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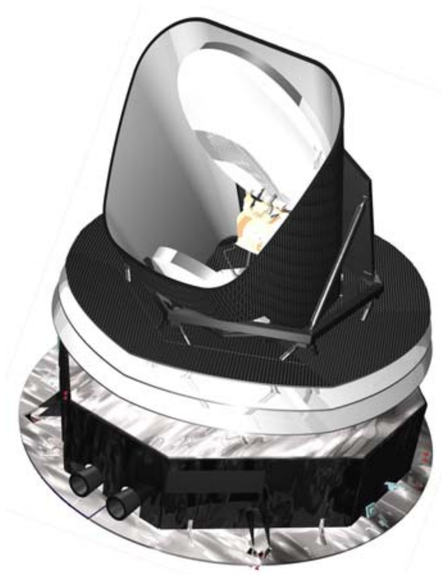


PLANCK

The European mission to map the Cosmic Microwave Background

J. Tauber, on behalf of the Planck Collaboration

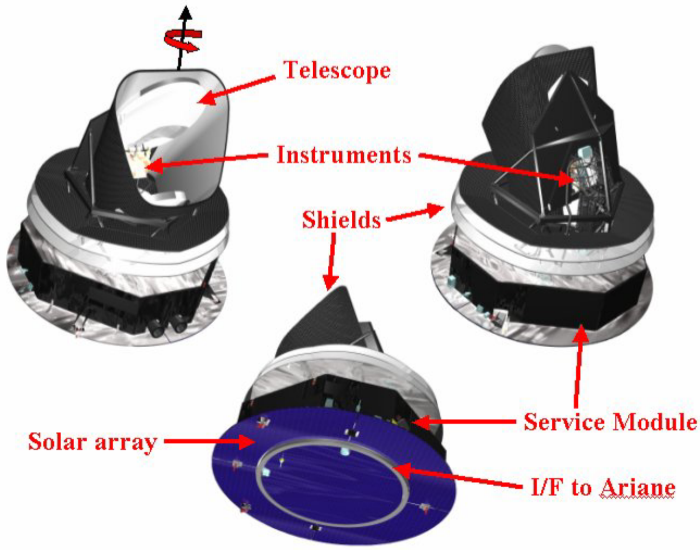
Main Observational Objective of PLANCK

To image the whole sky at wavelengths near the peak of the spectrum of the Cosmic Microwave Background Radiation Field (CMB), with an instrument sensitivity $\Delta T/T \sim 10^{-6}$, an angular resolution ~5 arcminutes, wide frequency coverage, and excellent rejection of systematics .

Observational Strategy

- Two successive all-sky surveys
- 1.5 metre aperture telescope
- wide frequency coverage (25 GHz - 950 GHz)
- State-of-the-art detectors
- extreme attention to systematic effects

Spacecraft elements



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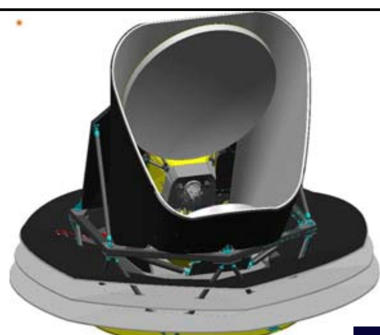
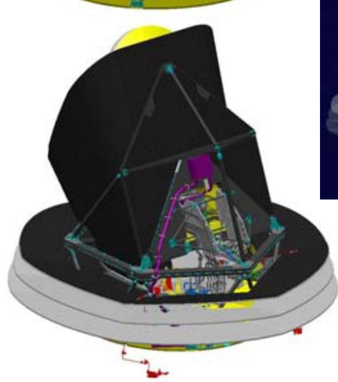
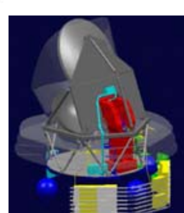
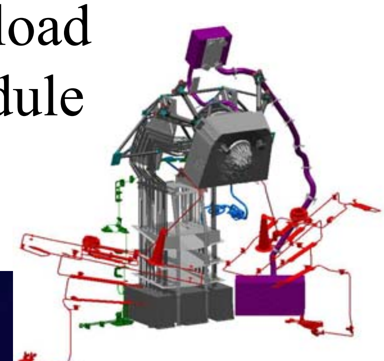
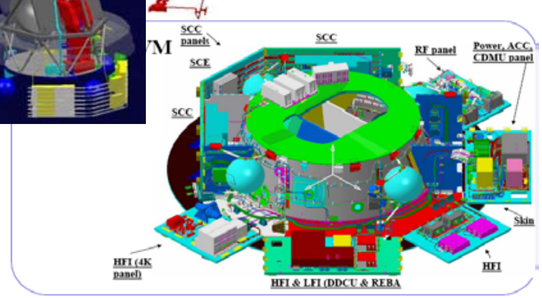
Payload module





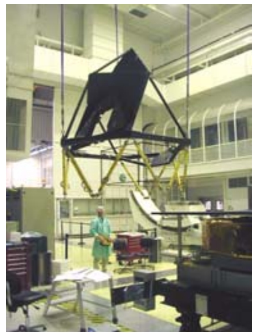


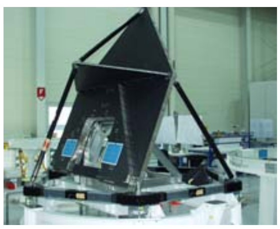


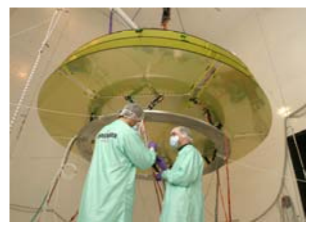


Spacecraft hardware

Prime contractor: Alcatel Space (Cannes)

