Analysis of the pseudocorrelation radiometers for the Low Frequency Instrument on board the PLANCK satellite

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ABSTRACT

The Low Frequency Instrument aboard the PLANCK satellite will employ pseudo-correlation radiometers, operating over three broad bands centred at 30, 44, and 70 GHz. The radiometer scheme is based on the simultaneous comparison of two input signals, one coming from the sky and the other coming from a reference blackbody at a stable cryogenic temperature (near 4K) as close as possible to the sky temperature (about 2.7K). This choice is made in order to minimize non-white instrumental noise, typically exhibiting a $1/f$ spectrum. Effects due to the residual offset are minimised with a gain modulation factor applied in software. Fluctuations of the reference signal, due to fluctuation in the cooling chain or to straylight radiation, can also produce a parasitic signal which would mimic a true sky fluctuation. The PLANCK scientific goal of a high precision imaging of the CMB anisotropy requires an accurate characterisation of each part constituting the chain by using tools of modellisation and experimental tests. In this work we describe the concept of the radiometric chain, its functioning and the main sources of systematic errors, showing how, only with a hard modelling effort, it is possible to characterise, reduce and then remove in the data processing those systematic effects that may in principle compromise the quality of the whole instrument response.

Keywords: Cosmic Microwave Background, PLANCK, Low Frequency Instrument, radiometer, RF, $1/f$ noise.

INTRODUCTION

This paper describes the design, the modellisation and the expected properties of the millimetre wave radiometers of the Low Frequency Instrument\textsuperscript{2} on board the PLANCK satellite. PLANCK represents the third generation of microwave instruments designed for an extremely accurate space observation of the cosmic microwave background (CMB) anisotropies: it is scheduled to be launched in 2007, with the aim of producing full-sky multi-frequency maps, in a range between 30 GHz and 900 GHz. Two instruments are matched to reach this ambitious scope: the Low Frequency Instrument (LFI)\textsuperscript{2} and the High Frequency Instrument (HFI)\textsuperscript{3}. They will employ respectively the state of the art of microwave radiometers (three channels, centered at 30, 44, and 70 GHz) and of bolometers (six channels between 100 and 857 GHz).

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The final LFI design answers to the need of complying with four main observing goals: large frequency coverage, high angular resolution, high sensitivity, and suppression of systematic effects, in the design phase rather than in the data processing by means of software removal tools. Systematic effects affecting the radiation detection can be mainly divided in two families, depending on the source originating them: astrophysics effects and instrumental effects. Both the classes can be moreover divided in two categories, depending on the characteristic frequency of the signal involved: spin synchronous (having the same frequency of the spinning satellite, 1rpm=0.0166Hz) and non spin synchronous signals (showing long time or random frequency and phase). Spin synchronous signal fluctuations are the most critical one because of their ability to mimic the true sky signal, while non spin synchronous can be averaged out with the integration time.

All the above undesired effects can be limited by choosing the appropriate scanning strategy and carefully taking care of the possible sources of errors. Therefore, an accurate modellisation of single parts and of the whole instrument is needed to evaluate the impact of systematics and to subtract unwanted effects from the data, whenever it would not be possible making them negligible in the hardware optimisation.

An overview of the LFI Radiometric chains will be given, focusing on the software modellisation capabilities of investigating systematic effects.

1. THE LOW FREQUENCY INSTRUMENT

The LFI is a system of 22 wide-band coherent radiometers, employing very low noise amplifiers based on InP (Indium phosphide) HEMTs (High Electron Mobility Transistors), distributed on three frequency channels: 30, 44, 70 GHz. They are coupled to the sky by an off-axis aplanatic telescope, passively cooled by the surrounding environment at about 50K.

The horns feeding the radiometers are corrugated and dual-profiled: they are located in the outermost region of the telescope focal surface (the innermost is used by the HFI). The whole Front End (feedhorns, orthomode transducers, and radiometers) is actively cooled at 20K by a vibrationless sorption cooler, in order to achieve the best possible sensitivity. Each channel is sensitive to linear polarization, achieving an accuracy of few µK over two areas each of about 30 square degrees around of the ecliptic caps. Fig. 1 and Fig. 2 show the instrument design while Tab. 1 summarizes the main instrumental performances.

