Reconstruction and Removal of Thermal Effects in Planck/LFI Scientific Data Streams Using Telemetry Information

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Abstract

The ESA CMB Planck mission will require an accurate control and removal of instrumental systematics below a level of few μK . Although instruments and spacecraft are designed to be intrinsically very stable, the extremely tight requirements concerning signal stability call for the development of software strategies to remove the residual spurious effects during data analysis. A particularly important class of systematic effects is represented by low-frequency periodic fluctuations that can be removed using properly designed ‘Blind’ filters applied to the scientific data streams. However, telemetry information monitoring the instrument status may improve the effectiveness of removal procedures. A good example is given by thermal instabilities of the 20 K stage of the PLANCK cooling chain. A successful, yet simple approach to remove such fluctuations has been developed; the method combines thermal housekeeping data with scientific data to reconstruct the transfer functions connecting the 20 K stage temperature fluctuations with the perturbations detected by each radiometer. The work has been carried out using temperature measurements of the prototype of the Planck 20K Sorption Cooler combined with a thermal model of the LFI instrument and a software specifically developed to simulate long term-variations which are not available from the Cooler experimental data. This code (named GLISSANDO) is also discussed at the end of this paper.

1. INTRODUCTION

The ESA PLANCK satellite¹, scheduled for launch in 2007, is a full-sky surveyor dedicated to CMB and (sub)mm astronomy and represents a third generation mission after COBE and WMAP. Planck is equipped with a 1.5 m Gregorian aplanatic telescope, carrying in the focal surface two instruments covering the frequency bands 30, 44, and 70 GHz (Low Frequency Instrument, LFI) and 100, 143, 217, 353, 545, and 857 GHz (High Frequency Instrument, HFI). The survey will be carried out from a small Lissajous orbit around the Sun-Earth Lagrangian point L2 of the Sun-Earth system from which it will observe the microwave sky for at least 14 months. The LFI beams are located in a ring with a radius of about 4° on the PLANCK telescope field of view around the telescope line of sight (LOS). In the baseline scanning strategy the LOS points at a scan angle $\alpha = 85^\circ$ from the satellite spin axis which is always parallel to the antisolar direction during the mission. The sky is scanned at the frequency of 1 rpm and the LOS is repointed every hour by $\Delta\theta_s \sim 2.5'$ (1° per day) in order to follow the revolution of L2. This scanning strategy implies that each circle in the sky is scanned consecutively 60 times per hour to increase data redundancy and to reduce white noise (e.g. by successively averaging data through a *coadding* procedure). In the baseline mission time of 14 months PLANCK will produce at least two full sky maps for each frequency channel with an unprecedented resolution (FWHM from $\simeq 33'$ to $\simeq 5'$) and sensitivity (in the range of $\simeq 10 - 40$ mJy on a FWHM² resolution element).

The high sensitivity of PLANCK detectors calls for the highest level of systematic error control, which will be achieved by combining in-hardware stability and specifically developed data analysis tools.

“Blind” filters are often used to remove periodic signals and drifts when the frequency of the effect is much lower than the spin frequency; however, housekeeping data from the on-board thermal and electrical sensors may significantly improve the ability to detect and remove these unwanted effects, provided that the relationship (“transfer function”) linking the sensor data to the effect in the detector output is known or reconstructed.

An example is represented by the effect of thermal fluctuations of the 20 K stage provided by the Sorption Cooler, which cools the LFI detectors and pre-cools the Helium in the HFI 4K Stirling cooler.

¹See the presentation of F. Pasian in these proceedings and <http://astro.estec.esa.nl/Planck/>.

FIGURE 1: The left panel represents the reconstruction of the modulus of the original transfer function for a 30 GHz feed-horn (full line) using a single data chunk of 40000 sec (red dots), or averaging over a year of data split in equal-size chunks (black dots). The right panel represents a simulated ΔT_{sc} from the transfer function reconstructed (red full line), compared with the input signal (blue dots). Since differences are small, to allow a better comparison the input is shifted of +0.5 mK and the worst case (broken PID) is considered.

Given the design of the Sorption Cooler system, the fluctuations at the level of the cooler cold end are expected to be mainly periodic, with main harmonics at 1/4000 Hz and 1/667 Hz, with a peak-to-peak amplitude of the order of ~ 100 mK. This fluctuation propagates through the structure of the LFI instrument (which behaves like a low-pass filter) and couples with the radiometric output causing a periodic spurious signal with a peak-to-peak amplitude of the order of ~ 1 mK.

A set of 12 temperature sensors will be located over the focal plane to monitor the temperature level and stability during the mission. Five of these sensors, in particular, will have the necessary sensitivity to allow detection of temperature variations at the level of few mK. The housekeeping data provided by these sensors will be used during data analysis to improve the detection and removal of thermal effects from the measured data streams.

For such an analysis, however, it is necessary to estimate the transfer functions linking the temperature fluctuation at the level of the detectors with the measured systematic effect.

