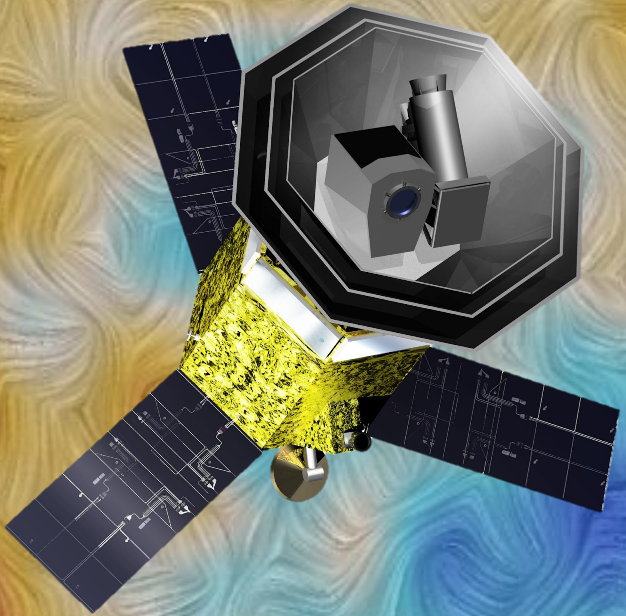
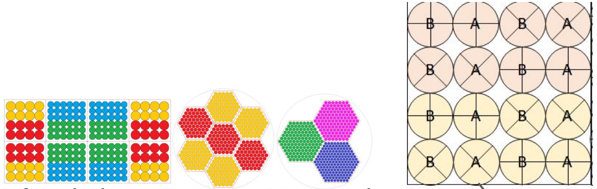


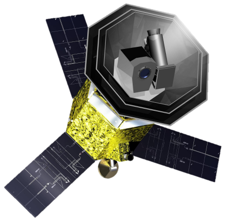
LiteBIRD: (instrumental) Systematics and Calibration

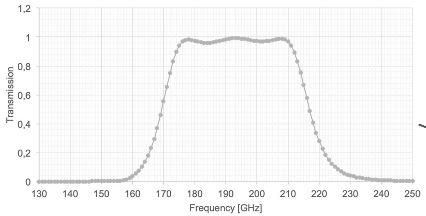
Sophie Henrot-Versillé on behalf of the LiteBIRD collaboration

To get to r we need to know our instruments

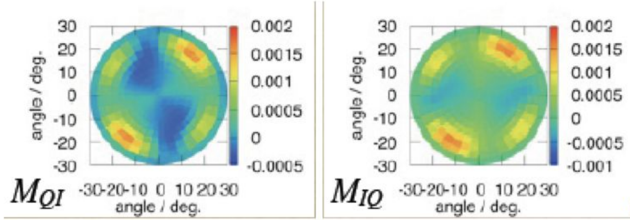


focal plane arrangement + polarisation (credit: Toki)

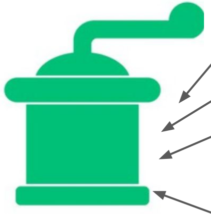




Bandpass (credit: Toki)

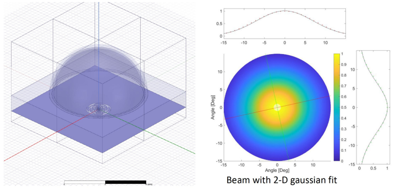


HWP (credit: Hiroaki)

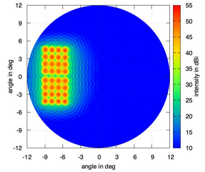


data analysis

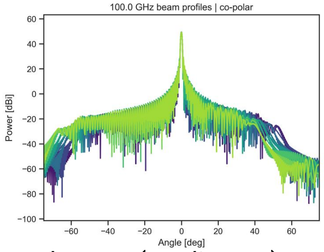
r



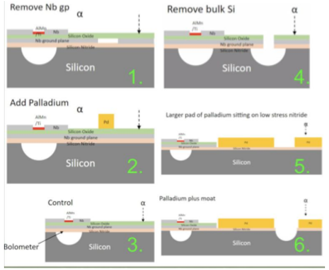
beam former (credit: Aritoki)



beams (credit: Hiroaki)

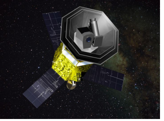


beams (credit: Jon)

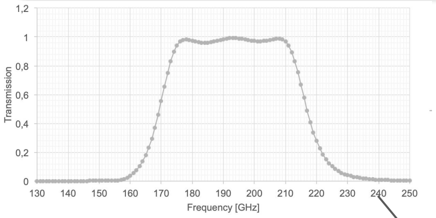


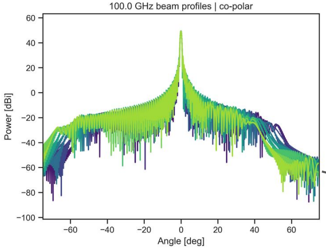
Cosmic Rays
(credit: S. Beckman, A. Lee)

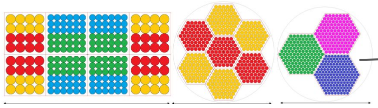
LiteBIRD

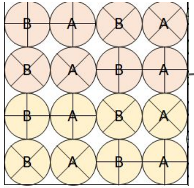


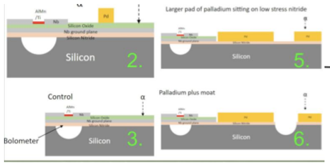
Otherwise….











Name	Origin	Description	Major mode of Leakage
Bandpass Mismatch	Spectral Filters	Edges and shape of the spectral filters vary from detector to detector.	I -> P
Beam Mismatch and Asymmetry	Optical beams	Beam shape differs from an ideal Gaussian form.	I -> P E -> B
Pointing Uncertainty	Attitute control, pointing reconstruction	Detector pointing at location different from that given by reconstructed pointing data.	I -> P E -> B
Polarisation Misalignment	Detectors	Uncertainty in polarisation calibration. Polarisation axis misaligned with measured direction.	E -> B
Gain mismatch and stability	Detectors and Calibration	Gain calibration mismatch between detectors. These could also be variable over time	I -> P

LiteBIRD

From Ranajoy Banerji

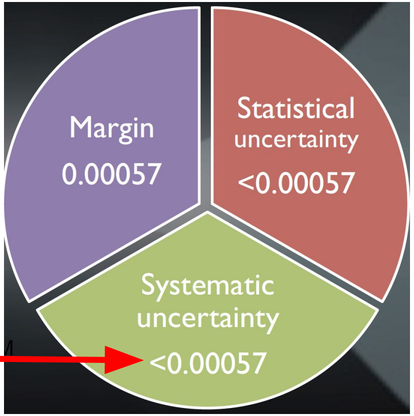
Up to which level ?