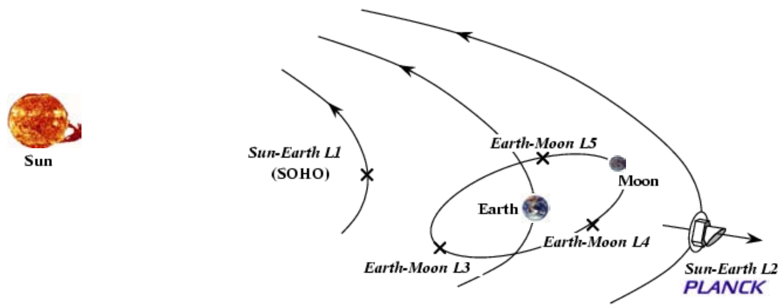






Launch in 2007

Choice of orbit



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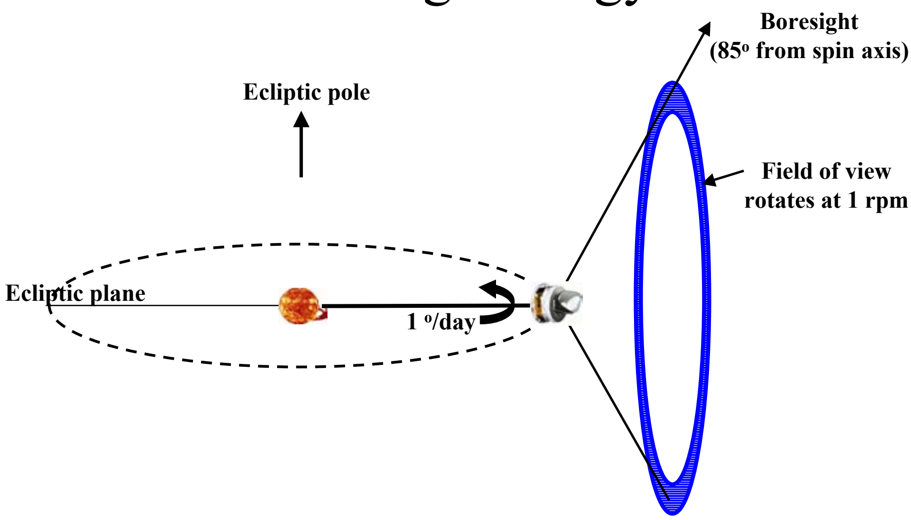
Observing strategy



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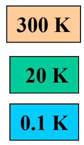
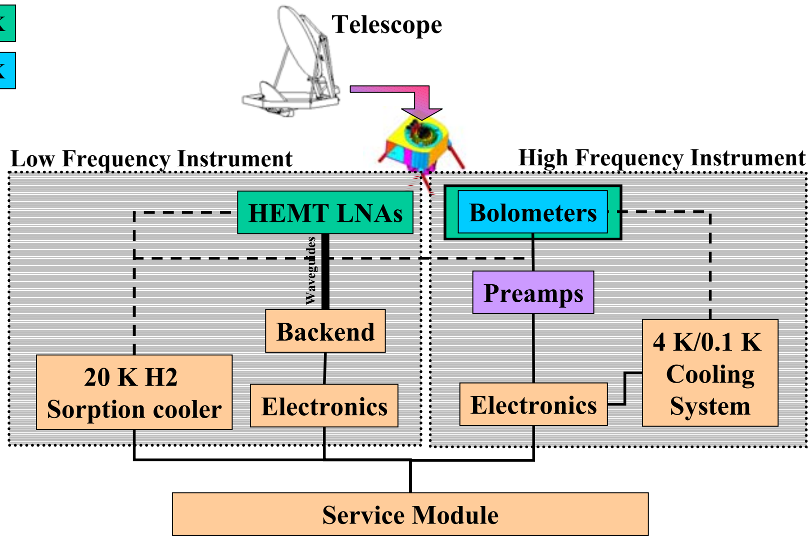
Payload elements





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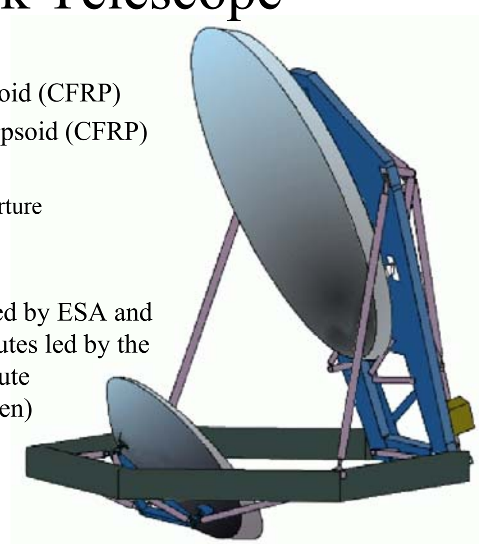
Planck Telescope



- Primary: 1.50 x 1.89 m ellipsoid (CFRP)
- Secondary: 1.02 x 1.04 m ellipsoid (CFRP)
- System:
  - 1.5 m circular projected aperture
  - Total MWFE<40 µm rms
  - Total ε <0.01
- Reflectors are being developed by ESA and a Consortium of danish institutes led by the Danish Space Research Institute (PI: Dr. H.U. Norgaard-Nielsen)

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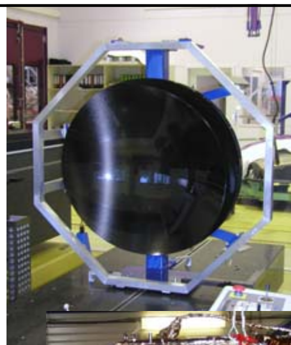
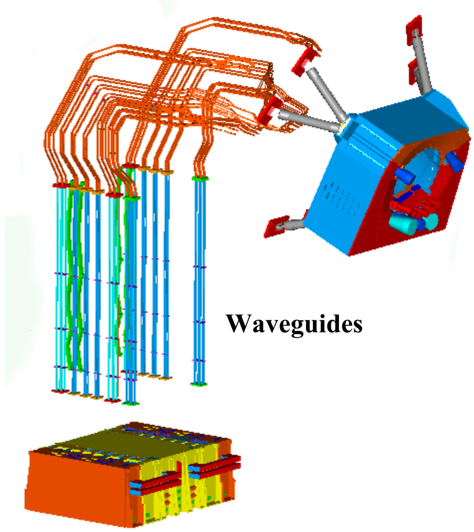
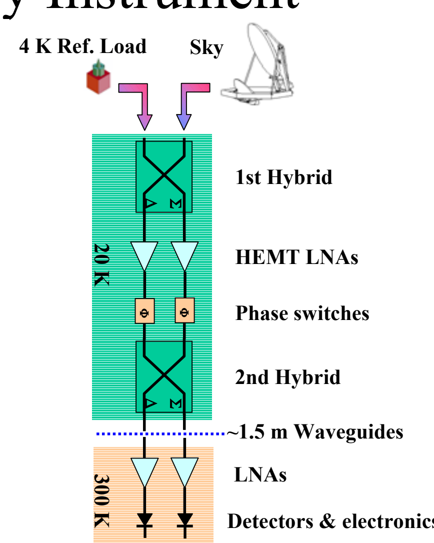
Reflectors



