The Planck High Frequency Instrument, a third generation CMB probe and the first submillimeter surveyor

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ABSTRACT

The High Frequency Instrument of the Planck satellite is dedicated to the measurement of the anisotropy of the Cosmic Microwave Background (CMB). Its main goal is to map the CMB with a sensitivity of $\Delta T/T=2.10^{-6}$ and an angular resolution of 5 arcmin in order to constrain cosmological parameters. Planck is a project of the European Space Agency based on a wide international collaboration, including United States and Canadian laboratories. The architecture of the satellite is driven by the thermal requirements resulting from the search for low photon noise. Especially, the passively cooled telescope should be at less than 50K, while a cascade of cryo-coolers will ensure the cooling of the HFI bolometers down to 0.1K. This last temperature will be produced by a gravity insensitive 3He/4He dilution cooler. This will be achieved at the L2 Lagrangian point of the Sun-Earth system. The whole sky will be observed two times in the 14 months mission with a scanning strategy based on a 1RPM rotation of the satellite. In addition to the cosmological parameters that can be derived from the CMB maps, Planck will deliver nine high sensitivity submillimeter maps of the whole sky that will constitute unique data available to the whole astronomical community.

Keywords: Cosmology, submillimeter astronomy, Cosmic Microwave Background

1. INTRODUCTION

Astronomy from space has in the past provided us with complete sky maps in spectral bands not accessible from the ground, giving new images of the sky and data to prepare the design and the efficient use of observatories in similar spectral ranges. One of the most promising surveys that can be achieved during this decade may be the coverage of wavelengths in several bands around one millimeter (0.3 - 3 mm) with the goal of extending to larger wavelengths the maps of the Infrared Astronomical Satellite (IRAS) and to higher angular resolutions the maps obtained by the Cosmic Background Explorer.

Such a mission would dramatically increase our knowledge of the universe in several domains. The most exciting result that can be expected is surely the mapping of the Cosmic Microwave Background Anisotropy (CMBA) with sensitivities and angular resolutions high enough to give new insights in cosmology and physics. Even with respect to the most recent results[1,2,3,4] and to the expected results from the satellite MAP[5], the increase of sensitivity that we are considering now will give a renewed view of the CMBA. In addition, the maps in the different bands and the possible separation of

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components from different physical origins would be important for galactic studies and for the knowledge of large scale structures in the universe[6].

Going from the 7deg. pixels and the 26°µK noise level of the COBE-DMR maps to 0.1deg. and 6°µK expected now supposes an increase of the detector sensitivity by more than two orders of magnitude, and an identical improvement in the control of other potential sources of noise. This is the goal of the Planck project, a medium mission of the scientific programme of the European Space Agency. The High Frequency Instrument (HFI) of the Planck project is one of the two focal plane instruments of the Planck satellite. It is based on the use of low temperature bolometers cooled by active cryogenic systems. It is developed by a large international collaboration under the leadership of French Institutes. The next section describes the HFI instrumental concept, how it has been optimized, and how it is implemented in the Planck project. Section 3 is dedicated to the scientific capabilities of the Planck satellite and especially of its high frequency instrument. Conclusions are included in section 4.

2. HFI DESIGN

1.1 A new instrumental concept

The goals of the HFI inside the Planck project is to provide maps of the full sky with sensitivity limited mainly by the photon noise of the observed source itself. The design of this instrument was highly dependent on the conditions in which it will be used. It proposes solutions in all domains that make it a consistent project from its scientific goals to its detailed design.

The following specific features were designed from the first beginning of the project and did not change much in the various versions it has known:

- Thermal architecture, with a passively cooled telescope
- Active cryogenics
- Sophisticated and compact optical design
- Use of spider-web bolometers at 0.1K
- New interference filters to select frequencies
- Total power readout electronics
- Scanning strategy based on six months sky coverage

These choices impacted the performance requirements on nearly every HFI subsystem. The inclusion of number of new features was made necessary to reach a consistent design. When compared to previous projects, this makes Planck-HFI a new instrument concept used an original mission concept.

A halo orbit (fig. 1) around the second Lagrangian point of the sun-earth system has been chosen consistently with the need to be far from the Earth and the Moon, possible strong source of straylight. The satellite is spinning at one round per minute with a spin axis nearly anti-solar. The instrument beam describes large circles on the sky that are slowly shifted so that the full sky is covered in half a terrestrial year.

