \left(1 + \overset{\text{noise term}}{\frac{\int n(t) m_0(t) dt}{\int m_0(t)^2 dt}} \right)$$

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

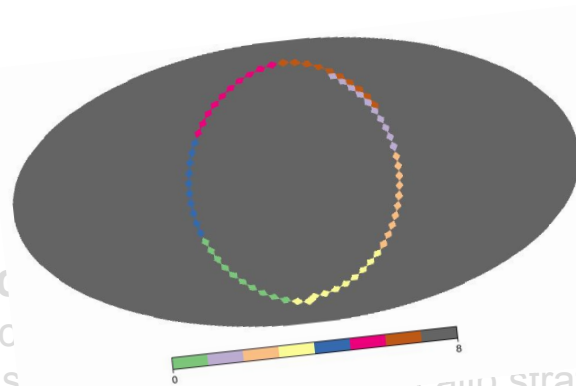
- I want to be able to simulate the effect of multiple calibrations on the sky to introduce them in the analysis
 - I need to know how the gain uncertainty scales with the calibration time (• as a function of ←---→) 



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

I can use
approach

- match
- NO s
- easy to simulate



Data model sky emission (all sources) noise

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

gain estimate noise term

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

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

Here are the results!

- Longer integration times produce larger features

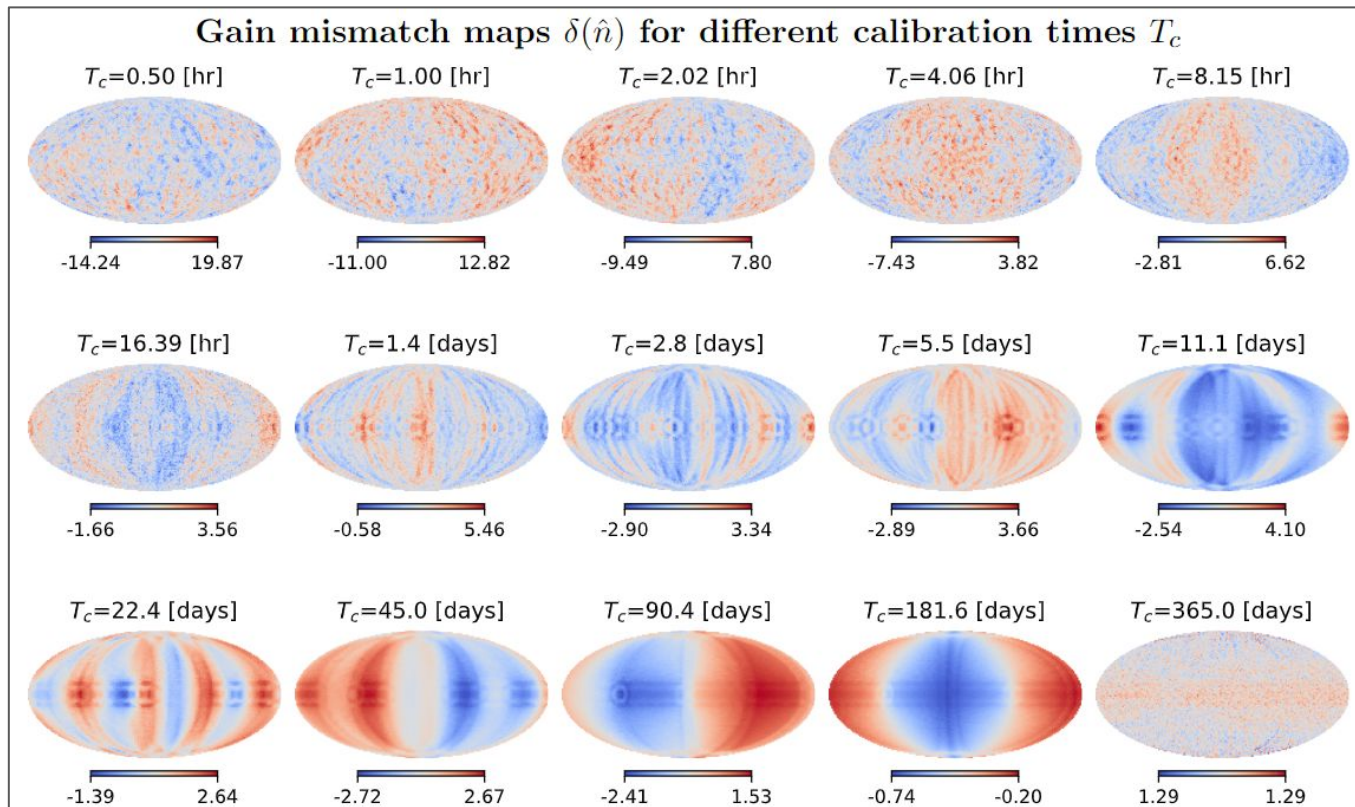


Figure 4: Gain miscalibration maps obtained computing Eq. 4.1 with different re-calibration times and a reference value for $\sigma_{\tilde{g},m} = 1$.

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

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

T. Ghose^{1,2}, T. Matsumori¹, G. Patrino¹, H. Ishino¹, M. Yamaguchi¹

Table 2: A summary of the requirements in terms of the gain calibration accuracy for the CMB satellites. The gain calibration accuracy is required to be better than 0.1%.

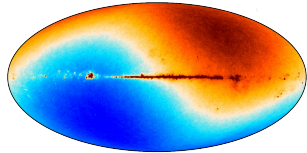
Frequency (GHz)	Gain Calibration Accuracy (%)
100	0.1
143	0.1
160	0.1
220	0.1
230	0.1
245	0.1
270	0.1
280	0.1
300	0.1
330	0.1
350	0.1
370	0.1
390	0.1
410	0.1
430	0.1
450	0.1
470	0.1
490	0.1
510	0.1
530	0.1
550	0.1
570	0.1
590	0.1
610	0.1
630	0.1
650	0.1
670	0.1
690	0.1
710	0.1
730	0.1
750	0.1
770	0.1
790	0.1
810	0.1
830	0.1
850	0.1
870	0.1
890	0.1
910	0.1
930	0.1
950	0.1
970	0.1
990	0.1

Table 3: Requirements on the relative calibration accuracy for the CMB satellites. The relative calibration accuracy is required to be better than 0.1%.