In this work we present an approach based on Fourier transforms to reconstruct such transfer functions combining the temperature sensor data the scientific data streams.

This activity includes the generation of realistic simulations of the fluctuations induced by the cooler, considering also its degradation in time.

2. THE PLANCK SORPTION COOLER

The Planck satellite is characterised by a very complex cryogenic chain with thermal stages ranging from 300 K to 0.1 K. This chain is driven by the H_2 Sorption Cooler, a closed-cycle cryo-cooler designed to provide 1.2 Watt of heat lift at a temperature of ~ 18 K using isenthalpic expansion of hydrogen through a Joule-Thompson (JT) valve. 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. The engine of the Planck Sorption Cooler is the compressor system, based on the intrinsic property of a metal hydride alloy to absorb large quantities of low-pressure hydrogen and to desorb it at high pressure when heated in a limited volume. The compressor system, with no moving parts, is made of six elements, each containing the sorbent material which is periodically cycled between heating and cooling phases: their cycle phases are staggered in order to produce a continuous stream of liquid refrigerant. In such a system, there is a basic clock time period over which each step of the process is conducted: since each phase lasts 667 seconds, the cooler total cycle time is ~ 4000 s.

In order to control the temperature stability of the 20 K cold end, an active temperature control system has been designed, based on a PID (Proportional-Integrative-Derivative) loop controlling a resistance and a temperature sensor placed at the interface between the 20 K cooler cold end and the instrument. With this system the residual instability of the physical temperature is less than 100 mK peak-to-peak, which causes a quasi-periodic spurious signal in the differential² radiometric output with a peak-to-peak amplitude of the order of 1 mK.

Long term variations are also expected because of ageing effects of the Sorption Cooler compressor system, which will alter the shape of the systematic effect during the mission. The transfer function that links the physical temperature variation at the cooler cold-end to the detected systematic effect in the radiometric output is denoted by $R_{\text{sky-load}}$ and is the result of the low-pass filtering provided by the thermal conductivity and thermal capacity of the instrument structure and the radiometric response to physical temperature variations of its components.

3. REMOVAL TECHNIQUES OF THERMAL EFFECTS CAUSE BY THE SORPTION COOLER

In Planck the main signal periodicity is at frequencies ~ 17 mHz while the main peaks of the thermal effects induced by the Sorption Cooler are at frequencies which are about 10 times smaller. Therefore it is possible, in principle, to remove these effects from the time-ordered-data (TOD) using a “blind” high pass filter with a properly tuned knee frequency and shape.

Because of the considerable amount of data present in a full-mission TOD for any Planck detector, it is unfeasible to apply a filter to all the TOD at once; on the contrary it is necessary to cut the data streams in pieces long enough to maintain the periodicity of the systematic effect but also short enough not to filter out the astrophysical signal at large angular scales. A limitation of this process is that the filtering creates spurious offsets from circle to circle that need to be re-balanced after filtering using destriping algorithms, which may nevertheless leave unwanted spurious effects, especially at large angular scales.

A second approach is to use the housekeeping data provided by the available thermal sensors in the focal plane to estimate the spurious thermal effect in the instrument output and then subtract it from the TOD. In other words if we denote with $\widehat{\Delta T}_{\text{sc}}$ the estimated effect in the receiver differential output caused by a temperature fluctuation ΔT_{sc} at the cooler cold end, then we can estimate the “cleaned” data stream as: $\widehat{\Delta T}_{\text{sky-load}} \approx \Delta T_{\text{out}} - \widehat{\Delta T}_{\text{sc}}$, where ΔT_{out} represents the receiver output containing the sought signal plus the systematic effect.

In order to calculate $\widehat{\Delta T}_{\text{sc}}$ using the temperature housekeeping information (which is sampled at 1 Hz) it is necessary to estimate (for each detector) the transfer function $R_{\text{sky-load}}$ such that $\widehat{\Delta T}_{\text{sc}} = R_{\text{sky-load}} \tilde{T}_{\text{scce}}$ where the symbol $\tilde{\cdot}$ indicates the Fourier Transform. Although approximations of these transfer functions are available from the instrument thermal and radiometric models, their exact shape is not known since they are sensitive to unpredictable details as the strength of couplings between mechanical components. A simple estimator $\hat{R}_{\text{sky-load}}$ of $R_{\text{sky-load}}$ is $\hat{R}_{\text{sky-load}} = \widehat{\Delta T}_{\text{out}} / \tilde{T}_{\text{scce}}$ which, however, is biased since $\hat{R}_{\text{sky-load}} - R_{\text{sky-load}} = \Delta T_{\text{sky-load}} / \tilde{T}_{\text{scce}} + \tilde{n} / \tilde{T}_{\text{scce}}$. Figure 1 compares the damping factor for a simulated transfer function with its estimate for a 40000 sec data chunk. From the figure is apparent that although the transfer function is quite well reconstructed at the cooler frequencies, there is a large distortion induced by the sky signal at 1/60 Hz, and a high frequency rise due to the white noise component.