<table>
<thead>
<tr>
<th>Channel (GHz)</th>
<th>Beam size (arc min)</th>
<th>Num. detectors</th>
<th>Band width</th>
<th>Sens. to lin., Polarization</th>
<th>Average ΔT/T (µK/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>33.0</td>
<td>4</td>
<td>27-33</td>
<td>✔</td>
<td>2.2</td>
</tr>
<tr>
<td>44</td>
<td>23.0</td>
<td>6</td>
<td>39.6-48.8</td>
<td>✔</td>
<td>2.8</td>
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<tr>
<td>70</td>
<td>13.0</td>
<td>12</td>
<td>63-77</td>
<td>✔</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Tab. 1 Main LFI characteristics and capabilities

The main scientific goals of PLANCK – LFI are: i) to make full sky maps of the temperature CMB anisotropies, at angular scales larger than 10 arcmin., ii) to characterize the state of CMB polarization, iii) to produce full-sky maps for the most important Galactic and extragalactic sources, permitting to remove source contribution to fluctuations also in the HFI channels, iv) to provide a detailed analysis of various important astrophysical phenomena (SZ effect, source variability, weak lensing).

The LFI performance requirements are basically driven by the main scientific objective, that is the anisotropy science: in particular the goal, at the end of the nominal 14 months survey, is to get an average sensitivity per pixel better than 25µK (18 µK as a goal) at the highest angular resolution.

2. THE LFI RADIOMETERS

The LFI radiometers were designed in order to reduce the 1/f noise (by a factor of at least 1000) induced by gain, noise temperature and phase fluctuations in the HEMT amplifiers. A differential pseudo-correlation scheme was chosen, increasing the sensitivity by a factor √2 respect to a standard Dicke radiometer scheme. The power coming from
the sky is received by each feedhorn/OMT assembly and continuously compared with a reference black body signal at a temperature as close as possible to the sky temperature. In LFI the reference signal is provided through a pyramidal horn facing a microwave reference load thermally linked to the HFI 4K stage.

1/f noise fluctuations of cryogenic HEMT amplifiers can be statistically described by the formulas 4,5,2:

\[
\Delta G(f) = \frac{C}{f^\alpha}, \quad \Delta T_n(f) = \frac{A}{f^\beta}, \quad \text{with} \quad A = \frac{C}{2\sqrt{N_s}}, \quad \text{where} \quad N_s \text{ is the number of amplification stages and} \quad C \text{ is a normalization factor.}
\]

Gain fluctuations, although small, when combined with broad band amplifiers reduce the maximum sensitivity achievable by a total power radiometer, according to (Kraus, 1986)

\[
dT = T_{sys} \left[ \frac{1}{\Delta V_{eff} \tau_{int}} + \left( \frac{\Delta G}{G} \right)^2 \right] , \quad \text{where} \quad \tau_{int} \text{ is the integration time and} \quad \Delta V_{eff} \text{ is the bandwidth, and this can not be avoided by increasing integration time. The knee frequency} \quad f_K \text{ is defined as the frequency at which the ideal white noise equals the non-white noise fluctuations. Producing spurious correlations in the maps, that appear in the form of 'stripes', whose amplitude depends on the frequency} \quad f_K . \text{ This effect can be limited either in the design, making} \quad f_K \text{ much smaller than the typical scanning frequency for PLANCK (0.016 Hz) or in the post-detection phase by applying specific algorithms to time ordered data (TODs).}^{17,18}

2.1. The radiometer scheme

The whole LFI radiometric chain can be ideally divided in two sections, depending on the amplification stage temperature: the front end, held at 20K by the sorption cooler and the back end, living at 300K (see Fig. 1). The sky signal \( x(t) \), through the Orto Mode Transducer (OMT), is separated into two linear polarizations, then coupled to a reference load signal \( y(t) \) (one for each polarization) by a first hybrid and amplified by low noise HEMT amplifiers; one of the signals runs through a switch that applies a phase delay, modulated at a frequency of 4096 Hz. The phase-switcher introduces a \( \pi \) phase difference between the two signals to compensate fluctuations in the diodes. Also the second radiometer arm contains a phase switch, but its presence is exclusively due to symmetry (in fact it introduces a \( 0^\circ \) phase difference). The two signals are then recombined by a second hybrid coupler, leading to an output which is a sequence of signals alternating at twice the phase switch frequency. The function of the second hybrid is to separate the signals again, in order to have two output signals proportional to the incoming ones; they are again amplified, filtered by a low-pass filter, detected by a diode, integrated, digitized and acquired. This pseudocorrelation receivers design implies several benefits:

i) The radiometer is nearly (at the first order) insensitive to small imbalance in gain and phase.

ii) The sensitivity is independent, at least within a range of a few Kelvin in the temperature difference, from the reference load temperature.

iii) Minimization of amplifiers and detectors 1/f noise.