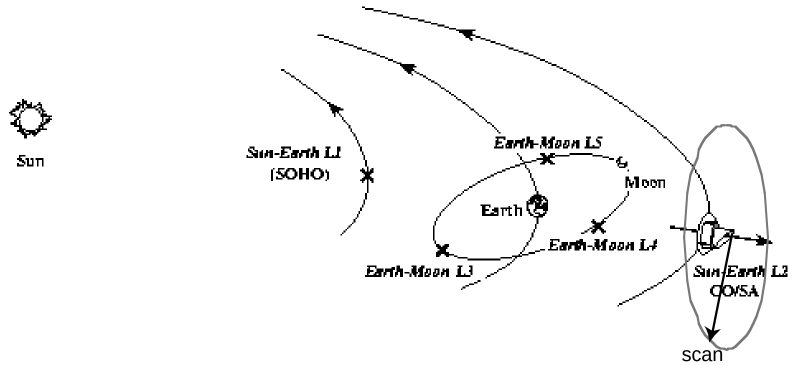

FIGURE 1. Schematic representation of the Planck orbit and scanning strategy.

1.2 Optimization of the design for the science goals

The cosmological part of the scientific objectives has been taken as the basis for the instrument optimization. The six spectral bands of the high frequency instrument (HFI) cover the frequency range between 100 and 1000GHz with an angular resolution ranging from 5°arcmin to 9 arcmin. Its sensitivity will be limited, in the CMB channels, by the statistical fluctuations[6] of the CMB itself[7], which makes it a kind of ultimate experiment. It will also measure the polarization of the CMB in three channels, which will give independent and unique information on the CMB anisotropy[8]. This kind of accuracy on the CMB can be achieved only by removing the various foregrounds formed by the evolving universe situated between us and the warm primordial universe. Among these, we see the emission of dust and gas in our own galaxy and from other galaxies. Clusters of galaxies, that contain high temperature gas detected in the X-rays, distort the CMB by inverse Compton scattering. This is the Sunyaev-Zeldovich Effect (SZE) that makes clusters of galaxies good tracers of the dynamics of the universe at large scales.

Table 1. Channels resulting from the HFI optimization

Central Frequency	**(GHz)**	**100**	**143**	**217**	**353**	**545**	**857**
Beam Full width Half Maximum	arcmin	9.2	7.1	5.0	5.0	5.0	5.0
Number of unpolarized detectors		4	4	4	4	4	4
Number of polarized detectors		-	8	8	8	-	-

Sophisticated simulations of the measurement and data inversion were performed to assess possible design options, such as the number and the frequency of channels and the number of detectors in each channel. The theoretical emission of a patch of sky including all expected foregrounds was computed, and simulated measurement data, including a total noise equal to twice photon noise was used to separate the components and derive the cosmological parameters from the recovered CMBA. The resulting design is presented in table 1. It is worth noting that special channels are dedicated to the measurement of CMB polarization, which is a specific problem of bolometer detectors, unlike coherent radio receivers that are all sensitive to polarization.

1.3 Thermo-optical and cryogenic designs

For all practical temperatures of space instruments, thermal emission from optical elements contributes to the submillimeter radiation that reach the detectors. The design of any submillimeter instrument is a simultaneous and intricate effort mixing optics and cryogenics to keep this radiation down to acceptable values. The goal of building an instrument limited by the photon noise of the source in the CMB frequency range was a major driver for the design of the HFI and of the Planck satellite itself.

Table 2. Cooling powers available at various temperatures in the Planck mission

Optical element	Temperature (K)	Cooler type	Cooling power (W)
Telescope	40	Passive	2
N/A	18	Sorption H2 J-T	1
Entrance horn	4.5	Mechanical He J-T	2.10^{-2}
Lens and Filter#1	1.6	3He/4He J-T	5.10^{-4}
Horn and Bolometer	0.1	3He/4He Dilution	2.10^{-7}

