

FLASK: Full-sky Lognormal Astro-fields Simulation Kit

Usage and installation manual

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Chapter 1

Disclaimer

FLASK is free software, written by Henrique S. Xavier; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation; either version 2 of the License, or (at your option) any later version.

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Thank you for using this software. Please report any bugs to hsxavier@if.usp.br and acknowledge FLASK by citing the publication [Xavier et al. \(2016\)](#).

Chapter 2

Installation

2.1 Requirements

FLASK is a code written in C++ that uses OPENMP for parallelization; HEALPIX¹ for mapping the sky and performing harmonic transforms; the Gnu Scientific Library² (GSL) to generate pseudo-random numbers, to perform Cholesky decompositions and other tasks; and the CFITSIO³ library to input and output FITS files. Apart from HEALPIX, all the remaining dependencies should be available on Linux and Mac repositories. HEALPIX however should be easy to install (just follow their instructions); FLASK requires version 3.11 or later of the C++ HEALPIX implementation due to specific functions implemented only on these versions.

So far FLASK has been tested only on Linux distributions – Scientific Linux 5.6 and Ubuntu 14.04 – and compiled with g++ (GCC) versions 4.8.1 and 4.8.4. Besides the main code and other routines in C++, FLASK also includes auxiliary PYTHON and SHELL scripts. These were tested in BASH shell and PYTHON versions 2.7.3 and 2.7.6. The PYTHON scripts require the a few packages like NUMPY, SCIPY and HEALPY (which can be installed by following HEALPIX instructions). Check the scripts for further dependencies.

2.2 Compiling

Before compiling, you will have to modify the Makefile in the src subdirectory of FLASK. The following lines must be changed according to the location of the HEALPIX installation directory:

```
CXXHEAL = -I<path to Healpix header files>
LDHEAL = -L<path to Healpix library files>
```

In case other libraries such as CFITSIO, GSL are installed in non-standard locations, you might need to specify their locations with similar compiler flags. The default compiler in the Makefile is g++, you might need to change the keyword COMP as well if using a different compiler.

¹<http://healpix.jpl.nasa.gov>

²<http://www.gnu.org/software/gsl>

³<http://heasarc.gsfc.nasa.gov/fitsio>

After changing the `Makefile`, run the command `make` in the `src` directory. The executables will be build in `FLASK bin` subdirectory. You may add this subdirectory to your `PATH` environment variable in order to be able to run `FLASK` anywhere; otherwise, you will require to run it from there or to provide the full path as usual.

Chapter 3

Usage

3.1 Using FLASK

3.1.1 Quick start

3.1.2 Basic operation

FLASK is executed through the command line, and it always requires a configuration file (e.g. `example.config` in the FLASK directory):

```
flask <config file>
```

Any keyword in the configuration file can be altered from the command line by specifying its name `<keyword_i>` and value `<value_i>` after passing the configuration file to FLASK:

```
flask <config file> <keyword_1>: <value_1> <keyword_2>: <value_2>...
```

For example,

```
flask example.config RNDSEED: 334 MAP_OUT: ./map-002.dat
```

FLASK outputs to the screen a comprehensive description of what it is doing. In case you want to store this information for later, you might want to redirect the output to a file, e.g.:

```
flask example.config RNDSEED: 334 MAP_OUT: ./map-002.dat > r334.log
```

3.1.3 Inner workings

The internal process followed by FLASK is described in [Xavier et al. \(2016\)](#). Fig. 3.1 shows a flow chart that roughly described the operations sequences. Some processes are only performed when simulating lognormal fields (Gaussian simulations may skip a few of them). Other processes like creating triangular matrices used for generating correlated random variables and performing a density line-of-sight (LoS) integration to



Figure 3.1: FLASK basic flow chart.

get the convergence are optional (they are executed according to the specifications in the configuration file).

3.1.4 Configuration file keywords

FLASK is built in a way that all the existing keywords in the code must be present in the configuration file otherwise a warning message is issued; this is to avoid setting keywords to values unknown by the user and to disclose to the user all available options in the code. FLASK will also complain if keywords that do not exist in the code are present in the configuration file or are passed through the command line; keywords are identified by a colon (:) after it, so this should not be used for other purposes inside configuration files. Although the hash (#) is used to identify comments, this is only for aesthetic reasons and does not have any effect on the parsing of the configuration file (# DENS2KAPPA: is still identified as the DENS2KAPPA keyword). More information about this can be found in the `example.config` file.

FLASK goes through a series of sequential computations that transforms the simulated data somehow; after each step, the code can output the current status of the data. These possible outputs are presented in the `example.config` file in the exact order they are produced. Thus, one can have an idea of the simulation process by reading the output options in that file. All outputs can be turned off by assigning 0 to the respective keyword.

