DESTRIPING OF POLARIZED DATA IN A CMB MISSION WITH A CIRCULAR SCANNING STRATEGY

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A major problem in Cosmic Microwave Background (CMB) anisotropy mapping, especially in a total-power mode, is the presence of low-frequency noise in the data streams. If unproperly processed, such low-frequency noise leads to striping in the maps. To deal with this problem, solutions have already been found for mapping the CMB temperature fluctuations but none have yet been proposed for the measurement of CMB polarization. Complications arise due to the scan-dependent orientation of the measured polarization. We present a method for building temperature and polarization maps with minimal striping effects in the case of a circular scanning strategy mission such as the PLANCK mission.

1 Introduction

Theoretical studies of the CMB have shown that the accurate measurement of the CMB anisotropy spectrum C_ℓ^T with future space missions such as PLANCK will allow for tests of cosmological scenarios and the determination of cosmological parameters with unprecedented accuracy. Nevertheless, some near degeneracies between sets of cosmological parameters yield very similar CMB temperature anisotropy spectra. The measurement of the CMB polarization and the computation of its power spectrum [1] may lift to some extent some of these degeneracies. It will also provide additional information on the reionization epoch and on the presence of tensor perturbations, and may also help in the identification and removal of polarized astrophysical foregrounds [2,3].

A successful measurement of the CMB polarization stands as an observational challenge; the expected polarization level is of the order of 10% of the level of temperature fluctuations ($\Delta T/T \simeq 10^{-5}$). Efforts have thus gone into developing techniques to reduce or eliminate spurious non-astronomical signals and instrumental noise which could otherwise easily wipe out real polarization signals. In a previous paper [4], we have shown how to configure the polarimeters in the focal plane in order to minimize the errors on the measurement of the Stokes parameters. Here, we address the problem of low frequency noise.

Low frequency noise in the data streams can arise due to a wide range of physical processes connected to the detection of radiation. $1/f$ noise in the electronics, gain instabilities, and temperature fluctuations of instrument parts radiatively coupled to the detectors, all produce low frequency drifts of the detector outputs.

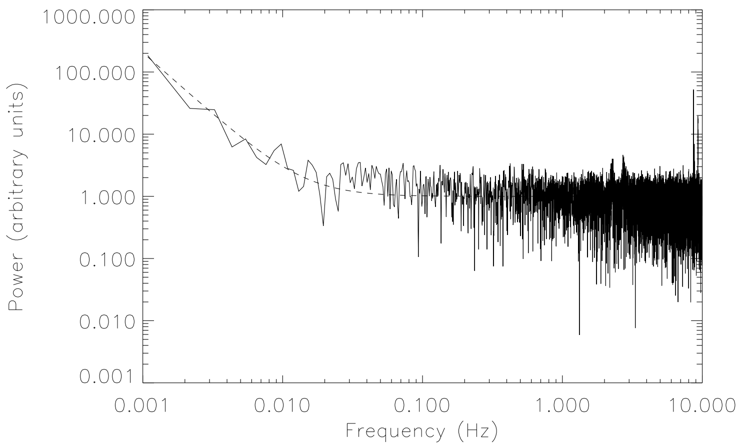

Figure 1: The power spectrum of the K34 bolometer from Caltech, the same type of bolometer planned to be used on the PLANCK mission. The measurement was performed at the SYMBOL test bench at I.A.S., Orsay (supplied by Michel Piat). The knee frequency of this spectrum is ~ 0.014 Hz and the planned spin frequency for PLANCK is 0.016 Hz. We can model the spectrum as the function $S(f) = 1 + \left(1.43 \times 10^{-2}/f\right)^2$ (dashed line).

The spectrum of the total noise can be modeled as a superposition of white noise and components behaving like $1/f^{\alpha}$ where $\alpha \geq 1$, as shown in Figure 1.

This noise generates stripes after reprojection on maps, whose exact form depends on the scanning strategy. If not properly subtracted, the effect of such stripes is to degrade considerably the sensitivity of an experiment. The elimination of this "striping" may be achieved using redundancies in the measurement, which are essentially of two types in the case of PLANCK:

- each individual detector's field of view scans the sky on large circles, each of which is covered consecutively many times (~ 60) at a rate of about $f_{\text{spin}} \sim 1$ rpm. This permits a filtering out of non scan-synchronous fluctuations in the circle constructed from averaging the consecutive scans.
- a survey of the whole sky (or a part of it) involves many such circles that intersect each other; the exact number of intersections depends on the scanning strategy but is of the order of 10^8 for the PLANCK mission: this will allow to constrain the noise at the intersection points.

