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 hours	20 k	35 M	500 M

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:

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

Those contaminants are largely unpolarized, which motivates the **pair differencing** approach, where the timestreams of two orthogonal detectors are subtracted in order to eliminate non polarized signals.

Evaluation of the pair differencing approach

I use the map-making library `mappraiser` [1] to process simulations produced with the `TOAST` software:

- instrument: SO-SAT @ 90 GHz
- schedule: one day per month during one year
- sky: CMB lensed scalar anisotropies (from Planck FFP10 simulations)
- high-resolution atmosphere simulation
- instrumental noise
- gain errors in detector pairs
- in the future: elliptical beams

Figure of merit ?

Results: gain errors

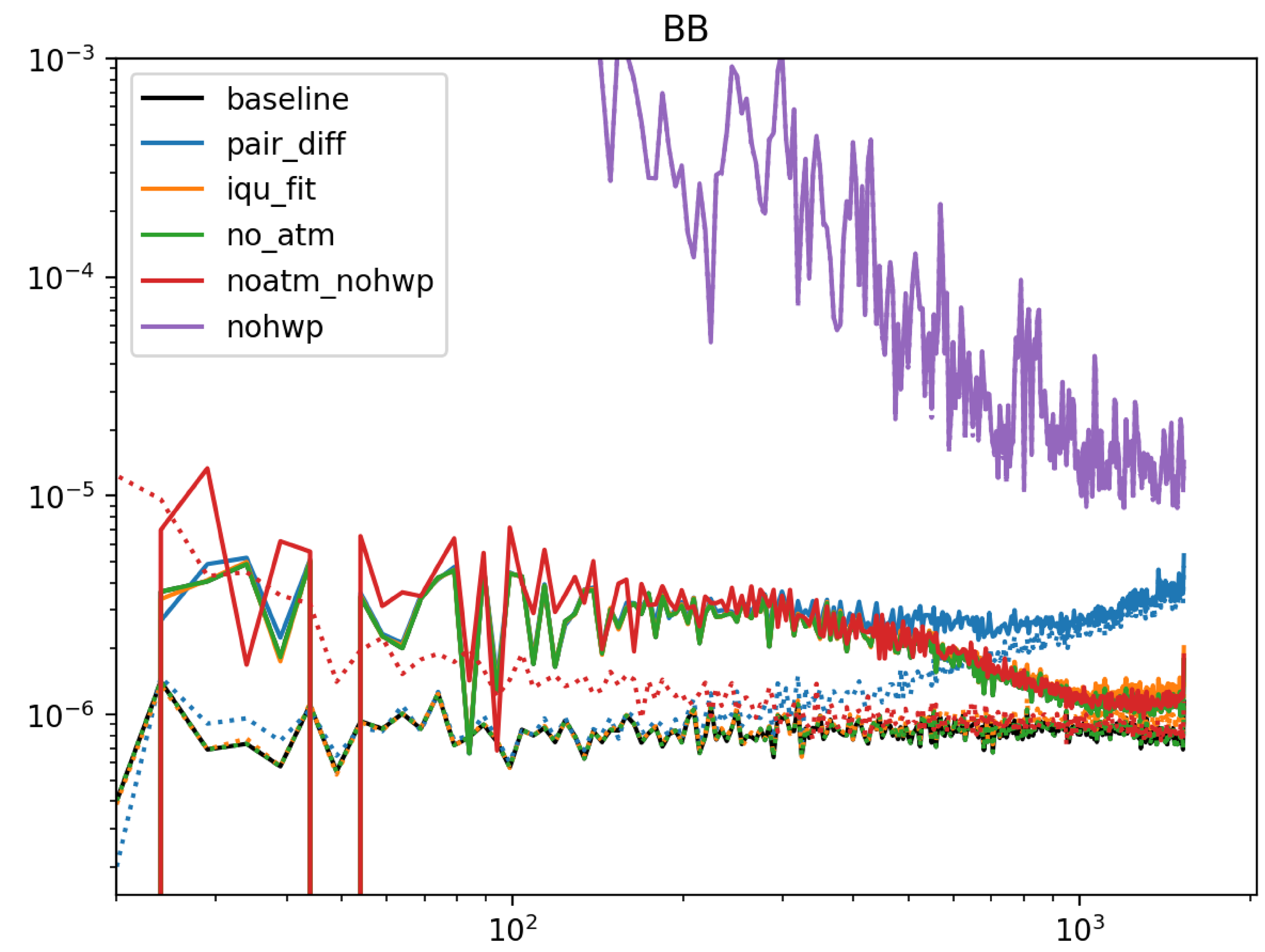

Figure 1. B-mode spectrum in different configurations. Solid lines are the measured spectrum, dotted lines are the difference with respect to the input spectrum (residual).

