Mem. S.A.It. Vol. 74, 223
© SAIt 2003
Memorie della

The Planck Project *

F. Villa, N. Mandolesi, R.C. Butler

IASF–CNR, Sezione di Bologna, via P.Gobetti,101, 40129 Bologna
e-mail: `villa@tesre.bo.cnr.it`

Abstract. PLANCK is the third Medium-Sized Mission (M3) of ESA's Horizon 2000 Scientific Programme. It is designed to measure the anisotropies and polarization of the Cosmic Background Radiation Field over the whole sky, with unprecedented sensitivity and angular resolution. An overview of the Planck Project is presented in this paper.

Key words. Cosmology – Space Missions – Millimeter wave Astronomy

1. Introduction

In 1992, the Cosmic Background Explorer (COBE) satellite detected the existence of small temperature irregularities ($\Delta T/T \simeq 10^{-5}$) in the Cosmic Microwave Background (CMB) radiation field (see Smoot et al. 1992). Experimental groups have been devoting much effort to the design of new ground-based, balloon-borne and satellite experiments to improve on the poor angular resolution and sensitivity of COBE. This effort has been complemented by theoretical calculations that have revealed a wide horizon of new science that can be extracted from high precision measurements of the CMB anisotropies both in amplitude and in polarization, the last expected to be at a level of $\sim 1/10$ of the amplitude fluctuations.

The recent results of the BOOMERanG experiment (de Bernardis et al. 2000) improved the knowledge of the CMB Power Spectrum by detecting three peaks at multipoles up to $l \sim 850$ (de Bernardis et al. 2001), but NASA's MAP mission (launched in June 2001) and the third generation ESA PLANCK (which will be launched on 2007) will accurately reveal the Science imprinted in the CMB anisotropy field.

Specifically, PLANCK will provide a definitive full−sky high−angular resolution mapping of the microwave background over a wide frequency range. The simultaneous mapping of the sky between 30 GHz and 900 GHz by PLANCK will permit a separation of Galactic and extragalactic foregrounds from the primordial cosmological signal with a very high precision over much of the sky. PLANCK will have about four times the sensitivity of the MAP satellite and will far exceed the performance of balloon-borne and ground-based experiments. Moreover, it is expected that PLANCK will measure the statistics of the predicted E-component of the CMB on sub-

---

Send offprint requests to: F. Villa
* On behalf of the Planck Collaboration
Correspondence to: IASF/CNR Sezione di Bologna, Via P.Gobetti, 101 - 40129 Bologna, Italy

degrees angular scales with excellent sensitivity, especially in the regions near the ecliptic caps. The detection of the (partial) polarization of the CMB on different angular scales would allow a fundamental test of basic cosmological assumptions. Moreover, polarization measurements will provide independent estimates of the cosmological parameters and will help break degeneracies in their determination.

The unprecedented quality of the maps provided by PLANCK will have a major impact on the physics of the early Universe, on the determinations of the extragalactic distance scale, primordial nucleosynthesis, stellar ages, dynamical measurements of the mean mass density and the origin of large-scale structure in the Universe. Many thousands of individual extragalactic and Galactic sources will be detected by PLANCK via their spectral signature, including clusters of galaxies, infrared luminous galaxies and Galactic star forming regions. Furthermore, the PLANCK maps will revolutionize our understanding of diffuse background emissions, again with wide ranging implications extending from the contribution of primordial galaxies to the far-infrared background, to the origin of Galactic synchrotron emission and the nature of Galactic dust.

While primarily a mission designed to solve cosmological problems, PLANCK will provide data that will be invaluable to an extremely wide astronomical community and will also have a strong impact on particle physics. Observations of the CMB anisotropies are one of the very few ways of testing physics at energies greater than $\sim 10^{15}$ GeV and are of crucial importance in developing fundamental theories of high energy physics and provide a critical link between high energy physics and the formation of structures that can be observed by astronomers.

In this paper, the PLANCK project is described. In Section 2 and 3 the satellite and the telescope are described. The two instruments (The High Frequency Instrument and the Low Frequency Instrument) onboard PLANCK are outlined in Sections 4 and 5 respectively, as well as the summary of the activities of its Data Processing Centers (Section 6). A brief description of the ongoing work on the PLANCK systematic effects is reported in Section 7. This work is being carried out by the PLANCK community with the aim to completely control the systematics, both for amplitude and polarization measurements that will be performed by PLANCK.

