

¹ cosmo-numba: B-modes and COSEBIs computations accelerated by Numba

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¹⁵ ¹⁶ ¹⁷ ¹⁸ ¹⁹

⁶ Summary

⁷ Cosmic shear important probe. B-modes computation as null test This software propose at ⁸ the same time a user friendly interface and fast computation for E-/B-mode decomposition.

⁹ Statement of need

¹⁰ The E-/B-mode composition for cosmic shear poses a significant computational challenge given ¹¹ the need for high precision (required to integrate oscillatory functions over a large integration ¹² range and achieve accurate results) and speed. Cosmo-numba meets this need, facilitating the ¹³ computation of E-/B-modes decomposition using two methods. One of them is the Complete ¹⁴ Orthogonal Sets of E-/B-mode Integrals (COSEBIs) as presented in P. Schneider et al. (2010). ¹⁵ The COSEBIs rely on very high precision computation requiring more than 80 decimal places. ¹⁶ P. Schneider et al. (2010) propose an implementation using mathematica. cosmo-numba uses ¹⁷ a combination of sympy and mpmath to reach the required precision. This python version ¹⁸ enables an easier integration within cosmological inference pipelines, which are commonly ¹⁹ python-based, and facilitates the null tests.

²⁰ This software package also enables the computation of the pure-mode correlation functions ²¹ presented in Peter Schneider et al. (2022). Those integrals are less numerically challenging ²² than the COSEBIs, but having a fast computation is necessary for computing the covariance ²³ matrix. One can also use those correlation functions for cosmological inference, in which case ²⁴ the large number of calls to the likelihood function will also require a fast implementation.

²⁵ COSEBIs

²⁶ The COSEBIs are defined as:

$$E_n = \frac{1}{2} \int_0^\infty d\theta \theta [T_{n,+}(\theta) \xi_+(\theta) + T_{n,-}(\theta) \xi_-(\theta)], \quad (1)$$

$$B_n = \frac{1}{2} \int_0^\infty d\theta \theta [T_{n,+}(\theta) \xi_+(\theta) - T_{n,-}(\theta) \xi_-(\theta)]; \quad (2)$$

²⁸ where $\xi_\pm(\theta)$ are the shear correlation functions, and $T_{n,\pm}$ are the weight functions for the ²⁹ COSEBI mode n . The complexity is in the computation of the weight functions. Cosmo-numba ³⁰ carries out the computation of the weight functions in a logarithmic scale defined by:

$$T_{n,+}^{\log}(\theta) = t_{n,+}^{\log}(z) = N_n \sum_{j=0}^{n+1} \bar{c}_{nj} z^j; \quad (3)$$

31 where $z = \log(\theta/\theta_{\min})$, N_n is the normalization for the mode n , and \bar{c}_{jn} are defined iteratively
 32 from Bessel functions (we refer the readers to P. Schneider et al. (2010) for more details).

33 We have validating our implementation against the original version in Mathematica from P.
 34 Schneider et al. (2010). In Figure 1 we show the impact of the precision going from 15 decimal
 35 places, which corresponds to the precision one could achieve using float64, up to 80 decimal
 36 places, the precision used in the original Mathematica implementation. We can see that classic
 37 float64 precision would not be sufficient, and with a precision of 80 our code exactly recovers
 38 the results from the original implementation. Similarly, the impact on the COSEBIs is shown
 39 in Figure 2.