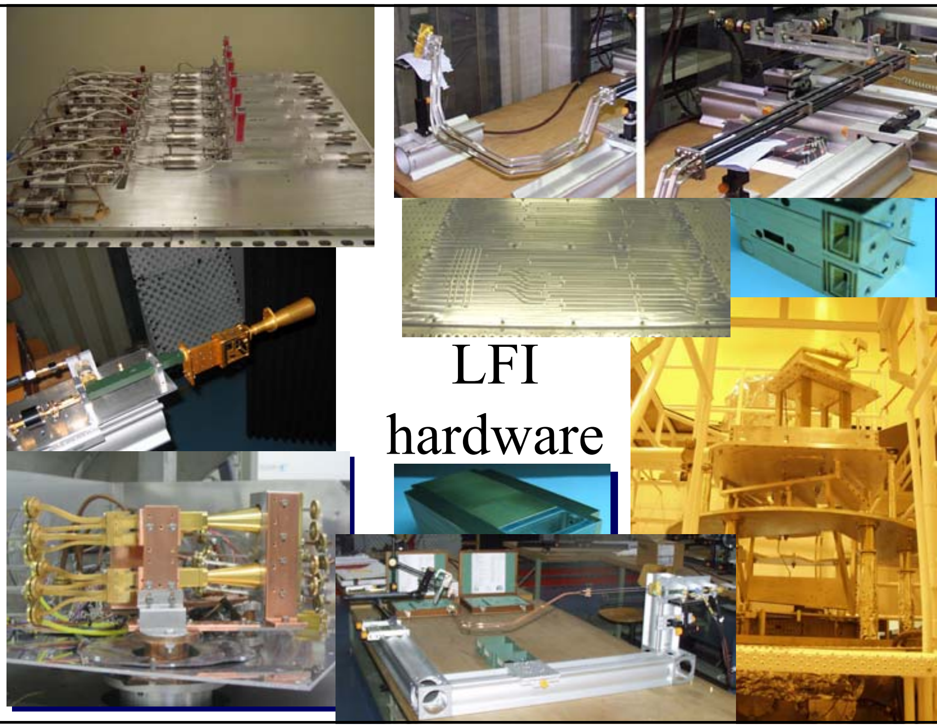
Manufacturer: Astrium Gmbh (Friedrichshafen)

Low Frequency Instrument

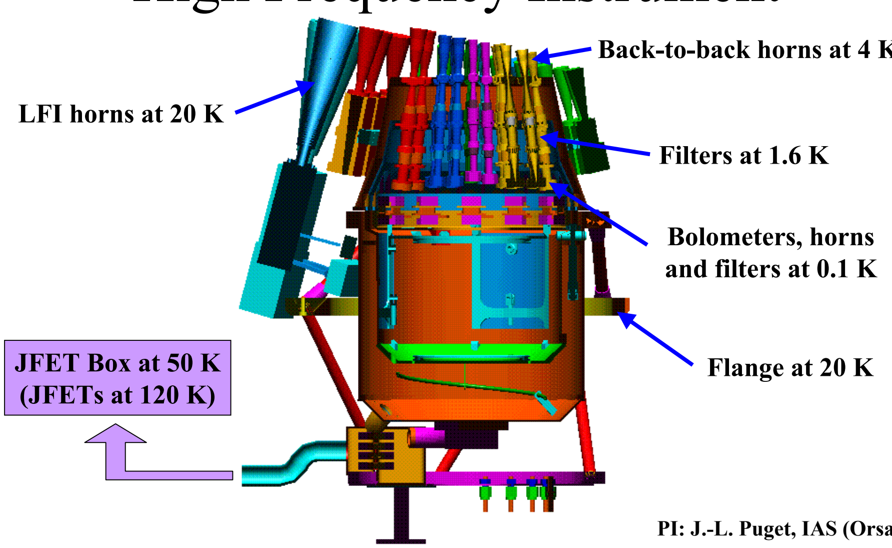




P.I.: R. Mandolesi, IASF (Bologna)

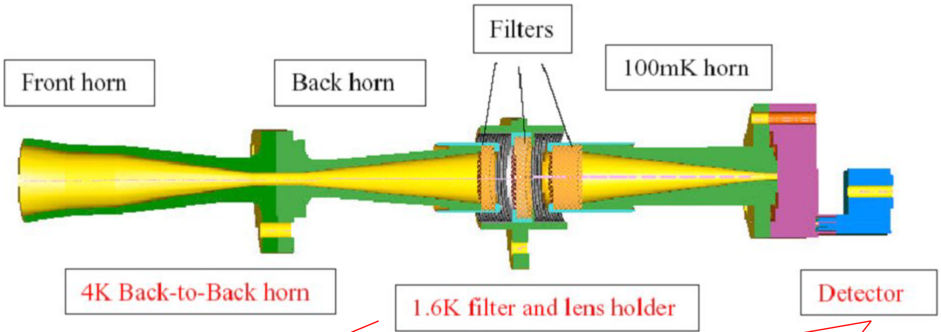


High Frequency Instrument

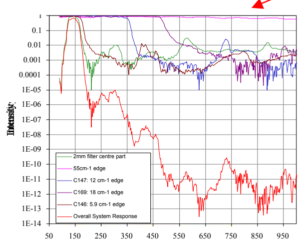


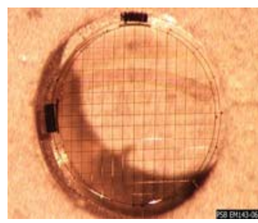
PI: J.-L. Puget, IAS (Orsay)

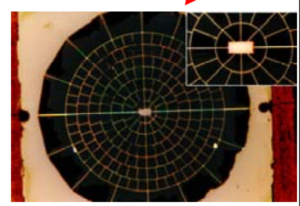
High Frequency Instrument



Filters (QMW)