We want to measure r with an accuracy of (68%CL):

$$\sigma_r = 0.001$$

Assuming:

$$(\sigma_r = 0.001)^2 = \sigma^2_{\mathbf{syst}} + \sigma^2_{\mathbf{fg}} + \sigma^2_{\mathbf{margin}}$$



For each potential source of instrumental systematics:

1. We assign an error budget:
   $\sigma(r)_{sys} < 5.7 \times 10^{-6}$ as the budget (1% of total budget for systematic error)

2. From this we derive a requirement on the knowledge of the underlying instrumental parameters.

3. Those requirements are used to best define the calibration method.

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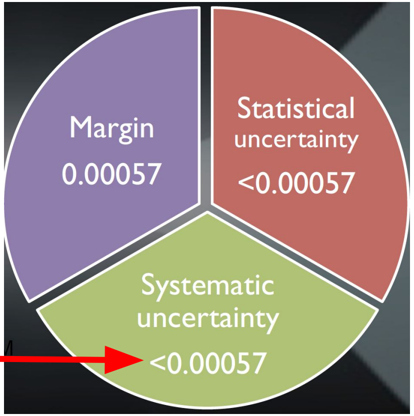

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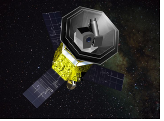
Systematics JSG !

Calibration JSG !



A lot of studies have been performed

ID	Item	sub-ID	Source	w/o HWP	w/ HWP	Comment
6	Beam shape	6-1	Far side-lobes	√	√	Beam knowledge: Leakage mainly from E to B, T to B may contribute
		6-2	Near side-lobes	√	√	Beam knowledge
		6-3-1	Main beam width	√	√	Knowledge of the beam width
		6-3-2	Main beam flattening	√	√	Main beam ellipticity knowledge
		6-4	Ghost		√	Effect happening inside the 5K shell
		6-5	cross polarization w/ HWP		√	Requirement to the knowledge of the cross pol characteristics in beam
		6-6	Diff. Beam Pointing btw. det.	√		Leakage from T to B
		6-7	Diff. Beam ellipticity btw. det.	√		Leakage from T to B
		6-8	Diff. Beam width btw. det.	√		Leakage from T to B
		6-9	Diff. Cross-pol btw. det.	√		Leakage from E to B, similar to the pol. angle offset
		6-10	Diff. Side-lobes btw. det.	√		Leakage from T to B
7	Instrumental polarization	7-1	HWP at $4f$		√	Knowledge of $4f$ signal
		7-2	HWP at $4f$ side-band		√	Direct leakage to the science band
		7-3	HWP at $2f$ leakage		√	Leakage from $2f$ to $4f$ due to finite observing time and non-linearity
		7-4	HWP at harmonics		√	Lekakage from $3f$, $5f$ and so on to $4f$
		7-5	Optical system	√		Differential effect in the optical system
8	Polarization efficiency	8-1	HWP modulation efficiency		√	Knowledge of the HWP modulation efficiency
		8-2	Detector polarization efficiency	√	√	Knowledge of the detector polarization efficiency
9	Relative Gain	9-1	Variation in time (random)	√	√	Random variation per 600sec.
		9-2	Variation in time (1/f noise like)	√	√	Requirement in $f_{\rm knee}$
		9-3	Inter frequency channels	√	√	Related to FG subtraction, and Band pass effect ID=15
		9-4	Diff. gain btw. det.(bias)	√		Leakage from T to B
		9-5	Diff. gain btw. det. (random)	√		Leakage from T to B
10	Absolute Gain	10-1		√	√	No E to B as Parity conserved. Related to the Pol. efficiency in ID=8 Calibration with CMB dipole. Absolute power of Cl, i.e., the absolute value of r
11	Pointing	11-1	Offset	√	√	E to B Expectation value from Vender's info.
		11-2	Time variation in random	√	√	Disturbances in time uncorrelated way: Perhaps in a way that all the FC plane detector coherently
		11-3	Time variation in time with $1/f$	√	√	Disturbances in time correlated way:
		11-4	Time variation with HWP rotation		√	Wedge in transmissive HWP, tilt of the rotation axis of reflective HWP
12	Polarization angle	12-1	Absolute Polarization angle	√	√	Using CMB channels with C_l^{EB}.
		12-2	Relative Polarization angle	√	√	Inter frequency channels, inter detectors
		12-3	Polarization leakage intrinsic to HWP		√	knowledge of M_{QU} or M_{UQ} in Mueller matrix
		12-4	Polarization leakage due to HWP position error		√	Requirement to the knowledge to the HWP rotation position
		12-5	Variation in time (white like, 1/f like)	√	√	Variance of pol. angle determination by STT
13	1/f noise	13-1	Individual Detector w/o HWP	√		Detector originated
		13-2	Individual Detector after demodulation		√	in req. flow L3.08 1/10 of white noise at the spin frequency 0.1rpm=1.6mHz
		13-3	Common mode	√		Common mode in FP
		13-4	Inter channels	√		With FG component separation
		13-5	Noise modeling	√	√	Requirements to determine the noise stationarity; how long period the noise to be stable
		13-6	HWP temperature variation in time with $1/f$ like for monopole		√	Loading from HWP changes the detector noise, the time correlated variation would cause the 1/f noise
		13-7	HWP temperature variation in time with $1/f$ noise for $2f$		√	Differential emissivity in the two axes will produce $2f$ signal. The $1/f$ time variation of HWP temperature produces the fluctuation of the $2f$ which may be leaked to the $4f$. Note that the multi-layer stacked AHWP may smear out this effect.
14	Cosmic ray glitches	14-1	Common mode	√	√	Wafer base due to phonon propagation
		14-2	Data acquisition (including data compression)	√	√	Additional noise due to down-sampling, Data compression
15	Band pass effect	15-1-1	Frequency shift of the band w/o HWP in differentiation.	√		Band shift in a detector pair
		15-1-2	Frequency shift of the band	√	√	Knowledge of the band position
		15-2-1	Band shape w/o HWP	√		Diff. of the band shape in a detector pair
		15-2-2	Band shape	√	√	Knowledge of the band shape
		15-3-1	Beam shape in band w/o HWP	√		Diff. of frequency dependence of beam shape in band, caused by the spectrum difference. Calibration using planets may cause difference
		15-3-2	Beam shape in band	√	√	Frequency dependence of beam shape in band, caused by the spectrum difference. Calibration using planets may cause difference
		15-4-1	Pol. angle wobble in band	√	√	Sinuous antenna wobble, may be canceled out using combination of Q/U and two sides
		15-5	Gain variation in band	√	√	Gain calib. using CMB dipole may differ from that of FG due to spectrum diff.
		15-6	Instrumental Polarization in band		√	Frequency dependence of IP in HWP
		15-7	Polarization efficiency in band		√	Related to the frequency dependence of the HWP retardance and/or sinuous antenna responsivity
		15-8	Outer band	√	√	Contamination from the outside of frequency band.
16	Transfer function	16-1	Detector time constant knowledge	√	√	Detector time constant
		16-2	Digital filter in readout system	√	√	Possible effect in time correlated way which cause the spatial correlation
		16-3	Cross-talks	√	√	Cross-talks in frequency domain
		16-4	Time constant variance in time coupled to HWP revolution		√	random 1/f type variation in time
17	Non-linearity	17-1	Detector response: parameterized as g in a model of $(1+gd(t))d(t-\tau d(t))$	√	√	Assuming maximal loading to the instrument in uK to set the working position
		17-2	Variation in time on g, white like or $1/f$ like	√	√	Non-stationarity of the non-linearity due to the change of the loading position
		17-3	HWP $2f$ synchronous: leakage from $2f$ to $4f$		√	May be related to ID=7, causing leakage to $4f$, due to large $2f$ signal, To be related 2f emission in 18-1-2
		17-4	time constant τ [sec/uK] in the PB model $(1+gd(t))d(t-\tau d(t))$	√	√	Knowledge of the time response τ
		17-5	Variation in time of τ in a white like or $1/f$ like	√	√	Possible time dependence of the time constants
		17-6	Data Compression	√	√	Possible effect in data compression process
18	Non-uniformity in HWP	18-1-1	Transmissive HWP		√	Azimuthal angle dependence in oblique incidence of light
		18-1-2	Differential emissivity of transmissive HWP		√	Production of $2f$ signal, can be leaked to $4f$ with the position dependence.
		18-2	Reflective HWP		√	Azimuthal dependence in oblique incident angle. We will not consider this source.
		18-3	Position dependent HWP temperature fluctuation in white noise like		√	Increase the detector noise. We do not consider this source as this is related to the reflective HWP.
19	Uncertainties difficult to model and simulate	19-1	Multiple reflection between HWP and FP		√	Requirement to HWP AR. Two ways: back-of-the envelope calculation to get first order req. In GRASP, the multiple reflection with HWP is difficult to simulate. One way is to measure the beam pattern w/ and w/o HWP using the real instruments.
		19-2	$f_{\rm knee}$	√		$1/f$ noise $f_{\rm knee}$ is unknown unless the real instruments are tested, assigned for the case w/o HWP
		19-3	Gain variation	√	√	Actual gain variation strongly depend on the instrument environment, and difficult to model in a simulation
		19-4	FG spectrum and unknown components	√	√	Unknown features of the spectra and components in foregrounds

