PICO optics I&T

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Outline

- What can we learn from what Planck has gone through?
- What should PICO I&T do?

What do I mean by optics in this presentation?

- I define “optics” in this presentation as
  1. two mirrors that form open Dragone for PICO (or Gregorian for Planck)
  2. the baffles including the surrounding structure
  3. focal plane “feed” beam
- It is difficult to test the entire system in flight condition. Thus, the ground tests were carried out at sub-system level. I may refer optics#X to point which sub-system test is relevant in the following slides.

Planck I&T for optics

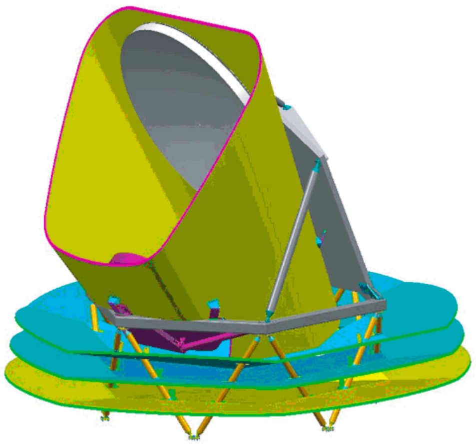
1. two mirrors that form open Dragone
2. the baffles including the surrounding structure

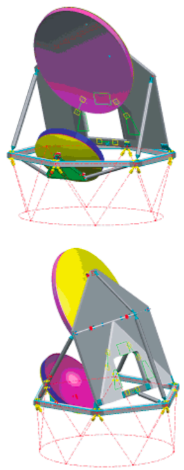
This is tested separately from #3.
The reference is Tauber et al.

3. focal plane “feed” beam

This is tested separately from #1, #2. the main test is done at IAS, Saturn cryostat. This is simply because the FP has to be cooled down to 100 mK to do the test.
The reference is Pajot et al.

Requirement to I&T in Planck





5.1.7. Polarisation specific parameters

Cross-polar leakage is measured at the level of individual pixel assemblies. The results show a typical value for the cross-polarisation leakage of PSB of 5%, ranging from 2 to 9%. The errors in these parameters is very low, below 0.2% (absolute error) except for one PSB for which it is 1.3%. The SWB are also minimally sensitive to polarisation, with cross-polarisation leakage ranging from 84% to 97%, and errors typically about 0.5%, except 3% for one SWB.
The axes of polarisation sensitivity are measured in the Saturne cryostat. The distribution of errors in angle measurement is 0.6° for PSB and 5° for SWB. A detailed analysis and results are presented in Rosset et al. (2010).

Pajot et al.

Table 1. Design requirements of the *Planck* telescope reflectors.

Requirement	Primary reflector	Secondary reflector
Contour shape	off-axis ellipsoid	off-axis ellipsoid
Size (mm)	1555.98 × 1886.79	1050.96 × 1104.39
Radius of Curvature (mm)	1440 ± 0.25	−643.972 ± 0.2
Conic constant	−0.86940 ± 0.0003	−0.215424 ± 0.0003
Stability of best fit ellipsoid		
along each axis	±0.1 mm	
around each axis	±0.1 mrad	
Mechanical surface errors rms spec (goal)[a]		
ring 1	7.5 μm (5 μm)	
ring 2	12 μm (8 μm)	
ring 3	20 μm (13 μm)	
ring 4	33 μm (22 μm)	
ring 5	50 μm (33 μm)	
Surface roughness	R_q < 0.2 μm on scales <0.8 mm	
Surface dimpling[b]	±2 μm PTV	
Reflector thickness	80 mm	65 mm
Reflectivity (25−1000 GHz)		
Beginning of life	>99.5 per cent	
End of life	>98.5 (goal 99.0)[c]	
Mass	30.6 kg	14.5 kg
First eigenfrequency	>120 Hz	
Temperatures		
Operational	45 K	
Qualification	30−325 K	

Notes. [a] Each ring is a concentric ellipse with the same ellipticity as the rim of the reflector, dividing the major axis in 5 equal pieces. Ring 1 is the innermost ring and ring 6 the outermost one.
[b] Defined in Sect. 3.1.
[c] At telescope level, the total emissivity is specified to be <6% (<3% goal), including also the effect of dust deposited on the reflectors.

J. Tauber et al.

Planck I&T for optics

The telescope test is subdivided into a matrix of as followings.

