

# SNANA User's Manual: Simulation, Lightcurve Fits, BBC, Create-Covariance, Batch Utilities

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# 1 Introduction

This manual describes how to use the lightcurve simulation and fitting programs in the **SNANA** product. This code was originally developed for the SDSS-II Supernova Survey, and then it was modified to simulate and fit SN Ia lightcurves for an arbitrary survey. Current SN models include MLCS2k2 [1], SALT-II [2], SNooPy [3], stretch [4], two-stretch[5], and Core Collapse[6].

The simulation is designed to be fast, generating  $\sim 10^2$ - $10^3$  lightcurves per second, and still provide an accurate and realistic description of supernova lightcurves. In particular, the simulation accounts for variations in noise, atmospheric transmission, and cadence. The reliability of the simulation is based on the accuracy of the “observing conditions” in a “SIMLIB” file that describes the seeing, sky-noise, zeropoints, and cadence. A SIMLIB file is easy to prepare post-survey; predicting the SIMLIB file before the survey is crucial to making reliable predictions for the lightcurve quality. This simulation does not use pixels or images directly, although it makes use of information generated from the images, such as scaling the flux-errors.

The underlying programs are binary executables based on a mix of fortran and C. Each program (fitting or simulation) requires an input file as an argument, plus optional command-line overrides (§12.2.3). The command-line overrides allow making small perturbations so that a new input file is not needed for each variation. For typical analyses that require many variations in both the fitting and simulations, “`submit_batch_jobs.sh`” is a utility (§12.2.1) to launch job sequences on multiple cores using batch systems such as “qsub” or “sbatch.”

Finally, while the simulation is a stand-alone program with no user interface, the analysis programs allow for user interaction in multiple ways using the *private* option (§6.1). The idea is to layer code on top of the underlying **snana** code that reads data (real and sim) and applies basic selection cuts. This architecture allows users to focus on writing new analysis features without worrying about the overhead of reading data files. Three ways to use the private interface are 1) write an entire analysis or fitting package (e.g., `snlc_fit` or `psnid`), 2) use existing code, but modify an underlying algorithm, and 3) add private code in the user-interface routines (`USRINI`, `USRANA`, `USREND`), such as computing a new variable, writing information in a specific format, etc.



## 2 SNANA Basics

After installing SNANA (see install guide), make sure that the two main environment variables are defined:

```
> echo $SNANA_DIR/  
> echo $SNDATA_ROOT/
```

The environment variable `$SNANA_DIR` points to the software that should be accessible to a group of users. The SNANA developers use github<sup>1</sup> to share and distribute code, and occasional tags are released. SNANA codes are updated often with bug fixes and improvements; each github update follows a successful regression test checking more than 100 SNANA jobs. The main science codes are:

```
> $SNANA_DIR/src/snlc_sim.c      # simulation  
> $SNANA_DIR/src/snlc_fit.car    # light curve fitting  
> $SNANA_DIR/src/psnid.car       # psnid classifier  
> $SNANA_DIR/src/SALT2mu.car     # implement BBC to create hubble diagram  
  
> $SNANA_DIR/util/create_covariance.py # create stat+syst cov matrix  
> $SNANA_DIR/util/submit_batch.sh      # submit batch jobs
```

The environment variable `$SNDATA_ROOT` points to a directory that contains publicly released information from survey teams, and is downloadable from zenodo.<sup>2</sup> `$SNDATA_ROOT` includes public data, filter transmissions, CalSpec SEDs, SN models, cadence libraries (SIMLIB), host libraries (HOSTLIB), Milky Way extinction map, etc.

A 200+ page manual is part of github (`$SNANA_DIR/doc/snana_manual.pdf`). For beginners, however, it is recommended to get help from an expert.

### 2.1 Dr. Evil-ABORT-Face

The SNANA programs include intensive error checking throughout the execution. If anything looks fishy, the program aborts with an easy-to-identify message looking like

```
‘|‘‘‘‘‘|‘  
<| o\ /o |>  
| ’ ; ’ |  
| _ _ _ |      ABORT program on Fatal Error.  
| |’ ’| |  
| ‘ _ _ ’ |  
\_ _ _ _ _/
```

```
FATAL ERROR ABORT called by RDSNNML  
Could not open namelist file:  
dummy.nml
```

While some of these aborts may at first seem frustrating, they are crucial for catching bugs as early as possible so that you don't waste months (years) doing something silly.

<sup>1</sup><https://github.com/RickKessler/SNANA>

<sup>2</sup><https://zenodo.org/record/4728252>

## 2.2 Data Files

Data files can be written in TEXT (§4.36.2) or FITS (§4.36.1) format. Large data & sim samples should use FITS format because it is much more compact and much faster to read. With TEXT format, each event is written to a separate ASCII file. With FITS format, there are two FITS files: a summary HEAD file with a one-row summary per event (Fig. 1), and a PHOT file with the light curves (Fig. 2). For fast reading, the HEAD file includes pointers to the PHOT table (PTROBS\_MIN, PTROBS\_MAX), so do not catenate FITS files without updating these pointers.

## 2.3 Citations

While an SNANA citation is always appreciated ([7]), please make sure to reference underlying work that is used by SNANA. Referencing the appropriate light curve model (§1) is the most obvious example. However, there may be other features to reference such as the source of spectra for the SIMSED model, survey efficiencies, host-galaxy correlations, etc ... If you read a published article and suspect SNANA usage with a missing reference, please contact the lead author and one of the SNANA authors.

HEAD file:	
variable name	description
#	-----
* SNID	integer or character ID
* FAKE	0=real data, 1=fake overlaid on image, 2=SNANA sim,
* RA,DEC	sky coordinates (degrees)
* SNTYPE	integer type assigned by survey (e.g., SPEC type)
* NOBS	number of obs (all bands)
* PTROBS_MIN	pointer to 1st light curve obs in PHOT file
* PTROBS_MAX	pointer to last light curve obs
* MWEBV[_ERR]	E(B-V) for Milky way
* REDSHIFT_HELIO[_ERR]	best heliocentric redshift; zSpec if available; else zPhot; else -9
* REDSHIFT_FINAL[_ERR]	best CMB redshift (no VPEC correction)
* VPEC[_ERR]	pec velocity (km/sec) and error on correction
* PEAKMJD	approx PEAKMJD; useful to init light curve fit
* MJD_TRIGGER	MJD when survey trigger is satisfied
* MJD_DETECT_FIRST	MJD of first detection
* MJD_DETECT_LAST	MJD of last detection
* HOSTGAL_SB_FLUXCAL_[band]	Surface brightness mag at SN location
* HOSTGAL_NMATCH	number of host matches with DDLR < 4
* HOSTGAL_NMATCH2	number of host matches with DDLR < 7
* HOSTGAL_OBJID	integer id of host (long long int)
* HOSTGAL_RA	R.A. (deg) for center of host
* HOSTGAL_DEC	declination (deg) for center of host
* HOSTGAL_SNSEP	transient-host separation, arcsec
* HOSTGAL_DDLR	SN-host sep in distance-light-radii (d_DLR)
* HOSTGAL_SPECZ[_ERR]	zSpec of host (-9 -> not available)
* HOSTGAL_PHOTOZ[_ERR]	zphot (mean of PDF); -9 -> not available
* HOSTGAL_ZPHOT_Q[PPP]	redshift containing PPP percent of zPDF prob
* HOSTGAL_LOGMASS[_ERR]	logmass and error
* HOSTGAL_LOGSFR[_ERR]	log(star formation rate) and error
* HOSTGAL_MAG_[band]	host mags for band=u,g,r,i,z,Y
* HOSTGAL_MAGERR_[band]	uncertainty on above mags
[Each hostgal_xxx has hostgal2_xxx for 2nd host-match; -999 indicates no 2nd host; else values are filled. First listed host has smallest DDLR and may not be the true host]	
For simulated data:	
* SIM_TYPE_INDEX	true integer transient type (e.g., 1 for SNIa)
* SIM_[SSS]	true sim property SSS

Figure 1: FITS data structure for header file (\*HEAD.FITS).

```

PHOT file:
* MJD                modified Julian date (-777 -> end of light curve)
* BAND              e.g., 'u', 'g', 'r' etc ...
* CCDNUM            CCD or detector number
* IMGNUM            image number; e.g. exposure number, visit id ...
* FIELD             name of field; e.g., SHALLOW, DEEP, etc ...
* PHOTFLAG          bit-mask of information (check data README)
* PHOTPROB          float metric; e.g. RealBogus score, chi2, ...
* FLUXCAL           calibrated flux : mag = 27.5 - 2.5*log10(FLUXCAL)
* FLUXCALERR        Poisson uncertainty on FLUXCAL; sky+galaxy+source

    image properties
* PSF_SIG1          PSF Gauss sigma, pixels
* SKY_SIG           sky noise (ADU/pixel)
* SKY_SIG_T         template sky noise (for DIFFIMG, not for SMP)
* ZEROPT           image zero point
* GAIN              N_photoclectron/ADU
* XPIX             x-location on CCD (pixels)
* YPIX             y-location on CCD (pixels)

    For simulated data:
* SIM_MAGOBS        true model mag

```

Figure 2: FITS data structure for photometry file (\*PHOT.FITS)

## 2.4 Community Code Contributions

First and most important, avoid the temptation to make quick-and-dirty fixes for your private use. Anything you need is likely to be useful for somebody else, so please work with SNANA developers to integrate your updates into the public github repository.

Before making code modifications, it is good practice to inform the primary SNANA developers, but permission is not needed, especially for urgent fixes. The SNANA code is stored on github<sup>3</sup>, and you need to become a collaborator to submit a pull request (PR). If it is not practical to become a code collaborator (e.g., one-line code fix), an update may be sent to SNANA developers via e-mail.

Before submitting a PR, it is important to perform a regression test using the command

```
SNANA_code_tests.py --snana_dir <my_snana_dir>
```

This regression test has been setup on clusters at Fermilab (des\*.fnal.gov), U.Chicago (midway2 at RCC), and NERSC (Cori). Please contact SNANA developers for help on setting up regression tests on other clusters. If you create a code update on a private laptop or cluster, an SNANA developer can run the regression test for you.

A few other requests for coding habits:

- post github issue.
- clone or update SNANA code before making changes.
- Verify that update/fix actually works; successful compilation is not adequate.
- Do not fall into this dangerous logic trap: “*I only changed one line of code, so no need to test it.*” As a post-doc working on the KTeV experiment, I accepted this logic and installed a one-line code fix that crashed the entire experiment.
- annotate history section at top of file and/or function so that future code editors can easily notice who/when previous changes were made. A very brief description is adequate.
- annotate end of doc/README\_UPDATES in the appropriate category of IMPORTANT (e.g., major bug-fix or new feature), USEFUL (new feature with limited scope), or MISCELLANEOUS (little interest to anyone except the person posting issue). While this document is redundant with github comments, searching key-words in this file has been very useful to track histories.
- for a significant new feature, consider updating SNANA manual (pdf you are reading now).
- To avoid conflicts that are difficult to resolve, avoid editing code for long time periods without merging. Rather than waiting several weeks for all coding to finish, send multiple PR’s, each with small changes. Make sure that your development does not interfere with normal code usage; e.g., use DEBUG\_FLAG or new input key to invoke your new code.
- after submitting PR, contact Kessler or Narayan to merge it (free github usage does not include automated e-mail alert).
- for major bug-fixes or improvements, inform your collaborators.

---

<sup>3</sup><https://github.com/RickKessler/SNANA>

### 3 The Calibration + K-Correction file

Before running the simulation or light curve fitting program, a “K-correction” file must be created. This file contains

- filter transmissions.
- native mag for each filter.
- SED of the primary reference (i.e., AB, BD17, ...) and each SN epoch.
- zeropoint offsets (native – synthetic mags)
- Optional AB offsets (to apply to data)
- for rest-frame models requiring K-correction,
  - K-correction tables vs. redshift, epoch,  $A_V$ -warp.
  - rest-frame magnitudes.
  - Galactic extinction corrections.

The purpose of this file is two-fold: (1) collect the relevant information in one file that can be used for any model such as SALT2 or mlcs2k2, and (2) for K-corrections, pre-compute quantities that vastly speeds up the simulation and fitting programs. The  $A_V$ -warp parameter warps the SN SED to match a grid of colors, and is used to quickly find the warped SN SED that matches the observed colors. Example kcor-input files are here: `$SNDATA_ROOT/sample_input_files/kcor` and the command to create a K-corr file is

```
kcor.exe myKcor.Input
```

The output file is specified by the kcor-input file key

```
OUTFILE: mySurvey.fits
```

#### 3.1 Changing the Mean Filter Wavelength

The mean filter wavelength can be adjusted via the command-line argument

```
kcor.exe myKcor.Input FILTER_LAMSHIFT r 2.1 i 3.2
kcor.exe myKcor.Input FILTER_LAMSHIFT r 2.1 i 3.2 OUTFILE kcor_lamshift.fits
```

which shifts the mean  $r$ - and  $i$ -band wavelengths by 2.1 and 3.2 Å, respectively. These shifts can be entered only via command-line arguments, and it is therefore recommended to also include a unique `OUTFILE` name as well, as shown in the 2nd example above. The LAMSHIFT info is written into the output header. Note that to implement more complex wavelength variations requires a new set of transmission-vs- $\lambda$  curves.

§5.25 shows how to define a duplicate set of filters with a common wavelength shift, and how to select the  $\lambda$ -shifted band(s) in the fitting program.

### 3.2 Defining a SPECTROGRAPH

A SPECTROGRAPH instrument is defined as a list of SNR-vs-wavelength,  $\text{SNR}(\lambda)$ , for two distinct magnitudes.  $\text{SNR}(\lambda)$  is defined for two (and only two) mag values so that in each  $\lambda$ -bin an effective zero point and skyNoise is computed analytically, allowing  $\text{SNR}(\lambda)$  to be computed for any mag. For each spectroscopic bin-center, the zeropoint (ZP) and skyNoise ( $\sigma_{\text{sky}}$ ) are given by

$$\text{ZP} = 2.5 \log_{10} \left[ \frac{10^{-0.4m_1} - 10^{-0.4m_2}}{(10^{-0.4m_1}/\text{SNR}_1)^2 - (10^{-0.4m_2}/\text{SNR}_2)^2} \right] \quad (1)$$

$$\sigma_{\text{sky}}^2 = (F_1/\text{SNR}_1)^2 - F_1 \quad ; \quad F_1 \equiv 10^{-0.4(m_1 - \text{ZP})} \quad (2)$$

where  $m_{1,2}$  are the two AB mag-reference values, and  $\text{SNR}_{1,2}$  are the corresponding SNR. Beware that there is no solution if  $m_2 - m_1 < 2.5 \log_{10}(\text{SNR}_1/\text{SNR}_2)$ . To account for exposure-time ( $T_{\text{expose}}$ ) dependence,  $\text{SNR}(\lambda)$  can be defined for multiple  $T_{\text{expose}}$  values. The SPECTROGRAPH is defined in a separate text file as shown in Fig. 3. The required keys include name of instrument, two ref mag

```
# required keys:
INSTRUMENT: MYSPECDEVICE
MAGREF_LIST: 20 28          # defines SNR1 and SNR2 (only 2 allowed)
TEXPOSE_LIST: 300 1000 2000 # seconds (arbitrary list size)

# optional keys to check for bad SNR inputs
SNR_POISSON_RATIO_ABORT_vsMAGREF: 5      # default
SNR_POISSON_RATIO_ABORT_vsTEXPOSE: 1.2    # default

#          LAM    LAM    LAM
#          MIN    MAX    RES    SNR1 SNR2    SNR1 SNR2    SNR1 SNR2
SPECBIN:  4200   4210   12.4   11.39 0.017   24.78 0.063   50.72 0.168
SPECBIN:  4210   4222   14.5   12.39 0.018   24.94 0.066   50.82 0.172
etc ...
```

Figure 3: Spectrograph table format for kcor program and simulation.

values ( $m_1, m_2$  in Eq. 2), and a list of exposure times. The optional keys to check for bad SNR inputs are described below.

Each  $\lambda$ -bin (SPECBIN key) includes  $\lambda_{\min}$  and  $\lambda_{\max}$  (Å) to avoid confusion with non-uniform  $\lambda$  bins. The LAMRES column specifies the wavelength resolution as Gaussian  $\sigma$  in Å. Since there are three  $T_{\text{expose}}$  values in the example above (see TEXPOSE\_LIST key), three SNR pairs are given, where each SNR pair corresponds to the two mag values following the MAGREF\_LIST key. An arbitrary number of  $T_{\text{expose}}$  values can be defined, with the corresponding number of SNR pairs. For the simulation,  $T_{\text{expose}}$  can be defined in the SIMLIB file (§4.7.2) or in the sim-input file (§4.25).  $\text{SNR}(T_{\text{expose}})$  is interpolated based on the  $T_{\text{expose}}$  grid.

The above SPECTROGRAPH file is not read directly by the simulation, but instead it is ingested into a kcor file along with the filters and calibration references. If the above file is named MYSPECDEVICE.DAT, the following keys can be added to a kcor-input file, after a FILTPATH key:

```
SPECTROGRAPH: MYSPECDEVICE.DAT
#           name    minLam  maxLam  ABoff
```

SYN_FILTER:	IFU-0	4200	4500	0.0
SYN_FILTER:	IFU-1	6000	6600	0.0
SYN_FILTER:	IFU-2	7200	7600	0.0

The **SPECTROGRAPH** key defines the file containing the noise properties. Optional **SYN\_FILTER** keys define IFU-like synthetic filters from the **SPECTROGRAPH**.

The **SPECTROGRAPH**  $\lambda$ -bins can be re-binned in the kcor file as follows,

**SPECTROGRAPH:** `MYSPECDEVICE.DAT(rebin=3)`

In this example, every three consecutive  $\lambda$ -bins are combined into one, and the SNR values are added in quadrature. With 200  $\lambda$ -bins in **MYSPECDEVICE.DAT**, the **rebin=3** option results in keeping 66 combined bins. Since  $3 \times 66 = 198 < 200$ , the last two  $\lambda$ -bins are ignored.

