Map-making strategies for next generation CMB polarization experiments

Simon Biquard [1]

[1]AstroParticule et Cosmologie, Paris, France

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:

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

The binned estimate will not take these effects into account at all and the resulting map may be severely completely dominated by them. The GLS estimate will consider these components as noise and downweight them to make an optimal map. The filter-bin estimate will fit and remove a model of those signals from the TOD, but this will typically remove some sky signal as well; the effect must be quantified and corrected using transfer functions. Template map-making will jointly deproject the contaminants and estimate the sky signal in an unbiased way.

The pair differencing approach

We assume that the atmospheric signal and the ground pickup are *unpolarized*. This motivates the **pair differencing** approach, where the timestreams of two orthogonal detectors (see Figure 1) are subtracted in order to eliminate non polarized signals.

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

This operation 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, BICEP, (others ?)

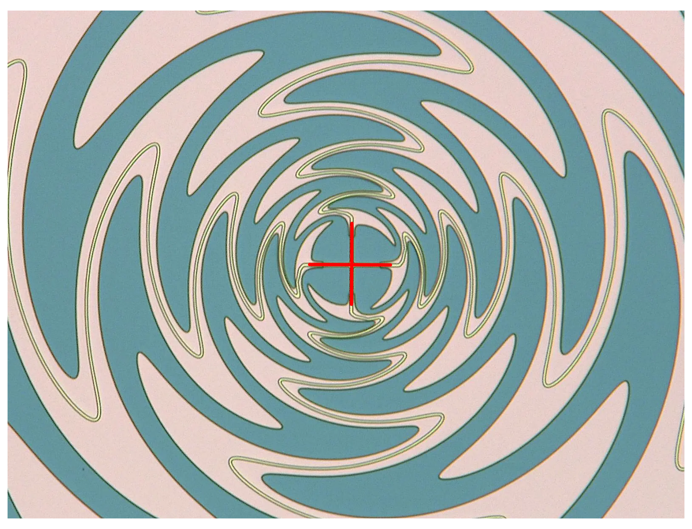

Figure 1. Center of a sinuous antenna detector used for Simons Observatory.

Advantages

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:

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

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).

We can show that pair differencing is nearly optimal [...]