This starts with the largest optical element, i.e. the telescope. It has been shown[9] that in this frequency range, passively cooled telescopes could be the proper solution if they are designed to minimize emissivity. This solution has the advantage over telescopes embedded in cryostats that the dimensions of the optical system can be chosen to meet the other requirements of the mission, such as the angular resolution and the control of straylight. An off-axis design will provide the low emissivity and has the additional advantage that it provides low-level side-lobes thanks to the absence of any obstruction in the main beam. Figure 1 shows the Planck satellite with its off-axis telescope and its characteristic V-shaped radiator. The expected temperature of the telescope is 40K, which keeps its thermal emission to reasonable values at frequencies relevant for the CMB measurement. Table 2 summarizes the cooling power of the various coolers and the elements that they cool, and figure 3 gives a view of the Russian doll architecture. Elements in the optical path have temperatures distributed between 0.1K and 4.5K. The design was optimized, accounting for the cooling power available at various cryogenic stages and on the requirement that their own thermal emission is kept negligible with respect to the CMB flux. For example, filters limiting the bands must be cooled at 0.1K, to minimize their thermal emission. But the cooling power at 0.1K is not large enough to cool them in the radiative environment of the telescope. Intermediate optical elements are therefore required to block the unacceptable radiative heat load on the 0.1K filters, and more generally on the 0.1K cryogenic stage. This is achieved by a set of interference filters on the 4K and the1.6K cryogenic stages and by the back to back horn architecture (fig. 4) that limits the throughput of the coupling with the thermal environment. On the right part of fig.3, the contributions of the various optical elements are compared to the Brightness of the sky.

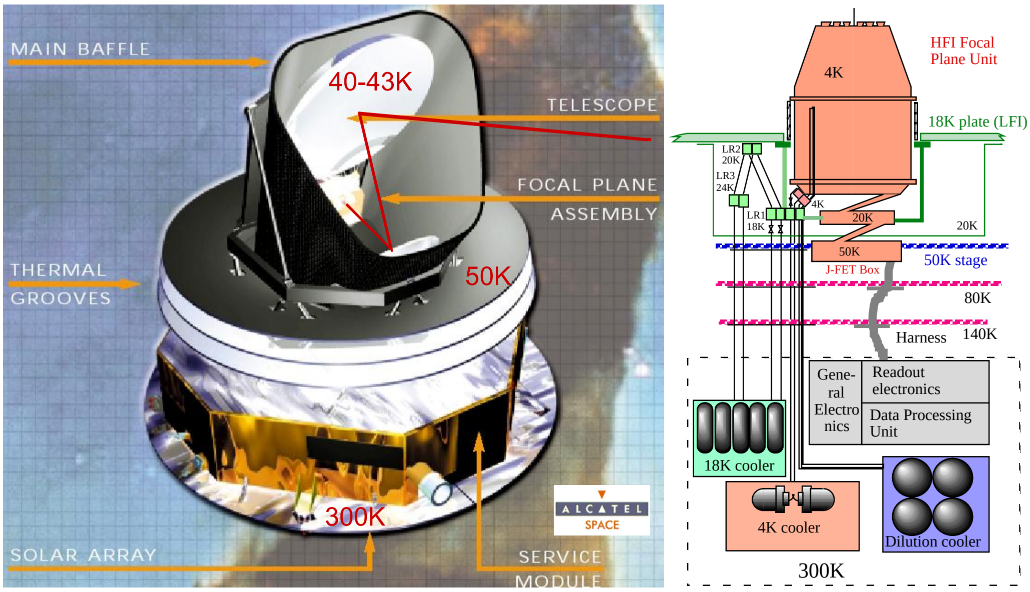

FIGURE 2. Left: The solar panels cover the bottom part of the satellite. The thermal architecture allows to passively cool the telescope down to 40K. Right: Three different active coolers are needed to cool the bolometers down to 0.1K.

