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

$$\mathbf{d} = \mathbf{P}\mathbf{s} + \mathbf{n} \tag{1}$$

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

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

Map-making is just a *linear operation*, $\mathbf{m} = \mathbf{L}\mathbf{d}$, mapping the TOD to an estimator $\mathbf{m}$ of the true sky map.

Method	Operator $\mathbf{L}$	Pros	Cons
Binning	$\left(\mathbf{P}^\mathsf{T}\mathbf{\Lambda}\mathbf{P}\right)^{-1}\mathbf{P}^\mathsf{T}\mathbf{\Lambda}$	unbiased, cheap	complex noise
GLS	$\left(\mathbf{P}^\mathsf{T}\mathbf{C}_\mathbf{n}^{-1}\mathbf{P}\right)^{-1}\mathbf{P}^\mathsf{T}\mathbf{C}_\mathbf{n}^{-1}$	unbiased, min. variance	expensive
Filter-and-bin	$\left(\mathbf{P}^\mathsf{T}\mathbf{\Lambda}\mathbf{P}\right)^{-1}\mathbf{P}^\mathsf{T}\mathbf{F}$	easy to compute	biased
Templates	$\left(\mathbf{P}^\mathsf{T}\mathbf{F}\mathbf{P}\right)^{-1}\mathbf{P}^\mathsf{T}\mathbf{F}$	unbiased filtering	iterative

Table 2. Comparison of different map-making approaches. Legend: $\mathbf{\Lambda}$ = diagonal noise weights; $\mathbf{C}_\mathbf{n}^{-1}$ = noise covariance matrix; $\mathbf{F}$ = 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

Results: gain errors

Numerical advantages of pair differencing

Reduce noise 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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