

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

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⁶ Summary

⁷ Weak gravitational lensing is a widely used probe in cosmological analysis. It allows astrophysicists ⁸ to understand the contend and evolution of the Universe. We are entering an era where we are ⁹ not limitied by the data volume but by systematics. It is in this context that we are presenting ¹⁰ here a simple python based software package to help in the computation of E-/B-mode ¹¹ decomposition which can be use for systematic checks or science analysis. As we demonstrate ¹² after, our implementation has both the high precision required and speed to perform this kind ¹³ of analysis.

¹⁴ Statement of need

The E-/B-mode composition for cosmic shear poses a significant computational challenge given ¹⁶ the need for high precision (required to integrate oscillatory functions over a large integration range and achieve accurate results) and speed. Cosmo-numba meets this need, facilitating the ¹⁷ computation of E-/B-modes decomposition using two methods. One of them is the Complete ¹⁸ Orthogonal Sets of E-/B-mode Integrals (COSEBIs) as presented in P. Schneider et al. ([2010](#)). ¹⁹ The COSEBIs rely on very high precision computation requiring more than 80 decimal places. ²⁰ P. Schneider et al. ([2010](#)) propose an implementation using mathematica. cosmo-numba uses ²¹ a combination of sympy and mpmath to reach the required precision. This python version ²² enables an easier integration within cosmological inference pipelines, which are commonly ²³ python-based, and facilitates the null tests.

²⁵ This software package also enables the computation of the pure-mode correlation functions ²⁶ presented in Peter Schneider et al. ([2022](#)). Those integrals are less numerically challenging ²⁷ than the COSEBIs, but having a fast computation is necessary for computing the covariance ²⁸ matrix. One can also use those correlation functions for cosmological inference, in which case ²⁹ the large number of calls to the likelihood function will also require a fast implementation.

³⁰ Testing setup

³¹ In the following two sections we will need fiducial shear-shear correlation functions, $\xi_{\pm}(\theta)$, ³² and power spectrum, $P_{E/B}(\ell)$. They have been computed using the Core Cosmology Library¹ ³³ ([Chisari et al., 2019](#)) developed by the Dark Energy Science Collaboration. The cosmological ³⁴ parameters are taken from Aghanim et al. ([2020](#)).

¹<https://github.com/LSSTDESC/CCL>

35 COSEBIs

36 The COSEBIs are defined as:

$$37 E_n = \frac{1}{2} \int_0^\infty d\theta \theta [T_{n,+}(\theta) \xi_+(\theta) + T_{n,-}(\theta) \xi_-(\theta)], \quad (1)$$

$$38 B_n = \frac{1}{2} \int_0^\infty d\theta \theta [T_{n,+}(\theta) \xi_+(\theta) - T_{n,-}(\theta) \xi_-(\theta)]; \quad (2)$$