LFI is composed by 11 Radiometer Chain Assemblies (RCAs). Each RCA comprises a Feedhorn, an OMT, the Front End Module (FEM) of the radiometer, two 4K Reference Loads coupled with two Reference Horns, four composite waveguides (approximately two meters long) and the Back End Module (BEM) (Fig. 1, Fig. 2).

The average output power \( p \), exiting the radiometer, can be written as:

\[
\bar{p} = a k T G \left[ T_s + T_n - r (T_y + T_n) \right]
\]

\( T_s \), \( T_r \), and \( T_n \) are respectively the sky noise temperature, the reference noise temperature, and the radiometer noise temperature. The \( r \) factor in (1), named ‘gain modulation factor’, is analytically inserted to balance the temperature differences between the two branches of the radiometer.

\[
r = \frac{T_s + T_n}{T_y + T_n}
\]
2.2. Radiometer systematic errors

The global contribution from all systematic effects in a pixel at the end of mission must be lower than 3µK, as specified in the scientific requirements of LFI\textsuperscript{14}. Systematic errors typically arise from two sources: astrophysical sources (external straylight), and instrumental sources (internal straylight and intrinsic effects).

Astrophysical non-CMB signals (radiation coming from celestial objects such as Sun, Moon, Earth, Planets, and diffuse radiation emitted by the galaxy) could enter the radiometers through the feed horn or through the reference horn–load gap. These signals are intrinsically spin-synchronous and can be avoided only limiting the incoming spillover radiation.
by design optimisation. The most straylight contribute, in terms of contamination produced on maps, is due to Galaxy15; other contributes, coming also from non-point celestial sources can be considered as negligible (< 0.1 µK)16. Instrumental error sources are directly tied to the radiometers or to thermal fluctuations in the environment surrounding the instrument. These effects will be discussed together with the modeling in the next chapter.

3. MODELLING THE PLANCK – LFI RCAs

Many systematic effects could affect the LFI radiometers performances. Only a small part of them can be removed from data. Also this operation needs a perfect knowledge of the instrument; others need to be taken into account in the design by implementing proper modelling tools. Here, a summary of the radio frequency and thermal modelling is presented, showing the importance of accurate models both in design and in the instrument characterisation. Three main areas have been identified. They are the modellisation (i) of the imperfect components of the radiometer, (ii) of the imperfect reference horn – reference load coupling, and (iii) of thermal fluctuation in PLANCK whole spacecraft. For each of them, different techniques have been used in the modelling and are described here.

3.1. The PLANCK-LFI RCA Advanced Simulator

The full RCA radio-frequency characterisation (RCA Advanced Simulation) allows to characterise, element by element, the RCA behaviour in all the three LFI channels. Output voltage, noise temperature and scattering parameters have been tested for each part separately and cascaded, performing successively functional and performance tests. These tests permitted moreover to make a qualitative estimation of the gain G in equation (1). The expected performances will be compared with experimental on ground tests when they will be available from calibrations. This simulation considers the Reference Load as a perfect resistance held at a specific fixed temperature. However, this is not precise: the 4K Reference Load could be an important source of systematics, both due to its thermal instability and to the internal and external straylight fluctuations in the radiometric signal.

3.1.1. Advanced Design System

To perform the PLANCK LFI radiometer system simulation the Communication System Designer (CSD®19) software has been used. CSD contains an RF simulator able to predict performance of complete RF systems and including a set of block–level RF models for linear and non–linear components. It includes: a Design Environment (allowing components to be inserted along with their parameters ready to connections by lines or transmission line connectors), a Data Display, and a RF System Simulator, which allows high accuracy linear and non-linear simulations of complete RF systems.