**SNR\_POISSON\_RATIO\_ABORT\_vsMAGREF** ( $\mathcal{R}_{\text{Abort}}$ ) is used to check each SNR pair: SNR1 and SNR2. The **MAGREF** difference is used to predict the SNR-ratio ( $R_{\text{SNR}} = \text{SNR2}/\text{SNR1}$ ) from Poisson statistics,

$$R_{\text{SNR-Poiss}} = 10^{0.2*(\text{MAG1}-\text{MAG2})} . \quad (3)$$

The kcor program aborts if

$$|\log_{10}[R_{\text{SNR}}/R_{\text{SNR-Poiss}}]| > \log_{10}(\mathcal{R}_{\text{Abort}}) \quad (4)$$

The cut on absolute-value of log conveniently cuts on both  $R_{\text{SNR}}/R_{\text{SNR-Poiss}}$  and  $R_{\text{SNR-Poiss}}/R_{\text{SNR}}$ . Note that “R” refers to SNR ratios, while user-input  $\mathcal{R}_{\text{Abort}}$  is a ratio of R values.

**SNR\_POISSON\_RATIO\_ABORT\_vsTEXPOSE** ( $\mathcal{R}_{\text{Abort}}$ ) performs a similar test for SNR vs. exposure time. If the exposure time doubles, the naive Poisson noise expectation is that SNR increases by  $\sqrt{2}$ . With default  $\mathcal{R}_{\text{Abort}} = 1.2$ , the kcor program aborts if the SNR-ratio differs by more than 20% from the  $\sqrt{2}$  expectation.



## 4 The SNANA Simulation: `snlc_sim.exe`

### 4.1 Overview of Model Magnitudes and Noise Calculation

The available lightcurve models are described in §9. For a rest-frame model of supernova, such as MLCS2k2 or SNooPy, here is a brief overview of how the simulation generates observed fluxes in CCD counts,

1. pick random shape parameter (e.g.,  $\Delta$ , DM15) and random extinction ( $A_V$ ) according to measured distributions.
2. generate rest-frame light curve:  $U, B, V, R, I$  mag vs. time.
3. apply host-galaxy extinction to  $UBVRI$  mags.
4. add K-correction to transform  $UBVRI$  to observer-frame filters.
5. apply Galactic (MilkyWay) extinction.
6. apply zero-points to translate generated magnitude into CCD counts; this step account for atmospheric transmission and telescope efficiency.

For an observer-frame mode such as SALT-II, steps 2-4 are replaced by a function that generates observer-frame magnitudes.

The noise in the simulation is computed as follows,

$$\sigma_{\text{SIM}}^2 = \left[ F + (A \cdot b) + (F \cdot \hat{\sigma}_{\text{ZPT}})^2 + (\hat{\sigma}_0 \cdot 10^{0.4 \cdot \text{ZPT}_{\text{pe}}})^2 + \sigma_{\text{host}}^2 \right] \hat{S}_{\text{SNR}}^2 \quad (5)$$

where

- $F$  is the simulated flux in photoelectrons (p.e.).
- $A$  is the noise-equivalent area given by  $[2\pi \int PSF^2(r, \theta) r dr]^{-1}$ .
- $b$  is the background per unit area (includes sky + CCD readout + dark current).
- $\hat{\sigma}_{\text{ZPT}}$  is the zeropoint uncertainty.
- $\hat{\sigma}_0$  is a constant FLUXCAL uncertainty, and  $\text{ZPT}_{\text{pe}}$  transforms  $\hat{\sigma}_0$  into an uncertainty in p.e.
- $\hat{S}_{\text{SNR}}$  is an empirically determined scale that depends on the signal-to-noise ratio (SNR)
- $\sigma_{\text{host}}$  is from the underlying host galaxy.

The terms with hats ( $\hat{\sigma}_0$ ,  $\hat{\sigma}_{\text{ZPT}}$ ,  $\hat{S}_{\text{SNR}}$ ) may be difficult to compute from first principles, but these terms can be determined empirically from fits that match simulated uncertainties to those from the data. The  $A, b, \hat{\sigma}_{\text{ZPT}}$  terms are discussed in §4.7. The  $\hat{\sigma}_0$ ,  $\hat{S}_{\text{SNR}}$  terms are discussed in §4.14. The host-galaxy noise ( $\sigma_{\text{host}}$ ) is discussed in §4.22.

## 4.2 Getting Started Quickly

In this section, you should be able to start simulating lightcurves in a few minutes. There are many options that may take some practice to use properly. The first step is to copy a sample input file to your private area,

```
> cp $SNDATA_ROOT/sample_input_files/SALT2/sim_[SURVEY].input .
```

where [SURVEY] is one of the surveys for which a sample sim-input file is available. Edit the file and change the GENVERSION name:

```
GENVERSION: CHANGE_ME
```

We recommend just adding your initials and/or project name so that you do not over-write somebody else's files. Now you can run the simulation, for example, with

```
> snlc_sim.exe sim_SDSS.input
```

which should generate 100 lightcurves using the SALT2 model. The next step is to modify the input file to suit your needs. The input parameters are internally commented within the source code; for example, to get more information about the GENMAG\_SMEAR keyword,

```
> grep GENMAG_SMEAR $SNANA_DIR/src/snlc_sim.h
> grep GENMAG_SMEAR $SNANA_DIR/src/snlc_sim.c
```

will help you trace the meaning of this variable. All of the input options are defined in a structure called INPUTS in `snlc_sim.h`. Please report variables that are not commented, or that have confusing comments. Don't hesitate requesting help from other people familiar with SNANA.

The simulated lightcurves are located in `$SNDATA_ROOT/SIM`. Do NOT try 'ls' !!! Instead, try 'ls -d \*' to see all versions. To avoid sifting through hundreds of versions from multiple users, use your initials (or project acronym) as a prefix for your versions. Each simulated version has an auto-generated README file. If your version is called 'MYFIRSTSIM', then do

```
> more $SNDATA_ROOT/SIM/MYFIRSTSIM/MYFIRSTSIM.README
```

which contains a list of all your simulation options. The default sim-data format is FITS: one FITS file for the header info with one row per SN, and a second FITS file with all of the light curves. Instead of FITS format, you can generate a text file per SN with the option "FORMAT\_MASK: 2" (§4.36). The SNANA fitting programs read both the FITS and TEXT formats. You can get a list of files with the commands

```
cd $SNDATA_ROOT/SIM/MYFIRSTSIM/
ls MYFIRSTSIM_SN*
or
more MYFIRSTSIM.LIST
```

## 4.3 Search Hierarchy for Supplemental Input Files

The simulation has input options for more than a dozen different maps that are read in as supplemental files. These maps include: cadence, host galaxy, detection efficiency vs. SNR, spectroscopic selection efficiency, etc ... To see all maps in your simulation job, see dashboard utility in §12.3.1. The simulation will search for each supplemental file with the following priority

1. current directory (i.e., no path appended to file name)
2. path specified by sim-input `PATH_USER_INPUT: <path>`
3. default path under `$SNDATA_ROOT`.

Priority (1) allows over-riding defaults by simply copying a map file to your local directory. Priority (2) is useful in higher-level pipelines that copy the top-level sim-input file to a separate directory, but doesn't copy the supplemental files. Priority (3) checks for default files from previous analyses or publications. For example, a SIMLIB file is checked under `$SNDATA_ROOT/simlib`, a k-correction file is checked under `$SNDATA_ROOT/kcor`, trigger files are checked under `$SNDATA_ROOT/models/searcheff`, etc ...

Note that the most robust method is to specify file names with a full path that has an environment (ENV) variable; the ENV ensures that the sim job will run on other computer platforms.

## 4.4 Cosmological Parameters

The default cosmological parameters are specified in `sntools.h`; as of March 2020,

```
// cosmo params from Planck 2018 (https://arxiv.org/abs/1807.06209)
#define OMEGA_MATTER_LCDM    0.315
#define OMEGA_LAMBDA_LCDM    0.685
#define w0_LCDM              -1.0
#define wa_LCDM              0.0
#define H0_SALT2              70    // km/s/Mpc : tied to SALT2 training
#define H0_MLCS              65    // km/s/Mpc : tied to MLCS training
#define H0_Planck            67.4  // 1807.06209 (Planck 2018)
#define H0_SHOES             74.03 // 1903.07603 (Riess 2019)
```

The default H0 value is `H0_SALT2`; if an MLCS model is requested, then `H0_MLCS` is used. The Planck and SHOES values of H0 are not used in the simulation. For specific analyses requiring different cosmo parameters, use the following sim-input keys:

```
OMEGA_MATTER: <value> # default = OMEGA_MATTER_LCDM
OMEGA_LAMBDA: <value> # default = OMEGA_LAMBDA_LCDM
w0_LAMBDA:    <value> # default = -1.0 [legacy W0_LAMBDA accepted too]
wa_LAMBDA:    <value> # default = 0.0
H0:           <value> # default = 70(SALT2), 65(MLCS)
or
HzFUN_FILE:   <fileName> # non-wCDM: 2 columns with z H(z)

MUSHIFT: <value> # mag shift for all distances (default=0)
```

It is recommended to *NOT* specify cosmological parameters and thus use the defaults; global default updates are easily propagated thru Github rather than modifying numerous sim-input files. The curvature is computed internally as  $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$ , and the radiation term is ignored.

For non-standard  $H(z)$ , `HzFUN_FILE` specifies an arbitrary function with 2-columns:  $z$  and  $H(z)$ . The  $z$ -bins need not be uniform; i.e.,  $\log(z)$ -binning. Since some of the cosmology functions integrate from  $z = 0$ , the first map bin must have  $z = 0$  (sim aborts if not satisfied).

Finally, `MUSHIFT` is not a physical model, but may be useful to generate bias-corrections with different `MUSHIFT` values in order to interpolate distances in a cosmology fitting program.

## 4.5 Synchronizing Random Numbers

The simulation is designed to preserve the random number sequence when input parameters and options are changed. This feature allows generating the exact same SNe (redshift, sky-coords, SN properties) when making changes such as the SIMLIB, HOSTLIB, exposure time, mag-offsets, intrinsic smearing, and model parameters. To ensure that different simulations are synchronized to the same random numbers, use the same random seed (RANSEED key) in each simulation job, and verify that the following output to the README file is identical:

Random Number Sync:

```
RANDOM SEED: 128473    (RANLIST_START_GENSMEAR: 1)
FIRST/LAST Random Number (List=1): 0.816247 0.216962  AVG(wrap) = 0.7 +- 0.2
FIRST/LAST Random Number (List=2): 0.622194 0.875059  AVG(wrap) = 0.6 +- 0.1
```

The first list is for the nominal generation, the second list is for the intrinsic scatter models, The optional sim-input key RANLIST\_START\_GENSMEAR can be used to pick different random numbers for the intrinsic scatter without affecting the main random sequence. Note that RANLIST\_START\_GENSMEAR is an offset in a list (not a SEED). The AVG(wrap) numbers is the average number of times that each finite list of randoms is re-used each event. Ideally,  $\text{AVG}(\text{wrap}) < 1$  so that randoms are not re-used.

Selection cuts may result in a different number of generated SNe, and hence a different last random number; in this case use the SIMGEN\_DUMP option (§4.37.2) to verify the sync.

For simulating spectra (§4.25), the number of randoms can be too large for practical storage; e.g., events with several spectra, each with  $\sim 10^4$  wavelength bins. A list of randoms that is too small results in obvious spectral ringing. To avoid this problem, two independent streams are used: 1st stream for generation and intrinsic scatter (List=1,2), and 2nd stream for unlimited spectral noise. The number of streams is controlled by sim-input “NSTREAM\_RAN: 2” and the default is 2. Only values of 1 or 2 are allowed.

The native C functions needed for two streams result in failed compilation on Macbook, although it works on many other platforms including Fermilab, NERSC, and U.Chicago RCC. For Mac, enable the pre-processor flag

```
#define ONE_RANDOM_STREAM    // enable for Mac only, in sntools.h
```

in sntools.h, which will force one and only one random stream, and avoid the native functions that don’t work on Mac. The default Github release has this flag commented out. Enabling ONE\_RANDOM\_STREAM should work fine, but the random-sync feature won’t work if spectra are generated.

## 4.6 Simulated TYPE

The simulation produces an SNTYPE value for the data header, allowing specific sub-types to be analyzed.<sup>4</sup> There are two basic SNTYPEs assigned: SNTYPE for spec-confirmed SNe (§4.18), and a different SNTYPE for unconfirmed SNe; the latter correspond to a photometrically identified sample. By default, the integer SNTYPE for unconfirmed SNe is 100 + the SNTYPE of spec-confirmed SNe.

The SNIa-SNTYPE is determined with the sim-input key “SNTYPE\_Ia” or “SNTYPES\_Ia”. For example, the SDSS-II code for type Ia is

```
SNTYPE_Ia: 120      # spec Ia -> type 120; photo-Ia -> type 220
or
SNTYPES_Ia: 120 106 # spec-Ia -> type 120; photo-Ia -> type 106
```

where the 2nd key allows specifying the photometric-id type to be different than 100 + spec-confirmed type. This integer code appears in the header of each output data file after the “SNTYPE:” key. For spec-confirmed SNIa, the default SNTYPE\_Ia value is 1.

The SNTYPE values for NON1ASED and NON1AGRID models are given in the sim-input file as described in §9.6. To specify TYPE for non-SN models, or over-ride the above, use GENTYPE as follows:

```
GENTYPE: 80      # specType=80, photoType=180
or
GENTYPES: 80 81  # specType=80, photoType=81
```

**Beware of SNTYPE collisions !** The user must beware of SNTYPE collisions between SNIa and Non-Ia. For example, consider the example above with “SNTYPE\_Ia: 120” in the SNIa sim-input file, and a separate Non-Ia input file in which SNTYPE=20 for one of the species. The unconfirmed Non-Ia SNTYPE value will be  $20 + 100 = 120$ , which conflicts with the SNIa-SNTYPE value. There is no problem if the SNIa and Non-Ia samples are analyzed separately, but there could be a problem if the samples are combined. There is no way for the simulation code to identify these conflicts because the Ia and Non-Ia are generated separately; hence the user must check.

---

<sup>4</sup>See &SNLCINP namelist variable SNTYPE\_LIST in the `snana.exe` and `snlc_fit.exe` programs.

## 4.7 The ‘SIMLIB’ Cadence Library File

A user-generated ‘SIMLIB’ file<sup>5</sup> is needed to define the cadence (MJD, ZP, PSF, SKY), translate magnitudes into CCD counts, and compute the uncertainty as described in Eq. 5. As an example, the start of the SIMLIB file for the SDSS-II 2005 survey is shown in Fig. 4. The public SIMLIB files are located in `$SNDATA_ROOT/simlib`, and a SIMLIB file is specified in the sim-input file with the keyword

```
SIMLIB_FILE: SDSS2005_ugriz.SIMLIB
```

A SIMLIB file is created by someone with knowledge of the telescope and observation conditions. There is a C-code utility, `SNANA_DIR/src/simlib_tools.c`, that can be used to create the SIMLIB file in the correct format. This utility has a lot of error checking to avoid accidentally writing absurd values such as negative PSF. In principle, a SIMLIB file need be created only once per survey, although systematic studies may require multiple SIMLIBs. If there are several exposures per filter per night, the utility `simlib_coadd.exe` (§12.3.2) re-makes a SIMLIB file with all exposures per filter combined into a single effective exposure per night.

The SIMLIB file begins with a required DOCUMENTATION block (§12.3.5). Next is a global header with the following keys:

# Required keys:

```
SURVEY: <SURVEY>      # must find match in $SNDATA_ROOT/SURVEY.DEF
FILTERS: <filtList>    # must find match in kcor/calib file
```

# Optional keys:

```
SKYSIG_UNIT: ADU_PER_SQARCSEC # change SKYSIG unit from default per-pixel
PSF_UNIT:    ARCSEC_FWHM      # change PSF unit from default pixels
PSF_UNIT:    NEA_PIXEL        # give Noise-Equiv-Area instead of PSF1,PSF2,PSFRATIO
NPE_PIXEL_SATURATE: <VAL>     # pixel-flux Saturation, photo-electrons
PHOTFLAG_SATURATE: <MASK>     # saturation mask in output PHOTFLAG column
NLIBID:      <VAL>            # Number of obs-sequences (LIBIDs) in file
PIXSIZE:     <VAL>            # size of pixel, arcSec
SOLID_ANGLE: <VAL>            # sr, used if SOLID_ANGLE=0 in input file
```

For batch jobs submitted with `submit_batch_jobs.sh` script, NLIBID is used to assign a different starting LIBID (see below) for each batch core, ensuring uniform library sampling.

---

<sup>5</sup>“SIMLIB” is an abbreviation for SIMulation LIBrary, although “cadence library” is a more appropriate name.

Following the global header is a list of observation sequences. Each sequence starts with a header as follows:

```
# Required
LIBID: <ID>      # integer id (does not have to be sequential)
NOBS:  <VAL>     # number of observations
RA:    <VAL>     # Right ascension, degrees
DEC:   <VAL>     # Declination, degrees

# Optional
MWEBV: <VAL>     # MW E(B-V). If zero, use software options.
PIXSIZE: <VAL>   # pixel size, arcSec
FIELD:  <NAME>   # name of FIELD1 e.g., DEEP, WIDE, etc
CCDNUM: <VAL>   # CCD number (to locate on focal plane)
```

For a non-overlapping field, the “FIELD:” header should appear only once per MJD-sequence. For overlapping fields, the FIELD key appears more than once as indicated in Fig. 4. Different FIELD names can be repeatedly toggled withing a LIBID, or simply list all the MJDs for one field (i.e, 82N) followed by all of the MJDs for the other field (i.e., 82S). The MJDs need not be chronological in the SIMLIB, as the simulation will sort them internally. You can ignore the FIELD key in the SIMLIB as well, in which case the SNDATA files and analysis lose track of the field.