2. Satellite Description

PLANCK is the third Medium-Sized Mission (M3) of ESA's Horizon 2000 Scientific Programme, and will be injected in orbit together with the HERSCHEL Space Observatory by an Ariane V ESV launcher from Kourou (French Guiana, South America). The spacecraft will travel for approximately three months before insertion into a small Lissajou orbit around the second Lagrangian point (L2) of the Earth-Sun system, at about 1.5 millions of kilometers from Earth. With its telescope and the two multi−beam instruments (LFI and HFI) located at the focus, PLANCK will simultaneously observe the sky in nine frequency bands from 30 to 857 GHz, with a typical sensitivity of $\Delta T/T \sim 2 - 4\ \mu K/K$ and angular resolution between 5 to 30 arcmin, depending on frequency.

In the nominal configuration, referred to the nominal scanning strategy, the line of sight of the telescope is offset at 85 degrees with respect to the spin axis direction which is pointing in the anti−Sun direction to reduce Sun, Earth and Moon contamination. PLANCK will operate in a survey mode observing great circles separated by 2.5 arcmin one from each other on the sky and performing a nearly−full sky coverage (95% at least) in six months, thus allowing two sky surveys during 1 year of nominal mission lifetime. Each pixel on the sky will be measured repeatedly by several different detectors at each of several frequencies on many different time scales. This process allows full characterization and subtrac-

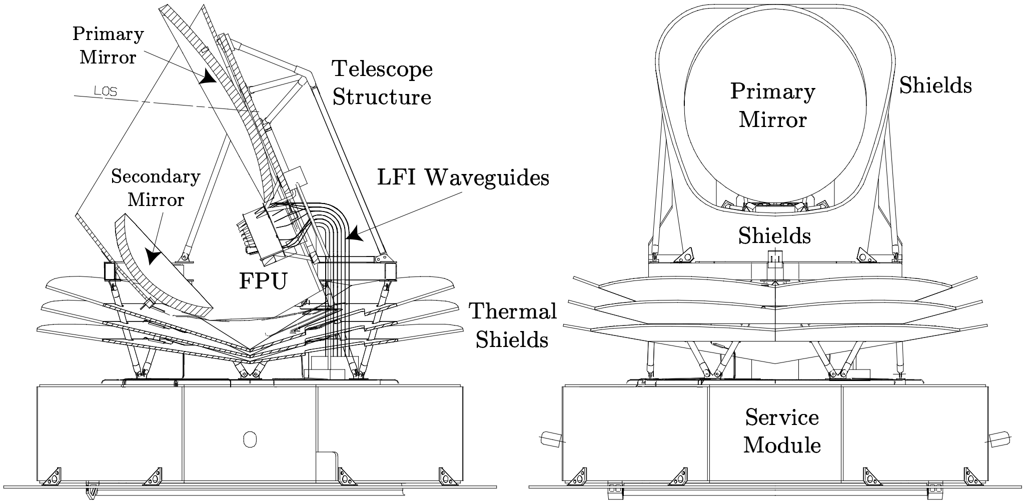

Fig. 1. Side section (on the left) and front (on the right) view of the entire Planck Satellite.

tion of any instrumental offsets and drifts and provides for separation of astrophysical foregrounds. A definitive CMB anisotropy measurement requires both extremely good sensitivity and rejection of systematic effects. The designs of the the spacecraft, the telescope and the two instruments are driven by these two requirements.

The satellite configuration (see Fig.1) follows a modular concept with a physical separation into a Payload Module (PLM) and a Service Module (SVM). The SVM provides all the servicing functions to the PLM and also accommodates the warm instrument electronics. The PLM is composed of a 1.5 meter shielded off-axis telescope, thermal shields, and the cold stages of the two instruments that share the focal region of the telescope: the Low Frequency Instrument (LFI) and the High Frequency Instrument (HFI). The two instruments are coupled mechanically and thermally by a round flange cooled to 18K. LFI provides also the mechanical support to HFI, being this last at the center of the Focal Plane and LFI in a ring around it.

The telescope will be passively cooled to $\sim$ 50K while the two instruments will be actively cooled to achieve the best possible sensitivity. A series of three thermal shields decouple the payload from the warm ($\sim$ 300K) SVM, and provide intermediate temperature stages for the payload structures, piping, harness, and waveguides. The shields radiate to free space very efficiently in the environment of the Earth- Sun Lagrangian L2 orbit. Respectively at 150K, 100K, and 50K, the three shields will provide the needed thermal stability and environment to permit the cooling at lower temperatures of the two instruments (20K and 0.1K for LFI and HFI respectively).