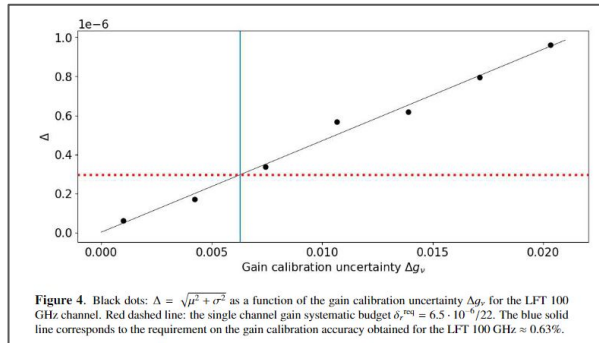
Frequency (GHz)	Relative Calibration Accuracy (%)
100	0.1
143	0.1
160	0.1
220	0.1
230	0.1
245	0.1
270	0.1
280	0.1
300	0.1
330	0.1
350	0.1
370	0.1
390	0.1
410	0.1
430	0.1
450	0.1
470	0.1
490	0.1
510	0.1
530	0.1
550	0.1
570	0.1
590	0.1
610	0.1
630	0.1
650	0.1
670	0.1
690	0.1
710	0.1
730	0.1
750	0.1
770	0.1
790	0.1
810	0.1
830	0.1
850	0.1
870	0.1
890	0.1
910	0.1
930	0.1
950	0.1
970	0.1
990	0.1

From:

$$\text{MAP}_{\text{INPUT}} = (1 + \Delta g) \times$$



Results:



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

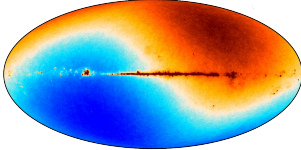
Requirements for future CMB satellite missions: photometric and band-pass response calibration

T. Ghose,^{1,2} T. Matsumori,¹ G. Patanchan,¹ H. Ishino,¹ M. Yamaguchi,¹

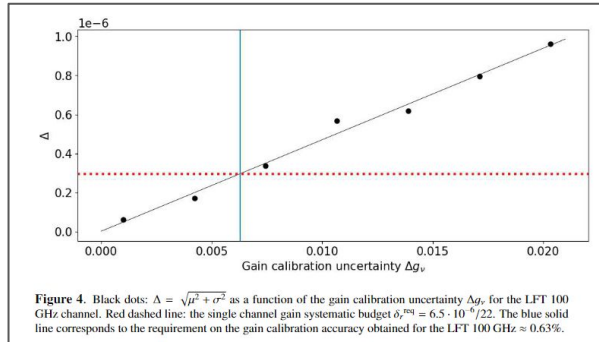
Table 2. A summary of the requirements in terms of the 100 GHz channel gain calibration accuracy for the LFT 100 GHz channel. The number of channels is 100.

Table 3. Requirements on the relative photometric gain calibration for the LFT 100 GHz channel. The number of channels is 100.

From:

$$\text{MAP}_{\text{INPUT}} = (1 + \Delta g) \times \text{Map}$$


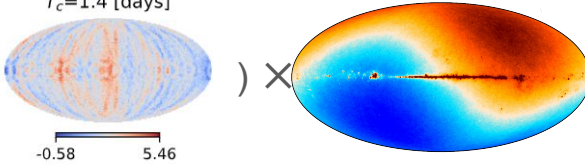
Results:



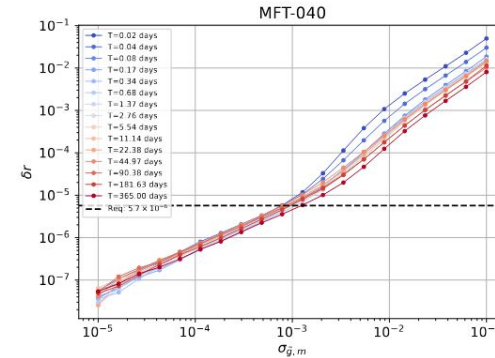
To:

$$\text{MAP}_{\text{INPUT}} = (1 + \Delta g) \times \text{Map}$$

$T_c = 1.4$ [days]



Results:



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

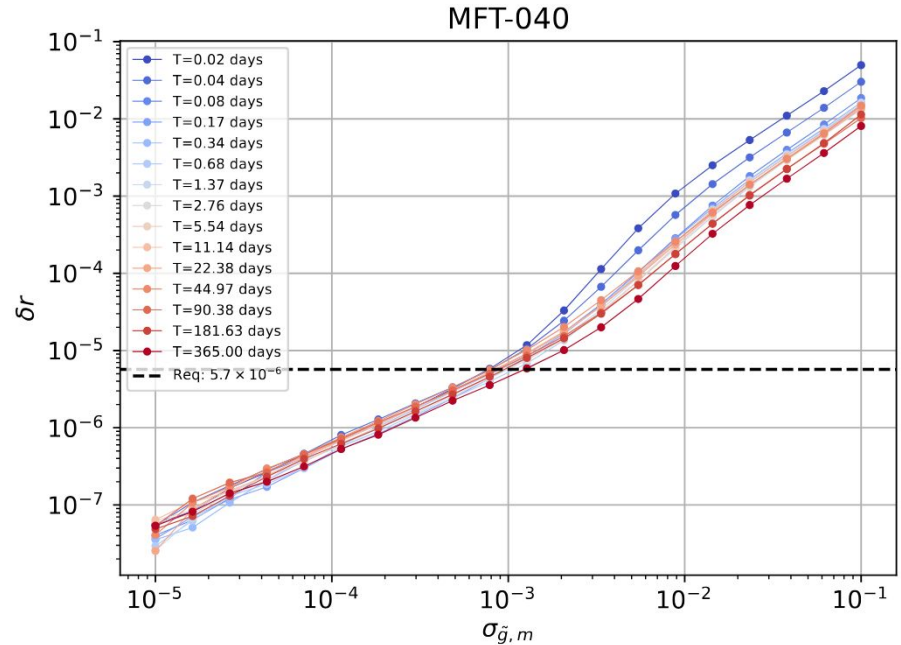
Requirements for future CMB satellite missions: photometric and band-pass response calibration