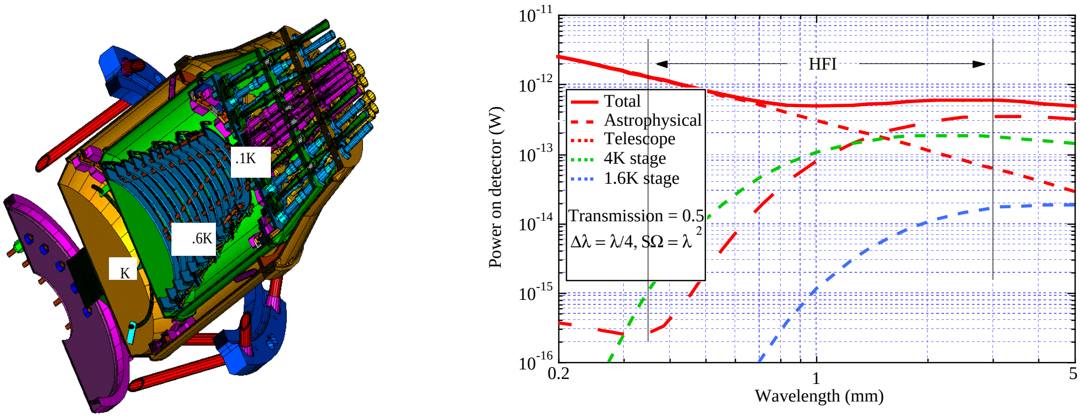

FIGURE 3. The focal plane unit of the HFI consists of three stages at 4K, 1.6k, and 0.1K. The coupling of the bolometer with the telescope is made thanks to corrugated horns at 4K. These stages radiate on the detectors and contribute to the background as well as the telescope (right).

Joule-Thomson (J-T) expansion of hydrogen activated by sorption pumps provides about 1 Watt of cooling power at 18K, which is essential for the operation of the Low Frequency Instrument (LFI) and for the pre-cooling of the next cryogenic stage. A prototype of the Sorption Cooler is now working with the predicted cooling performances at the Jet

Propulsion Laboratory (Pasadena). A helium J-T cooler based on the use of frictionless mechanical pumps provides the cooling power at 4.5K. The lowest temperature (0.1K) is provided by the helium3/helium4 open loop dilution cooler, while the 1.6 K cooling capability is obtained by J-T expansion of the 3He/4He mixture. A prototype of this cooler has been successfully used for astronomical observations from the ground and with the balloon-borne experiment Archeops.

1.4 Optical design

A major challenge of the optical design was to insure a proper rejection of straylight. The body of the satellite, i.e. its solar panels, its service module, electronics, and so on, have to be at around 300K, while we aim at measuring micro-Kelvin. The Earth and the Sun are also bright sources that can disturb the measurement. In consequence, very good control and knowledge of the beam shape are required to avoid parasitic radiation that could reach the detectors or remove it during the data processing. The illumination of the primary reflector (PR) by the focal plane horns is critical for the level of straylight as well as for the angular resolution. Illuminating widely the PR improves the angular resolution but increases the spillover, i.e. the part of the beam that fall outside the PR. The resulting trade-off has led to a strongly tapered beam, only the central part of the PR being used by the main beam.

Table 3. Performances of the HFI horns and telescope

ν (GHz)	Spillover (%)	Edge taper (dB)	Beam FWHM (arcmin)
100	0.6	-25	9.2
143	0.4	-28	7.1
217	0.2	-35	5.0
353	0.1	-35	5.0
545	0.1	-30	5.0
857	0.1	-30	5.0

In order to optimize these parameters, corrugated horns have been developed and their shape has been optimized[10]. The resulting performance is presented in table 3. Horn patterns show side lobes down to -40dB or less outside of their quasi-Gaussian central section. The optical architecture of one channel is shown (figure 4). The overall optical efficiency of this system has been measured and can be as high as 50%.

