Map-making strategies for next generation CMB polarization experiments

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Introduction

Map-making is the reconstruction of the observed sky from the time-ordered data (TOD) collected by a telescope. It compresses the volume of data by many orders of magnitude, while trying to preserve cosmological information.

In the quest for B-mode polarization of the CMB, modern experiments are lining up tens, even hundreds of thousands of detectors to extract the primordial signal. As a result, the size of the TOD is increasing to an unprecedented volume, challenging our ability to analyze it correctly and efficiently.

	Polarbear	SO	CMB-S4
Data volume	100 TB	2 PB	50 PB
CPU time	20 kh	35 Mh	500 Mh

Table 1. Data volume and current CPU time needed to produce *one* sky map.

Quick review of map-making flavors

Data model and estimators

$$d = Ps + n \tag{1}$$

This is the usual assumed data model for the map-making problem.

- d = TOD (calibrated)
- P = pointing matrix, encodes scanning and orientation of the telescope
- s = true sky map
- n = noise vector

Map-making is just a *linear operation*, $m = Ld$, mapping the TOD to an estimator m of the true sky map.

Method	Operator L	Pros	Cons
Binning	$(P^\top \Lambda P)^{-1} P^\top \Lambda$	unbiased, cheap	complex noise
GLS	$(P^\top C_n^{-1} P)^{-1} P^\top C_n^{-1}$	unbiased, min. variance	expensive
Filter-and-bin	$(P^\top \Lambda P)^{-1} P^\top F$	easy to compute	biased
Templates	$(P^\top F P)^{-1} P^\top F$	unbiased filtering	iterative

Table 2. Comparison of different map-making approaches. Legend: Λ = diagonal noise weights; C_n^{-1} = noise covariance matrix; F = filtering and weighting operator.

Observing from the ground

Ground-based experiments have to deal with two specific contaminants which are very bright compared to the CMB anisotropies:

- *atmospheric signal*, a major source of noise correlations
- *ground pickup*, typically due to the far side-lobes of the beam

All methods listed above can account for such effects (by either introducing appropriate filters, or defining templates, or adding extra degrees of freedom) and offer different trade-offs between precision, accuracy, and computational efficiency. In particular, the *filter-bin* techniques are very computationally efficient and require only a general knowledge of the contaminants. But they produce a *biased representation* of the sky signal and require extensive simulations to correct for this effect later. The *GLS and template methods* are in turn *computationally heavy* and require precise *contaminant models*. However, they provide high accuracy and high precision estimates of the sky maps.

Here we study a hybrid approach, which could in principle benefit from the advantages of the GLS and template techniques while being numerically efficient and only requiring generic assumptions about the contaminants.

The pair differencing approach

We assume that the atmospheric signal and the ground pickup are *unpolarized*. The idea is to use the dual-polarization detectors to eliminate non polarized signals:

$$d_{A/B} = I \pm P \quad \longrightarrow \quad d_- = \frac{1}{2}(d_A - d_B) = P$$

This subtraction ideally decouples intensity and polarization components so that we can reconstruct the polarization signal *exclusively* from the differenced TOD. This simple approach has been (and still is) used in CMB experiments such as Polarbear [2] and BICEP/Keck [1].

Advantages

- *Control of atmospheric effects*: remove (most of) the unpolarized signals without any further assumptions or atmosphere models.
- *Numerical efficiency*: atmosphere introduces long noise correlations, which worsen the *conditioning* of the map-making system; removing those greatly speeds up the convergence (see Figure 1).
- *Near optimality*: polarization maps reconstructed from the differenced TOD are formally equivalent to the GLS solution if we assume no particular model for the atmosphere (i.e. only that it is unpolarized and common to the orthogonal detectors in a pair).

Pitfalls

For the intensity signal to fully cancel, the two orthogonal detectors have to be *identical*. Even with careful calibration, this can never be achieved perfectly. Because the contaminants are much brighter than the CMB polarization, this is a real problem for pair differencing. The most important effects which are expected to cause leakage of the intensity signal into the differenced TOD are:

- miscalibration of the detector gains
- bandpass differences
- different beam shapes

We want to assess the impact of those effects and find out in what conditions pair differencing is a viable approach for producing maps of the CMB polarization for B-mode search.