The 20K Hydrogen Sorption Cooler system (Wade et al. 2000) provides the cooling stage for LFI and pre-cooling stage for HFI. The Sorption Cooler is a closed cycle cooler using Joule-Thomson (J-T) expansion of high pressure hydrogen gas. A set of six compressor elements provide continuous circulation of hydrogen at the appropriate pressure and flow rate. Two Sorption cryocooler units (primary and redundant) will be integrated on Planck. The compressor assemblies are located on the SVM and connected to radiators for heat rejection. Pipes, passing through the V-grooves, transport the gas to the cold-end where it is liquefied to provide refrigeration to the Focal Plane Unit box (FPU).

The launch of PLANCK is foreseen in February 2007. The development is now in Phase B, and the Phase C/D will start at the end of the year 2002. The Qualification Models of both instruments will be delivered to the European Space Agency in April 2003 and the Flight Models in July 2004.

3. The Telescope

The Planck telescope represents a challenge for telescope technology and optical design (Villa et al. 2001). The wide frequency coverage (from 25 GHz to 1000 GHz), the $\pm 5^\circ$ Field of View, the high performance of both HFI and LFI sharing the 400×600 mm wide focal region, and the cryogenic environment $(40-65\mathrm{K})$ in which the telescope will operate, set stringent requirements on the design, development and manufacturing of the telescope itself. These requirements have never been requested before in experimental cosmology.

The telescope design is based on a two-mirror off-axis scheme which offers the advantage of accommodating large focal plane instruments with an unblocked aperture. Both the primary and the secondary mirrors have an ellipsoidal shape as in the Gregorian aplanatic design (Villa et al. 1998). The optical scheme has been obtained during the Planck Payload Architect Study by the Industrial Contractor, the Instrument teams, and ESA, within an activity devoted to optimizing the telescope (Dubruel et al. 2000; Villa et al. 2001). The telescope has been selected among several candidates as the best design in terms of stray light rejection, beam symmetry, angular resolution, and flatness of the focal surface. The primary mirror physical dimensions are about 1.9 x 1.5 meters, allowing a projected circular aperture of 1.5 meter of diameter. The secondary reflector has been oversized to approximately 1 meter in diameter to avoid any additional under illumination of the primary.

The mirrors will be fabricated using Carbon Fiber (CFRP) technology. The baseline consists of an all-CFRP rounded triangular tube sandwich array arranged in a honeycomb-like structure. This kind of structure has been chosen to satisfy the requirements of low mass, high stiffness, high dimensional accuracy, and low thermal expansion coefficient. The sandwich concept consists of a thick (4-10 cm) honeycomb-like core with the desired shape, to which are bonded two thin (1-1.5 mm) reflecting skins.

The typical roughness of the mirror surface is required to be 1 μm at any scale up to 0.8 μm and the average mechanical surface error will be 10 μm with respect to the best fit surface (2 μm of amplitude maximum for periodic structures).

4. The High Frequency Instrument (HFI)

The High Frequency Instrument (HFI) is a novel instrument concept based on an array of 48 very sensitive stable spider-web bolometers cooled to 100 mK by a space qualified dilution refrigerator. It will cover the $100-857$ GHz frequency range in six observing bands centered at 100, 143, 217, 353, 545 and 857 GHz (see Puget et al. 1998). Half of the channels at 143GHz, 217GHz and 353GHz will be equipped with Polarization Sensitive Bolometers (PSB) (Delabrouille & Kaplan 2002) in order to detect the polarization of the incoming radiation. The cooling system includes a ^{4}He closed cycle Joule-Thomson (JT) cooler and an open loop dilution cooler, since the precooling at 20K is provided by the sorption cooler. The dilution cooler is similar in principle to the dilution refrigerator used in ground based low temperature laboratories, except that it runs in an open loop. ^{3}He and ^{4}He gas are precooled at various stages and then mixed to produce the required cooling at 0.1K. The JT cooler uses the ^{4}He as a fluid, and a pair of mechanical compressors. These compressors are controlled by a low vibration drive electronics with force transducers and a servo feedback loop to minimise the vibrations. The JT

Table 1. HFI bolometer array characteristics and expected performances. The detector temperature is ~ 0.1K

Central Frequency (GHz)	100	143	217	353	545	857
Beam size (arcmin)	9.2	7.1	5.0	5.0	5.0	5.0
# of unpolarized Detectors	4	4	4	4	4	4
# of polarized Detectors	–	8	8	8	–	–
Average $\Delta T/T$ (μK/K)	2.2	2.4	3.8	15	80	8000

provides the precooling of the gases used in the dilution cooler at 4K.