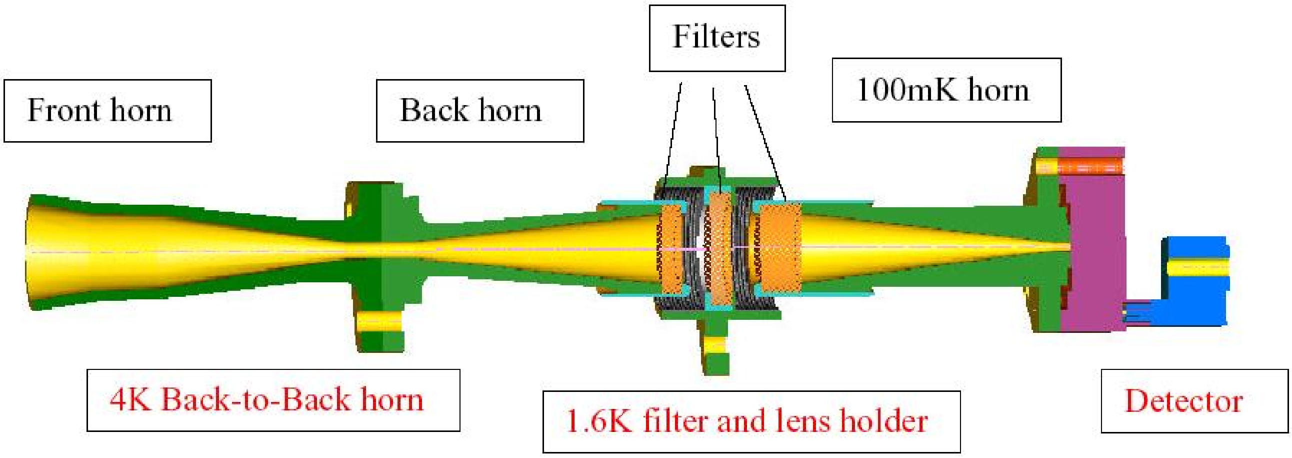

Figure 4. Design of a single channel. The back-to-back corrugated horn at 4.5K determines the beam allowed to reach the colder stages and in fine the detector. A lens conjugates the exit horn with the entrance of the 0.1K horn leading to the bolometer. The spectral content of this beam is determined by a set of interference filters at 4K, 1.6K and 0.1K, and by the throat of the 0.1K horn, that acts like a high-frequency pass filter. This architecture efficiently limits the heat loads on the most sensitive cryogenic stages.

1.5 Bolometers

The two major requirements on the bolometers are the sensitivity and the time response. Scanning a 5 arcmin beam at 6˚deg/s produces frequencies up to 100Hz and thus times constants less than 2ms are required for a proper measurement.

In the same time, the intrinsic noise of the bolometer has to be less than the photon noise, which requires typically a Noise Equivalent Powers (NEPs) of the order of 10^{-17} WHz$^{-1/2}$. These requirements could possibly met only by the spider web 0.1K bolometers developed in Pasadena[11]. Together with the development of zero gravity compatible dilution coolers, the existence of such detectors was one of the triggers of the Planck-HFI conception. The special point in spider-wed bolometers is that the radiation absorber is made of a grid with impedance matched with that of vacuum. Among other advantages these detectors are much less sensitive to ionizing radiation that conventional bolometers.

Table 4. Requirements on the bolometer performances. Suffix P indicates a Polarization sensitive Bolometer

Frequency	Optical load	Required NEP	Goal time constant	Required Time cst.
	pW	1.10^{-17} WHz$^{-1/2}$	ms	ms
100	1.0	1.2	3.9	7.8
143	1.1	1.5	2.9	5.7
217	1.1	1.8	2.2	4.4
353	1.0	2.2	2.2	4.4
545	5.0	6.0	2.2	4.4
857	16.0	13.5	2.2	4.4
143P	0.57	1.1	3.0	5.7
217P	0.54	1.3	2.2	4.4
545P	2.50	4.3	2.2	4.4

Polarization sensitive bolometers were developed especially for this project. They are very similar to spider-web bolometers but for the grid that consist mainly of parallel resistive wires that absorb only the polarized component with electrical field parallel to the wires. A second absorber with perpendicular wires detects the other component. The detail of the design will be published elsewhere. All the optics has to be consistent with this design. In particular, it has to properly keep the polarization of the transmitted wave. The main characteristics of the bolometers are given in table 4. The bolometers of the qualification model have been fabricated and proven to meet or exceed the required performances.

1.6 Signal and noise in the frequency domain

Every hour, the spin axis of the satellite is shifted by about 2.5 minutes of arc, so that to keep it in a nearly anti-solar direction. In-between these changes of attitude, detectors are observing again and again the same circles with a periodicity of one minute. The signals from the detectors are quasi-periodic and consist in the frequency domain of a DC component and of all the harmonics of the spin frequency, i.e. of 1/60th of a Hertz (0.017Hz). The scientific signal is contained in the first 5000 harmonics, which includes all possible frequencies that are not filtered out by the beam shape. The DC component is the mean value of the sky brightness. Planck-HFI is not well adapted to measure it. There is no calibration process to get it, excepted for the sky itself, very well known after the COBE mission. The useful information for the HFI mission ranges from 0.017Hz and 100Hz and all subsystem are required to be stable within this range of frequencies. Special developments had to be performed to meet these requirements for several sub-systems, especially for the cryogenic stages and for the readout electronics[12].