We now provide a description of every keyword available in the code (a brief descrip-

tion of each one is also provided in `example.config`):

- **DIST**: This takes as value one string that can be either `GAUSSIAN`, `LOGNORMAL` or `HOMOGENEOUS`, specifying what kind of distribution all the simulated random fields will follow. The `HOMOGENEOUS` in fact ignores all input power spectra $C(\ell)$ s as if they were all zero and creates homogeneous field maps. Density fields can be later Poisson sampled according to the selection function, so the `HOMOGENEOUS` choice is useful to create the random catalogues used in [Landy and Szalay \(1993\)](#), for instance. Weak lensing shear produced under this choice is currently zero, and ellipticities are completely random according to `ELLIP_SIGMA`. For simulating Gaussian and lognormal correlated fields simultaneously, one should use the `LOGNORMAL` choice and adjust the input information so to approximate the desired fields to a Gaussian distribution.
- **RNDSEED**: This is a single integer number, the seed for the pseudo-random number generator. In fact, the seed is transformed into N_{proc} seeds, where N_{proc} is the number of processors available for parallel computing with `OPENMP`. This transformation is such that every seed provided to `RNDSEED` will result in different and exclusive set of N_{proc} so that different seeds truly result in independent realisations. Note that a given seed passed to `RNDSEED` will only result in the same realisation as long as N_{proc} remains the same.
- **POISSON**: This can be 1 or 0, and specifies if the galaxy density fields should be Poisson sampled or not, respectively. If not sampled (useful for debugging reasons), the value attributed to the `HEALPIX` map is the expected number of galaxies (a non-integer number). This map can then be output through the `MAPWER_OUT` and `MAPWERFITS_PREFIX` keywords. Generating a galaxy catalogue from this map (with `POISSON: 0`) would not make much sense and is likely to cause the code to crash.
- **OMEGA_m**: This takes a real number that represents the total matter (dark matter plus baryons) density parameter. It is only used if the user sets: (1) `DENS2KAPPA: 1`; or (2) `SELEC_TYPE: 1` or `SELEC_TYPE: 3`.
- **OMEGA_L**: This takes a real number that represents the dark energy density parameter. It is only used if the user sets: (1) `DENS2KAPPA: 1`; or (2) `SELEC_TYPE: 1` or `SELEC_TYPE: 3`.
- **W_de**: This takes a real number that represents the w_0 parameter of a constant dark energy equation of state. It is only used if the user sets: (1) `DENS2KAPPA: 1`; or (2) `SELEC_TYPE: 1` or `SELEC_TYPE: 3`. Currently this is the only kind of dark energy model implemented in the code.
- **ELLIP_SIGMA**: This takes a real number that represents the standard deviation of the zero mean Gaussian distribution from which each component of the galaxy intrinsic

ellipticity ε_s is randomly drawn. The final ellipticity in the catalogue is $\varepsilon = \varepsilon_1 + i\varepsilon_2$:

$$\varepsilon = \begin{cases} \frac{\varepsilon_s + g}{1 + g^* \varepsilon_s}, & |g| \leq 1; \\ \frac{1 + g \varepsilon_s^*}{\varepsilon_s^* + g^*}, & |g| > 1; \end{cases} \quad (3.1)$$

where $g \equiv \gamma/(1 + \kappa)$ is the reduced shear, $\gamma = \gamma_1 + i\gamma_2$ is the shear, κ is the convergence, and $\varepsilon_s = \varepsilon_{s,1} + i\varepsilon_{s,2}$ is the galaxy intrinsic ellipticity (we follow [Bartelmann and Schneider, 2001](#), eq. 4.12).

