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Simulating Calibration and Beam Systematics for future CMB space mission with TOAST package

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ABSTRACT

We address in this work the instrumental systematic errors that can potentially affect the forthcoming and future Cosmic Microwave Background experiments aimed at observing its polarized emission. In particular, we focus on the systematics induced by the beam and calibration, which are considered the major sources of leakage from total intensity measurements to polarization. We simulated synthetic data sets with TOAST, a publicly available simulation and data analysis package. We also propose a mitigation technique aiming at reducing the leakage by means of a template fitting approach. This technique has shown promising results reducing the leakage by 2 orders of magnitude at the power spectrum level when applied to a realistic simulated data set of the LiteBIRD satellite mission.

Keywords: cosmology, cosmic microwave background, systematics uncertainties, simulations, surveys

INTRODUCTION

The Cosmic Microwave Background (CMB) emission provides one of the most favorite channels for probing the Universe at large scales. In particular, CMB forthcoming experiments are increasingly focusing on measuring the primordial CMB polarization B-mode (expected to peak at the degree scales (Seljak and Zaldarriaga 1997; Wayne and White 1997)) which is directly linked to a stochastic gravitational wave background emitted at the time of inflation(Guth 1981; Starobinsky 1982). The amplitude of the primordial B-modes is quantified by the tensor-to-scalar ratio, r. To date, the best constraints on r have recently been set to $r < 0.07$ by BICEP/Keck Collaboration et al. (2018); BICEP/Keck and SPTpol Collaborations et al. (2020).

A critical piece of this framework will necessarily be the ability of generating synthetic mission data sets of sufficient realism, both in their complexity and their size, to be truly representative of the data set that would be gathered by a given mission configuration. In this research note, we aim at showing preliminary results of simulations encoding systematic effects injected with the Time-Ordered Astrophysics Scalable Tools (TOAST) package, namely calibration errors, gain fluctuations and optical beam asymmetries.

CALIBRATION SYSTEMATICS

We consider two source of calibration systematics: calibration uncertainties and a long term fluctuation of the calibration gain (commonly referred as *gain drift*) due to thermal instabilities in the focal-plane. The former essentially quantifies the error affecting the calibration measurements performed between two consecutive observations, e.g. for the LiteBIRD satellite, (Sugai et al. 2020), we assume the calibration to happen every 24 hours. Calibration errors can be thus simulated by drawing Gaussian random values centered around 1 and with a width (hereafter assumed to be 1%).

We also simulate the instrumental thermal instability which can lead into changes of the gain calibration during one observation time scale, injected as a slowly varying drift with a $1/f$ frequency spectrum, typical for the CMB measurements. Moreover, the amplitude of the drift fluctuations can be directly linked to an effective temperature related to fluctuations in the focal-plane unit.

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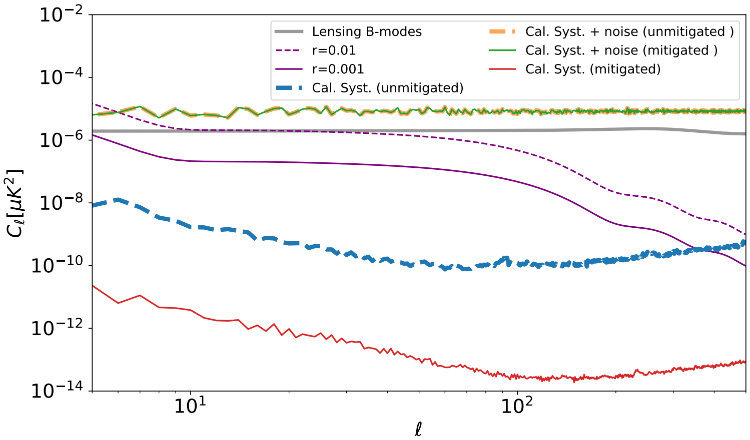

Figure 1. Angula power spectra of B-modes. Spectra obtained from the residual maps encoding noiseless simulations with (dashed thick blue) calibration systematics and (solid red) mitigated systematics with the template fitting procedure outlined in Section2.1. Spectra obtained with noisy simulations encoding no-mitigation and mitigation cases are shown respectively in (dashed thick orange) and (solid green). As a reference, we include the theoretical angular spectra for primordial $r = 0.01$ (dashed thin purple) and $r = 0.001$ (solid thin purple) and from the gravitational lensing B-modes (thick solid grey).

