Cosmology and astrophysics with Planck

Satellite, instruments and data processing

Aniello Mennella

Università degli Studi di Milano – Dipartimento di Fisica

Osservatorio Astronomico di Trieste
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Particular thanks for some of the material to:

- Fabrizio Villa and Maura Sandri (INAF-IASF Bologna) for material on optics
- Gianluca Morgante (INAF-IASF Bologna) and JPL team for material on Sorption Cooler
- ESA for material on orbit and scanning strategy

Outline

Overall description of Planck

From the scientific goals to technology requirements

Orbit and scanning strategy

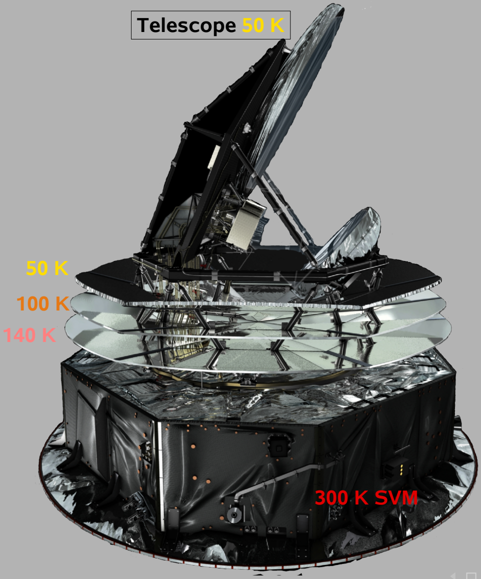
Optics
- Telescope
- Feed horns

Instruments
- High Frequency Instrument
- Low Frequency Instrument

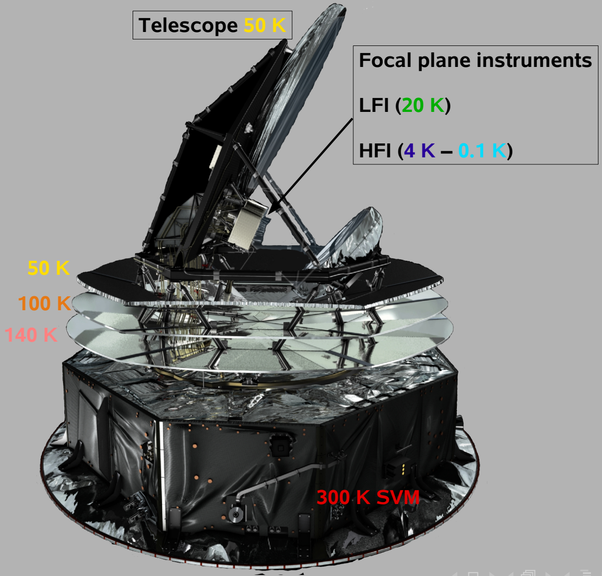
Thermal design
- Passive thermal design
- Active cooling
- The Planck sorption cooler

Data processing

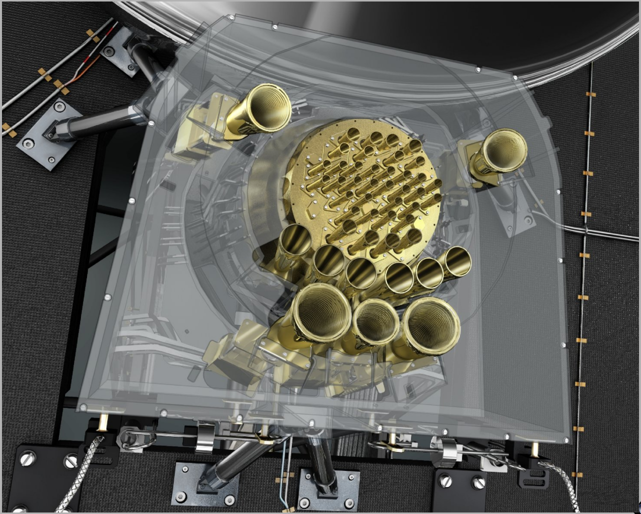
The Planck satellite



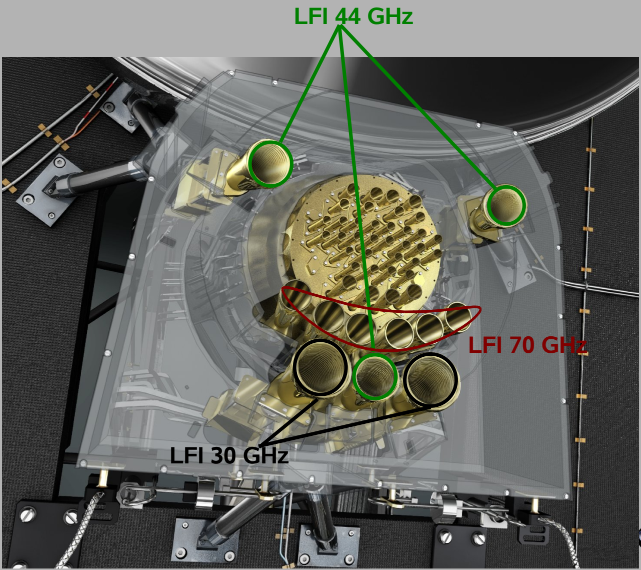
The Planck satellite



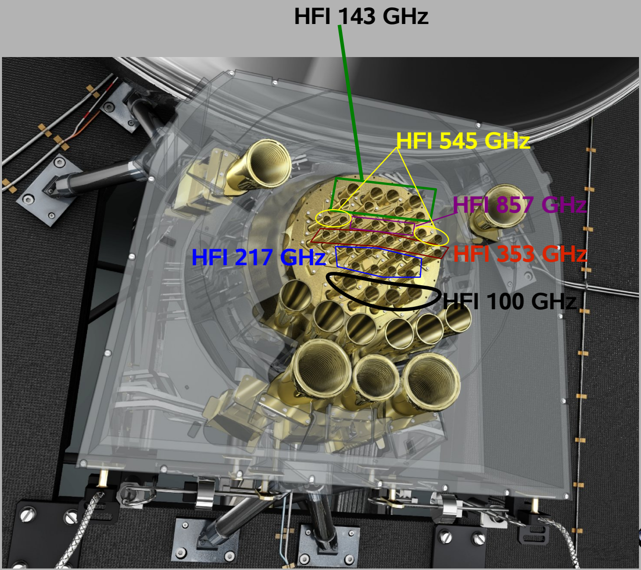
Planck instruments



Planck instruments - LFI

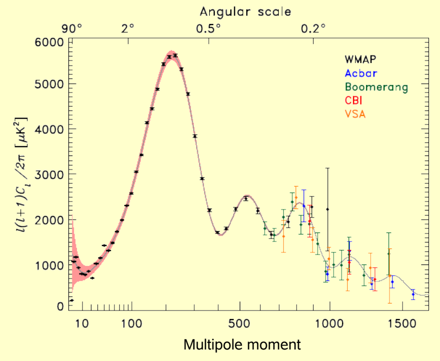


Planck instruments - HFI

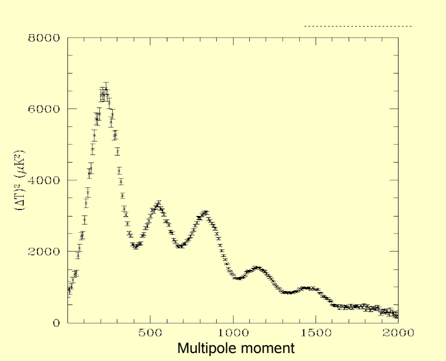


From science to technology

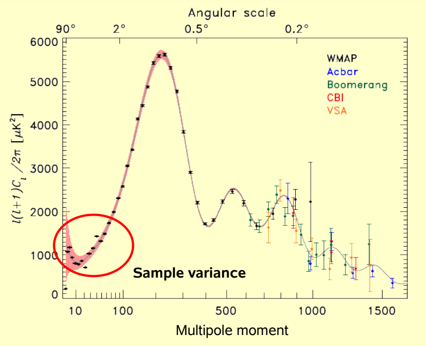
WMAP



Planck



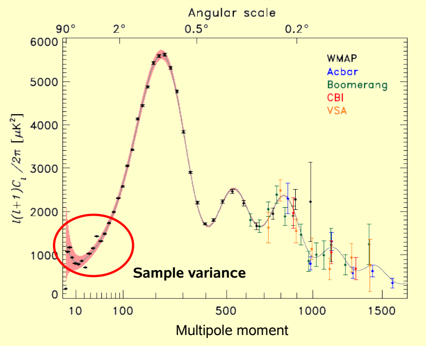
Sources of uncertainties - sample variance