Following the LIBID header, below is a brief explanation for each column in the observation table, along with references to terms in Eq. 5,

1. **S:** key starts a line with search-image info.
2. **IDEXPT:** arbitrary identifier. You can set this to zero if you want. For SDSS, it glues together the run and field numbers.
3. **FLT:** single character to specify a filter for this observation.
4. **CCD Gain:** Number of photo-electrons per ADU or DN.
5. **CCD Noise:** CCD read noise in photo-electrons, per pixel. This term is usually much smaller than the SKYSIG term below.
6. **SKYSIG:** Standard deviation of sky (including dark current), in ADU (or DN) per pixel. See §4.15 for noise calculation. You can optionally enter the skysig values per arcsec<sup>2</sup> by specifying the simlib global header key

SKYSIG\_UNIT: ADU\_PER\_SQARCSEC

The simulated README file includes the SKYSIG\_UNIT value.

7. **PSF1,2 and RATIO:** The PSF is specified by a double-Gaussian with  $\sigma$ -widths (pixels) of  $\sigma_1 = \text{PSF1}$  and  $\sigma_2 = \text{PSF2}$ . **RATIO** refers to the ratio at the origin,  $\text{PSF2}(\text{origin})/\text{PSF1}(\text{origin})$ . Note that the default PSF unit is in pixels, not arcsec. You can optionally give the PSF values in the more astronomy-friendly units of arcsec-FWHM by specifying the simlib header key

PSF\_UNIT: ARCSEC\_FWHM

The simulated README file includes the PSF\_UNIT value. These PSF values are used to determine a noise-equivalent area ( $A$  in Eq. 5 and Eq. 12). If you have computed  $A$  from the measured PSF, then you can simply define  $\text{PSF1} = \sqrt{A/4\pi}$  and set **PSF2=RATIO=0**.



8. **NEA:** Rather than providing 3 PSF parameters, the noise-equiv-area (NEA) can be provided using header key `PSF_UNIT: NEA_PIXEL` (see Fig. 5).
9. **ZPTAVG:** Zero point relating the source magnitude ( $m$ ) to the CCD flux measured in ADU:

$$\text{Flux(ADU)} = 10^{-0.4(m - \text{ZPTAVG})}.$$

For example, if  $F_{20}$  is the flux (in ADU) for a point source with  $\text{mag} = 20$ , then  $\text{ZPTAVG} = 20 + 2.5 \log_{10}(F_{20})$ . Note that **ZPTAVG** encodes information about the atmospheric transparency, telescope aperture & efficiency, and the exposure time. For any given simlib file, the simulated **ZPTAVG** can be changed globally or by filter as explained in §4.20. Note that the zeropoint in photoelectrons is given by  $\text{ZPT}_{\text{pe}} = \text{ZPTAVG} + 2.5 \log_{10}(\text{GAIN})$ .

10. **ZPTSIG:** See  $\hat{\sigma}_{\text{ZPT}}$  term in Eq. 5.

A sequence of MJDs that span the survey constitutes one entry in the **SIMLIB**, and the index “LIBID” labels each entry. A **SIMLIB** can have one LIBID, or hundreds. Large-area surveys, like SDSS-II, need hundreds of LIBIDs to properly sample the sky. A small area survey, like DES, may need just one LIBID per pointing, and per season.

```
DOCUMENTATION:
  PURPOSE:  SDSS 1st-year cadence for SNANA simulation
  [provide doc in YAML format]
DOCUMENTATION_END:
# =====
SURVEY: SDSS
FILTERS: gri
BEGIN LIBGEN  Tue Apr 17 13:32:33 2007

# -----
LIBID: 1
RA: 26.430172    DECL: 0.844033    NOBS: 42    MWEBV: 0.026    PIXSIZE: 0.400
FIELD: 82N
#
#           CCD  CCD           PSF1 PSF2 PSF2/1
#   MJD      IDEXPT FLT GAIN NOISE SKYSIG (pixels)  RATIO  ZPTAVG ZPTSIG
S: 53616.383 556600405 g 4.05  4.25  4.04  1.85 3.61 0.247 28.36 0.020
S: 53616.383 556600405 r 4.72  4.25  5.28  1.64 3.62 0.142 28.17 0.022
S: 53616.383 556600405 i 4.64 12.99  6.95  1.60 3.81 0.103 27.84 0.017
FIELD: 82S
S: 53622.395 558200552 g 4.03  5.45  4.09  1.58 3.31 0.107 28.45 0.018
S: 53622.395 558200552 r 4.89  4.65  5.00  1.46 3.55 0.065 28.15 0.028
S: 53622.395 558200552 i 4.76 10.71  6.43  1.53 3.65 0.075 27.85 0.029
S: 53626.359 560300625 g 4.05  4.25  4.40  1.83 3.50 0.282 28.24 0.020
etc ...
```

Figure 4: Header and part of first entry of the **SIMLIB** file used for the SDSS-II survey.



```

DOCUMENTATION:
  PURPOSE:  SDSS 1st-year cadence for SNANA simulation
  [provide doc in YAML format]
DOCUMENTATION_END:
# =====
SURVEY: SDSS
FILTERS: gri
PSF_UNIT: NEA_PIXEL # <== describe PSF with noise-equiv-area (NEA) in pixels
BEGIN LIBGEN  Tue Apr 17 13:32:33 2007

# -----
LIBID: 1
RA: 26.430172    DECL: 0.844033    NOBS: 42    MWEBV: 0.026    PIXSIZE: 0.400
FIELD: 82N
#
#           CCD  CCD
#   MJD      IDEXPT  FLT  GAIN  NOISE  SKYSIG  NEA    ZPTAVG  ZPTSIG
S: 53616.383  556600405 g  4.05  4.25  4.04  80.38  28.36  0.020
S: 53616.383  556600405 r  4.72  4.25  5.28  61.64  28.17  0.022
S: 53616.383  556600405 i  4.64 12.99  6.95  57.23  27.84  0.017
FIELD: 82S
S: 53622.395  558200552 g  4.03  5.45  4.09  48.43  28.45  0.018
S: 53622.395  558200552 r  4.89  4.65  5.00  41.15  28.15  0.028
S: 53622.395  558200552 i  4.76 10.71  6.43  46.53  27.85  0.029
etc ...

```

Figure 5: Same as Fig. 4, but using NEA column instead of three PSF params.

#### 4.7.1 SIMLIB Options in the Sim-Input File

```

SIMLIB_MSKOPT:  nnn      # bit-mask of options (see below)
SIMLIB_MINOBS:  nnn      # require at least this many obs per LIBID
SIMLIB_MAXOBS:  nnn      # require fewer than this many obs per LIBID
SIMLIB_IDSTART: nnn      # start at LIBID nnn
SIMLIB_IDLOCK:  nnn      # use only LIBID nnn ; skip all others
SIMLIB_MAXRANSTART: nnn # start at random LIBID among first nnn entries
SIMLIB_NSKIPMJD: n       # use every 'n+1'th observation
SIMLIB_NSKIPMJD: 2(50),4(100) # PS=1 for Trest>50, PS=4 for Trest>100 days.
SIMLIB_IDSKIP:  nn1      # ignore LIBID nn1
SIMLIB_IDSKIP:  nn2      # ignore LIBID nn2 (add as many as you want)
SIMLIB_DUMP:    1        # dump summary of simlib
SIMLIB_NREPEAT: nn       # repeat each LIBID nn times (for speed)
SIMLIB_FIELDLIST xyz    # plus-separated list of field-substrings
SIMLIB_MINSEASON nn     # remove seasons less than nn day duration
USE_SIMLIB_PEAKMJD: 1    # use peakMJD in header (if there)
USE_SIMLIB_REDSHIFT: 1   # use redshift in header (if there)
USE_SIMLIB_DISTANCE: 1   # use lumi-distance in header (invert to get zCMB)
USE_SIMLIB_SPECTRA:  1   # use TAKE_SPECTRUM keys in header
USE_SIMLIB_SALT2:    1   # use SALT2c & SALT2x1 keys in header

SMEARFLAG_FLUX:    1    # apply Poisson noise to fluxes
SMEARFLAG_ZEROPT:  1    # apply ZPTSIG to true flux, but not reported flux
SMEARFLAG_ZEROPT:  3    # apply ZPTSIG to true and reported flux

```

More information about the SIMLIB\_DUMP option is in §4.37.1. The SIMLIB\_MSKOPT options are

- MSKOPT += 2 : for each LIBID in the simlib, keep generating until an event is accepted. The number generated for each LIBID is stored in the output tables(s) and SIMGEN-DUMP file as NGEN\_LIBID. To avoid infinite loop, generation for a given LIBID stops when NGEN\_LIBID > MXGEN\_LIBID. To preserve NGEN\_LIBID information for no-accept LIBIDs, these events are forced to be accepted with NOBS = NEPOCH = 0 to ensure that forced events fails all analysis cuts.
- MSKOPT += 4 : stop generating after one pass through SIMLIB file. Set NGENTOT\_LC to large value to avoid stopping before end of SIMLIB. Beware: if APPLY\_CUTWIN\_OPT is set, the number of events written to data file may be fewer than number of SIMLIB entries.
- MSKOPT += 8 : debug option to replace correlated template noise (TEMPLATE\_XXX keys below) with random (uncorrelated) noise.
- MSKOPT += 16 : ignore template noise in SIMLIB file.
- MSKOPT += 32 : ignore FLUXERR\_COR map in SIMLIB file.
- MSKOPT += 128 : if any part of  $T_{\text{rest}}$  range overlaps a season, include entire season in light curve. Season defined by gap  $\geq 90$  days.
- MSKOPT += 256 : include every MJD in survey, regardless of  $T_{\text{rest}}$ -range.

- `MSKOPT += 512` : see §4.7.7

When the trigger efficiency is low, such as for `NON1A` models at high redshift, the simulation speed is limited by reading the ascii `SIMLIB` file. The simulation speed can be improved by a factor of few using `'SIMLIB_NREPEAT: 10'`, where 10 is a suggested value. This option generates 10 SNe with each `SIMLIB` entry before reading the next `SIMLIB` entry, and thus reduces the amount of reading by a factor of 10. Be careful to make sure that your `SIMLIB` is fully sampled. For example, if a `SIMLIB` has 1000 entries and 1000 SNe are generated with `SIMLIB_NREPEAT=10`, then the first 100 `SIMLIB` entries are used and the remaining 900 are ignored. In this situation at least 10,000 SNe should be generated to sample each `SIMLIB` entry.

**SIMLIB\_NREPEAT BEWARE:** this option results in non-uniform sampling of the `SIMLIB`, and it can be corrected with `NGEN_LIBID` in the output table. However, if you are not sure how to correct with `NGEN_LIBID` then you should not be using this option.

For `SIMLIB_FIELDLIST`, see §4.9.2.

`SIMLIB_MAXRANSTART` is useful when using `submit_batch_jobs.sh` (§12.2.1) and each job generates fewer events than the number of `SIMLIB` entries. For example, suppose a `SIMLIB` has 1000 entries, and a sim-job generating 2000 events is distributed among 50 cores using `submit_batch_jobs.sh`. The problem is that each of the 50 jobs generates  $2000/50 = 40$  events, and each job samples only the first 40 `SIMLIB` entries, which does not properly sample the `SIMLIB`. Using

```
SIMLIB_MAXRANSTART: 1000
```

each job will start at a random entry among the first 1000 `SIMLIB` entries, thereby assuring a proper sampling of the full `SIMLIB`. If each of the 50 jobs has enough statistics to sample the full `SIMLIB`, there is no need to use this feature. However, be careful when using `SIMLIB_NREPEAT` because the number of sampled `SIMLIB` entries is reduced by this `NREPEAT` factor.

## 4.7.2 SIMLIB SPECTROGRAPH

A `SPECTROGRAPH` instrument is defined in the `kcor-input` file as described in §3.2. The `SIMLIB` Search-epoch key for a broadband filter is “S:” and the corresponding `SIMLIB` key for a spectrum is

```
SPECTROGRAPH: 54997.3 1840 # MJD & Texpose (seconds)
```

An arbitrary number of `SPECTROGRAPH` keys are allowed in a `SIMLIB` file. In addition to computing a spectrum at the listed MJD, the optional synthetic magnitudes (`SYN_FILTERS` key in `kcor-input` filers) are evaluated in the same way as any other broadband filter.

Correlated template noise in both the spectra and synthetic filters can be included by specifying the template exposure time in the `LIBID` header as follows:

```
TEMPLATE_TEXPOSE_SPECTROGRAPH: 5010 # seconds
```

### 4.7.3 SIMLIB Options for each LIBID

The following header options can follow each LIBID key in a SIMLIB file.

```
RA:      xxx    # right ascension, degrees
DECL:    xxx    # declination, degrees
NOBS:    nnn    # number of obs to follow (i.e., number of 'S:' rows)
PIXSIZE: xxx    # size of each pixel, arcsec

#      optional
MWEBV:   xxx    # E(B-V) from Galactic extinction
FIELD:   sss    # name of field (optional)
REDSHIFT: xxx    # force this redshift
PEAKMJD: xxx    # force this peak-MJD

CUTWIN_REDSHIFT: xxx xxx # reject if zCMB is not in this range
REDSHIFT_RANGE:  xxx xxx # idem with legacy key

GENRANGE_REDSHIFT: xxx xxx # regenerate zCMB in this range

GENRANGE_PEAJMJD:  xxx xxx # regenerate PEAKMJD in this range
GENSIGMA_PEAJMJD:  xxx     # pick from Gaussian profile; otherwise flat

GENRANGE_SALT2x1:  xxx xxx # regenerate SALT2x1 in this range
GENSIGMA_SALT2x1:  xxx     # pick from Gaussian profile; otherwise flat

GENRANGE_SALT2c:   xxx xxx # regenerate SALT2c in this range
GENSIGMA_SALT2c:   xxx     # pick from Gaussian profile; otherwise flat

#      correlated template noise
TEMPLATE_ZPT:      <value for each filter>    # ADU
TEMPLATE_SKYSIG:   <value for each filter>    # ADU/pix
TEMPLATE_CCDSIG:   <value for each filter>    # e-/pix
```

If GENSIGMA\_XXX is not specified, a flat distribution is generated within GENRANGE\_XXX. If the GENSIGMA\_XXX are specified, each XXX value is generated from a Gaussian distribution whose peak value is the center of the GENRANGE\_XXX window.

For more info on the TEMPLATE\_XXX keys, see §4.10. The USE\_SIMLIB\_XXX keys are specified in the sim-input file (§4.7.1).

#### 4.7.4 Saturation Option

Saturation is specified by two SIMLIB keys in the global header before the “BEGIN LIBGEN” key:

```
NPE_PIXEL_SATURATE: 65000 # Npe to saturate central pixel, per exposure
PHOTFLAG_SATURATE: 2048 # add this to PHOTFLAG for each epoch
```

The central PSF-pixel fluxes are summed for source, galaxy and sky. If the resulting number of photoelectrons exceeds NPE\_PIXEL\_SATURATE, then this epoch is flagged as saturated as follows:

- PHOTFLAG = PHOTFLAG\_SATURATE
- FLUXCAL =  $0 \pm 10^8$

Saturated epochs are not used to form trigger logic, and SNANA programs (snana.exe, snlc\_fit.exe) ignore saturated epochs.

For co-added observations, the exposure-averaged flux is compared with NPE\_PIXEL\_SATURATE. The number of exposures in the co-add (NEXPOSE, default=1) can be optionally included with the IDEXPT column as follows:

```
#                               PSF1 PSF1 PSF
#      MJD   ID*NEXPOSE  FLT GAIN NOISE SKYSIG (pixels) RATIO  ZPTAVG ZPTERR  MAG
S: 59770.366 13819*6    r  1.00  1.12 138.55 1.45 0.00 0.000  34.89  0.005   99
etc ..
```

which corresponds to 6 exposures in the co-add. Note that ID\*NEXPOSE is a single string with no blank spaces between the characters. In this example, a saturated epoch is flagged if

$$\text{FLUX}(\text{central pixel})/6 > \text{NPE\_PIXEL\_SATURATE}$$

The fraction of flux in the central pixel ( $f_A$ ) is computed analytically using a Talyor expansion of a Gaussian:

$$f_A = \frac{P^2}{2\pi\sigma^2} \left[ 1 - \frac{P^2}{4\pi\sigma^2} \right]$$

where  $P$  is the pixel size and  $\sigma$  refers to the PSF. Beware that when  $P > \sigma$ , the analytic approximation degrades. However, the computation of  $f_A$  only affects the saturation flag, and is not used in determining the broadband fluxes.

Finally, the total number of saturated/unsaturated observations can be included in the SIMGEN\_DUMP file (§4.37.2): NOBS\_SATURATE and NOBS\_NOSATURATE. CUTWIN options can be used to select based on the number of [un]saturated observations per filter (§4.19).