Table 4.1. List of sources of systematics identified so far. We add mark(s) to individual systematic sources relevant to the options with and without HWP. The column of Δr or σ_r shows the expected error of r. Details are given in each section. N.A. means "Not Available" for the sources that we have not yet studied and assign the 1% error budget of 5.6×10^{-6} as the requirement. The ID=13 ($1/f$ noise) shows the σ_r values, while other sources show Δr values.

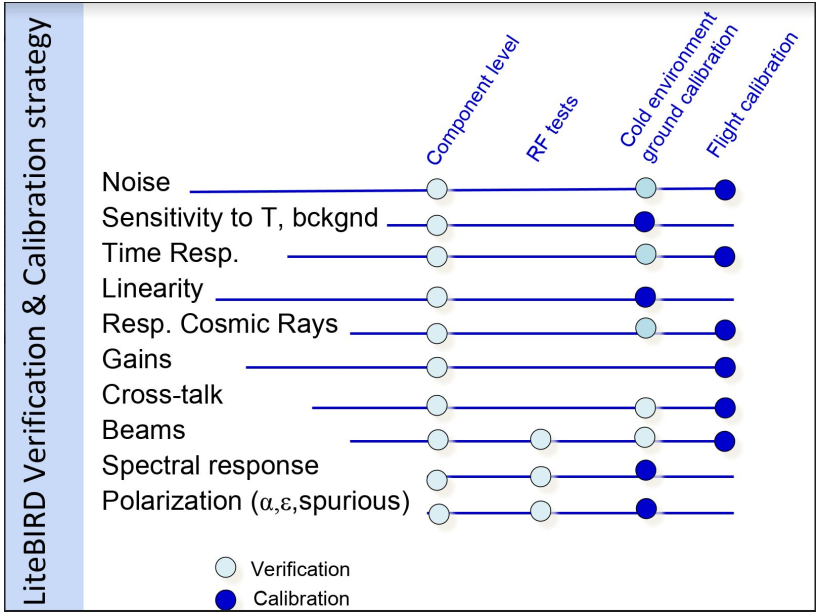
credit: Concept Design Report

The requirements are being and will be updated and further refined

How ? verification and calibration strategy

To reach the required accuracies the calibration strategy is setup in several steps. We will rely on measurements:

- on the ground and in-flight
- from component level to full integrated instruments



LiteBIRD verification and calibration strategy

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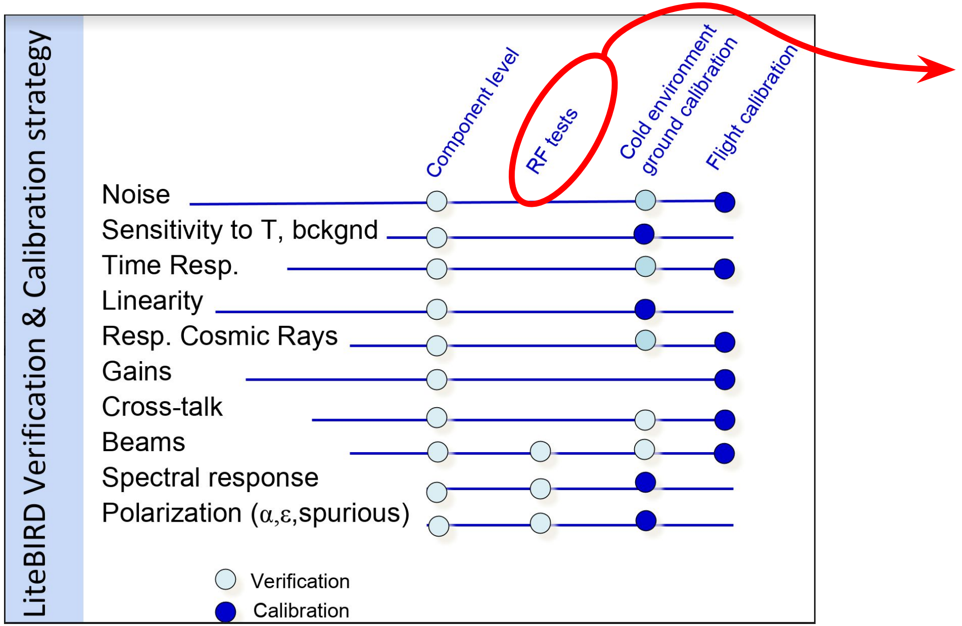