	Component level test	sub-system level test	integrated system test
warm	mirrors • photogrammetry • interferometry • theodolite feed	optics sub-system • photogrammetry • theodolite	• N/A
cold	mirrors • photogrammetry • interferometry	optics sub-system • photogrammetry FPU sub-system • Saturn test	• CSR

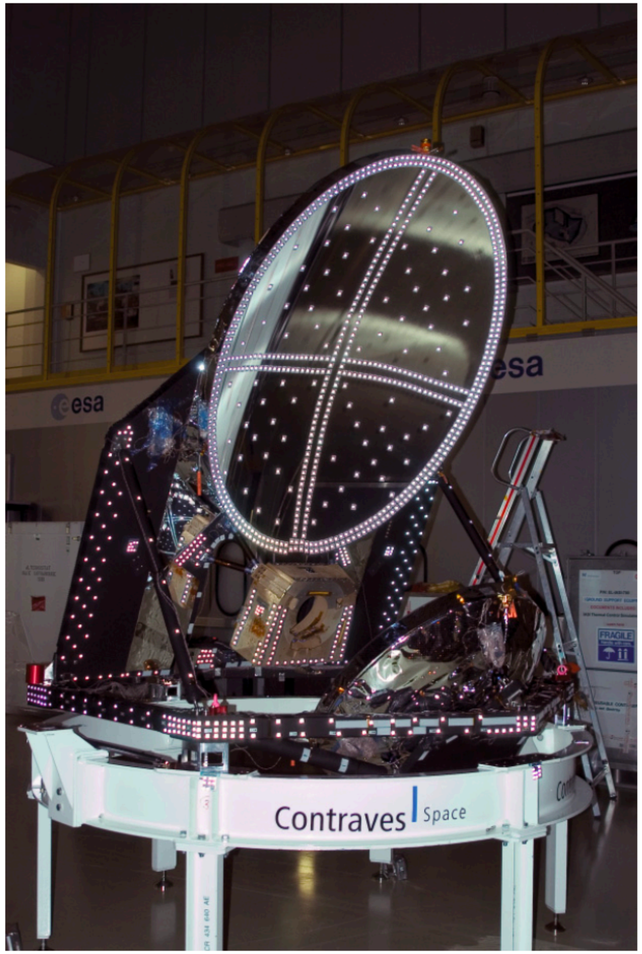
Component and sub-system level tests at warm and "cold"

1. Photogrammetry of the PR and SR from ambient temperature down to ~95 K (Amiri Parian et al. 2006a, 2007b).
2. Interferometry at λ=10 μm of the SR at several temperatures between ambient temperature and ~40 K (Roose et al. 2005, 2006).
3. Photogrammetry of the whole telescope at several temperatures between ambient temperature and ~95K (Amiri Parian et al. 2007a).
4. Theodolite measurements of targets placed on all the critical elements (reflectors, structure, focal plane) were used to tie together the coordinate frames of photogrammetry at reflector and telescope level to each other and to the spacecraft frame.

Photogrammetry of the PR and SR

"Photogrammetry of the PR and SR from ambient temperature down to ~95 K (Amiri Parian et al. 2006a, 2007b). This technique, which was first tested on a qualification model of the SR (Amiri Parian et al. 2006b), allowed us to measure the figure of each reflector (radius of curvature R and conic constant k) and the large-scale angular deformations at several temperatures between warmest and coldest. The measured trends of R and k were used to extrapolate these parameters to the operational temperature."

"Photogrammetry of the whole telescope at several temperatures between ambient temperature and ~95K (Amiri Parian et al. 2007a). These measurements yielded the thermo-elastic deformations of the telescope structure, and the trend was used to extrapolate them to operational temperature. To provide representative loads, the object measured also included the two flight reflectors and a structure representative of the focal plane. Measurements of the focal plane deformations were correlated against thermo-elastic predictions and used to predict the deformations of the focal plane in-flight. The number of targets on the reflectors was too low to achieve high accuracy on a determination of their surface deformations, but adequate enough to establish that their thermo-elastic behaviour was consistent with the photogrammetry at the reflector level.4." Tauber et al.