#### 4.7.5 APPEND Option

The SIMLIB-APPEND feature prevents epochs from being MJD-sorted. This feature allows appending SIMLIB observations without changing the original light curve fluxes and their Poisson fluctuations. The SIMLIB syntax is shown below. Epochs after the APPEND key are not MJD-sorted, and thus won't change the random sync for epochs before the APPEND key. The integer argument after the APPEND key is a mask that is added to the PHOTMASK column in the data file.

```
...
S: 53616.383 556600405 g 4.05 4.25 4.04 1.85 3.61 0.247 28.36 0.020
S: 53616.383 556600405 r 4.72 4.25 5.28 1.64 3.62 0.142 28.17 0.022
S: 53616.383 556600405 i 4.64 12.99 6.95 1.60 3.81 0.103 27.84 0.017
APPEND: 4
S: 53612.395 558200552 g 4.03 5.45 4.09 1.58 3.31 0.107 28.45 0.018
S: 53612.396 558200552 r 4.89 4.65 5.00 1.46 3.55 0.065 28.15 0.028
S: 53612.397 558200552 i 4.76 10.71 6.43 1.53 3.65 0.075 27.85 0.029
...
```

#### 4.7.6 SNR Monitor

To monitor the quality of observing conditions at each epoch, the SNR for a fixed magnitude can be computed with the following sim-input:

```
MAGMONITOR_SNR: 20 # only integer mag allowed
```

which results in computing SNR for mag= 20 at each MJD in the SIMLIB. The results are stored in the data files under a photometry column labelled SIM\_SNRMAG20. Beware that SIM\_SNRMAG20 depends on the SIMLIB quantities (ZP,PSF,SKY) and does not depend on the light curve model. The argument of MAGMONITOR\_SNR must be an integer in order to construct the variable name of the output photometry column.

If SIM\_SNRMAG## exists, it is automatically read by the analysis programs and included in output tables with epoch columns: in particular, the tables SNANA+EPOCHS and FITRES+RESIDUALS.

#### 4.7.7 Ideal Cadence with fixed MJD Grid

This option (SIMLIB\_MSKOPT | 512) is designed to reduce the necessary size of an ideal SIMLIB cadence that i) has fixed MJD grid, ii) has no seasonal gaps, and iii) has the same SKYSIG/ZP/PSF for every epoch. An ideal cadence is useful to generate model magnitudes (and SEDs) without instrumental signatures.

To illustrate the potential problem, consider an ideal 0.1 day cadence for a fast transient such as Kilonova, 10 passbands, and a 5 year (1825 day) survey duration in which we want to randomly generate model light curves. The size of the ideal SIMLIB cadence is  $10 \times 1825 / 0.1 = 182,500$  rows, which vastly exceeds the default  $MXOBS\_SIMLIB = 15,000$ .

A practical solution is to define an ideal SIMLIB with an MJD range that covers the min-to-max  $T_{\text{obs}}$  range of the model, and shift the resulting light curve to an MJD range outside of the SIMLIB range. This strategy is implemented by setting the 512-bit of SIMLIB\_MSKOPT. More specifically, this option does the following:

- defines required MJD range to be  
 $(\text{GENRANGE\_TREST}[1] - \text{GENRANGE\_TREST}[0]) * (1 + \text{GENRANGE\_REDSHIFT}[1])$   
The sim aborts if the SIMLIB MJD-range is smaller than the required MJD range.
- after picking a random peak-MJD (`PEAKMJD_SURVEY`) within `GENRANGE_PEAJMJD`, a temporary `PEAKMJD_TMP` is selected inside the SIMLIB cadence such that (i)  $\text{TRESTMIN}(1+z)$  to  $\text{TRESTMAX}(1+z)$  is contained, and (ii) the MJD-difference,  
 $\text{MJD\_SHIFT} = \text{PEAKMJD\_SURVEY} - \text{PEAKMJD\_TMP}$ ,  
is an integer multiple of the MJD grid size.
- After reading and storing the cadence, all MJDs are shifted by `MJD_SHIFT`.

## 4.8 Simulating Coordinates and Random Shifts

The RA and DEC coordinates are read from each SIMLIB entry (§4.7), which has the advantage of exactly correlating observation properties (ZP,PSF,SKY,MWEBV) with each coordinate. The host galaxy coordinate option (see `MSKOPT+=8` in §4.22.1) enables generating SN light curves to overlay on real images. An artifact of these strategies is that coordinates are repeated for large samples that read through the SIMLIB (or HOSTLIB) multiple times. This artifact can be problematic, for example, when using/testing codes that spatially match observations.

To significantly reduce spatial overlaps, there is an option to shift the coordinates to a random location in a circle centered on the originally chosen coordinate,

```
MXRADIUS_RANDOM_SHIFT: 0.01 # circle radius, degrees
```

The assumption is that shifts are  $\ll 1$  deg, and thus MWEBV and CMB-redshift are *not* updated. The RA,DEC shifts are not stored in the data files, but the shifts can be monitored via the `SIMGEN_DUMP` utility (§4.37.2), e.g.,

```
SIMGEN_DUMP: CID,ZCMB,DLmag,RA,DEC,shift_RA,shift_DEC,shift_RADIUS,shift_PHI
```

## 4.9 Simulating Fields

### 4.9.1 Overlapping Fields

The simulation can handle overlapping fields, such as for the SDSS **82N/82S** overlap, and the 20% overlap of the LSST fields. Overlapping fields are specified in the SIMLIB file by specifying the `FIELD` keyword as needed. Figure 4 above illustrates an overlap between the SDSS fields **82N** and **82S**. Note that overlapping fields make no sense if there is just one simlib entry per field with the position selected at the (non-overlapping) center of the field. To generate light curves in overlapping fields, the SIMLIB should include many LIBID entries per field, where each LIBID is associated with a random RA & DEC. This mechanism accounts for dithering as well as variations within a field from Galactic extinction and observing conditions.

If the fields are small and non-overlapping (e.g., SNLS), then a single LIBID per field, with the RA & DEC at the center, may work reasonably well. However, this simlib will not probe variations in Galactic extinction that can occur even on small angular scales.

The `&SNLCINP` namelist includes two `FIELD`-selection variables (§5.20) that work for both data and simulations. First you can pick specific fields with

```
SNFIELD_LIST = 'field1', 'field2', 'field3'
```



By default all fields are analyzed when running the fitting program. The second option is `CUTWIN_NFIELD` so that you can select SN that overlap more than 1 field.

#### 4.9.2 Field Subset and Field Prescales

There are two distinct methods to simulate a subset of fields, and the difference is important for getting the right normalization of generated events. The `FIELD`-subset options are illustrated here with a hypothetical survey with 10 fields: 8 of them are called `SHALLOW` and 2 of them are called `DEEP`. Assume that each field has the same area of  $10 \text{ deg}^2$ , or  $100 \text{ deg}^2$  total. Finally, consider a `SIMLIB` file with 200 `DEEP`-field entries and 800 `SHALLOW`-field entries. If we select only `DEEP` fields, there are two different ways in which the simulation can work: 1) count every `SHALLOW` and `DEEP` field as part of `NGENTOT_LC`, or 2) ignore `SHALLOW` fields as if they were not in the `SIMLIB`. For the first option, only 20% of the events land on a `DEEP` field, and thus the efficiency will be less than 20%. For the 2nd option, all events are processed with a `DEEP` field `SIMLIB` entry, and thus the efficiency can be as high as 100%. For the 2nd option, one should reduce the solid angle by a factor of 5 in order to get the same number of events as in the first option.

These two `SIMLIB`-counting options are implemented in the `sim-input` file as follows:

```
SOLID_ANGLE:      0.03      # 100 deg^2
SIMLIB_FIELDLIST: DEEP1+DEEP2  # NGENTOT counts both SHALLOW and DEEP
or
SOLID_ANGLE(DEEP1+DEEP2): 0.006 # 20 deg^2 for DEEP only
```

Used with `submit_batch_jobs.sh`, both options result in the same number of output events (within statistical errors), but 2nd efficiency will be  $\times 5$  larger than the first to compensate the first job generating  $\times 5$  more events.

Be careful with `SIMLIB_FIELDLIST` because it checks for substring matches rather than an exact match. For the example above,

```
SIMLIB_FIELDLIST: DEEP      # select all fields with DEEP in name
```

is equivalent to explicitly selecting `DEEP1+DEEP2`. This sub-string select feature is convenient when there are many fields, but it can also lead to undesirable behavior as illustrated in the following example. Consider ten `SIMLIB` fields: `F1, F2, ... F10`. Naively, the first field is selected with “`SIMLIB_FIELDLIST: F1,`” but it actually selects both `F1` and `F10` since `F1` is a sub-string of both. To avoid such mistakes, define ten fields as `F01, F02, ... F10`, and select “`SIMLIB_FIELDLIST: F01.`”

To simulate large bias-correction (`biasCor`) samples for BBC,<sup>6</sup> it may be useful to *prescale* some fields to reduce processing time for simulation and light curve fitting. In the above `DEEP+SHALLOW` example, suppose that BBC needs  $\text{few} \times 10^5$  events in `SHALLOW` and `DEEP` separately, but the physical distribution results in  $\times 4$  more `SHALLOW` events. To generate enough `DEEP`-field events requires over-generating `SHALLOW` field by a factor of 4. To balance the `biasCor` load, a prescale can be used as follows,

```
SIMLIB_FIELDLIST: SHALLOW/4+DEEP
or
SIMLIB_FIELDLIST: DEEP+SHALLOW/4
```

---

<sup>6</sup>BBC = “Beams with Bias Corrections; see §10 and §9.3.1



A few warnings: 1) DEEP fields have a larger redshift range and thus it may be prudent to generate a larger DEEP sample by prescaling shallow by 5 or 6. 2) data/sim overlays using the biasCor will give good agreement only if a FIELD-select cut is applied: will have very poor agreement if all fields are combined. 3) Rather than matching biasCor statistics in BBC, another approach is to match BBC loss per FIELD (see IDSAMPLE losses printed at top of BBC output FITRES files).

Finally, there is a subtle issue using “SOLID\_ANGLE(DEEP)” as a command line argument. Unix tries to parse the parentheses, resulting in bad arguments passed to the simulation. To avoid this problem, use single quotes or back-slashes:

```
snlc_sim.exe mySim.input  'SOLID_ANGLE(DEEP)' 0.006
or
snlc_sim.exe mySim.input  SOLID_ANGLE\ (DEEP\ ) 0.006
```

The `submit_batch_jobs.sh` script automatically adds the backslashes, so there is no need to modify the GENOPT argument.

## 4.10 Correlated Template Noise

Coherent template noise is simulated with the following SIMLIB keys:

TEMPLATE_ZPT:	<value for each filter>	# ADU	[required]
TEMPLATE_SKYSIG:	<value for each filter>	# ADU/pix	[optional]
TEMPLATE_CCDSIG:	<value for each filter>	# e-/pix	[optional]

where the list of ‘NFILT’ values corresponds to the list of NFILT filters following the FILTERS key in the header. For example, if 6 filters are defined by “FILTERS: ugrizY” then each TEMPLATE\_XXX key must be followed by 6 values, even for LIBIDs that use a subset of filters. The TEMPLATE\_XXX keys can appear before the first LIBID to specify a global set of values for every generated SN. Alternatively, these TEMPLATE\_XXX keys can appear after each LIBID (along with RA, DECL, etc ...) to specify an independent template noise for each LIBID entry. Note that TEMPLATE\_ZPT is required if one or both of the noise keys (SKYSIG or CCDSIG) is specified. For each generated SN epoch, a filter-dependent random template fluctuation is normalized to the search image using the ZPT information, and the normalized fluctuation added to the flux.

Internally the simulation adds two sets of fluctuations: all errors excluding the template are used to pick one fluctuation and the template error is used for the other fluctuation. The first fluctuation is independent for all epochs; the 2nd fluctuation is coherent among epochs in the same filter. The reported FLUXCAL\_ERR combines these two sources in quadrature.

Off-diagonal errors coming soon ...

## 4.11 Simulating Multiple Instruments

SN photometric observations may come from more than one instrument, such as optical and infrared observations. To simulate all of the light curves together, each simlib entry can contain information from multiple instruments. The only caveat is that FIELD name and pixel size must be re-defined as illustrated in Fig. 6.

Since the default units for the noise (CCD and SKY) and the PSF are both in pixels, the PIXSIZE value has no practical effect. However, when using optional units of arcsec (§4.7), the correct PIXSIZE values are important.

```
LIBID: 4
FIELD: F4  RA: 0.50    DECL: -43.0    MWEBV: 0.008
TELESCOPE: CTIO  PIXSIZE: 0.270 asec
NOBS: 120
#
#          CCD  CCD          PSF1 PSF2 PSF2/1
#  MJD  IDEXPT FLT  GAIN NOISE  SKYSIG  (pixels)  RATIO ZPTAVG ZPTSIG MAG
S: 56249.039 1002 g  1.00 10.00  91.90  1.93 0.00 0.000  33.02 0.020 99.
S: 56249.000 1003 r  1.00 10.00 151.40  1.49 0.00 0.000  33.29 0.020 99.
S: 56249.008 1004 i  1.00 10.00 275.66  1.62 0.00 0.000  33.42 0.020 99.
S: 56249.016 1005 z  1.00 10.00 442.18  1.40 0.00 0.000  34.31 0.020 99.

FIELD: V8    PIXSIZE: 0.339  # <== for different instrument
S: 56250.323 1006 Y  4.0 160.0 114.22  1.09 0.0  0.0    31.70 0.010 99.
S: 56256.033 1007 J  4.0 160.0 282.14  1.16 0.0  0.0    31.99 0.010 99.
```

Figure 6: Excerpt from SIMLIB with two instruments: DES optical (*griz*) and VIDEO infrared (*YJ*).

## 4.12 Simulating Multiple Seasons

Multiple seasons can be simulated with a separate SIMLIB file for each season, but this strategy requires multiple generations and bookkeeping to generate a full multi-season sample. An alternative is to construct a single SIMLIB file containing all seasons, either as separate LIBID entries for each season or as long LIBID entries that each spans all of the seasons/years.

For the latter option using a single SIMLIB for multiple seasons, there are typically long MJD gaps with no observations, leading to inefficient generation. MJD masks can be specified in the SIMLIB header, as illustrated here for the SDSS-II,

```
GENSKIP_PEAKMJD: 53710 53970 # skip the off-season
GENSKIP_PEAKMJD: 54070 54340 # idem
```

Each GENSKIP\_PEAKMJD key must appear before the “BEGIN LIBGEN” key, and it specifies an MJD-range to ignore in the generation.

### 4.13 Simulating a Filter as a Sum of Components

#### OBSOLETE as of SNANA version v10\_50m

There are some cases where the flux in a filter should be simulated as a sum of components in order to avoid ambiguities in the zeropoint. Examples are red-leakage in a UV filter, cross-correlation filters, or a very broad filter. If the filter transmission for '0' is the sum of filter-transmissions 1+2+3+4, the following SIMLIB entries are needed:

#				CCD	CCD		PSF1	PSF2	PSF2/1			
#	MJD	IDEXPT	FLT	GAIN	NOISE	SKYSIG	(pixels)		RATIO	ZPTAVG	ZPTSIG	MAG
...												
S:	56190.000	1000	0	1.00	10	100.00	2.00	0	0	1+2+3+4	0.020	99
S:	56190.000	1001	1	1.00	10	47.63	2.35	0	0	32.98	0.020	99
S:	56190.000	1002	2	1.00	10	98.63	2.35	0	0	32.33	0.020	99
S:	56190.000	1003	3	1.00	10	122.63	2.35	0	0	32.21	0.020	99
S:	56190.000	1004	4	1.00	10	147.63	2.35	0	0	32.16	0.020	99
...												

The ZPTAVG value for filter-0 is assumed to be ambiguous because it depends on the magnitude of the object (see below), and hence this entry is replaced by 1+2+3+4 to indicate that its flux is a sum of filters that have well-determined properties. Filters 01234 must all be defined in the usual way in the kcor/calib file, and the GENFILTERS key must include these five filters. The MJDs for 012345 must be exactly the same; if not, the simulation will abort. The SIMLIB entries for 1234 must be accurately defined, and any reasonable values for '0' are sufficient since the filter-0 flux will get over-written with the sum of fluxes from 1+2+3+4. The zeropoint ( $Z_0$ ) for filter-0 is calculated to be

$$Z_0 = 2.5 \times \log_{10} \left[ \sum_i 10^{-0.4(m_i - M_0 - Z_i)} \right] \quad (6)$$

where  $m_i$  are the simulated magnitudes in filter components  $i = 1, 2, 3, 4$ ,  $Z_i$  are the user-determined zeropoints in  $i = 1, 2, 3, 4$ , and  $M_0$  is the simulated magnitude in filter-0. Note that for a coadd we have  $m_i = M_0$  and recover the usual expression for the co-added zeropoint.

## 4.14 Noise Corrections: $\hat{S}_{\text{SNR}}$ and $\hat{\sigma}_0$

From the noise calculation in Eq. 5 there are two quantities which the simulation cannot determine from the SIMLIB file: 1) global scale  $\hat{S}_{\text{SNR}}$ , and 2) offset  $\hat{\sigma}_0$ . §4.14.1 explains how a survey team provides this information via tables, and §4.14.3 suggests a general strategy on how to determine  $\hat{S}_{\text{SNR}}$ .

### 4.14.1 FLUXERRMODEL Tables

$\hat{S}_{\text{SNR}}$  and  $\hat{\sigma}_0$  are each defined as an arbitrary multi-dimensional function of the following 8 variables:

MJD:	Modified Julian date
PSF:	FWHM, arcsec
SKYSIG:	ADU/pixel
ZP:	zero point, ADU
LOGSNR:	log10(SNR) # calculated SNR before error fudge
SBMAG:	surface-brightness mag, per arcsecond <sup>2</sup>
GALAMG:	total galaxy mag
SNSEP:	SN-host separation, arcsec

For each observation, the set of 8 values is called  $\vec{O}_\sigma$ . Several 1D maps can be defined, or a single multi-dimensional map can be used to capture correlations. The 1D maps are illustrated for the 3-year SDSS sample in

```
$SNDDATA_ROOT/simlib/SDSS/SDSS_fluxErrModel.DAT
```

The first NVAR-1 columns are input variables among the 8 variables above. The last column is either ERRSCALE (=  $\hat{S}_{\text{SNR}}$ ) or ERRADD (=  $\hat{\sigma}_0$ ). The BAND key specifies that each map corresponds only to that band. There is also an optional FIELD key, but since the FIELD key is not used in this example, the map is applied to all fields (82-N and 82-S). Similarly, leaving out the BAND key would apply the map to all filters.