- **GALDENSITY**: This takes a real number representing the 3D comoving galaxy number density in $(h^{-1}\text{Mpc})^{-3}$. It is only used if **SELEC_TYPE**: 1 or **SELEC_TYPE**: 3.
- **FIELDS_INFO**: This takes a string representing the path to the fields information file described in Sec. 3.1.5.
- **CHOL_IN_PREFIX**: This takes the character 0 or a string representing the path, including a file prefix, to the files written by the keyword **CHOLESKY_PREFIX** in a previous **FLASK** run. If set to 0, the code: takes as input the power spectra $C_{\text{in}}(\ell)$ s specified by **CL_PREFIX**; process it to obtain the associated Gaussian power spectra $C_g(\ell)$ s [if **DIST**: **LOGNORMAL**, otherwise $C_g(\ell) = C_{\text{in}}(\ell)$]; build independent covariance matrices for each ℓ ; regularize the matrices if necessary and requested; and perform a Cholesky decomposition to obtain triangular matrices – which can be written to files by the **CHOLESKY_PREFIX** keyword – used to generate correlated Gaussian variables. If **CHOL_IN_PREFIX** is not set to 0, **FLASK** therefore skips all the processing above and loads its final product – the triangular matrices, previously computed – into the memory.
- **CL_PREFIX**: This takes a string that represents the path (including a prefix) to all power spectra $C^{ij}(\ell)$ required to specify the statistical properties of the set of fields listed in the fields information file specified by **FIELDS_INFO**. Each $C^{ij}(\ell)$ must be in a separate file with two columns (ℓ and $C^{ij}(\ell)$). This string is only used if **CHOL_IN_PREFIX** is set to zero.
- **ALLOW_MISS_CL**: This can be 0 or 1. If 0, **FLASK** will abort if any required $C^{ij}(\ell)$ is not found. If 1, the code will assume that the missing $C^{ij}(\ell)$ s are zero. This works for cross power spectra but will cause the program to abort if auto power spectra are missing.
- **WINFUNC_SIGMA**: In case you want to simulate fields that have been convolved (smoothed) in each redshift slice with a 2D Gaussian, you can adjust the Gaussian's standard deviation here (this takes a real number). The power spectra will be adjusted accordingly. To skip applying this smoothing, set this value to something less than zero.
- **APPLY_PIXWIN**: To compute the value of a pixel from the map's harmonic coefficients, **HEALPIX** sums the multipoles weighted by their coefficients (i.e. performs

an inverse harmonic transformation) and computes the result at the angular coordinates of the pixel's centre (the pixel value is not the field average inside the pixel). In case you want the pixel value to be the field average inside the pixel, you must apply the HEALPIX window function to the input power spectra; this is done by setting `APPLY_PIXWIN` to 1. To skip this multiplication, set `APPLY_PIXWIN`: 0.

- `SUPPRESS_L`: This takes a real number that represents the scale ℓ_{sup} at which the input power spectra $C_{\text{in}}^{ij}(\ell)$ will be exponentially suppressed with index n given by `SUP_INDEX`. The suppressed power spectra $C_{\text{sup}}^{ij}(\ell)$, used for all subsequent computations and simulations, will be:

$$C_{\text{sup}}^{ij}(\ell) = C_{\text{in}}^{ij}(\ell) \exp \left[- \left(\frac{\ell}{\ell_{\text{sup}}} \right)^n \right] \quad (3.2)$$

To avoid applying this suppression, set either `SUPPRESS_L` or `SUP_INDEX` (or both) to something less than zero.

- `SUP_INDEX`: This takes a real number that represents the index n in Eq. 3.2 (see `SUPPRESS_L` description). You can avoid the use of such suppression by setting this value to a negative number.
- `SELEC_SEPARABLE`: This specifies if the galaxy selection function is separable between radial and angular parts (1) or not (0). If separable: the selection function value is the multiplication of the two; the keyword `SELEC_PREFIX` will actually take a single FITS filename representing the angular selection function as a HEALPIX map that will be used for all galaxy fields and all redshift slices; and the keyword `SELEC_Z_PREFIX` will take a prefix leading to one radial selection function for each galaxy field. If not separable, the keyword `SELEC_PREFIX` will take a path with a prefix that should lead to one HEALPIX map in FITS format for each galaxy field and redshift slice, representing the entire selection function. In this case, `SELEC_Z_PREFIX` is ignored.
- `SELEC_PREFIX`: This takes a string that represents either a path plus a prefix for a bunch of HEALPIX maps in FITS format representing the galaxies selection functions or the filename of a single HEALPIX map, representing the angular part of the selection function (see `SELEC_SEPARABLE` keyword). It can also be set to 0; in this case, the code works as if the selection function (or the angular selection if `SELEC_SEPARABLE`: 1) was equal to one in every pixel. For separable selection functions, this corresponds to a full-sky simulation; for non-separable selection function, this is just weird. In the current implementation, the selection functions must have the same N_{side} as the one passed to the `NSIDE` keyword.
- `SELEC_Z_PREFIX`: This takes a string representing the path plus a prefix for two column (redshift and selection function) text files, one for each galaxy field. This is ignored if `SELEC_SEPARABLE`: 0. The files can have headers if they start with #, and they have to be named according to the prefix, followed by `f[fi].dat`, where `[fi]` is the field number “naming” the field in the fields information file (see Sec. 3.1.5).