Photogrammetry of the PR and SR

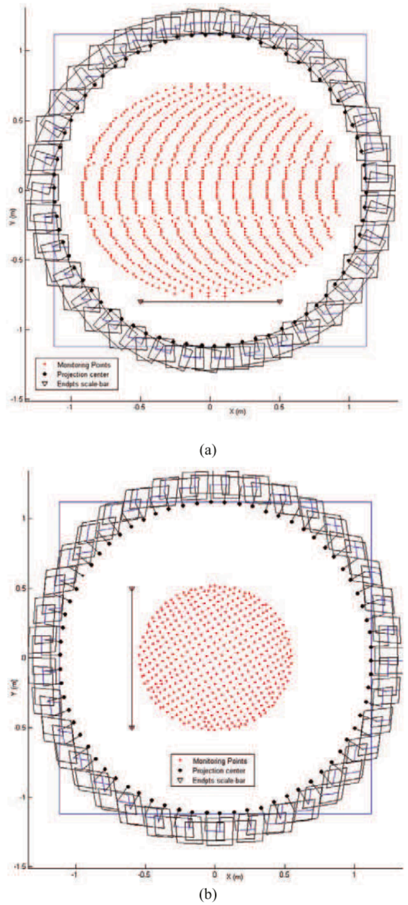


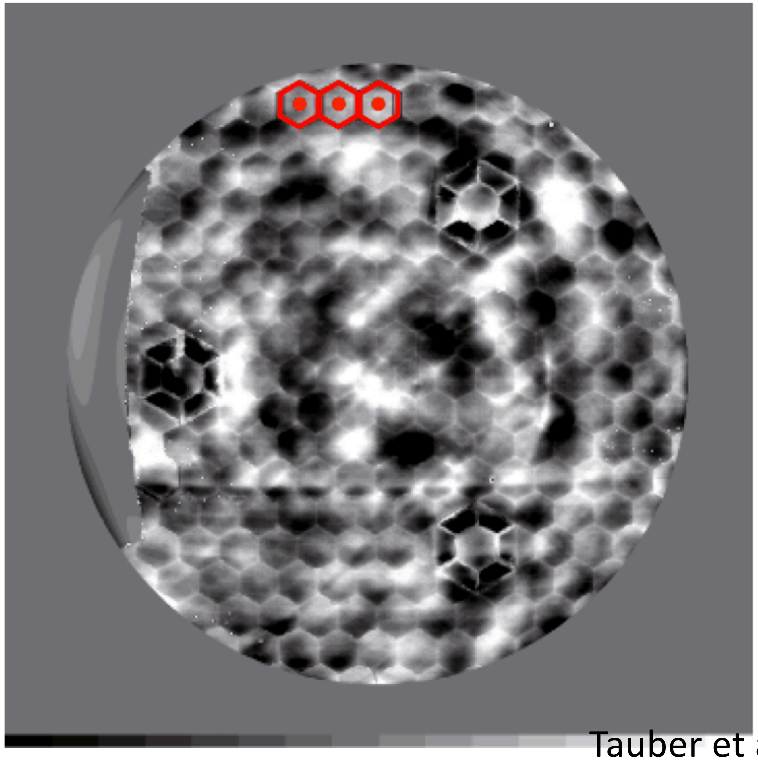
Fig. 2. Photogrammetric network configuration for the Planck reflectors with one scale-bar. a) XY-view of the network configuration of PR and b) XY-view of the network configuration of SR.

This facility consists of a large cryostat with the cold stage at center and a ring-rail in the cryostat is placed around the cold stage to move a camera at room temperature and take photos of a telescope from various locations.

I thought I saw a picture of facility somewhere and looking for it now.

Interferometry

"Interferometry at λ=10 μm of the SR at several temperatures between ambient temperature and ~40 K (Roose et al. 2005, 2006). These measurements traced the small-scale deformations of the SR down to operational temperature. The deformation map of the SR at around 50 K is shown in Fig. 6. The core walls and "dimples" are clearly visible for nearly all cores. It is worth noting that the dimples do not behave as expected, i.e. they do not all form a regular concave deformation. Instead, the core deformations show multiple peaks whose amplitudes do not vary systematically across the sur- face (see also Sect. 5.2). Since interferometry does not pre- serve large-scale information, it was combined with the photogrammetric data to yield an accurate picture of the surface of the SR at 40 K on all spatial scales of interest (Fig. 7). Although interferometric measurements of the PR were also carried out, its large size and long focal length required the acquisition of interferograms in double-pass configuration. The noise due to diffraction of light from the core walls in- creased considerably relative to the SR, rendering the phase information contained in the interferograms too noisy to be useful.3." Tauber et al.