The MAPNAME is chosen by the user, and only one of each MAPNAME can be used per observation. If the simulation finds two valid maps with the same MAPNAME, the code will abort. Multiple maps can be applied per observation, as long as each map has a different MAPNAME. In the SDSS example, two maps are applied for each observation: FLUXERR\_ADD and FLUXERR\_SCALE. For a given  $\vec{O}_\sigma$ ,  $\hat{S}_{\text{SNR}}$  and  $\hat{\sigma}_0$  are computed from linear interpolation of the map. The map binning must be uniform, and the maps are not extrapolated which means that the map range must cover all possible  $\vec{O}_\sigma$  values from the survey: violating either criteria results in an abort.

While the example file above (SDSS\_fluxErrModel.DAT) illustrates 1D maps, Fig. 7 shows an explicit example of a 2D map for the Dark Energy Survey (DES). This map has 3 ZP bins and 5 PSF bins; the total map size is  $3 \times 5 = 15$  bins. Fig. 7 illustrates an optional feature, DEFINE\_FIELDGROUP, to associate a key with a group of fields. The map corresponds to the DEEP fields, which is internally translated to C3 and X3 fields. The map applies to all four (*griz*) passbands.

The maps can be applied to simulations and to data. For simulations, the following sim-input command will use the SDSS set of maps:

```
FLUXERRMODEL_FILE: SDSS_fluxErrModel.DAT
```

```
# option: suppress map(s) in reported errors for systematic tests:
```

```
FLUXERRMAP_IGNORE_DATAERR: FLUXERR_ADD
```

```
or
```

```
FLUXERRMAP_IGNORE_DATAERR: FLUXERR_SCALE
```

```
or
```

```
FLUXERRMAP_IGNORE_DATAERR: FLUXERR_ADD,FLUXERR_SCALE
```

```
# Option: re-write maps in FITRES format (for plotting,analysis, etc...)
```

```
# One output text file per MAPNAME
```

```
FLUXERRMODEL_OPTMASK: 256
```

The maps are always applied to the generated fluxes to modify the true scatter on  $F - F_{\text{true}}$ . By default the maps also modify the reported errors, but `FLUXERRMAP_IGNORE_DATAERR` allows suppressing some maps from the reported errors in the data file to study the impact of underestimated errors. The third `IGNORE` key suppresses both maps, which is equivalent to removing the `FLUXERRMODEL_FILE` key.

To modify data uncertainties in the analysis programs (`snana.exe`, `snlc_fit.exe`, `psnid.exe`),

```
&SNLCINP
```

```
FLUXERRMODEL_FILE      = 'SDSS_fluxErrModel.DAT'  ! data only
```

```
FLUXERRMODEL_OPTMASK   = 256  ! optional text dump of maps
```

```
SIM_FLUXERRMODEL_FILE  = 'SDSS_fluxErrModel.DAT'  ! force on SIMs
```

By default, the `FLUXERRMODEL_FILE` key operates only on real data by adjusting the reported errors. `FLUXERRMODEL_FILE` is ignored for simulated samples because the simulated scatter and errors can be altered during generation. To force simulated errors to be altered in the analysis stage, use the optional key `SIM_FLUXERRMODEL_FILE`.

Finally, the `FLUXERRMODEL_OPTMASK=256` option (for simulation and analysis) writes out the maps in the same `TEXT` format as the `FITRES` files, and writes one `TEXT` file per `MAPNAME`. This format may be more useful for making plots and debugging.

```

DEFINE_FIELDGROUP:  SHALLOW  E1+E2+S1+S2+C1+C2+X1+X2
DEFINE_FIELDGROUP:  DEEP      C3+X3

REDCOV:  g:0.3,r:0.5  # reduced corr = 0.3 & 0.5 for g & r, respectively
REDCOV:  iz:0.4       # reduced corr = 0.4 for i+z combined

MAPNAME:  ERRSCALE_2D_ZPPSF
BAND:  griz  FIELD:  DEEP
SCALE_FLUXERR_DATA:  1.2  # scale reported error, but not true err
SCALE_FLUXERR_TRUE:  1.1  # scale true error, but not reported err
VARNAMEs:  ZP  PSF  ERRSCALE
ROW:       29  0.5  1.02
ROW:       29  1.5  1.25
ROW:       29  2.5  1.72
ROW:       29  3.5  2.06
ROW:       29  4.5  2.20
ROW:       32  0.5  1.0
ROW:       32  1.5  1.05
ROW:       32  2.5  1.12
ROW:       32  3.5  1.19
ROW:       32  4.5  1.30
ROW:       35  0.5  1.0
ROW:       35  1.5  1.05
ROW:       35  2.5  1.12
ROW:       35  3.5  1.19
ROW:       35  4.5  1.30
ENDMAP:

```

Figure 7: Illustration of FLUXERRMODEL\_FILE with 2D map to define  $\hat{S}_{\text{SNR}}$  for DEEP fields in DES. While the bands and fields correspond to DES, this map is made up for illustration and should not be used in any analysis.

#### 4.14.2 Modeling Flux Correlations

The anomalous flux uncertainty may be from a process that is correlated among each epoch: e.g, image-subtraction artifacts. Optional flux correlations in the *anomalous* scatter can be defined with reduced covariances among bands and fields. Since the Poisson noise components are independent, the correlation is introduced only in the anomalous part of the uncertainty. Defining  $\sigma_{\text{final}} = \hat{S}_{\text{SNR}}\sigma_{\text{calc}}$ , where  $\hat{S}_{\text{SNR}}$  is the error scale from the map, the simulation breaks the final uncertainty into two components:  $\sigma_{\text{final}}^2 = \sigma_{\text{calc}}^2 + \sigma_{\text{fudge}}^2$ . Correlations are introduced among the  $\sigma_{\text{fudge}}$  components, while the Poisson- $\sigma_{\text{calc}}$  components are independent.

Reduced covariances are specified with REDCOV keys (Fig. 7). The first key (REDCOV: g:0.3,r:0.5) specifies a 30% reduced correlation among g-band epochs, and 50% correlation among r-band epochs; there are no correlations between the g & r bands. This one-line specifier can also be broken into two lines: “REDCOV: g:0.3” and “REDCOV: r:0.5.” The second key (REDCOV: iz:0.4) specifies a 40% reduced correlation among the i & z bands. For correlations among all bands, REDCOV: griz:0.4.

A field dependence can be specified in parentheses as follows:

```
REDCOV(DEEP): griz:0.6
REDCOV(SHALLOW): g:0.1,r_0.2,i_0.3,z:0.4
or
REDCOV(C3+X3): griz:0.6
REDCOV(E1+E2+S1+S2+C1+C2+X1+X2): g:0.1,r_0.2,i_0.3,z:0.4
```

where DEEP and SHALLOW are convenient FIELDGROUP definitions in Fig. 7. Note that the FIELDGROUPS are defined only in the FLUXERRMODEL\_FILE, and not in the sim-input file. However, the FIELDGROUP names can be used in the sim-input file and command-line overrides.

To vary the correlations without modifying FLUXERRMODEL\_FILE (e.g., systematic studies using submit\_batch\_jobs.sh), use the following sim-input keys;

```
FLUXERRMODEL_REDCOV: g:0.3,r:0.5,iz:0.5
or
FLUXERRMODEL_REDCOV(DEEP): griz:0.6
or
FLUXERRMODEL_REDCOV: NONE # disable flux covariances.
```

```
FLUXERRMODEL_SNRMIN_REDCOV: 2.0 # default to avoid slow Cholesky decomp
```

For command line overrides and GENOPT options for submit\_batch\_jobs.sh, remove the colon. The parentheses are properly handled by submit\_batch\_jobs.sh, but for command-line overrides quotes are needed, e.g.,

```
snlc_sim.exe <inpFile> 'FLUXERRMODEL_REDCOV(DEEP) griz:0.6'
```

Just as multiple REDCOV keys are allowed in the FLUXERRMODEL\_FILE, multiple FLUXERRMODEL\_REDCOV keys are allowed in the sim-input file, or as command line overrides.

With very dense sampling over a long survey time, the Cholesky decomposition for the resulting large covariance matrix can be very slow because the decomposition time scales as  $N_{\text{obs}}^3$ . To avoid this potential CPU bottleneck, and 1) covariance is applied among subset with  $\text{SNR} > 2$  (change default with FLUXERRMODEL\_SNRMIN\_REDCOV), and 2) the REDCOV feature is disabled for LCLIB (Galactic) and AGN models.



#### 4.14.3 Suggested Strategy for Determining FLUXERRMODEL Tables

For analyses requiring simulated bias corrections, here is a general strategy for determining the FLUXERRMODEL maps from fake SN-like objects overlaid on images and processed through the same photometry pipeline as the data. We do not make proposals for surveys without fakes.

Two FLUXERRMODEL maps are needed. The first map corrects the simulated scatter to match the scatter in the fake data. Correcting  $\sigma_{\text{SIM}}$  with  $\hat{S}_{\text{SNR}}$  (Eq. 5) will correct both the true and reported uncertainties in the simulations. The second map corrects the reported uncertainty in the fake data to reflect the true scatter. This 2nd map is applied in the analysis stage via namelist parameter,

```
&SNLCINP
  FLUXERRMODEL_FILE = 'DataCorMap.dat'
```

This map is applied to the fake data and the real data. It is not applied in the simulation because the simulated true scatter corresponds to the reported uncertainty.

There are two reasons for using fakes: 1) the true flux is known, and 2) the true model and rate are known. The first  $\hat{S}_{\text{SNR}}$  map is created from both the fakes and the SNANA simulation:

$$\hat{S}_{\text{SNR}}(\vec{O}_\sigma) = \frac{\text{RMS}[(F_{\text{true}} - F)/\sigma_{\text{SIM}}]_{\text{fake}}}{\text{RMS}[(F_{\text{true}} - F)/\sigma_{\text{SIM}}]_{\text{sim}}} \quad (7)$$

where the  $\vec{O}_\sigma$ -dependence is also on the right-hand side, and RMS indicates root-mean-square in a bin of  $\vec{O}_\sigma$ . The fakes and SNANA simulation must be generated with exactly the same light curve model and redshift-dependent rate. Any bugs or features used to generate fakes should be reproduced in the simulation. An example of such a feature is interpolating the fake flux on a pre-computed grid in few-day bins; this same interpolation should be used in the SNANA simulation. While Eq. 7 shows a general strategy, each survey team must decide the appropriate subset of  $\vec{O}_\sigma$  variables to use, if the maps depend on band and field, and if there are sufficient correlations to motivate multi-dimensional maps. Note that dividing by  $\sigma_{\text{SIM}}$  (Eq. 5) is optional, but may be useful for debugging since each term should be near unity.

The second map is created solely from the fakes,

$$\hat{S}_{\text{SNR}}(\vec{O}_\sigma) = \frac{\text{RMS}[(F_{\text{true}} - F)/\sigma_{\text{SIM}}]_{\text{fake}}}{\langle \sigma_{\text{PhotPipe}}/\sigma_{\text{SIM}} \rangle_{\text{fake}}} \quad (8)$$

where  $\sigma_{\text{PhotPipe}}$  is the uncertainty from the photometry pipeline, and  $\langle \rangle$  indicates an average in the  $\vec{O}_\sigma$  bin. If there are flux-outliers, it may be prudent to replace RMS with  $1.48 \times \text{median}$ .

#### 4.14.4 Extracting Information for FLUXERRMODEL

Here are some suggestions for extracting the 8 variables at the top of §4.14.1. The first suggestion is to simply parse the data file with your own script. The second method is to use the FITRES+RESIDUALS table feature (§12.1) in the light curve fitting program (snlc\_fitexe). This feature produces information for each observation in ROOT or HBOOK format. The epoch information can be extracted into TEXT format using the sntable\_dump.py utility (§12.1.3):

```
sntable_dump.py myFile.root FITRES obs
```

A few of the output variables must be converted for the FLUXERRMAP:

```
SBMAG      = 27.5 - 2.5*log10(SBFLUXCAL) [and protect SBFLUXCAL<0]
sigma_SIM   = ERRTEST * FLUXCAL_DATA_ERR
PSF(arcSec) = PSF(sig,pixels) * 2.35 * PIXSIZE
```

BEWARE that full epoch information is available *only* with FITS format (not with TEXT format).

#### 4.14.5 Legacy Noise Corrections

Here is a legacy correction based on a table near the top of a SIMLIB file. These corrections are still supported, but it is recommended to use the newer and more general flux-error maps in §4.14. Note that if the flux-error maps are used, the SIMLIB noise terms below are ignored.

Global noise-terms  $\hat{\sigma}_0$  and  $\hat{S}_{\text{SNR}}$  (Eq. 5) can be specified in the simlib header. The  $\hat{\sigma}_0$  term can be used to account for additional noise from the SN-photometry.  $\hat{S}_{\text{SNR}}$  is a global correction as a function of the log of the signal-to-noise ratio,  $\log_{10}(\text{SNR})$ ; this correction may be useful for PSF forms that are highly non-Gaussian (e.g., in space), or as a global correction so that the simulated uncertainties better match the those from the data.

```

FLUXERR_ADD:  YJH  33  55 85    # sig_0 term for each filter

# Below is the S_SNR map,
#          FILTs  LOG10(SNR)  ERROR/ERROR(SNANA)
FLUXERR_COR:  YJH   -5.00    1.0000  1.0000  1.0000
FLUXERR_COR:  YJH   -4.80    1.0000  1.0000  1.0000
FLUXERR_COR:  YJH   -4.60    1.0000  1.0000  1.0000
...
FLUXERR_COR:  YJH    0.40    1.1387  1.1719  1.1775
FLUXERR_COR:  YJH    0.60    1.1368  1.1704  1.1751
FLUXERR_COR:  YJH    0.80    1.1295  1.1611  1.1654
FLUXERR_COR:  YJH    1.00    1.1189  1.1470  1.1512

BEGIN LIBGEN

```

For SNR values outside the map-range, the correction at the min or max edge of the map is used. Thus for the above map,  $\text{SNR} > 10$  results in corrections corresponding to the last FLUXERR\_COR row.

To determine  $\hat{\sigma}_0$ , plot the calibrated flux-uncertainty “FLUXCAL\_ERRTOT” (or FLUXERR in ntuple 7799) for both data and simulation; adding the best-fit  $\hat{\sigma}_0$  in quadrature to the simulated uncertainty should match the measured distribution. It is recommended to check the data-simulation comparison in PSF bins. There is a utility in the SNANA fitting program that calculates the noise analytically, allowing a more direct comparison of the true uncertainty to the uncertainty that would be computed in a simulation. This feature is automatically enabled for verbose-formatted data that includes the SKY, PSF and ZPTAVG for each observation. See the SDSS data as an example of the verbose format. The quantity “ERRTEST,” the ratio of calculated-to-true uncertainty, is included in ntuple 7799 for each observation.

To determine  $\hat{S}_{\text{SNR}}$ , plot ERRTEST vs.  $\log_{10}(\text{SNR})$  and the construct the FLUXERR\_COR map from a polynomial fit or spline fit.

Finally, note that there are no SNANA utilities to construct these maps.

## 4.15 Example Noise Calculation

Here is an example of how the simulation analytically computes the noise from the signal and sky-background. The error on the signal (in photoelectrons) is simply  $\sqrt{N_{\text{pe}}}$ . To get the error in observed CCD counts (ADU), we start by relating the signal counts in ADU to the number of photoelectrons,

$$\mathcal{N}_{\text{ADU}} = N_{\text{pe}} \times G^{-1} \times \mathcal{S}_{ZP} \quad (9)$$

where  $N_{\text{pe}}$  is the number of observed photoelectrons,  $G$  is the number of photoelectrons per ADU (CCD gain), and  $\mathcal{S}_{ZP}$  is a scale factor applied to the signal so that the SN magnitude is referenced to the template zeropoint. This factor is  $\mathcal{S}_{ZP} = 10^{0.4(ZP_t - ZP_s)}$ , where  $ZP_{s,t}$  are the zeropoints for the search and template runs. In cloudy conditions,  $\mathcal{S}_{ZP} \gg 1$  because the signal is much smaller than it would have been in the template run. If no template is given, then  $\mathcal{S}_{ZP} = 1$ . The error on the signal (in ADU) is

$$\sigma^2(\mathcal{N}_{\text{ADU}}) = \mathcal{N}_{\text{ADU}} \times G^{-1} \times \mathcal{S}_{ZP} \quad (10)$$

The sky-background error is computed from

$$\sigma_{\text{skytot}} = \mathcal{S}_{ZP} \times \sqrt{A \times (\sigma_{\text{skypix}}^2 + \bar{\sigma}_{\text{skypix}}^2)} \quad (11)$$

where  $\sigma_{\text{skypix}}$  is the search-run skynoise per pixel,  $\bar{\sigma}_{\text{skypix}}$  is the template-run skynoise,  $A$  is the noise-equivalent area in square-pixels, and the units are ADU. There is a similar term for the CCD readout noise per pixel (summed over the area), but it is left out here in this example.

Using double-Gaussian fit parameters for the PSF, in which  $\sigma_{1,2}$  are the PSF-sigma for the two Gaussians, and  $h_{1,2}$  are the heights at the origin<sup>7</sup>, the noise-equivalent area is

$$A = \frac{1}{\int \text{PSF}^2(r, \theta) r dr d\theta} = \frac{4\pi(\sigma_1^2 + \sigma_2^2)}{1 + 4\pi^2\sigma_1^2\sigma_2^2(h_1 + h_2)^2} = 4\pi\sigma_1^2 \left[ \frac{(1 + R_\sigma^2)(1 + R_\sigma^2 r_h)^2}{R_\sigma^2(1 + r_h)^2 + (1 + R_\sigma^2 r_h)^2} \right], \quad (12)$$

where in the second step  $R_\sigma \equiv \sigma_2/\sigma_1$  and  $r_h \equiv h_2/h_1$ . For a single-Gaussian PSF,  $r_h \rightarrow 0$  for any value of  $R_\sigma$ , and the area is just  $4\pi\sigma^2$ . For typical ground-based surveys  $A/(4\pi\sigma_1^2) \sim 1.5$ .

