# Hunting the polarization of the Cosmic Microwave Background using component separation methods

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**Resumen** / La radiación de Fondo Cósmico de Microondas (FCM) es una herramienta muy útil para estudiar el Universo primigenio. La detección de los modos B primordiales de la polarización del FCM se considera la piedra fundamental para probar la inflación. La caracterización de la polarización del FCM es un reto debido a la presencia de contaminantes astrofísicos que emiten en el mismo rango de frecuencias, lo cual requiere de métodos de separación de componentes (MSC) para recuperar la señal primordial del FCM. Aquí, presentamos el método *Hybrid Internal combination with Template Fitting* (HIT FITTING) el cual es un nuevo enfoque de los métodos de combinación lineal. Un conjunto de simulaciones en multifrecuencias se usan para evaluar la eficiencia del HIT FITTING y también se compara con otros métodos bien conocidos tales como el de combinación lineal interna y el de ajuste interno por patrones.

**Abstract** / The Cosmic Microwave Background (CMB) is a powerful tool to study the primitive Universe. The detection of the primordial B-modes of CMB polarization is considered a milestone for proving inflation. The characterization of primordial CMB polarization is challenging due to the contribution of astrophysical foregrounds emitting in the same frequency range, and we require of component separation methods (CSM) to recover the primordial CMB signal. Here, we present the *Hybrid Internal combination with Template Fitting* (HIT FITTING) method which is a new approach of linear combination methods. Multifrequency sets of simulations are used to assess the performance of the HIT FITTING and compare with other well-known methods, the *Internal Linear Combination* and the *Internal Template Fitting.*

*Keywords* / cosmology: cosmic background radiation — diffuse radiation

## 1. Introduction

The Cosmic Microwave Background (CMB) has been a powerful tool to study the primitive Universe. The CMB anisotropies have produced groundbreaking results, providing us cosmological parameters with a high precision supporting what is now accepted as the standard model of Cosmology (the ΛCDM, Bennett et al., 2013; Planck Col. et al., 2018, and references therein). In addition, the information contained in the CMB polarization patterns opens the door to characterize the inflation epoch. The E-modes (curl-free component) due to fluctuations in density were detected by DASI (Leitch et al., 2005) and several experiments. The B-modes (curl component) induced by primordial gravitational waves remain undetected and it is expected to be around an order of magnitude lower than E-modes. The B-modes signal induced from the gravitational lensing, a CMB foreground, were recently detected by experiments like SPT, BICEP, Keck and Planck. The detection of primordial B-modes is an important milestone in Cosmology, because it would confirm the presence of gravitational waves in the primordial Universe generated in the inflationary epoch. Moreover, the B-modes amplitude would determine the energy scale of inflation.

In the last decade, several new experiments have been deployed to measure the B-mode power spectrum, consequently improving the current constraints on the inflationary B-mode signal. In this context, the BICEP2 experiment, combined with Planck data, produced the tightest constraints to inflationary B-mode power (BICEP2/Keck Col. et al., 2015), setting an upper limit on scalar-to-tensor ration of $r < 0.12$. These results also demonstrated that the foreground emission of the Galaxy is a dominant effect that limits the determination of the signal of interest. Therefore, a comprehensive characterization of the galactic and extragalactic foregrounds is essential to clean and recover the primordial B-mode signal out of the CMB observations.

Given the relevance of the foregrounds, the use of component separation methods (CSMs) to extract the CMB signal is fundamental. There is a wide range of CSMs that can be found in the literature and that exploit different approaches to the problem. The methods are diverse as whether they operate in angular, Fourier or wavelet space, or whether they recover only the CMB component (e.g. Internal Linear Combination, or ILC) or if they extract several components (e.g. the *spectral fitting* approach). For example, the Planck team used NILC (Needlets Internal Linear Combination), SMICA, SEVEM and COMMANDER methods Planck Col. et al. (2016). However, irrespective of the approach, the performance of all CSMs depends on the physical assumptions used to characterize the foregrounds. For this reason, the correct characterization of the Galactic polarized signal is a critical task in the quest to detect primordial B-modes.