- **SELEC_SCALE**: This takes a real number that will serve as a re-scaling of the selection function (the selection function will be multiplied by this value). To use the exact values in the files specified by **SELEC_PREFIX** and **SELEC_Z_PREFIX**, set **SELEC_SCALE**: 1.0.
- **SELEC_TYPE**: There are two types of selection functions: one specifies the expected number of observed galaxies per unit redshift, per square arcmin (**SELEC_TYPE**: 0), and the other specifies the fraction of existing galaxies that are actually observed at each angular position and redshift (**SELEC_TYPE**: 1). In the latter case, the total existing galaxies is computed from the galaxy density given at **GALDENSITY** and the comoving volume calculated according to the pixel size (determined by **NSIDE**), the redshift slice width (set in the fields information file) and the cosmological parameters **OMEGA_m**, **OMEGA_L** and **W_de**. The option **SELEC_TYPE**: 1 is currently not fully implemented. On top of these two options, the user can specify that the angular part of the selection function is only used for bookkeeping (that is, it does not affect the number of galaxies generated and the simulation is actually full sky) by adding 2 to choice made, leading to the following possible options for **SELEC_TYPE**: 0, 1, 2 and 3. Currently the bookkeeping option only works for separable selection functions.
- **STARMASK**: Besides the selection function specified in **SELEC_PREFIX**, the user can multiply the selection function by a HEALPIX map in FITS file format, passed to this keyword. All selection functions are affected by this angular mask. In the current implementation, this map must have the same N_{side} as the one passed to the **NSIDE** keyword. To not use this extra angular selection function, the user can set **STARMASK**: 0.
- **EXTRAP_DIPOLE**: Many power spectra calculators like CLASS¹ or CAMB SOURCES² write $C(\ell)$ s for $\ell \geq 2$. If this keyword is set to 1, then the dipole $C(\ell = 1)$, if missing, is linearly extrapolated from $C(\ell = 2)$; otherwise, if **EXTRAP_DIPOLE**: 0 and the dipole is missing, then the dipole is set to zero (NOTE: the monopole is always set to zero).
- **LRANGE**: This takes two integers separated by space representing the minimum ℓ_{min} and maximum ℓ_{max} , respectively, that will be used to generate the associated Gaussian multipoles. They should obey $1 \leq \ell_{\text{min}} \leq \ell_{\text{max}} \leq \ell_{\text{in}}$, where ℓ_{in} is the highest ℓ provided in the input power spectra.
- **NSIDE**: This takes an integer representing the HEALPIX N_{side} parameter. The number of pixels N_{pix} used in each redshift slice is $N_{\text{pix}} = 12N_{\text{side}}^2$. Any number can be provided here, although some applications depend on powers of 2.
- **USE_HEALPIX_WGTS**: This keyword states if the code should use (1) or not (0) the HEALPIX weights to perform the map2alm (harmonic transform) operation. The weights are only available for $N_{\text{side}} = 2^n$, where $n \in \mathbb{N}$. If **USE_HEALPIX_WGTS**: 0, the weights will all be set to unity.

¹<http://class-code.net/>²<http://camb.info/sources>

- **BADCORR_FRAC**: This takes a real number f . In case some covariance matrix entries lead to forbidden correlations ρ_{ij} ($\rho_{ij} > 1$ or $\rho_{ij} < -1$), FLASK will add this fractional change to both variances related to the forbidden correlation: $v_i^{\text{new}} = (1 + f)v_i^{\text{old}}$ and $v_j^{\text{new}} = (1 + f)v_j^{\text{old}}$.
- **REGULARIZE_METHOD**: In case some associated Gaussian multipoles covariance matrix is non-positive-definite, FLASK can make it positive-definite by changing its entries. There are two methods currently implemented for that, described in [Xavier et al. \(2016\)](#): option **REGULARIZE_METHOD**: 1 performs an eigendecomposition of the matrix and sets the negative eigenvalues to a new value specified by **NEW_EVAL**; option **REGULARIZE_METHOD**: 2 looks for a direction of greatest change in the negative eigenvalues and apply successive distortions (up to **REG_MAXSTEPS** times) of size given by **REGULARIZE_STEP** in that direction, until all eigenvalues are positive. You may set **REGULARIZE_METHOD**: 0 to make FLASK abort in case of non-positive-definite matrices.
- **NEW_EVAL**: This takes a real number. If **REGULARIZE_METHOD** is set to 1, covariance matrices negative eigenvalues will be replaced by this value. This value is not used for other **REGULARIZE_METHOD** options.
- **REGULARIZE_STEP**: This takes a real number. If **REGULARIZE_METHOD** is set to 2, this will be the size of the step taken in the direction in the covariance matrix elements space that changes the negative eigenvalues the most. This value is not used for other **REGULARIZE_METHOD** options.
- **REG_MAXSTEPS**: This takes an integer number that specifies the maximum amount of steps taken in the covariance matrix elements space when trying to regularize the matrix with **REGULARIZE_METHOD**: 2. This value is not used for other **REGULARIZE_METHOD** options.
- **ADD_FRAC**: If the covariance matrix regularization fails or if it succeeds but the Cholesky decomposition still fails, FLASK will take the real value passed to this keyword, multiply by the smallest element of the covariance matrix diagonal and add the result to all diagonal elements of that matrix.
- **ZSEARCH_TOL**: When building the galaxy catalogue, FLASK will randomly select a redshift inside the galaxy's redshift slice according to the selection function. To do that, it has to find the selection function local maximum inside the redshift bin. The real value passed to **ZSEARCH_TOL** specifies the precision in redshift to which the maximum is found.
- **EXIT_AT**: This keyword takes a string that must be either 0 or any other keyword that specifies an output (without the colon, case sensitive). The code will stop right after the point where that output is produced, even if it is not set to be produced. If **EXIT_AT**: 0, FLASK will run until the end. The output keywords in the `example.config` file are ordered just like they are produced.
- **FITS2TGA**: This can take the options: 0, all HEALPIX map outputs remain only in HEALPIX map FITS format; 1, all HEALPIX map outputs also result in a TGA image format version; 2, all HEALPIX map outputs are transformed into TGA images.