3.1.2. RCA model architecture

Each subsystem unit of the radiometric chain has been modelled using CSD. In its original design the RCA input sky and 4K reference load signals have been modelled using a port component (a resistance of 50 Ohm at a physical temperature T producing a thermal noise). Feedhorns (Fig. 3), reference load horns, LNAs (Low noise amplifiers), phase switches, and the diodes where modelled as two-port devices. To create the hybrid model in the Front End Module, a general four - port scattering – parameters has been used. This is basically an equation – based system, where scattering parameters are defined by a polar coordinate system, so that it is possible to correctly reproduce the in-phase and anti-phase addition of the inputs.

That of waveguides assembly is a complex model because of the different materials and temperatures (to reduce the heat load on the 20K stage, the waveguides are different materials made and have three thermal break stages at approximately 140, 80, 50 K). At first level two main blocks representing the copper section and the stainless steel and gold plated one, with their own parameters, can be detected. In order to take into account the temperature distribution along the waveguide length, the stainless steel section has been broken into smaller subsections. A linear behaviour for the temperature was assumed and intermediate insertion losses were interpolated using a set of measured resistivity values for given temperatures in the range 70K to 300K.
The band pass filter in the Back End Module has been modelled with a Chebyshev response band pass filter, while the detector is a two - port system characterised by a return loss value. The power conversion and the integration over the band are performed by an appropriate calculation envelope.

Basic functional tests have been performed at this stage, i.e. a calibration test of the system and a switching test. They both were successful. Similarly for the evaluation of the system noise temperature and system gain, showing then an important auto – consistency of the model and a good agreement with theory.

Fig. 3(left) The first level of the feedhorn schematic, with the parameters of interest for the component model; (right) Second level of the feedhorn schematic

3.1.3. In-band characterization of the LFI software model

Providing the components of the radiometer chain assembly model with their in band measured behaviour, a more and more complex system can be studied and the global performances of the LFI radiometers can be evaluated and forecasted. The model has been improved so that it is possible to load external data files by a DAC (Data Access Component). By setting the parameter of the component of interest to point to the DAC, the data in the specified file can be accessed. In this way, an in-band description of the LFI software model was provided: each parameter, from the passive components insertion loss and return loss to the LNAs noise Fig. and gain, was set pointing to the corresponding DAC parameter, so that its value, e.g. dependent on frequency, is read from the external file. A typical simulation result is displayed in Fig. 4

Fig. 4 Simulated RCA in-band total gain relevant to different LNA configurations, as from measured in-band performances (noise temperature and gain) of each LNA.

3.1.4. Application to non-idealities and systematic effects

Non-idealities and systematic effects, which degrade the radiometer performances, have been added to the model to verify the RCA response. Asymmetries - in terms of signal losses of the various radiometer components (feed, OMT, phase switches, hybrids) between the two OMT legs cause the RCA unbalancing; this behaviour is strictly tied to Front
End physical temperature fluctuations, producing a signal fluctuation in the radiometer response. All these effects have been taken into account and investigated. Hereafter some simulation results are presented: Fig. 5 shows the total gain difference due losses and reflections between the two RCA legs, referring to the Elegant BreadBoard model (EBB) and to the Qualification Model (QM).

Fig. 6 analyses the radiometers response to thermal fluctuations in the LFI Front End: differences between the three channels depend on the different instruments’ position, on their mass, on the thermal link and on various other physical parameters. The period considered is 667s, that is the sorption cooler typical one. The result is a radiometric signal fluctuations decreasing with increasing frequency.

Furthermore, the LFI software model will be used as a support tool during the incoming integration and calibration phases of the PLANCK-LFI qualification models. In particular, it will be able to independently reproduce the main test results during the RCA testing phase, in order to analyse and forecast eventual RCA unexpected behaviours.

Fig. 5 30 GHz OMT insertion loss and return loss combined effect on the system total gain for both LFI radiometer legs, in presence of the OMT EBB prototype (left) and the qualification model of the OMT (right).

Fig. 6 Fluctuations of the 30, 44 and 70 GHz radiometer output signal due to the physical temperature fluctuations at the LFI Front End (blue line). Output signal fluctuations decrease as passing from the 30 GHz radiometer chain assembly to the 70 GHz one.

3.2. 4KRL straylight evaluation with the Finite Elements Method

A Finite Elements Method modelling has been implemented to investigate some non ideal aspects concerning the 4K Reference Load. In particular, specific application to the straylight analysis is shown here.