Here we present a new approach called HIT FITTING, based on linear combination methods, to recover the polarized CMB and to study their impact in the characterization of the primordial B-modes.

## 2. Component Separation Methods

Methods based on a linear combination of maps are a simple, fast and practical methodology to recover the CMB signal. Therefore, we will consider methods focused on recovering only CMB signal and operating in the pixel space: the *Internal Linear Combination*, the *Internal Template Fitting* and the new approach HIT FITTING.

We consider that each frequency map, $T_i$, consists of the contribution of $c$ astrophysical components (with amplitude $A_c$ and frequency dependence $a_{c,i}$) and noise. In the description of each method, we assume maps are in thermodynamic temperature, i. e. the CMB spectrum is constant ($a_{CMB,i} = 1$).

### 2.1. Internal Linear Combination

In thermodynamic temperature, the Internal Linear Combination (ILC, Tegmark, 1998; Eriksen et al., 2004; Fernández-Cobos et al., 2016) recovers the CMB signal from a weighted linear combination of different frequency maps $T_i$:

$$\hat{T}_{\text{CMB,ILC}} = \sum_{i=1}^{n_\nu} \omega_i \; T_i \; , \text{ and } \sum_{i=1}^{n_\nu} \omega_i = 1 \tag{1}$$

where the coefficients $\omega_i$ are estimated by minimizing the variance of the resulting map and considering the condition that ensures an unbiased measurement of the studied component (the sum of weights must be one). Using the Lagrange multipliers we obtain:

$$\omega_i = \frac{\sum_{j=1}^{n_\nu} C_{ji}^{-1}}{\sum_{i,j=1}^{n_\nu} C_{ji}^{-1}} \tag{2}$$

where $C_{ij}$ is the covariance matrix of maps ($\langle T_i T_j\rangle - \langle T_i\rangle\langle T_j\rangle$), and $\langle\ldots\rangle$ identify the average over all pixels. The ILC only requires maps at the same resolution.

### 2.2. Internal Template Fitting

The Internal Template Fitting (ITF, Fernández-Cobos et al., 2012, 2016) computes an estimator of the CMB signal ($\hat{T}_{\text{CMB,ITF}}$) from a map ($T_{\nu_c}$) which is foregrounds cleaned using a lineal combination of templates ($\mathcal{T}_k$, without CMB component information):

$$\hat{T}_{\text{CMB,ITF}} = T_{\nu_c} - \sum_{k=1}^{n\alpha} \alpha_k \; \mathcal{T}_k \tag{3}$$

where $\alpha_k$ are weights. These coefficients are estimated minimizing the variance of the $\hat{T}_{\text{CMB,ITF}}$ map and assuming the same $\alpha_k$ for all pixel, which provides us:

$$\alpha = \mathbf{C}^{-1}\mathbf{b}, \tag{4}$$

Table 1: Simulations: frequency [GHz], Full Width at Half Maximum [arcmin] and sensitivity [$\mu$K-arcmin].

| Freq | 21 | 29 | 40 | 95 | 150 | 220 | 270 |
|---|---|---|---|---|---|---|---|
| FWHM | 120 | 91 | 66 | 28 | 18 | 12 | 10 |
| Sensitivity | 6.4 | 4.6 | 2.9 | 1.6 | 1.8 | 5.7 | 8.2 |

where $\mathbf{C}$ and $\mathbf{b}$ are the covariance matrix of templates ($\langle\mathcal{T}_k\mathcal{T}_j\rangle - \langle\mathcal{T}_k\rangle\langle\mathcal{T}_j\rangle$) and the covariance vector between the cleaned map and templates ($\langle T_{\nu_c}\mathcal{T}_k\rangle$), respectively.