T. Ghose, T. Majumdar, G. Patanchan, H. Ishino, M. Yamamoto

Channel	Band	Frequency (GHz)	Bandwidth (GHz)	Gain (mK/Jy)	Gain Error (%)	Bandwidth Error (%)	Gain Error (mK/Jy)	Bandwidth Error (GHz)
EPIC1	EPIC1	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC2	EPIC2	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC3	EPIC3	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC4	EPIC4	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC5	EPIC5	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC6	EPIC6	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC7	EPIC7	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC8	EPIC8	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC9	EPIC9	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC10	EPIC10	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC11	EPIC11	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC12	EPIC12	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC13	EPIC13	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC14	EPIC14	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC15	EPIC15	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC16	EPIC16	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC17	EPIC17	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC18	EPIC18	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC19	EPIC19	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC20	EPIC20	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC21	EPIC21	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC22	EPIC22	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC23	EPIC23	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC24	EPIC24	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC25	EPIC25	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC26	EPIC26	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC27	EPIC27	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC28	EPIC28	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC29	EPIC29	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC30	EPIC30	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC31	EPIC31	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC32	EPIC32	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC33	EPIC33	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC34	EPIC34	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC35	EPIC35	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC36	EPIC36	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC37	EPIC37	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC38	EPIC38	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC39	EPIC39	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC40	EPIC40	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC41	EPIC41	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC42	EPIC42	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC43	EPIC43	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC44	EPIC44	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC45	EPIC45	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC46	EPIC46	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC47	EPIC47	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC48	EPIC48	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC49	EPIC49	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC50	EPIC50	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC51	EPIC51	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC52	EPIC52	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC53	EPIC53	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC54	EPIC54	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC55	EPIC55	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC56	EPIC56	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC57	EPIC57	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC58	EPIC58	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC59	EPIC59	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC60	EPIC60	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC61	EPIC61	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC62	EPIC62	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC63	EPIC63	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC64	EPIC64	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC65	EPIC65	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC66	EPIC66	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC67	EPIC67	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC68	EPIC68	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC69	EPIC69	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC70	EPIC70	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC71	EPIC71	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC72	EPIC72	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC73	EPIC73	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC74	EPIC74	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC75	EPIC75	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC76	EPIC76	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC77	EPIC77	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC78	EPIC78	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC79	EPIC79	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC80	EPIC80	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC81	EPIC81	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC82	EPIC82	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC83	EPIC83	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC84	EPIC84	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC85	EPIC85	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC86	EPIC86	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC87	EPIC87	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC88	EPIC88	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC89	EPIC89	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC90	EPIC90	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC91	EPIC91	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC92	EPIC92	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC93	EPIC93	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC94	EPIC94	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC95	EPIC95	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC96	EPIC96	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC97	EPIC97	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC98	EPIC98	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC99	EPIC99	100.000	0.010	0.010	1.0	1.0	0.001	0.001
EPIC100	EPIC100	100.000	0.010	0.010	1.0	1.0	0.001	0.001

RESULTS:

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



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

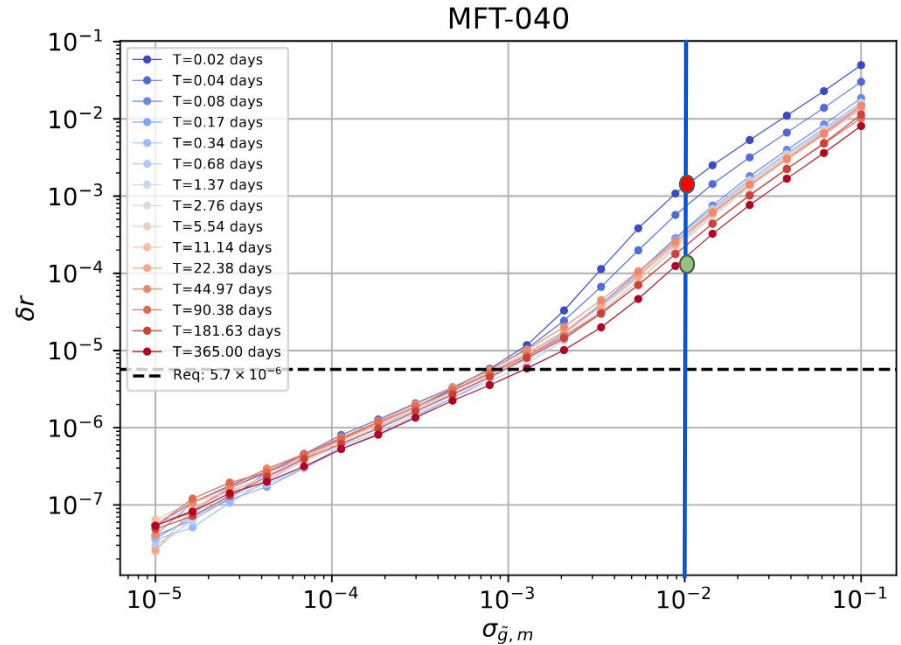
Requirements for future CMB satellite missions: photometric and band-pass response calibration