RF tests for beam characterization

LiteBIRD

LiteBIRD verification and calibration strategy

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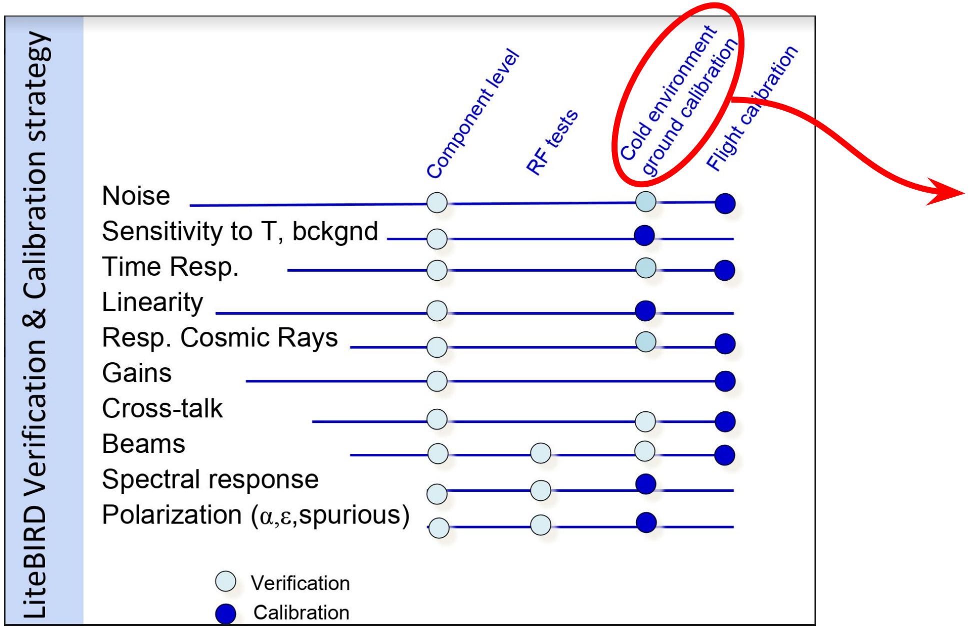

RF measurements for beam characterization

Cold environment “flight-like” loading conditions on the instruments+calibration sources in a big cryogenic facility

LiteBIRD verification and calibration strategy

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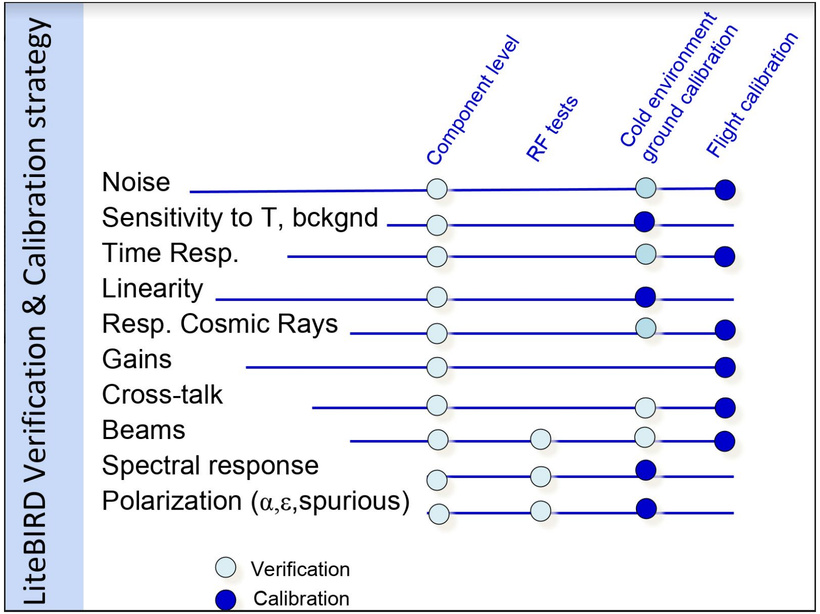


RF tests for beam characterization

Cold environment "flight-like" loading conditions on the instruments+calibration sources in a big cryogenic facility

=> In this talk I will focus on:

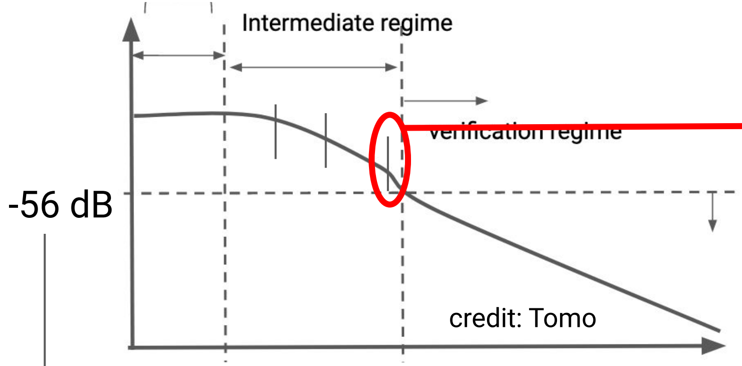
- Beams
- Spectro-polarimetry

(and will not address component level tests)

LiteBIRD

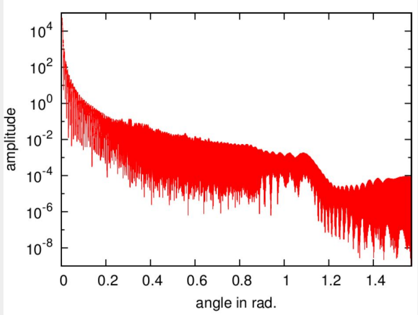
beams requirements

credit: Ryo and Davide

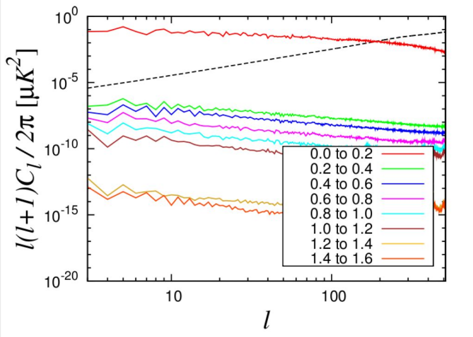


Far side lobes requirements

Power spectra of the foreground contamination leaks through the FSL



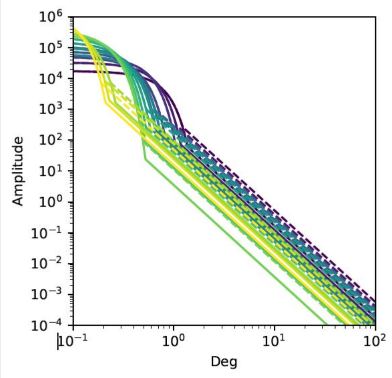
a) 100GHz beam function.