To reduce the effect of this bias it is possible to take advantage from the periodical nature of the sky signal over 12 - 14 months, due to simple symmetries in the scanning strategy. In our example we have cut the radiometric TOD, ΔT_{out} and the temperature fluctuation, T_{scce} in time intervals short enough to avoid important variations in the sky signal, but long enough to encompass more T_{scce} cycles (in our example we take slices of ≈ 40000 sec). Then we have labelled them with an index $s = 0, 1, 2, \dots, N_{\text{slices}} = 1 \text{ year} / 40000 \text{ sec}$, and compared the bias for the $\hat{R}_{\text{sky-load},s}$

²The LFI radiometers measure the difference between the sky signal and a reference load at ~ 4 K provided by the HFI 4 K stage

calculated for each slice. In this case it is possible to demonstrate that at each frequency the bias $\Delta T_{\text{sky-load}_s} / \bar{T}_{\text{scce}_s}$ is the sum of a periodical term plus noise so that its average over the year has null expectation (the demonstration may be easily obtained analytically for the case of the cosmological dipole) (Maris et al. [2]). Then the averaging over the year of the values of $\hat{R}_{\text{sky-load}_s}$ will result in an estimator with a null bias (Maris et al. [2]) which may be used to build $\widehat{\Delta T}_{\text{sc}}$ for any slice. An example of the application of this method is given in Figure 1 for the modulus of the transfer function. Similar results (not shown) are obtained for the phase.

4. RESULTS

Simulated signals for sky + noise + sorption cooler have been generated for some of the radiometric channels of Planck/LFI and for a full one-year mission. A realistic thermal model has been used to generate realistic transfer functions used for the simulation. Thermal fluctuations at the cold end are provided by laboratory measures of a Sorption Cooler prototype. Simulated data have been processed according to the discussed procedure. Combining data over one year it is possible to reconstruct the transfer function allowing removal of 6 mK peak-to-peak fluctuations (i.e. those expected with a broken PID) down to a peak-to-peak 20 μ K level without further filtering. Residuals are equivalent to an additive, normal distributed, white noise. With an r.m.s. $\approx 4 \mu$ K, to be compared with the ≈ 1.5 mK instrument sensitivity of the considered radiometer. Coadding observed rings in the sky will reduce this residual down to μ K level. Filtering of the reconstructed transfer function as parameterization may improve this result since currently, not being parameterized, the resulting transfer function has as many degrees of freedom as Fourier modes. Quantitative assessment on maps as on correlation between radiometers is in progress.

5. FUTURE IMPROVEMENTS

An important issue is the effect of long term variations induced by the ageing of the sorption cooler units over time scales of 6 $\div$ 12 months. Since long-term measures on prototypes do not exist, a dedicated package, GLISSANDO (Maris, Terenzi [3]), has been developed to model the effect of ageing and to generate one year long data streams useful to test and train diagnostic methods under different hypothesis for ageing. GLISSANDO assumes that phases of the cooling units are fixed in time, being locked to the invariable cooling cycle, so that only amplitudes of the Fourier modes vary in time over time scales much longer than the typical duty cycle of the cooler. Time series from models of the nominal cooler and of the degraded cooler are used as templates to instruct a morphing procedure (analogous to computer graphics morphing) applied to the spectrum of the real data coming from laboratory prototypes. The morphing procedure morphs continuously the spectrum as a function of time. Morphing is done at a preselected rate and following a given morphing path in the configuration space connecting the starting state with the expected final state. It has to be noted that GLISSANDO is not designed as a predictive tool but rather as a training tool. Its output is just a reasonable representation of what is expected from a time degrading cooler. Slight departures from the hypothesis of periodicity shall be taken in account, since the horns do not follow exactly great circles in the sky so that sky signals are not always exactly periodical. Methods to study the time variability of single Fourier modes without assuming their periodicity may be developed as well. Other sources of degradation of the performances of this method which shall be quantitatively assessed are the cross-correlation with 1/f noise and the relative removal methods and the small noises in the thermometers and possible time dependencies in the transfer functions.

Possible improvements comes from the fact that the current baseline allows to download data from LFI sky and load separately for each radiometric channel, allowing a more accurate reconstruction of the transfer functions at least on the reference load side of each radiometric chain. The method will surely gain in accuracy by integrating a thermal model of the instrument which will allow the fusion of information from ground tests (QM and FM campaign), with measures taken from all of the high accuracy thermometers spread over the focal plane as a full parameterization of the transfer functions. This will increase the amount of data and decrease the number of degrees of freedom, allowing a better rejection of noise perturbations and leading to the possibility of

removal without having to wait a full year in order to characterize the instrument. The use of more sophisticated numerical tools than Fourier Transforms, as wavelets, neural networks, genetic algorithms and so on is being investigated. The integration of the code in the final data reduction pipeline for PLANCK/LFI (Pasian [6]) is in progress.

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