Straylight contamination in the 4K Reference Load (4KRL), i.e. the radiation coming from sources external to the system reference load (RL) – reference horn (RH), can degrade significantly the RCAs performances. Moreover, spin-synchronous fluctuations of the temperature of the reference load have to be carefully evaluated since they impact drastically on the radiometer performances since they can mimic a true sky signal. Other fluctuations, on larger time scales, although can be removed with success by using destriping algorithms, have to be characterised, to understand if these methods can get the desired results.
A simplified model – fully representative of the whole system – was implemented, based on a Finite Elements Method (employing HFSS® software). This model allowed to characterise the spillover power of the 4KRL, when it is mounted on the PLANCK Payload. This study is based on previous works characterising the single 4KRL units and is their extension to a more general case.

### 3.2.1. Overview

The total radiation ($P_{wg}$) received by the waveguide connected to the Reference horn can be described as:

$$ P_{wg} = (P_{\text{noise}} + P_{\text{load}}) \times (1 - R_H) + P_{\text{inst}} $$

where $P_{\text{noise}}$ is the noise power coming from the astrophysical external (dipole, point and extended sources) and internal (payload emission, instrumental emission inside the cavity between the HFI cryostat and the LFI 20K main frame) sources, $P_{\text{load}}$ is the power emitted by the RL (hold at about 4K), $P_{\text{inst}}$ mainly formed of two components: (i) Power emitted by the instruments (Radiometers) in the horn direction and received by the horn after a reflection on the RL; (ii) power emitted from the horn (at a known temperature) because of its non-ideal reflectivity: the radiation is back reflected from the target toward the horn–radiometers direction. ($R_H$): is a measure of the mismatching between the horn’s mouth and the surrounding.

We focus here on the term $P_{\text{noise}}$, composed of the two straylight terms representing the internal (SPO) and external (SPO$_{\text{EXT}}$) to the payload contributes.

$$ P_{\text{noise}} = T_{\text{INT}} \cdot \text{SPO} + (T_{\text{EXT}} \cdot \text{SPO}_{\text{EXT}} + T_{\text{PAYLOAD}} \cdot \text{SPO}_{\text{PAYLOAD}}) $$

A two ports system was modelled, following the schema in Fig. 7: the PORT2 is located on the reference horn waveguide; the PORT1 belongs to a waveguide located on the top of the cavity, injecting a unitary power inside the cavity itself.

![Fig. 7 Power contributes incoming the 4K Reference load.](image)

The radiation spreads over the entire structure but only a small part of it reaches the RLSy and is peaked up by the reference horn (PORT2). We evaluate the S12 component (i.e. radiation emitted by PORT1 and detected by PORT2).

$$ \text{SPO}_{\text{EXT}} = S_{12} $$

It is possible to relate the external spillover ($\text{SPO}_{\text{EXT}}$) to the quantity defined internal spillover ($\text{SPO}_{\text{INT}}$), term that identifies the radiation reaching the RH through the gap RH-RL from the very near environment surrounding it (supposed as a box enclosing the 4K RL). The external spillover component is expected to be sensibly lower than the internal one, because of the radiation absorbance by non perfect conductors and of the radiation spreading (Fig. 8) inside the cavity.

It is so possible to define a Transfer Function $\mathcal{Z}_{\text{SPO}}$ relating the external spillover power to the internal one, in order to make safe the unitary of the SPO definition:
\[ SPO_{\text{out}} = SPO_{\text{in}} \cdot \mathcal{F}_{\text{SPO}} \]

Comparison with results reported in [12], giving the 
\((S_{12\text{ out}})_{70\text{GHz}}\), allows to evaluate the attenuation factor \(\mathcal{F}_{\text{SPO}}\) (averaged over the full band 63GHz-77GHz):

\[ \mathcal{F}_{\text{SPO}} = 10 \left( \frac{S_{12\text{ in}} - S_{12\text{ out}}}{10} \right) = 0.00022 \]

Fig. 8 3D E-total field distribution (in a grey tone logarithmic scale) inside the 20K-4K environments cavity; E values. The LFI 20K shield is not displayed to allow the view inside the cavity. Left panel displays the radiation coming from PORT1 (waveguide on top) surrounding the 4KRL at 70GHz. In the right panel a detail of the power coming from PORT1 propagating inside the Reference Load an picked up by the waveguide (PORT2) is shown; an entire 4K reference Load system (Reference Load plus Reference Horn is displayed).

