Cosmic Microwave Background Polarization

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Abstract

- Goal: testing a new algorithm for data analysis of CMB experiments for the detection of polarization B-modes
- There are several forthcoming experiments devoted to B-modes detection, following the Planck satellite mission
- I concentrated on the LSPE experiment to take into account possible correlation among different detectors
- I tested the algorithm on simulations and on previously collected data from B2K experiment
- The expected improvement on the experiment sensitivity for B-modes detection is at least 20% with respect to the standard algorithms.

CMB: Introduction

- The CMB is the thermal radiation left over from the Big Bang
- Dated to the epoch of Recombination, it is the oldest light in the Universe
- It is the most perfect Black Body ever observed in nature
- It is an extremely isotropic radiation with temperature $2.7K$.

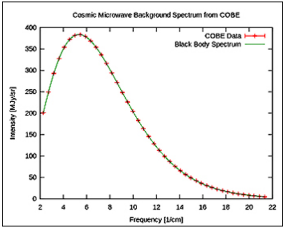


Figure: CMB spectrum from COBE (1992)

CMB Temperature

- The CMB is characterized by a temperature pattern
- Temperature anisotropies of some parts out of 10^5 have been observed
- These fluctuations can be expanded in spherical harmonics:

$$\frac{\triangle T}{T}(\theta,\phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

$$a_{lm} = \int_{4\pi} \frac{\triangle T}{T}(\theta,\phi) Y^*_{lm} d\Omega$$

CMB Temperature

- We define the power spectrum as:

$$C_l \equiv < |a_{lm}|^2 >$$

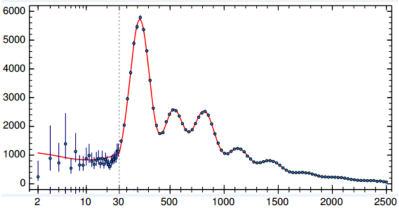


Figure: Temperature power spectrum from Planck (2015). On y-axis: $C_l(l+1)l/2\pi$; on x-axis: l

CMB Polarization

- The CMB is characterized also by a polarization pattern
- We define the polarization tensor as:

$$P_{ab}(\hat{n}) = \frac{1}{2}\begin{pmatrix} Q(\hat{n}) & -U(\hat{n})sin\theta \\ -U(\hat{n})sin\theta & -Q(\hat{n})sin^2\theta \end{pmatrix}$$

- It must be expanded in tensor spherical harmonics:

$$\frac{P_{ab}(\hat{n})}{T_0} = \sum_{l=2}^{\infty}\sum_{m=-l}^{l}[a^E_{(lm)}Y^E_{(lm)ab}(\hat{n}) + a^B_{(lm)}Y^B_{(lm)ab}(\hat{n})]$$

- The temperature/polarization power spectra are:

$$< a^{X*}_{(lm)} a^{X'}_{(l'm')} >= C_l^{XX'}\delta_{ll'}\delta_{mm'}, \qquad X, X' = \{T, E, B\}$$

CMB Polarization

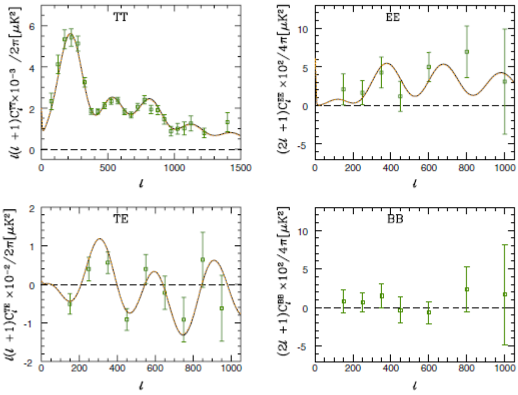


Figure: Power spectra from BOOMERanG (2003)

Cosmological Perturbation Theory

- CPT is aimed at describing how primordially generated perturbations grow into galaxies and clusters of galaxies due to self-gravity
- The linear perturbed metric tensor is:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

- The perturbation $h_{\mu\nu}$ can be decomposed into a scalar, a vector and a tensor mode:

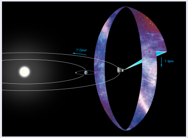
$$h_{\mu\nu} = h^{s}_{\mu\nu,4} + h^{v}_{\mu\nu,4} + h^{t}_{\mu\nu,2}$$

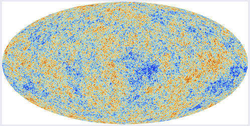
Cosmological Perturbation Theory

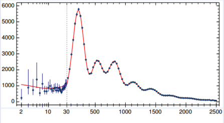
- The scalar mode represents the density perturbations
- Two important stages of their evolution: at last scattering surface (CMB anisotropies) and at present time (Large Scale Structures)
- The tensor mode represents the Gravitational Waves (GW)
- Inflation predicts a GW background
- GW generate the B-mode of CMB polarization
- The detection of B-modes would provide a confirmation of inflation theory

Data Analysis

- From detector observations d to maps m (map-making)
- From maps m to power spectra C_l
- From power spectra C_l to cosmological parameters Ω_i