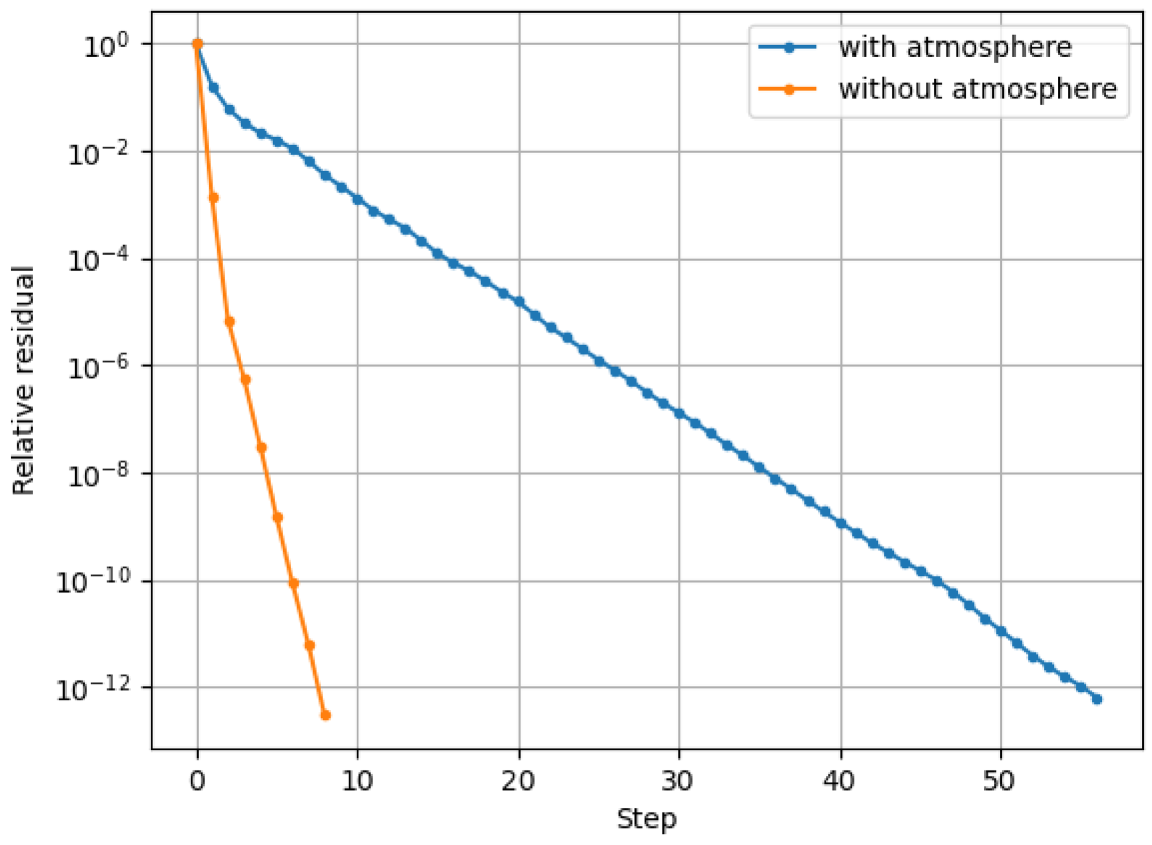


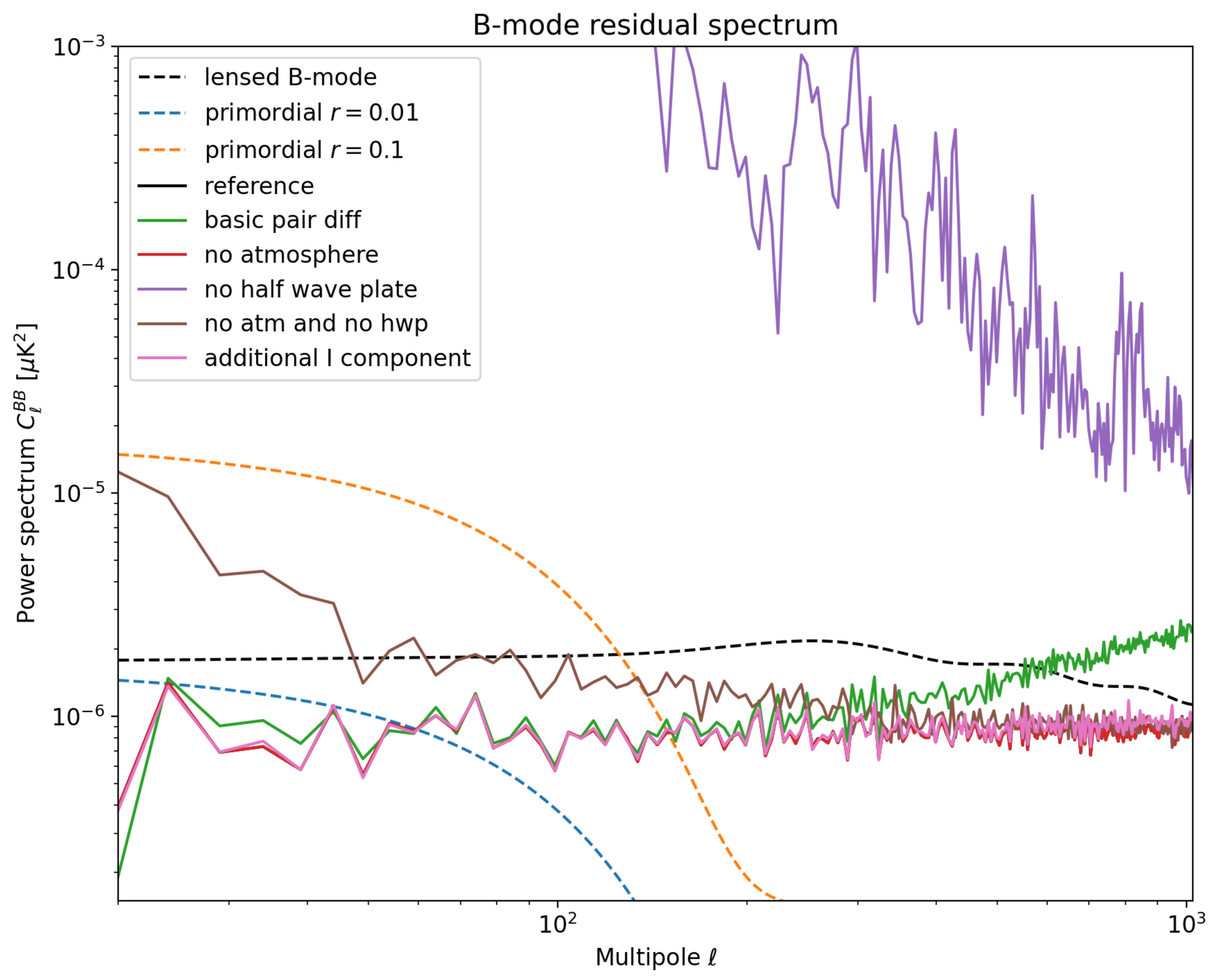
Figure 1. Convergence comparison with and without atmospheric correlations.

Preliminary results

Our current setup uses the Time-Ordered Astrophysics Scalable Tools (TOAST) package [4] for simulating data and the MAPPRAISER library [5] for producing the sky maps.

- instrument: Simons Observatory Small Aperture Telescope @ 90 GHz
- rotating half wave plate (HWP) at 120 rpm for polarization modulation
- schedule: one day per month during one year
- sky: CMB lensed scalar anisotropies (from Planck FFP10 simulations [3])
- high-resolution atmosphere simulation
- instrumental noise
- gain errors of one percent in detector pairs

For the moment, we simply compare the *residual spectra* (measured on the difference between the reconstructed and input sky maps) with the theory predictions.



Dashed lines represent theory BB spectra. In black are the lensed B modes; in blue and orange are the primordial B modes for a tensor-to-scalar ratio of 0.01 and 0.1 respectively. Solid lines are the residual spectra reconstructed in different configurations.

- black: reference case (no gain errors)
- green: pair differencing (PD) run according to description above
- red: PD run, but without including atmospheric signal (aligned with black)
- purple: PD run, but without the HWP modulation
- brown: PD run, without atmosphere and without HWP (only the CMB intensity is leaking into the differenced TOD)
- pink: PD run, additionally fitting for the leaked intensity signal

Overall, the plot highlights the importance of a rotating half wave plate to modulate the polarization signal. It effectively prevents the leaked intensity signal to contaminate the *large scales* of the map, where the signal of interest lives. Also, fitting for a leaked intensity component comes very close to the reference case.

Future work and improvements

- Refine simulations by adding bandpass and beam differences.
- Include realistic gain calibration error distributions.
- Perform a likelihood analysis to estimate biases and sensitivities to the tensor-to-scalar ratio.

References

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