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

M. Maris[1], A. Mennella[2], L. Terenzi[3], D. Maino[4], G. Morgante[2], M. Prina[5], F. Pasian[1], M. Bersanelli[4]

[1] INAF - Osservatorio Astronomico di Trieste, Via G.B.Tiepolo 11, I-34131, Trieste, Italy
[2] INAF- IASF, Milano section, Via Bassini, 15, I20133, Milano, Italy
[3] IASF - Bologna, Via Gobetti 101, I40129, Bologna, Italy
[4] Dip. Fisica Univ. di Milano, Via G.Celoria 16, I20133, Milano, Italy
[5] JPL, CalTech, 4800 Oak Grove Drive, Pasadena, California, 91109-8099, USA

Abstract. The ESA CMB Planck mission will require an accurate control and removal of instrumental systematics below a level of few μK. Telemetry information monitoring the instrument status may improve the effectiveness of procedures for the removal of systematic effects in the time domain. A good example is given by thermal instabilities of the 20 K stage of the Planck cooling chain. A successful, yet simple approach, based on the use of telemetry information has been developed and is presented here.

Key words. 1 (cosmology:) diffuse radiation 2 (cosmology:) cosmic microwave background 3 space vehicles: instruments

1. Introduction

The ESA Planck satellite [1], 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 - A more complete account on Planck and the LFI is given by C. Burigana in these proceedings, it is sufficient here to recall that LFI is a multichannel differential radiometer, designed to provide differences of antenna temperatures (ΔT) between the region of sky observed and an internal reference thermal load held at a stable temperature of 4 K.

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. Housekeeping data from the on-board thermal and electrical sensors may significantly improve the abil-

Send offprint requests to: M. Maris
⋆ Email to: maris@ts.astro.it
Correspondence to: via G.B. Tiepolo 11, I34131 - Trieste - Italy - e-mail: maris@ts.astro.it

[1] http://astro.estec.esa.nl/Planck/.

ity of software removal of these unwanted effects. For the LFI 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 as part of the telescope focal plane (Bowman Jr. et al. , 2003; Mennella et al. , 2002, 2003). An active control of its thermal output is provided by a PID (Proportional-Integrative-Derivative) loop integrated in the hardware, nevertheless, a fluctuation with a peak-to-peak amplitude of the order of $\sim$ 100 mK at the level of the cooler cold-end still persist. Due to the design of the Sorption Cooler system such fluctuations are nearly periodical, with principal harmonics at 1/4000 Hz and 1/667 Hz, The cooler is interfaced to the Planck Focal Plane through a cold-end, from which fluctuations 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 $\sim$ 1 mK.

A set of five high sensitivity temperature sensors will be located over the focal plane monitoring temperature fluctuations. To use this information to improve the removal of thermal fluctuations, however, it is necessary to estimate the transfer functions linking the fluctuation at the level of the detectors with the measured effect at the cold-end and/or in the focal plane. 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. Removal techniques of thermal effects cause by the Sorption Cooler

In Planck the main signal periodicity is at frequencies $\sim$ 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 $\widehat{\Delta T}_{\rm sc}$ the estimated effect in the receiver differential output caused by a temperature fluctuation $\Delta T_{\rm sc}$ at the cooler cold end, then we can estimate the "cleaned" data stream as: $\widehat{\Delta T}_{\rm sky-load} \approx \Delta T_{\rm out} - \widehat{\Delta T}_{\rm sc}$. where $\Delta T_{\rm out}$ represents the receiver output containing the sought signal plus the systematic effect.