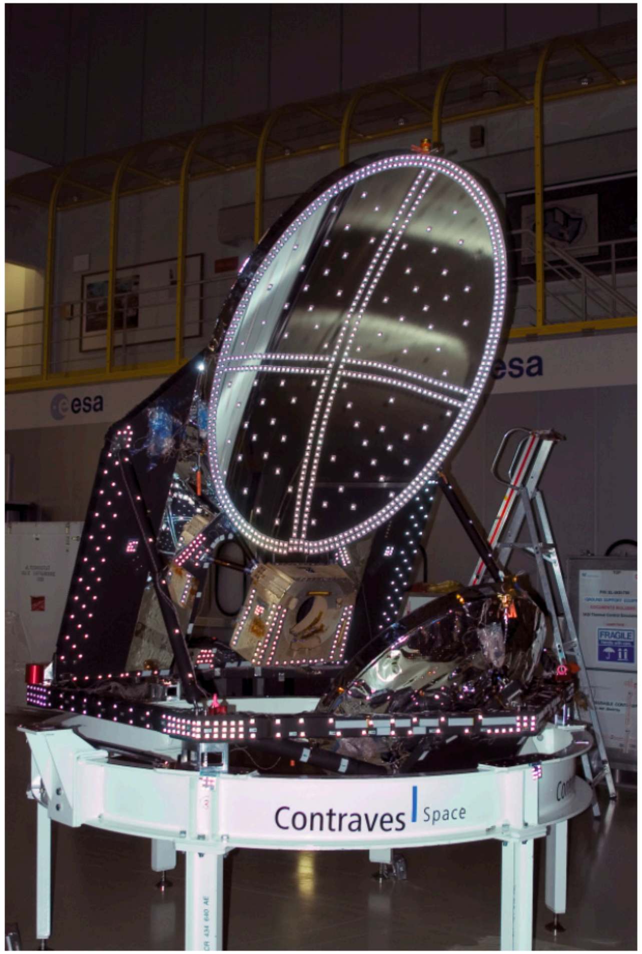


Tauber et al.

Fig. 6. The deformations of the SRFM on small scales at about 50 K as measured with $\lambda 10\ \mu m$ interferometry (the indentation at left is caused by vignetting in the interferometer optics). The gray scale is $\pm 10\ \mu m$. The print-through of the core walls is clearly seen for most cores. The imprints of the three isostatic mounts are also clearly seen; we note that the cells around them were reinforced with additional core walls. To quantify the core-wall print-through and the dimpling, 3 masks per core cell have been applied: one mask covering the core wall, one mask covering similar areas on both sides of the core wall and one mask cov- ering the central part of each cell. A few of these sets of masks are shown in red in the upper part of the figure. Using these masks, the av- erage print-through effect is estimated to be $\sim 0.4\ \mu m$ in average, while the mean (systematic) dimpling effect is smaller than $0.7\ \mu m$.

Theodolite measurements

“Theodolite measurements of targets placed on all the critical elements (reflectors, structure, focal plane) were used to tie together the coordinate frames of photogrammetry at reflector and telescope level to each other and to the spacecraft frame. These measurements were performed frequently, until integration of the satellite with the launcher, to verify the stability of the optical system throughout the satellite’s assembly and integration program.



I&T of the FP unit

Fig. 6. The Saturne cryostat in the class 10000 clean room. The two upper rings and the lid are removable for the integration of the calibration optics and the instrument. The optical port is on the opposite side.

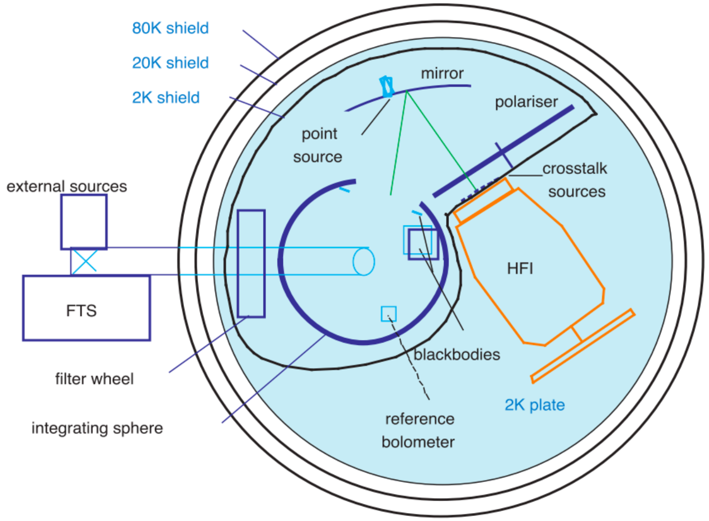


Fig. 3. Optical diagram of the HFI FPU calibration setup in the Saturne cryostat

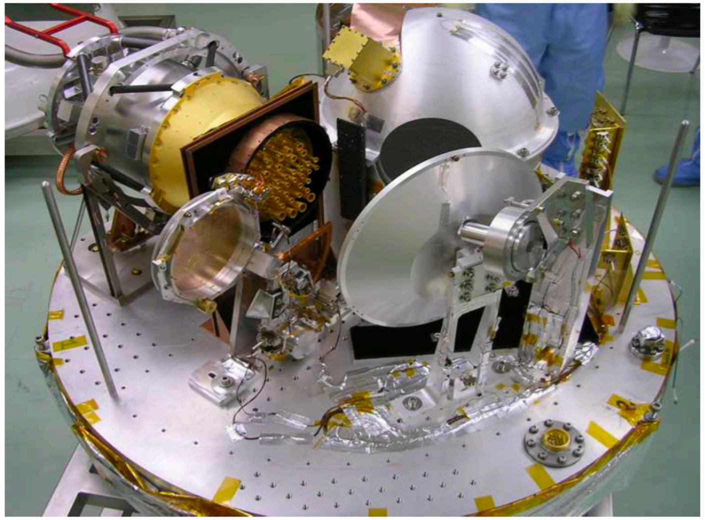


Fig. 4. Optical setup on the 2 K Saturne cryoplate with the HFI PFM. The polariser and sources on the instrumented wheel are positioned out of the optical path to the integrating sphere.

