# 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

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

- 2. the baffles including the surrounding structure
- 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).

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

Requirement	Primary reflector	Secondary reflector	
Contour shape	off-axis ellipsoid	off-axis ellipsoid	
Size (mm)	$1555.98 \times 1886.79$	$1050.96 \times 1104.39$	
Radius of			
Curvature (mm)	$1440 \pm 0.25$	$-643.972 \pm 0.2$	
Conic constant	$-0.86940 \pm 0.0003$	$-0.215424 \pm 0.0003$	
Stability of best fit el	lipsoid		
along each axis	±0.1 mm		
around each axis	$\pm 0.1$ mrad		
Mechanical surface errors rms spec $(goal)^a$			
ring 1	$7.5 \mu{ m m} (5 \mu{ m m})$		
ring 2	$12 \mu m (8 \mu m)$		
ring 3	$20 \mu m (13 \mu m)$		
ring 4	$33 \mu m (22 \mu m)$		
ring 5	50 μm (33 μm)		
Surface roughness	$R_q < 0.2 \mu m$ on scales <0.8 mm		
Surface dimpling <sup>b</sup>	$\pm 2 \mu$	m PTV	
Reflector thickness	80 mm 65 mm		
Reflectivity (25–100	0 GHz)		
Beginning of life	>99.5 per cent		
End of life	>98.5 (goal 99.0) <sup>c</sup>		
Mass	30.6 kg	14.5 kg	
First eigenfrequency	>120 Hz		
Temperatures			
Operational	45 K		
Qualification	30–325 K		

**Notes.** <sup>(a)</sup> 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.

<sup>(b)</sup> 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.

5

Pajot 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 <ul> <li>photogrammetry</li> <li>interferometry</li> <li>theodolite</li> <li>feed</li> </ul>	optics sub-system <ul> <li>photogrammetry</li> <li>theodolite</li> </ul>	• N/A	
cold	mirrors • photogrammetry • interferometry	optics sub-system • photogrammetry FPU sub-system • Saturn test	• CSR	
				<u> </u>

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

- Photogrammetry of the PR and SR from ambient temperature down to ~95 K (Amiri Parian et al. 2006a, 2007b).
- 2. Interferometry at  $\lambda$ =10  $\mu$ m 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  $\lambda$ =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.



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



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



4.6m

### **Toward PICO I&T for optics**

red: potential required facility/large scale device

integrated system test



### 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 thermalstructural 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)



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

### **Systematics and Calibration**



• Cosmic ray susceptibility of the system including the detector

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

# Slide for 2018-2-15

## **Optics I&T philosophy**

- I&T's T is testing. This "testing" includes both calibration and verification.
- The plan for the optics I&T should be driven by the systematics/calibration requirements.



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

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

We assume that the PICO optics I&T will go through the similar test plan as the Planck optics I&T had gone through.

In addition to the Planck I&T, here is one difference to be highlighted.

The in-flight beam map measurement will likely be limited by the S/N (and systematics), and thus we need the extrapolation using a GRASP or something equivalent particularly for a near/far sidelobe. In such a case, the telescope parameters together with the feed beam information is critical. The feed beam from a single mode corrugated feed can be well modeled by a simulation software, e.g. HFSS. As for a multicolor feed and/or lenslet, this may be something to be explored yet. Thus, it is essential to include the thorough characterization of the feed beam.

### Suggestions to PICO Optics I&T

We shall lay out the two options for the PICO optics I&T as

- Minimum
- Comprehensive

### Toward PICO I&T for optics

### red: potential required facility/large scale device



### Toward PICO I&T for optics

### **Minimum option**



#### Comprehensive **Toward PICO I&T for optics** integrated system test Component level test sub-system level test mirrors overall shape assembled mirrors on a structure w/ filter In principle one can repeat the theodolite, and mock FP same/similar measurements done in the lab. photogrammetry sub-system level. surface accuracy photogrammetry interferometry interferometry theodolite filters RF performance $\rightarrow$ anechoic chamber spectrum, pol. effect (VNA/FTS) feed lab. beam pattern (VNA) lab. at this phase, the detector performance mirrors assembled mirrors on a structure w/ filter chamber1 custom cryo together with the flight cryo-cooler will overall shape and mock FP custom cryo. chamber3 dominate the schedule and the cost. There photogrammetry photogrammetry is not much thing one can do for the optical surface accuracy interferometry characterization except the check to see the interferometry detector being optical alive or not. filters → space chamber spectrum, pol. effect (VNA/FTS) FP unit To be completeness, one can in principle feed feed beam, pol. angle, spectrum, imagine JWST like beam/optical beam pattern w/ rep. det. optical time response characterization in the cryogenic custom cryo. chamber2 for -> custom cryo. chamber4

a component test

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warm

cold

6

environment.

## Slides for 2018-2-21

### Telescope alignment and characterization

The mirror shape and the alignment of the mirrors with respect to the support structures.

	large to mid spatial scale	short scale
warm	CMM Theodolite Photogrammetry	Interferometry
cold	Photogrammetry	Interferometry





	What you can learn from?	Pros/Cons
СММ	mirror shape (continuous) and potentially an alignment of structures/mirrors	This works only at warm. A potential scratch on a surface. Laser CMM might not have this issue. This is very handy and accurate method to check the shape after the production at the component level.
Theodolite	mirror shape and the relative positions among the structures/mirrors with in the resolution of the target marker	Commonly used method. If photogrammetry works fine, then this theodolite can be a backup as this cannot be used at cold.
Photogrammetry	mirror shape and the relative positions among the structures/mirrors with in the resolution of the target marker	This is the only shape and alignment method that was used in cold.
Interferometry	finer spatial resolution of the mirror shape within the wavelength of the reference light (10um for Planck).	this was particularly useful to catch the Planck honeycomb dimple. This can still be useful even for an aluminum mirror to catch an asymmetric tension due to the CTE mismatch.

## Pre-flight verification plan and post-flight analysis

What's the relationship among the pre-flight verification plan, inflight calibration, and the post-flight analysis?



### Comments

- The feed beam is an interface between the focal plane and the telescope. Under the assumptions of not being able to do the pre-flight end-to-end beam map, we need to characterize the feed beam with enough accuracy. This would be an important input to the GRASP to simulate the far-sidelobe.
- The model capability of the feed beam may be well understood for a corrugated beam. For sinuous antenna, we need to study how much we can model and the extrapolation capability to the required accuracy.