T. Ghose, T. Majumdar, G. Patanchu, H. Ishino, M. Yamamoto

Channel	Frequency (GHz)	Bandwidth (GHz)	Beam Size (arcmin)	Resolution (arcmin)	Stability (mK)	Calibration Accuracy (mK)
1	30	10	10	10	10	10
2	40	10	10	10	10	10
3	50	10	10	10	10	10
4	60	10	10	10	10	10
5	70	10	10	10	10	10
6	80	10	10	10	10	10
7	90	10	10	10	10	10
8	100	10	10	10	10	10
9	110	10	10	10	10	10
10	120	10	10	10	10	10
11	130	10	10	10	10	10
12	140	10	10	10	10	10
13	150	10	10	10	10	10
14	160	10	10	10	10	10
15	170	10	10	10	10	10
16	180	10	10	10	10	10
17	190	10	10	10	10	10
18	200	10	10	10	10	10
19	210	10	10	10	10	10
20	220	10	10	10	10	10
21	230	10	10	10	10	10
22	240	10	10	10	10	10
23	250	10	10	10	10	10
24	260	10	10	10	10	10
25	270	10	10	10	10	10
26	280	10	10	10	10	10
27	290	10	10	10	10	10
28	300	10	10	10	10	10
29	310	10	10	10	10	10
30	320	10	10	10	10	10
31	330	10	10	10	10	10
32	340	10	10	10	10	10
33	350	10	10	10	10	10
34	360	10	10	10	10	10
35	370	10	10	10	10	10
36	380	10	10	10	10	10
37	390	10	10	10	10	10
38	400	10	10	10	10	10
39	410	10	10	10	10	10
40	420	10	10	10	10	10
41	430	10	10	10	10	10
42	440	10	10	10	10	10
43	450	10	10	10	10	10
44	460	10	10	10	10	10
45	470	10	10	10	10	10
46	480	10	10	10	10	10
47	490	10	10	10	10	10
48	500	10	10	10	10	10
49	510	10	10	10	10	10
50	520	10	10	10	10	10
51	530	10	10	10	10	10
52	540	10	10	10	10	10
53	550	10	10	10	10	10
54	560	10	10	10	10	10
55	570	10	10	10	10	10
56	580	10	10	10	10	10
57	590	10	10	10	10	10
58	600	10	10	10	10	10
59	610	10	10	10	10	10
60	620	10	10	10	10	10
61	630	10	10	10	10	10
62	640	10	10	10	10	10
63	650	10	10	10	10	10
64	660	10	10	10	10	10
65	670	10	10	10	10	10
66	680	10	10	10	10	10
67	690	10	10	10	10	10
68	700	10	10	10	10	10
69	710	10	10	10	10	10
70	720	10	10	10	10	10
71	730	10	10	10	10	10
72	740	10	10	10	10	10
73	750	10	10	10	10	10
74	760	10	10	10	10	10
75	770	10	10	10	10	10
76	780	10	10	10	10	10
77	790	10	10	10	10	10
78	800	10	10	10	10	10
79	810	10	10	10	10	10
80	820	10	10	10	10	10
81	830	10	10	10	10	10
82	840	10	10	10	10	10
83	850	10	10	10	10	10
84	860	10	10	10	10	10
85	870	10	10	10	10	10
86	880	10	10	10	10	10
87	890	10	10	10	10	10
88	900	10	10	10	10	10
89	910	10	10	10	10	10
90	920	10	10	10	10	10
91	930	10	10	10	10	10
92	940	10	10	10	10	10
93	950	10	10	10	10	10
94	960	10	10	10	10	10
95	970	10	10	10	10	10
96	980	10	10	10	10	10
97	990	10	10	10	10	10
98	1000	10	10	10	10	10
99	1010	10	10	10	10	10
100	1020	10	10	10	10	10

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 be convenient to calibrate on longer timescales (lower bias on r)



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

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

T. Ghose,¹ T. Matsumori,² G. Patanchan,³ H. Ishino,⁴ M. Yamamoto,⁵

Table 2. A summary of the requirements in terms of the CMB. The unit of measurement is μK for the temperature and μK for the polarization.