I&T of the FP unit

Table 3. Determination of main HFI parameters status and references for their values.

	Status and/or determination error	Reference
Beams and far side lobes	computed from front horns and telescope measurements	Maffei et al. 2010, Tauber et al. 2010
Spectral bands	0.1 cm^{-1} resolution, $\nu < 400$ GHz : 3 % error, $\nu > 400$ GHz : 1 % error *final determination within requirement*	Ade et al. 2010
Polarisation orientation Cross-polarisation leakage	0.3°/0.6°/2.1° (min/avg/max) for Polarisation Sensistive Bolometers 0.1%/0.2%/2.2% (min/avg/max) for PSB *final determination requires sky data*	Rosset et al. 2010
4K stage emissivity 1.6 K stage emissivity	better than 1% better than 3% for $\nu < 300$ GHz *within requirements to allow correction of remaining systematics coming from thermal stability below*	Sect. 5.1.5 Sect. 5.1.5
Thermal stability	determined within range [1 mHz, 100 Hz] *flight data required for the final stability determination*	Sect. 5.3.2
Linearity	0.1 % determination within requirements	Sect. 5.2.1
Time response	measured to better than 0.1% for 20 detectors *sky data expected for the complete set of detectors*	Sect. 5.2.2
Response	3 % determination error *sky data required to provide the absolute calibration*	Sect. 5.1.3, Sect. 5.2.1
Total detector noise Compatibility	explored within range [1 mHz, 100 Hz] checked to 1 % to 3 % of noise level *flight data required to provide the ultimate values, including particle hits rate*	Sect. 5.2.5, Lamarre et al. 2010 Sect. 4.2
Optical crosstalk Electrical crosstalk	down to 60 dB down to 80 dB *determination within requirement, sky data to reach goal of 80 dB*	Sect. 5.1.6 Sect. 5.2.4