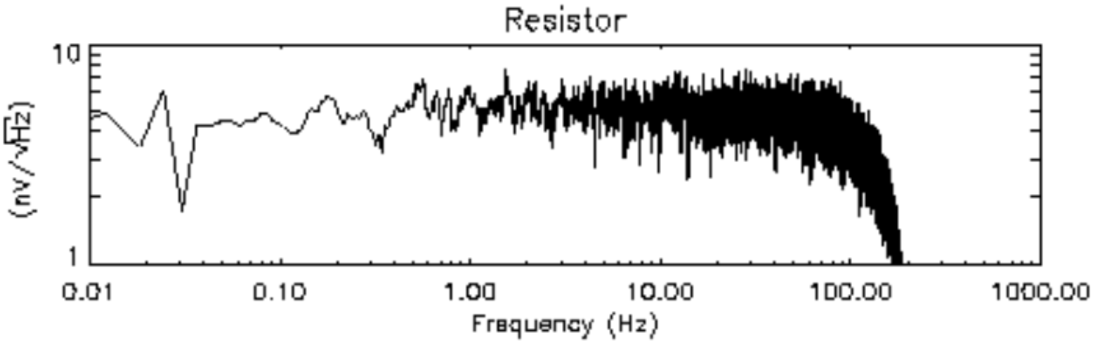

Figure 5: Noise spectrum of the readout electronics measured on a 10M‰ resistor cooled at 0.1K.

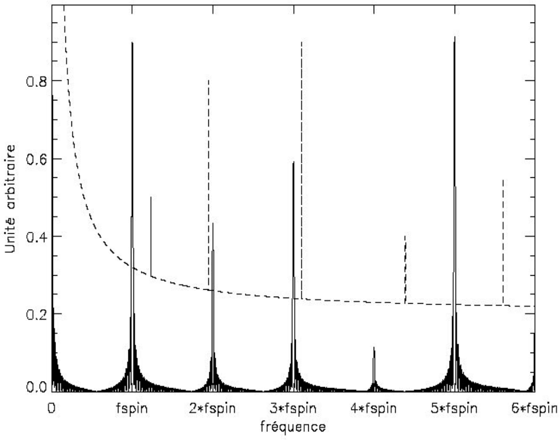

FIGURE 6. The scientific signal is periodic at the frequency of the spin rate of the satellite (1RPM). The first 5000 harmonics contain useful information, which determines the working frequency range of the bolometers: from 0.016Hz to about 100Hz.

The temperature of the various cryogenic stages is also a potential source of noise. Especially, temperature fluctuations of the 0.1K stage translate immediately in fluctuations of the bolometer temperature and cannot be separated from a scientific signal. Other stages support optics and fluctuations of their temperatures would have similar consequences. A complex thermal architecture using both passive damping and active temperature control has been developed to achieve these stringent temperature requirements presented in table 5. Special thermometers have been developed to measure and control the temperature of the 100mK stage[13]

Table 5: Temperature stability required to keep negligible the impact of temperature fluctuations.

Stage temperature	18K	4.5K	1.6K	0.1K
Required temperature stability	100mK p-p	10μKHz$^{-1/2}$	30μKHz$^{-1/2}$	20nKHz$^{-1/2}$

1.7 Sensitivity requirements at mission level

The HFI has been optimized (see section 1.2) by assuming that the total instrument noise was twice the total photon noise produced by the sky and the instrument itself, i.e. mainly the telescope. From this assumption the table 6 of sensitivities has been derived, published, made available on the project web site and updated all along the life of the project. This table gives the sensitivity by square pixel with the size of the beam (FWHM), for a 14 months mission, assuming uniform coverage of the full sky.

Table 6. Expected Average Noise (EAN) at mission level (see text for detailed definitions)

Central Frequency (ν)	Ghz.	**100**	**143**	**217**	**353**	**545**	**857**
Spectral resolution	ν/Δν	3	3	3	3	3	3
Beam Full Width Half Maximum.	arcmin.	9.2	7.1	5.0	5.0	5.0	5.0
$\Delta T/T_{CMB}$ Sensitivity (Intensity) (EAN)	μK/K	2.0	2.2	4.8	15	147	6700
$\Delta T/T_{CMB}$ polarisation (U and Q) (EAN)	μK/K	_	4.2	9.8	30	_	_
Total Flux Sensitivity per pixel.	mJy.	9.8	10.2	14.3	27	43	49
ySZ per FOV (x10^{6}) .		1.3	2.1	615	6.5	26	605

In the same time, additional simulations have tested the robustness of this design. It has been shown, for example, that the failure of any channel, excepted for the 217GHz, would have really small consequences. It has also been shown that a degradation of a factor 2 of the sensitivity would not have a major impact on the core of the science objectives, i.e. the derivation of cosmological parameters from the CMB maps. This particular conclusion results from the fact that it is predicted that the main source of uncertainty will come, in fine, from the imperfect subtraction of the contaminating foregrounds, and not by the ultimate sensitivity of the experiment. It was therefore considered as acceptable for the core science objectives to have a sensitivity twice worse than table 6, which, in the Planck-HFI vocabulary, makes the current requirement on sensitivity at mission level.