- At low multipoles only a limited number of samples are available for C_ℓ estimation

$$\delta C_\ell = \sqrt{\frac{2}{(2\ell+1)}}C_\ell$$

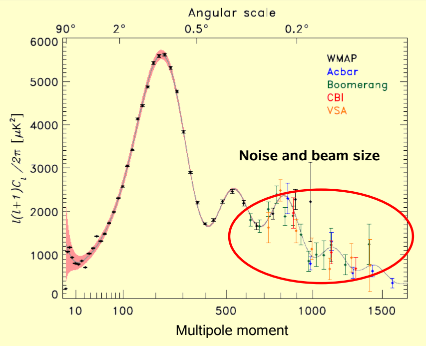
Sources of uncertainties - sample variance



- At low multipoles only a limited number of samples are available for C_ℓ estimation
- If only a fraction of the sky is observed then the uncertainty increases

$$\delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} C_\ell$$

Sources of uncertainties - noise and beam size

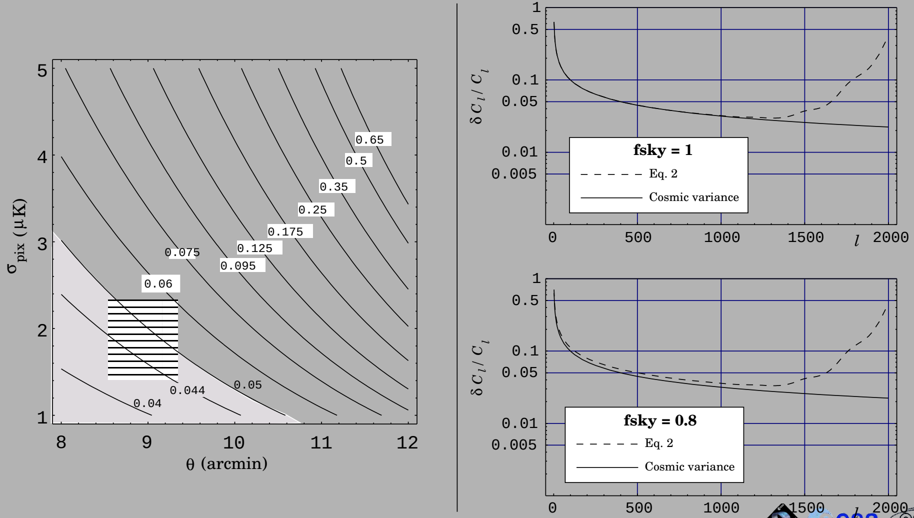


- At high multipoles the accuracy is limited mainly by noise and beam size

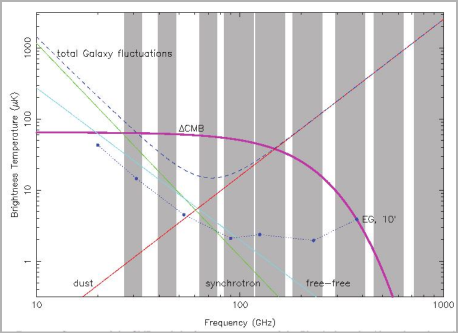
$$\delta C_\ell = \sqrt{\frac{2}{(2\ell+1)f_{sky}}}\left(C_\ell + \frac{A\sigma^2_{pix}}{N_{pix}W^2_\ell}\right)$$

with $W^2_\ell = \exp[-\ell(\ell+1)\sigma^2_B]$ and $\sigma_B = \theta_{FWHM}/\sqrt{8\ln(2)}$

Requisites for Planck

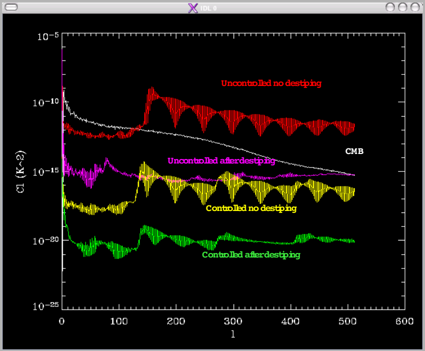


Other sources of uncertainty



Optimal foreground subtraction with wide range of frequencies spanning more than 1 order of magnitude in frequency

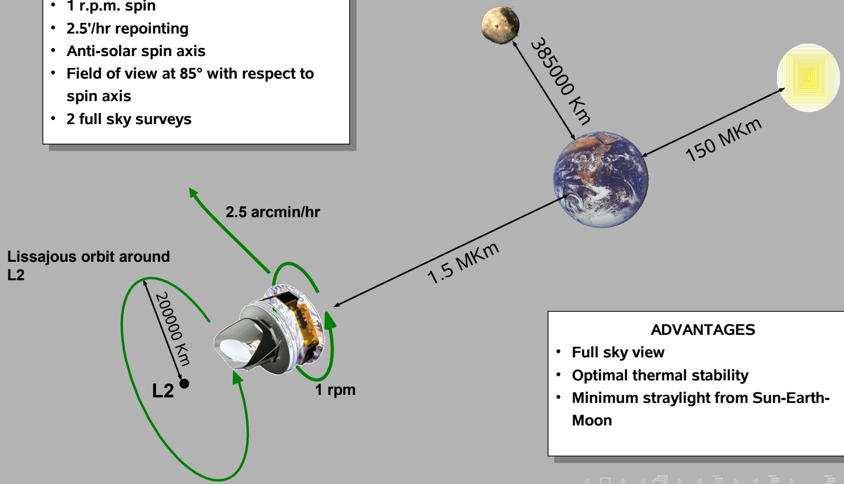
Other sources of uncertainty



Systematic effects must be controlled at the level of $\sim$3-4 μK on the final sky pixel

Orbit and scanning strategy

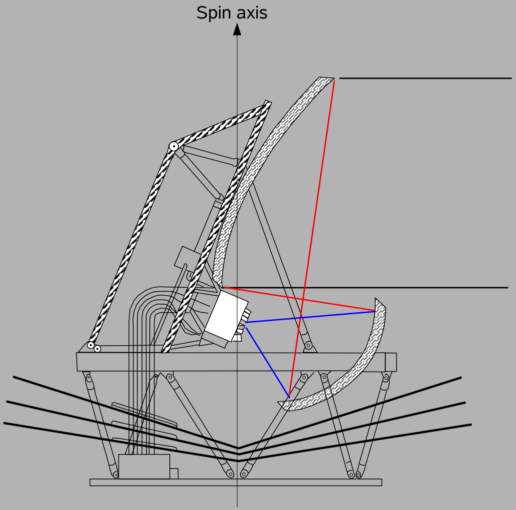
- **Orbit Around L2**
- **1 r.p.m. spin**
- **2.5'/hr repointing**
- **Anti-solar spin axis**
- **Field of view at 85° with respect to spin axis**
- **2 full sky surveys**



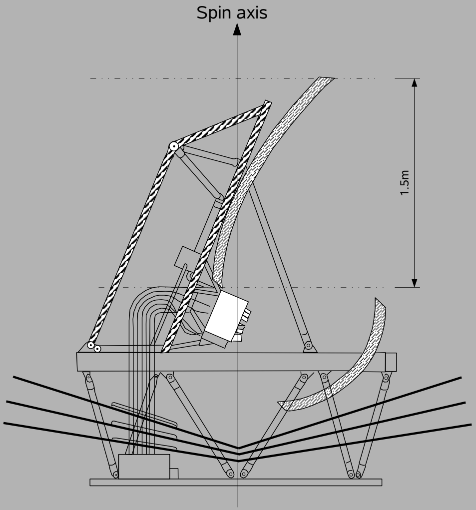
ADVANTAGES

- **Full sky view**
- **Optimal thermal stability**
- **Minimum straylight from Sun-Earth-Moon**

The Planck Telescope

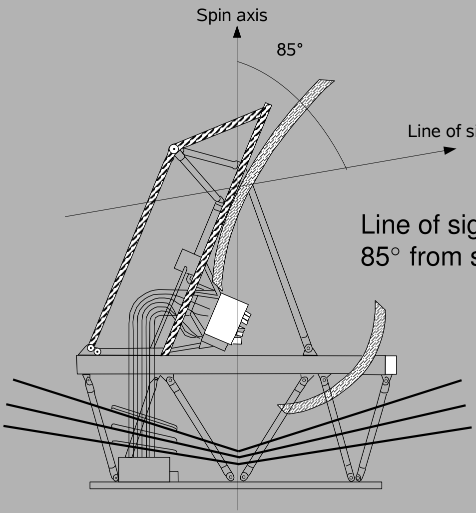


The Planck Telescope



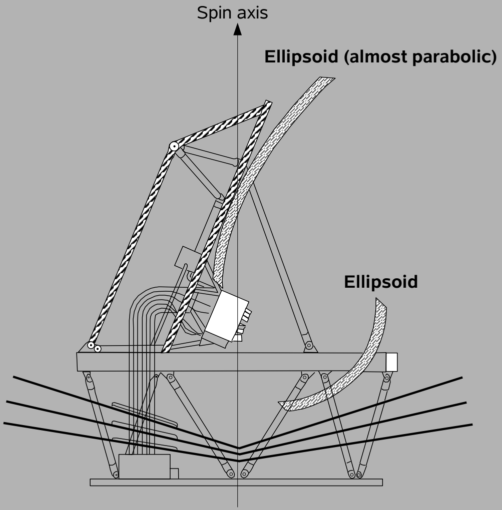
Primary aperture of 1.5 m provides $\sim$ 9 arcmin angular resolution at 100 GHz