HFI will use concentrating optics and filters to couple the bolometers to the Planck telescope. 48 back-to-back corrugated horns, attached to the 4K stage, will couple the telescope with the detectors. The horn pair is constructed from two horns separated by a corrugated waveguide section. For a given throughput, the sidelobe response, beamwidth on the sky, and spillover are precisely controlled by the design of the front horn. The filters are attached to the 1.6K stage, and the bolometers to the 0.1K stage, which corresponds to an optimal distribution of heat loads on the different stages.

The bolometers are read out via cryogenically cooled J-FETs located very close to them in a box thermally insulated from the cold focal plane of the HFI. The readout electronics are based on the principle of AC bias for detecting signals at very low frequency without sky-chopping.

5. The Low Frequency Instrument (LFI)

The Low Frequency Instrument (LFI) is an array of 56 tuned radio receivers which will be placed in the focal plane of the Planck telescope, in a ring around HFI cryostat. LFI will image the sky in four frequency channels at 30, 44, 70, and 100 GHz (see Mandolesi et al. 1998).

It consists of three main units: the Front End Unit (FEU), the Back End Unit (BEU), the Radiometer Electronics Box Assembly (REBA). The FEU is located at the focus of the telescope and is composed by 27 corrugated feed horns, 27 Ortho Mode transducers, 27 Front End Modules (FEM) each containing two receivers. The BEU is mounted on the equipment platform and includes 27 Back End Modules (BEM). The FEU is cooled to 20K by the hydrogen sorption cooler and it is connected to the BEU, which is at 300 K, by 108 high performance 1.5 meter long bent twisted composite (copper - stainless steel - gold plated stainless steel) rectangular waveguides. The waveguides are thermally connected to the three thermal shields of the satellite. With this configuration, the power dissipation for the Front End Unit can be kept at sufficiently low value to enable active cooling of the HEMTs to 20 K. The active cooling of the LFI front end reduces the noise temperature substantially, roughly a factor of 3 compared to an optimized passive cooling design.

LFI takes full advantage of the dramatic progress of transistor amplifier technology achieved over the last decade, particularly for low noise performance and reliability of cryogenically cooled indium phosphide (InP) high-electron-mobility transistors (HEMTs). These devices exhibit the best noise performance ever reached in the LFI frequency range. The signal entering the corrugated feed horn is divided by the Ortho Mode Transducer into two orthogonal linearly polarized signals that propagate through two independent pseudo-correlation receivers. This solution maximizes the number for channels per available focal plane area, and, at the same time, adds polarization capability to the instrument. In addition, the pseudo correlation architecture reduces the 1/f noise of the front end amplifiers. The signal coming

Table 2. LFI HEMT radio receiver array characteristics and expected performances. The detector temperature is ∼ 20K

Central Frequency (GHz)	30	44	70	100
Beam size (arcmin)	30	23	14	10
Number of Detectors	4	6	12	32
Average $\Delta T/T$ (μK/K)	2.2	2.8	4.9	6.6
Sensitive to linear pol.	yes	yes	yes	yes

from the sky is continuously compared with the signal coming from a reference load attached to the HFI external shield at 4K .

The amplifiers at 30 and 44 GHz will use discrete InP HEMTs incorporated into a microwave integrated circuit (MIC). At these frequencies, cryogenic MIC amplifiers have demonstrated noise temperatures approaching 10K, with 20% bandwidth. At 70 and 100 GHz, MMICs (Monolithic Microwave Integrated Circuits) architectures, which incorporate all circuit elements and the HEMT transistors on a single InP chip, are used. The LFI will fully exploit both MIC and MMIC technologies at their best.

6. The Planck Data Processing Centers

The Data Processing Centers of both LFI and HFI instruments will receive data from the Mission Operations Center (MOC) of Herschel/Planck located at ESA/ESOC (Darmstadt, Germany). The data processing activity (the LFI DPC is located in Trieste, Italy) is divided in five levels, each characterized by specifics tasks described below.

The Level 1 of the DPC will operate on telemetry with the major aim of controlling House Keeping and Scientific Telemetry and producing Time Order Information (TOI). Realtime analysis will be performed in order to check the instrument performance, and instrument alarms could be generated and sent to the MOC. Quick-look analysis will be performed on the compressed packets of the Scientific Telemetry, with the aim to detect sources and to generate alarms for unexpected, according to pre-compiled source catalogs, strong sources for scientific follow up.

