Calibration requirements

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COrE / PRISM workshop for a M4 ESA mission
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From the COrE proposal

- No on-board calibration system
- Ground calibration
  - Sub-system level
  - Focal Plane Unit level
  - Warm test
  - Dedicated calibration facility
    - Space environment simulator
    - Orientable polarized far field source
- In flight through
  - Sources
  - CMB E mode polarization

Calibration parameters, for ~5000 detectors !

- With HWP
  - Polarimeters angles
    - Can depend on source spectrum if HWP properties are not “flat” in frequency
  - Transmission (bands) for both HWP axes
  - Pointing
    - Can depend on HWP position if it perturbs the optical path
  - HWP induced effects into the beam (as ellipticity)
    - Should be limited by design
  - Sidelobes
  - Beams
  - Gain

- Without HWP
  - Beams
  - Instrumental polarization
  - Gain
  - Pointing
  - Polarimeter angles
  - Sidelobes
  - Polarimeter efficiency
  - Transmission (bands)

Simplification strategies

- To be investigated if the calibration can benefit from “focal plane” calibration rather than single detector calibration
  - Can be combined:
    - All the channels at a frequency
    - All the channels in a “row”
    - Each single channel in an automated processing

Keck array receivers example

Optical Characterization of the Keck Array Polarimeter at the South Pole

A. G. Vieregg[a], P. A. R. Ade[b], R. Aikin[c], C. Bischoff[a], J. J. Bock[c,d], J. A. Bonetti[d], K. J. Bradford[a], J. A. Brevik[c], C. D. Dowell[c,d], L. Duband[e], J. P. Filippini[c], S. Fliescher[f], S. R. Golwala[c], M. S. Gordon[a], M. Halpern[g], G. Hilton[h], V. V. Hristov[c], K. Irwin[h], S. Kernasovskiy[i], J. M. Kovac[a], C. L. Kuo[i], E. Leitch[j], M. Lueker[c], T. Montroy[k], C. B. Netterfield[l], H. T. Nguyen[c,d], R. O'Brient[c,d], R. W. Ogburn IV[i], C. Pryke[f], J. E. Ruhl[k], M. Runyan[c], R. Schwarz[f], C. Sheehy[f,j], Z. Staniszewski[c,d], R. Sudiwala[b], G. Teply[c], J. Tolan[i], A. D. Turner[d], P. Wilson[d], and C. L. Wong[a]

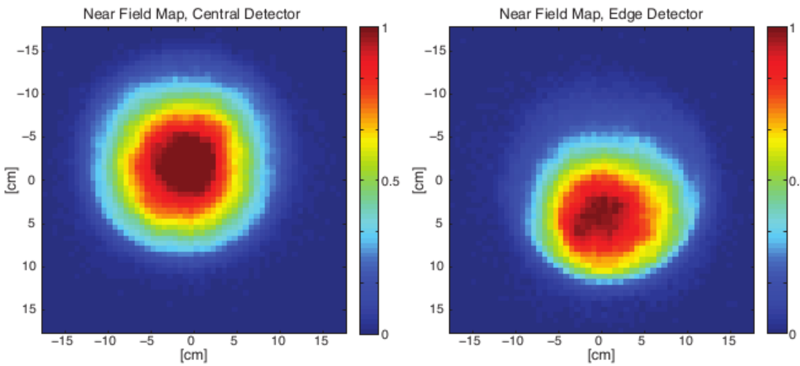

Figure 2: Measurement of the near-field beam pattern for two example Keck Array channels, measured above the aperture stop at the vacuum window. Left: A detector near the center of the focal plane; Right: A detector near the edge of the focal plane, showing significant truncation by the aperture (worst case).