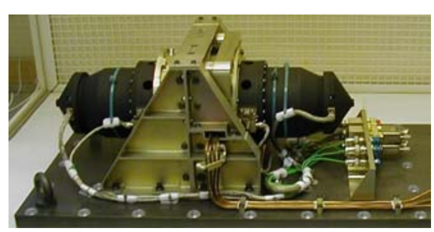




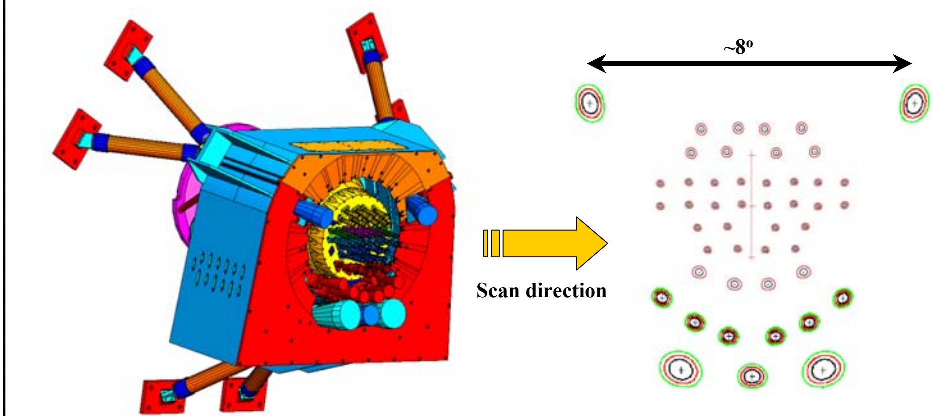


Spider-web or polarisation-sensitive bolometers (CalTech/JPL

HFI hardware



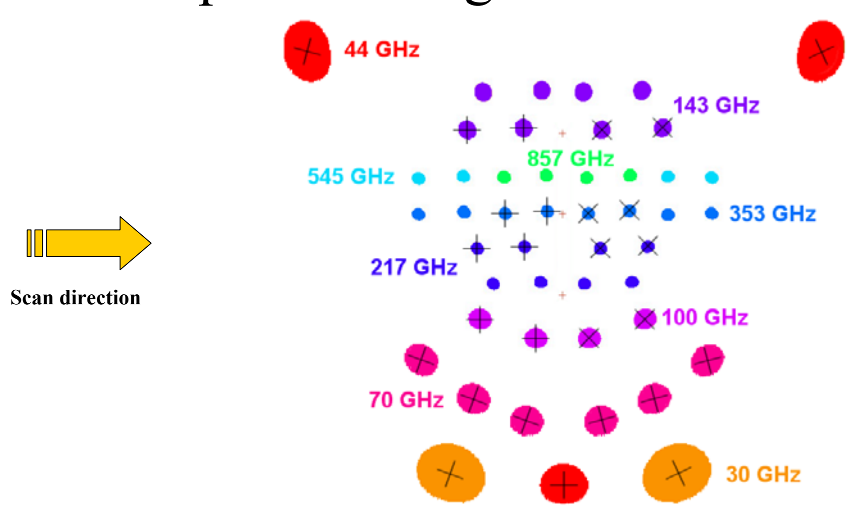
Optical configuration



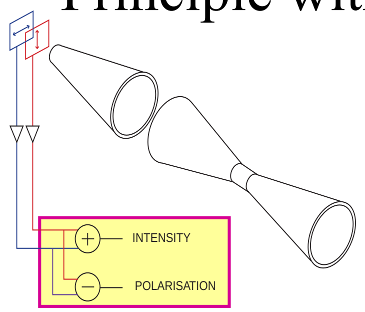
In the focal plane

On the sky

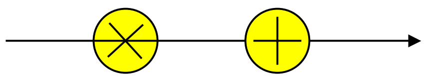
Optical configuration



Polarisation Measurement Principle with the Planck HFI



Both bolometers in a PSB pair share the same optics but have different readouts



- Each PSB pair measures (I & U) or (I & Q)
- Two pairs, rotated by 45°, together measure (I, U, Q)

Stokes Parameters

$I = E_x^2 + E_y^2$ $\quad Q = E_x^2 - E_y^2$ $\quad U = 2E_xE_y$

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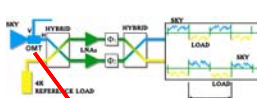
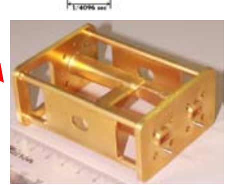
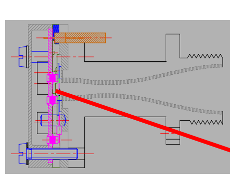
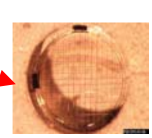
Polarisation Measurement with LFI and HFI





- Principle is the same for both LFI and HFI
- Polarisation separation mechanism is different
  - LFI: Ortho-mode Transducer separates two orthogonal polarisations
  - HFI: Orthogonally oriented grids select polarisation and deliver to separate thermistors





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Estimated Instrument Performance Goals

Telescope	1.5 m (proj. aperture) aplanatic; shared focal plane; system emissivity 1% Viewing direction offset 85° from spin axis; Field of View 8°								
Instrument	LFI			HFI					
Center Freq. (GHz)	30	44	70	100	143	217	353	545	857
Detector Technology	HEMT LNA arrays			Bolometer arrays					
Detector Temperature	~20 K			0.1 K					
Cooling Requirements	H_2 sorption cooler			H_2 sorption + 4 K J-T stage + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	24	14	9.5	7.1	5	5	5	5
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T_I{}^*$ per pixel#	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T_{U,Q}{}^*$ per pixel#	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

* Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($\times10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

\# A pixel is a square whose side is the FWHM extent of the beam.

* Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($\times10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

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Table last updated Feb. 2004

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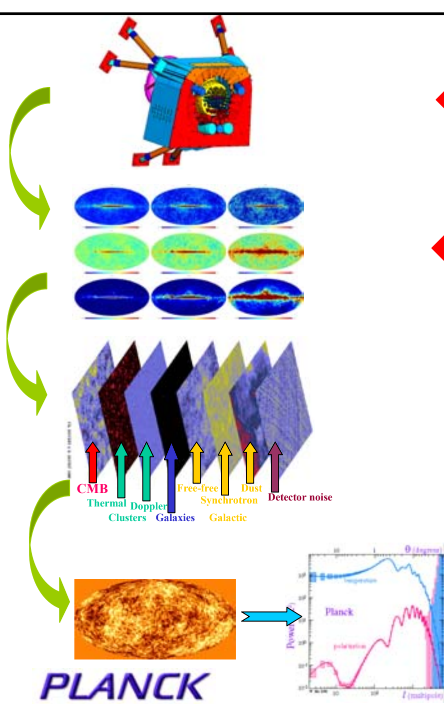

Acquiring and processing
Time-ordered information

Converting TOI to maps of
the sky emission
at many frequencies

Converting frequency
Maps to component maps

Estimating the CMB
Angular power spectrum
And cosmological parameters

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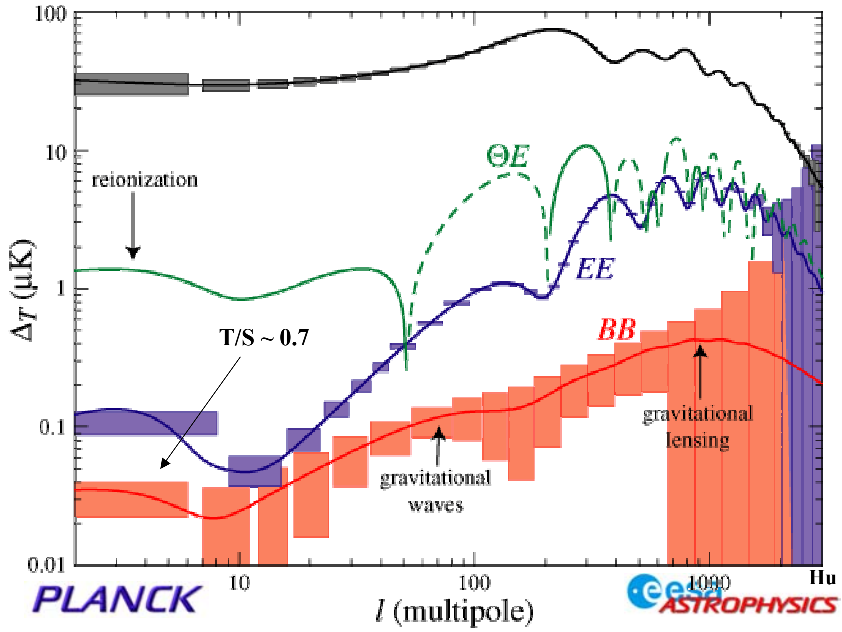

Hu 2002

B-mode recovery

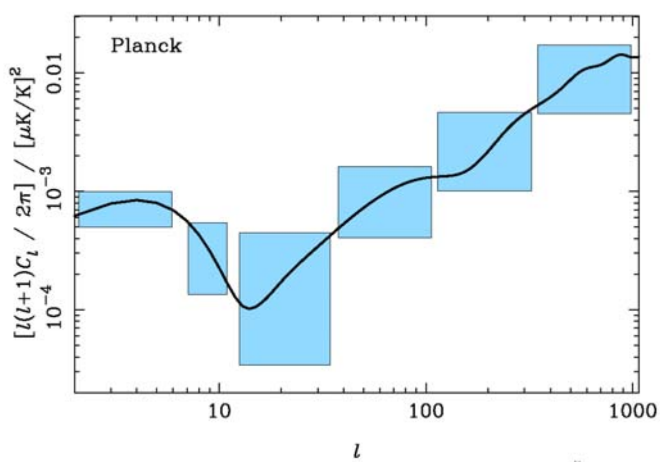

FIG 2.17.—Forecasts for the $\pm 1\sigma$ errors on the B-mode polarization power spectrum C_ℓ^B from *Planck* (for $r = 0.1$ and $\tau = 0.17$). Above $\ell \sim 150$ the primary spectrum is swamped by weak gravitational lensing of the E-polarization produced by the dominant scalar perturbations. The cosmological model, and the assumptions about instrument characteristics, are the same as in Fig. 2.13.