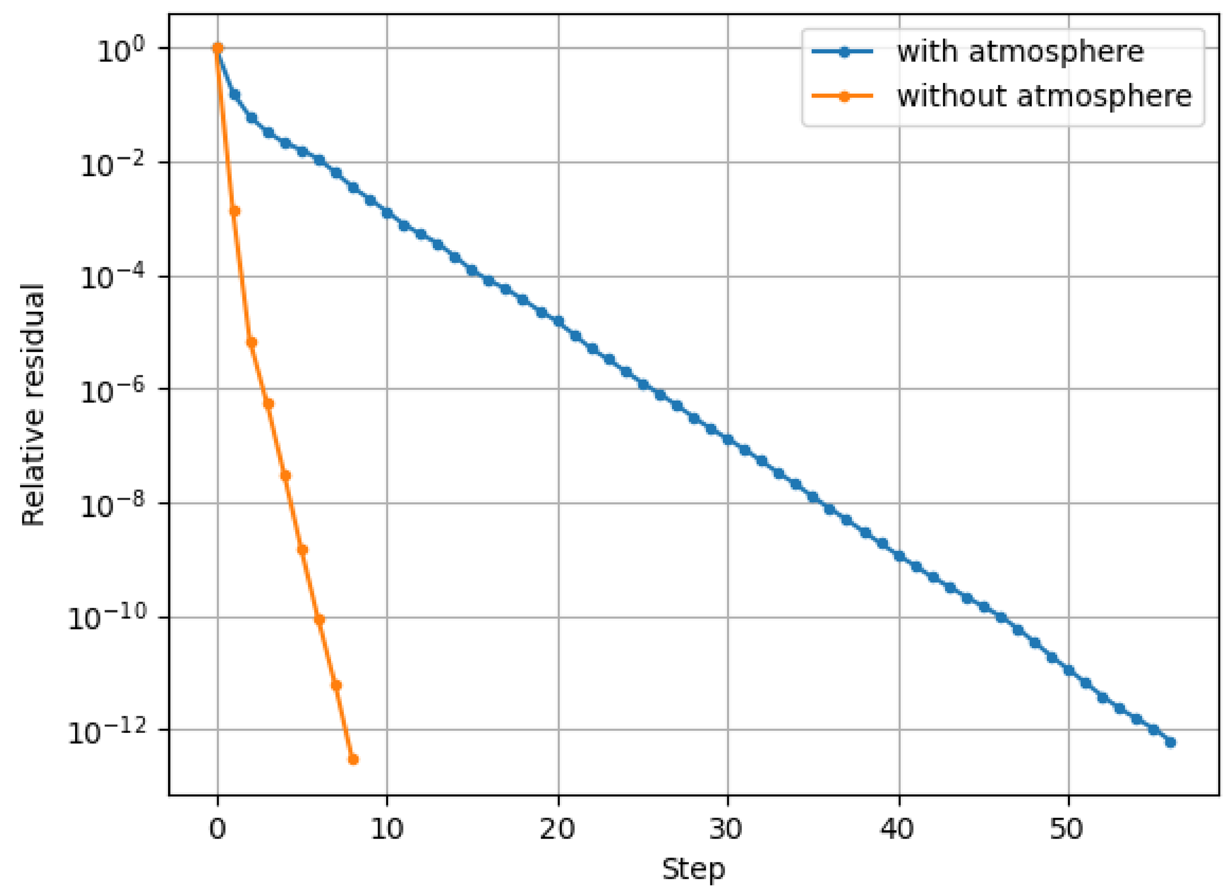

Figure 2. Convergence comparison with and without atmospheric correlations.

Drawbacks

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. 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

Simulations and results

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 ?

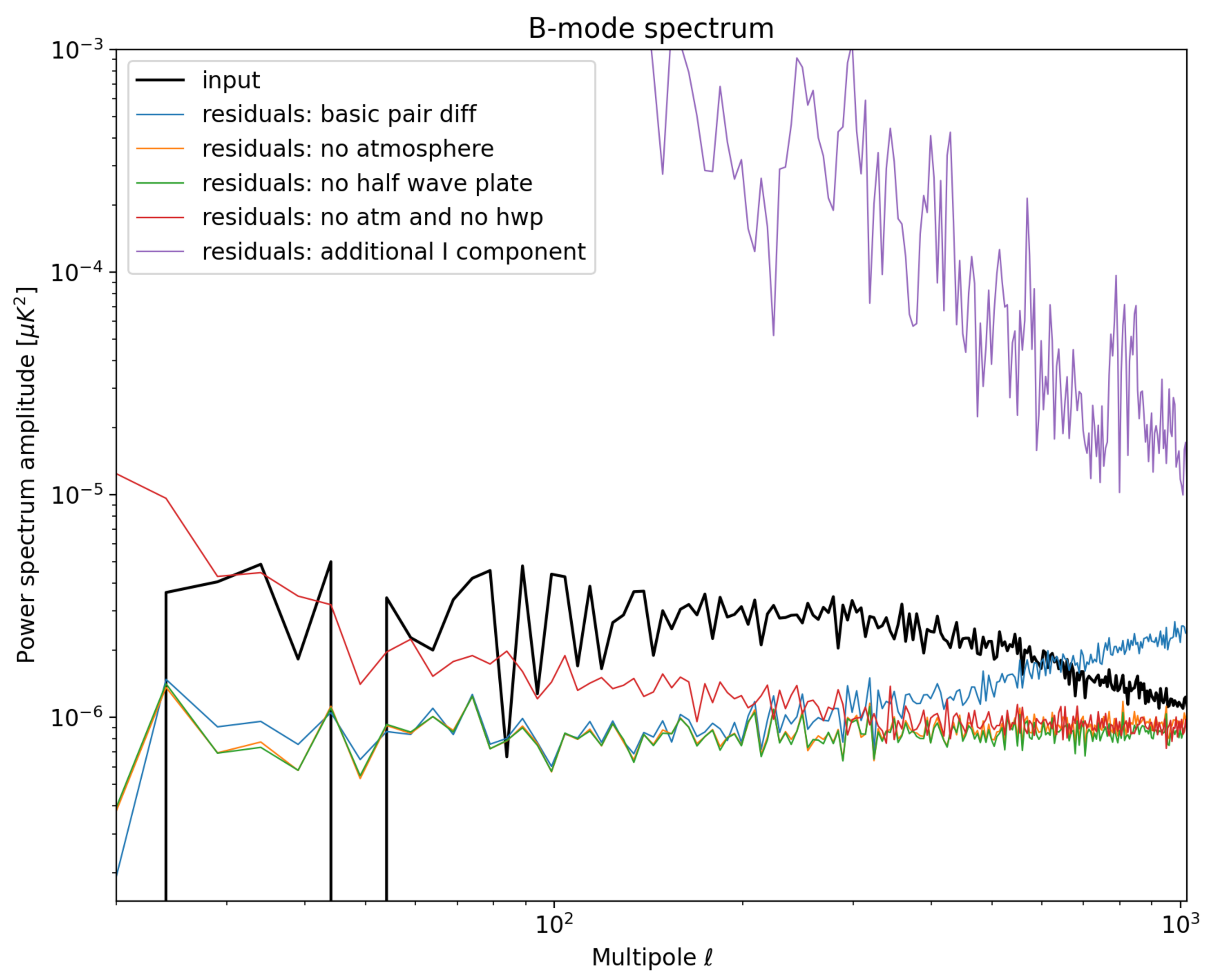

Figure 3. B-mode spectrum in different configurations. Solid lines are the measured spectrum, dotted lines are the difference with respect to the input spectrum (residual).

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.

biquard@apc.in2p3.fr