While the project was developing, a better knowledge was acquired on all elements of this deeply new design, and the following philosophy was settled and maintained: All elements had to be designed to be at least able to give the sensitivity of table 6, that became the expected average noise (EAN). A goal was set at system level to do better than the EAN. A monitoring of all sources of noise and of all parameters related to sensitivity is currently performed. Everything indicates to-day that the HFI sensitivity will be equal to the published EAN or better. In particular, the most unknown of the parameters, the efficiency of the optical system, is known to be most probably equal to its highest expected value.

1.8 Archeops: a balloon-borne demonstration

The Archeops balloon experiment[14] translates in the most faithful way the optical design of Planck-HFI, with the aim of both obtaining original data on the CMB and to demonstrate the new instrumental principles that constitute the basis of the HFI concept. Archeops has been successfully flown in early 2002 and its most important results will be published elsewhere. We can keep from this flight, in the frame of this communication, the sensitivity obtained on some of the Archeops channels similar to HFI s. The comparison has to account for the main differences between both experiments. Archeops warm optics is at about 300K, instead of 40K for Planck, and includes a warm window. The noise is expected to be dominated by photon noise from this origin. In addition, the optical efficiency is less than that demonstrated for HFI, due to a different solution for the coupling between the back-to-back horn and the 0.1K horn. Nevertheless, as shown in table 7, the sensitivity of Archeops is already inside the HFI requirement. Extrapolation of these numbers, as well as models using measured performances of individual HFI elements, allows to be confident about the sensitivity of Planck-HFI.

Table 7: Comparison of Archeops sensitivity and HFI requirement and goal

Frequency	Archeops flight	HFI requirement	Planck-HFI EAN
	$\mu K_{CMB} s^{1/2}$	$\mu K_{CMB} s^{1/2}$	$\mu K_{CMB} s^{1/2}$
143GHz	85–20	123	62
217GHz	110–30	182	91

3. PLANCK SCIENTIFIC CAPABILITIES

The accuracy with which the cosmological parameters can be determined from CMB anisotropy measurements increases rapidly with angular resolution and the accuracy of the measurements. The aim of HFI is to perform such measurements through the whole range of spatial frequencies containing cosmological information and with accuracy limited only by fundamental limits (photon noise and the understanding of the foregrounds). The nine frequency channels of Planck will be a powerful tool to measure the foregrounds, which is a scientific objective in itself, but should also significantly improve the knowledge of the CMB. The wanted accuracy on the CMB can be achieved only by removing the various foregrounds formed by the evolving universe situated between us and the warm primordial universe emitting the CMB. Among these, we see the emission of dust and gas in our own galaxy and from other galaxies. Clusters of galaxies, that contain high temperature gas detected in the X-rays, distort the CMB by inverse Compton scattering. This is the Sunyaev-Zeldovich Effect (SZE), that makes clusters of galaxies good tracers of the dynamics of the universe at large scales. More detailed views on the scientific capabilities of Planck will be found for example in Bouchet et al[15].

The accuracy of the Planck data will be essential for the measurement of the polarization and also for an improved knowledge of the cosmological parameters. The more complete and more accurate Planck data may be necessary to break degeneracy of the solutions to the data inversion. An example of such a degeneracy is given in figure 7 and a comparison of Planck and MAP is given in figure 8 in the case of the measurement of polarization. These two simulations show how much Planck will bring more information on the CMBA spectrum.