### 2.3. Hybrid Internal combination with Template Fitting (HIT Fitting)

The Hybrid Internal combination with Template Fitting (HIT FITTING, López-Caraballo et al., in prep.) is a new approach combining the ILC and ITF methodology. Our CMB estimator, $\hat{T}_{\text{CMB,HIT}}$, is described as:

$$\hat{T}_{\text{CMB,HITF}} = \sum_{i=1}^{n\alpha} \alpha_i \; T_i \; - \; \sum_{j=1}^{n\beta} \beta_j \mathcal{T}_j \tag{5}$$

where $T_i$ are the $n\alpha$ maps operating as the ILC approach, and $\mathcal{T}_j$ are the $n\beta$ foreground templates used in the template fitting approach. The $\alpha_i$ and $\beta_j$ linear coefficients are estimated by minimizing the variance of the CMB estimator, and taking into account that the CMB signal is preserved when:

$$\sum_{i=1}^{n\alpha} \alpha_i = 1 \; . \tag{6}$$

Similar to ILC and ITF, $\alpha_i$ and $\beta_j$ are obtained minimizing the variance of the CMB estimator and considering the Eq. 6. Using the Lagrange multipliers we obtained the solutions:

$$\alpha_i = \frac{\sum_{m=1}^{n\alpha} G_{m,i}^{-1}}{\sum_{m,i=1}^{ni} G_{m,i}^{-1}} \text{ and } \beta_j = \frac{\sum_{m=1}^{n\beta} H_{m,j}^{-1}}{\sum_{m,j=1}^{nt} G_{m,j}^{-1}} \tag{7}$$

where

$$G^{-1} = \left(A - CB^{-1}C^T\right)^{-1} \text{ and } H^{-1} = B^{-1}C^T G^{-1}$$

$A$, $B$ and $C$ are the covariance matrices of the $T_i$ maps ($\langle T_i T_l\rangle - \langle T_i\rangle\langle T_l\rangle$), of the $\mathcal{T}_i$ templates ($\langle\mathcal{T}_j\mathcal{T}_k\rangle - \langle\mathcal{T}_j\rangle\langle\mathcal{T}_k\rangle$) and of the maps and templates ($\langle T_i\mathcal{T}_j\rangle - \langle T_i\rangle\langle\mathcal{T}_j\rangle$), respectively.

In this method, the $T_i$ maps of the ILC approach must be smoothed to the same beam resolution. Templates contain only the foregrounds contribution, and they can be constructed from external or internal data.

The HIT FITTING, and similar to the ILC and ITF, does not require prior information about foregrounds, and the method only needs to know the behavior of the CMB's spectrum.

## 3. Forecasting

We use multifrequency sets of simulations to evaluate the performance of the HIT FITTING. In particular, we follow a preliminary version of Simons Observatory

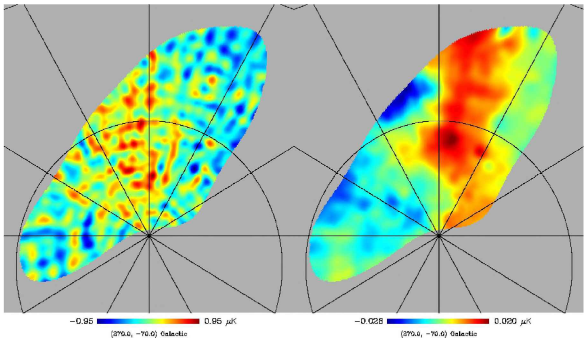


Figure 1: Stokes Q maps of the CMB input (left) and of the foreground residuals from the HIT Fitting (right).