From: Efstathiou 2004

WMAP vs Planck: **Key differences**

	WMAP	**Planck**
P/L Technology	Dual telescope Passive cooling	Single telescope Active cooling
Detectors	HEMT LNAs	HEMT LNAs Bolometers
Freq. range	22-94 GHz	30-857 GHz
Ang. resolution	13.8 arcmin	5 arcmin
Sensitivity @ 90-100 GHz	35 μK ($0^o.3 x 0^o.3$)	2.2 μK ($0^o.3 x 0^o.3$)
Sensitivity to CMB (after avg. & fg. Subtr.)	Min. 31 μK Typ. 35 μK	Min. 3 μK Typ. 5 μK

Power spectrum recovery

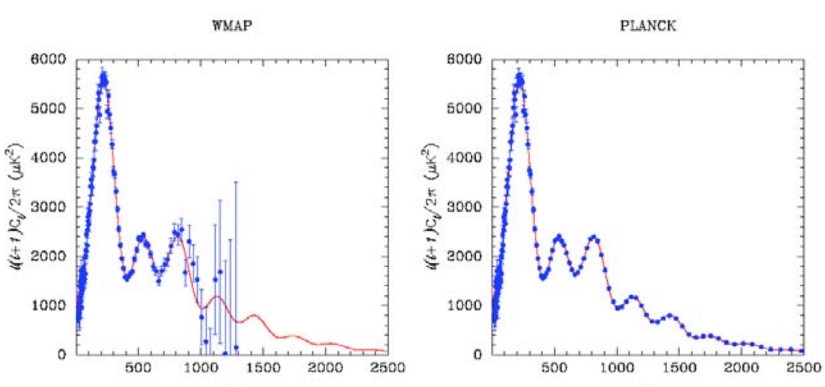

FIG 2.8.—The left panel shows a realisation of the CMB power spectrum of the concordance ΛCDM model (red line) after 4 years of *WMAP* observations. The right panel shows the same realisation observed with the sensitivity and angular resolution of *Planck*.

From: Efstathiou 2004

E-mode recovery

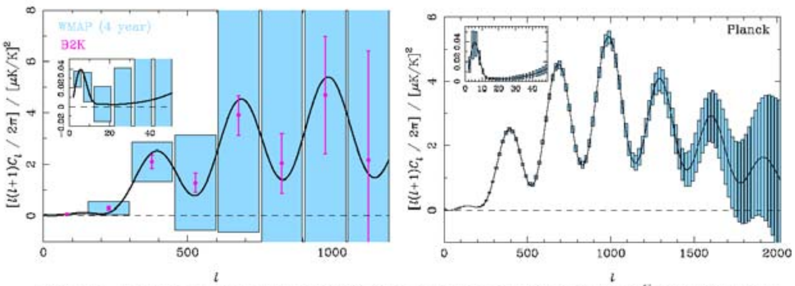

FIG 2.14.—Forecasts for the $\pm 1\sigma$ errors on the E-mode polarization power spectrum C_ℓ^E from *WMAP* and B2K (left) and *Planck* (right). The cosmological model, and the assumptions about instrument characteristics, are the same as in Fig. 2.13. For *WMAP* and B2K, flat band powers are estimated with $\Delta\ell = 150$ (with finer resolution on large scales for *WMAP* in the inset). For *Planck* we have used the same ℓ-resolution as in Fig. 2.13.

From: Efstathiou 2004

PLANCK

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The need for accuracy

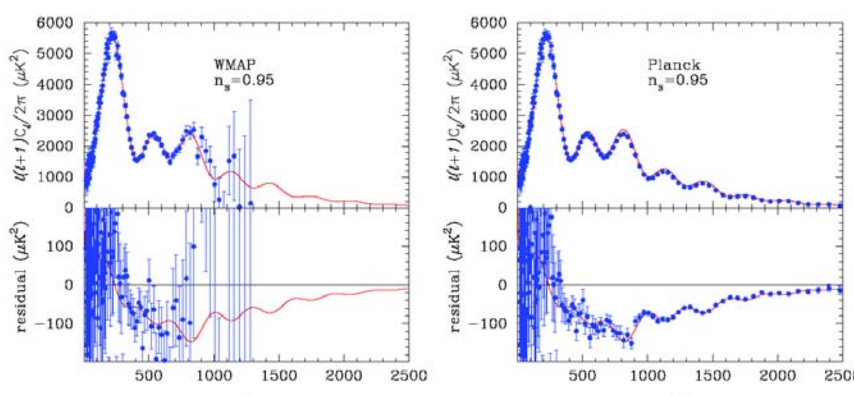

FIG 2.11.—The solid lines in the upper panels of these figures show the power spectrum of the concordance ΛCDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model (the solid lines show the theoretical expectation for these residuals). The left and right plots contain simulations for *WMAP* and *Planck*, respectively.

From: Efstathiou 2004

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The need for accuracy

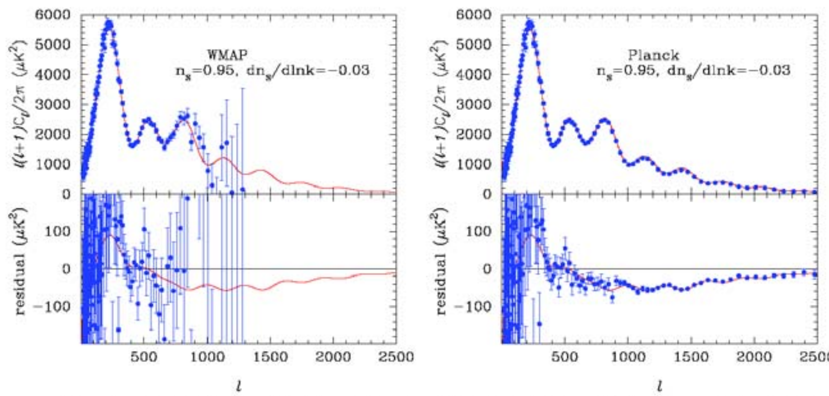

FIG 2.12.—Same as Fig. 2.11, but now comparing the concordance ΛCDM model, having $n_S = 0.95$ and zero run (solid line), with a realisation of a model having with $n_S = 0.95$ (at a fiducial wavenumber of $k_0 = 0.05$ Mpc^{-1}) and a run of $dn_S/d\ln k = -0.03$.

