Removing $1/f$ noise stripes in cosmic microwave background anisotropy observations

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Removal of systematic effects is crucial in present and future CMB experiments mapping large fraction of the sky. Accurate CMB measurements ask for multi-feed array instruments observing the sky with a redundant scanning strategy covering the same sky region on different time scales and with different detectors for a better control of systematic effects. We investigate the capability to suppress $1/f$ noise features in Time Ordered Data (TOD) by using the destriping technique described in Maino 1999, under realistic assumptions for crossing condition between different scan circles and sky signal fluctuations on small angular scales. We perform, as a working case, Planck-LFI simulated observations with few arcminutes pixel size convolved with LFI beam resolutions. In the noiseless case for crossing condition based on pixels with side larger than the input one, the destriping algorithm inserts extra-noise in the final map of the order of $\sim \mu K_{\text{rms}}$ and few $\mu K$ in peak-to-peak amplitude at 30 GHz. However including instrumental noise (white and $1/f$ noise) in the TOD, the impact of the sky signal on the destriping is found to be very small. In addition, for crossing condition based on pixels with side half of the one of the final map (typically $\sim 1/3$ of the FWHM), we find only a small improvement ($\sim 1\%$ level) in the destriping quality with respect to the case when crossings are searched on pixels with same size of the final map one. We can conclude that the receiver noise is the driver for destriping quality. We extend the analysis to high values of the knee frequency and find that, although significantly suppressed by destriping, the residual additional noise $\text{rms}$ is $\sim 31\%$ larger than the pure white noise $\text{rms}$ at $f_k = 1$ Hz which could be a critical issue in the extraction of CMB angular power spectrum. We verified that the approximation of the $1/f$ noise on averaged scan circles as a single baseline still works well even for these high values of the knee frequency. Furthermore, by comparing simulations with different noise levels and different sampling rates, we find that the destriping quality does not significantly depend on the receiver sensitivity whereas it improves proportionally to the improvement of sampling rate. Therefore given a noise level, the higher the sampling rate, the better the destriping quality. This paper is based upon Planck-LFI activities. methods: data analysis; cosmology: cosmic microwave background

Introduction

In recent years a substantial improvement in measurements of Cosmic Microwave Background (CMB) radiation has taken place leading to several CMB anisotropy detections which support the gravitational instability scenario for structures formation (Smoot 1992, Górski 1996) and a universe with $\Omega_0 \sim 1$ (Miller 1999, De Bernardis 2000, Balbi 2000, Pryke 2001). A more complete analysis of current data implies multi-dimensional fits to jointly constrain several cosmological parameters (e.g. Lineweaver 1998, Tegmark & Zaldarriaga 2000). These estimations relay always on the accuracy by which foreground emissions and experimental systematic effects are known and properly accounted for. One of the major problems in present and future CMB anisotropy experiments, are all those possible systematic effects which affect the experiments in several ways.

In this respect a space mission is the optimum being free from the unwanted contamination from ground and Earth atmosphere emission. The Microwave Anisotropy Probe (MAP, http://map.gsfc.nasa.gov/) satellite (Bennett 1996) by NASA has begun its mission aimed at all-sky imaging of the last scattering surface of CMB photons, at several frequencies and with high angular resolution. In 2007 the Planck...
satellite http://astro.estec.esa.nl/SA-general/Projects/Planck/Mandolesi 1998, Puget 1998) by ESA, will probe the very early phase of the Universe with even higher spectral coverage, sensitivity and angular resolution. Both satellites will operate around the $L_2$ Lagrangian point of the Sun-Earth system. This will allow a considerable rejection of the Sun, Earth and Moon radiation (see, e.g., Burigana 2000), and the adopted redundant scanning strategy observing the same sky region several times on different time scales and by different detectors, allows a high control of systematic effects. In particular, Planck is a third generation of CMB mission, covering the widest frequency range ($\nu \sim 30 - 900$ GHz) ever probed, necessary for a high accuracy subtraction of foreground contamination, and reaching a sensitivity per $0.3^\circ$ pixel size of few $\mu$K at each frequency channel $\nu 400$ GHz. Therefore an accurate monitoring and removal of systematic effects is crucial to reach the planned scientific objectives.

In the context of the Planck-LFI (Low Frequency Instrument) a detailed study of the major sources of systematic effects has been carried out. Burigana (1998) and Mandolesi (2000a) considered the impact of main beam distortions on CMB observations. Maino (1999) took into account the problem of the so-called $1/f$ noise due to gain fluctuations in HEMT amplifiers in Planck-LFI receivers. A detailed study of the Galactic straylight contamination in LFI observations has been carried out by Burigana (2001), where the effects of optical distortions are compared with the $1/f$ noise contamination.