The rest of this section will perform an explicit calculation of the noise, using an example from a DES simulation. Here is the information for a random epoch on a random simulated lightcurve:

---

<sup>7</sup>A double-Gaussian PSF with normalization  $\int \text{PSF}(r, \theta) r dr d\theta = 1$  has  $2\pi(\sigma_1^2 h_1 + \sigma_2^2 h_2) = 1$

PASSBAND:	g	r	i	z	Y	
GAIN:	1.000	1.000	1.000	1.000	1.000	e/ADU
RDNOISE:	10.000	10.000	10.000	10.000	10.000	e-
SKY_SIG:	108.81	105.36	217.58	378.84	848.53	ADU
PSF_SIG1:	1.500	1.500	1.500	1.500	1.500	pixels
FLUX:	14707.89	12515.67	30756.55	28334.23	62748.97	ADU
FLUX_ERRTOT:	590.695	571.406	1170.485	2022.083	4518.783	ADU
FLUXCAL:	18.52	42.21	46.13	46.59	51.71	(x10 <sup>11</sup> )
FLUXCAL_ERRTOT:	0.986	2.403	2.385	3.683	4.141	
MAG:	24.3311	23.4364	23.3402	23.3292	23.2160	
MAG_ERRPLUS:	0.0569	0.0624	0.0565	0.0898	0.0892	
MAG_ERRMINUS:	0.0569	0.0624	0.0565	0.0898	0.0892	
ZEROPT:	34.7500	33.6800	34.5600	34.4600	35.2100	
ZEROPT_SIG:	0.0350	0.0340	0.0350	0.0340	0.0350	

For simplicity, note that the PSF is modeled as a single-Gaussian, and that the gain is unity. Now let's compute that flux and noise for *i*-band.

The measured flux (in ADU) and the calibrated flux (for lightcurve fits) are given in terms of the magnitude ( $m_i$ ) and zeropoint ( $Z_i$ ),

$$\text{FLUX} = 10^{-0.4(m_i - Z_i)} = 10^{-0.4(23.3402 - 34.56)} = 30755 \text{ ADU} \quad (13)$$

$$\text{FLUXCAL} = 10^{-0.4m_i} \times 10^{11} = 46.13 \quad (14)$$

which agrees with the simulated values above. Since the gain is unity, 1 ADU = 1 photoelectron (p.e.), and the noise from signal-photostatistics is  $\sigma_{sig} = \sqrt{N_{pe}} = 175.4 \text{ p.e.}$ .

To include the sky-noise, we use the following information from the simulation library (see above dump): SKYSIG= 217.58 ADU/pixel,  $\text{PSF}(\sigma) = 1.50\sqrt{\text{pixels}}$ , and 1 pixel is  $0.27'' \times 0.27''$ . The effective aperture area is  $A = 4\pi \times \text{PSF}^2 = 28.27 \text{ pixels}$ . The total skynoise is thus  $\sigma_{sky} = \text{SKYSIG} \times \sqrt{A} = 1156.95 \text{ p.e.}$ . The total noise on the flux is  $\text{FLUX\_ERRTOT} = \sqrt{\sigma_{sig}^2 + \sigma_{sky}^2} = \sqrt{1156.94^2 + 175.4^2} = 1170.2 \text{ p.e.} = 1170.2 \text{ ADU}$ . The signal-to-noise ratio (SNR) is  $30755/1170 \simeq 26$ .

## 4.16 K-corrections

For the stretch and MLCS2k2 models, K-corrections are needed in both the simulation and the fitter. K-corrections are applied using a technique very similar to that used in [8, 1]. The basic idea is that for each epoch and each pass-band, the spectral template is warped by applying the CCM89 extinction law with a variable  $A_V$ ; “ $A_V$ -warp” is the value of  $A_V$  for which the synthetic color matches the color of the rest-frame lightcurve. The K-correction is then determined from this  $A_V$ -warped spectral template. Note that this method is model-independent and can therefore be applied to any lightcurve model.

The K-corrections and synthetic magnitudes are NOT computed internally because this would result in slow code, especially for the fitter. To speed up the calculations of these convolution-integrals, K-corrections and synthetic mags are read from a lookup table generated with `SNANA_DIR/bin/kcor.exe`. Before running the simulation or fitter, the program `kcor.exe` must run, although it runs once and only once until you need K-corrections that are not defined. The `kcor` program reads a self-documented input file such as

```
$SNDATA_ROOT/sample_input_files/kcor/kcor_[SURVEY].input
```

and then generates lookup tables as a function of redshift, epoch, and extinction parameter  $A_V$ . A typical table binning is 0.05 in redshift, 1 day in rest-frame epoch, and 0.25 in  $A_V$ ; this binning is used to store every user-defined  $K_{xy}$ , and to store synthetic lightcurves for every user-defined filter.

A linear interpolation routine<sup>8</sup> determines a K-correction for arbitrary  $z, \text{epoch}, A_V$ . A special function, `GET_AVWARP`, finds the magic  $A_V$ -warp parameter such that the warped spectral template has the same color as your lightcurve. The table format is CERNLIB’s `HBOOK`, and is stored in

```
$SNDATA_ROOT/kcor .
```

The subroutines that read and interpolate the `kcor` tables are written in fortran, and are stored in `snana.car`. The SNANA product includes a fortran library `../lib/libsnana.a`, which allows C programs to use the fortran utilities. The `extern` statements at the top of `snlc_sim.c` declare the fortran functions used to lookup K-corrections.

---

<sup>8</sup>a double precision version of CERNLIB’s `FINT` is used for multi-dimensional linear interpolations.

## 4.17 Intrinsic Brightness Variations

### 4.17.1 Supernova Brightness Variations

There are six general methods to introduce intrinsic variations that result in anomalous scatter in the Hubble diagram:

```
# method 1: coherent variation in all epochs & passbands
#           note: colors are not varied.
GENMAG_SMEAR: 0.1 # coherent mag-smear in all measurements

# method 2: independent variation in each passband (coherent among epochs)
#           that results in color variations
GENMODEL_ERRSCALE: 1.1 # scale MLCS peak-model error
GENMAG_SMEAR_FILTER: UBV 0.05 # and/or fixed smearing per filter
GENMAG_SMEAR_FILTER: RI 0.08 # and/or fixed smearing per filter

# method 3: Pick model name from specialized code in genSmear_models.c
GENMAG_SMEAR_MODELNAME: G10 # or C11
GENMAG_SMEAR_SCALE: 1.2 # scale all magSmear values
GENMAG_SMEAR_SCALE(c): 0.95,0.3 # scale magSmear by 0.95 + 0.3*c
GENMAG_SMEARPAR_OVERRIDE: BLA 1.234 # optional param override
GENMAG_SMEARPAR_OVERRIDE: BLALIST[3] 1.8 2.2 3.4 # idem
GENMAG_SMEAR_ADDPHASECOR: 0.03 7.0 # magSmear expTau(days)

# method 4: vary RV with asymmetric Gaussian distribution
GENPEAK_RV: 1.6 # location of Gauss peak
GENSIGMA_RV: 0.1 0.9 # lower, upper Gaussian-sigmas
GENRANGE_RV: 1.3 4.5 # gen-range for RV

# method 5: apply intrinsic scatter matrix (SALT2 only)
COVMAT_SCATTER_SQRT[0][0]: 0.10 ! mB : sqrt(COV) = uncertainty
COVMAT_SCATTER_SQRT[1][1]: 0.22 ! x1 : sqrt(COV) = uncertainty
COVMAT_SCATTER_SQRT[2][2]: 0.05 ! color : sqrt(COV) = uncertainty
COVMAT_SCATTER_REDUCED[0][2]: 0.50 ! rho(mB,c) = COV/[sig(mB)*sig(c)]

# method 6: function of wavelength (SALT2 only); see text for details
GENMAG_SMEAR_USRFUN: <SIGCOH> <A5500> <LAMSEP> <LAMPHASE> <TAU_LAM> <TAU_DAY>
0. 0.
```

Note that methods 1&2 can be used together, as well as methods 1&3. However, methods 2&3 cannot be used together. Methods 5-6 (scatter matrix) cannot be combined with any other method.

For rest-frame models, the argument of `GENMAG_SMEAR_FILTER` should be a list of rest-frame filters; for observer-frame models, the argument is a list of observer-frame filters.

`GENMAG_SMEAR_MODELNAME` allows the most flexibility with an arbitrarily complex function to describe the smearing as a function of wavelength and/or phase. These functions are in a separately compiled module (`$SNANA_DIR/src/sntools_genSmear.c`), and these functions can in principle be used in non-SNANA applications. The top of `sntools_genSmear.c` provides a list of model-name options. The models include a “PRIVATE” option so that anyone can quickly implement a

model of intrinsic smearing by adding code to the blank functions `init_genSmear_private` and `get_genSmear_private`. The “NONE” option can be used as a command-line override to turn off this option. `GENMAG_SMEARPAR_OVERRIDE` allows overriding default smear-model parameters; a list of allowed keys can be seen by grepping the source code,

```
grep exec_genSmear_override $SNANA_DIR/src/sntools_genSmear.c
```

Finally, `GENMAG_SMEAR_ADDPHASECOR` is a phase dependent brightness variation that can be combined with `GENMAG_SMEAR_MODELNAME`. The two `ADDPHASECOR` arguments are 1) Gaussian sigma, and 2) coherence parameter ( $\tau$ ) such that for epoch separation  $\Delta T$  days, the reduced correlation is  $\rho = \exp(-\Delta T/\tau)$ . Note that  $\rho = 1$  for  $\Delta T = 0$ .

While these smearing models are functions of rest-frame wavelength, there are two implementation modes for the SNIa models. The mode is controlled by `FLAG_GENSMEAR` that is internally initialized in the simulation. The first mode is to properly include the wavelength dependence, and this mode is currently set only for the SALT-II model. The second mode is an approximation in which the smearing value at  $\bar{\lambda}_{\text{obs}}/(1+z)$  is applied to the magnitude of the entire passband, where  $\bar{\lambda}_{\text{obs}}$  is the central wavelength of the passband. This mode is set for rest-frame models (i.e., `SNooPy`, `MLCS2k2`). If/when the wavelength-dependent smearing is upgraded to work for rest-frame models, `FLAG_GENSMEAR` will be modified accordingly.

Each element of the intrinsic scatter matrix (method 5) can be entered as a covariance, as an uncertainty, or as a reduced covariance. It is recommended to enter uncertainties for the diagonal elements, and to enter reduced covariances ( $-1$  to  $+1$ ) for the off-diagonal terms. This model-smearing option currently works only for SALT2, but can easily be extended to other models as needed.

The function for method 6 is as follows. `SIGCOH` is a coherent scatter term that is added independent of the other parameters. The wavelength-dependent part is first defined at  $\lambda$ -nodes separated by `LAMSEP` Å with an initial phase of `LAMPHASE` Å. The  $1\sigma$  scatter magnitude ( $\sigma_{\text{mag}}$ ) at each  $\lambda$ -node ( $\lambda_n$ ) is

$$\sigma_{\text{mag}} = A_{5500} \times \exp[-(\lambda_n - 5500)/\tau_\lambda] \times \exp[T_{\text{rest}}/\tau_{\text{day}}] \quad (15)$$

where  $\tau_\lambda = \text{TAU\_LAM}$  and  $\tau_{\text{day}} = \text{TAU\_DAY}$ . The last two zeros (7th and 8th params) are reserved for future upgrades. After a Gaussian random scatter at each node is selected, a continuous function of  $\lambda$  is made by connecting the nodes with cosine functions that ensure that the derivative is zero at each node.

#### 4.17.2 Weak Gravitational Lensing

The effect of weak lensing is simulated using a pre-computed map of lensing probability as a function of redshift and  $\Delta\mu \equiv -2.5 \log(\text{magnification})$ . Maps are stored in `$SNDATA_ROOT/models/lensing`, and the lensing effect is implemented with the following sim-input keys:

```
WEAKLENS_PROBMAP_FILE:  LENSING_PROBMAP_LogNormal+MICE.DAT
WEAKLENS_DMUSCALE:      2.1      # default is 1.0
or
LENSING_PROBMAP_FILE:   LENSING_PROBMAP_LogNormal+MICE.DAT # legacy key
LENSING_DMUSCALE:       2.1      # legacy key
```



A MICE simulation [9] is used for  $z < 1.4$ , and a log-normal approximation [10] is used for  $z > 1.4$ .<sup>9</sup> The magnification grid extends to about 4 ( $\Delta\mu \simeq -1.5$ ), and thus does not include strong lensing, nor multiple lenses. The distance-modulus ( $\mu$ ) scatter is about  $0.04 \times z$ , about a factor of 2 smaller than the largest scatter values found in the literature. Input key `LENSING_DMUSCALE` is used to increase or decrease the scatter.

The randomly chosen `SIM_LENSDMU` is stored in the simulated data files, and also stored in the output tables created by the analysis programs. Users should examine and validate the distribution of `SIM_LENSDMU` vs. redshift.

### 4.17.3 Strong Gravitational Lensing

Strong lensing is simulated by including a library of lenses with sim-input

```
STRONGLENS_FILE: <fileName>
```

and the library contents are as follows:

```
RESOLVED: 1
```

VARNAME:	LENSID	NIMG	ZLENS	ZSRC	XIMG	YIMG	MAG	DELAY
LENS:	101	2	0.286	0.68	0.71,+0.02	-0.15,-0.02	0.1,2.2	1.8,5.2
LENS:	102	2	0.328	0.87	-2.85,-0.12	-1.01,+0.08	0.2,2.8	2.2,6.4
LENS:	103	3	0.966	3.39	-.2,-.3,.4	-0.1,-.2,.7	.8,.3,2.	4,2,3

where ...

Simulated data files include `SIM_STRONGLENS_XXX` variables, where XXX includes

```
ID z DELAY XIMG YIMG MAGSHIFT NIMG IMGNUM
```

For resolved light curves, each light curve has a unique CID. `SIM_STRONGLENS_ID` has the same integer value for lensed light curves from the same event, and the redshifts are also the same. For unresolved light curves ... TBD ...

The `SIMGEN_DUMP` list can include `STRONGLENS_MAGSHIFT` (or `SL_MAGSHIFT`).

If the number of light curves from a lens exceeds `NGENTOT_LC`, then additional light curves are generated so that all lensed events are included. For example, suppose `NGENTOT_LC` is 100, and on the 99th event there are 4 lensed events. The simulation will generate 102 light curves, not 100, in order to include all of the lensed events for the last SN.

Beware of `GENRANGE_PEAKMJD` clipping events. For example, a common debugging feature is to set `GENRANGE_PEAKMJD` to a delta function (e.g., `MJDO`). For strong lenses, however, the time delays will move each generated `PEAKMJD` away from the generated `MJDO` value. Therefore, zero events would be generated unless some of the time delays are zero. With finite range for `GENRANGE_PEAKMJD`, keep in mind that the time delays will push events outside the generation range.

---

<sup>9</sup>We thanks Jacobo Asorey for creating this lensing library.

## 4.18 Search Efficiency

The simulation includes options to model the search efficiency of the survey. The search efficiency is broken into three parts: (i) image subtraction pipelines characterized by efficiency vs. S/N or mag, (ii) spectroscopic efficiency that describes visual scanning and spectroscopic targeting and selection, and (iii) for spectroscopically-unconfirmed SNe, the “zHOST” efficiency for obtaining an accurate host-galaxy redshift. Some explicit examples of sim-input options will be given at the end of this section. To ensure that your settings are correct, it is *essential* to always check that the simulated redshift distribution matches that of the data, and to check separately for the spectroscopically-confirmed and unconfirmed sub-samples.

Default efficiency files are stored in the directory `$SNDDATA_ROOT/models/searcheff`, and the file-name includes the name of the survey. However, you can specify an efficiency file in your private directory, or ignore the efficiency file by specifying a file-name as `NULL` or `NONE`.

### 4.18.1 Software-Pipeline Efficiency

The image subtraction pipeline efficiency,  $\epsilon_{\text{subtr}}$ , is based on software algorithms and therefore in principle this part of the efficiency can be rigorously determined. The simplest  $\epsilon_{\text{subtr}}$  requirement is a minimum number of observations with the sim-input keyword “`MINOBS_SEARCH: <MINOBS>`” (default is 2). The simulation also parametrizes  $\epsilon_{\text{subtr}}$  as a function of signal-to-noise (SNR) or magnitude in each filter. The motivation is that fake SNe overlaid onto images during the survey can be used to measure the efficiency curves. Examples of each type of efficiency curve (vs. SNR and vs. MAG) are in

<code>\$SNDDATA_ROOT/models/searcheff/SEARCHEFF_PIPELINE_SDSS.DAT</code>	(vs SNR)
<code>\$SNDDATA_ROOT/models/searcheff/SEARCHEFF_PIPELINE_HST.DAT</code>	(vs. MAG)

and one can add more files corresponding to different surveys. If no `SEARCHEFF_PIPELINE` file is found, then  $\epsilon_{\text{subtr}} = 1$ . Warning: do NOT define both the SNR-based and MAG-based efficiency for a survey. For ground-based surveys we recommend using the SNR-based efficiency to properly account for variations in observing conditions. The sim-input keyword

```
SEARCHEFF_PIPELINE_EFF_FILE: MY_PIPELINE.DAT
or
SEARCHEFF_PIPELINE_FILE: MY_PIPELINE.DAT
or
SEARCHEFF_PIPELINE_EFF_FILE: NONE # disable feature
```

overrides the default file or disables this feature. The simulation always checks first if a file exists in your private directory: if not there then the public directory above is checked. The `SEARCHEFF_PIPELINE_FILE` allows for two kinds of maps as shown in Fig. 8. These maps are very coarse for illustration, but much finer-grid maps can be used. The first and more common map is the detection efficiency vs. SNR, or MAG or `ABS(SNR)`. The `ABS(SNR)` option is useful for galactic transients, which can have positive or negative signals in a subtracted image. The map must be contained between the keys “`MAPNAME_DETECT: <name>`” and “`ENDMAP:`”. The example below shows one map valid for *griz* bands, but a separate map for each band can be included.