From: Efstathiou 2004

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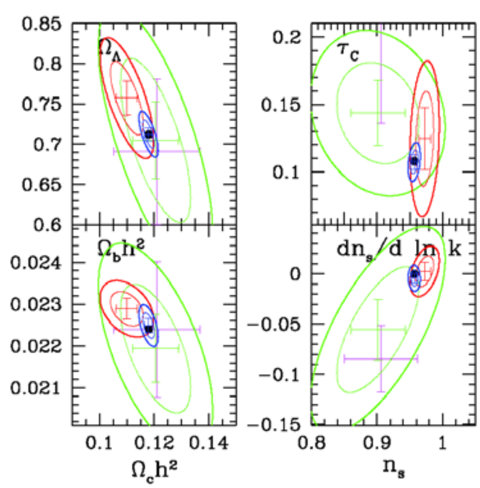
Parameter recovery



WMAP 4 yr

WMAP 4 yr +ACT/SPT

Planck

FIG 2.18.—Forecasts of 1 and 2σ contour regions for *WMAP* 4 years (green), for *Planck* 1 year (blue) and *WMAP* 4 years +ACT/SPT (red, see text) . The input values of the parameters are given by the black dots. The error bars in magenta show the precision from current CMB data when the spectral index is allowed to run.

From: Bond 2004

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Science with accurate cosmological parameters

- Cosmological parameters to high accuracy
  - Geometry of Universe
  - Age of Universe, H_o, Ω_o, Λ, …
  - Neutrino mass, …
- Testing inflation, contraining the inflaton potential
- Finding non-gaussianities
  - Primordial
  - "local"
- Finding signatures of gravitational waves
- physics beyond standard model, e.g. superstrings
- Evolution of structure and nature of dark matter, epoch of reionisation
- …

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Key Non-CMB Science with Planck

- Sunyaev-Zeldovich effect
  - Measurement of y in > 10^4 galaxy clusters
  - Cosmological evolution of clusters to z > 1
  - H_o and X-ray measurements, gas properties
  - Bulk velocities on scales > 300 Mpc
- Extragalactic sources and backgrounds
  - IR and radio galaxies
  - AGN's, QSO's, blazars
  - Evolution of galaxy counts to z > 1
  - Far-IR background fluctuations
- Maps of Galaxy at frequencies 30 - 1000 GHz
  - Dust properties, Cloud and cirrus morphology
  - Star forming regions, Cold molecular clouds
  - Cosmic ray distribution
  - Polarisation-based science, e.g. Galactic magnetic field

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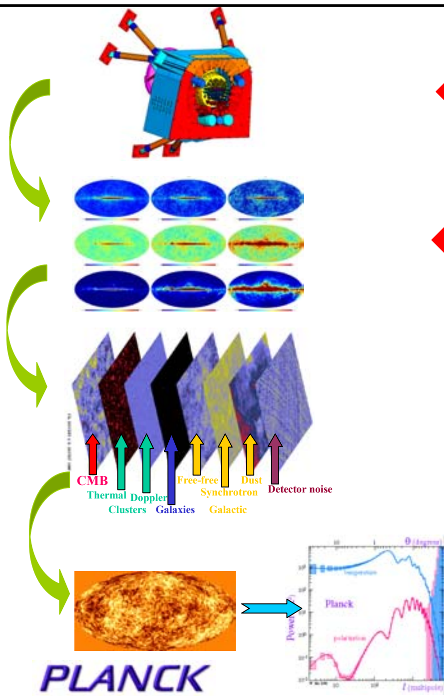

Acquiring and processing time-ordered information

Converting TOI to maps of the sky emission at nine frequencies

Converting frequency maps to component maps

Estimating the CMB angular power spectrum and cosmological parameters

esa ASTROPHYSICS

Extracting the science

Measurements (15 Gbit/day)
105 detectors, 15000 samples/sec, total ~ 6×10^{11} samples

Frequency maps
10 channels, total ~3×10^{7} pixels

Instrument response
Systematic effects

Foreground maps
~6 foreground components
~500 parameters

Point source catalogs
>10^4 sources

CMB temperature map
~5×10^6 pixels

CMB polarisation maps
~10^7 pixels

CMB temp. ang. power spectrum
~2000 numbers

CMB pol. ang. Power spectrum
~1000 numbers

Cosmological parameters
~12 numbers

Polarisation Systematics

- Far sidelobes
  - Galactic *I* straylight
  - (Galactic *p* straylight)
- Main beam
  - Differences between *Q,U* beams
  - "Cross polarization"
- Pointing
- Instrument specific
  - $1/f$ noise
  - Noise mismatch
  - Bandpass mismatch
  - Time constant mismatch
- Thermal
- Scan strategy
- Calibration
  - Incorrect polarization calibration parameters

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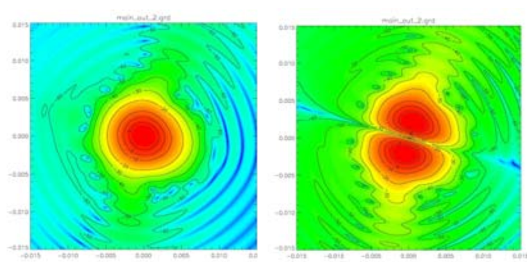
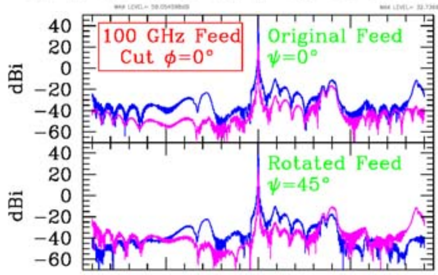
Beam mismatch effects





Main beam mismatch introduces fake polarisation of <1%

Far sidelobe mismatch has to be considered as well

From: Fosalba 2001

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Polarised beams

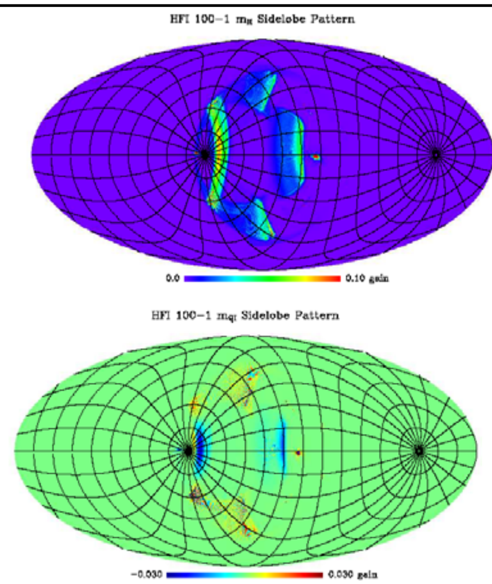


Figure 11: Full-sky sidelobe patterns for a 100 GHz HFI horn.