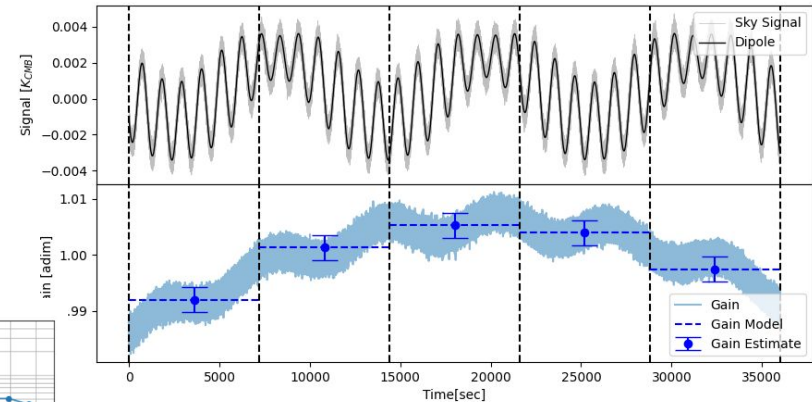
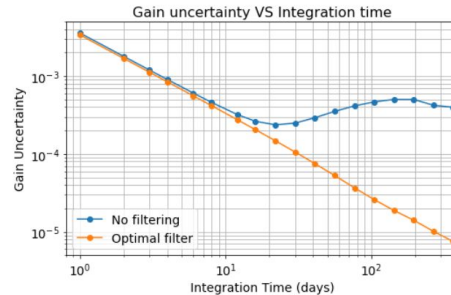
Channel	Frequency	Bandwidth	Gain	Gain Error	Gain Error
1	30.0 GHz	0.5 GHz	0.01	0.01	0.01
2	30.0 GHz	0.5 GHz	0.01	0.01	0.01
3	30.0 GHz	0.5 GHz	0.01	0.01	0.01
4	30.0 GHz	0.5 GHz	0.01	0.01	0.01
5	30.0 GHz	0.5 GHz	0.01	0.01	0.01
6	30.0 GHz	0.5 GHz	0.01	0.01	0.01
7	30.0 GHz	0.5 GHz	0.01	0.01	0.01
8	30.0 GHz	0.5 GHz	0.01	0.01	0.01
9	30.0 GHz	0.5 GHz	0.01	0.01	0.01
10	30.0 GHz	0.5 GHz	0.01	0.01	0.01
11	30.0 GHz	0.5 GHz	0.01	0.01	0.01
12	30.0 GHz	0.5 GHz	0.01	0.01	0.01
13	30.0 GHz	0.5 GHz	0.01	0.01	0.01
14	30.0 GHz	0.5 GHz	0.01	0.01	0.01
15	30.0 GHz	0.5 GHz	0.01	0.01	0.01
16	30.0 GHz	0.5 GHz	0.01	0.01	0.01
17	30.0 GHz	0.5 GHz	0.01	0.01	0.01
18	30.0 GHz	0.5 GHz	0.01	0.01	0.01
19	30.0 GHz	0.5 GHz	0.01	0.01	0.01
20	30.0 GHz	0.5 GHz	0.01	0.01	0.01
21	30.0 GHz	0.5 GHz	0.01	0.01	0.01
22	30.0 GHz	0.5 GHz	0.01	0.01	0.01
23	30.0 GHz	0.5 GHz	0.01	0.01	0.01
24	30.0 GHz	0.5 GHz	0.01	0.01	0.01
25	30.0 GHz	0.5 GHz	0.01	0.01	0.01
26	30.0 GHz	0.5 GHz	0.01	0.01	0.01
27	30.0 GHz	0.5 GHz	0.01	0.01	0.01
28	30.0 GHz	0.5 GHz	0.01	0.01	0.01
29	30.0 GHz	0.5 GHz	0.01	0.01	0.01
30	30.0 GHz	0.5 GHz	0.01	0.01	0.01
31	30.0 GHz	0.5 GHz	0.01	0.01	0.01
32	30.0 GHz	0.5 GHz	0.01	0.01	0.01
33	30.0 GHz	0.5 GHz	0.01	0.01	0.01
34	30.0 GHz	0.5 GHz	0.01	0.01	0.01
35	30.0 GHz	0.5 GHz	0.01	0.01	0.01
36	30.0 GHz	0.5 GHz	0.01	0.01	0.01
37	30.0 GHz	0.5 GHz	0.01	0.01	0.01
38	30.0 GHz	0.5 GHz	0.01	0.01	0.01
39	30.0 GHz	0.5 GHz	0.01	0.01	0.01
40	30.0 GHz	0.5 GHz	0.01	0.01	0.01
41	30.0 GHz	0.5 GHz	0.01	0.01	0.01
42	30.0 GHz	0.5 GHz	0.01	0.01	0.01
43	30.0 GHz	0.5 GHz	0.01	0.01	0.01
44	30.0 GHz	0.5 GHz	0.01	0.01	0.01
45	30.0 GHz	0.5 GHz	0.01	0.01	0.01
46	30.0 GHz	0.5 GHz	0.01	0.01	0.01
47	30.0 GHz	0.5 GHz	0.01	0.01	0.01
48	30.0 GHz	0.5 GHz	0.01	0.01	0.01
49	30.0 GHz	0.5 GHz	0.01	0.01	0.01
50	30.0 GHz	0.5 GHz	0.01	0.01	0.01
51	30.0 GHz	0.5 GHz	0.01	0.01	0.01
52	30.0 GHz	0.5 GHz	0.01	0.01	0.01
53	30.0 GHz	0.5 GHz	0.01	0.01	0.01
54	30.0 GHz	0.5 GHz	0.01	0.01	0.01
55	30.0 GHz	0.5 GHz	0.01	0.01	0.01
56	30.0 GHz	0.5 GHz	0.01	0.01	0.01
57	30.0 GHz	0.5 GHz	0.01	0.01	0.01
58	30.0 GHz	0.5 GHz	0.01	0.01	0.01
59	30.0 GHz	0.5 GHz	0.01	0.01	0.01
60	30.0 GHz	0.5 GHz	0.01	0.01	0.01
61	30.0 GHz	0.5 GHz	0.01	0.01	0.01
62	30.0 GHz	0.5 GHz	0.01	0.01	0.01
63	30.0 GHz	0.5 GHz	0.01	0.01	0.01
64	30.0 GHz	0.5 GHz	0.01	0.01	0.01
65	30.0 GHz	0.5 GHz	0.01	0.01	0.01
66	30.0 GHz	0.5 GHz	0.01	0.01	0.01
67	30.0 GHz	0.5 GHz	0.01	0.01	0.01
68	30.0 GHz	0.5 GHz	0.01	0.01	0.01
69	30.0 GHz	0.5 GHz	0.01	0.01	0.01
70	30.0 GHz	0.5 GHz	0.01	0.01	0.01
71	30.0 GHz	0.5 GHz	0.01	0.01	0.01
72	30.0 GHz	0.5 GHz	0.01	0.01	0.01
73	30.0 GHz	0.5 GHz	0.01	0.01	0.01
74	30.0 GHz	0.5 GHz	0.01	0.01	0.01
75	30.0 GHz	0.5 GHz	0.01	0.01	0.01
76	30.0 GHz	0.5 GHz	0.01	0.01	0.01
77	30.0 GHz	0.5 GHz	0.01	0.01	0.01
78	30.0 GHz	0.5 GHz	0.01	0.01	0.01
79	30.0 GHz	0.5 GHz	0.01	0.01	0.01
80	30.0 GHz	0.5 GHz	0.01	0.01	0.01
81	30.0 GHz	0.5 GHz	0.01	0.01	0.01
82	30.0 GHz	0.5 GHz	0.01	0.01	0.01
83	30.0 GHz	0.5 GHz	0.01	0.01	0.01
84	30.0 GHz	0.5 GHz	0.01	0.01	0.01
85	30.0 GHz	0.5 GHz	0.01	0.01	0.01
86	30.0 GHz	0.5 GHz	0.01	0.01	0.01
87	30.0 GHz	0.5 GHz	0.01	0.01	0.01
88	30.0 GHz	0.5 GHz	0.01	0.01	0.01
89	30.0 GHz	0.5 GHz	0.01	0.01	0.01
90	30.0 GHz	0.5 GHz	0.01	0.01	0.01
91	30.0 GHz	0.5 GHz	0.01	0.01	0.01
92	30.0 GHz	0.5 GHz	0.01	0.01	0.01
93	30.0 GHz	0.5 GHz	0.01	0.01	0.01
94	30.0 GHz	0.5 GHz	0.01	0.01	0.01
95	30.0 GHz	0.5 GHz	0.01	0.01	0.01
96	30.0 GHz	0.5 GHz	0.01	0.01	0.01
97	30.0 GHz	0.5 GHz	0.01	0.01	0.01
98	30.0 GHz	0.5 GHz	0.01	0.01	0.01
99	30.0 GHz	0.5 GHz	0.01	0.01	0.01
100	30.0 GHz	0.5 GHz	0.01	0.01	0.01

