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Thermal stability in precision cosmology experiments: the Planck LFI case

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Abstract

After the great success of NASA's satellite missions COBE and WMAP, the Planck mission represents the third generation of mm-wave instruments designed for space observations of CMB anisotropies. Two instruments, the Low-Frequency Instrument (LFI) and the High-Frequency Instrument (HFI) will produce CMB maps with unprecedented angular resolution, sensitivity and frequency coverage. This ambitious task will be achieved by using low noise HEMT detectors cryogenically cooled at ~20 K for the LFI and bolometric detectors cooled at 0.1 K for the HFI; in particular, the LFI is based on pseudo-correlation receivers in which the sky signal is continuously compared to a cryogenic reference load in thermal contact with the HFI 4 K stage. Such high sensitivity in Planck detectors calls for a strict control of systematic effects, which must be kept at μK level in the final maps; this in turn imposes tight requirements on the thermal and electrical stability of the different stages in the instrument. In this paper we discuss a study of the impact of thermal fluctuations at the level of the 20 K cooler cold-end on the Planck-LFI measurements and present some viable solutions that have been adopted to keep the residual systematic error within the required values for Planck-LFI.

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1. Introduction

The ESA satellite Planck [1] will measure the full-sky CMB anisotropy with unprecedented angular resolution and sensitivity thanks to the combination of ultra-low noise cryogenic detectors and a high performance optical design. Scanning the sky at almost great circles at the rate of 1 rpm it will perform two full sky surveys in about one year of observations, allowing the reconstruction of the CMB angular power spectrum up to $l \sim 1500$ with an accuracy of few percent, and a consequent very precise determination of the cosmological properties of our Universe.

Such high performances call for a strict control of astrophysical and instrumental systematic effects, that must be kept at the level of few μK

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per pixel in the final maps. One of the most important sources of systematic effects is represented by temperature fluctuations, which couple with the measured signal showing up as spurious anisotropy structures in the final CMB maps.

A very stable temperature environment is guaranteed by the Planck orbit around the Lagrangian L2 point, which allows to maintain the detectors in the focal plane always in a constant shadow with respect to the Sun and the Earth.

The other sources of temperature instabilities are represented by the on-board cryo-coolers that are necessary to provide the cold stages to the radiometric receivers in the Low-Frequency Instrument (LFI) and the bolometric detectors in the High Frequency Instrument (HFI).

In this paper we present an analysis of the effect of temperature fluctuations at the cold end of the 20 K Hydrogen Sorption Cooler on the maps produced by the LFI instrument. In particular we will discuss how such fluctuations couple with the detected signal and show how the combination of hardware design and data analysis allow to maintain the residual systematic contamination at sub-μK levels.

2. Propagation of temperature fluctuations in the Planck-LFI instrument

The LFI instrument consists of an array of 11 pseudo-correlation differential radio receivers [2] at 30, 44 and 70 GHz, in which the sky signal, approximately at 2.7 K, is continuously compared to a reference load at ~4 K. Each receiver consists of a corrugated feed-horn and an orthomode transducer connected to cryogenic front-end module in which the sky and reference signals are correlated and amplified by means of low noise HEMT amplifiers. Further RF amplification is provided by a warm (300 K) back-end stage connected to the front-end by waveguides.

Thermal stability of both the front-end temperature and of the reference signal are key to avoid undesirable systematic effects in the final results. The analysis of thermal effects on the Planck-LFI measurements involves different steps to link the temperature stability properties of the on-board cryo-coolers to the systematic error in the final maps and power spectra. Here we concentrate on temperature oscillations at the cold-end of the 20 K Sorption Cooler that affect the stability of the front-end physical temperature and of the reference 4 K signal.

The Sorption Cooler [3,4] is a vibration-free cooler exploiting the absorbing/desorbing capacity of certain hydrides alloys to pressurize and circulate hydrogen gas. The expansion through a JT valve produces a 20 K sink with a cooling capacity of more than 1 W.

