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augr: an end-to-end differentiable framework for forecasting and optimizing CMB instrument design

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Abstract

Observations of the polarization of the cosmic microwave background (CMB), and in particular the search for primordial gravitational waves from inflation, were named a high priority by the Astro2020 decadal survey, but the cancellation of CMB-S4 has made it clear that the time for a probe-scale CMB space mission is now. A NASA-led microwave imaging polarimeter offers a route to these goals and beyond, made more feasible by recent instrument technology developments and advances in launch capability. Designing such a mission demands careful optimization of parameters with respect to the overall science goals. We present augr, a JAX-native, open-source framework that computes the marginalized constraint on the tensor-to-scalar ratio r directly from physical instrument specifications including aperture, focal-plane geometry, feedhorn packing, detector counts, and sensitivities, and is differentiable end-to-end. Because the uncertainty on r is a differentiable function of the design, gradient descent replaces brute-force grid searches, and we optimize instrument parameters jointly given realistic data-processing and foreground-separation efficiencies and a realistic instrument cost model. augr features an internal map-based component separation pipeline (needlet and constrained-moment internal linear combination), self-consistent iterative full- and flat-sky delensing, and both Gaussian and moment-expansion treatments of dust and synchrotron foregrounds, with end-to-end gradients enabling optimization of instrument parameters over the cleaning and analysis pipeline itself, to our knowledge the first public code to do so. A Hamimeche–Lewis likelihood with Hamiltonian Monte Carlo sampling and simulation-based calibration provides honest non-Gaussian uncertainties at large angular scales, and Bayesian experimental design (expected information gain with active subspace dimension reduction) identifies the design directions that most improve r. Validated against published PICO, BICEP/Keck, and component-separated forecasts, augr is a fast, reproducible trade-study engine for maturing a CMB mission concept.

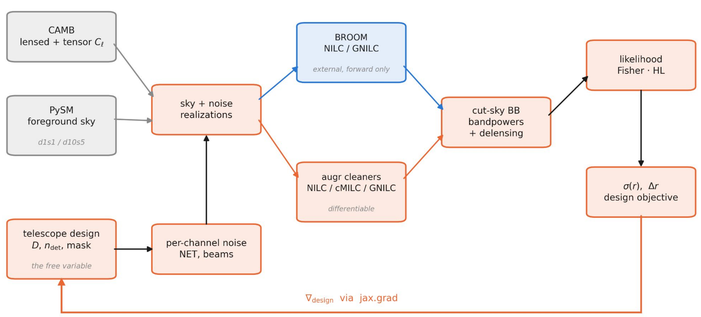

Figure 1. augr pipeline layout. Sky inputs are provided by CAMB and PySM, and combined with instrument noise and survey properties to produce as-observed realizations which are then passed through the component separation and likelihood pipelines. Gradients flow through the full augr-side chain (orange), enabling reoptimization of the instrument parameters and foreground cleaning with respect to the input foreground models.

References

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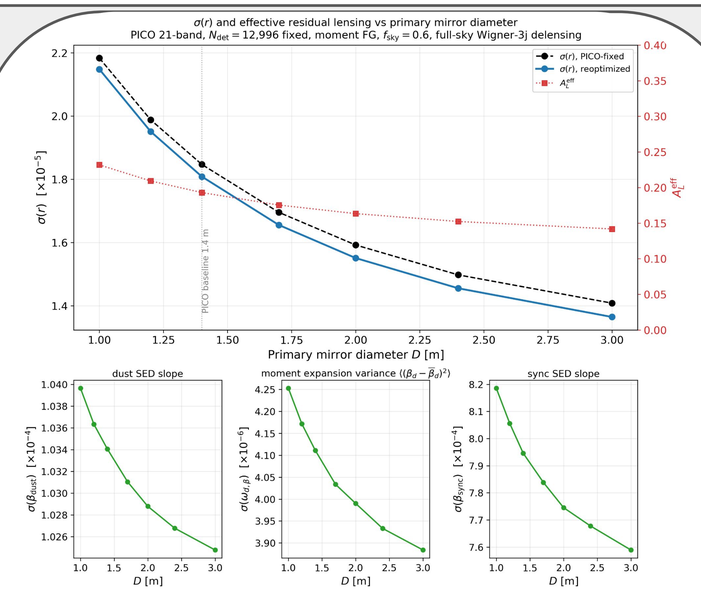

Figure 2. Sensitivity scaling with primary aperture diameter for the parametric moment-based foreground model for a PICO-like (21-band) configuration. Top: σ(r) and the effective lensing residual A_L as a function of primary diameter. The PICO detector-band allocation is shown in the black dashed line, while an augr gradient-reoptimized allocation with the same detector count and bands is shown in blue. Bottom: Uncertainties on recovered foreground parameters. Left: dust spectral index; right: synchrotron spectral index; center: dust spectral index moment variance.

Features

- Physics-up forward modeling of instrument parameters all the way to cosmology
- Map-based (NILC/cMILC) and parametric foreground cleaning with various options
- PySM (PanEX group et al. 2025) foreground model integration
- Realistic detector noise and anisotropic depth, multi-patch integration
- BROOM (Carones et al. 2025) integration for validation and to explore alternative models
- Self-consistent iterative full-sky quadratic estimator (QE) delensing
- Validated against PICO (space-based) and BICEP/*Keck* (ground-based) parametric forecasts
- Fisher matrix-based forecasts or full MCMC (NUTS HMC), with option of a Hamimeche-Lewis likelihood

Differentiability and Optimization: From a Forecast Code to a Design Tool

- Joint gradient-based optimization of instrument and pipeline parameters
  - Optimize analysis output with respect to frequency band arrangement, detector count distribution/focal plane packing, foreground cleaning parameters
- Bayesian expected information gain (EIG) and Hamiltonian Monte Carlo (NUTS) to directly solve for the optimal instrument configuration, subject to realistic constraints
  - Constrained by a realistic instrument/mission cost model, physical sizing/packing considerations, and mission scope/budget

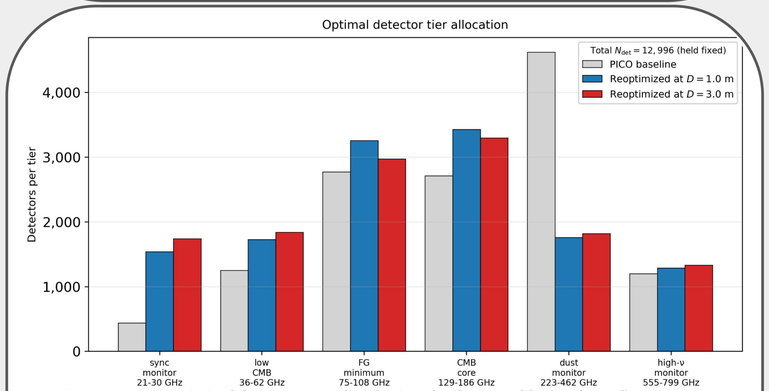

Figure 3. augr-reoptimized detector count distributions for the PICO-like (21-channel) configuration shown in Figure 2 (that which drives the difference between the black dashed and blue curves in that figure). Total detector count and spacing of bands is held fixed, while the distribution between them is reoptimized (for this simple study, neglecting physical focal plane packing) to minimize σ(r). This is done through the parametric path rather than the map-based, but full-sky iterative QE delensing is used, as is the moment expansion dust mode. Note that the this is intended to be schematic, but optimization is a strong function of the foreground modeling and cleaning, which remains an active area of investigation.

https://github.com/jrcheshire/cmb-augr

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pip install cmb-augr
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