RESULTS:

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

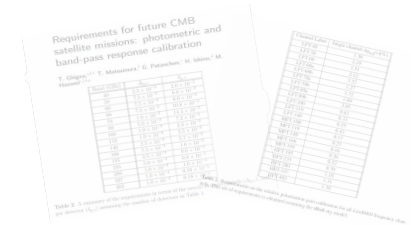
This gives us:

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



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

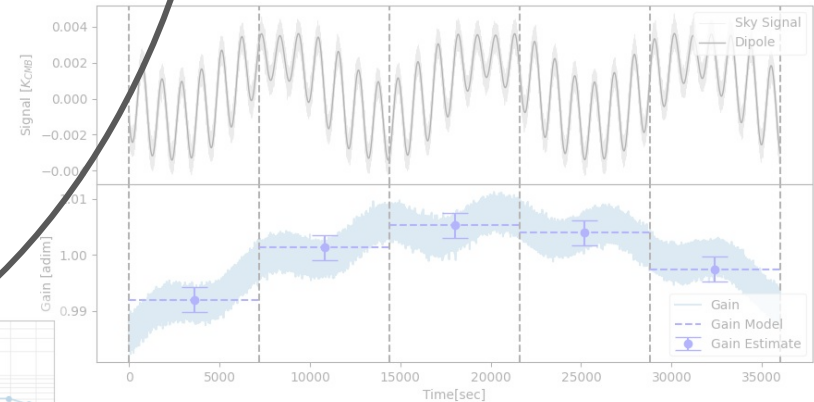
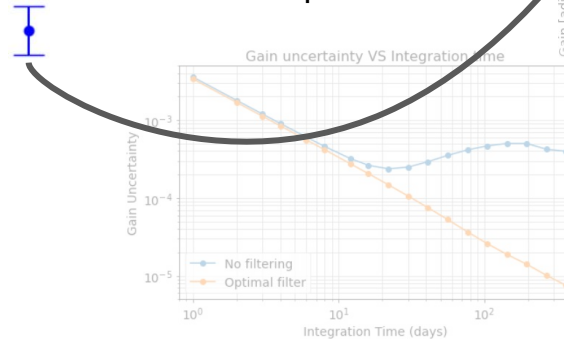


RESULTS:

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

This gives us:

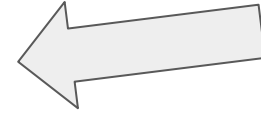
- The optimal calibration time: 20~30 min
- The maximum calibration error that is acceptable in each calibration chunk



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?

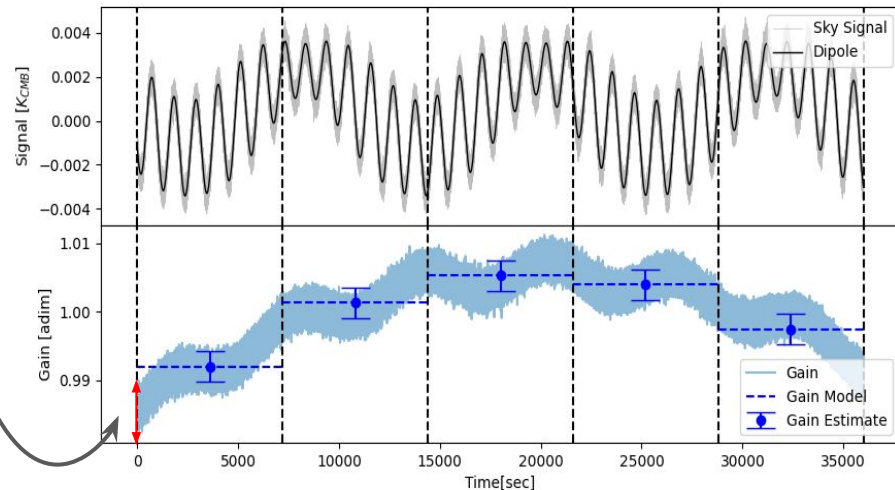


Step 2: What is our requirement on the instrument?