The Planck Telescope



Line of sight inclined at 85° from spin axis

The Planck Telescope

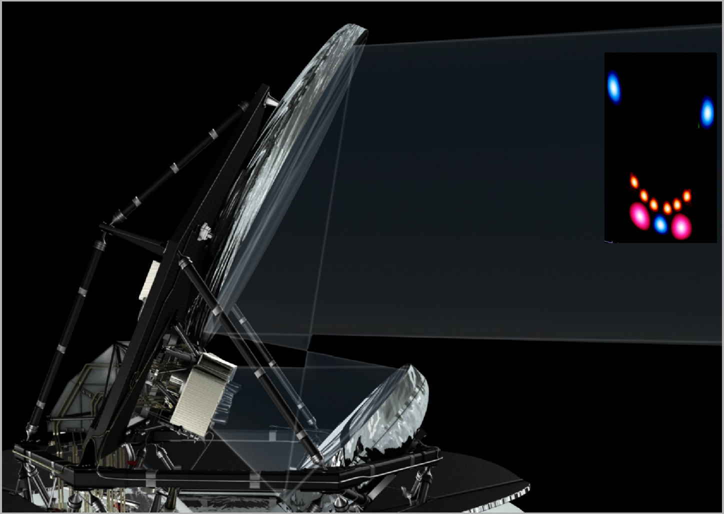


Aplanatic design minimises beam aberrations

The Planck Telescope

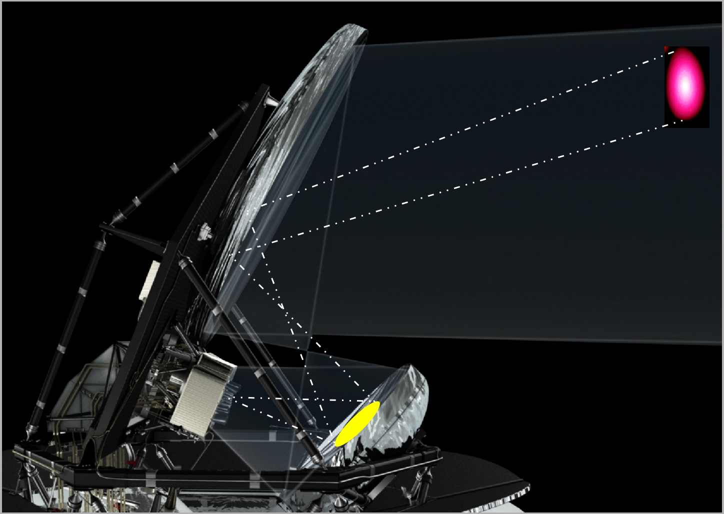
- Telescope realised in CFRP (Carbon Fiber Reiforced Plastic) for optimal weight and best thermal performances
- Hexagonal cell structure
- Surface made of aluminum coated by silicon oxide
- Emissivity $< 1\%$

Telescope-feed coupling



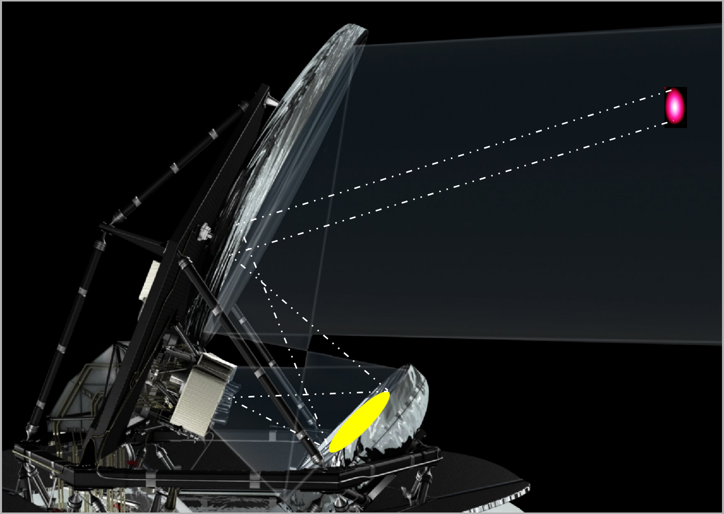
Telescope-feed coupling

Underillumination → poor angular resolution



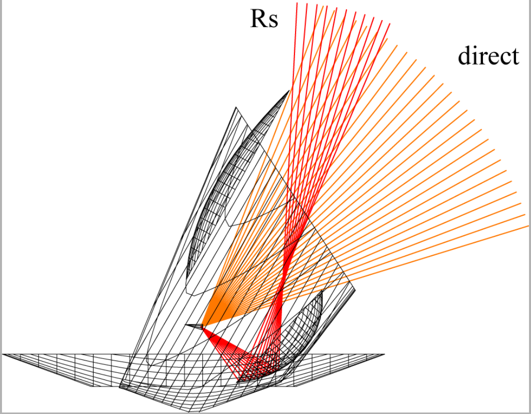
Telescope-feed coupling

Overillumination → improved resolution but...

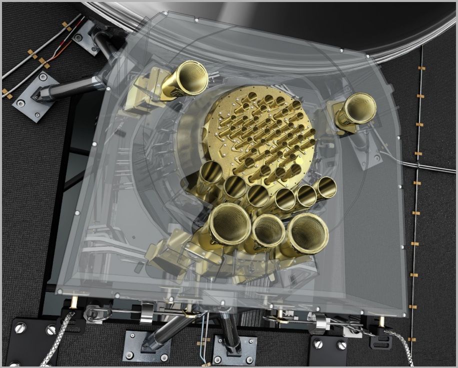


Telescope-feed coupling

Overillumination → improved resolution but... sensitivity to straylight



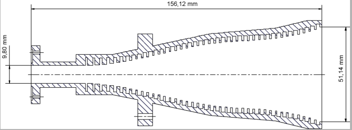
Feed-horns [R.Nesti (LFI), B. Maffei (HFI)]

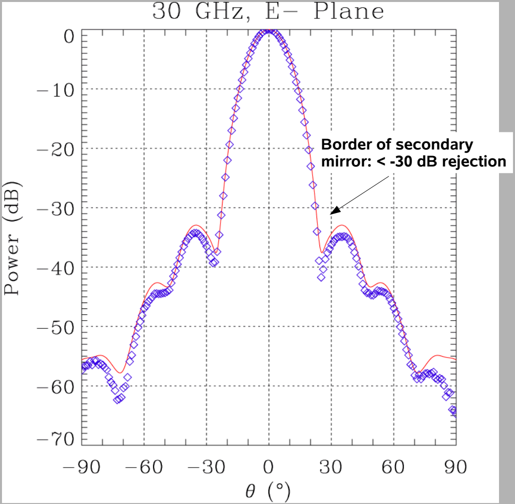


Dual profiled corrugated horns have been selected as the best solution in terms of:

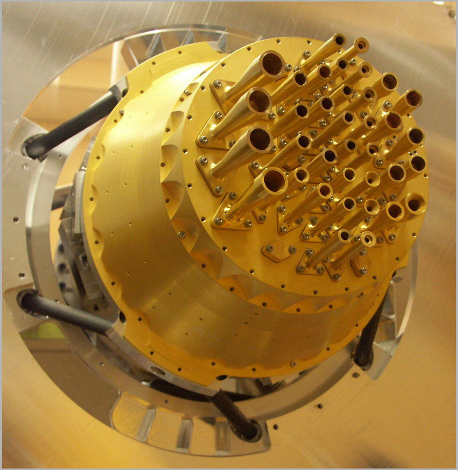
- level of cross polarization
- level of sidelobes
- return and insertion losses
- shape of the main lobe
- low weight
- compactness

Feed-horns [R.Nesti (LFI), B. Maffei (HFI)]