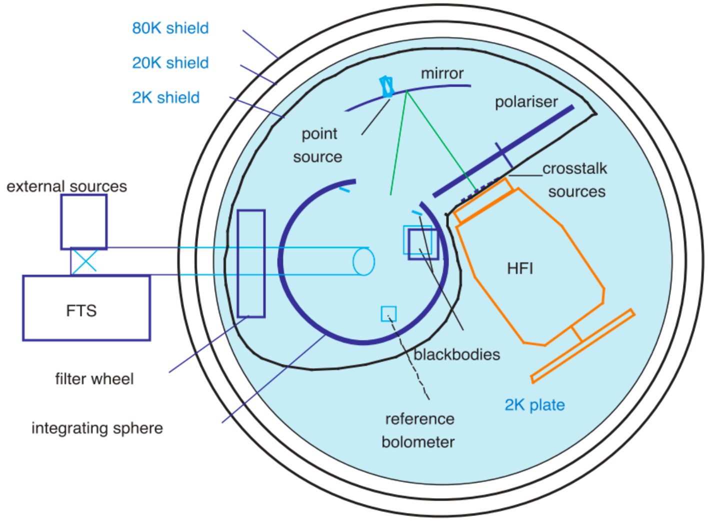


Fig. 3. Optical diagram of the HFI FPU calibration setup in the Saturne cryostat

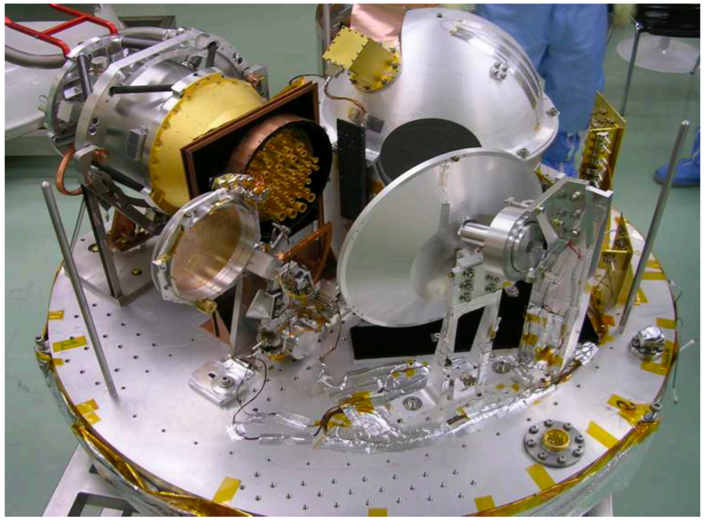
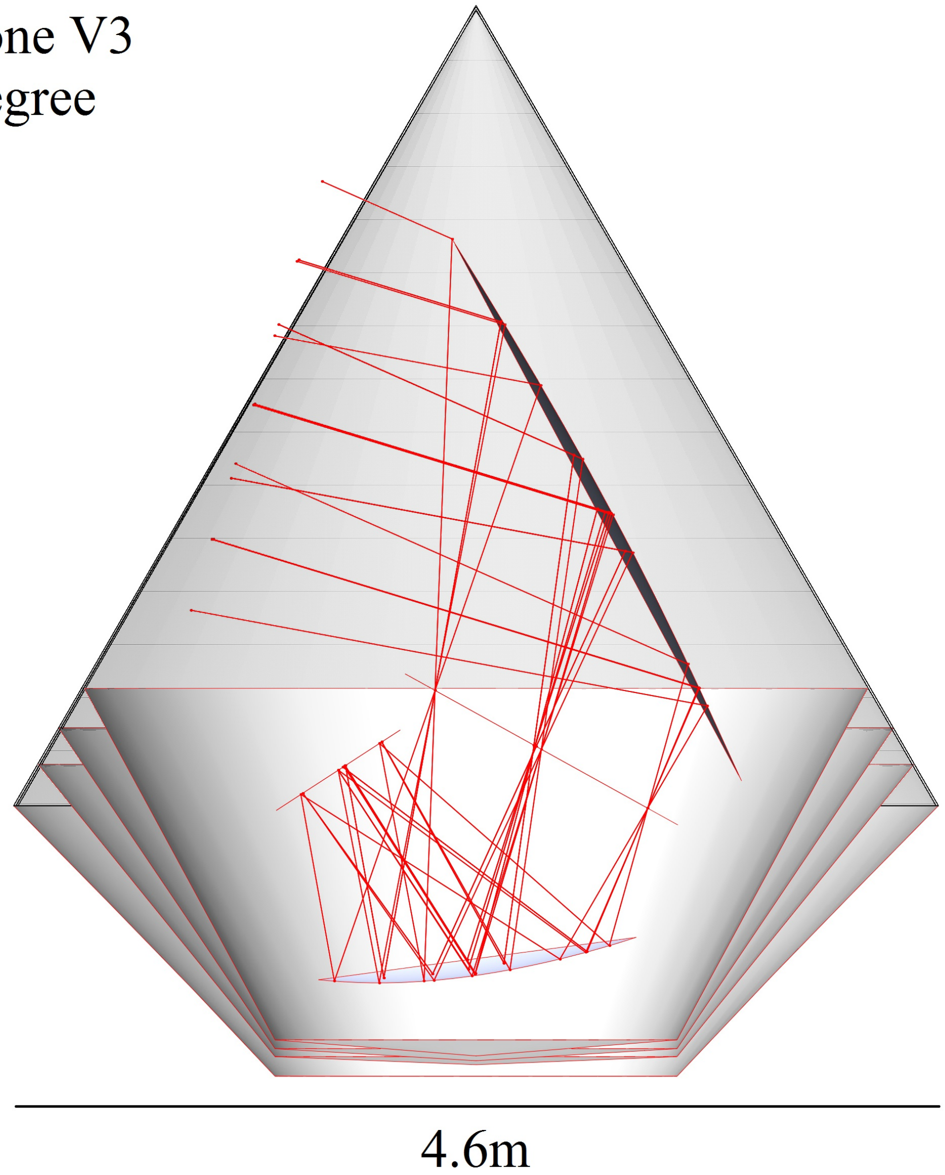


Fig. 4. Optical setup on the 2 K Saturne cryoplate with the HFI PFM. The polariser and sources on the instrumented wheel are positioned out of the optical path to the integrating sphere.

Comments to PICO I&T for optics

Open Dragone V3
alpha: 30 degree



Toward PICO I&T for optics

red: potential required facility/large scale device

Component level test

warm

mirrors
- overall shape
  - theodolite,
  - photogrammetry
- surface accuracy
  - interferometry

→ lab.

filters
- spectrum, pol. effect (VNA/FTS)

lab.

feed
- beam pattern (VNA)

lab.

cold

mirrors
- overall shape
  - photogrammetry
- surface accuracy
  - interferometry

→ custom cryo. chamber1

filters
- spectrum, pol. effect (VNA/FTS)

feed
- beam pattern w/ rep. det.

→ custom cryo. chamber2 for a component test

sub-system level test

warm

assembled mirrors on a structure w/ filter and mock FP
- photogrammetry
- interferometry
- theodolite
- RF performance → anechoic chamber

cold

assembled mirrors on a structure w/ filter and mock FP
- photogrammetry
- interferometry

→ custom cryo. chamber3

FP unit
- feed beam, pol. angle, spectrum, optical time response

→ custom cryo. chamber4

integrated system test

warm

In principle one can repeat the same/similar measurements done in the sub-system level.

cold

at this phase, the detector performance together with the flight cryo-cooler will dominate the schedule and the cost. There is not much thing one can do for the optical characterization except the check to see the detector being optical alive or not.