GAIN STABILITY

We can set requirements on:

- The amplitude of noise-like gain fluctuations P_G

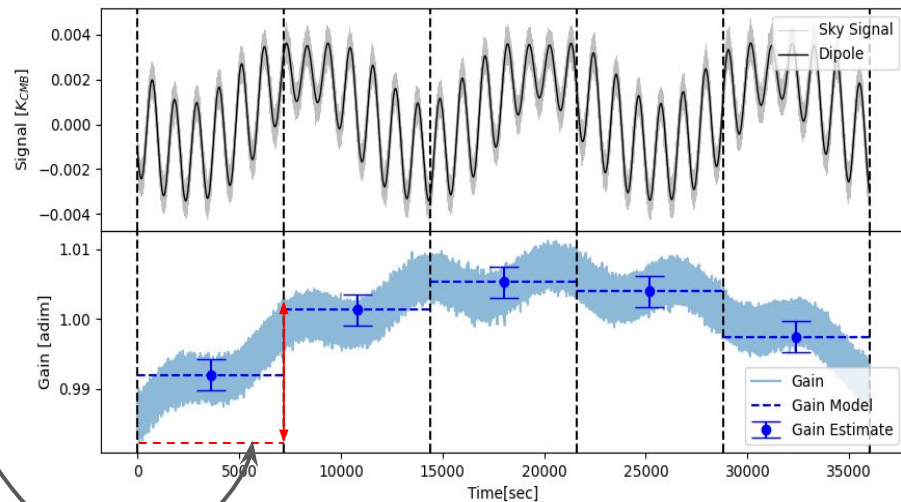


Step 2: What is our requirement on the instrument?

GAIN STABILITY

We can set requirements on:

- The amplitude of noise-like gain fluctuations P_G
- Systematic gain fluctuations on a 20-min timescale δ_{MAX}



Step 2: What is our requirement on the instrument?

GAIN STABILITY

We can set requirements on:

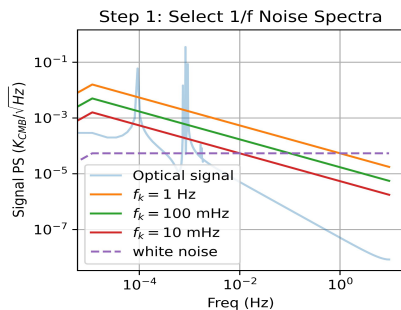
- The amplitude of noise-like gain fluctuations P_G
- Systematic gain fluctuations on a 20-min timescale δ_{MAX}

INSTRUMENT NOISE

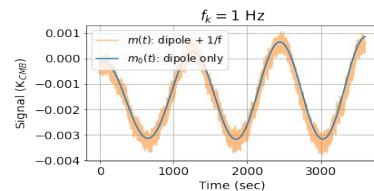
We can set requirements on:

- The amplitude of $1/f$ noise P_N

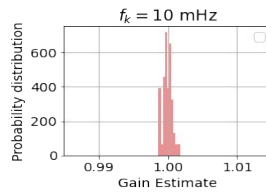
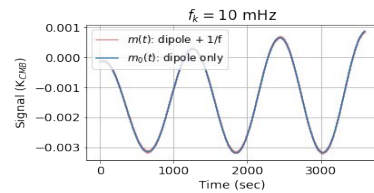
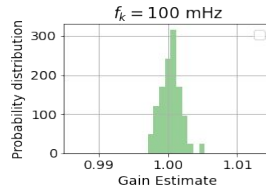
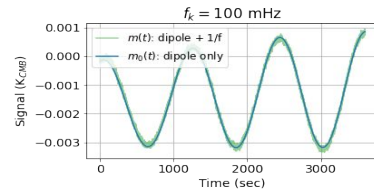
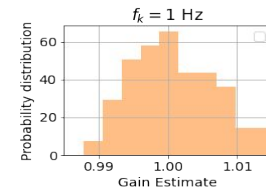
- $1/f$ Noise with different values of f_k



- Simulate TOD



- Calculate Uncertainty on our gain estimate



Step 2: What is our requirement on the instrument?

GAIN STABILITY

We can set requirements on:

- The amplitude of noise-like gain fluctuations P_G
- Systematic gain fluctuations on a 20-min timescale δ_{MAX}

INSTRUMENT NOISE

We can set requirements on:

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

Step 2: What is our requirement on the instrument?

GAIN STABILITY

We can set requirements on:

- The amplitude of noise-like gain fluctuations P_G
- Systematic gain fluctuations on a 20-min timescale δ_{MAX}

INSTRUMENT NOISE

We can set requirements on:

- The amplitude of 1/f noise P_N
 - It is best summarized by the amplitude of
 - Can be converted into maximum thermal f

Requirements using FgBuster

Band [GHz]	Gain stability		Detectors' noise	
	P_G [1/ $\sqrt{\text{Hz}}$]	δ_{MAX} [adim]	$P_N(f_{dip})$ [$\mu\text{K}_{\text{CMB}}/\sqrt{\text{Hz}}$]	$A_T(f_{dip})$ [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}

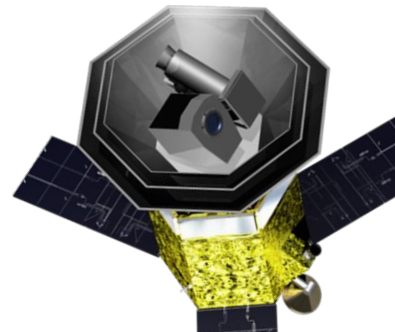
Table 2: Gain calibration requirements for the LiteBIRD satellite using parametric methods for component separation. The requirements have been derived for:

- 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.

