Forecast of B-mode detection at large scales in the presence of noise and foregrounds

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ABSTRACT
We investigate the detectability of the primordial cosmic microwave background (CMB) polarization B-mode power spectrum on large scales in the presence of instrumental noise and realistic foreground contamination. We have worked out a method to estimate the errors on component separation and to propagate them up to the power spectrum estimation. The performance of our method is illustrated by applying it to the instrumental specifications of the Planck satellite and to the proposed configuration for the next-generation CMB polarization experiment COre. We demonstrate that a proper component separation step is required in order to achieve the detection of B-modes on large scales and that the final sensitivity to B-modes of a given experiment is determined by a delicate balance between the noise level and the residual foregrounds, which depend on the set of frequencies exploited in the CMB reconstruction, on the signal-to-noise ratio of each frequency map and on our ability to correctly model the spectral behaviour of the foreground components. We have produced a flexible software tool that allows a comparison of performances on B-mode detection of different instrumental specifications (choice of frequencies, noise level at each frequency, etc.) as well as of different proposed approaches to component separation.

Key words: methods: data analysis – cosmic background radiation – cosmological parameters.

INTRODUCTION
Primordial B-mode (curl component) polarization of the cosmic microwave background (CMB) provides a unique opportunity to detect the imprint of the primordial gravitational waves predicted by the inflationary paradigm. Measuring the amplitude of these tensor perturbations would fix the energy scale of inflation and its potential and would provide a powerful constraint on a broad class of inflationary models. Moreover, the confirmation of inflation and the determination of the inflationary potential would have profound implications, by providing a direct observational link with the physics of the early Universe.

The bulk of the statistical information on inflationary B-modes is concentrated in two features of the power spectrum: the reionization bump at multipoles ℓ ~ 2–10 and the main bump at multipoles ℓ ~ 20–100. Given that most of the signal lies on large angular scales (larger than ~1°), full-sky surveys, and thus satellite experiments, are required to limit cosmic variance.

When designing a satellite experiment targeted to B-mode detection on large scales it is mandatory to consider, together with the signal-to-noise ratio, also the issues related to foreground contamination and component separation. In fact, as demonstrated by the WMAP data (Gold et al. 2009), the cleaning of CMB E-modes from polarized foregrounds is still a manageable problem. But polarized foregrounds are expected to dominate by a wide margin over the CMB B-mode because foreground E- and B-modes have similar amplitudes while the CMB B-mode is far weaker than the E-mode.

The constraints in detecting primordial B-modes due to foreground contamination and residuals from foreground subtraction have been investigated by several authors. Many papers include a modelling of the residuals in the Fisher matrix (see e.g. Amari, Hirata & Seljak 2005; Tucci et al. 2005; Verde, Peiris & Jimenez 2006) but generally bypass any realistic component separation approach and thus cannot properly deal with component separation errors. Other analyses focused on a certain component separation method and evaluated its performance through simulations tailored for a specific experiment. For example, Betoule et al. (2009) and Efstathiou, Gratton & Paci (2009) propose different strategies (a
spectral matching component separation method and an internal template fitting method, respectively targeted to B-mode detection for the Planck experiment. More recently, Stivoli et al. (2010) assessed the capabilities of a parametric component separation method to detect B-modes for suborbital experiments.

The purpose of our work is different: while we understand the need to perform detailed simulations once the experimental configuration is established, we want to provide a fast, agile and flexible tool to forecast the detectability of B-modes allowing us to easily change both the instrumental specifications and the CMB reconstruction strategy. Such a tool can usually be exploited to help optimize the instrumental design and the data reduction pipeline for future CMB polarization experiments.

The different components are reconstructed as a suitable linear mixture of the data. Different choices for the linear mixture operator are available, and we carry out a comparison of their performances. The forecast, targeted to large scales, of the B-mode detectability is performed at the power spectrum level and includes the computation of the final power spectra of noise and foreground residuals on the CMB map. We explicitly account for errors in the frequency scalings assumed for the foreground components. On the other hand, we do not account for errors due to actual power spectrum estimation (leakage effects) nor for instrumental systematics. The former should be subdominant for the almost full-sky coverage considered here, especially when exploiting a power spectrum estimation method optimized for low multipoles (e.g. Gruppuso et al. 2009). Instrumental systematics obviously depend on the particular instrument and thus cannot be included in our general treatment.