Legend: See Fig. 10. Simulation by ALCATEL, from Tauber (priv. comm.). The horn orientation in the final design is offset by 22°.5 from the one simulated here. The approximate symmetry of the b_{QI} pattern around the mid-line of the plot (corresponding to the spacecraft symmetry plane) may not apply once the feeds are rotated to the correct orientation (see text).

Note that the fine structure in the broad sidelobes is not a plotting artefact: It is real.

From: Leahy and Hamaker 2004

PLANCK

Polarised straylight

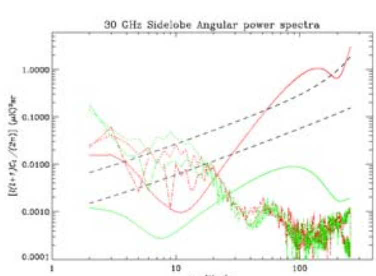
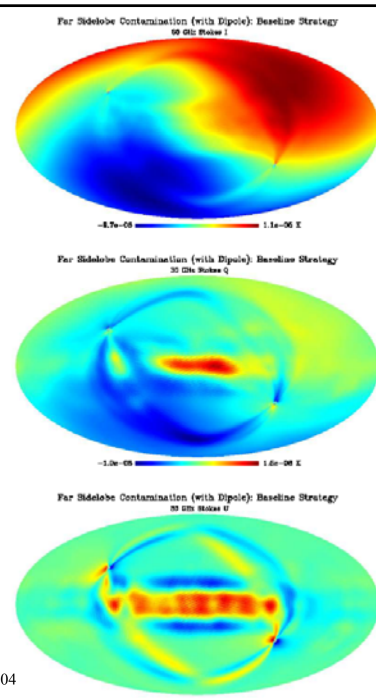


Figure 20: Contribution of straylight to polarized spectra.

Dotted lines: Angular power spectra of the polarized straylight, including the dipole, unmasked. Dot-dashed: recovered from masked sky. Solid lines: theoretical model with relatively low polarization (recombination at $z = 6$, tensor-to-scalar ratio = 0.07). Dashed lines: expected errors due to noise (upper: 30 GHz; lower: 100 GHz) for 14 months observations, 80% observing efficiency, 30% bin width in C_ℓ. Red is E-mode and green is B-mode. The upturn in the C_ℓ at $\ell > 150$ is due to the coarse pixelisation of the model foreground sky. The hump at $\ell \approx 60$ appears to be due to the small-scale structure around the Ecliptic poles.



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From: Leahy and Hamaker 2004

"Realistic" case

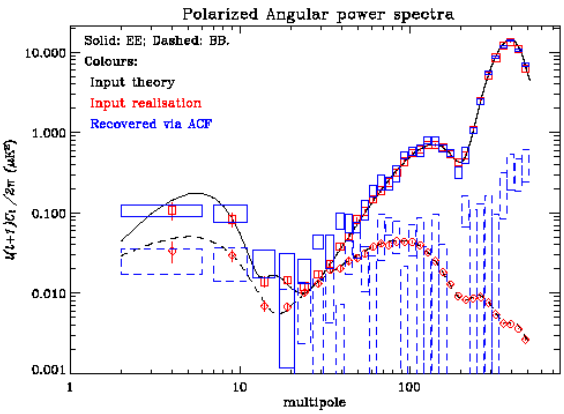


Figure 26: Input and recovered polarized C_ℓ spectra for an optimal combination of 100 and 143 GHz data.

PLANCK From: Leahy and Hamaker 2004 esa ASTROPHYSICS

Worst case

Parameter	30 GHz	100 GHz	353 GHz
Horn rms position errors	50 μm	50 μm	50 μm
Horn rms orientation errors	1°	1°	1°
'a' to 'b' rms orientation errors	0°.5	1°	1°
...hence error in $\mu_{\rm H}$	1°.1	1°.2	1°.2
Noise uniformity $\sigma(T_{\rm sys})$	0.075	0.2	0.2
Mean polarization efficiency $\langle\Lambda_{\rm R}\rangle$	0.99	0.93	0.95
Efficiency uniformity $\sigma(\Lambda_{\rm R})$	0.01	0.1	0.1

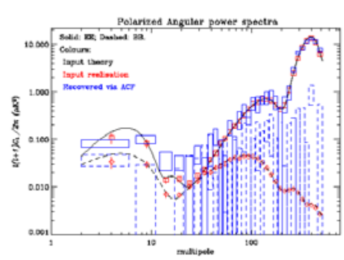
Table 17: Worst-case receptor parameters

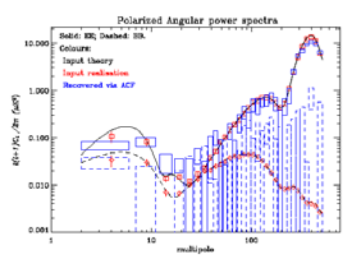
RMS parameters were derived from requirements by assuming the required limits correspond fluctuations. We also assume a 1° misalignment between the true spin axis and the satellite sym plane. As per discussion in the text, there is a case for a worst-case error in $\mu_{\rm H}$ of ≈ 2°, but the listed in the main table were the ones used in the simulations.

Parameter	30 GHz	100 GHz	353 GHz
Horn rms position errors	25 μm	25 μm	25 μm
Horn rms orientation errors	0°.5	0°.5	0°.5
'a' to 'b' rms orientation errors	0°.25	0°.5	0°.5
...hence error in $\mu_{\rm H}$	0°.5	0°.6	0°.6
Noise uniformity $\sigma(T_{\rm sys})$	0.04	0.1	0.1
Mean polarization efficiency $\langle\Lambda_{\rm R}\rangle$	0.995	0.97	0.98
Efficiency uniformity $\sigma(\Lambda_{\rm R})$	0.005	0.05	0.05

Table 18: Best-case receptor parameters

We also assume a 1° misalignment between the true spin axis and the satellite symmetry plan





Imperfect knowledge

Figure 28: Effect of perfect versus nominal polarimetric corrections.

(a) [top]: As for Fig. 25, except for a 'worst-case' system as detailed in the text, with the image derived assuming perfect knowledge of the Mueller matrices.

(b) [bottom]: the same data, with no polarization calibration; that is, the sky images were constructed with Mueller matrices that assumed the nominal orientations and expected mean efficiencies for the receptors.