Gain calibration requirement for each LiteBIRD frequency band

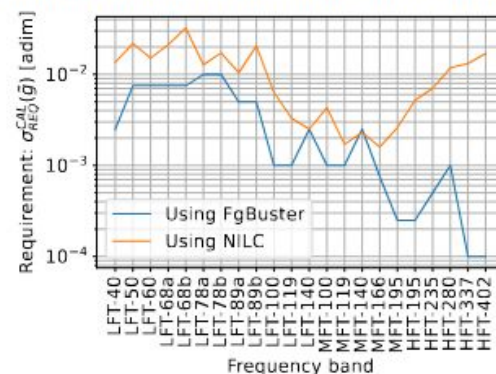


Figure 1: Gain calibration requirements for each LiteBIRD frequency band. The blue line shows the results obtained in [1] performing the component separation with `fgbuster` while the orange line shows the results obtained in [2] using NILC.

Requirements using NILC

Band [GHz]	Gain stability		Detectors' noise	
	P_G [1/ $\sqrt{\text{Hz}}$]	δ_{MAX} [adim]	$P_N(f_{dip})$ [$\mu\text{K}_{\text{CMB}}/\sqrt{\text{Hz}}$]	$P_T(f_{dip})$ [mK/ $\sqrt{\text{Hz}}$]
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

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

Data model
sky emission (all sources)
noise

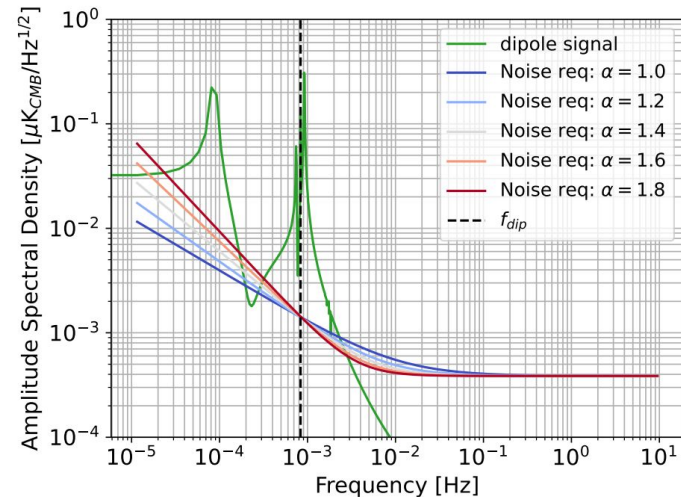
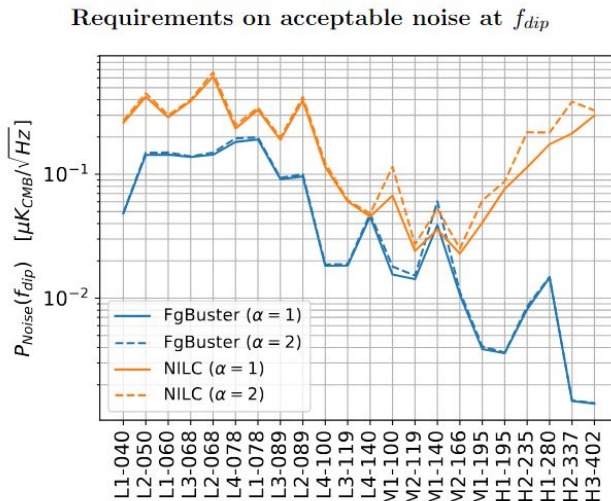
And convolve it with a reference signal:

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

gain estimate
noise term

Results:

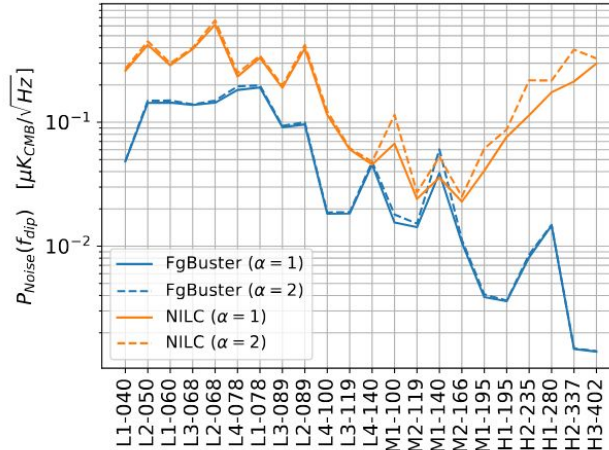
- The requirements on the noise level can be summarized into a requirement on the noise at the dipole frequency: $\mathbf{P}_N(\mathbf{f}_{\text{DIP}})$
 - (removes any dependency from the noise power spectrum shape)



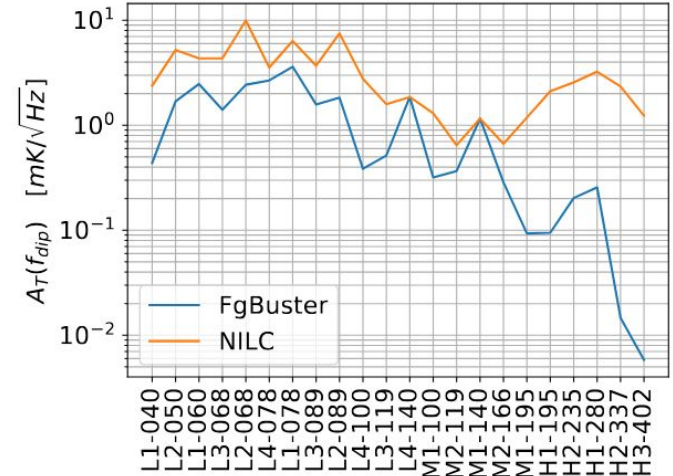
Results:

- The requirements on the noise level can be summarized into a requirement on the noise at the dipole frequency: $\mathbf{P}_N(\mathbf{f}_{\text{DIP}})$
 - (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: $\mathbf{A}_T(\mathbf{f}_{\text{DIP}})$

Requirements on acceptable noise at f_{dip}



Requirements on acceptable thermal fluctuations at f_{dip}





That's all Folks!

Thank you for the attention