The `PHOTFLAG_DETECT` key (Fig. 8) is a mask that is added to the `PHOTFLAG` column in the data file for each detection. The `PHOTFLAG_TRIGGER` key specifies the `PHOTFLAG` mask to add on the first epoch satisfying the trigger logic (see `LOGIC` file below). In the analysis, setting `&SNLCINP` input

PHOTFLAG\_DETECT=nnn results in the following variables added to the SNANA & FITRES tables: NEPOCH\_DETECT (number of detections) and TLIVE\_DETECT (time between first and last detection).

The second type of optional map is used to specify a PHOTPROB value between zero and one. This quantity is not used in the simulation, but is passed to the output data files so that cuts can be applied. For example, PHOTPROB can represent a machine-learning score from difference-imaging, or from cuts that reject flux-outliers. The map consists of a PHOTPROB distribution in bins of SNR (or LOGSNR) and/or SBMAG (surface brightness), and/or REDSHIFT. The PHOTPROB\_WGTLIST is a histogram of events in each bin. The simulation internally determines the cumulative distribution function (CDF) for each SNR-SBMAG bin, and interpolates for each simulated epoch based on the generated SNR, SBMAG, and REDSHIFT. The interpolated CDF is used to generate a random PHOTPROB value for each observation. Finally, this example applies to all fields and bands, but separate maps can be read for each band and/or each field.

The optional REQUIRE\_DETECTION flag results in PHOTPROB=0 when there is no detection, and PHOTPROB>0 for detections. By default the PHOTPROB are independent for each observation. Optional PHOTPROB correlations are introduced with the key “REDUCED\_CORR: <rho>,” where  $-1 < \rho < +1$ . The example below introduces 50% correlations. If there is a separate map for each band, the correlation between epochs in different bands is the geometric mean of each map-correlation,  $\text{CORR}_{12} = \sqrt{\text{CORR}_1 \cdot \text{CORR}_2}$ , where CORR1, CORR2 are the reduced correlations. Note that if either correlation is zero,  $\text{CORR}_{12} = 0$ . The correlation method for  $N_{\text{PhotProb}}$  PHOTPROB values is as follows. First, the Cholesky decomposition technique is used to determined  $N_{\text{PhotProb}}$  correlated randoms from Gaussians with  $\sigma = 1$ . Call these correlated Gaussian randoms  $G_i$ ,  $i = 1, N_{\text{PhotProb}}$ . Each  $G_i$  is converted to a uniform random between zero and one,  $U[0, 1]$ , from the Gaussian distribution:

$$U[0, 1]_i = (2\pi)^{-1/2} \int_{-\infty}^{G_i} dx \exp(-x^2/2) \quad (16)$$

where the explicit  $\sigma$  terms are dropped since  $\sigma = 1$ . The correlations between the  $G_i$  are transferred to the  $U[0, 1]_i$ . Finally,  $U[0, 1]_i$  and the PHOTPROB CDF are used to compute  $\text{PHOTPROB}_i$ :

$$U[0, 1]_i = \int_0^{\text{PHOTPROB}_i} dP \text{ CDF}(P) \quad (17)$$

Beware that while generating correlated  $G_i$  is rigorous and robust, the PHOTPROB correlations are ad-hoc and not rigorous. It is therefore recommended to check the correlations using the NDUMP option, which produces a one-line per event dump to standard-out as follows:

```
777777 [SNID] [PHOTROB-1] [PHOTROB-2] . . . [PHOTROB-NDUMP]
```

The “777777” string allows using grep to extract the dump rows. The first NDUMP PHOTPROB>0 values per event are included. If there are not enough PHOTPROB values for the dump, the dump is skipped for the event.

Figure 8: Illustration of SEARCHEFF\_PIPELINE\_FILE

```
# optional keys to set bit(s) in PHOTFLAG column of data files.
PHOTFLAG_DETECT: 4096 # set this bit for each detection
PHOTFLAG_TRIGGER: 2048 # set this bit on epoch when trigger forms

MAPNAME_DETECT: EFFDETECT_SNR-g
FILTER: griz
SNR: 0.0 0.0002
SNR: 2.0 0.22
SNR: 4.0 0.45
SNR: 6.0 0.75
SNR: 8.0 0.87
SNR: 10.0 0.98
SNR: 12.0 1.00
ENDMAP:

MAPNAME_PHOTPROB: MLSCORE_FAKES
BAND: griz FIELD: ALL # map applies to all fields and bands
REQUIRE_DETECTION: 1 # generate PHOTPROB only for detections, 0 otherwise
REDUCED_CORR: 0.6 # induce correlation among all PHOTPROB per event
CUTVAL: 0.5 # require PHOTPROB>0.5 for detection
NDUMP: 3 # DEBUG: one-line dump of 3 PHOTPROB per event
NVAR: 6 # LOGSNR, SBMAG + 4 PHOTPRPB_WGTLIST bins
VARNAMES: LOGSNR SBMAG PHOTPROB_WGTLIST
ROW: 0.0 20 W11 W12 W13 N14
ROW: 1.0 20 W21 W22 W23 W24
ROW: 2.0 20 W31 W32 W33 W34
ROW: 0.0 22 W12 W12 W13 N14
ROW: 1.0 22 W22 W22 W23 W24
ROW: 2.0 22 W32 W32 W33 W34
ROW: 0.0 24 W13 W12 W13 N14
ROW: 1.0 24 W23 W22 W23 W24
ROW: 2.0 24 W33 W32 W33 W34
ENDMAP:
```

The above **SEARCHEFF** information gives the probability of a single-epoch detection in a particular filter, but does not specify if the supernova would have been discovered. The *discovery* or *trigger* logic is defined for each survey in the file:

```
more $SNDATA_ROOT/models/searcheff/SEARCHEFF_PIPELINE_LOGIC.DAT
SDSS: 3 gr+ri+gi # require 3 epochs, each with detection in two bands.
DES   2 g+r+i+z  # require 2 epochs, any band
HST:  1 6        # require 1 epoch with detection in filter '6' = F850LP_ACS
```

where the first number is the minimum number of epochs required, and the string that follows defines the logic for a detection. In the above examples, the SDSS discovery logic requires three epochs, where each epoch has a detection in at least two of the three *gri* filters. The DES logic requires two single detections in any band. The HST discovery logic requires a single detection in filter '6'. As described above, a single detection is defined by the efficiency curves in **SEARCHEFF\_PIPELINE\_[SURVEY].DAT**. The final caveat is the epoch time-window used to count a detection. The sim-input key

```
NEWMJD_DIF: 0.4 # days
```

specifies combining all observations within 0.4 days (i.e., one night) into a single detection. For the DES logic, observations of all four *griz* bands in one night would count as one epoch and fail the trigger; an additional observation on a different night is required to pass the trigger. If **NEWMJD\_DIF** is reduced to 0.001 (1.4 minutes), then observations with any two of the four DES filters in one night would pass the trigger.

The pipeline efficiency can be applied in the simulation, or the results can be stored in the data files for future analysis: the user control flag **APPLY\_SEARCHEFF\_OPT** is discussed below after the spectroscopic efficiency is discussed.

The **LOGIC** file can be specified explicitly with sim-input key

```
SEARCHEFF_PIPELINE_LOGIC_FILE: $SNDATA_ROOT/models/searcheff/SEARCHEFF_PIPELINE_LOGIC.DAT
```

#### 4.18.2 Spectroscopic-Confirmation Efficiency

The human/spectroscopic efficiency ( $\epsilon_{\text{spec}}$ ) cannot be rigorously computed since it involves human decision making during the survey. The **SNANA** simulation parametrizes  $\epsilon_{\text{spec}}$  as an arbitrary function of redshift, peak-mags, peak colors, and closest time to peak. §4.18.5 suggests how to determine this function from the data and simulations. Rather than using an analytical form for  $\epsilon_{\text{spec}}$ , the simulated efficiency is defined on a multi-dimensional grid of redshift, peak-magnitudes and peak-colors. An example is shown here,

```
SEARCHEFF_SPEC_FILE: $SNDATA_ROOT/models/searcheff/SEARCHEFF_SPEC_SDSS.DAT
SEARCHEFF_SPEC_SCALE: 0.8 # default=1.0
or
SEARCHEFF_SPEC_FILE: ZERO # force EFF_SPEC=0 without map
```

If this file is not specified, then  $\epsilon_{\text{spec}} = 1$ . For each simulated SN,  $\epsilon_{\text{spec}}$  is determined from multi-dimensional (linear) interpolation. If more than one grid is given the logical OR among the efficiencies is used; this feature may be useful in cases where different telescopes take spectra for SNe in different magnitude ranges. It is important to note that  $\epsilon_{\text{spec}} = 0$  outside the redshift/magnitude

range given by the grid. This feature allows using different telescopes to cover different magnitude ranges, but be careful that very bright SNe can have  $\epsilon_{\text{spec}} = 0$  if the magnitude range is not wide enough at the bright end. To avoid mistakenly losing very bright SNe, we recommend adding an artificial grid with 100% efficiency for low redshifts; this is the first grid-map in Fig. 9.

Fig. 9 below illustrates a spectroscopic-efficiency grid with three tables. The first table ensures 100% efficiency for redshifts  $z < 0.1$ . The second table describes the efficiency for  $r$ -band magnitudes below 22, and the last table defines the efficiency for  $i$  band magnitudes above 22. The second map depends on the absolute peak  $r$ -band magnitude and the  $g - r$  color at peak. The 3rd map depends on the  $i$ -band magnitude and redshift, and applies only for the field named 'DEEPFIELD': the 'FIELD:' option allows for field-dependent maps. There essentially is no limit to the complexity: for example, one could define "VARNAMES: g r i g-r r-i REDSHIFT SPECEFF" assuming that such a function could be determined. A list of valid VARNAMES is shown in Fig. 10.

Figure 9: Illustration of spectroscopic efficiency format for the SNANA simulation.

```
# TABLE 1 -- ensure 100% eff at low redshift
VARNAMES: REDSHIFT SPECEFF
SPECEFF: 0.0 1.00
SPECEFF: 0.1 1.00

# TABLE 2 -- 4m telescope
VARNAMES: g-r r SPECEFF # can add comments here
SPECEFF: -0.5 18.0 1.0
SPECEFF: -0.5 20.0 0.6
SPECEFF: -0.5 22.0 0.3
SPECEFF: +0.5 18.0 0.2
SPECEFF: +0.5 20.0 0.08
SPECEFF: +0.5 22.0 0.02

# TABLE 3 -- 8m telescope
VARNAMES: REDSHIFT i SPECEFF
FIELD: DEEPFIELD
SPECEFF: 0.0 22.0 1.0
SPECEFF: 0.0 24.0 0.66
SPECEFF: 0.0 26.0 0.31 # can add comments here
SPECEFF: 0.5 22.0 0.22
SPECEFF: 0.5 24.0 0.14
SPECEFF: 0.5 26.0 0.022
```

In principle there is just one function of redshift and peak-magnitudes to describe the spectroscopic efficiency. In practice, however, this efficiency can depend on the particular SN model for two reasons. First, there is an overall magnitude offset between different SN models. Second, asymmetric (dim-side) tails in the stretch and color distributions may not be properly modeled. To correct for the first case there is a sim-input parameter "MAGSHIFT\_SPECEFF: <shift>" to shift the peak magnitude used to determine  $\epsilon_{\text{spec}} = 0$  from the grid-map. The second problem can be fixed only by using distributions with appropriate tails.



For multiple maps in one SEARCHEFF\_SPEC\_FILE file, the default logic is “OR”, meaning that random selection from any map results in spectroscopic confirmation. This logic accomodates multiple telescopes covering different mag ranges, but is not appropriate for selection *requirements* such as PEAKMJD, DTPEAK, or DTSEASON\_PEAK. To force selection from a particular map, add a REQUIRE key before the VARNAMES key as shown in this example:

```
REQUIRE: 1
VARNAMES: DTSEASON_PEAK SPECEFF
SPECEFF: 0 1.0 # 100% eff for in-season peakMJD
SPECEFF: 999 1.0
```

which forces spec-confirmed events to have PEAKMJD in-season; i.e., between the first and last observation of a season, where a season is defined as a set of observations with gaps less than 90 days. This map alone would select every in-season event as spec-confirmed, but addition peakmag-dependent maps can be added to the same file.

For each simulated SN, the search algorithm is evaluated separately for the image-subtraction and spectroscopic efficiencies. Random numbers are compared against the efficiencies to determine which epochs/SNe are selected. The results of these two search algorithms are stored in a bit-mask in each data file, defined as follows:

```
SIM_SEARCHEFF_MASK += 1 # detected by image-subtraction
SIM_SEARCHEFF_MASK += 2 # spectroscopically confirmed
SIM_SEARCHEFF_MASK += 4 # unconfirmed with host redshift (next section)
```

And here are some command examples,

```
SIM_SEARCHEFF_MASK = 1 # detected by image-subtr; spec-unconfirmed
SIM_SEARCHEFF_MASK = 2 # failed image-subtr, but spec-confirmed
SIM_SEARCHEFF_MASK = 3 # detected by image-subtr & spec confirmed
SIM_SEARCHEFF_MASK = 5 # detected by image-subtr, unconfirmed with zHOST
```

Note that SIM\_SEARCHEFF\_MASK= 2 corresponds to an unphysical case since it is unlikely to get a spectrum of a SN that was not identified by the image-subtraction pipeline. Although the search efficiencies are always evaluated, the user has the option to apply these efficiencies in the simulation, or to write out all simulated SNe and use the SIM\_SEARCHEFF\_MASK for further investigation. The following sim-input keys control trigger selection:

```
APPLY_SEARCHEFF_OPT: 0 # keep all SNe (default)
APPLY_SEARCHEFF_OPT: 1 # keep SN if software trigger passes
APPLY_SEARCHEFF_OPT: 3 # keep SN if software and spec triggers pass
APPLY_SEARCHEFF_OPT: 5 # keep SN if software trigger and zHOST
```

When “APPLY\_SEARCHEFF\_OPT: 3” is set, then SIM\_SEARCHEFF\_MASK=3 for all SNe because those that fail either of the search criteria are rejected. Setting “APPLY\_SEARCHEFF\_OPT: 1” results in SNe with SIM\_SEARCHEFF\_MASK=1 and 3; i.e., SNe with and without spectroscopic confirmation.

Finally, SIM\_SEARCHEFF\_MASK can be specified as a SIMGEN\_DUMP variable (§4.37.2) and it appears in the analysis tables (§12.1).

Figure 10: Valid VARNAMES to describe  $\epsilon_{\text{spec}}$  in Fig. 9

* g r i	# peak mag in any band
* PEAKMAG_[band]	# idem for any [band]
* g-r	# peak color
* g-i	# another peak color
* REDSHIFT	# redshift
* PEAKMJD	# MJD at time of peak brightness
* DTPEAK	# closest T-Tpeak; can be pos or negative
* DTSEASON_PEAK	# positive if PEAK is in-season; else negative
* SALT2mB	# SALT2 mB
* SALT2x1	# SALT2 stretch parameter
* SALT2c	# SALT2 color parameter
* LOGMASS	# hsot galaxy LOGMASS
* HOSTMAG_[band]	# mag of host galaxy in [band]
* SBMAG_[band]	# surface brightness mag/arcsec <sup>2</sup> in [band]

### 4.18.3 Unconfirmed Efficiency for Host-Galaxy Redshift

For the unconfirmed SNe, i.e., those with `SIM_SEARCHEFF_MASK=1`, the default redshift is assumed to have the same precision as for the confirmed SNe, presumably from a host-galaxy spectroscopic redshift. However, a redshift-dependent fraction of unconfirmed spectroscopic (host-galaxy) redshifts can be specified with

```
SEARCHEFF_zHOST_FILE: <fileName>
or
SEARCHEFF_zHOST_FILE: NONE      # Eff(zHOST) = 1.0
or
SEARCHEFF_zHOST_FILE: ZERO      # Eff(zHOST) = 0.0
```

where the file contains an efficiency map. There are two kinds of maps: 1) legacy map which depends only on true redshift, and 2) nominal map (starting with `v10_70`) defining an arbitrary function of `HOSTLIB` parameters (see “`VARNAMES:`” key in Fig. 11).

Here we show an example of the redshift-dependent legacy map:

```
# LEGACY SEARCHEFF_zHOST map:
CUTWIN_SNRMAX: 5 1E8 # optional SNRMAX cut on source (not on host)

FIELDLIST: F1+F2      # optional
HOSTEFF: 0.0 1.0      # required: args are redshift & effic.
HOSTEFF: 0.50 0.8
HOSTEFF: 1.00 0.6
HOSTEFF: 1.50 0.2

FIELDLIST: F3+F4+F5
HOSTEFF: 0.0 1.0
HOSTEFF: 0.50 0.9
HOSTEFF: 1.00 0.8
HOSTEFF: 1.50 0.7
etc ...
```

The `FIELDLIST` arguments are optional, as leaving this out will apply the map to all fields. `HOSTEFF` keys are required. In analogy with the spectroscopic efficiency, the default survey-dependent file is

`$SNDATA_ROOT/models/searcheff/SEARCHEFF_zHOST_SDSS.DAT`

and similary with ‘SDSS’ replaced by an arbitray survey name. This feature can be used even if there is no host-galaxy simulation (§4.22).