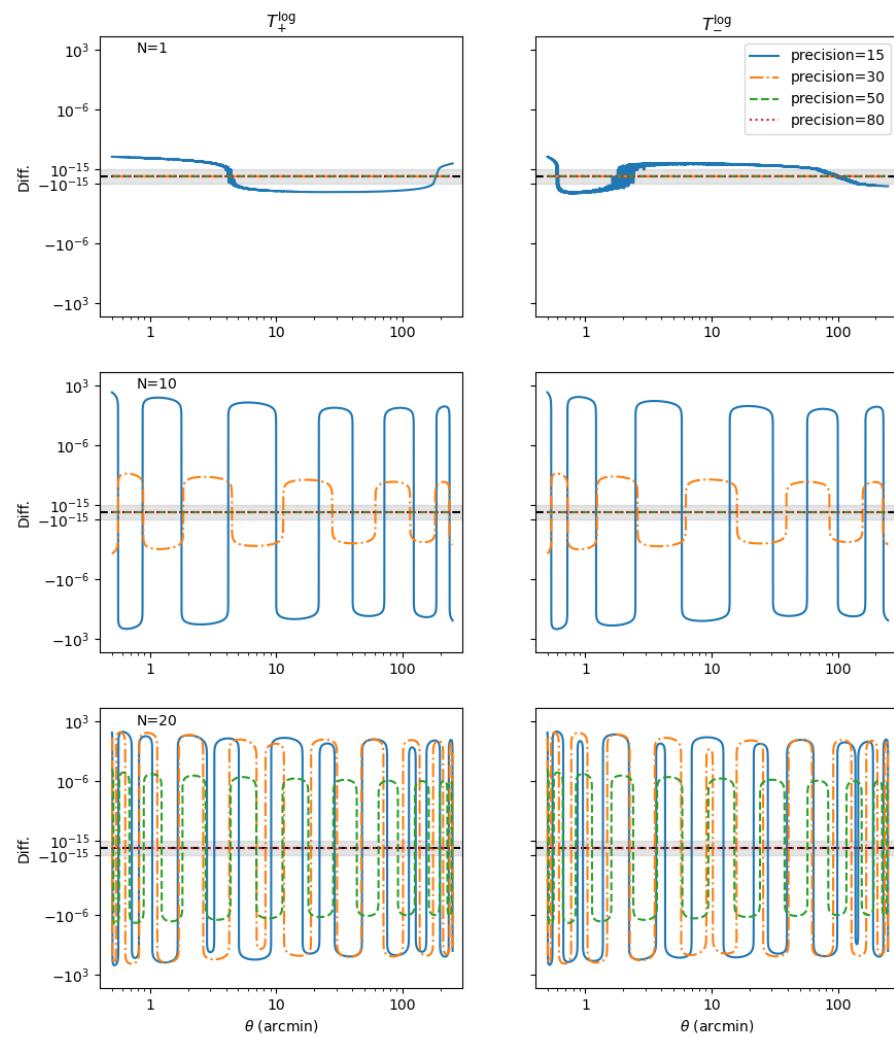


Figure 1: In this figure we show the impact of the precision in the computation of the weight functions T_{\pm}^{\log} . For comparison, a precision of 15 corresponds to what would be achieved using numpy float64. The relative error is computed with respect to the original Mathematica implementation presented in P. Schneider et al. (2010).

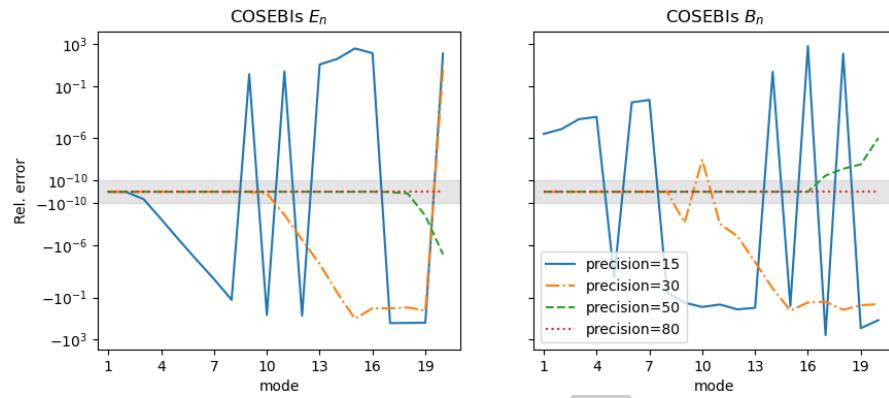


Figure 2: Same as figure [Figure 1](#) for the COSEBIs E- and B-mode.

⁴⁰ COSEBIs can also be defined from the power spectrum as:

$$E_n = \int_0^\infty \frac{d\ell \ell}{Z\pi} P_E(\ell) W_n(\ell); \quad (4)$$

$$B_n = \int_0^\infty \frac{d\ell \ell}{Z\pi} P_B(\ell) W_n(\ell); \quad (5)$$

⁴² where $P_{E/B}(\ell)$ is the power spectrum of E- and B-modes and $W_n(\ell)$ are the filter functions
⁴³ which can be computed from $T_{n,+}$ as:

$$W_n(\ell) = \int_{\theta_{\min}}^{\theta_{\max}} d\theta \theta T_{n,+}(\theta) J_0(\ell\theta); \quad (6)$$

⁴⁴ with $J_0(\ell\theta)$ the 0-th order Bessel function. The [Equation 6](#) is a Hankel transform of order 0.
⁴⁵ It can be computed using the FFTLog algorithm presented in [Hamilton \(2000\)](#) implemented
⁴⁶ here in Numba. [Figure 3](#) shows the comparison between the COSEBIs computed from $\xi_{\pm}(\theta)$
⁴⁷ and from $C_{E/B}(\ell)$. We can see that the COSEBI E-modes agree very well but the B-modes
⁴⁸ are more stable when computed from the $C(\ell)$ space.