PLANCK From: Leahy and Hamaker 2004

Planck Data Products

- Cleaned & calibrated time-ordered data
- All-sky maps in nine frequency bands
- "First generation" all-sky component maps
  - Cosmic Microwave Background
  - Galactic emission maps (synchrotron, free-free, dust)
  - Extra-galactic source catalogues

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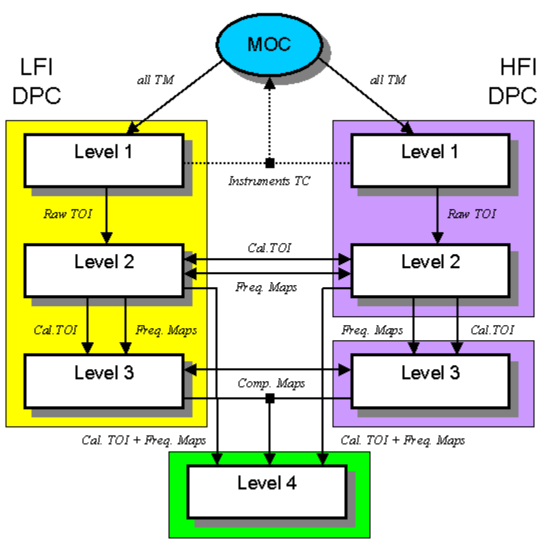
Data Processing Centres



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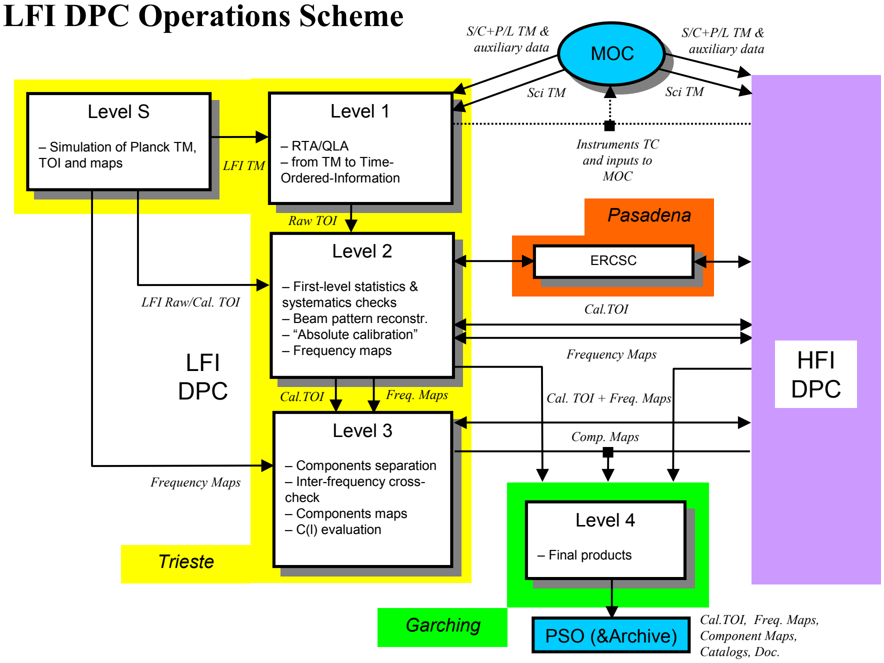
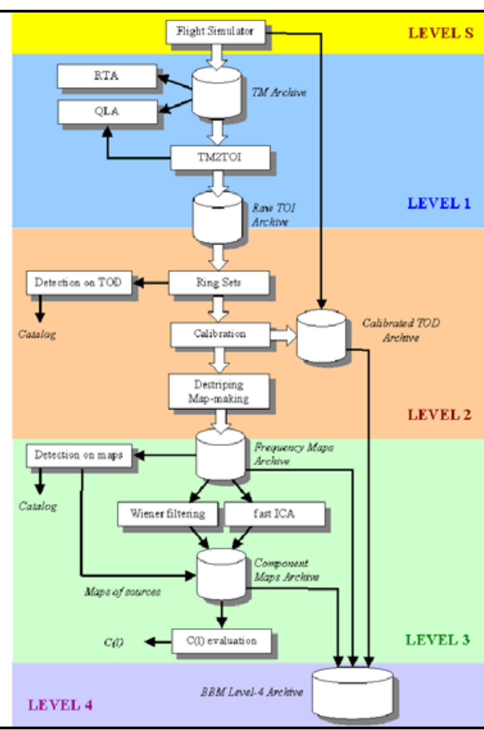
LFI DPC Operations Scheme



LFI DPC Pipeline Breadboard Model Concept



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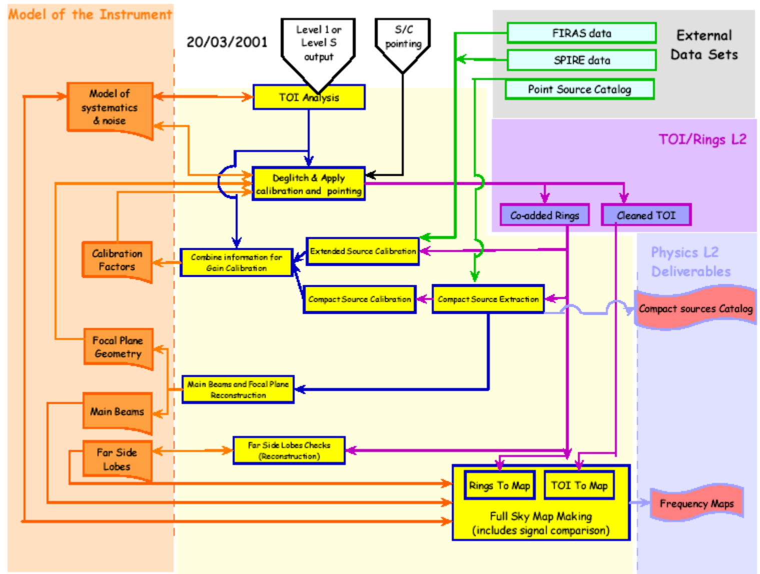
HFI Level 2 Concept



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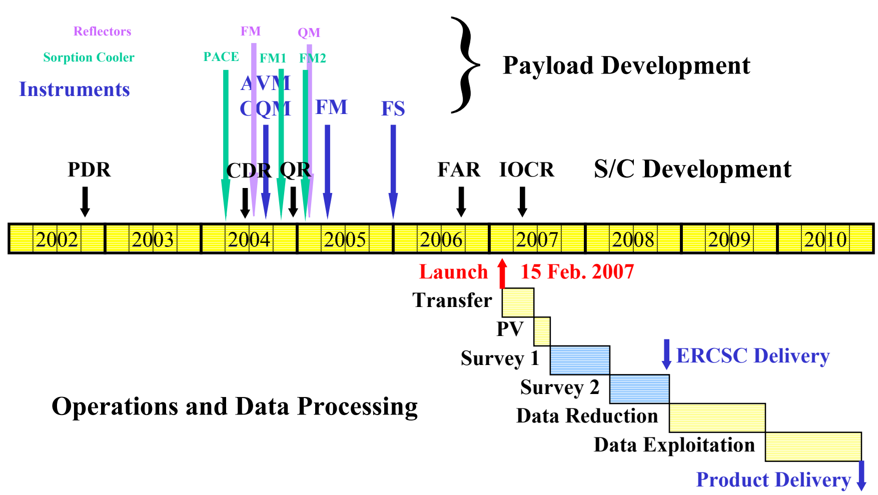
System Schedule



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Last updated: May 2004

Key dates

- Start of spacecraft Phase B: mid-2001
- Start of spacecraft Phase C/D: end-2002
- Payload model deliveries: 2003-2004
- Launch: February 2007
- Insertion into orbit: June 2007
- Operations: 2007-end 2008
- Scientific product delivery: 2010

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