→ space chamber

To be completeness, one can in principle imagine JWST like beam/optical characterization in the cryogenic environment.

minimal requirement to the custom chamber

- custom cryogenic chamber 1
  - The size of the cryostat (~40K) is defined by the primary, assuming that the same cryostat can be used for the secondary.
  - Do not forget the potential reimaging optics in the cryostat for interferometry test, which grows the cryostat size.
- custom cryogenic chamber 2
  - Depending how what temperature the feed will sit and what feed technology to use, the required chamber might be different. This cryostat might be as simple as one wafer test type cryostat.
- custom cryogenic chamber 3
  - This cryostat has to be large enough to encase the entire assembly of the primary, secondary and FP together with the supporting structure but not the satellite service module. The main purpose of the cryostat will be to check the thermal-structural verification in the context of the optical characterization. Perhaps one of the NASA space chambers may suffice the purpose. One feature we want is to monitor the shape at the cryogenic temperature. This might require the change to the existing space chamber. Depending on the flexibility to the existing facility, it may be quicker to make the new facility for this purpose.
- custom cryogenic chamber 4
  - This cryostat is to test the FP unit, and that drives the size and the required temperature. The corresponding example is the Saturn cryostat in the Planck test campaign.
- anechoic chamber
  - Probably NASA has the facility that can accommodate PICO optics? Perhaps the frequency range of our interest may exceed from the existing RF frequency range. The accumulated cost to prepare the VNA is generally expensive.
- space chamber
  - Search the NASA facility to accommodate the entire PICO.
- comments: a large cryostat can cover the full list of tests which is expected to be done with a smaller cryostat. Nevertheless, an operation with a large cryostat is the schedule driver and so having a sperate small chamber is believed to be cheaper in the end.

Some considerations about the cost drivers and tradeoffs

- choice of the mirror material
  - aluminum athermal design is cheaper and heavier
  - CFRP/CSiC is known to be difficult to control its shape and expensive while it’s light
  - SiC is heavy and hard to machine
- surface roughness
  - optical finish is more expensive and over specified from the CMB measurement point of view but we can use the optical wavelength base interferometer. The infrared base interferometer is not commonly used, and thus it may require a custom development.
- cryogenic RF test
  - unless one tries to do an optical characterization which JWST does, the infligth condition base optical characterization is not an option. Given the aperture size, the inflight point source calibration is probably sufficient but something to check.

Systematics and Calibration

From “Planck pre-launch status: HFI ground calibration” (2010)

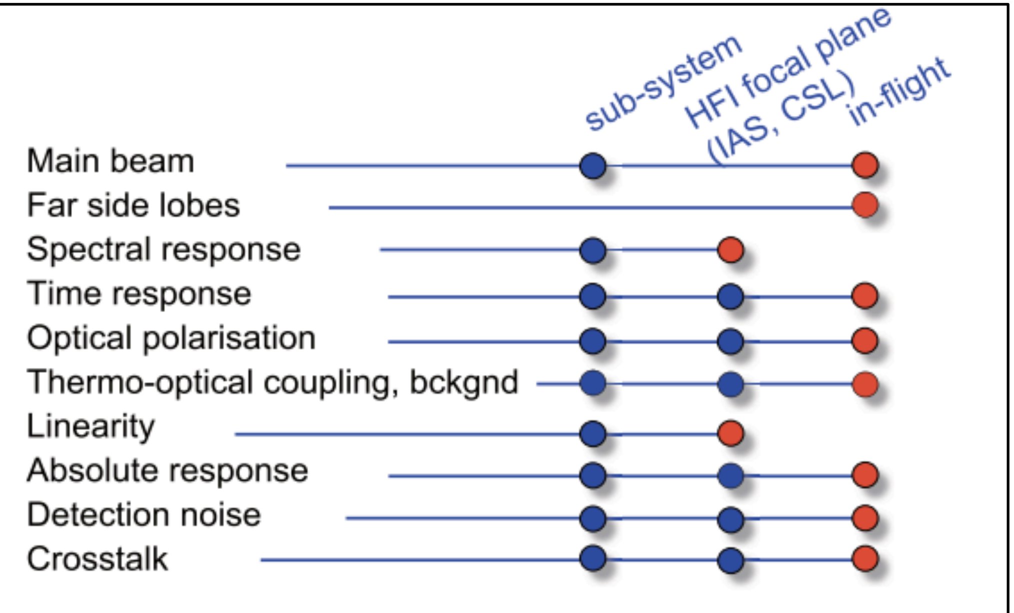


Fig. 1. Calibration philosophy. Blue dots indicate preliminary determinations, red dots indicate final determination.