- **LRANGE_OUT**: This takes integers separated by space, representing the minimum and maximum ℓ s that will be output in any $C(\ell)$ or $a_{\ell m}$ outputs; this range does not affect calculations, only outputs, and is has to be included in the range set by **LRANGE**.
- **MMAX_OUT**: This takes an integer. In $a_{\ell m}$ outputs, the multipoles will all be written out if this is set to a negative number. If this is set to m_{\max} , only $a_{\ell m}$ s with $m \leq m_{\max}$ will be written. In the current implementation, m_{\max} must be less than or equal to the minimum ℓ specified in **LRANGE_OUT**.
- **ANGULAR_COORD**: This can take three options: 0, all text outputs referring to angular position will use the polar and azimuthal angles θ and ϕ , given in radians, as angular coordinates (HEALPIX style); 1, these outputs will use θ and ϕ in degrees; 2, these outputs will use right ascension and declination in degrees as angular coordinates. This choice does not affect **XIOUT_PREFIX** and **GXIOUT_PREFIX** outputs which are always in degrees.
- **DENS2KAPPA**: If set to 1, **FLASK** computes a convergence field by integrating the matter density fields along the line of sight (see [Xavier et al., 2016](#), for details). This option requires that density fields in the fields information file are specified in contiguous and ordered redshift bins. The resulting convergence fields are added to the field list and from now on are treated the same way as ordinary convergence fields. If **DENS2KAPPA** is set to 0, no integration is performed and no new convergence is computed.
- **FLIST_OUT**: This keyword takes a string. If anything other than 0, the code treat it as a filename and writes the list of fields in use by the code to this file.
- **SMOOTH_CL_PREFIX**: Path plus prefix for the power spectra output, after applying Gaussian and/or HEALPIX pixel window functions according to keywords **WINFUNC_SIGMA** and **APPLY_PIXWIN**. Set to 0 for no output.
- **XIOUT_PREFIX**: Path with prefix for angular correlation functions $\xi^{ij}(\theta)$, written as two column (angle θ in degrees and $\xi^{ij}(\theta)$) text files. Currently it can only be calculated if **DIST**: **LOGNORMAL**. Set to 0 for no output.
- **GXIOUT_PREFIX**: Path, including a prefix, for angular correlation functions $\xi_g^{ij}(\theta)$ of the associated Gaussian fields, written as two column (angle θ in degrees and $\xi_g^{ij}(\theta)$) text files. This is only calculated if the input fields are lognormal. Set to 0 for no output.
- **GCLOUT_PREFIX**: Prefix (including path) for angular power spectra $C_g^{ij}(\ell)$ of the associated Gaussian fields. This is only calculated if **DIST**: **LOGNORMAL**. Set to 0 for no output.
- **COVL_PREFIX**: Path plus prefix for the Gaussian $a_{\ell m}^i$ s covariance matrices [for a fixed ℓ , $C_g^{ij}(\ell)$ is the element (i, j) of the covariance matrix]. Set to 0 for no output.

