The low frequency instrument on-board the Planck satellite: Characteristics and performance

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Abstract

Planck is the third generation space mission, after COBE/DMR and WMAP, devoted to image the CMBR anisotropies. The low frequency instrument (LFI) will simultaneously observe the sky in three frequency bands centered at 30, 44 and 70 GHz. It is composed by 11 pseudo-correlation receivers, actively cooled to 20 K, able to detect both orthogonal polarisation of the incoming signal. The LFI will be located, along with the high frequency instrument (HFI), in the focal region of a 1.5 m aperture telescope. The LFI will produce full-sky maps of the anisotropies of the CMBR with a FWHM angular resolution of 33’, 27’ and 14’ for the 30, 44 and 70 GHz LFI bands, respectively.

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1. Introduction

The Planck mission, whose launch is foreseen in 2008, will extend our knowledge of the Cosmic Microwave Background beyond the actual limits set by past and present experiments (see for instance WMAP, B2K, CBI, ACBAR).

From the second Lagrangian point of the Sun–Earth system, Planck will produce a survey that will cover the whole sky with unprecedented sensitivity, angular resolution and frequency coverage, and it will likely lead us to the final comprehension of the CMB temperature anisotropies. A critical issue for any CMB experiment is the accurate removal of the foregrounds. While WMAP is not sensitive at frequency higher than \( \sim 100 \) GHz, the Planck instruments will produce cross calibrated full sky maps spanning a very large frequency range. The HFI, operating between 100 and 857 GHz, is able to monitor, for instance, the dust contamination, the LFI, covering from 27 to 77 GHz, is sensitive to the synchrotron and free–free emission. The combination of the two instrument will therefore produce the cleanest image of the CMB ever obtained. Moreover, the wide frequency range covered, delivering all-sky maps for each channel, will provide at the same time a gold-mine of astrophysical information (see Table 1).

Comparing the three generation of space mission devoted to the CMB anisotropies, COBE/DMR, first mapped the temperature anisotropies; WMAP, after successful balloon-borne and ground-based experiments (see among others de Bernardis et al., 2000; Dickinson et al., 2004; Kuo et al., 2004) determined with high accuracy the temperature power spectrum (Bennett et al., 2003; Hinshaw et al., 2003) up to the third peak (Hinshaw et al., 2006) and improved (Page et al., 2006) the first determination of the TE and EE power spectrum (along with other experiments Readhead et al., 2004a,b; Leitch et al., 2005; Piazzentini et al., 2005, 2006). Planck will not only extend the high precision determination of the TT-spectrum up to \( \ell \sim 2000 \), but it will determine the EE-spectrum with high sensitivity up to \( \ell \sim 1000 \) (The Scientific Programme of Planck, 2005). Planck will represent for the E-mode CMB polarisation what WMAP is for the temperature spectrum. Moreover, it will also reach the sensitivity to detect the B-modes under certain theoretical assumptions (relatively large tensor to scalar perturbation ratio and Thomson scattering optical depth).

The LFI is described from the general point of view in many papers (see for instance The Scientific Programme of Planck, 2005, Bersanelli and Mandolesi, 2000, Mandolesi et al. (2002), Villa et al. (2002c), Lawrence (2003), Mennella et al. (2004), Sandri et al. (2004a), Bersanelli et al. (2005), Terenzi et al. (2006)) and in some specific design issues (Seiffert et al., 2002; Mennella et al., 2002, Maris et al., 2006). We limit ourselves here to review to some specific topics, mainly related to the 4K reference load unit, LFI optics, the sorption cooler and the LFI contribution to Planck science.

2. LFI characteristics

The design philosophy for the LFI is to minimise any systematic effect, from instrument intrinsic effects and from astrophysical origin, in the design of the instrument instead of removing it in data reduction. It results in a very complex instrument, especially for the radiometric (Seifert et al., 2002), optical (Burigana et al., 2001) and thermal aspects (Mennella et al., 2002). Moreover an enormous effort is made to model the impact of any known effect on the final maps. The goal of the LFI is to produce the cleanest images of the CMBR at its frequencies, only limited by contamination from astrophysical origin.

2.1. LFI receivers

The LFI is an array of 22 pseudo-correlation receivers (Bersanelli and Mandolesi, 2000), based on radio detectors (Mennella et al., 2003; Cuttaia et al., 2004). They are continuously comparing the signal of the sky and of a stable reference load (see below for a detailed description).