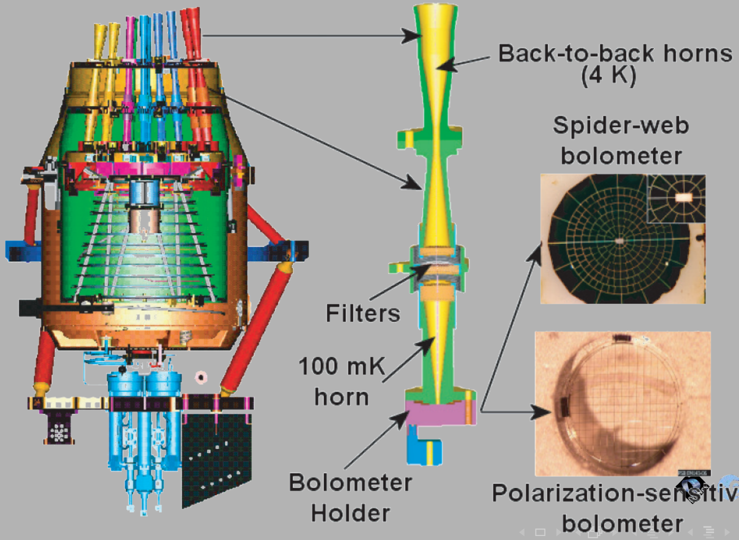


High Frequency Instrument



- Array of 52 bolometric detectors cooled at 0.1 K in 6 frequency bands between 100 and 857 GHz
- Focal plane feed horns cooled at 4 K
- Sensitive to polarisation at four lower frequencies
- Developed by consortium lead by IAS-Orsay (P.I. J-L. Puget, I.S. J-M. Lamarre)

High Frequency Instrument - details



High Frequency Instrument - performances

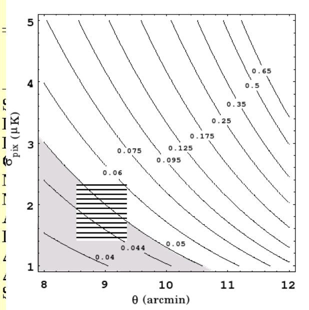
HFI PERFORMANCE GOALS[a]

INSTRUMENT CHARACTERISTIC	CENTER FREQUENCY [GHz] 100	143	217	353	545	857
Spectral resolution $\nu/\Delta\nu$	3	3	3	3	3	3
Detector technology	Spider-web and polarisation-sensitive bolometers					
Detector temperature	0.1 K					
Cooling system	20 K Sorption Cooler + 4 K J-T + 0.1 K Dilution					
Number of spider-web bolometers	0	4	4	4	4	4
Number of polarisation-sensitive bolometers	8	8	8	8	0	0
Angular resolution [FWHM arcminutes]	9.5	7.1	5.0	5.0	5.0	5.0
Detector Noise-Equivalent Temperature [μK$s^{0.5}$]	50	62	91	277	1998	91000
$\Delta T/T$ Intensity [b] [$10^{-6}\mu$K/K]	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ Polarisation (U and Q)[b] [$10^{-6}\mu$K/K]	4.0	4.2	9.8	29.8	...	...
Sensitivity to unresolved sources [mJy]	12.0	10.2	14.3	27	43	49
ySZ per FOV [10^{-6}]	1.6	2.1	615	6.5	26	605

[a] Goal sensitivities. All subsystems have been designed to reach or exceed the performances of this table, which are expected to be achieved in orbit. Sensitivity requirements are a factor of two worse, and would still achieve the core scientific objectives of the mission.

[b] Average 1σ sensitivity per pixel (a square whose side is the FWHM extent of the beam), in thermodynamic temperature units, achievable after 2 full sky surveys (14 months).

High Frequency Instrument - performances



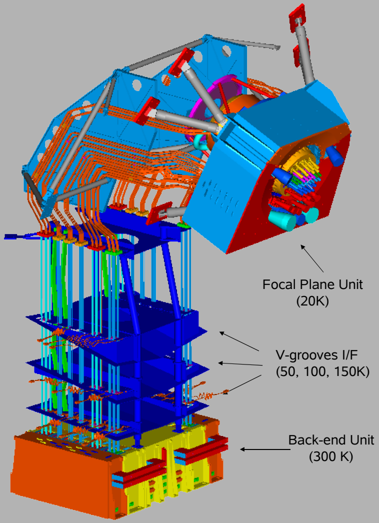
FI Performance Goals[a]

	Center Frequency [GHz]					
	100	143	217	353	545	857
	3	3	3	3	3	3
	Spider-web and polarisation-sensitive bolometers					
	0.1 K					
	20 K Sorption Cooler + 4 K J-T + 0.1 K Dilution					
	0	4	4	4	4	4
	8	8	8	8	0	0
	9.5	7.1	5.0	5.0	5.0	5.0
$K_s^{0.5}$]	50	62	91	277	1998	91000
	2.5	2.2	4.8	14.7	147	6700
]	4.0	4.2	9.8	29.8	...	...
	12.0	10.2	14.3	27	43	49
ySZ per FOV [10]	1.6	2.1	615	6.5	26	605

[a] Goal sensitivities. All subsystems have been designed to reach or exceed the performances of this table, which are expected to be achieved in orbit. Sensitivity requirements are a factor of two worse, and would still achieve the core scientific objectives of the mission.

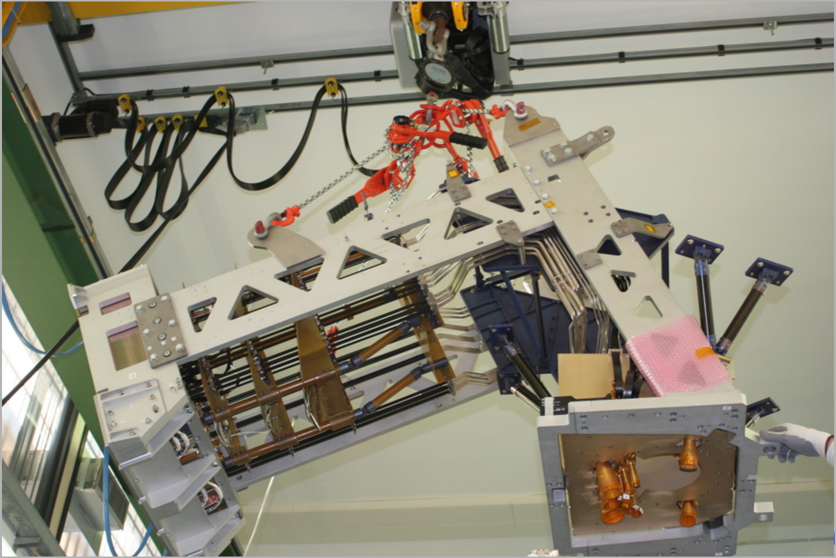
[b] Average 1σ sensitivity per pixel (a square whose side is the FWHM extent of the beam), in thermodynamic temperature units, achievable after 2 full sky surveys (14 months).

Low Frequency Instrument



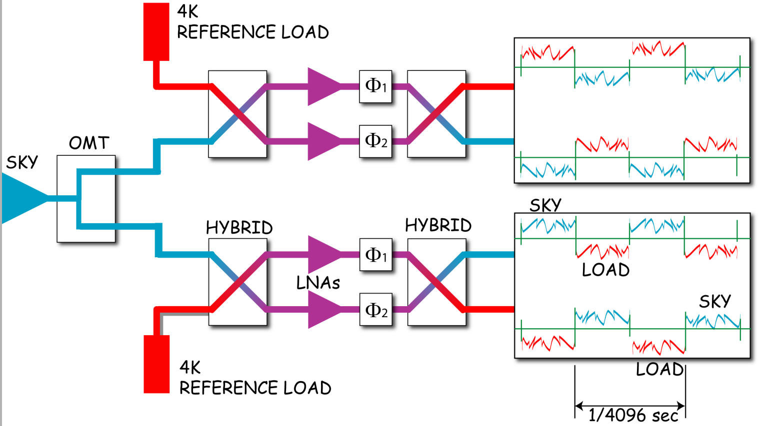
- Array of 44 radiometric detectors cooled at 20 K in 3 frequency bands centred at 30, 44 and 70 GHz
- Sensitive to polarisation at all frequencies
- Developed by consortium lead by INAF-IASF (P.I. R. Mandolesi, I.S. M. Bersanelli)
- Thales Alenia Space (formerly Laben) - Milan as industrial partner