- **REG_COVL_PREFIX**: Path with prefix for the covariance matrices that would be output by **COVL_PREFIX** but after being regularized according to the choice in **REGULARIZE_METHOD**. Set to 0 for no output.
- **REG_CL_PREFIX**: Prefix (including path) for the regularized $C^{ij}(\ell)$ s. In the current implementation this can only be computed for **DIST: LOGNORMAL**; therefore the $C^{ij}(\ell)$ s output here are for the lognormal fields. For no output, set this keyword to 0.
- **CHOLESKY_PREFIX**: Path plus prefix for the outcome of the Cholesky decomposition as implemented by the *GNU Scientific Library* (GSL).³ Set to 0 for no output. These files can be passed as input to **FLASK** by using the keyword **CHOL_IN_PREFIX**.
- **AUXALM_OUT**: Filename (with path) for the table with multipoles coefficients $a_{\ell m}^i$ of every associated Gaussian field and redshift slice i being simulated. Since the fields are real, only $a_{\ell m}^i$ with $m \geq 0$ are written. Set to 0 for no output.
- **AUXMAP_OUT**: Filename (with path) for a text table containing the pixel's centre angular coordinates and the values at that point of every associated Gaussian field at every redshift slice being simulated. Set to 0 for no output.
- **DENS2KAPPA_STAT**: This can be set to 0 for no output, to 1 for output on the screen, or to a filename in case the user wants the output to be written to a file. The output is a table with statistical properties of the convergence obtained from density LoS integration. This information is only produced if **DENS2KAPPA: 1**.
- **MAP_OUT**: Path plus filename for a text table containing the pixel's centre angular coordinates and the values at that point of every field (Gaussian or lognormal, according to **DIST**) at every redshift slice being simulated. This does not include the selection function nor noise apart from cosmic variance. Set to 0 for no output.
- **MAPFITS_PREFIX**: Prefix (including path) for a HEALPIX map FITS file for each simulated field and redshift slice. The output format can be altered by **FITS2TGA**. This does not include the selection function nor noise apart from cosmic variance. Set to 0 for no output.
- **RECOVALM_OUT**: Path plus filename for a text table of multipole coefficients $a_{\ell m}^i$ recovered, using the `map2alm` HEALPIX function, from the maps that can be output by **MAP_OUT** and **MAPFITS_PREFIX**. Set to 0 for no output.
- **RECOVCLS_OUT**: Path plus filename for a text table of power spectra $C_{\text{rec}}^{ij}(\ell)$ recovered from the maps that can be output by **MAP_OUT** and **MAPFITS_PREFIX**. In other words, $C_{\text{rec}}^{ij}(\ell)$ is the average over m of $a_{\ell m}^i a_{\ell m}^{j*}$, where $a_{\ell m}^i$ can be output by **RECOVALM_OUT**. Set to 0 for no output.
- **SHEAR_ALM_PREFIX**: Prefix (including path) for files containing the weak lensing shear E -mode multipole coefficients $a_{\ell m}^i$, one for each lensing field and redshift slice. Set to 0 for no output.

³ Check http://www.gnu.org/software/gsl/manual/html_node/Cholesky-Decomposition.html for details.

- **SHEAR_FITS_PREFIX**: Prefix (including path) for HEALPIX maps of weak lensing attributes, obtained from lensing $a_{\ell ms}$ (E -modes that can be output by **SHEAR_ALM_PREFIX**) by the HEALPIX function `alm2map_spin`. These FITS files contain three columns: convergence κ and shear components γ_1 and γ_2 . This does not include the selection function nor noise apart from cosmic variance. Set to 0 for no output.
- **SHEAR_MAP_OUT**: Path plus filename for a text table containing the pixel's centre angular coordinates and the values at that point of the two shear components γ_1 and γ_2 of every weak lensing field at every redshift slice. This does not include the selection function nor noise apart from cosmic variance. Set to 0 for no output.
- **MAPWER_OUT**: Path plus filename for a text table containing the pixel's centre angular coordinates and the values at that point of the fields after applying the selection function and Poisson sampling the galaxy density fields; that is, the values are the number of galaxies in each pixel in each redshift slice (i.e. in each cell). Convergence fields remain the same, without any noise apart from cosmic variance. Set to 0 for no output.
- **MAPWERFITS_PREFIX**: Prefix (including path) for the HEALPIX maps version of the **MAPWER_OUT** output, one file per field per redshift slice. Set to 0 for no output.
- **CATALOG_OUT**: Path plus filename for a galaxy catalogue in text, FITS or compressed FITS formats, chosen accordingly to the filename extension: `.dat`, `.fits` or `.fits.gz`, respectively. Each row is one galaxy from the map described in **MAPWER_OUT** and the columns are chosen by the user using the **CATALOG_COLS** key-word. Set to 0 for no output.
- **CATALOG_COLS**: This takes as input everything in the same line of the configuration file after it, and it specifies the columns to be included in the galaxy catalogue output by **CATALOG_OUT**. They can be:
 - `theta`, the polar angle θ of the galaxy position (or the declination, according to **ANGULAR_COORD**), randomly sampled inside the corresponding pixel;
 - `phi`, the azimuthal angle ϕ of the galaxy position (or the right ascension, according to **ANGULAR_COORD**), randomly sampled inside the corresponding pixel;
 - `z`, the galaxy's redshift, which is randomly sampled inside the corresponding cell according to the selection function;
 - `galtype`, i.e. the field's name as in the fields information file, see Sec. 3.1.5;
 - `kappa`, the convergence κ at the corresponding cell (pixel and redshift slice);
 - `gamma1`, the first component of the shear, γ_1 , at the corresponding cell;
 - `gamma2`, the second component of the shear, γ_2 , at the corresponding cell;
 - `ellip1`, the first component of the ellipticity of the galaxy ε_1 , given by Eq. 3.1;
 - `ellip2`, the second component of the ellipticity of the galaxy ε_2 , given by Eq. 3.1;