To remove the effect of instability in the back-end amplifiers and detector diodes, it is necessary to modulate the sign of the signals using phase switches, located in the front-end modules. This design was chosen over a much simpler total-power scheme (consisting of one of the two parallel chains) because the latter exhibits inadequate gain stability at time scales larger than a few seconds. LFI design minimises systematic effects such as thermal instabilities (Mennella et al., 2002), \( 1/f \) (Seifert et al., 2002) noise. Each amplification stage will be provided by indium phosphide high electron mobility transistors (HEMTs). This technology offers the best compromise between sensitivity
and ease of implementation in the frequency range of the LFI. To minimise the effects of power dissipation in the critical focal plane area, the receivers are split into two parts, the Front-end and the Back-end. The former is placed in the focal plane unit (FPU) at 20 K, and the latter at 300 K on the top part of SVM. Both include a number of amplification stages, and are connected together by waveguides. Each receiver provides signal detection at the end of the amplification chain. The output of each receiver is a low-level DC signal.

The front-end unit (FEU) contains 11 radiometers, each containing one feed horn, one orthomode transducer (OMT), two hybrid couplers, the 4KRL arm and four cryogenic amplifiers. The radiation focused by the telescope (Villa et al., 2002a; Sandri et al., 2004c) is coupled to the radiometers by double profiled, corrugated feed-horns (Fig. 2, left). Feed-horn, in particular, are optimised for angular resolution as a trade-off with straylight rejection and low sidelobes (Burigana et al., 2001; Sandri et al., 2004b), minimal beam ellipticity (Sandri et al., 2002). In addition, the electromagnetic field inside the horn must propagate with low attenuation and low return loss. The OMTs separate the orthogonal polarizations with minimal losses and cross-talk. Just below OMTs, we can find the front end modules (FEMs), which include the first hybrid couplers block, and the amplifiers block with phase switches and output hybrids. Each hybrid has two inputs, one of which sees the sky, the other of which looks at the reference load. The low-noise amplifiers use InP HEMTs in cascaded gain stages. Following amplification the signals are passed through a phase switch, which adds a 180° phase lag to the signals at 4096 Hz, thus selecting the input source as either the sky or the reference load at the radiometer output. The phase lagged pair of signals is then passed into a second hybrid coupler, separating the signals.

The front-end and back-end portions of each radiometer are connected with wave-guide sections. Each radiometer will need two wave-guides, for a total of 44 connections. The main requirement is thermal isolation since wave-guides will link the 20 K front-end to the 300 K back-end. While WMAP radiometers (Jarosik et al., 2003), where the second hybrid is in the BEM, use phase-matched waveguides, the LFI design does not require this features. This allowed a complicated routing (see Fig. 1). The first sector of each waveguide, with bends and twists (Fig. 2), is made of electroformed copper. A thermal insulating section, made out of stainless steel, decouples the front-end unit by the back-end unit, held at 300 K in the satellite service module. LFI waveguides are connected to the satellite V-grooves radiators and a black painted section contribute to thermal dissipation of the instrument (see Fig. 3).

The back-end unit is mainly composed by the radiometer back end modules (BEM) and the data acquisition electronics (DAE), which are connected by an internal harness. Each receiver BEM contains two parallel chains of amplification, filtering, detection. The DAE comprises the analog conditioning electronics, the multiplexers, the analog-to-digital converters, the parallel-to-serial converters, the control electronics, the communication interface, and the power conditioning and distribution electronics. The DAE communicates with the radiometer electronic box assembly (REBA), which consists of one nominal and one redundant unit. The REBA performs all the functions necessary for the operation of the LFI.
that allow LFI scientific and housekeeping data to be transmitted from the satellite to the ground.

2.2. The 4K reference load

The reference signal for the LFI radiometers is provided by the 4K reference load (4KRL) unit (Valenziano et al., 2002a, 2003; Cuttaia et al., 2004b; Valenziano et al., 2006), which uses the HFI outer shield to reach an operating temperature expected less than 5 K. The overall design of the 4KRL was driven by high-level constraints: total heat load on the HFI less than 1 mW and the small allowed volume within the two instruments. Among the possible options, it was chosen to have a mechanical separation (only radiative thermal coupling) and a minimum clearance to prevent any contact between the LFI and the HFI due to vibrations at launch. We call load the system providing the reference signal for each radiometer, one for each polarisation, for an overall number of 22. The functional scheme for each load is separated two parts: small reference horns on the LFI FEMs, connected to the radiometer hybrid, facing an evolution of waveguide terminations, called targets, mounted on the HFI. There is a gap of at least 1.5 mm between horn and target.