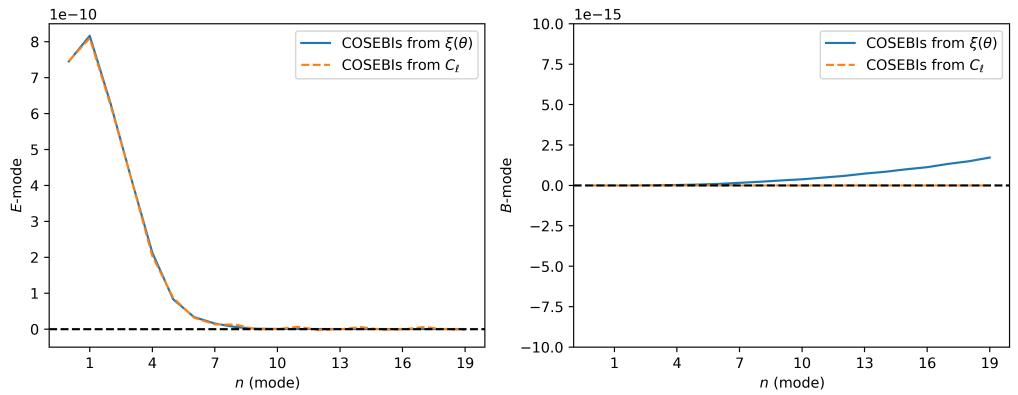


Figure 3: Comparison of the COSEBIs E- and B-mode computed from $\xi_{\pm}(\theta)$ and $C_{E/B}(\ell)$.

49 Pure-Mode Correlation Functions

50 In this section we describe the computation of the pure-mode correlation functions as defined
 51 in Peter Schneider et al. (2022). There are defined as follow:

$$\xi_+^E(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) + \xi_-(\vartheta) + \int_{\vartheta}^{\vartheta_{\max}} \frac{d\theta}{\theta} \xi_-(\theta) \left(4 - \frac{12\vartheta^2}{\theta^2} \right) \right] - \frac{1}{2} [S_+(\vartheta) + S_-(\vartheta)], \quad (7)$$

$$52 \quad \xi_+^B(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) - \xi_-(\vartheta) - \int_{\vartheta}^{\vartheta_{\max}} \frac{d\theta}{\theta} \xi_-(\theta) \left(4 - \frac{12\vartheta^2}{\theta^2} \right) \right] - \frac{1}{2} [S_+(\vartheta) - S_-(\vartheta)], \quad (8)$$

$$\xi_-^E(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) + \xi_-(\vartheta) + \int_{\vartheta_{\min}}^{\vartheta} \frac{d\theta \theta}{\vartheta^2} \xi_+(\theta) \left(4 - \frac{12\theta^2}{\vartheta^2} \right) \right] - \frac{1}{2} [V_+(\vartheta) + V_-(\vartheta)], \quad (9)$$

$$53 \quad \xi_-^B(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) - \xi_-(\vartheta) + \int_{\vartheta_{\min}}^{\vartheta} \frac{d\theta \theta}{\vartheta^2} \xi_+(\theta) \left(4 - \frac{12\theta^2}{\vartheta^2} \right) \right] - \frac{1}{2} [V_+(\vartheta) - V_-(\vartheta)]; \quad (10)$$

54 where $\xi_{\pm}(\theta)$ correspond to the shear-shear correlation function. The functions $S_{\pm}(\theta)$ and $V_{\pm}(\theta)$
 55 are themselves defined by integrals and we refer the reader to Peter Schneider et al. (2022)
 56 for more details about their definition. By contrast with the computation of the COSEBIs,
 57 these integrals are more stable and straightforward to compute but still require some level of
 58 precision. This is why we are using the quads method with a 5-th order spline interpolation.
 59 In addition, as one can see from the equations above, the implementation requires a loop over
 60 a range of ϑ values. This is why having a fast implementation will be required if one want to
 61 use those correlation functions in cosmological inference.

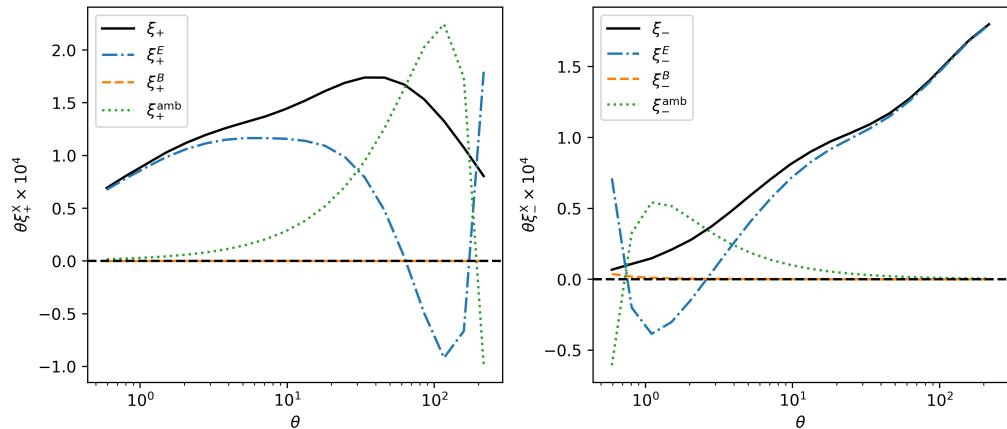


Figure 4: This figure shows the decomposition of the shear-shear correaltion functions in E- and B-modes (and ambiguous mode).

62 Acknowledgements

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