It is worth noting that, given the differential nature of the RCAs, it does not represent a concern having a reference temperature higher than 4K, but it does its stability. Hence, design optimisation must minimise the possibility of fluctuating contributes, especially those that we are not able to control with a good precision.

The term \(T_{\text{dipole+source+payload}}^{\text{EXT}}\) can take very different values depending on the emitting source. Anyway, the only important terms are those relative to diffuse sources and to the external payload temperature fluctuations (the latter could vary with the observation strategy, depending for example on the satellite exposure to the solar radiation); in fact, point or compact sources are seen under a solid angle too small to be appreciable.

Each contribute \(i\), fluctuating with time, whatever its nature is, can be described as a sum:

\[ T_i(t) = T_i(0) + \delta T_i(t) \]

To a difference \(\delta T_i(t)\) in the emitting source (external or internal) corresponds a fluctuation in the radiometer signal:

\[ \delta T_{\text{S}}(t) = \left[ \delta T_i(t)_{\text{EXT}} + \delta T_i(t)_{\text{EXT}} \cdot \mathcal{F}_{\text{SPO}} \right] \cdot SPO_{\text{IN}} \]

Most important contributes are summarized in Tab. 3

| Fluctuations in thermodynamic temperature\(^{12}\) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \(\delta T_{\text{payload}}\)\(^{\text{EXT}}\) | \(\delta T_{\text{dipole}}\) | \(\delta T_{\text{sources}}\) | \(\delta T_{\text{Galaxy}}\) | \(\mathcal{F}_{\text{SPO}}\) |
| <1 \(\mu\)K | 3mK | Neg. | <10mK | 1.6 mK | 0.03 |

<table>
<thead>
<tr>
<th>Expected fluctuations in radiometer signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;1E-06 \mu)K</td>
</tr>
</tbody>
</table>

Tab. 3 Expected fluctuations in the radiometer signal caused by thermodynamic fluctuations in the straylight sources
Modellisation tells us that whichever internal temperature fluctuation, coupling radiatively with the RH-RL gap, is damped at least by a factor of $10^2$ while external temperature fluctuations are damped by a factor $10^6$. This result contributes to make safe the requirement\textsuperscript{11} that spin synchronous fluctuations of the reference load temperature must be less than 1$\mu$K.

3.3. Thermal analysis

The high sensitivities of PLANCK instruments are reached also thanks to a dedicated cryogenic chain, ensuring the low temperatures needed for both bolometers and radiometers optimal performances. In particular, for the Low Frequency Instrument, two low temperature stages are important. The hydrogen sorption cooler 1 keeps the front end unit at 20 K, while the helium JT cooler cold end at 4 K 1 is connected to the HFI outer stage, where LFI reference load are mounted. Many radiometric features are connected to the physical temperature: HEMT amplifiers gain and noise temperature, 4K load emissivity are the most strictly tied. The accurate control of temperature fluctuations, due to the cooler instability, is needed to avoid unwanted spurious fluctuations in the signal. A set of analysis was then performed to characterize thermal fluctuations sources and, by means of dedicated thermal models, the propagation of such fluctuations through the instrument to sensitive radiometer devices. This allowed to single out critical issues and provide valuable solutions, in order to have a small final impact on LFI measurements.

The 20 K sorption cooler\textsuperscript{9,10} provides a 1W nominal cooling power to the LFI front end unit where feed horns, OMTs and first stage of amplification are located. It also works as a pre-cooling stage for the 4 K cooler, affecting its low frequency stability.

Starting from the cooler data, a transfer function of temperature fluctuation is evaluated by means of instruments’ thermal model results. Furthermore, as preliminary investigated with the CSD analysis and shown in , the physical temperature fluctuation is translated into antenna temperature fluctuation evaluating a radiometric transfer function: the detector power output (see also (1) is expressed as:

$$p = p(k_j, \omega_j, \nu)$$

where $\nu$ is the frequency, $k_j$ are temperature independent parameters and $\omega_j$ are temperature dependent parameters (emissivity, amplifier gain, etc.).