Targets are small structures casted in ECCOSORB CR. Targets are small structures casted in ECCOSORB CR. The particular geometry of each part, constrained by the allowed volume, is specifically designed for each of the LFI radiometer. Targets are made of a combination of two flavours of ECCOSORB: CR110 and CR117. The first is used for the front part and for the pyramid, which is mainly designed to minimise incoming wave reflections. The latter forms the high absorbing layer at the back of the target (see Fig. 4, left panel). The principle of operation is to have a gradual increase of the index of refraction.

within the target. The fields inside each target have been modelled with a finite elements method code in order to optimise the design (Cuttaia, 2005). As an example, the cross in the front section of the targets closely matches the near-field pattern of pyramidal horn and the pyramid tip in the 70 GHz targets is protruding from the front surface to reduce signal leakage. Each part is bonded inside an Al6061 case, which confines the fields and, at the same time, provides thermal contact with the HFI (see Fig. 5).

Each target is illuminated by a reference pyramidal horn (Fig. 2, left). Small grooves are located around the horn aperture to reduce spillover radiation which can enter the gap between the horn and the target. Reference horns for the 70 GHz channels are located within FEM. The position of 30 and 44 GHz FEM in the FPU requires the implementation of external waveguides to connect the reference horn to the FEMs. The 4K waveguides routing is designed to allow the integration of the HFI into the LFI. Each part shows up to four bends and the whole waveguide and the horn are electroformed by depositing pure Copper on an Aluminum mandrel, which is then solved in caustic soda bath. The gold-plated brass flange and the grooves are then soft-welded at the ends of the waveguide. Flanges are aligned with pins, to allow reproducibility in the assembling and disassembling phase during testing.

Two figures-of-merit were used in designing the 4KRL unit: reflectivity and leakage. Since the LFI radiometers are comparing the signal from the CMBR (whose temperature is know with an accuracy of about 1%) and the reference signal from the 4KRL, the loads’ emissivity should be better than $\epsilon = 0.99$. Therefore the requirement is an average return loss $RL \leq -20$ dB. The small dimension of the reference horns, due to the constraints imposed by the allowed overall volume for the 4KRL unit, set an upper limit for the return loss; However, the 4KRL unit fulfills the above mentioned requirement. Horn and target design was optimised for each of the LFI bands in a iterative process: first the horn (aperture dimension, flare length) within the volume allowed; then the target geometry was optimised and the coupling was studied.

The leakage definition is more complex. It is defined as the spillover signal that can enter the horn-target gap. These radiation are expected to have several different ori-
gins: *internal* leakage within the FPU (thermal fluctuations of the environment, cross talk between the two polarisation within the same FEM, etc.) and *external* leakage coming from the outside the FPU (payload environment, pick-up from the Galaxy and from planets, CMBR dipole). The strategy for addressing this design issue is separated in two steps. External signals are rejected by preventing as much as possible the visibility of external environment from the 4KRL system. This is accomplished by designing roofs over the horn-target gap (70 GHz loads) and shielding the back part of the FPU (low frequency loads). From finite element method (Cuttaia, 2005) simulations we found that the rejection is better than 20 dB. *Internal* leakage is addressed by reducing as much as possible the horn-target gap and by designing grooves around the horn aperture. In this case also, we have been able to demonstrate a rejection of the order of 20 dB. An example, if a signal of 1 mK is coming from the sky, it is first dumped by 20 dB entering the FPU and then another 20 dB when entering the horn-target gap. It results on less than 0.1 μK systematic effect, well within the allowed systematic budget for the 4KRL (Bersanelli et al., 2002).

Particular care is posed on thermal aspects, which could be an important source of systematic effects. A detailed thermal model of the 4KRL unit (Terenzi, 2005) was produced, measuring directly the thermal properties of the materials (Valenziano et al., 2003), scarcely present in the literature (Peterson and Richards, 1984; Hemmati et al., 1985; Halpern et al., 1995; Lamb, 1999). Thermal fluctuations, induced mainly by the HFI 4K cooler, are propagated in the LFI radiometer global model up to the final effect expected on the sky maps (Mennella et al., 2002). As an example, stainless steel washers are introduced to dump temperature fluctuation of the heat sink. Each single part was tested for mechanical properties (vibrations, defects), thermal and RF properties. A dedicated cryo chamber (Valenziano et al., 2002b) allowed us to test the thermal properties of the unit in a fully representative environment. In particular the fluctuation dumping and the heat load were measured. Return loss of each target, coupled with the relative reference horn, were measured with a Scalar Network Analyser. Cross talk between adjacent loads resulted lower than −40 dB, as expected.