One of us [5] has proposed to remove low frequency drifts for unpolarized data in the framework of the PLANCK mission by requiring that all measurements of a single point, from all the circles intersecting that point, share a common sky temperature signal. The problem is more complicated in the case of polarized measurements since the orientation of a polarimeter with respect to the sky depends on the scanning circle. Thus, a given polarimeter crossing a given point in the sky along two different circles will not measure the same signal.

2 Averaging noise to offsets on circles

As shown in Figure 1, the typical noise spectrum expected for the PLANCK High Frequency Instrument (HFI) features a drastic increase of noise power at low frequencies $f \leq 0.01$ Hz. We model this noise spectrum as:

$$S(f) = \sigma^2 \times \left(1 + \sum_i \left(\frac{f_i}{f}\right)^{\alpha_i}\right). \tag{1}$$

The knee frequency f_{knee} is defined as the frequency at which the power spectrum due to low frequency contributions equals that of the white noise. The noise behaves as pure white noise with variance σ^2 at high frequencies. The spectral index of each component of the low-frequency noise, α_i, is typically between 1 and 2, depending on the physical process generating the noise.

The Fourier spectrum of the noise on the circle obtained by combining N consecutive scans depends on the exact method used. The simplest method, setting the circle equal to the average of all its scans, efficiently filters out all frequencies save the harmonics of the spinning frequency. Since the noise power mainly resides at low frequencies (see Figure 1), the averaging transforms — to first order — low frequency drifts into constant offsets different for each circle and for each polarimeter. This is illustrated in the comparison between Figures 2(a) and 2(b). More sophisticated methods for recombining the data streams into circles can be used, as χ^2 minimization, Wiener filtering, or any map-making method projecting about 3×10^5 samples onto a circle of about 5×10^3 points. For simplicity, we will work in the following with the circles obtained by simple averaging of all its consecutive scans.

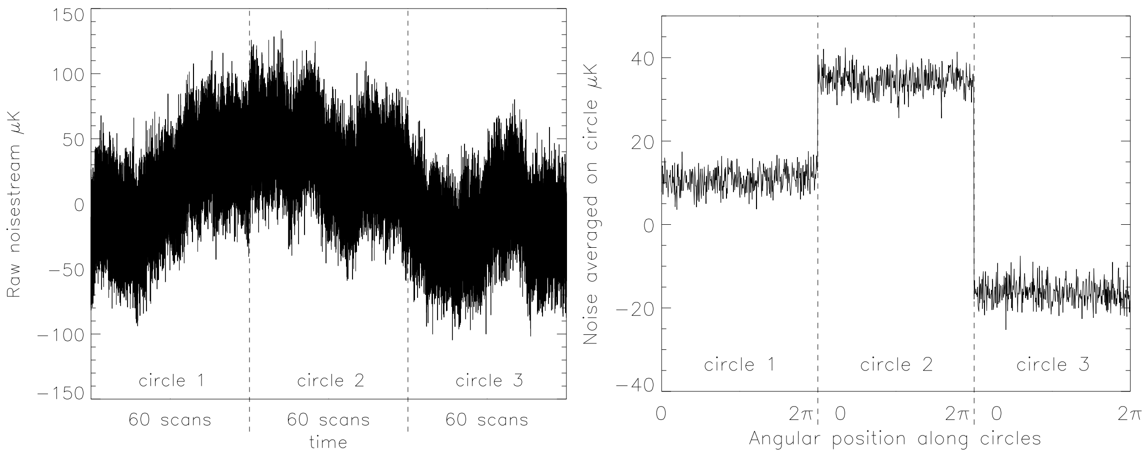

Figure 2: (a) Typical $1/f^2$ low frequency noise stream. Here, $f_{\mathrm{knee}} = f_{\mathrm{spin}} = 0.016$ Hz, $\alpha = 2$ and $\sigma = 21$ μK (see Eq. 1). This noise stream corresponds to 180 scans or 3 circles (60 scans per circle) or a duration of 3 hours. (b) The residual noise on the 3 circles after averaging. To first approximation, low frequency drifts are transformed into offsets, different for each circle and each polarimeter.