Low Frequency Instrument - flight hardware

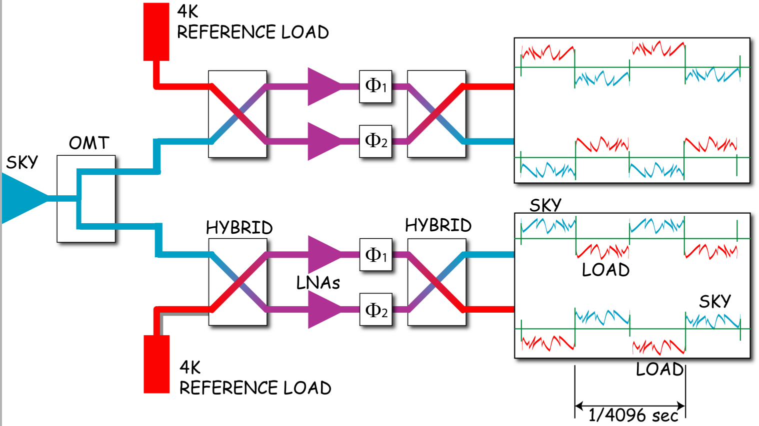


Low Frequency Instrument - flight hardware

The Planck-LFI pseudo-correlation receivers

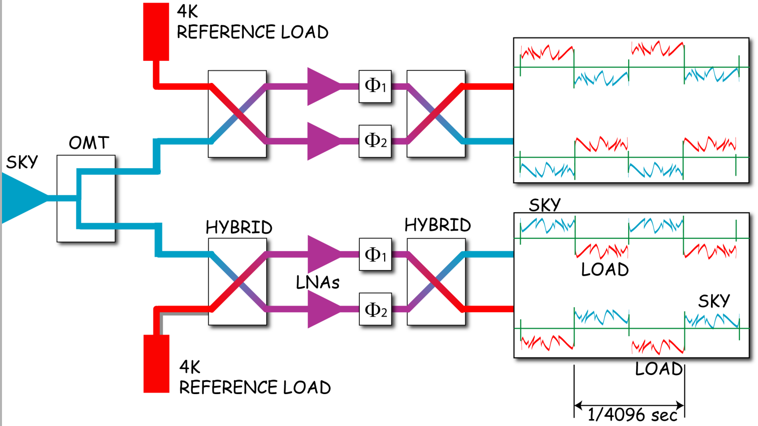


The Planck-LFI pseudo-correlation receivers



Four outputs: R0D0, R0D1, R1D0, R1D1

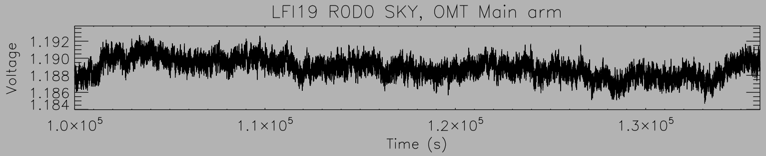
The Planck-LFI pseudo-correlation receivers



$$\Delta V(t) = V_{sky}(t) - r \times V_{load}(t)$$

$$r \sim \langle V_{sky} \rangle / \langle V_{load} \rangle$$

The Planck-LFI pseudo-correlation receivers



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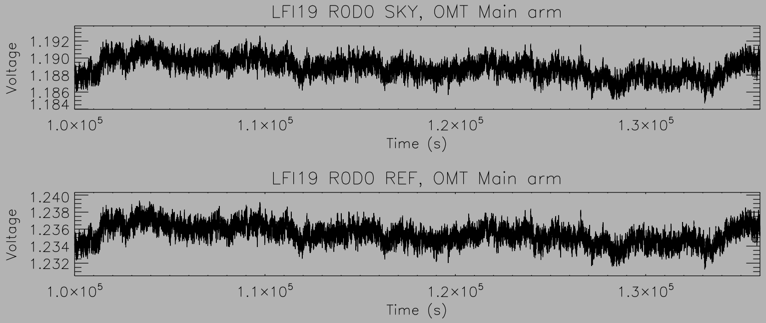

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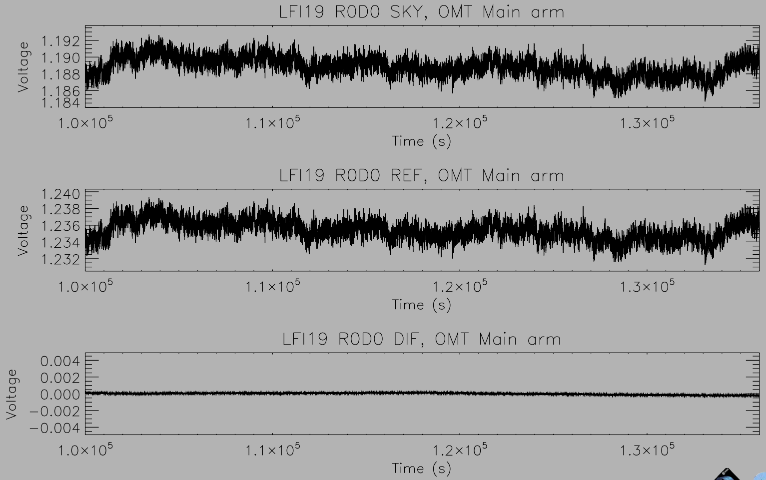

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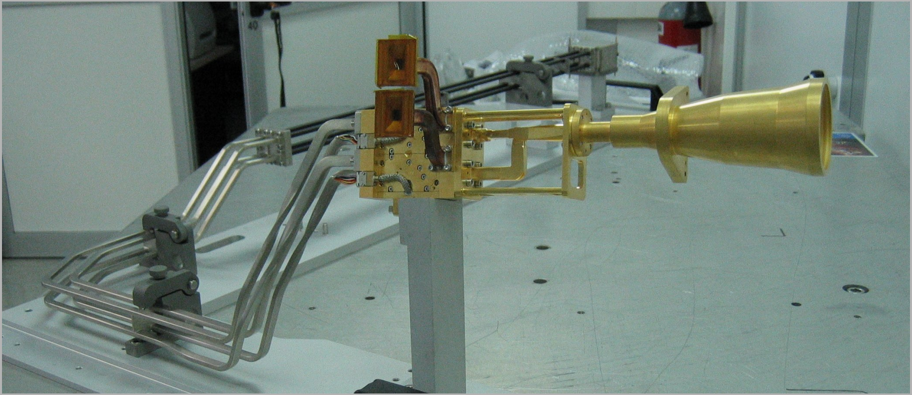

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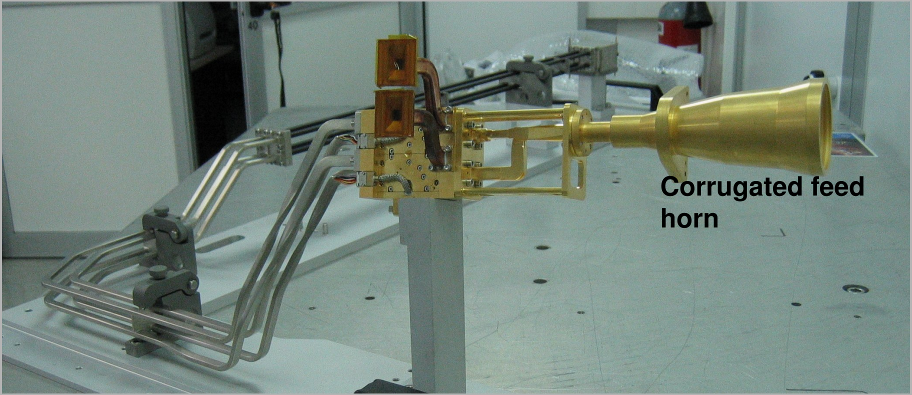

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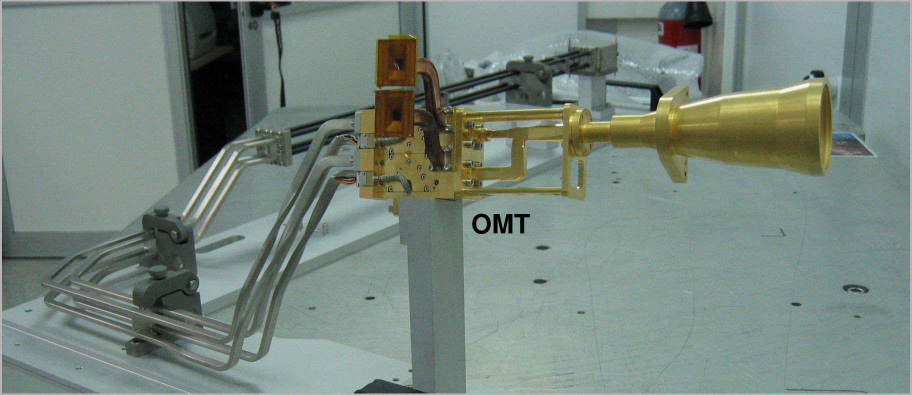