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

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

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

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

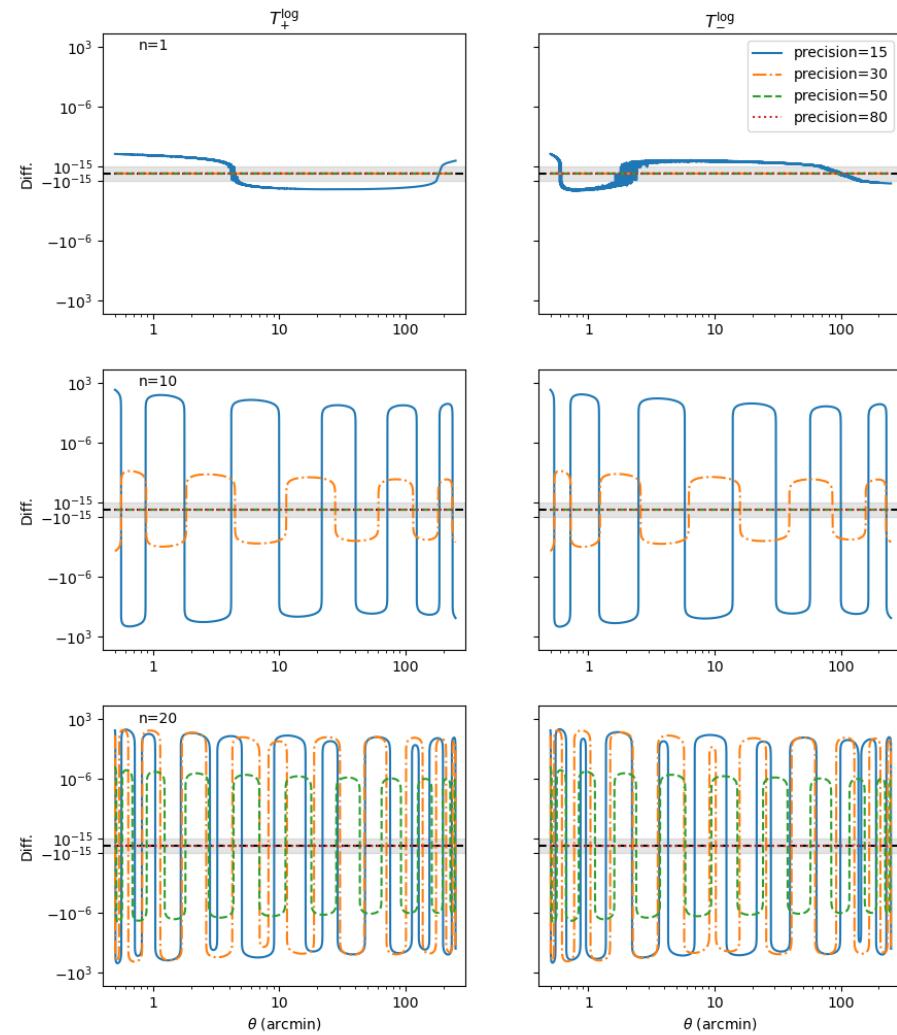


Figure 1: In this figure we show the impact of the precision in the computation of the weight functions T_{\pm}^{\log} . For comparison, a precision of 15 corresponds to what would be achieved using numpy float64. The difference is computed with respect to the original Mathematica implementation presented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

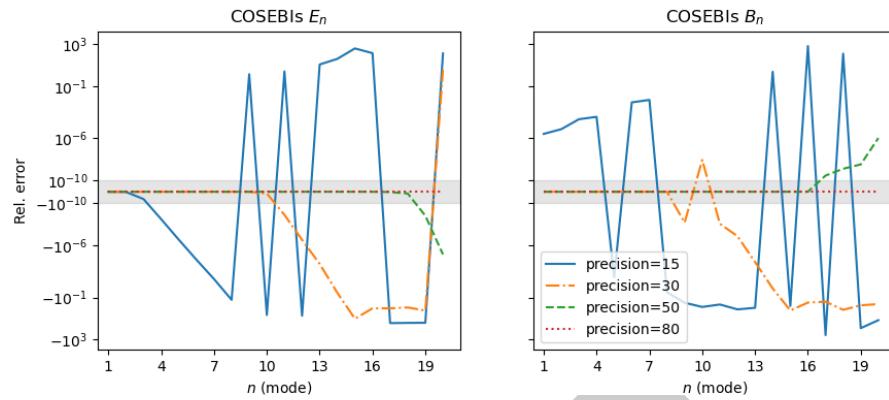


Figure 2: This figure shows the difference on the COSEBIs E- and B-mode relative to the original Mathematica implementation. We see that using only 15 decimal places would lead to several percent error making an implementation based on numpy float64 not suitable. The figure uses symlog, the shaded region represent the linear scale.