The outline of our paper is as follows. In Section 2 we describe our models for the data and the component separation process. In Section 3 we derive analytical expressions for the noise and residual foreground contributions to the errors in the BB power spectrum. In Section 4 we apply our method to the specifications of the Planck satellite and of a proposed CMB polarization experiment (The CoRe Collaboration 2011). Our results are presented in Section 5 and our main conclusions are summarized in Section 6.

2 STATEMENT OF THE PROBLEM

2.1 Data model

The microwave sky contains, besides the CMB, several foreground components, both diffuse and compact. For our analysis, which is focused on large and intermediate scales, we will consider only diffuse foregrounds. The main diffuse polarized foregrounds are Galactic synchrotron and thermal dust (the free–free emission is essentially unpolarized). The synchrotron component dominates at the lower frequencies. Its spectral behaviour in antenna temperature can be modelled as a power law:

$$T_{A,\text{synh}}(v) \propto v^{-\beta_s},$$

where the synchrotron spectral index $\beta_s$ can vary in the sky in the range $2.5 < \beta_s < 3.5$ (Gold et al. 2009). The spectral behaviour of thermal dust emission, which takes over at high frequencies, follows approximately a greybody law:

$$T_{A,\text{dust}}(v) \propto \frac{v^{\mu_d+1}}{\exp(hv/kT_d) - 1}. \tag{2}$$

Both $\beta_s$ and $T_d$ are spatially varying around $\beta_s \sim 1.7$ and $T_d \sim 18$ K. The polarized CMB signal has a blackbody spectrum:

$$T_{A,\text{CMB}}(v) \propto \frac{(hv/kT_{\text{CMB}})^3 \exp(hv/kT_{\text{CMB}})}{[\exp(hv/kT_{\text{CMB}}) - 1]^2}. \tag{3}$$

with $T_{\text{CMB}} = 2.73$ K.

The sky radiation, $\hat{x}$, from the direction $\vec{r}$ at the frequency $v$ is the superposition of signals coming from $N_c$ different physical processes $\hat{s}_j$:

$$\hat{x}(\vec{r}, v) = \sum_{j=1}^{N_c} \hat{s}_j(\vec{r}, v). \tag{4}$$

The instrument integrates the signal over frequency in each of its $N_d$ channels; convolves it with a certain kernel, representing the spatial response function; and adds noise. The measurement yielded by the generic channel centred at the frequency $v$, with beam axis in the direction $\hat{r}$, is

$$x_r(\vec{r}) = \int B(\vec{r} - \vec{r}', v)v^2 t_c(v') \hat{s}_j(\vec{r}', v')d\Omega' + n_r(\vec{r}), \tag{5}$$

where $B(\vec{r} - \vec{r}', v')$ is the (azimuthally symmetric) beam, $t_c(v')$ is the frequency response of the channel and $n_r(\vec{r})$ is the noise map. The data model in equation (5) can be simplified under the following assumptions:

- (i) each source signal, $\hat{s}_j(\vec{r}, v)$, is a separable function of direction and frequency at least within limited sky patches;
- (ii) $B(\vec{r}, v)$ is independent of frequency within the passband of each channel;
- (iii) $B(\vec{r}, v)$ is the same for all the channels.

The first two are reasonable approximations. To meet the third one we need to smooth the data to the lowest resolution we are dealing with. This is not a problem in the present context, since we are interested in large angular scales.

Under these assumptions, the linear mixture data model applies. In vector form, for each direction of the sky (each pixel) we may write

$$x = Hs + n, \tag{6}$$

where $x$ and $n$ are $N_d$-vectors containing data and instrumental noise, respectively; $s$ is the $N_c$-vector containing sources; and $H$ is the $N_d \times N_c$ mixing matrix, containing the frequency scaling of the components. The spatial variability of the synchrotron and dust spectral indices implies that the mixing matrix $H$ is in general different for different pixels.