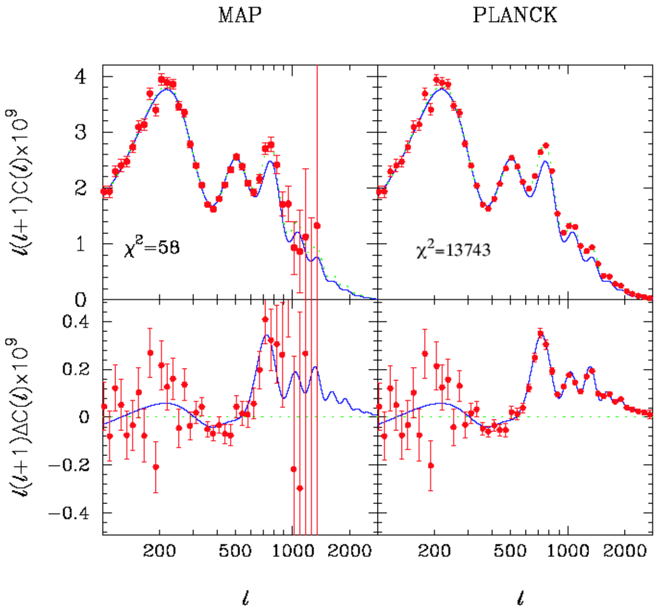

Fig 7. Illustration of degeneracies amongst cosmological parameters. Power spectra for two almost degenerate CDM cosmological models with different parameters are plotted in the upper panels and the residuals are plotted in the lower panels. The error bars show simulated power spectra with the experimental sensitivities of MAP and Planck. Although the baryonic density in the two models differs by 24%, and the CDM density differs by 5%,the two models are barely distinguishable by MAP, but easily distinguishable by Planck.

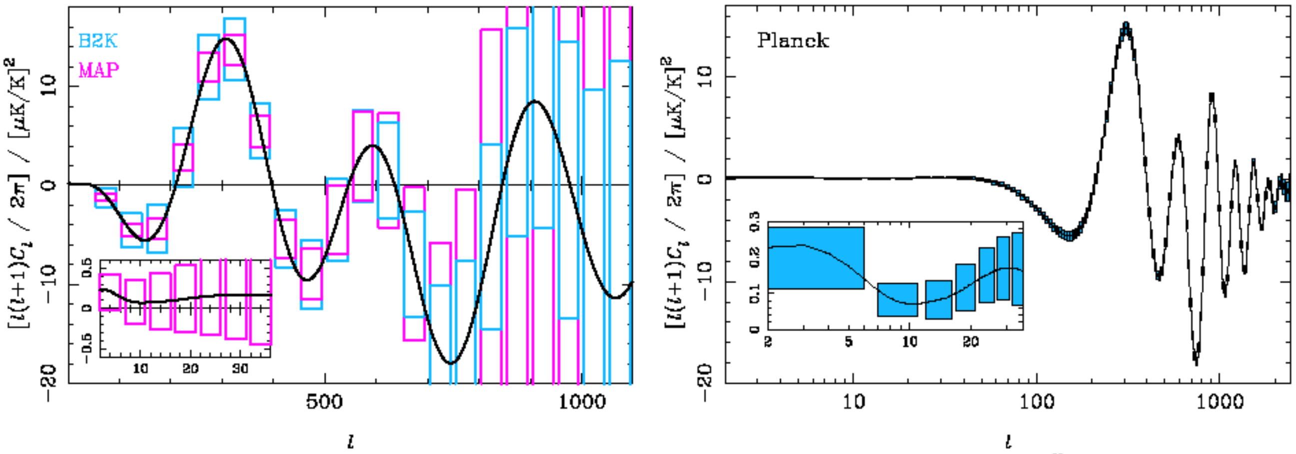

Figure 8. Projections for the 1σ errors on the temperature-polarization cross-correlation power spectrum C^X_l in a ΛCDM model for MAP and BOOMERanG2K (left) and Planck (right). In the left-hand plot, flat band powers are estimated with $\Delta l = 50$ for both experiments for ease of comparison. Below $l = 50$ a finer banding has been adopted for MAP with the error estimates shown in the inset. The solid lines are the power spectrum C^X_l for CDM model.

4. CONCLUSIONS

We have described a new instrument concept that is used to develop the Planck High Frequency Instrument. This concept uses nearly all most recent progresses in submillimeter instrumentation and will procure unprecedented sensitivity. This project is expected to provide the scientific community with new data of incomparable accuracy on the CMB that will allow testing cosmological models and deriving number of cosmological parameters. Planck will also provide the astronomical community with nine full maps of the sky in unexplored frequencies with angular resolutions of a few minutes of arc.

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