The DPC Level 2 will produce calibrated Time Ordered Data (TOD), as a principal task. The second major task is the production of frequency maps calibrated and free from systematic effects. In addition several other tasks will be performed as, for example, trend analysis making use of the raw TOI produced by the Level 1.

The main task of Level 3 will be the isolation of the different astrophysical and cosmological components present in the sky signal. Several types of separation algorithms (e.g. Maximum Entropy Method, Independent Component Analysis, Wiener Filter, etc) will be exploited. Their inputs are the four calibrated receiver maps from LFI together with the six calibrated HFI frequency maps that are planned to be exchanged. At the level 3 the two DPCs will work with the full set of calibrated maps produced by Planck (both LFI and HFI) in order to fully exploit the widest frequency coverage ever probed in a single mission.

At level 4 the final data will be delivered to the community. The Proprietary period has a nominal duration of 1 year and will start one year after the completion of the second full sky survey of Planck. The major activity during this period will be the scientific analysis of the data products by members of the PI Consortia and preparation for product delivery to the community.

The Data Products distribution will start 2 years after the completion of the second survey. The Planck data products will be located for storage into the overall

HERSCHEL/PLANCK Archive which will be established by ESA.

During the Development Phase of the satellite, there is a strong need to produce simulated flows of data as provided by the instrument and packaged by the SVM during the flight. These simulations are crucial and performed during the instrument development phase within the so called DPCs Level S (Simulations). The aim of this level is essentially to develop any algorithm or prototype of the data processing levels and implementing and testing parts of the DPCs.

7. The Planck Systematic Effect Working Groups

To reach the extremely challenging scientific goals of PLANCK, a dedicated activity with the aim to study the systematics effects of Planck as a whole instrument has been setup by the community. Nine technical working groups have been identified and the activity started during 2001. Several potential systematics sources have been grouped in five categories: main beam distortions, stray light contamination, instrument intrinsics effects, thermal effects, pointing errors. Four working groups are specifically working on the implication on polarization measurements, on the impact of the systematics on science, on the detection and removal of systematics, and finally on the calibration. In addition this organization of working groups will ensure that the much needed knowledge of both instruments and satellite characteristics will be obtained and that the adequate expertise in data reduction is developed since the software produced by the working groups will be integrated in the pipeline of the LFI and HFI data processing.

8. Conclusions

The overview of the PLANCK Project have been presented in this paper.

PLANCK will be the third generation of space missions dedicated to imaging the sky fluctuations at mm-wavelength after NASA's COBE and MAP missions. The active cooling of the two instruments (HFI and LFI), the unprecedented wide frequency coverage (from 30 GHz to 900 GHz) and angular resolution (from 5 to 30 arcmin), the redundancy of the most important band for Cosmology (at 100 GHz) which is covered both by radiometric and bolometric detectors, the entire satellite designed to minimize all the potential sources of systematic effects, will render PLANCK the definitive mission for imaging the primordial CMB anisotropies.

Acknowledgements. This paper represents the work carried out by a large number of people who are working on the development of PLANCK. We wish to thank the Planck Project and the instrument consortia.

References

de Bernardis, P., Ade, P.A.R., Bock, et al. 2000, Nature 404, 955.

de Bernardis, P., Ade, P.A.R., Bock, J.J., et al. 2001, astro-ph/0105296.

Delabrouille, J. & Kaplan, J. 2002 AIP Conference Proceedings 609, 135

Dubruel, D., Cornut, M., Fargant, G., et al. 2000 Proceedings of AP2000 Millennium Conference on Antennas & Propagation ESA SP-444 Proceedings on CD.

Hu, W., Seljak U., Withe, M., Zaldarriaga, M. 2001 Phys.Rev. D 57, 3290.

Kosowsky, A. 1999 New Astronomy Reviews 43, Issue 2-4, 157

Mandolesi, N. et al. 1998 Planck LFI, A proposal submitted to ESA

Puget, J-L., et al.: 1998, HFI for the Planck Mission, A proposal submitted to ESA

Smoot, G. et al. 1992 APJ 396 L1.

Villa, F., Mandolesi, N., Burigana, C. 1998 TESRE Internal Report 221/1998

Villa, F., Bersanelli, M., Burigana, C., et al. 2001, astro-ph/0112173 Proceeding of the 2K1BC Workshop, AIP conference proceedings, in press

Wade, L.A., Bhandari, P., Bowman, R., et al. 2000 Advances in Cryogenic Eng. 45