2.2 CMB recovery

If the linear mixture data model holds, the components which are mixed in the channel maps $x$ (equation 6) can be reconstructed as

$$\hat{s} = Wx, \tag{7}$$

where $\hat{s}$ is an estimate of the components $s$ and $W$ is an $N_c \times N_d$ matrix called the reconstruction matrix. We choose to rely on a linear estimator basically because it will allow us to easily deal with the component separation process in the forecast of B-mode detection, as we will see in the next section. In addition, this approach is handy for Monte Carlo simulations needed to accurately control error sources.

We adopt the so-called generalized least-squares solution (GLS):

$$W = [\hat{H}^T N^{-1} \hat{H}]^{-1} \hat{H}^T N^{-1}. \tag{8}$$

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This requires the noise covariance $N$ of the channel maps and an estimate $H$ of the mixing matrix $W$ that can be obtained exploiting any of the successful component separation methods discussed in the literature (see e.g. Bonaldi et al. 2006; Eriksen et al. 2006; Stompor et al. 2009). We stress that this choice is not completely general, as other reconstruction matrices could be used. The adaptation of our approach to other choices for $W$, still in the framework of the linear mixture data model, is, however, straightforward.

The fact that our reconstruction matrix explicitly contains the estimated mixing matrix will allow us to easily introduce in our forecast also the effect of errors in the mixing matrix estimation (see Section 3).

The noise covariance term, $N$, in equation (8) allows us to perform the component separation keeping the noise level under control. Nevertheless, every component separation leads to a noise amplification by an amount that ultimately depends on the conditioning of the mixing matrix $H$, as we will show in Section 4. Despite this drawback, in the low-multipole regime considered we cannot dispense with the component separation step (e.g. by resorting to an aggressive masking of foreground-contaminated regions) because the foreground contamination is more troublesome than the noise amplification and large areas are essential to restraining cosmic variance.

On the contrary, the use of a suitable mask could be enough to keep foreground contamination under control on smaller scales, where the power spectra of diffuse foregrounds decrease more rapidly than those of CMB and noise. In this case we could completely change strategy and simply recover the CMB as a weighted mean of the channels with weights given by the inverse noise variance. This can be viewed again as a linear combination as in equation (7), where the reconstruction matrix $W$ has null elements for the foregrounds and inverse noise variance weights for the CMB. This approach is complementary to the one previously described: it allows noise reduction but does not separate the components; only one component is reconstructed and considered as CMB.

In this work we will consider both the approaches, which will be labelled as ‘component separation’ (CS) and ‘minimum variance’ (MV). A comparison of the results is presented in Section 5, which will give the reader an idea of the multipole ranges where each approach works better.

### 3 FORECAST OF B-MODE DETECTION

Our forecast is made at the power spectrum level and accounts for both noise errors and foreground residuals:

$$\Delta C_\ell = \Delta C_{\ell,\text{noise}} + \Delta C_{\ell,\text{foreg}}.$$  

(9)

In this section we formalize the estimate of the two contributions $\Delta C_{\ell,\text{noise}}$ and $\Delta C_{\ell,\text{foreg}}$ to the error on the power spectrum, exploiting the model of the sky (equation 6) and of the component separation process (equation 7) described in the previous section.

To compute the noise error $\Delta C_{\ell,\text{noise}}$ we have to estimate the noise bias on the CMB power spectrum, say $N_{\text{CMB}}$, i.e. the power spectrum of the noise in the reconstructed CMB map. This can be done with ‘noise-only’ Monte Carlo simulations whereby several sets of realistic noise maps are generated and each of them is mixed with the matrix $W$. Then the power spectrum is computed for each simulation and, finally, all the noise power spectra are averaged. Here we make the simplifying assumptions of Gaussian white noise and spatially invariant foreground spectral properties. This allows us to proceed analytically. In the framework of a realistic spatially varying spectral model, we have verified that the analytic computation of the noise error with mean spectral dependences over the sky is still accurate enough for the purpose of the forecast considered here. In fact, due to the absence of intrinsic correlation between noise and foregrounds, the mean level of the noise bias is predicted with good accuracy.