Map-making

- The observation can be written as

$$d = Pm + n$$

- A good estimator of the map is:

$$\tilde{m} = (P^T N^{-1} P)^{-1} P^T N^{-1} d$$

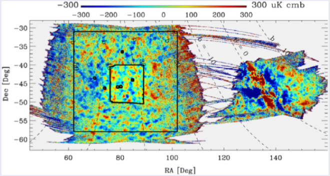
$$N = < nn^T >$$

- If the experiment is provided with more than one detector, the noise is given by:

$$n_t^i = \tilde{n}_t^i + \alpha^i c_t$$

BOOMERanG

- It consists of a balloon-based telescope mounted on a stratospheric long duration balloon.
- The main goal is the accurate measurement of the sky in the microwave band.
- Two missions were launched: in 1998 and 2003
- The observation strategy was designed to cover three regions: the "deep" region, the "shallow" region and a portion of the Galactic Plane.



Cross-correlation

- The cross-correlation between the instrumental noises of the detectors is important at low frequencies
- The main sources are temperature changes of the focal plane and atmospheric fluctuations
- The noise spectral density has the following form:

$$P(f) = A\left[1 + \left(\frac{f_k}{f}\right)^{\alpha}\right]$$

- It has been measured and tested on BOOMERanG

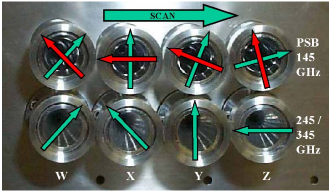
Cross-correlation

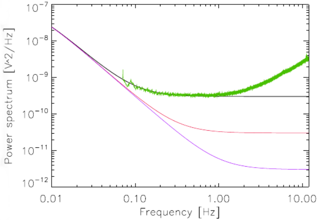
We create a theoretical noise spectral density:

$$P_{ii}(f) \propto w_{ii} + \left(\frac{f_k}{f}\right)^{\alpha},$$

$$P_{ij}(f) \propto w_{ij} + \left(\frac{f_k}{f}\right)^{\alpha}$$

$$P_{ir}(f) \propto w_{ir} + \left(\frac{f_k}{f}\right)^{\alpha}$$





Cross-correlation

- Results for the Deep region: 20% improvement in sensitivity at low multipoles

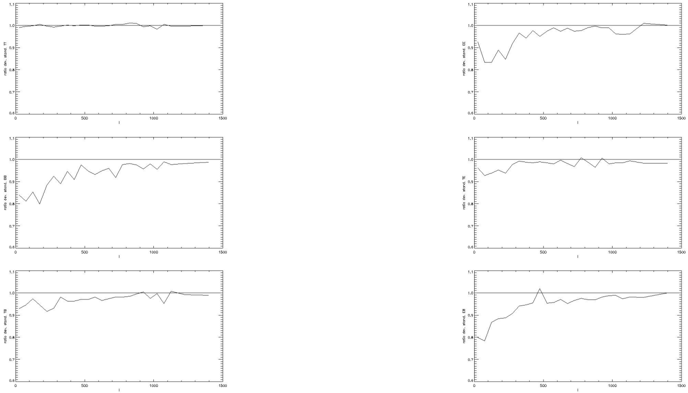


Figure: Ratios of standard deviations. On the left, from top to bottom: TT, BB, TB. On the right, from top to bottom: EE, TE, EB.

Cross-correlation

- Results for the Shallow region: 20% improvement in sensitivity at low multipoles

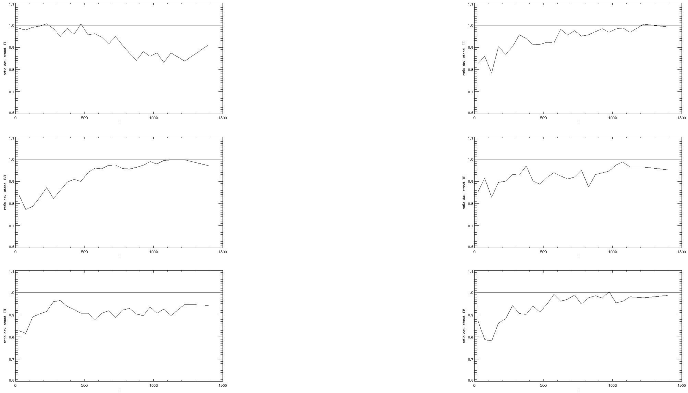


Figure: Ratios of standard deviations. On the left, from top to bottom: *TT*, *BB*, *TB*. On the right, from top to bottom: *EE*, *TE*, *EB*.

Conclusions

- The new algorithm provided a relevant improvement in the estimate of the power spectra
- In particular we are interested in the *BB* spectrum
- The error bars have been reduced up to 20%
- The benefit is larger at low multipoles

Future Perspectives

- The new algorithm has a general validity
- The method is very effective when the low-frequency part cannot be excluded
- A suitable future application is the Large Scale Polarization Explorer (LSPE) experiment
- Its launch is expected in 2016 and it is aimed at observing CMB polarization at large angular scales
- The primary target is to constrain the curl component of the polarization (B-modes)
- A significant reduction of the error bars in the experimental C_l^{BB} power spectrum may provide an important step ahead in the discovery of a “pure” B-mode signal.