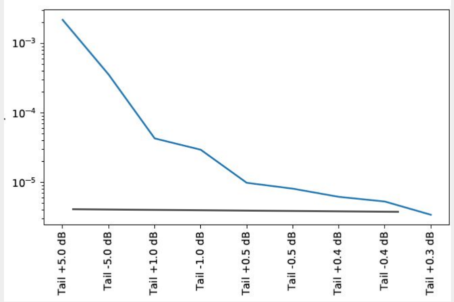
=> need to know the beams down to -56dB

Side lobes requirements

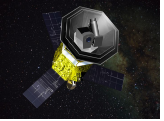
1- Simulate a mismatch between the data (dashed) and the model used to analyse them (solid line)



2- s(r)=f(effect)



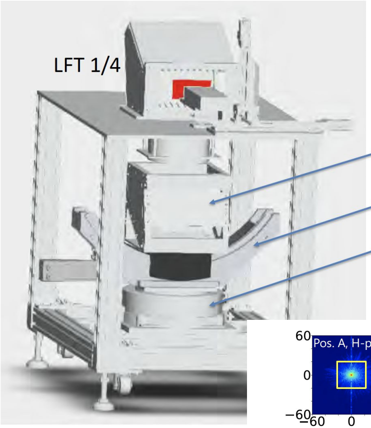
=> the regime between -20 and -35 dB has to be determined to better than 10%.Need to be checked at all frequencies



RF ground measurements for LFT

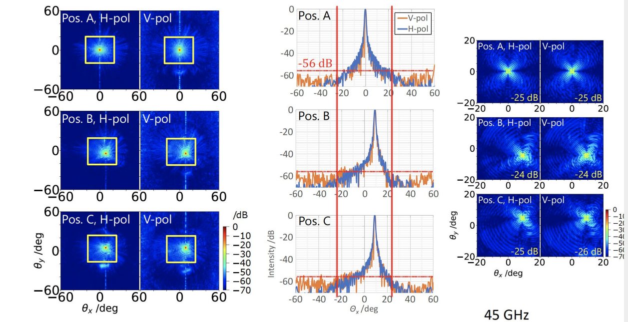
The full strategy is being addressed and further refined with on-going measurements in Japan

In the last months: **very successful** measurements of beams at warm temperature on a small scale LFT model



	Angular range
Reference antenna FoV	±2 deg
Gonio stage	± 25 degree
Az rotor	± 180 degree
Total	± 25 degree

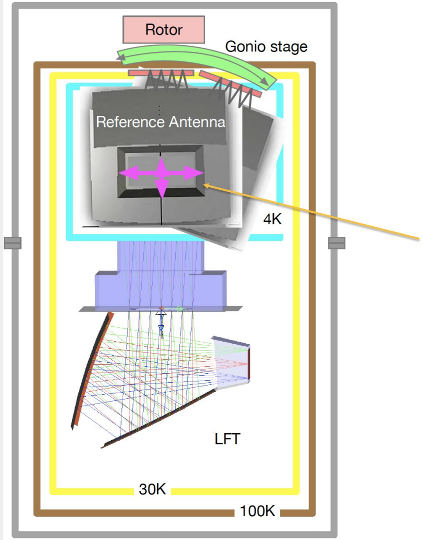
019/06/12



2019/06/12 Hayato Takakura et al. 7

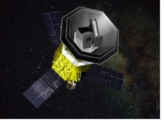
=> Next steps: cold measurements

Reference antenna + Gonio + Az rotor



	Angular Range
Reference antenna FoV	±10 deg x ±2 deg
Gonio stage	-1 ~ +15 degree
Az rotor	± 180 degree
Total	± 25 degree

2019/06/12 credit: Yutaro 5



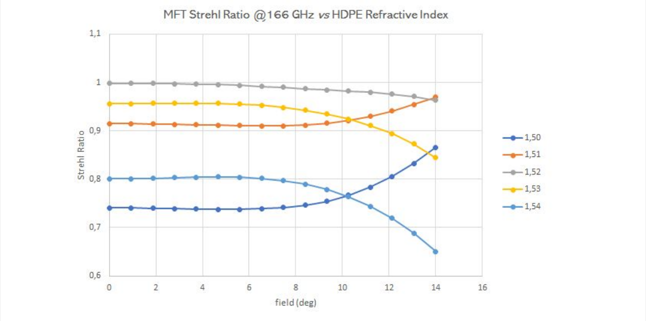
RF ground measurements for MHFT

credit: the MHFT RF working group +CNES
Bruno, Jon, Cristian, Hiro, Marco, Marco

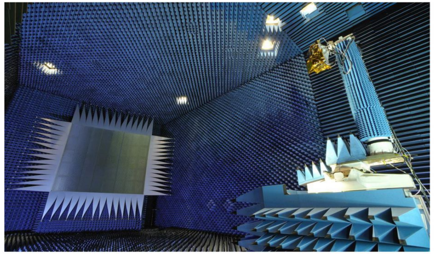
We are currently studying the best strategy, to build up a model fed with:

- sub-system, semi-integrated and integrated level measurements
- warm/cold measurements

Strehl ratio for various refraction indices of lenses (typical of cold->warm variations)



Examples of on-going studies

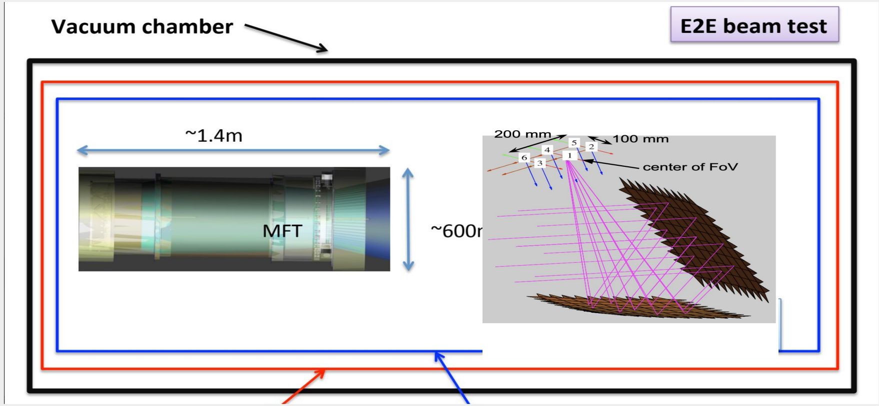


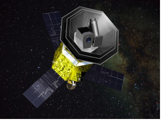
Modèle de vol de Saphir, instrument du satellite Megha-Tropiques, en essais en BCMA.