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

$$51 \quad E_n = \int_0^\infty \frac{d\ell \ell}{2\pi} P_E(\ell) W_n(\ell); \quad (4)$$

$$52 \quad B_n = \int_0^\infty \frac{d\ell \ell}{2\pi} P_B(\ell) W_n(\ell); \quad (5)$$

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

$$54 \quad W_n(\ell) = \int_{\theta_{\min}}^{\theta_{\max}} d\theta \theta T_{n,+}(\theta) J_0(\ell\theta); \quad (6)$$

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

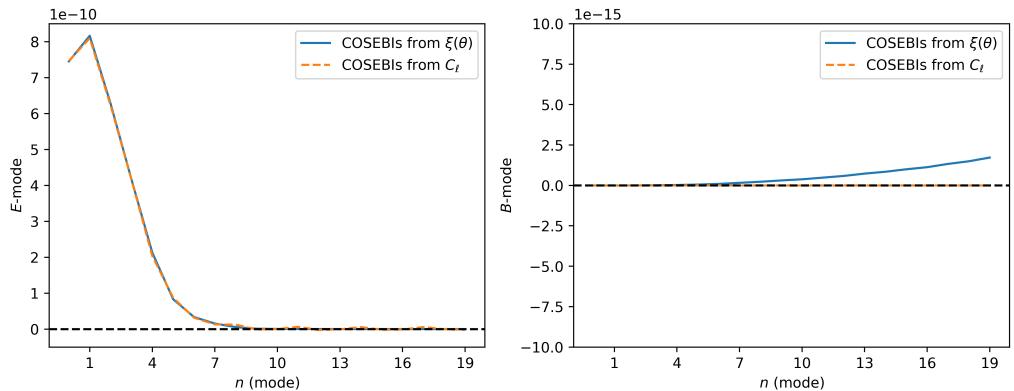


Figure 3: Comparison of the COSEBIs E- and B-mode computed from $\xi_\pm(\theta)$ and $C_{E/B}(\ell)$.

59 Pure-Mode Correlation Functions

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

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

$$62 \quad \xi_+^B(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) - \xi_-(\vartheta) - \int_{\vartheta}^{\vartheta_{\max}} \frac{d\theta}{\theta} \xi_-(\theta) \left(4 - \frac{12\vartheta^2}{\theta^2} \right) \right] - \frac{1}{2} [S_+(\vartheta) - S_-(\vartheta)], \quad (8)$$

$$63 \quad \xi_-^E(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) + \xi_-(\vartheta) + \int_{\vartheta_{\min}}^{\vartheta} \frac{d\theta \theta}{\vartheta^2} \xi_+(\theta) \left(4 - \frac{12\theta^2}{\vartheta^2} \right) \right] - \frac{1}{2} [V_+(\vartheta) + V_-(\vartheta)], \quad (9)$$

$$64 \quad \xi_-^B(\vartheta) = \frac{1}{2} \left[\xi_+(\vartheta) - \xi_-(\vartheta) + \int_{\vartheta_{\min}}^{\vartheta} \frac{d\theta \theta}{\vartheta^2} \xi_+(\theta) \left(4 - \frac{12\theta^2}{\vartheta^2} \right) \right] - \frac{1}{2} [V_+(\vartheta) - V_-(\vartheta)]; \quad (10)$$

65 where $\xi_{\pm}(\theta)$ correspond to the shear-shear correlation function. The functions $S_{\pm}(\theta)$ and $V_{\pm}(\theta)$
 66 are themselves defined by integrals and we refer the reader to Peter Schneider et al. (2022)
 67 for more details about their definition. By contrast with the computation of the COSEBIs,
 68 these integrals are more stable and straightforward to compute but still require some level of
 69 precision. This is why we are using the qags method from the QUADPACK² (Piessens et al.,
 70 2012) with a 5-th order spline interpolation. In addition, as one can see from the equations
 71 above, the implementation requires a loop over a range of ϑ values. This is why having a fast
 72 implementation will be required if one want to use those correlation functions in cosmological
 inference.