In order to calculate $\widehat{\Delta T}_{\rm sc}$ using the temperature housekeeping information (which is sampled at 1 Hz) it is necessary to estimate (for each detector) the transfer function $R_{\rm sky-load}$ such that $\widetilde{\widehat{\Delta T}}_{\rm sc} = R_{\rm sky-load}\tilde{T}_{\rm scce}$ where the symbol $\tilde{}$ 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 $\widehat{R}_{\rm sky-load}$ of $R_{\rm sky-load}$ is $\widehat{R}_{\rm sky-load} = \widetilde{\Delta T}_{\rm out}/\tilde{T}_{\rm scce}$ which, however, is biased since $\widehat{R}_{\rm sky-load} - R_{\rm sky-load} = \Delta T_{\rm sky-load}/\tilde{T}_{\rm scce} + \tilde{n}/\tilde{T}_{\rm scce}$. Figure 1 compares the damping factor for a simulated transfer function with its estimate for a 40000 sec data chunk. From the figure it is apparent that although the transfer function is quite well reconstructed at the cooler frequen-

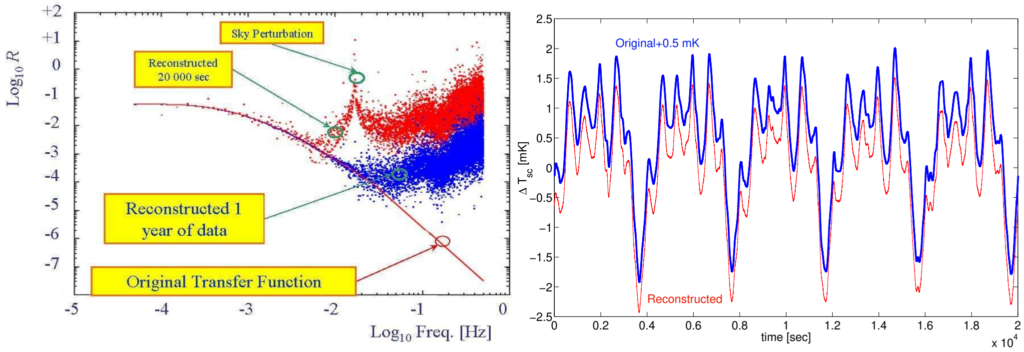

Fig. 1. The left panel represents the reconstruction of the modulus of the original transfer function for a 30 GHz feed-horn (full line) using a single data chunk of 40000 sec (red dots), or averaging over a year of data split in equal-size chunks (black dots). The right panel represents a simulated $\Delta T_{\rm sc}$ 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.

cies, 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 remove the 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, $\Delta T_{\rm out}$ and the temperature fluctuation, $T_{\rm scce}$ in time intervals short enough to avoid important variations in the sky signal, but long enough to encompass more $T_{\rm scce}$ cycles (in our example we take slices of $\approx$ 40000 sec). Then we have labeled them with an index $s = 0, 1, 2, \ldots$, $N_{\rm slices} = 1$ year/40000 sec, and compared the bias for the $\widehat{R}_{{\rm sky-load},s}$ calculated for each slice. In this case it is possible to demonstrate that at each frequency the bias $\Delta T_{{\rm sky-load}_s}/\tilde{T}_{{\rm scce}s}$ 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 & Mennellla , 2002). Then the averaging over the year of the values of $\widehat{R}_{{\rm sky-load},s}$ will result in an estimator with a null bias (Maris & Mennellla , 2002) which may be used to build $\widehat{\Delta T}_{\rm sc}$ 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.

3. 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 μK 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 $\approx$ 1.5 mK instrument sensitivity of the considered radiometer. Coadding repeated observed rings in the sky will reduce this residual down to μK 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.

4. 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 , 2003), 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. In GLISSANDO 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 path as the morphing rate are selected according to the ageing hypothesis of choice. A more detailed account on GLISSANDO (as on the Sorption Cooler) is reported in Maris et al. (2003).

Degradation of performance due to slight departures from the hypothesis of periodicity, cross-correlation with 1/f noise and the relative removal methods, small noises in the thermometers and possible time dependencies in the transfer functions have to be quantitatively assessed.

The method will surely gain in accuracy from the separate analysis of sky and load data streams in place of ΔT. From the integration of a thermal model allowing the fusion of information from ground tests with measures taken from all of the high accuracy thermometers and full parameterization of the transfer functions. From the use of more sophisticated methods than Fourier Transforms. The integration of the code in the final data reduction pipeline for PLANCK/LFI is in progress (Pasian , 2003).

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