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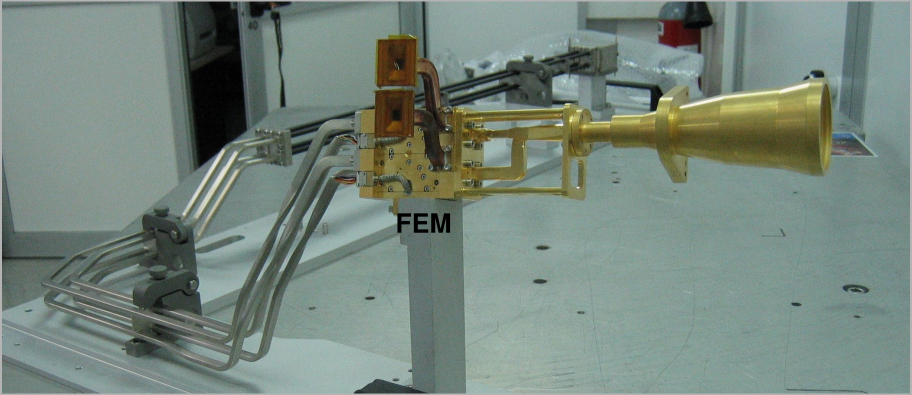

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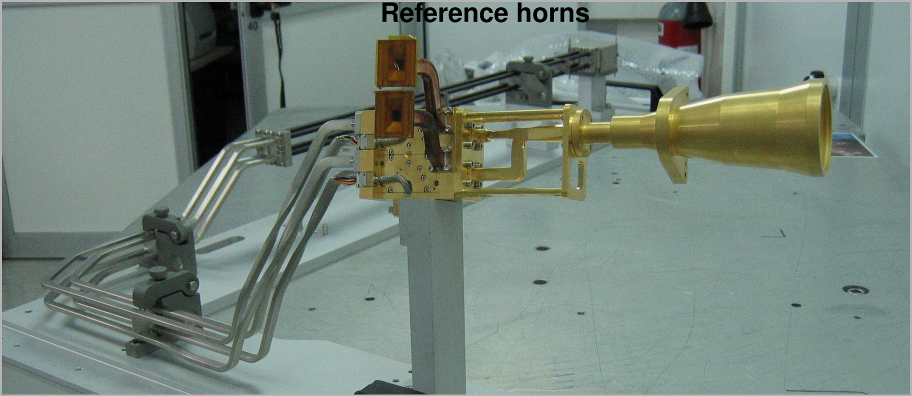
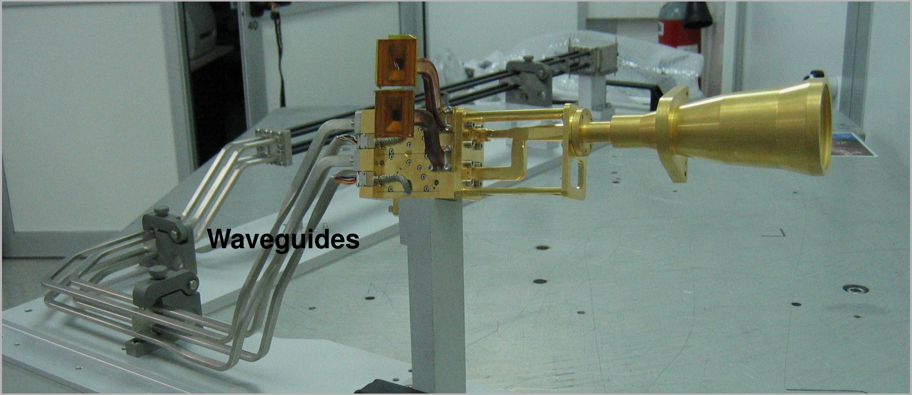


The Planck-LFI pseudo-correlation receivers



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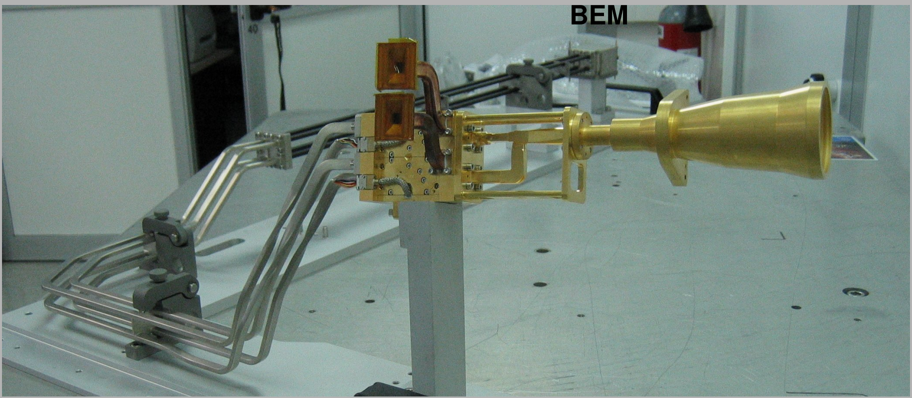

Low Frequency Instrument - performances

LFI PERFORMANCE GOALS[a]

INSTRUMENT CHARACTERISTIC	CENTER FREQUENCY [GHz] 30	44	70
InP HEMT Detector technology	MIC		MMIC
Detector temperature	20 K		
Cooling system	H_2 Sorption Cooler		
Number of feeds	2	3	6
Angular resolution [arcminutes FWHM]	33	24	14
Effective bandwidth [GHz]	6	8.8	14
Sensitivity [$\mathrm{mK\,Hz^{-1/2}}$]	0.17	0.20	0.27
System temperature [K]	7.5	12	21.5
Noise per 30′ reference pixel [μK]	6	6	6
$\Delta T/T$ Intensity [b] [10^{-6} μK/K]	2.0	2.7	4.7
($\Delta T/T$) Polarisation (Q and U) [b] [μK/K]	2.8	3.9	6.7
Maximum systematic error per pixel [μK]	< 3	< 3	< 3

[a] All subsystems are designed to reach or exceed the performances of this table.

[b] Average 1σ sensitivity per pixel (a square whose side is the FWHM extent of the beam), in thermodynamic temperature units, achievable after 2 full sky surveys (14 months).

Cold is cool!

A cold and stable environment is key for telescope, focal plane and instruments:

- High sensitivity requirements call for cold optics and detectors
- Bolometric detectors need to be cooled at sub-K level to work (0.1 K for Planck-HFI)
- Stringent systematic effect control requires stable thermal conditions.

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- High sensitivity requirements call for cold optics and detectors
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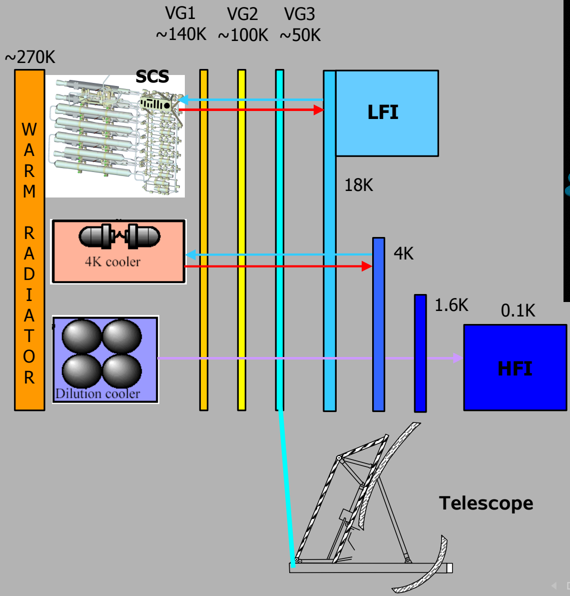
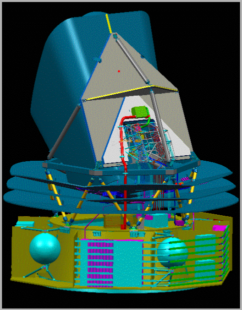
- Stringent systematic effect control requires stable thermal conditions.