The $1/f$ noise typically leads to stripes in the final map (Janssen 1996) altering the statistical properties of the cosmic signal which is particularly relevant for CMB anisotropy. This effect can be parameterized by the knee-frequency $f_k$ (the frequency at which the white and $1/f$ noise power spectra are equal) which should be as small as possible with respect to the spin-frequency of the satellite (for Planck $f_s = 0.0167$ Hz corresponding to 1 r.p.m. spin velocity). It is therefore crucial to properly correct this effect both by hardware and software techniques. The LFI, pseudo-correlation receivers, are properly designed to reduce the $1/f$ noise (Bersanelli 1995). Delabrouille (1998) has implemented a technique for destriping Planck observations starting from the Time Ordered Data (hereafter TOD) and taking advantage of the redundancy of the Planck scanning strategy. Maino (1999) have considered a similar technique in the more specific context of Planck-LFI observations and using the current theoretical predictions on LFI receiver properties. The results show that the destriping quality is remarkably good, except for the degenerate case in which all the crossings between different scan circles are concentrated very close to the ecliptic poles.

Although destriping algorithms are sometimes considered approximations of proper map making algorithms (recently implemented for large data time ordered data by, e.g., Natoli 2001 and Dore 2001) they should be considered as methods to remove drifts in the TOD’s and returning TODs cleaned from many classes of systematic effects (see, e.g., Mennella 2001 for an analysis of periodic fluctuations). This is more suitable for many data analysis purposes directly on TODs such as monitoring of variable and transient sources (Terenzi 2001). In the following analysis we make use of maps obtained by co-adding the TOD’s cleaned by destriping codes: this way of proceed is one of the possible methods to quantify the quality of the destriping algorithms.

A key issue of destriping techniques is the operative definition of crossing between two different scan circles, since these techniques are based on the condition that the observed temperatures in the sky have to be the same for identical sky directions, although the samplings are taken along different scan circles at different times. Of course one can be more or less restrictive on the definition of the crossing condition: a more restrictive definition therefore may reduce the number of crossing possibly affecting the destriping quality while a less one may insert an extra-noise due to the different sky signals in the two not exactly coincident sampling directions.

Another issue is the validity of the $1/f$ noise drift approximation in terms of a constant baseline (offset) for each averaged scan circle (or significant fraction of it), which in general holds as long as $f_k$ is not far larger than $f_s$. Of course, the values of $f_k$ appropriate to LFI receivers will be probed in future real hardware analysis. It is therefore interesting to assess the maximum values of $f_k$ for which the destriping algorithm still works well removing $1/f$ noise stripes at a level which does not compromise the determination of CMB angular power spectrum.

In this paper we want to address these issues, evaluate the impact of different crossing conditions for different models of the microwave sky, including instrumental noise. Furthermore we push the knee-
frequency to extremely high, and hopefully unrealistic, values (~ 1 Hz) to evaluate the destriping quality also for pessimistic cases.

We want to stress the fact that, although applied for the specific case of the Planck mission, these arguments are relevant to almost any CMB anisotropy observations. In typical CMB experiments, the scanning strategy implies repeated observations of the same sky regions on different time scales such as, , BEAST (Seiffert 1996), COSMOSOMAS (Watson 1997). Note that the actual implementation of our destriping algorithm is completely independent of the details of the scanning strategy and of the pixelisation scheme. Our first implementation (Burigana 1997b) worked in fact with the QUAD-CUBE scheme and the subsequent applications (Maino 1999) with the HEALPix scheme (Górski 1998) did not imply any modification at all.

This paper is organized as follows. We briefly describe the Planck scanning strategy and the generation of the TOD’s in Sect. scanning. The basic recipes of our destriping technique and the discussion of the crossing conditions are presented in Sect. destri. We report our simulation results in Sect. simul, where we assess the impact of the choice of crossing condition and intrinsic sky fluctuations on destriping quality. We dedicate Sect. knee to the evaluation of the impact of possible high values of the knee-frequency on the destriping quality. We discuss there also the dependence of the destriping efficiency on the instrumental parameters (sensitivity and sampling rate) at different frequencies and introduce the functional form for noise power spectrum after destriping. Finally, we discuss our results and draw our conclusions in Sect. conclu.