The gain drift signal is parametrized by the following power spectrum density:

$$PSD(f) = \delta_g \left(\frac{f_{knee}}{f} \right)^{\alpha},$$

with $\alpha = 1$, $f_{knee} = 20$ mHz, $\delta_g = 10 \mu$K.

Both calibration errors and gain drift are simulated independently for each detector and observation.

Template fitting mitigation

In order to mitigate the systematic residuals induced by calibration systematics described in the previous Section, we outline below a technique aimed at further reduce the leakage.

We assume that both calibration errors and gain drifts can be approximated as a linear combination of *Legendre polynomials* up to a certain order, $n_{poly} \lesssim 4$, within each observation:

$$g(t) = \sum_{i}^{n_{poly}} \hat{a}_i \mathcal{L}^{(i)}(t). \tag{1}$$

The template fitting mitigation proposed in this study consists in estimating the weights $\hat{a}$ that minimize a χ^2 problem provided we have an approximated estimate of the underlying signal via a *template map* (a similar approach can be found in (Planck Collaboration 2020; Keihänen et al. 2010)):

$$(F^t C_n^{-1} Z F) \hat{a} = F^t C_n^{-1} Z d, \tag{2}$$

with C_n being the noise covariance matrix, F the matrix built from the template signal, Z encodes the scanning strategy informations and d the time-ordered data acquired by the detector encoding astrophysical signal, noise and (eventually) systematics errors. The linear problem in eq.2 is solved iteratively by means of the Preconditioned Conjugate Gradient (PCG) algorithm.

Note that this mitigation relies on how much the template signal is a good approximation of the simulated one d. Furthermore, the more *redundant* the scanning strategy, i.e. the more a give line of sight is observed with different scanning orientation, the higher the signal-to-noise will be in determining the amplitudes $\hat{a}$.

LiteBIRD Calibration systematic simulations

We implement in TOAST the injection of calibration errors and gain drifts as well as the template fitting mitigation[1]. We then perform simulations for one LiteBIRD frequency channel, i.e. 48 polarization sensitive detectors 140 GHz observing for 1 year with the nominal observing strategy. We adopt the parameter values for calibration errors and gain drifts as reported in this note and inject both calibration systematics.

The simulated signal encodes: i) the CMB polarized anisotropies (including Solar dipole), ii) realistic polarized and unpolarized Galactic emissions at the sub-mm wavelengths. On the other hand, we built a template signal encoding only unpolarized Galactic emission and the dipole, to assess the quality of the mitigation in the presence of an incomplete template signal.

The output maps are estimated with `libmadam` map-maker (Keihänen et al. 2010). The residuals in Figure 1 are only due to the systematic errors pre- and post-mitigation, the other set includes also instrumental noise. We note that the template fitting procedure is able to reduce the leakage by two orders of magnitude at the angular power spectrum level indicating that even without a representative template map the LiteBIRD scanning strategy is optimized in such a way that we are able to estimate with good signal-to-noise ratio the gain amplitude. Moreover, as expected, this procedure is not affected by instrumental noise. In fact, we do not see any effect in the post-mitigation power spectra with noisy simulations.

CONCLUSIONS

We implemented into TOAST package several modules to inject systematic uncertainties due to beam and calibration. Although not mentioned in this work, TOAST can also simulate frequency bandpass mismatches, correlated noise and half-wave plate non-idealities, making it a promising simulation and data analysis framework for the forthcoming CMB experiments (both ground-based and space experiments). We propose a mitigation technique that aims at further reducing the leakage induced by gain drifts and calibration errors. The template fitting approach can be thus extended to other kind of systematics effects, e.g. bandpass mismatches, beam imperfections.

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[1] For further details see https://github.com/hpc4cmb/toast/tree/master/src/toast, DOI Zenodo 10.5281/zenodo.4270476

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