The cold end temperature is strongly coupled to the compressor pressure of absorption: low-pressure oscillations induce temperature fluctuations in the liquid H_2 at the cold end of about 400 mK peak to peak. The typical time signature of these instabilities is therefore related to the compressor elements switch time (667 s) and the cooler full cycle (4000 s), as shown in the top panel spectrum of Fig. 1. Particularly dangerous are the fluctuations with a period synchronous to the satellite spin (60 s): the amplitude of the fluctuation at this frequency is about 1 mK.

Temperature fluctuations at the sorption cooler cold end propagate through the mechanical structure of the instrument. The 20 kg aluminum LFI main frame is effective in damping high-frequency components, in particular spin-synchronous fluctuations are reduced by a factor 300. This thermal low-pass filter behaviour has been eval-

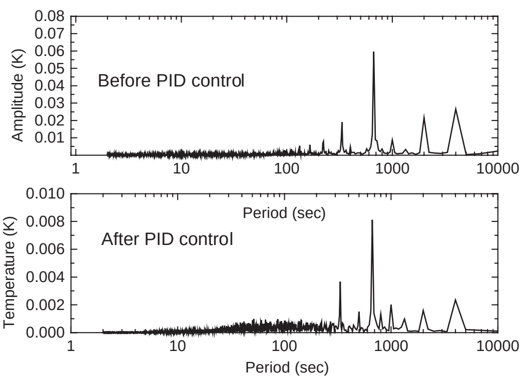

Fig. 1. Spectrum of temperature fluctuations of the LFI cold end without (top) and with an active control (bottom).

uated by means of thermal models of the instrument subsystems.

Fluctuations in the front-end and 4 K load physical temperature can be "translated" into antenna temperature fluctuations at the radiometer output using an analytical radiometer model, as shown in detail in Ref. [5]. The oscillation of the radiometric output in time domain is then projected onto a sky map where the peak-to-peak systematic error can be evaluated, also considering the application of algorithms to detect and partially remove these effect from the data. In the analysis presented here we have applied a "destriping" algorithm that was developed to reduce the effect of amplifier $1/f$ noise and that proved effective also in the case of low-frequency periodic systematic effects [6,7].

3. Results and conclusions

Preliminary results of this analysis showed an unacceptable level of residual contamination on the final maps, so that an active stabilization, operating at frequencies below 1 Hz, was implemented at the cooler/instrument interface. Preliminary results of the temperature active control are shown in the bottom panel spectrum of Fig. 1: the cooler low frequency dominant peaks are significantly reduced (about a factor of 10).

The values in Table 1 show the improvement in the peak-to-peak effect on the maps following the implementation of a PID active temperature controller.

Finally, we show in Fig. 2 an estimate of the effect in the power spectrum, compared with CMB signal.

A similar analysis on the fluctuations of 4 K reference load temperature induced by the sorption cooler is in progress. Preliminary results suggest a comparable low level of the effect.

Acknowledgements

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Table 1
Estimates of p–p systematic effect on LFI maps caused by thermal fluctuations at the level of the 20 K front end of the LFI radiometers. We compare values, before and after temperature active control and destriping on data

Frequency (GHz)	Destriping	30	44	70
ΔT (μK) - No PID	No	88.8	85.4	98.5
	Yes	5.68	5.95	6.91
ΔT (μK) - PID	No	11.1	10.4	14.6
	Yes	0.65	0.65	1

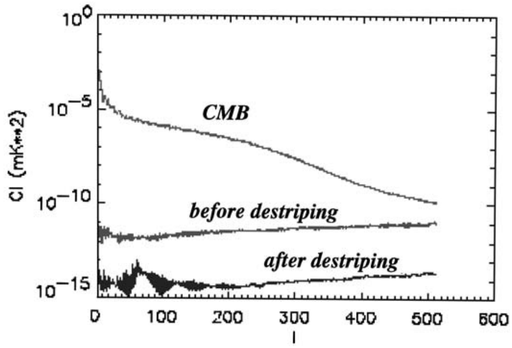

Fig. 2. Estimates of front end temperature fluctuations effect power spectrum compared with a typical CMB power spectrum.

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