Planck observations scanning

Scanning strategy

The orbit selected for Planck satellite will be a tight Lissajous orbit around the L$_2$ Lagrangian point of the Sun-Earth system (Mandolesi 1998, Puget 1998). The spacecraft spins at ~ 1 r.p.m. ($f_s$ ~ 0.0167 Hz) and, in the simplest scanning strategy, the spin axis is essentially kept on the antisolar direction at constant solar aspect angle by a re-pointing of 2.5′ every hour. This simple scanning strategy provides also a smooth and quite uniform sky coverage which covers 99% of the full sky. The LFI and HFI (High Frequency Instrument) share the focal plane of an Aplanatic telescope (see, e.g., Mandolesi 2000b for a discussion on the advantages of this configuration) of 1.5 meter size which field of view is at an angle $\alpha = 85°$ from the spin-axis. Therefore Planck will trace large circles in the sky. In the nominal 14 mission months ~ 10200 spin-axis positions will be exploited covering twice nearly the whole sky, some regions of which will be covered three times. The actual sampling frequency (the frequency at which the sky signal is sampled along a given scan circle) adopted for LFI is about 3 samplings per FWHM resulting in a different number of samplings at the four LFI frequencies.

The details of the scanning strategy are not yet frozen and it may or not include a precession of the spacecraft spin axis about another axis kept along the antisolar direction re-pointed of 2.5′ every hour.

From TOD to sky maps

We have implemented a code (“Flight Simulator”, Burigana 1997b, 1998 and Maino 1999) simulating the Planck scanning strategy and observations and applied to the study of some systematic effects. The relevant geometrical inputs of the code are the angle $\alpha$ between pointing and spin axis, beam position on the focal plane as well as beam response function. Other inputs are parameters describing the noise properties of the receivers.

We adopt here the nominal Planck scanning strategy, with 14 months of mission and re-pointing of the spin-axis every hour by 2.5′ assuming 3 samplings per FWHM, and refer in this section to the case of simulations at 30 GHz where the nominal resolution (FWHM) is 33′. The generation of instrumental noise is performed directly in Fourier space and FFT transformed back in real space (see Maino 1999 for details).

We use the HEALPix pixelisation scheme (Górski 1998), which is the adopted baseline for Planck products. The output of our Flight Simulator code are 4 matrices: $N$, with pointing pixel number at specified resolution (usually larger than the beam size for a proper sampling of beam resolution), $T$, with sky temperature plus full noise (white + $1/f$ noise), $W$, with sky signal plus white noise only and $G$, with sky signal only. Each matrix has $n_s$ rows equal to the number of spin axis positions ($n_s$ ~ 10200) and $n_p$ columns equal to the number of samplings, weakly dependent on $\alpha$, along a scan circle ($n_p$ ~ 1980 at 30 GHz). The matrices $W$ and $G$ are computed to evaluate respectively the degradation of $1/f$ with respect ideal white noise case and the impact of the scanning strategy geometry on the observed signal.
From these TOD we build sky maps: making use of $N$, possibly degraded at the desired resolution of the final map, and $T$ we simply coadd the temperatures of those pixels which are observed several times during the mission. In the same way we build maps with only white noise, from $W$, and, using $G$, without receiver noise.

Definition of the problem destri

As first pointed out by Janssen (1996) the effect of $1/f$ noise can be seen as one additive level (baseline or offset) different for each scan circle (or significant fraction of it). Since we work with scan circles averaged over 1-hour period, we strongly reduce drifts within the circle and we are left with the “mean” $1/f$ noise level for that observing period. Furthermore average is like a low-pass filter operation and, as long as the $f_k$ is not far larger than $f_s$, this leaves only the very low frequencies components of the $1/f$ noise. Therefore it is a good approximation to model the effect of $1/f$ noise on the averaged scan circles as a single baseline $A_i$. We want to recover these baselines in order to properly adjust the signal.

Destriping technique

The destriping technique considered here, developed by Burigana (1997b) and by Maino (1999), has been derived from the COBRAS/SAMBA Phase A study proposal (Bersanelli 1996) and from a re-analysis of Delabrouille (1998).

The first logical step of this method is the search of the crossings, i.e. to find the common pixels observed from different scan circles. This can be done at the desired resolution, not necessarily the same of the final map, if poorer than that at which the pixel stream is computed and stored. Let us indicate with $N_{il}$, $T_{il}$ and $E_{il}$ the pixel number, the observed signal and the “white” noise level for the pixel in the $i$th row (scan circle) and $j$th column (sampling along the circle) in matrices $N$, $T$ and $(W-G)$ respectively. Let also be $\pi$ the index that identifies a generic pair of observations of the same pixel: of course the index $\pi$ is related to two elements in the matrix $N$: $\pi \rightarrow (il, jm)$ where $i$ and $j$ are the indexes for two different scan circles and $l$ and $m$ the respective position of the observed pixel.

Following Maino (1999) baselines are recovered solving the linear system: equation 1

$$\sum_{\pi=1}^n [(A_i - A_j) - (T_{il} - T_{jm})] = 0$$