Several *models* of the 4KRL have been manufactured: the prototype demonstrator model (PD), where materials and target and reference horn design were defined; the elegant breadboard (EBB) model, where the advanced design was tested and the performance were evaluated with the 30 GHz EBB radiometer; the qualification model (QM), produced with the flight model design and materials: it was used not only during the QM test campaign at instrument level, but it is now, refurbished, the flight spare unit. The flight model was then manufactured, fully exploiting the lessons learned before. In addition, a fully equivalent (except the materials not certified) unit was produced to be used in QM radiometer chain assemblies test campaign in all the LFI bands. Moreover, a dummy model, representative of the mass and thermal properties of the 4KRL unit, was produced and delivered for the HFI qualification campaign.

The 4KRL unit was designed, manufactured and tested at INAF/IASF – Bologna, with collaboration from the LFI instrument team (Università di Milano, CNR/IFP, JPL).

2.3. LFI optics

One of the main limiting factors in terms of systematic effects in a CMB space-borne experiment is the optical system, because *main beam distortions* and *sidelobes* are two of the main sources of systematic errors (Burigana et al., 1998, 2001, 2004; Mennella et al., 2004). The former degrades the angular resolution, limiting the reconstruction of the anisotropy power spectrum at high multipoles, the latter drives unwanted radiation not coming from the boresight direction (the so-called *straylight*) into the feed horn, contaminating the measurement mainly at large and intermediate angular scales (i.e. at multipoles ℓ less than ≈100). Accurate predictions and measurements of the *beam shape* are essential both during the instrument development phase (to design and to properly locate each feed horn) and for an in-depth knowledge of the whole-instrument response in the development of the data reduction pipeline (to remove residual systematic effects by software). We present in this section the LFI effort to address these important systematic effects (see Sandri (2005) for details).

The LFI and the HFI are coupled to a 1.5 m off-axis dual reflector telescope (Villa et al., 2002b) by an array of 11 feed horns. Optical simulations are performed by considering the feed as a source and by computing the pattern scattered by both reflectors on the far field using GRASP, a software developed by TICRA (Copenhagen, DK) for analysing general reflector antennas. Dedicated software has been written to optimize the implementation of GRASP to the Planck case (Sandri et al., 2002). Main beam simulations (Fig. 6) have been performed using Physical Optics (PO) on both reflectors, also including the effect of the real telescope, using as input in the simulations the measured mirror surfaces of the qualification model of the planck telescope. The field of the source has been propagated on the sub reflector to compute the current distribution on the surface. Then, the currents have been used for evaluating the radiated field from the sub reflector. The calculation of the currents close to the edge of the scatterer has been modeled by the physical theory of diffraction. The radiated field from the sub reflector has been propagated on the main reflector and the current distribution on its surface is used to compute the final radiated field in the far field co- and cross-polar component, according to the Ludwig 3rd definition (see Sandri (2005) for details).

Beam parameters have been computed for each of the LFI feeds, producing the relevant quantities such as the full width half maximum, the ellipticity, the rotation angle of the polarisation ellipse, the main beam directivity, the cross
polar discrimination factor, the main beam depolarization parameter, and the spillover (Sandri et al., 2003). In this study, we found that a pure Gaussian feed model is not able to correctly predict the far-field, since relevant features in the beam are due to the sidelobes in the feed horn pattern. Not only the realistic pattern needs to be considered, but the detail of the corrugation design could also affect the beam characteristics. The edge taper being equal, different corrugation profiles involve differences of about 3% in the main beam angular resolution and about 40% in the straylight signal (Sandri, 2005).

Although physical optics is a powerful electromagnetic simulation method well understood and widely used, its applicability to real optical systems in $4\pi$ beam predictions can be very difficult, particularly when many reflecting structures have to be simulated. Multiple diffractions and reflections between optical elements (reflector, one or more shields, supporting structures) have to be considered and this leads to unacceptable computational time. To overcome this difficulty, an advanced simulation technique based on geometrical theory of diffraction has been originally implemented, named multi-reflector GTD (MrGTD). MrGTD computes the scattered field from the reflectors performing a backward ray tracing. It has been found that the contribution of more than two optical interactions is not required in the optimisation activity, since neglecting the 3rd order optical contributions involves differences on average less than 3% in the straylight evaluation, saving about 75% of the computational time.