Numerical advantages of pair differencing

The map-making equation is solved *iteratively* using a conjugate gradient (CG) algorithm. If m_t is the approximate solution obtained at the t-th step of the algorithm, and m_* the true solution, then an upper bound of the error is given by:

$$\|m_* - m_t\|_A \le 2\left[\frac{\sqrt{\kappa}-1}{\sqrt{\kappa}+1}\right]^t \|m_* - m_0\|_A \tag{2}$$

So the convergence rate of the algorithm essentially depends on the *condition number* κ of the system matrix. Strong noise correlations increase κ. By removing most of the intensity signal of the atmosphere, we also drastically improve the convergence speed of the algorithm.

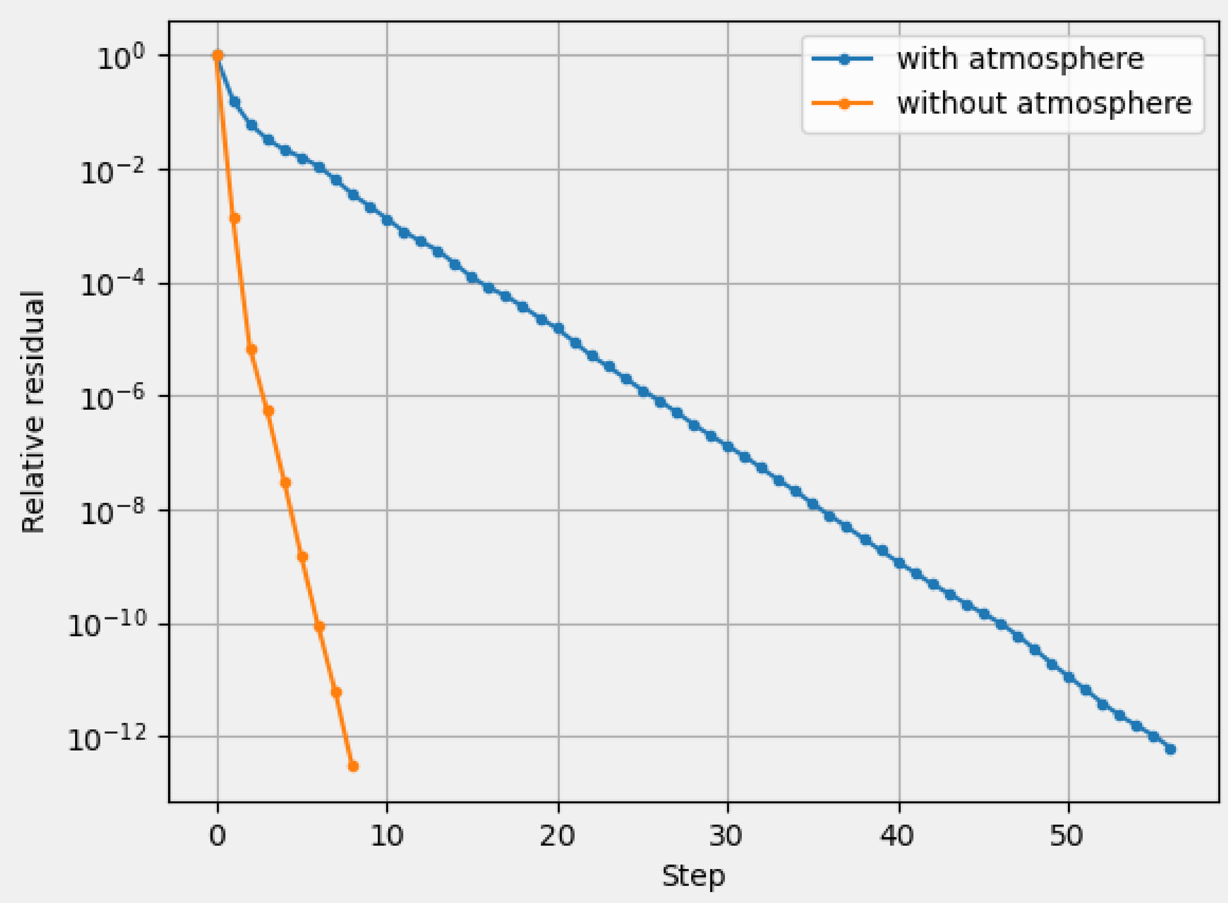

Figure 2. Convergence comparison with and without atmospheric correlations.

Conclusion / Discussion ?

In what conditions is pair differencing reasonable to use? What do we lose? What do we gain?

References

[1] Hamza El Bouhargani, Aygul Jamal, Dominic Beck, Josquin Errard, Laura Grigori, and Radek Stompor. MAPPRAISER: A massively parallel map-making framework for multi-kilo pixel CMB experiments. *Astronomy and Computing*, 39:100576, April 2022.

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