We thus model the effect of low frequency drifts as a constant offset for each polarimeter and each circle. This approximation is excellent for $f_{\mathrm{knee}} \le f_{\mathrm{spin}}$. The remaining white noise of the h polarimeters is described by one constant $h \times h$ matrix.

3 Destriping method and results

The destriping method consists in using redundancies at the intersections between circle pairs to estimate, for each circle i and each polarimeter p, the offsets O_i^p on polarimeter measurements. For each circle intersection, we require that all three Stokes parameters *in a fixed reference frame* in that direction of the sky, as measured on each of the intersecting circles, be the same. A χ^2 minimization leads to a linear system whose solution gives the offsets. By subtracting these offsets, we can recover the Stokes parameters corrected for low-frequency noise. For the mathematical details on the algorithm, see [6].

In order to test its efficiency, the destriping algorithm has been applied to raw data streams generated from simulated observations using various circular scanning strategies representative of a satellite mission as PLANCK, different "Optimized Configurations" [4], and various noise parameters. The resulting maps were then compared with input and untreated maps to test the quality of the destriping. The input temperature (I) maps are the sum of galaxy, dipole, and a randomly generated standard CDM anisotropy map (we used HEALPIX[a] and CMBfast[b]). Similarly, the polarization maps Q and U are the sum of the galaxy and CMB polarizations. To demonstrate visually the quality of the destriping, we produce projected sky maps with the input galaxy, dipole and CMB signal subtracted and we have computed the power spectra C_ℓ^T, C_ℓ^E, C_ℓ^B, C_ℓ^{TE} and C_ℓ^{TB} calculated from the I, Q and U maps [7], see Figures 3.

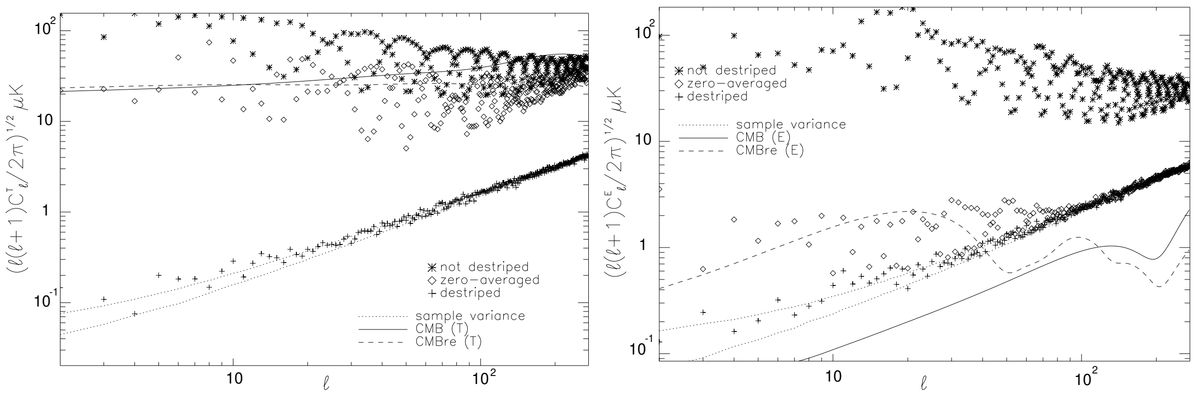

Figure 3: Efficiency of destriping for $f_{\rm knee}/f_{\rm spin} = 1$. (a) The sample variance associated to a pure white noise mission is plotted as the dotted lines. The "destriped spectrum" is very close to the white noise spectrum (within the limits due to the sample variance). The zero-averaged and the "not destriped" spectra are a couple of orders of magnitude above. The solid line represents a standard CDM temperature spectrum and the dashed line represents a CDM temperature spectrum with reionization. (b) Same as (a) but for the E polarization field.

Conclusion

This method permits to remove the effect of low-frequency drifts up to the white noise level provided that $f_{\rm knee}/f_{\rm spin} \leq 1$. The linear system is very small : $3n \times 3n$, where n is the number of circles and is of the order of 10^4 instead of 10^9 when dealing with the usual χ^2 involving all the samples.

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[a] `http://www.tac.dk/~healpix/`
[b] `http://www.sns.ias.edu/~matiasz/CMBFAST/cmbfast.html`