Slide by Tomo from the “Lessons learned from Planck” panel session in Planck2014 @ Ferrara

Systematics and Calibration

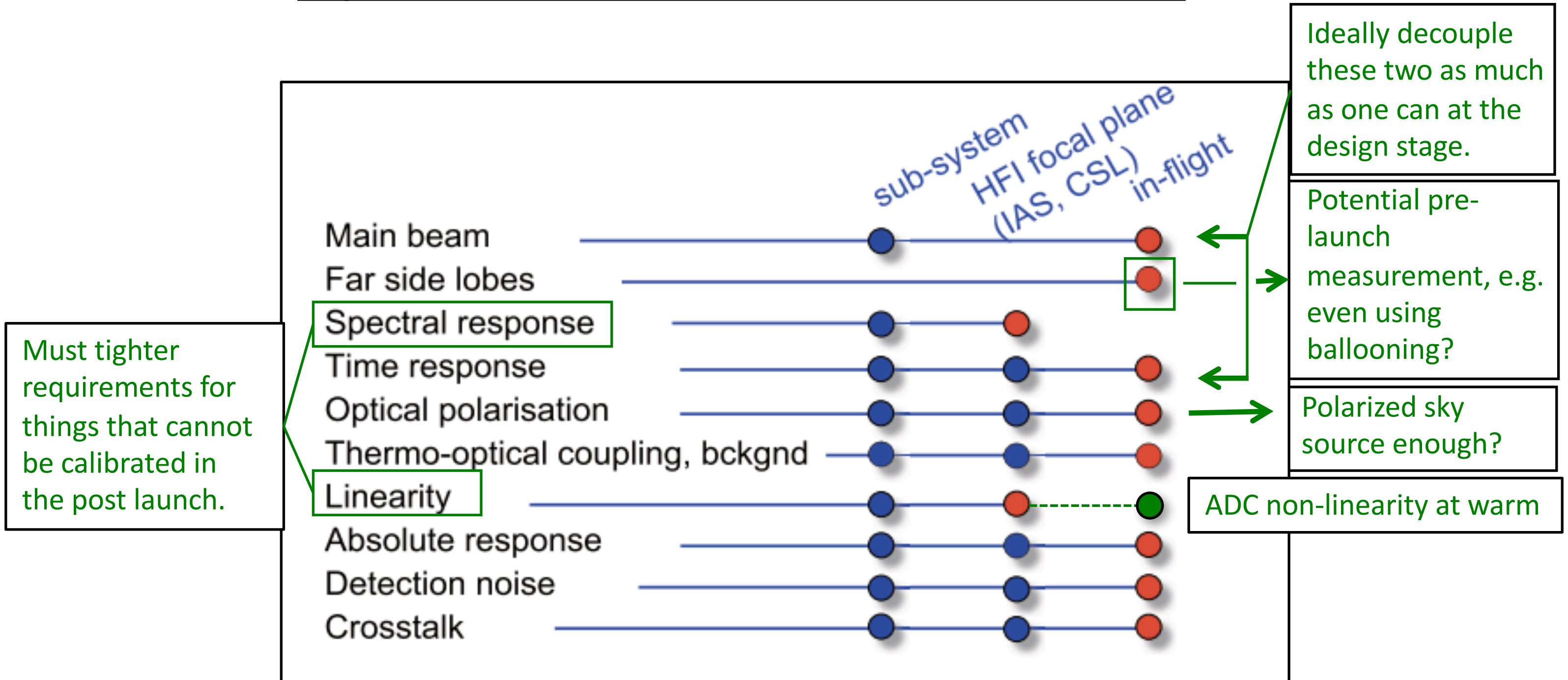


Fig. 1. Calibration philosophy. Blue dots indicate preliminary determinations, red dots indicate final determination.

- Cosmic ray susceptibility of the system including the detector

Slide by Tomo from the "Lessons learned from Planck" panel session in Planck2014 @ Ferrara

backup

Summary of the required facilities

to be completed

subsystem		method	facility	temperature	source/detector
optics #1 and #2			anechoic chamber	room	RF source (VNA)
optics #1 and #2	mirror shape	photogrammetry	cryostat	room	target/camera
	mirror shape/assembly	photogrammetry	cryostat	95	target/camera
PR and SR individually	mirror surface accuracy	interferometry	custom cryostat		10 um interferometer
		interferometry	custom cryostat		10 um interferometer
	mirror shape/assembly	Theodolite	lab	room	Theodolite
FP unit		angle w/ cryogenic rot. polarizer	Saturn cryostat ta IAS	100mK, 3K	
		FTS	Saturn cryostat ta IAS		
		Feed beam map			