Planck is an extraordinary technological challenge from the thermal point of view

The Planck cryo-chain

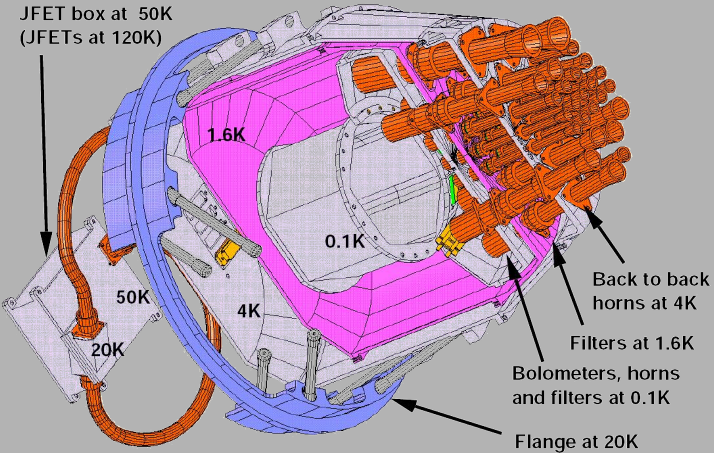




Passive cooling

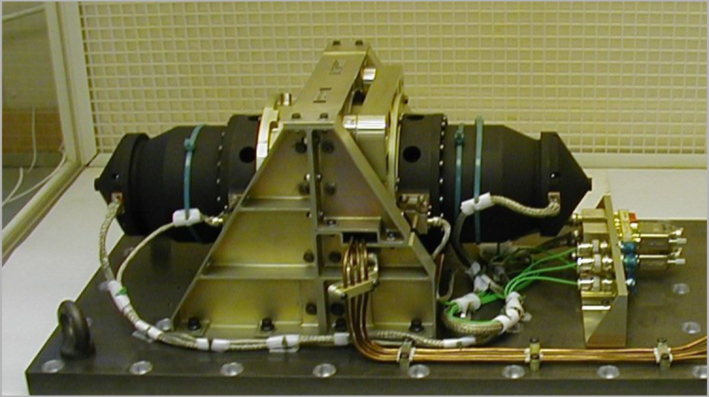
- About 16 m^2
- Open Honeycomb, black painted
- Reflection of thermal IR to space
- Cryocoolers heat exchangers on V-grooves
- Cryo structure support by fiberglass struts
- Parasitics interception of harness, struts, waveguides

The HFI cold stages (4K, 1.6K and 0.1K)



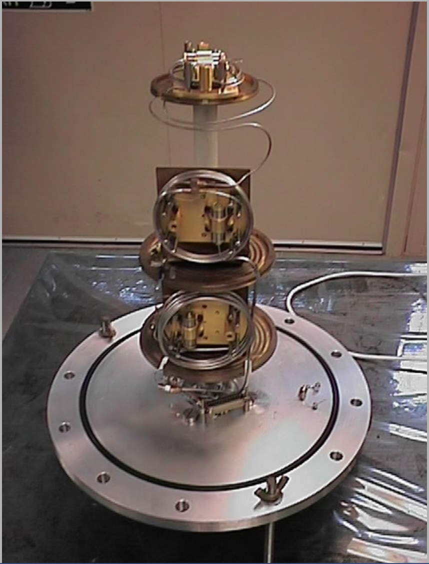
The 4 K mechanical cooler [RAL - UK]

Mechanical compressor



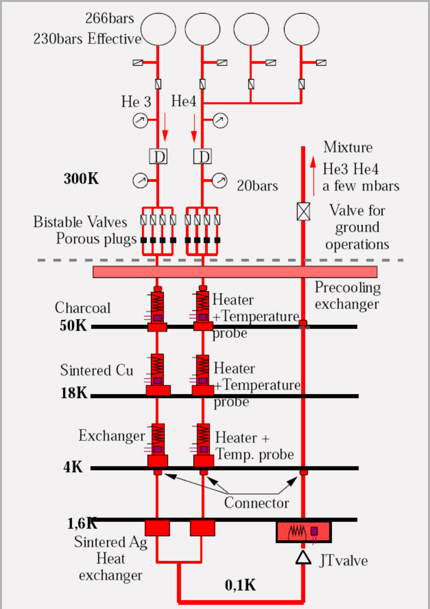
The 4 K mechanical cooler [RAL - UK]

J-T cold end



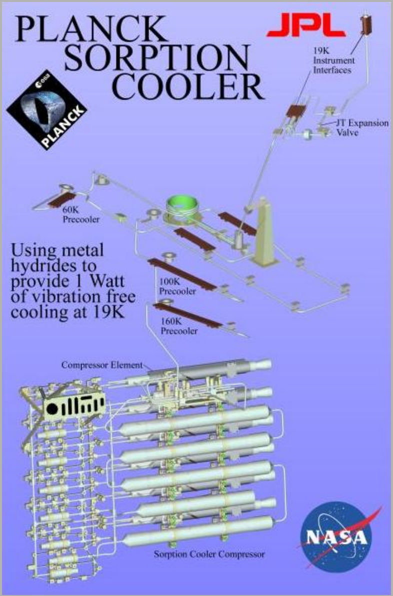
- Vibrations active control
- Heatlift 14mW @ 4.5K
- Input power 60W
- Total mass 40kg

The 0.1 K dilution cooler



- Capillary dilution, open cicle
- Heatlift 100 nW at 100 mK
- Built by Air Liquide
- Precooling at 50K, 20K, 4K.
- J-T expansion at 1.6K
- 4 tanks of 51 l at 295b (1 for 3He, 3 for 4He)

The Planck Sorption Cooler

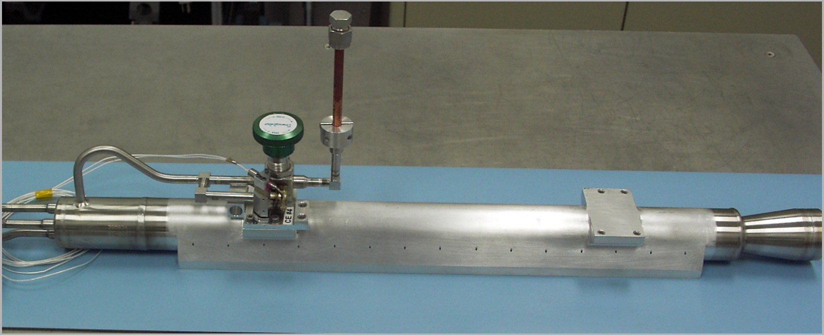


JPL has a pioneering heritage on hydrogen sorption coolers:

- 10K prototype demostrator in 1992 (single shot)
- BETSCE 10K solid H2 tested on Space Shuttle in 1996 (single shot)
- Planck SCS first H2 continuous cycle chemi-sorption cooler used in space
- Engineering Breadboard & FM's

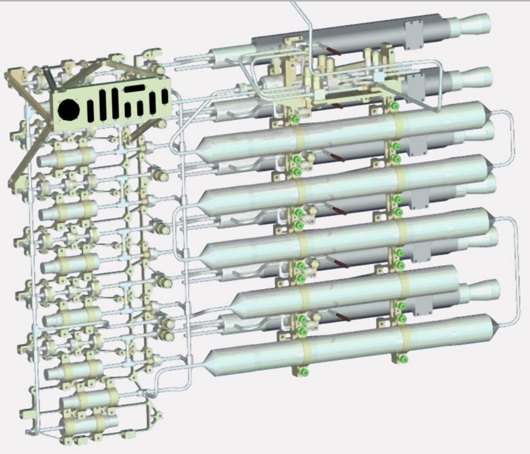
How the Sorption Cooler works

Each compressor element is a tube containing a metal hydride that absorbs or releases hydrogen depending on its temperature

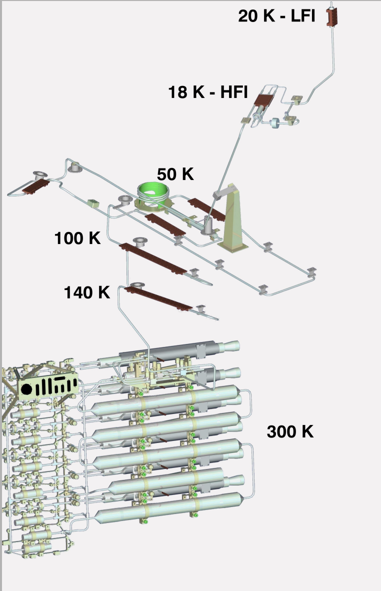


How the Sorption Cooler works

Six compressors alternatatively warming up and cooling down generate a constant high pressure hydrogen flow