The theoretical power spectrum of Gaussian white noise at the frequency $\nu$ is

$$N_\nu = \frac{4\pi f_{\text{sky}} \sigma^2_w}{N_{\text{pix}}} B^2_\nu,$$

(10)

where $f_{\text{sky}}$ is the sky fraction considered, $N_{\text{pix}}$ is the number of pixels, $\sigma^2_w$ is the noise variance at frequency $\nu$ and $B^2_\nu(\ell)$ is the beam function applied to the channel maps to obtain a common resolution. As in our case we deal with polarization, $\sigma^2_w$ is the noise of the detector at frequency $\nu$ multiplied by $\sqrt{2}$ which, in the Gaussian white noise hypothesis considered here, gives the rms of the noise in $Q$ and $U$ maps.

Given the linearity of the CMB recovery process (equation 7) and under the assumption of a spatially invariant reconstruction matrix, the noise bias is obtained by combining the channel noise spectra $N_\nu$ with the matrix $W^2$:

$$N_{\text{CMB}} = \sum_\nu w^2_{\nu,\text{CMB}} N_\nu,$$

(11)

where $w^2_{\nu,\text{CMB}}$ are the elements of the matrix $W^2$ pertaining to the CMB component.

The error on the CMB power spectrum is due to the fact that we do not know the actual noise realization, but only a mean noise bias. In other words, $\Delta C_{\ell,\text{noise}}$ is the error due to the sampling variance of the noise bias $N_{\text{CMB}}$:

$$\Delta C_{\ell,\text{noise}} = \sqrt{\frac{2/(2\ell + 1)}{f_{\text{sky}} n_{\text{bin}}(\ell)}} N_{\text{CMB}},$$

(12)

where $n_{\text{bin}}$ is a function containing the number of multipoles around any chosen $\ell$ to be averaged according to a certain binning scheme.

The error $\Delta C_{\ell,\text{foreg}}$ (equation 9) due to the imperfect foreground subtraction can be computed following Sivolini et al. (2010). The map of residuals, $s - \hat{s}$, for a linear mixture source reconstruction can be estimated as

$$s - \hat{s} = (W^\top I - I)\hat{s},$$

(13)

where $I$ is the identity matrix and $\hat{s}$ is a set of simulated components. $\Delta C_{\ell,\text{foreg}}$ is the power spectrum of the residuals computed over a certain area of the sky. We note that in the computation of the foreground residuals we do not proceed analytically up to the power spectrum level. This means that, in this case, we could easily exploit a realistic spatially varying foreground spectral model. Given the lack of observational constraint at present, however, for the purpose of the paper we are relying again on the spatially invariant model.

According to equation (13) the foreground residuals vanish for $W = H^{-1}$, which is the exact solution of the component separation problem in the absence of noise. For the reconstruction matrix of equation (8), the foreground contamination is non-null (although very low) even for $H = H$. It obviously increases with increasing error in the mixing matrix estimation. In the MV case the mismatch between $W$ and $H^{-1}$ is higher, and the foreground contamination increases.

It is clear that the estimate of $\Delta C_{\ell,\text{foreg}}$ through the previous relation is model-dependent since it relies on simulations of the data $\hat{s}$ which are hampered by our poor knowledge of polarized foregrounds. The situation will substantially improve in the near...
future as new polarization data, above all those from the Planck mission, will become available.

4 APPLICATION TO THE PLANCK AND COre EXPERIMENTS

The adopted experimental specifications for the Planck and CoRe experiments are reported in Table 1. Planck specifications are derived from Mandolesi et al. (2010) for the low-frequency instrument (LFI) and from Lamarre et al. (2010) for the high-frequency instrument (HFI) assuming a mission duration of 29 months. The specifications for CoRe are from the ESA M3 call (2010 December) available at http://www.core-mission.org.

For each experiment we computed the error on the power spectrum using equations (9)–(13) for both the minimum variance (MV) and component separation (CS) cases.