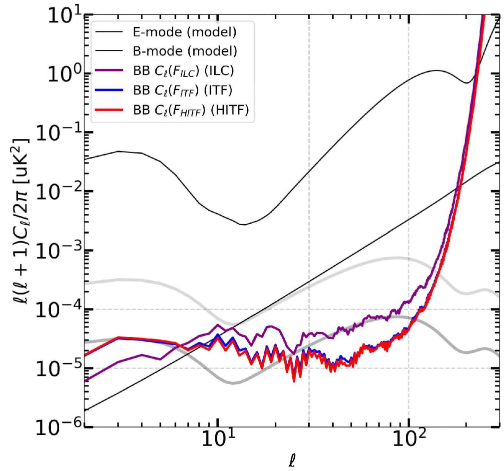


Figure 2: B-modes power spectra of the foreground residuals for the HIT Fitting (red), ILC (purple) and ITF (blue). The black lines drawn the theoretical E-modes and lensing B-modes ($r=0$) used in our simulations. The grey lines illustrate primordial B-modes with $r$ equal to 0.01 and 0.001.

simulations consisting of seven frequency bands and covering 5 % of sky from southern hemisphere (see Table 1). In polarization, we consider the synchrotron and thermal dust emission. The free-free emission is known to be practically unpolarized. The Anomalous Microwave Emission were not included because it is expected to be weakly polarized (see e.g. Lazarian & Draine, 2000) and we only found strong constraint on their polarization ($\lesssim$1%, see e.g. López-Caraballo et al., 2011; Dickinson et al., 2018). We assume Gaussian white noise to estimate the noise maps. CMB map is computed without the primordial B-modes contribution ($r=0$), i.e. only lensing contribution. The maps were smoothed to a common resolution of 130 arcmin (see Fig. 1).

### 3.1. Implementation and Foreground residuals

The ILC CMB maps were computed using the seven bands. The ITF CMB maps were obtained cleaning the 95 GHz map and using four templates: $\mathcal{T}_1 = T_{20} - T_{30}$, $\mathcal{T}_2 = T_{30} - T_{40}$, $\mathcal{T}_3 = T_{220} - T_{150}$ and $\mathcal{T}_4 = T_{270} - T_{220}$.

For the HIT Fitting, we used the $T_{30}$, $T_{95}$ and $T_{270}$ (for the ILC part) and the $\mathcal{T}_2$ and $\mathcal{T}_4$ templates. The three methods are compared using the foreground residual map ($F_{\rm CSM}$), which is obtained from the propagation of foregrounds once the weights are computed. In Fig. 1, we can see the low foreground residual levels compared to the input CMB signal. HIT Fitting and ITF have similar foreground residuals level, and they are lower than those from ILC.

The power spectrum is estimated for each foreground residuals map ($F_{\ell,\rm CSM}$), which is corrected for beam and pixel window functions and the sky fraction. If the power spectrum of foreground residuals is lower than the primordial B-modes signal (with a tensor-to-scale ratio $r$), we consider that our estimator $T_{\rm CMB}$ allows us to establish a strong constraint (or detection) on this $r$. Fig. 2 shows the $F_{\ell,\rm CSM}$ for each method, where $30 \lesssim \ell \lesssim 100$ is a reliable range because it is slightly affected by beam or the observed sky fraction.

The ILC shows a $F_{\ell,\rm ILC}$ residual compatible with the primordial B-modes with a $r=10^{-3}$, which could hinder the characterization of B-modes with such amplitude $r$. HIT Fitting and ITF have similar foreground residuals level in several multipoles ($\ell$). Moreover, the foreground residuals are lower than primordial B-mode with $r=10^{-3}$. In particular, HIT Fitting appears to be a better performance than ITF in several multipoles.

## 4. Conclusions

The HIT Fitting is a new approach to recover the CMB signal using a linear combination. The HIT Fitting and ITF have similar foreground residuals level in several $\ell$. We cannot confirm which of them has better performance, however, the HIT Fitting appears to be better performed. Our foreground residuals are lower than primordial B-modes with $r=0.001$. The HIT Fitting can be applied to multifrequency experiments such as liteBIRD, PICO and CORE, and in joint analysis (e.g. groundBIRD-QUIJOTE-Planck). Some other tests must be carried out (effect of gain, etc.). We expect to implement Needlet and Two Spin approaches.

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