Any physical temperature variation causes a variation of a corresponding parameter and then of the sky temperature through the power measured according to:

$$(9) \quad \frac{\partial p}{\partial T_{\text{sky}}} \Delta T_{\text{sky}} = \frac{\partial p}{\partial T_j} \Delta T_j \quad \text{where:} \quad \frac{\partial p}{\partial T_j} = \frac{\partial \omega_j}{\partial T_j},$$

where

$$\frac{\partial \omega_j}{\partial T_j}.$$ Propagating the temperature fluctuations deriving from coolers, through the thermo-mechanical and radiometric transfer functions in the frequency domain, to detector output, we are able to evaluate impact of this systematic effect upon final maps. Our first analysis revealed a too high level of fluctuations upon CMB maps, so that a further study has led to some solutions to reduce fluctuations in the two relevant stages: an active temperature control was implemented at the interface between the cooler cold end and the LFI, while the addition of passive thermal decouplers between the 4 K HFI shield and the LFI reference load is effective in damping target fluctuations.

3.3.1. Front end fluctuations

The core of the sorption cooler is a set of six compressor beds. They chemically absorb and desorb hydrogen gas depending on their temperature, which is regulated by means of electrical heaters. Hydrogen gas is pumped out of a heated compressor bed to the pipes then it undergoes to expansion through a JT valve so that it can condense in dedicated liquid reservoirs, and then it is reabsorbed by the cooling compressor bed to start the cycle again. The six beds work out of phase so that a quite continuous and homogeneous gas flow is provided. Single bed cycle has a period of 667 s, while full cooler cycle takes 4000 s. All these time scales were chosen to keep residual fluctuations, due to cooler non-ideal behaviour, uncorrelated with PLANCK spin synchronous period of 60 s. An optimised temperature control was simulated, with the SINDA/FLUINT software PID algorithm, testing the feasibility of such an additional device taking into account some project boundary conditions: limited additional mass (about 1 Kg) and power (about 100 mW) available for the PID stage, a limited thermal decoupling between PID stage and cold end in order not to rise LFI temperature above 22.5 K, which provide the maximum allowed power load upon the HFI instrument.
Successful results of this analysis led to the implementation of the temperature control. We report results in the spectra of the cooler cold end, with and without control, in Fig. 9.

![Figure 9](image)

**Fig. 9** Comparison between without PID control sorption cooler-LFI interface fluctuation spectrum (higher curve) and optimised setup (PID controlled) spectrum (lower curve).

It is evident how the controlled cold end is highly damped at the main coolers frequencies, while no relevant high frequency spurious effect appeared. This solution allows to keep the final peak to peak effect upon the maps, after a destriping algorithm is applied, below 1 $\mu$K$^6$.

### 3.3.2. 4 K Reference Load fluctuations

The precooling stage for the 4 K JT cooler is provided by the 18 K sorption cooler first stage, so that also 4 K stage temperature is affected by sorption cooler temperature fluctuations. We studied the additional damping provided by adding thermal washer between 4 K reference load mounting structure and HFI shield. We show results of our analysis (Fig. 10), in terms of a comparison between old interface damping and new set up. This solution led to a final impact of the systematic thermal effect to the desired $\mu$K level$^{13}$.

![Figure 10](image)

**Fig. 10** Comparison between old (dashed) and new (solid), with thermal washers, transfer functions between HFI shield interface and 4 K target at 30 GHz, 44 GHz, and 70 GHz (frequencies are shown in the labels).

### 4. CONCLUSIONS

The PLANCK-LFI radioneters are devices designed to perform high sensitivity measurements: this task can be achieved only with an extremely accurate control (at few $\mu$K level) of systematic effects. Some of them can be removed from the data by using dedicated algorithms, other confuse with the true sky signal so that it becomes mandatory to avoid them by instrument design. Detailed modelling tools are necessary to design and characterise the instrument, to...
verify requirements and to separate spurious from true signals. Three steps concerning the LFI RCAs optimisation and characterisation have been presented. Starting from the RF description of single passive and active elements by a circuital model (CSD), the radiometer response to non ideal behaviours was described; systematic effects, especially regarding the 4KRL, were analysed in detail by using a Finite Elements Method approach, allowing to estimate the internal and external straylight. A thermal analysis, taking into account the effect on radiometric signal of temperature fluctuations due to instabilities in the reference temperature sources, has been presented: dedicated models for implementing an opportune temperature active control (PID) and for designing the best thermal damping strategy are described.

Results from all analyses produced a detailed understanding of LFI radiometers and allowed to provide significant performance improvements, fitting with the challenging mission goals which will be checked in the incoming ground test campaign.

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