It has been derived that, in PLANCK LFI case, the antenna response features at large angles from the beam centre are determined mainly by the rays coming from the feed that are reflected by the lower part of the subreflector and that are not intercepted by the main reflector (see Fig. 7). These rays fall in the so called main spillover region with a power level up to $-60$ dB. Also the energy coming directly from the feed horn, without any interaction with the reflecting structures, increases the field and helps to increase the spillover. Moreover, other important contributions that increase the far sidelobes are due to the diffraction from the edge of the mirrors and from the shielding structure. Therefore the spillover (and consequently the straylight contamination) can be reduced by decreasing the illumination near the edge of the mirrors, i.e. by increasing the edge taper (ET), defined as the ratio of the power per unit area incident on the centre of the mirror to that incident on the edge. On the other hand, increasing the ET has a negative impact on the angular resolution (Burigana et al., 2004). For each LFI feed horn, several beams were simulated using the radiation patterns computed from different geometry and inner corrugation profile of the horn itself. Each beam has been convolved with the microwave sky, taking into account the PLANCK scanning strategy in the 14 months observational time, and the straylight noise induced by the Galaxy has been derived. From the comparison between these straylight values, and taking into account the beam characteristics, the best horn design has been selected.

While the main beam is highly polarized (greater than 99% linearly polarized, i.e. the cross-polar component is always 25 dB down to the co-polar component), the computed $4\pi$ beams have shown that the co- and cross-polar components in the sidelobe region could have the same intensity. Therefore, the cross-polar component will contaminate the co-polar component of the orthogonal polarization. This is relevant mainly in the lower LFI bands, where the Galaxy emission is strongly polarized. In other words, the strongly polarized Galaxy emission coming from the sidelobes into the two polarized detector is added to the slightly polarized CMB field entering the feed horn.

Fig. 6. Contour plot in the UV-plane ($-0.026 < U,V < 0.026$) of the main beam co-polar component computed for the 44 GHz feed horn #24, assuming an ideal telescope. The fit bivariate Gaussian contours are superimposed with dotted lines and the resulting averaged FWHM is 22.82$''$. 

Fig. 7. These rays fall in the so called main spillover region with a power level up to $-60$ dB. Also the energy coming directly from the feed horn, without any interaction with the reflecting structures, increases the field and helps to increase the spillover. Moreover, other important contributions that increase the far sidelobes are due to the diffraction from the edge of the mirrors and from the shielding structure. Therefore the spillover (and consequently the straylight contamination) can be reduced by decreasing the illumination near the edge of the mirrors, i.e. by increasing the edge taper (ET), defined as the ratio of the power per unit area incident on the centre of the mirror to that incident on the edge. On the other hand, increasing the ET has a negative impact on the angular resolution (Burigana et al., 2004). For each LFI feed horn, several beams were simulated using the radiation patterns computed from different geometry and inner corrugation profile of the horn itself. Each beam has been convolved with the microwave sky, taking into account the PLANCK scanning strategy in the 14 months observational time, and the straylight noise induced by the Galaxy has been derived. From the comparison between these straylight values, and taking into account the beam characteristics, the best horn design has been selected.

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from the main beam direction. This effect can be removed at the first order by the differential receiver concept adopted for Planck LFI. At the higher orders, the detailed knowledge of the beams ensures the adequate subtraction in the data reduction pipeline. Another straylight-induced effect, described in (Burigana et al., 2004), is the contamination from T-signal on polarisation reconstruction.

3. Sorption cooler

The vibration-less sorption cooler (Wade et al., 2000; Bhandari et al., 2000, 2001; Morgante et al., 2002) for the Planck Satellite is developed by the Jet Propulsion Laboratory (JPL). The Planck sorption cooler is a closed-cycle, continuous cryocooler designed to provide more than 1 W of heat lift at a temperature of less than 20 K using isenthalpic expansion of hydrogen through a Joule–Thompson valve (J–T). Some of this cooling power will be provided to cool the low-frequency instrument (LFI) onboard the Planck spacecraft. The remaining heat lift will be used as a pre-cooling stage for two further cryogenic refrigerators (He J–T cooler to 4 K; Dilution cooler to 0.1 K) that will in turn maintain the high-frequency instrument (HFI) at 100 mK.