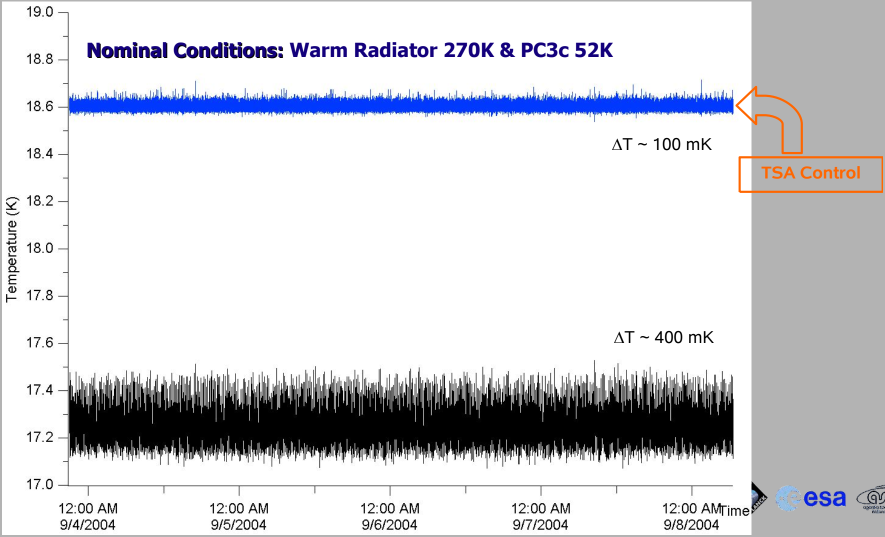


How the Sorption Cooler works

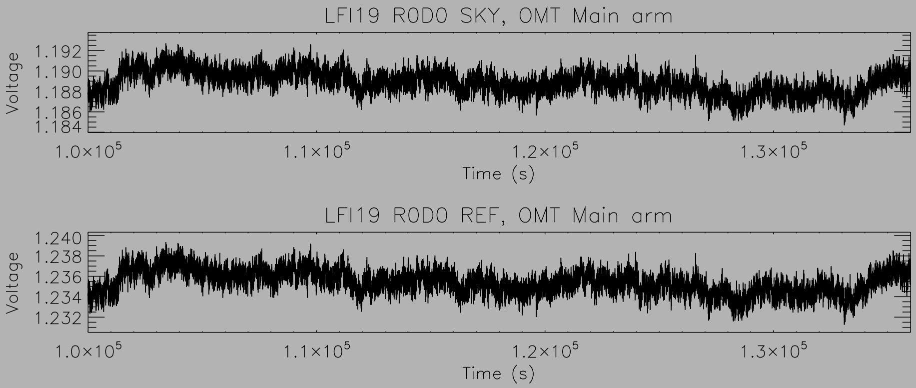


- Hydrogen flows in the Cooler piping from SVM to payload
- Three thermal interfaces with V-grooves precool the fluid
- Hydrogen expands and cool in two heat exchangers connected to HFI and LFI

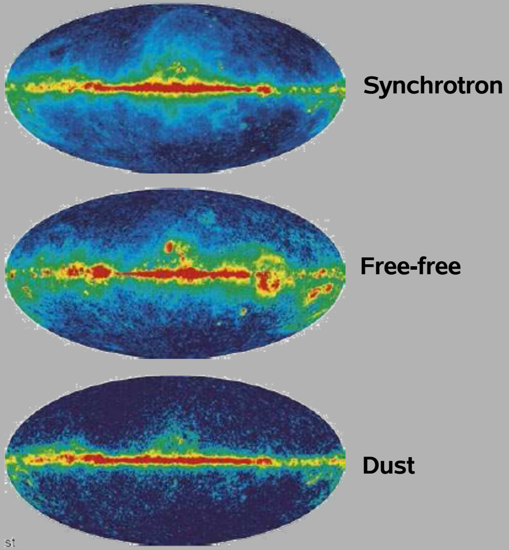
Sorption cooler temperature stability



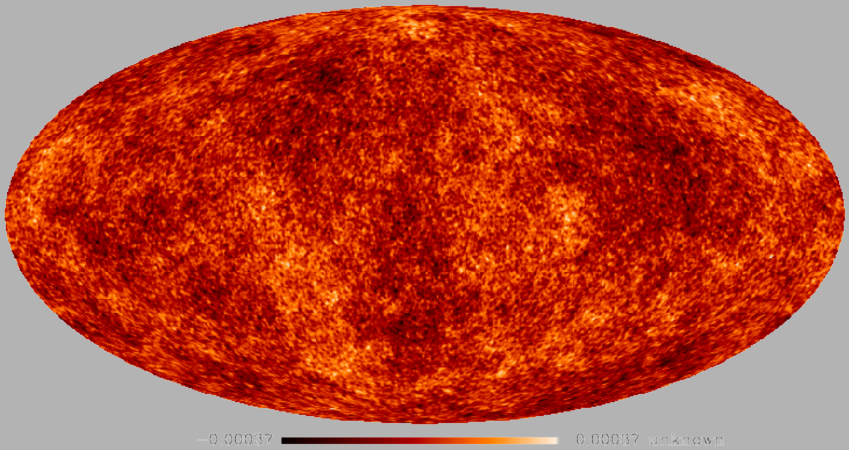
Data processing - from time ordered data ...



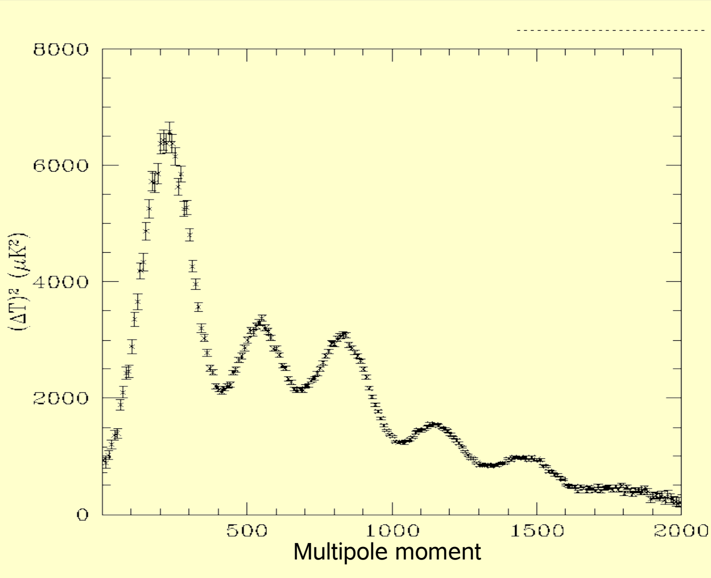
Data processing - ... to components maps ...



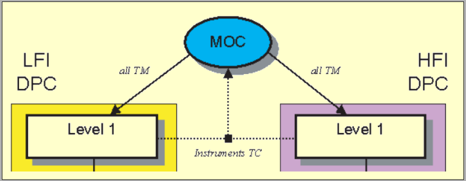
Data processing - ... to cmb map ...



Data processing - ... to power spectrum

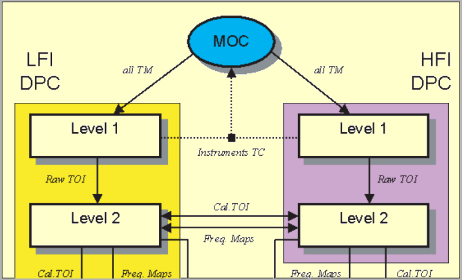


Data processing structure



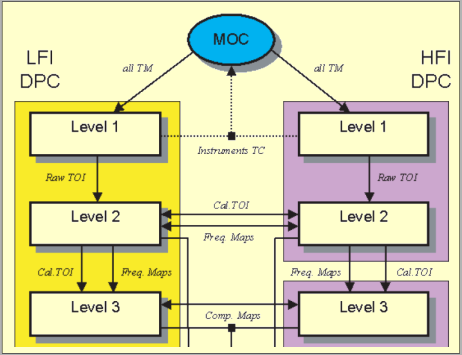
- Level 1: telemetry processig, generation of TOIs, instrument health checks

Data processing structure



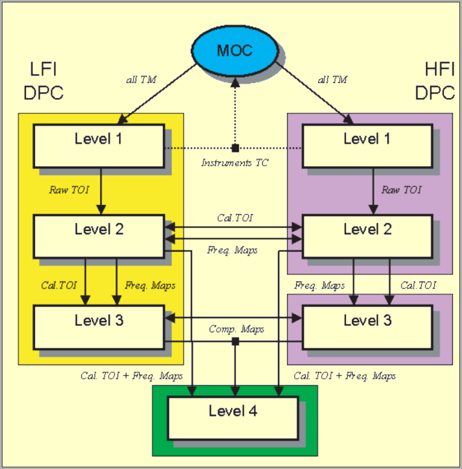
- Level 1: telemetry processig, generation of TOIs, instrument health checks
- Level 2: TOI processing, calibration and systematic error removal

Data processing structure



- Level 1: telemetry processig, generation of TOIs, instrument health checks
- Level 2: TOI processing, calibration and systematic error removal
- Level 3: Map generation at various frequencies, component separation

Data processing structure



- Level 1: telemetry processig, generation of TOIs, instrument health checks
- Level 2: TOI processing, calibration and systematic error removal
- Level 3: Map generation at various frequencies, component separation
- Level 4: Generation of final products

The Planck collaboration