Antenna models will be built from MHFT beam simulations provided by Jon for 100, 166, 195, 280 and 402 GHz (reminder: the BCMA - Base Compacte de Mesure d'Antenne - needs to be upgraded to match the higher frequencies)

Those models will be further tested & characterized with the use of submm sources, and the measurement compared to the model to assess the accuracy that can be reached for LiteBIRD. [feasibility study]

This will be performed in the coming months.





bandpass knowledge requirements

credit: Tommasso

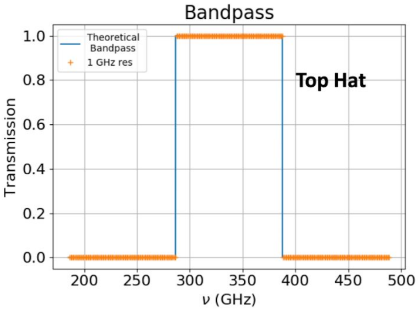
$$d = \boldsymbol{g}(I_{cmb} + \boldsymbol{\gamma_d} I_d + \boldsymbol{\gamma_s} I_s) \pm \boldsymbol{g}\varepsilon[(Q_{cmb} + \boldsymbol{\gamma_d} Q_d + \boldsymbol{\gamma_s} Q_s)cos2\varphi + (U_{cmb} + \boldsymbol{\gamma_d} U_d + \boldsymbol{\gamma_s} U_s)sin2\varphi] + n$$

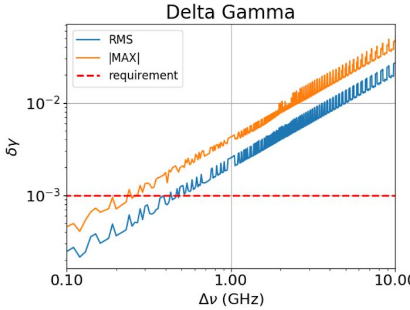
If $\boldsymbol{g}$ can be calibrated well enough using Dipole, $\boldsymbol{\delta_g}$ is dominated by $\boldsymbol{\delta_\gamma}$. We need to determine a bandpass measurement resolution that satisfies the requirement.

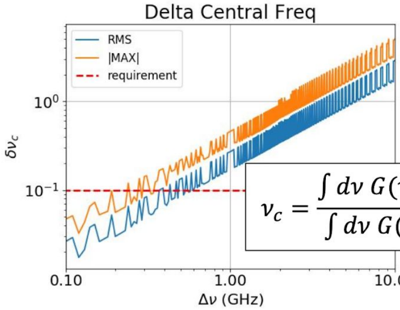
$$\gamma_d = \frac{I_{cmb}(\nu_0)}{I_d(\nu_0)} \frac{\int d\nu\, G(\nu) I_d(\nu)}{\int d\nu\, G(\nu) I_{cmb}(\nu)} \longrightarrow \delta\gamma = \frac{\gamma_{\Delta\nu} - \gamma_0}{\gamma_0}$$

Most stringent requirement is coming from channel 337 GHz (dust dominated): $\boldsymbol{\delta_g \sim 0.001}$.

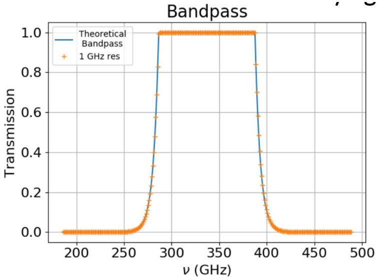
relative calibration of foreground wrt CMB

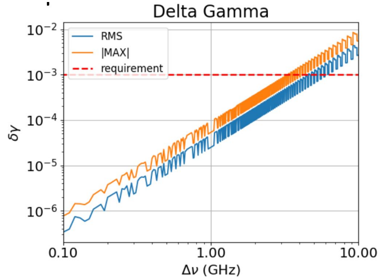






$$\nu_c = \frac{\int d\nu\, G(\nu)\, \nu}{\int d\nu\, G(\nu)}$$





Worst case scenario (top hat function):

- measurement resolution of the order of 0.5GHz
- driven by the 337 and 402GHz channels.

polarisation angle requirements

credit: Patricio & Enrique, Tommaso

The polarization angle requirements on each frequency induced by the component separation process:

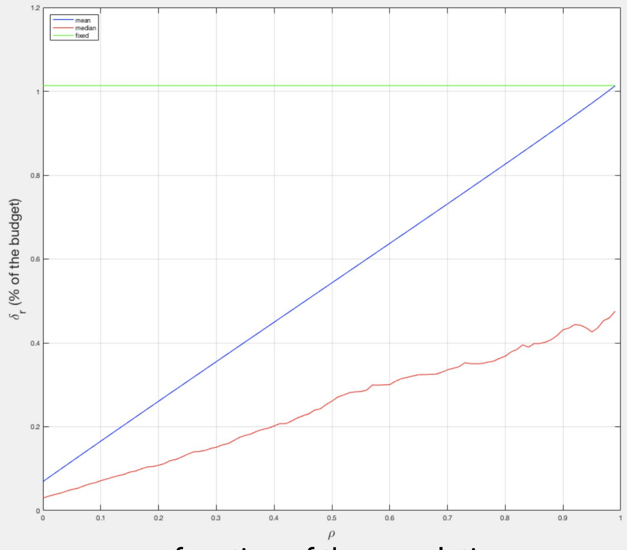
$$s(p) = \sum_{\nu=1}^{15} \omega_\nu d_\nu(p)$$

Estimated CMB (both, Q and U Stoke's parameters) at position *p*

Weight given at each frequency ν (pixel independent)