The sorption cooler performs a simple thermodynamic cycle based on hydrogen compression, gas pre-cooling by three passive radiators, further cooling due to the heat recovery by the cold low pressure gas stream, expansion through a J–T expansion valve and evaporation at the cold stage. To provide complete redundancy for the mission, two functionally identical sorption coolers are integrated onboard the spacecraft in order to provide full redundancy also beyond the 14-month mission. Each consists of a sorption cooler compressor (SCC) and the piping and cold end (PACE); a drawing of the cooler is shown in Fig. 8, left. The engine of the SCS TMU is the compressor (SCC), responsible for compressing and recovering the H2 gas circulated, while maintaining in the low pressure return line the vapor pressure needed to meet the cooler requirements. It is composed of six identical compressor elements each filled with metal hydride and provided with independent heating and cooling. Heating of the sorbent is accomplished by electrical resistance heaters while the cooling is achieved by thermally connecting the compressor element to a radiator (warm radiator). Heat switching is achieved by use of a gas gap surrounding the sorption bed that can alternately be filled with thermally conducting hydrogen gas, or evacuated to thermally insulate the gap. Hydrogen is pressurized and circulated in the fluid circuit by alternately heating (to about 470 K) and cooling the six sorbent beds one after another, causing them to release and absorb hydrogen gas by reversible chemical action. At any time, in order to produce a continuous gas flow, one element is heating, one is providing gas at the operational pressure, one is cooling down, while three are cold and absorbing gas. As with many space cryogenic missions, the Planck sorption cooler depends on passive cooling by radiation to space. This is accomplished on Planck by three V-groove radiators working as pre-cooling stages. The final V-groove is required to be between 45 and 60 K to provide the required cooling power for the two instruments. The high pressure gas leaving the
compressor, enters the PACE (piping assembly and cold end) and flows through successively colder pre-cooler heat sinks (at about 170 K, 100 K and 50 K) on each spacecraft radiator (or V-groove). The H2 is also pre-cooled through heat recovery by the cold low pressure returning gas stream in a tube-in-tube heat exchanger. The gas flow is then expanded through a JT flow restriction valve and the liquid hydrogen is collected in two liquid–vapor heat exchangers (LVHX1 for HFI and LVHX2 for LFI) where the liquid droplets evaporation provides the cooling power to the instruments. A third liquid reservoir (LVHX3) collects any excess liquid hydrogen. Hydrogen gas then passes back through all the heat exchangers in the low pressure line, returning to the hydride containers where it is re-absorbed. A temperature stabilization assembly (TSA), using active control, is placed between LVHX2 and the low frequency instrument interface to reduce temperature fluctuations.

4. The LFI contribution to the Planck science

Since the performance of the LFI radiometers, sensitive also to polarization, is the best ever obtained in a CMB space mission at $\nu \lesssim 70$ GHz, LFI data will play a crucial role in the context of the Planck scientific aims and, possibly, in the context of future CMB space missions dedicated to a more precise measure of CMB polarization anisotropies.

Recent WMAP results show that the minimum foreground contamination to CMB observations, both in temperature and polarisation, is in the 60–70 GHz range (Bennett et al., 2003; Page et al., 2006), within the LFI band. Fig. 9 compares the Galactic rms fluctuations as determined by WMAP with the LFI rms sensitivity.

Clearly, the better sensitivity and angular resolution of HFI (the latter obviously related to the resolution improve with frequency for a given telescope size) will make the frequency range at $\nu \sim 100–200$ GHz the best one for an accurate measurement of the CMB anisotropies at very small scales, corresponding to multipoles $\ell \gtrsim 10^3$.

On the other hand, at large and intermediate angular scales (i.e. small and intermediate multipoles) a very accu-

![Fig. 8. Left: Schematic view of the Planck sorption cooler. Right: The compressor elements.](image)

![Fig. 9. Typical rms fluctuations of the main Galactic foreground components out the Galactic plane, for two different masks, as estimated by WMAP (Bennett et al., 2003) compared with the LFI rms sensitivity at 30, 44 and 70 GHz at degree scale (at this scale the CMB anisotropy rms fluctuation is of 50–70 $\mu$K).](image)
rate CMB anisotropy pattern recovery, obviously based also on the increased instrument sensitivity, needs an extremely good separation of CMB anisotropies from foreground anisotropies. It is remarkable that some of the most intriguing results of WMAP appear exactly at low multipoles (low quadrupole, see for instance Bennett et al., 2003, de Oliveira-Costa et al., 2004, Copi et al., 2004, Eriksen et al., 2004, Weeks, 2004; low multipole alignments, see for instance de Oliveira-Costa and Tegmark, 2006, Schwarz et al., 2004, Tegmark et al., 2003, Abramo et al., 2006)).