4.1 Sky model

The polarization $Q$ and $U$ synchrotron and dust templates of our model were obtained at 100 GHz by running the Planck Sky Model (PSM). Extrapolations to lower and higher frequencies were made using the spectra of equation (1) with $\beta_s = 3$ for synchrotron and of equation (2) with $\beta_d = 1.7$ and $T_d = 18$ K for dust. It has been necessary to slightly adjust the intensity of the synchrotron template to reproduce the WMAP 7-year K-band polarization map. The polarized CMB simulation is based on a standard ΛCDM model with WMAP 7-year cosmological parameters (Larson et al. 2011), including gravitational lensing. We have added tensor modes with tensor-to-scalar ratio $r = [0.1, 0.03, 0.01, 0.001]$ and re-ionization optical depth $\tau = 0.1$.

4.2 Minimum noise variance weighting

As mentioned above, the MV approach assumes that, outside a suitable mask, foregrounds are negligible so that we need to deal only with CMB and noise. Therefore the reconstruction matrix, $\mathbf{W}$, contains only inverse noise variance weights for the CMB and null elements for the foreground components. For this assumption to be plausible we must restrict ourselves to a ‘CBM sensitive’ set of channels and adopt a wide Galactic mask. To compute $\mathbf{H}$ and $\mathbf{W}$ we have thus considered only the channels in the frequency range $70 \leq \nu < 200$ GHz and computed the power spectrum of the foreground

Table 1. Instrumental characteristics considered in the present study for the Planck and CoRe experiments. The rms per pixel is referred to nside 1024 (size ~ 3.5 arcmin).

| Parameter | LFI | HFI |
|-----------|-----|-----|
| $v$ (GHz) | 30  | 3  |
| FWHM (arcmin) | 70 | 150 |
| $29$ m rms $\Delta T$ (µK RJ) | 7.6 | 0.001 |

Table 2. Adopted errors in the estimation of the synchrotron and dust spectral indices for three different regimes.

| Regime     | $\beta_s$ | $\beta_d$ |
|------------|-----------|-----------|
| Conservative | 0.05      | 0.01      |
| Intermediate | 0.01      | 0.005     |
| Goal        | 0.005     | 0.001     |

Another issue is the choice of the set of channels to be used for the source reconstruction. On the one hand, using a wide frequency

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5 RESULTS

In Fig. 1 we show the result of the forecast for Planck (upper panels) and Core (lower panels) for the two frequency ranges

(left: $50 < \nu < 200$ GHz; right: $40 < \nu < 300$ GHz) used for the CMB map reconstruction. We can immediately note that the MV approach performs worse: the noise level is low, but the total error is strongly dominated by foregrounds even with a Galactic mask covering 50 per cent of the sky ($|b| \leq 30^\circ$). To verify whether this result depends critically on the mask, we also combined the $|b| \leq 30^\circ$ mask with the WMAP 7-year polarization mask, finally exploiting 46 per cent of the sky. In this case, the foreground contamination lowers approximately by 30 per cent at large scales. With a mask optimized for the frequency coverage considered here, we could do even better; none the less, the residual contamination would still be very high with respect to the CMB. We conclude that on large and intermediate scales a proper component separation is necessary.

In the Planck case, the total error for the CS approach is noise dominated even for 85 per cent sky coverage ($|b| \geq 10^\circ$). Extending the frequency range from $50 < \nu < 200$ GHz to $40 < \nu < 300$ GHz improves the noise level substantially. To be more quantitative, let us call $A^2$ the sum of the elements of the matrix $W^2$ pertaining to the CMB component. These elements weight the noise power spectra in the computation of the noise bias $N_{\text{CMB}}$. Thus $A$ can be interpreted as the amplification of the noise r.m.s. In our simulation, the smaller set of channels yields $A \sim 3$ while the larger one yields $A \sim 1.3$. Our simulations indicate that, using the wider frequency range, Planck can detect B-modes for $r = 0.1$ and, with a lower significance, for $r = 0.03$. The fact that the error is dominated by the noise term implies that the improvement in the mixing matrix estimation from the ‘conservative’ to the ‘intermediate’ case has a minor effect.
Although our conclusions on Planck’s capability for detecting B-modes are similar to those of Efstathiou & Gratton (2009), our approach differs substantially from theirs. These authors based their analysis on a minimum noise variance combination of the 70, 100 and 143 GHz channels and assumed that foregrounds can be removed with high accuracy if the highest and lowest polarized Planck channels are used as foreground templates and the most contaminated areas (37 per cent of the sky) are masked. However, as shown by our analysis, the foreground contamination corresponding to the minimum noise variance combination is very high even at a high Galactic latitude. Therefore a sufficiently accurate foreground removal by template fitting is very challenging. Conversely, a more standard component separation approach, as the one exploited for our forecast, keeps both foreground contamination and noise under control.