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1 receiver = 512 detectors

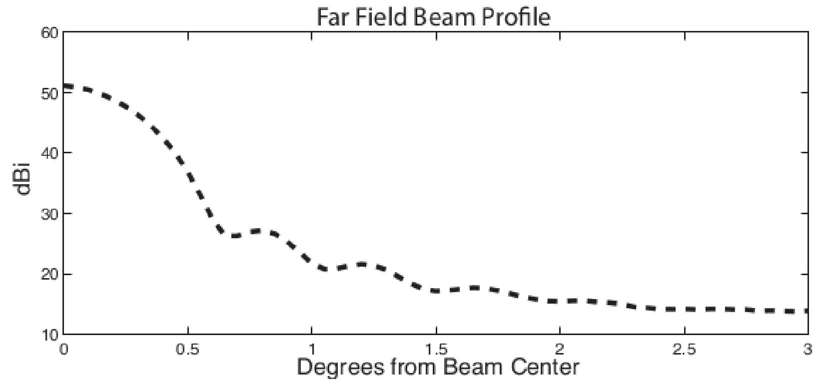


Figure 7: Radial profile of the Keck Array far-field beam pattern, averaged over one receiver. The profile shows the first few sidelobes and nulls before the beam pattern falls to the noise floor of the measurement.

More quantitative analysis of the HWP calibration

Study report for the HWP ESA ITT

G. Pisano, B. Maffei, M.W. Ng, V. Haynes, M. Brown, F. Noviello, A. Linton
University of Manchester

P. de Bernardis, S. Masi, L. Pagano, F. Piacentini, M. Salatino
Università di Roma “La Sapienza”

B. Ellison, M. Henry
Rutherford Appleton Laboratory

Imperfect HWP

$$\mathbf{J}_{\rm hwp}^{\rm ideal} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad \mathbf{J}_{\rm hwp}^{\rm real} = \begin{pmatrix} 1+h_1 & \zeta_1 e^{i\chi_1} \\ \zeta_2 e^{i\chi_2} & -(1+h_2)e^{i\beta} \end{pmatrix}$$

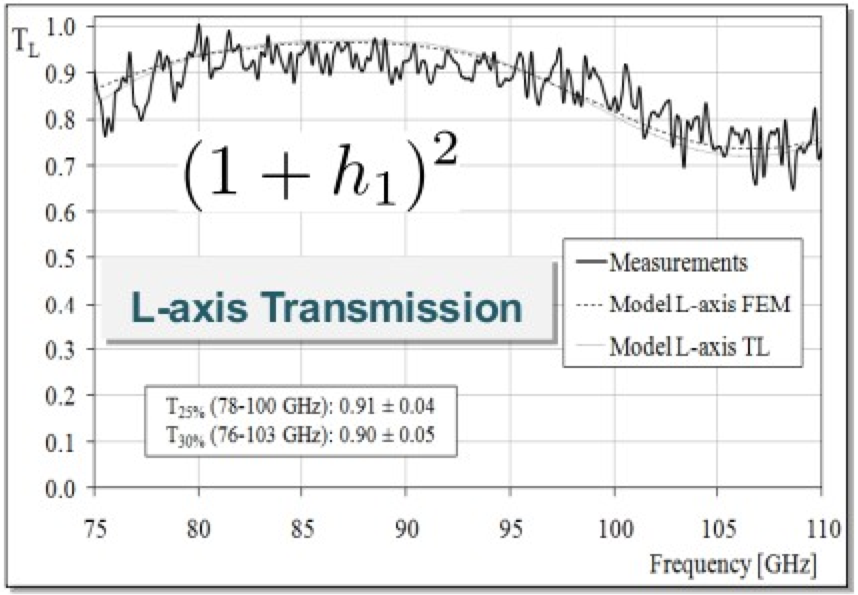
- $\boldsymbol{h_{1,2}}$ describe a departure from unitary transmission along the two HWP axes (capacitive-C and inductive-L). $h_{1,2} = \sqrt{T_{C,L}} - 1$
- $\boldsymbol{\beta} = \psi - 180°$ describes a departure of the phase-shift ψ between the two HWP axes from its ideal value of $\psi = 180°$
- $\boldsymbol{\zeta_{1,2}}$ cross-polarization terms, that is they describe the leakage from one axis to the other when the incoming polarization is aligned with one of the axes $\text{x-Pol(dB)} = 20 \log_{10} \zeta$
- $\boldsymbol{\chi_{1,2}}$ describe the phase of the cross-polar terms