In this regard, the LFI V band is of particular interest, particularly since the frequency location of the minimum of the foreground contamination at ~degree scales (mainly due to the Galactic diffuse components), as obtained by WMAP. We note that LFI will allow, in the nominal mission duration of 14 months, to improve the determination of the TT power spectrum with respect to WMAP results in the V-band, mainly because of its better angular resolution (~13′ for the LFI 70 GHz channels, ~20′ for WMAP V-band channels) and higher sensitivity.

On the other hand, at ~70 GHz all the three (two) main Galactic diffuse components in temperature (polarization), synchrotron, free-free and dust (synchrotron and dust) are in principle relevant, with a consequent increasing of the number of needed fit parameters for a precise component separation between CMB and foreground. It is then required to combine data at different microwave frequencies and, possibly, to add auxiliary information (Galactic templates) from radio to far-IR. The 30 and 44 LFI bands are crucial to determine the foreground contribution at low frequency. In fact, if the Galactic foreground close to the Galactic plane can be excluded by applying dedicated masks to the all-sky maps, the determination and careful subtraction of the Galactic synchrotron and the free-free contribution (De Zotti et al., 2003, Eriksen et al., 2006) at intermediate Galactic latitudes is critical to avoid a significant loss of statistical information. Finally, we note that the LFI information on Galactic foreground polarization will be useful to understand the level of accuracy needed in future high-accuracy CMB satellite polarization missions dedicated to the B-mode. In the case in which they will include frequency channels at \(\nu \leq 50 \text{ GHz} \), LFI will contribute to appropriately define their sensitivity. In the case in which they will operate only at \(\nu \geq 50 \text{ GHz} \), it will constitute the best uniformly calibrated all-sky survey for the intercalibration of collections of future dedicated observations of Galactic polarized synchrotron emission.

Other than for a precise component separation necessary for the CMB anisotropy pattern recovery, LFI channels are very interesting for the so-called non-CMB science. The accurate mapping of the Galactic synchrotron emission provide information of the Galactic magnetic field structure and on the electron density and energy distributions in the Galaxy, contributing to the construction of a detailed and physically complete 3-D Galactic model, in its turbulent and coherent components. The understanding of free-free emission and its correlation with dust emission, which low frequency tail is accessible to LFI channels, provide information on the enrichment of the interstellar medium related to the process of star formation and evolution. Still controversial is the possible contribution of an anomalous component to the global Galactic foreground. While the WMAP team suggested (Bennett et al., 2003) a minor contribution by these components in the WMAP data, other data (Verstraete and Davies, 2006) support an important role of this component at least on dedicated sky areas. LFI data will be also useful to clarify this aspect. Still remaining on Galactic science, various classes of late stage stars (Umana et al., 2006) may exhibit non-negligible free-free and dust emission, that can be jointly studied by combining LFI and HFI data.

Several thousands of extragalactic sources will be observed by Planck (Toffolatti et al., 1998). LFI data will extend down to fainter fluxes (100–300 mJy) the WMAP direct determination of various classes of some hundreds of (mainly flat spectrum) radiosources of various classes, being crucial to determine the high frequency tail of their spectral emissivity. In this regard, LFI data will constitute an all-sky survey with almost uniform sensitivity and allow to observe the same source at least twice per year (or also from few weeks to month timescales for sources close to the ecliptic poles) improving our knowledge on radiosource number counts and variability (Terenzi et al., 2002) in the microwaves.

5. Conclusions

Planck is the most ambitious space mission devoted to map the CMBR anisotropies for the next years. The two instrument exploit their technology at its best. We reviewed in this paper some topics related to the Low Frequency Instrument. In particular, the 4K reference load unit, the study on the optical properties of the Planck telescope and of the LFI feed horns, the sorption cooler. The last section illustrates how the LFI will contribute to Planck science. All this work reflects the main contribution to the LFI from IASF-Bologna.

References