The bottom panels of Fig. 1 show our expectations for the CoRE mission. Due to the higher sensitivity of this experiment, the total error for the CS case is dominated by noise only for very low errors in the mixing matrix estimation (‘goal’). For ‘conservative’ errors in the spectral indices, the best results are obtained with the restricted set of channels. B-mode polarization can be detected down to \( r = 0.01 \) even with the ‘conservative’ errors in the spectral indices. The minimum value of \( r \) that can be reached depends on our ability to estimate the mixing matrix.

6 CONCLUSIONS

We have presented a method to forecast the detectability of CMB B-mode polarization on large and intermediate angular scales given the experimental specifications of a full-sky multifrequency experiment. Our forecast accounts for both noise and residual foreground contamination after the CMB has been extracted from the data by means of a suitable linear combination of the frequency maps. The computation of foreground residuals explicitly includes errors in the modelling of the data and in the estimation of the frequency scalings of the components. The forecast is quick and flexible, and allows the selection of different sets of frequencies and of different methods for the CMB reconstruction. In this paper we considered the minimum noise variance (MV) and GLS component separation (CS) methods, but other methods can be easily implemented.

We have investigated several issues as follows.

(i) How do the performances of minimum noise variance methods compare with methods exploiting component separation? We have shown that, although component separation leads to a noise amplification by an amount ultimately depending on the conditioning of the mixing matrix, in the low-multipole regime considered in this paper we cannot dispense with the component separation step e.g. by resorting to an aggressive masking of foreground-contaminated regions, because the foreground contamination is more severe than that of noise and the mask cannot be too extended because large areas are essential to restrain cosmic variance.

(ii) Which is the optimal frequency range for the reconstruction of CMB polarization maps? Use of a wide frequency range brings in channels heavily foreground contaminated and, since the foreground spectra are not perfectly known, increases the foreground residuals in the final map. On the other hand, using too limited a set of channels in the linear combination leads to a higher noise level in the reconstructed CMB map, because the mixing matrix is less well conditioned. We find that if the total error is dominated by noise, like in the case of Planck, it is convenient to use a rather broad frequency range (40 < \( v \) < 300 GHz), while in the case of more sensitive experiments, like the planned CoRe mission, it is preferable to restrict ourselves to the ‘cleaner’ frequency range 50 < \( v \) < 200 GHz. We stress, however, that this applies to the CMB reconstruction step. For the preliminary ‘mixing matrix estimation’ step a much broader frequency coverage is essential.

(iii) How critical is a better understanding of polarized diffuse foregrounds for measurements of the power spectrum of primordial B-mode polarization? We find that in the case of Planck the main limitation comes from the detector noise. We estimate that with four all-sky surveys Planck can detect the re-ionization bump of the B-mode power spectrum for values of the tensor-to-scalar ratio \( r \) down to < 0.1, in agreement with the earlier conclusion by Efstathiou & Gratton (2009). On the other hand, to fully exploit the sensitivity of planned experiments specifically aimed at measuring the primordial B-mode anisotropies, it is essential to substantially improve the determination of spectral properties of polarized foregrounds. Planck maps will allow an important step forward in this direction.

As soon as more accurate multifrequency maps of polarized foreground emissions are available, our method will allow us to make more quantitative predictions that may help to design the next-generation CMB polarization experiments and optimize the data analysis strategy.

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