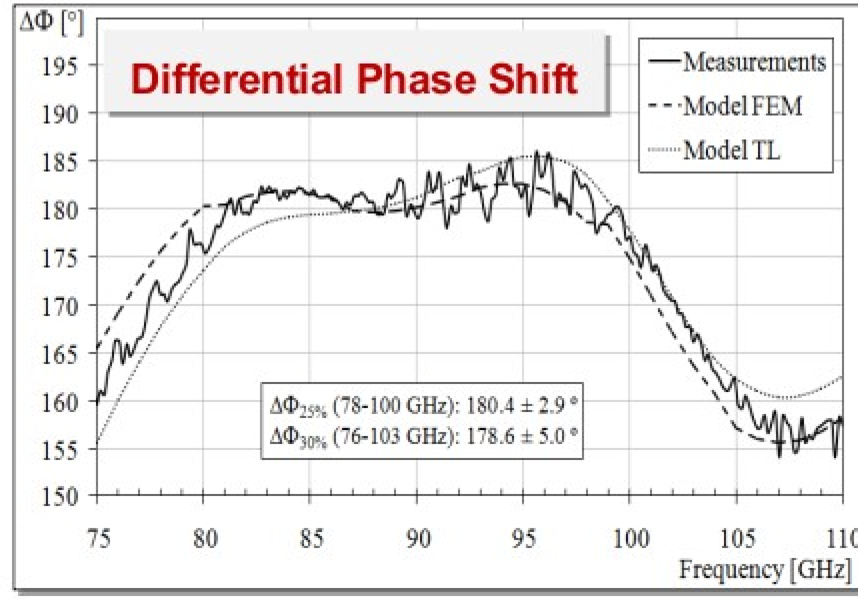
- Full system, with rotation and wire grid

$$\mathbf{J}_{\rm rhwp} = \mathbf{J}_{\rm wg}\mathbf{J}_{\rm rot}^{\mathbf{T}}\mathbf{J}_{\rm hwp}\mathbf{J}_{\rm rot}$$