Data at **frequency** ν and position *p*

ν(GHz)	α [arcmin] Updated Table 4.8 from CDR
40	63.6469
50	26.7163
60	17.2348
68	6.5142
78	4.3463
89	3.2250
100	1.7644
119	0.8153
140	0.8818
166	1.2091
195	1.5080
235	4.8186
280	8.7949
337	20.2555
402	101.8234
δ_r (% sys.)	1.014



as a function of the correlation between freq.channels

=> The absolute polarization angle should be known with a resolution of the order of the arcmin (the requirements are driven by the 119 and 140GHz frequency bands)

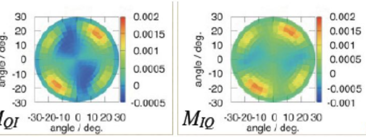
HWP related systematics

credit: Hiroaki & Guillaume

- Mueller matrix coefficients are estimated from the simulations. Decomposed in three terms:

$$M = \begin{pmatrix} M_{II} & M_{QI} & M_{UI} & M_{VI} \\ M_{IQ} & M_{QQ} & M_{UQ} & M_{VQ} \\ M_{IU} & M_{QU} & M_{UU} & M_{VU} \\ M_{IV} & M_{QV} & M_{UV} & M_{VV} \end{pmatrix}$$

$$M(\Theta, \rho - \psi) = A + B_0(\Theta)\cos(2\rho - 2\psi + \phi_B) + C_0(\Theta)\cos(4\rho - 4\psi + \phi_C)$$



The 4f terms are potentially biasing the B-mode spectra since they are modulated as the polarization signal. IP Imperfections at $4f_{HWP}$ of the order of 5. 10^{-5}

At 140 GHz, for $\Theta = 9^{o}$ (extreme case)

$$(C_{XY}) = \begin{pmatrix} 1.492 \times 10^{-6} & 5.471 \times 10^{-5} & 5.496 \times 10^{-5} & 1.586 \times 10^{-6} \\ 5.262 \times 10^{-5} & 9.769 \times 10^{-1} & 9.766 \times 10^{-1} & 2.422 \times 10^{-2} \\ 5.295 \times 10^{-5} & 9.767 \times 10^{-1} & 9.764 \times 10^{-1} & 2.421 \times 10^{-2} \\ 1.420 \times 10^{-6} & 2.099 \times 10^{-2} & 2.098 \times 10^{-2} & 5.204 \times 10^{-4} \end{pmatrix}$$

Credit: H. Imada

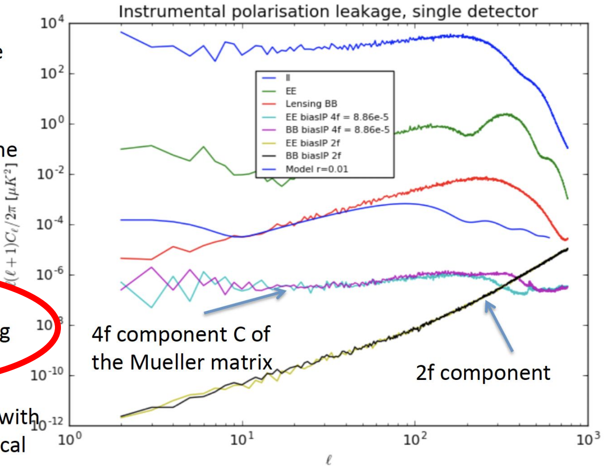
Evaluation of the effect on power spectra

- Simulations with CMB only
- Single detector, edge of the focal plane
- Use the full M matrix
- Assume an ideal HWP for the reconstruction

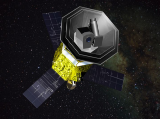
→ 4f components have more impact on the sky

→ Instr. polar. of 5. 10^{-5} gives roughly 1% of the BB lensing signal

→ Having a scanning strategy with many orientations of the focal plane reduces the effect



→ Combining several detectors at different locations of the focal plane reduces the effect since it is observed with different phases



Spectro-polarimetry ground measurements

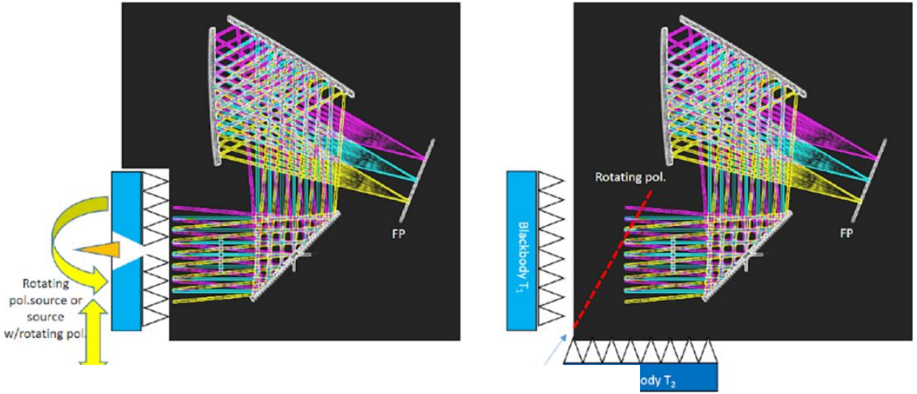
credit: Giorgio

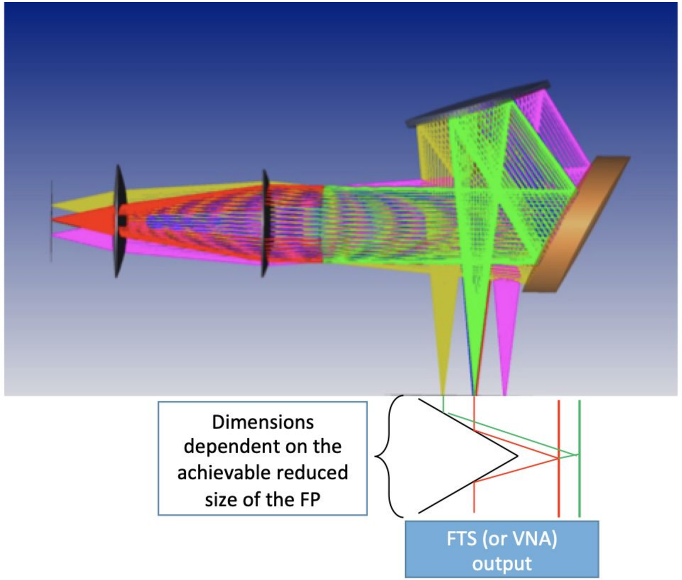
The presence of a polarization modulator couples the two tests:

- Spectral Response
- Polarimetric sensitivity

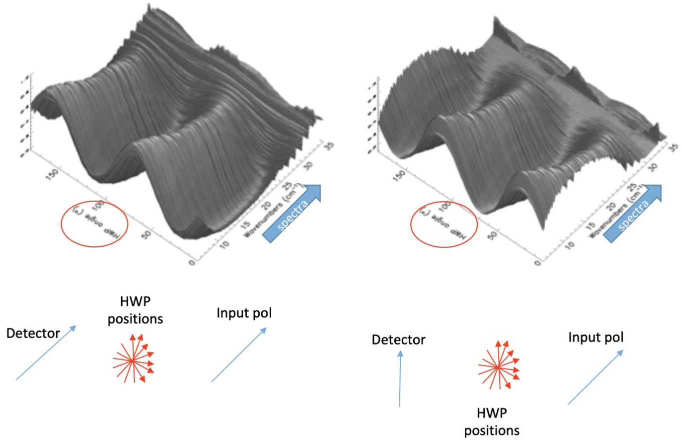
=> the instrument needs to be cold

=> within a cold "flight-like" environment





Expected output : the datacube



The combination of these two sets provides a complete set of information

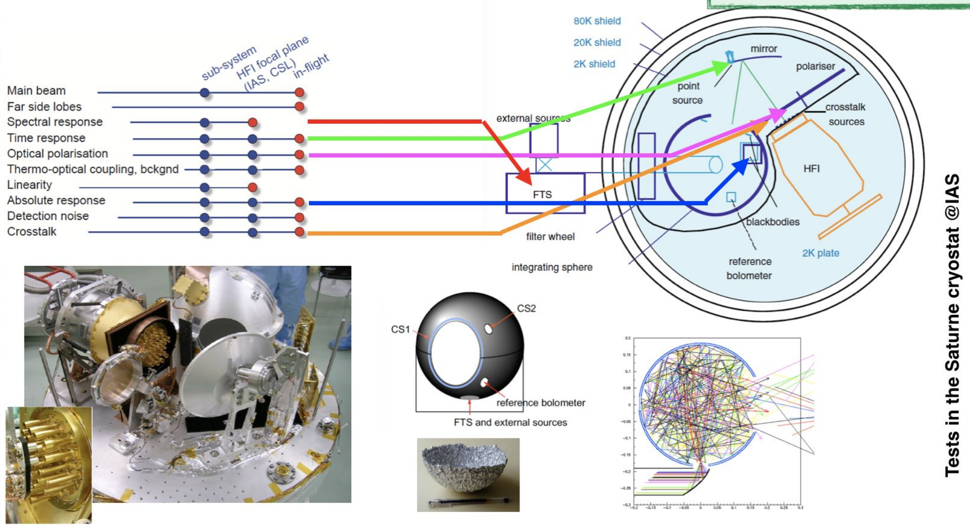
Rotate the input pol by 90 degree and you have the same sets by exchanging surfaces and adding a 90 degree offset.

cold “flight-like” ground measurements

“a la Planck-HFI” strategy:

Fully integrated HFT calibration
> preparation through the JSG
> lessons from Planck
> **experience from other experiment**
> design of a dedicated facility

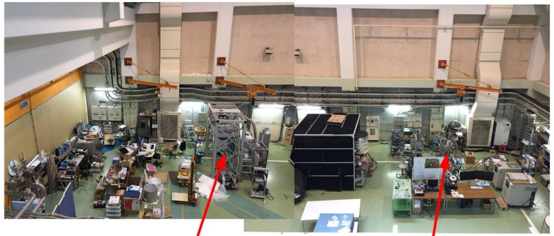
HFI example



Credit: F. Pajot et al. Astronomy and Astrophysics, Volume 520, id.A10, 15 pp.

Foreseen facilities

Advanced Instrumentation Lab. today



- We plan to clean up the laboratory and install a new cryo-chamber for LFT verification and calibration.
- The first meeting with our industrial partners (TAIYO NISSAN SANO and AES) was held last week to start designing the new cryo-chamber.

LFT
in Japan

credit: Masashi

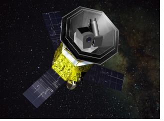
The Erios cryostat (6x4m) at LAM/Marseille

NB: needs to be upgrade to go to lower temperature (77K so far)

MHFT
in France

credit: Guilaine

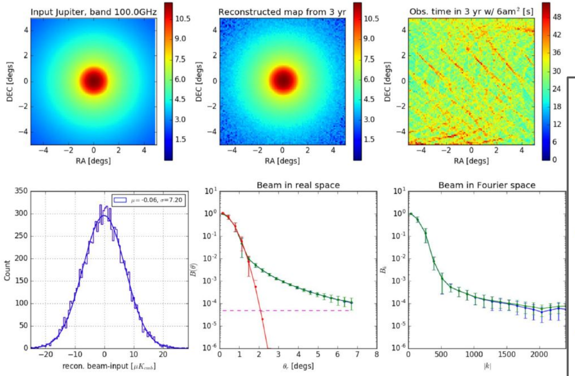
LiteBIRD



flight calibration

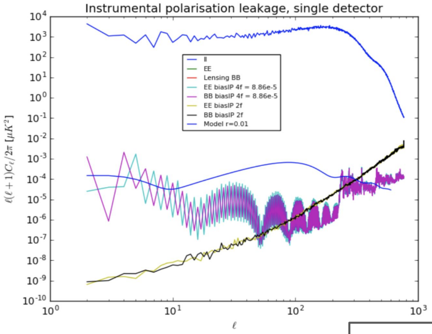
not exhaustive...

Main beam reconstruction from planets (Tomo)



Instrumental Polarization from the dipole signal (Guillaume)

- The dipole is a strong signal and also leaks into the polarization
- Again detector averaging will reduce the effect as 1/Ndet
- Since the dipole can be predicted, the signal can be used to fit the IP parameters



Polarization angle from ClEB

PTEP
DOI: 10.1093/ptep/0000000000

Simultaneous determination of the cosmic birefringence and miscalibrated polarisation angles from CMB experiments

Yuto Minami[1,*], Hiroki Ochi[2], Kiyotomo Ichiki[3,4], Nobuhiko Katayama[5], Eiichiro Komatsu[5,6], and Tomotake Matsumura[5]

looking into the future

The LiteBIRD calibration operations are very challenging !

- The Systematics JSG teams are working hard to update the requirements for each frequency bands. Next step will be to couple systematic effects and further refine the analysis in collaboration with the foreground JSG, and perform simulations. In parallel, mitigation is the key to get to low-ell: the implementation of HWPs and the LiteBIRD scan strategy will help for that.
- The Calibration JSG teams are deeply involved in defining the best strategy to meet the requirements, as well as to prepare the calibration devices and the facilities, but also making sure to get the longer possible time in the LiteBIRD schedule for the calibration operations (and with instruments as much integrated as possible).

Cosmic rays