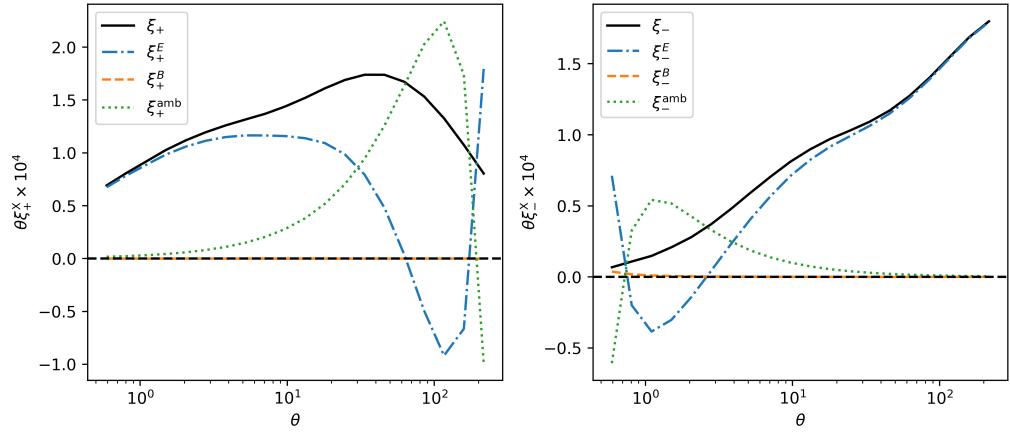


Figure 4: This figure shows the decomposition of the shear-shear correaltion functions in E- and B-modes (and ambiguous mode).

73 Acknowledgements

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²We use the C version of the library wrapped to python using Numba: <https://github.com/Nicholaswogan/NumbaQuadpack>

76 References

- 77 Aghanim, N., Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday,
78 A. J., Barreiro, R. B., Bartolo, N., Basak, S., Battye, R., Benabed, K., Bernard, J.-P.,
79 Bersanelli, M., Bielewicz, P., Bock, J. J., Bond, J. R., Borrill, J., Bouchet, F. R., ...
80 Zonca, A. (2020). Planck 2018 results: VI. Cosmological parameters. *Astronomy & Astrophysics*, 641, A6. <https://doi.org/10.1051/0004-6361/201833910>
- 82 Chisari, N. E., Alonso, D., Krause, E., Leonard, C. D., Bull, P., Neveu, J., Villarreal, A., Singh,
83 S., McClintock, T., Ellison, J., Du, Z., Zuntz, J., Mead, A., Joudaki, S., Lorenz, C. S.,
84 Tröster, T., Sanchez, J., Lanusse, F., Ishak, M., ... Wagoner, E. L. (2019). Core cosmology
85 library: Precision cosmological predictions for LSST. *The Astrophysical Journal Supplement
86 Series*, 242(1), 2. <https://doi.org/10.3847/1538-4365/ab1658>
- 87 Hamilton, A. J. S. (2000). Uncorrelated modes of the non-linear power spectrum. *Monthly
88 Notices of the Royal Astronomical Society*, 312(2), 257–284. [https://doi.org/10.1046/j.1365-8711.2000.03071.x](https://doi.org/10.1046/j.
89 1365-8711.2000.03071.x)
- 90 Piessens, R., Doncker-Kapenga, E. de, Überhuber, C. W., & Kahaner, D. K. (2012). *Quadpack:
91 A subroutine package for automatic integration* (Vol. 1). Springer Science & Business
92 Media.
- 93 Schneider, Peter, Asgari, M., Jozani, Y. N., Dvornik, A., Giblin, B., Harnois-Déraps, J.,
94 Heymans, C., Hildebrandt, H., Hoekstra, H., Kuijken, K., Shan, H., Tröster, T., & Wright,
95 A. H. (2022). Pure-mode correlation functions for cosmic shear and application to KiDS-
96 1000. *Astronomy & Astrophysics*, 664, A77. [https://doi.org/10.1051/0004-6361/202142479](https://doi.org/10.1051/0004-6361/
97 202142479)
- 98 Schneider, P., Eifler, T., & Krause, E. (2010). COSEBIs: Extracting the full e-/b-mode
99 information from cosmic shear correlation functions. *Astronomy and Astrophysics*, 520,
100 A116. <https://doi.org/10.1051/0004-6361/201014235>