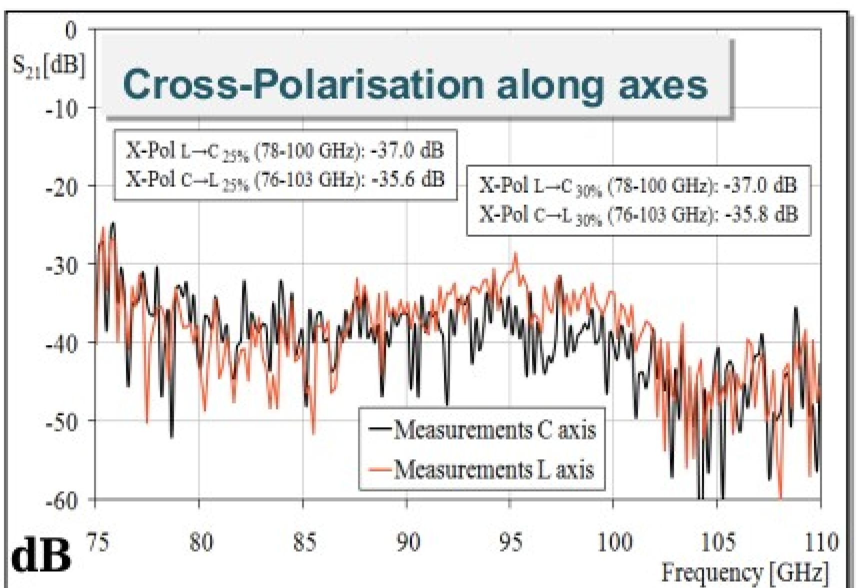
HWP parameters, model and measurements

G. Pisano et al.
PIER M, 25, p101 (2012)

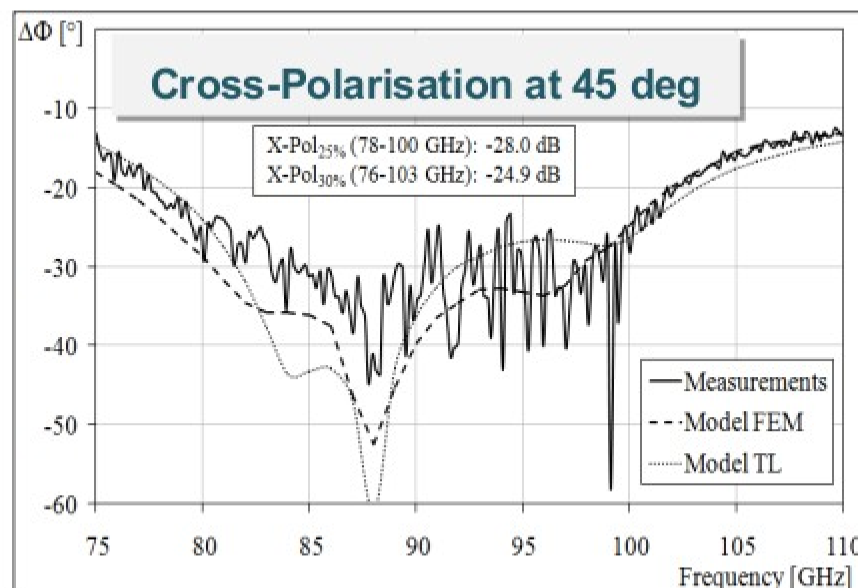




Ψ



ζ_1 dB



Simulations description

- Linear system

$$V = \frac{1}{2}\left(|J_{11}|^2 + |J_{12}|^2\right) T + \frac{1}{2}\left(|J_{11}|^2 - |J_{12}|^2\right) Q + \left(J_{11} J_{12}^*\right) U$$

$$\mathbf{V} = \mathbf{A}\mathbf{m}$$

- Map-making

$$\tilde{\mathbf{m}} = (\mathbf{B}^\mathbf{T}\mathbf{B})^{-\mathbf{1}}\mathbf{B}^\mathbf{T}\mathbf{V}$$

$$\tilde{\mathbf{m}} = (\mathbf{B}^\mathbf{T}\mathbf{B})^{-\mathbf{1}}\mathbf{B}^\mathbf{T}\mathbf{A}\mathbf{m}$$

- **A** is simulated with all HWP non idealities
- **B** is simulated with “measured” HWP non idealities
  - **B≠A** for many reasons (systematic effects, calibration errors)
- From the difference of input and output we assess requirements and calibration
  - As figure of merit we have selected the cosmological parameters
    - Tensor-to-scalar ratio, **r**, relevant at large angular scales
    - Baryon density $\boldsymbol{\Omega_b h^2}$, relevant at small angular scales, through lensing effects

Tests performed

- Incorrect knowledge of the HWP parameters, very close to the ideal case
  - We include in **A** mild non-idealities assuming an ideal **B**
  - We first analyzed the effect of non-null $\boldsymbol{\beta}$, $\boldsymbol{h}$ and $\boldsymbol{\zeta}$ separately then all together
- Incorrect knowledge of the HWP parameters, very far from the ideal case
  - We include in **A** strong non-idealities partially taken into account in **B**
  - Again we consider first the parameters separately then all together
- Frequency dependence of the HWP parameters
  - Considered as an average value of the parameters within the band (only CMB signal)
  - Same analyses described above
- Inhomogeneity of the HWP
  - Parameters vary with the HWP rotation
- Thermal emission of the HWP
  - Additive noise term due to the HWP temperature fluctuation
- Ellipticity by real space convolution
  - Telescope induced ellipticity
  - HWP induced ellipticity