- pixel, the HEALPIX map pixel number of the corresponding cell;
- maskbit, returns a sum of the following integers: 1 if the galaxy would be removed by the angular selection function, i.e., if the angular selection function value at the corresponding pixel is zero (currently this only happens if the selection function is separable); 2 if the galaxy would be removed by the star mask given by STARMASK, i.e., if the star mask value at the corresponding pixel is zero; 4 if the angular selection function value s obeys $0 < s < 1$ (only if the selection function is separable); and 8 if the star mask value m obeys $0 < m < 1$. For instance, a maskbit of 0 means that the galaxy would be observed while a maskbit of 3 means that the galaxy would be blocked both by the angular selection function and the star mask.

The column names have to be separated by spaces and they can appear in any number (no repeated columns, though) and order.

3.1.5 Fields information file

The fields information file is a text file that informs FLASK the fields and redshift slices it should simulate, along with their properties. In the current implementation, these files can have any number of lines serving as headers (that should always start with a #). Empty lines can also appear before the tabular data, but they cannot contain spaces. Once the tabular data appears, you should stick to it. The file can end at the last data line or with an empty line (no spaces allowed). An example of such file is given in Fig. 3.2.

# Field number, z bin number, mean, shift, field type, zmin, zmax						
# Types: 1-galaxies 2-lensing						
1	1	0.0000	1.0000	1	0.2500	0.3500
1	2	0.0000	1.0000	1	0.3500	0.4500
1	3	0.0000	1.0000	1	0.4500	0.5500
2	1	0.0000	0.0050	2	0.2500	0.3500
2	2	0.0000	0.0084	2	0.3500	0.4500
2	3	0.0000	0.0126	2	0.4500	0.5500

Figure 3.2: Example of a fields information file with two fields (one of type *galaxy* or *matter density* and the other of type *weak lensing convergence*) in three redshift slices. The column order is summarized in the header.

The fields information file columns must be, in this order:

- An arbitrary natural number “naming” the field (for multi-tracer simulations, they can identify different galaxy populations).
- An arbitrary natural number “naming” the redshift slice.
- The fields mean value at that redshift slice, usually zero (for density contrast and convergence, for instance);

- The fields shift parameter, if the field is lognormal (in case of a Gaussian simulation, this column still have to be present but it will be ignored).
- The field type, which determines how the field is treated inside the code. In the current implementation, this can be either 1 (CMB or gas temperature, matter density or matter density tracers like galaxies, quasars, etc.) or 2 (weak lensing convergence). These types affect how FLASK deals with selection functions, noise and field transformations. For details, one can look for `fshear` and `fgalaxies` in the code using the command `grep`.
- The lower boundary of the redshift slice;
- and the upper boundary of the redshift slice. The redshift slices may overlap, have any size and ordering (unless you are integrating the density, see the `DENS2KAPPA` keyword in Sec. 3.1.4). In the current implementation, these are only used either in the density LoS integration controlled by the `DENS2KAPPA` or to Poisson sample the density fields; in both cases, the redshift slice is assumed to be a top-hat redshift window function. If you are not performing these operations, these redshift boundaries are irrelevant and the slices can present arbitrary redshift window functions (e.g. Gaussians), according to the power spectra provided as input.