HWP level requirements, parameters and calibration

Table 4: Final requirements and goals on HWP parameters. We include the total efficiency, and consider that the other parameters must be such that the total efficiency requirement is maintained. The requirements indicated with σ are for the experimental knowledge of the parameter. $\mathrm{NET_{HWP}}$ is the power spectrum of the HWP noise fluctuation, and $\mathcal{R}$ converts the HWP temperature fluctuations into CMB brightness temperature ($\mathrm{K_{CMB}}$) taking into account the temperature and the emissivity properties of the plate; in the Rayleigh-Jeans regime $\mathcal{R}$ depends only on the emissivity and not on the temperature. More details of the definition of the requirements are in the text an in appendix A.

Systematic	Parameters	Requirement	Goal
HWP efficiency	η_{HWP}	$>76\%$	$>80\%$
Phase shift	β	$< 40°$	$< 30°$
	σ_β	$< 0.17° / \sin\beta$	$< 0.07° / \sin\beta$
Transmission	$\lvert\Delta h\rvert = \lvert h_1 - h_2\rvert$	< 0.05	< 0.05
	$\lvert h_1\rvert,\ \lvert h_2\rvert$	< 0.12	< 0.1
	$\sigma_{h_1},\ \sigma_{h_2}$	< 0.02	< 0.02
	T_C	> 0.76	> 0.8
	T_L	> 0.76	> 0.8
	$\lvert T_C - T_L\rvert$	< 0.1	< 0.1
	σ_{T_C,T_L}	< 0.04	< 0.04
Cross polarization	ζ_1, ζ_2	< 0.02	< 0.02
	σ_{ζ_1,ζ_2}	< 0.002	< 0.002
	σ_{ζ_1,ζ_2}	< 0.002	< 0.002
	x-Pol	-34 dB	-34 dB
	$\sigma_{\text{x-Pol}}$	-50 dB	-50 dB
HWP induced ellipticity	ε_{HWP}	$<2\%$	$<1\%$
Flatness[a]	Δx	$< 20\ \mu$m	$< 20\ \mu$m
Modulated dis-homegeneity	h^{mod}	<0.001	<0.001
Thermal stability	$\mathrm{NET_{HWP}}$	$\lesssim \frac{1\mu\mathrm{K}/\sqrt{\mathrm{Hz}}}{\mathcal{R}}$	$\lesssim \frac{1\mu\mathrm{K}/\sqrt{\mathrm{Hz}}}{\mathcal{R}}$

[a] The requirement on flatness is set by optical consideration (aberration) rather than by the impact into HWP parameter.

Gain calibration and CMB dipole removal

- 3 mK dipole signal, different day by day due to orbit and scanning strategy
- If we aim to remove it at the level of ~10 nK
- Then we need $3\ 10^{-6}$ calibration level to remove the dipole from each channel

- HWP reduces this requirement, if stability is at that level

Conclusion

- Criticality of the calibration parameters depends on the instrument design,
  - E.g. HWP, or no-HWP
- To be identified the most critical parameters in the selected design
- Assess the calibration requirement based on simulation

- Calibration strategy to be defined:
  - Ground based
  - In flight (?)
  - Ancillary satellite

Definition of calibration requirements

- We can use an approach similar to the one used for HWP ITT (and many literature papers):
  - Simulate the analysis in presence of calibration uncertainties
  - Define the figure of merit most relevant to the science goal

- For the proposal, identify the most critical:
  - If we select HWP option
    - Rotation of the polarization as a function of frequency (phase-shift)
    - Transmission of the HWP
  - If we select the no-HWP option
    - Beam properties, in particular beam asymmetries
    - Gain (and stability)
    - Try data analysis techniques to solve for polarization in presence of a real beam
      - Set requirements on beam knowledge