To simulate the fields and redshift slices mentioned in a fields information file, FLASK requires their auto power spectra and all cross power spectra (unless the keyword `ALLOW_MISS_CL` is set to 1). Each power spectrum has to be in a file with prefix given by the keyword `CL_PREFIX` followed by $f[f_i]z[z_i]f[f_j]z[z_j].dat$, where $[f_i]$ and $[z_i]$ are the numbers (no zero-padding allowed) in the first and second columns of the fields information file. For instance, if the configuration file have `CL_PREFIX: data/testCl-` and `FIELDS_INFO` referring to the file in Fig. 3.2, FLASK will look for the files:

data/testCl-f1z1f1z1.dat	data/testCl-f2z1f1z1.dat
data/testCl-f1z1f1z2.dat	data/testCl-f2z1f1z2.dat
data/testCl-f1z1f1z3.dat	data/testCl-f2z1f1z3.dat
data/testCl-f1z1f2z1.dat	data/testCl-f2z1f2z1.dat
data/testCl-f1z1f2z2.dat	data/testCl-f2z1f2z2.dat
data/testCl-f1z1f2z3.dat	data/testCl-f2z1f2z3.dat
data/testCl-f1z2f1z1.dat	data/testCl-f2z2f1z1.dat
data/testCl-f1z2f1z2.dat	data/testCl-f2z2f1z2.dat
data/testCl-f1z2f1z3.dat	data/testCl-f2z2f1z3.dat
data/testCl-f1z2f2z1.dat	data/testCl-f2z2f2z1.dat
data/testCl-f1z2f2z2.dat	data/testCl-f2z2f2z2.dat
data/testCl-f1z2f2z3.dat	data/testCl-f2z2f2z3.dat
data/testCl-f1z3f1z1.dat	data/testCl-f2z3f1z1.dat
data/testCl-f1z3f1z2.dat	data/testCl-f2z3f1z2.dat
data/testCl-f1z3f1z3.dat	data/testCl-f2z3f1z3.dat
data/testCl-f1z3f2z1.dat	data/testCl-f2z3f2z1.dat
data/testCl-f1z3f2z2.dat	data/testCl-f2z3f2z2.dat
data/testCl-f1z3f2z3.dat	data/testCl-f2z3f2z3.dat

However, since the cross power spectra are symmetric (`testCl-f[fi]z[zi]f[fj]z[zj].dat` = `testCl-f[fj]z[zj]f[fi]z[zi].dat`), FLASK only requires 21 of the files listed above.

In case you use CLASS⁴ (Blas et al., 2011; Dio et al., 2013) or CAMB SOURCES⁵ (Challinor and Lewis, 2011) to compute the input power spectra, it is possible to use the PYTHON scripts called `class2info.py` and `camb2info.py` in FLASK's `src/scripts` folder to create the fields information file corresponding to CLASS and CAMB SOURCES input (`.ini`) files. See Sec. 3.2 and the scripts' docstring for more information.

3.1.6 Angular power spectra files

Apart from the distribution's PDF – determined by the DIST keyword in the configuration file – and the fields mean and shift parameters in the fields information file, all statistical properties of the simulated fields are fixed by the input angular power spectra $C_{\text{in}}^{ij}(\ell)$, including their cross-correlations. All characteristics such as: tracer biases with respect to matter density; redshift space distortions; galaxy intrinsic alignments; integrated Sachs-Wolfe effect; tracer evolution with redshift; and magnification bias can be included in the simulations by providing the appropriate $C_{\text{in}}^{ij}(\ell)$ with such information encoded in them. The step of computing these power spectra is not part of FLASK and is left to the user. Some public codes available to perform such calculations are: CLASS⁶ (Blas et al., 2011; Dio et al., 2013) and CAMB SOURCES⁷ (Challinor and Lewis, 2011).

In the current implementation, the $C_{\text{in}}^{ij}(\ell)$ files must be named as explained in 3.1.5 and must have two columns: ℓ and $C_{\text{in}}^{ij}(\ell)$ (no headers allowed here). The $C_{\text{in}}^{ij}(\ell)$ is the power spectra itself and not something like $l(l+1)/(2\pi) \cdot C_{\text{in}}^{ij}(\ell)$. They are interpolated by the code so it is not necessary to specify them at every ℓ or at integer ℓ s. For the user's convenience, PYTHON scripts called `prepClassInput.py` and `prepCambInput.py` are available in FLASK's `src/scripts` folder that can translate CLASS and CAMB SOURCES output power spectra into FLASK input power spectra. See Sec. 3.2 and the scripts' docstring for more information.

3.2 Auxiliary codes

There are several

⁴<http://class-code.net/>

⁵<http://camb.info/sources>

⁶<http://class-code.net/>

⁷<http://camb.info/sources>

- 3.2.1** Dens2KappaCls
- 3.2.2** GenStarMask
- 3.2.3** camb2info.py
- 3.2.4** ChangeMapResolution.py
- 3.2.5** prepCambInput.py
- 3.2.6** prepClassInput.py
- 3.2.7** summarizeData.py
- 3.2.8** ViewMap.py

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