Next, we give an example of a map with more complex function of HOSTLIB properties:

```

OPT_EXTRAP: 1                # default is 0=>abort; 1=>use value at grid edge
PEAKMJD_RANGE: 55600 58900   # default is 10000 90000
FIELDLIST:  C3+X3           # default is ALL
VARNAMES:  g_obs i_obs  HOSTEFF
HOSTEFF:   18  20    1.
HOSTEFF:   18  22    0.95
HOSTEFF:   18  24    0.55
HOSTEFF:   20  20    1.
HOSTEFF:   20  22    0.9
HOSTEFF:   20  24    0.5
HOSTEFF:   22  20    1.
HOSTEFF:   22  22    0.8
HOSTEFF:   22  24    0.4
HOSTEFF:   24  20    0.9
HOSTEFF:   24  22    0.7
HOSTEFF:   24  24    0.2

FIELDLIST:  C1+C2+S1+S2+X1+X2+E1+E2
PEAKMJD_RANGE: 55600 58900
VARNAMES:  g_obs i_obs  HOSTEFF
HOSTEFF:   18  20    1.
HOSTEFF:   18  22    0.98
HOSTEFF:   18  24    0.58
HOSTEFF:   20  20    0.95
HOSTEFF:   20  22    0.85
HOSTEFF:   20  24    0.45
HOSTEFF:   22  20    0.95
HOSTEFF:   22  22    0.75
HOSTEFF:   22  24    0.34
HOSTEFF:   24  20    0.85
HOSTEFF:   24  22    0.65
HOSTEFF:   24  24    0.15

```

OPT\_EXTRAP is zero by default, which means that any parameter outside the map range results in an abort. OPT\_EXTRAP=1 forces the map-edge value for parameters outside the map range. FIELDLIST is optional for FIELD-dependent maps; C3+X3 means that the map applies to both C3 and X3 fields. Sub-string matching is used, and therefore “FIELDLIST: X” would apply to X1, X2, X3. Also note that FIELDLIST must come before the VARNAMES key. PEAKMJD\_RANGE allows for season-dependent maps. Finally, the first  $N - 1$  VARNAMES specifies arbitrary HOSTLIB properties from the VARNAMES key in Fig. 11. The last ( $N$ th) VARNAME must be HOSTEFF.

For unconfirmed SNe that have no redshift information, the redshift and its error are set to  $-9$ ; this value flags the photo- $z$  fitting option in `snlc_fit.exe` to ignore redshift-prior information (`OPT_PHOTOZ=2`, (§5.12). When an accurate host-galaxy redshift is used, the 4-bit is set in `SIM_SEARCHEFF_MASK`. There is a valid (i.e, positive) redshift when `SIM_SEARCHEFF_MASK` has either the 2-bit or 4-bit set. `SIM_SEARCHEFF_MASK=1` means that the SN is detected by the pipeline (§4.18.1) but that there is no valid redshift (`REDSHIFT_FINAL = -9`). Finally, recall from §4.6 that the unconfirmed SNTYPE in the data header is 100 plus the spec-confirmed SNTYPE.

Below are a few examples of sim-input settings. First, to simulate a spectroscopically confirmed sample using private search-efficiency files,

```
APPLY_SEARCHEFF_OPT: 3          # apply PIPELINE+SPEC efficiencies
SEARCHEFF_PIPELINE_EFF_FILE: TESTEFF_PIPELINE.DAT # private file
SEARCHEFF_SPEC_FILE:          TESTEFF_SPEC.DAT    # private file
```

To simulate a mix of confirmed and unconfirmed SN Ia:

```
APPLY_SEARCHEFF_OPT: 1          # apply only the software trigger
```

Events with `SIM_SEARCHEFF_MASK=3` or `5` have a spectroscopic redshift with uncertainty given by the `GENSIGMA_REDSHIFT` key. Events with `SIM_SEARCHEFF_MASK=1` (unconfirmed and no host spec- $z$ ) have a host-galaxy photo- $z$  if such information is available in the `HOSTLIB`; otherwise the redshift is set to  $-9$ .

To simulate and select events with spectroscopic host redshift,

```
APPLY_SEARCHEFF_OPT: 5          # apply software trigger & zHOST
SEARCHEFF_zHOST_FILE: SEARCHEFF_zHOST.DAT
```

**zHOST VALIDATION:** to validate the `zHOST` efficiency, include `SIM_EFFMASK` in the variable list for the `SIMGEN_DUMP` option (§4.37.2), and use command-line override “`APPLY_SEARCHEFF_OPT 1`.” The simulated `zHOST` efficiency is defined to be

$$\text{EFF}(\text{zHOST}) = \frac{N[\text{SIM\_EFFMASK}=5]}{N[\text{SIM\_EFFMASK}=1] + N[\text{SIM\_EFFMASK}=5]},$$

and note that spectroscopically-confirmed events (`SIM_EFFMASK=3`) are ignored here. `EFF(zHOST)` can be defined as a function of the `HOSTLIB` property(s) and compared against the expected efficiency defined in the file argument of `SEARCHEFF_zHOST_FILE`.

Lastly, for published results we recommend putting measured efficiency files in the public area `$SNDATA_ROOT/models/searcheff`.

#### 4.18.4 Simulating and Fitting Mix of $z_{\text{spec}}$ and $z_{\text{phot}}$ From Host Galaxy

For future surveys, it may be interesting to consider a mix of redshift sources: spectroscopic host redshifts ( $z_{\text{spec}}$ ) measured at lower redshifts, and photometric host redshifts ( $z_{\text{phot}}$ ) measured at higher redshifts. This mix- $z$  simulation requires two inputs: 1) SEARCHEFF\_ZHOST\_FILE specifying efficiency vs. redshift of acquiring  $z_{\text{spec}}$  of the host, and 2) ZPHOT and ZPHOTERR columns in the HOSTLIB, or use the HOSTLIB\_GENZPHOT\_FUDGEPAAR input (§4.22.1). The relevant sim-inputs are:

```
APPLY_SEARCHEFF_OPT:    1          # apply software trigger only
SEARCHEFF_ZHOST_FILE:   SEARCHEFF_ZHOST.DAT
```

The ZHOST efficiency map is used first to determine if the event has an accurate  $z_{\text{spec}}$ . If there is no  $z_{\text{spec}}$ , then the redshift is taken from ZPHOT and ZPHOTERR. Note that REDSHIFT\_FINAL[\_ERR] in the data file is either  $z_{\text{spec}}$  or ZPHOT, so there is only one redshift variable to access in the analysis. Supplemental data variables HOSTGAL\_ZSPEC and HOSTGAL\_ZPHOT are also available, for example, to compare  $z_{\text{phot}}$  against  $z_{\text{spec}}$  in the subset for which both are available.

In the light curve fitting stage, use &FITINP namelist option OPT\_PHOTOZ=2 to perform a 5-parameter  $z_{\text{phot}}$  fit with the host redshift as a prior (§5.12). The  $z$ -prior is a Gaussian with mean and  $\sigma$  taken from REDSHIFT\_FINAL[\_ERR]. The value of REDSHIFT\_FINAL\_ERR is much smaller for  $z_{\text{spec}}$  events compared with  $z_{\text{phot}}$  events. For  $z_{\text{spec}}$  events, the small  $\sigma$  value results in such a strong  $z$ -prior that the fit is essentially a 4-parameter fit with fixed redshift. To validate this process, plot the following from the output FITRES table,

```
zHD - SIM_ZCMB vs. SIM_ZCMB
zHDERR vs. SIM_ZCMB
```

Example input files for WFIRST are provided in

```
$SNDATA_ROOT/sample_input_files/WFIRST_zspec+zphot
```

#### 4.18.5 Determining $\epsilon_{\text{spec}}$

Since there is no rigorous method to determine  $\epsilon_{\text{spec}}$ , one must essentially start with a guess at the functional form and fit for parameters such as an exponential slope or power law. The spectroscopic efficiency must have the form  $\epsilon_{\text{spec}}(z, \vec{m}, \vec{E})$ , where  $z$  is the redshift,  $\vec{m}$  are the peak magnitudes and  $\vec{E}$  are efficiency-function parameters to be determined. Next generate a large simulated sample that includes the pipeline efficiency (i.e, APPLY\_SEARCHEFF\_OPT: 1) and the same selection requirements that are applied to the data. The last step is to fit for  $\vec{E}$  by minimizing

$$\chi^2 = \sum_i [(N_{\text{DATA}}^i - N_{\text{SIM}}^i \times E_0 \epsilon_{\text{spec}}(z, \vec{m}, \vec{E})) / \sigma_i^2] \quad (18)$$

where  $E_0$  is an overall scale such that the integrated data and simulation have the same statistics,  $i$  is an index over bins, and  $\sigma_i$  is the statistical uncertainty on the data. The bins can be simply redshift bins, or multi-dimensional bins of redshift and the peak magnitude(s). We suggest starting with the simple case of redshift bins, and trying more complex binning only if the simple case is not adequate. After determining  $\vec{E}$  from the fit, it is important to check data-simulation comparisons on distributions of other quantities, namely the fitted stretch and color parameters.

#### 4.18.6 Time Above Detection and Number of Detections

In some analyses, it is useful to cut on the time above detection (e.g., looking for fast or long-live transients), and also the number of detections. This section explains how to access this information in the SNANA and FITRES tables via the following variables:

```
TLIVE_DETECT    # MJD_DETECT(last) - MJD_DETECT(first)
NEPOCH_DETECT   # Nobs with detection
```

The detection information must be stored as one of the bits in the PHOTFLAG column of the data files. For real data, the survey team is responsible for setting this bit. For simulations, set the PHOTFLAG\_DETECT mask as shown Fig. 8. To get TLIVE\_DETECT and NEPOCH\_DETECT in the analysis-output tables, set the following analysis input:

```
&SNLCINP
  PHOTFLAG_DETECT = nnn      ! defines detection bt in PHOTFLAG
  CUTWIN_PHOTPROB = xxx, yyy ! optional cut on PHOTPROB, each epoch
```

where nnn is the mask value (e.g., 4096). If PHOTPROB values are included in the data files, CUTWIN\_PHOTPROB can be used to reject poor-quality observations. For simulations, default PHOTPROB=1, or a PHOTPROB map can be defined (Fig. 8).

#### 4.18.7 Trigger on Single-Detections instead of Coadd

SIMLIB cadences are typically co-added within a night to achieve optimal search depth. If the ID column of the SIMLIB includes the number of exposures that were co-added (see NEXPOSE in §4.7.4), there is a sim-input flag to trigger on single detections instead of the coadd,

```
APPLY_DETECT_SINGLE: 1
```

This flag results in the following changes in the pipeline-detection:

- $\text{SNR} \rightarrow \text{SNR}/\sqrt{\text{NEXPOSE}}$  is used to determine the detection efficiency ( $\epsilon_{\text{subtr}}$ ) from the efficiency-vs-SNR map (§4.18.1)
- While SNR is reduced in each exposure, there are NEXPOSE opportunities for detection; thus the final detection efficiency is re-computed as

$$\epsilon_{\text{subtr}} \rightarrow 1 - (1 - \epsilon_{\text{subtr}})^{\text{NEXPOSE}} \quad (19)$$



## 4.19 Selection Cuts

Although selection cuts are usually applied with the fitting program (§ 5) or some external program, the simulation allows for some basic selection cuts. This feature is particularly useful, for example, to simplify and speed up the generation of a large efficiency grid, and to estimate rates. The global flag to implement the “CUTWIN\_XXXX” selection criteria is

```
APPLY_CUTWIN_OPT: 0 # => ignore selection cuts (default)
APPLY_CUTWIN_OPT: 1 # => implement selection cuts
APPLY_CUTWIN_OPT: 3 # => apply cuts to data files; NOT to SIMGEN_DUMP
```

For option 1 the selection cuts are applied to both the data files and to the entries in the SIMGEN\_DUMP file (§4.37.2). The last option (3) is useful for keeping track of absolute efficiencies, along with the SIMGEN\_DUMPALL: key.

A list of available cut-commands are as follows:

```
EPCUTWIN_LAMREST: 3000 9500 # cut-window for <lamobs>/(1+z)
EPCUTWIN_SNRMIN: +3 1E8 # min SNR for each observation
CUTWIN_TRESTMIN: -19 -5 # at least 1 epoch before -5 d (rest-frame)
CUTWIN_TRESTMAX: +30 +80 # at least 1 epoch past +30 d
CUTWIN_TGAPMAX: 0 20 # largest Trest gap (days)
CUTWIN_TOGAPMAX: 0 10 # largest Trest gap near peak (days)
CUTWIN_NOBSDIF: 6 999 # Number of obs passing MJDDIF cut
CUTWIN_MJDDIF: 0.4 999 # NOBSDIF++ if this much later than last MJD
CUTWIN_NEPOCH: 7 +5 # require 7 epochs with SNR>5
CUTWIN_SNRMAX: 10 griz 1 -20 60 # SNR>10 for at least 1 of griz filters
CUTWIN_SNRMAX: 5 griz 3 -20 60 # SNR>5 for at least 3 of griz filters
CUTWIN_SNRMAX: 5 griz 3 0 60 # idem, but after max
CUTWIN_SNRMAX: 5 ri 2 -20 60 # r & i must each have SNR > 5
CUTWIN_MWEBV: 0.0 0.1 # Galactic E(B-V)
CUTWIN_PEAKMAG: 10 27 # any filter-peakmag between 10 and 27
CUTWIN_PEAKMAG_ALL: 15 30 # ALL filter-peakmag between 15 and 30
CUTWIN_EPOCHS_SNRMIN: 5 20 iz # SNR(iz) > 5 for < 20 days
CUTWIN_NOBS_SATURATE: 0 3 griz # require <=3 saturations in each griz band
CUTWIN_NOBS_NOSATURATE: 5 500 griz # require >=5 unsaturated epochs each band
CUTWIN_REDSHIFT_TRUE: 0 1 # cut on true cmb redshift
CUTWIN_REDSHIFT_FINAL: 0 1 # cut on best redshift (zSpec or zPhot)
CUTWIN_HOST_ZPHOT: 0 1 # cut on host photo-z
```

Each cut-command can be specified in the sim-input file, or using the command-line override (§12.2.3) without the colon. Any CUTWIN\_XXX that is not specified results in no cut. The cuts beginning with EPCUTWIN apply to every epoch (observation), and only measurements passing these EPCUTWIN\_XXX requirements are used to evaluate cuts on global light curve properties. CUTWIN\_NEPOCH includes its own SNR requirement; thus you could set “EPCUTWIN\_SNRMIN: -5 1E8” so that all measurements, regardless of SNR, are used for cuts on TRESTMIN, TRESTMAX and TGAPMAX, while still requiring 7 observations to have SNR > 5.

Multiple CUTWIN\_SNRMAX requirements can be specified. Note that this cut requires a certain number of passbands to have a minimum SNR value, but does not specify which bands. For the



example above, “CUTWIN\_SNRMAX: 5 griz 3 -20 60” is satisfied if the maximum SNR is  $> 5$  for either *gri*, *grz*, *giz*, or *riz*. You can require SNR cuts for specific filters as illustrated above with “CUTWIN\_SNRMAX: 5 ri 2 -20 60”; this requires both *r* and *i* to have a measurement with  $\text{SNR} > 5$ .

The TGAPMAX requirement applies to observations between the lower-TRESTMIN and upper-TRESTMAX cuts; i.e.,  $-19$  to  $+80$  days in the example above. The TOGAPMAX requirement applies to observations near peak, meaning that the gap must overlap the range between the upper-TRESTMIN and lower-TRESTMAX cuts; i.e.,  $-5$  to  $+30$  days. In this example, a gap defined by  $-12$  to  $-6$  days is included in the evaluation of the TGAPMAX cut, but not in the TOGAPMAX cut. Gaps of  $-6$  to  $+2$  and  $+20$  to  $+35$  days are included in the evaluation of both cuts. A gap of  $+8.0$  to  $+85$  is ignored for both cuts.

Adding “CUTMASK to the SIMGEN\_DUMP variable list shows which cuts pass/fail each generated event. The CUTMASK bit-definitions are obtained by grepping the source-code,

```
grep CUTBIT $SNANA_DIR/src/snlc_sim.h | grep define
#define CUTBIT_TRESTMAX      0    // (1)
#define CUTBIT_TRESTMIN     1    // (2)
#define CUTBIT_SNRMAX       2    // (4)    max SNR cut
#define CUTBIT_TGAPMAX      3    // (8)    max Tgap
#define CUTBIT_TOGAPMAX     4    // (16)   idem near peak
#define CUTBIT_NOBS_SNR     5    // (32)   NOBS with special SNR cut
#define CUTBIT_NOBS_MJDDIF  6    // (64)   NOBS with MJDDIF cut
#define CUTBIT_MWEBV        7    // (128)  galactic extinction
#define CUTBIT_REDSHIFT     8    // (256)  redshift
#define CUTBIT_PEAKMAG      9    // (512)  peak mag
```

The generation and cut-selection statistics are printed at the end of the sim-README file (§ 4.2). Here is an example when selection cuts are applied, while the search efficiency is not:

```
Generation Statistics:
    Generated    250 simulated light curves.
    Wrote        100 simulated light curves to SNDATA files.
Rejection Statistics:
    1 rejected by GEN-RANGE cuts.
    0 rejected by SEARCH-TRIGGER
    149 rejected by CUTWIN-SELECTION
SEARCH+CUTS Efficiency:  0.402 +-  0.031
```

An efficiency grid can be quickly computed by looping over the variables of interest (redshift, SN brightness, etc ) and using `grep` “SEARCH+CUTS” to extract the efficiencies.

The number of generated events is specified by the keyword “NGEN\_LC: 100”, which instructs the simulation to generate 100 lightcurves that pass the SEARCH-TRIGGER & CUTWIN-SELECTION (§4.29).

## 4.20 Varying the Exposure Time/Aperture/Efficiency

For testing future (i.e, non-existent) surveys, the exposure times can be varied relative to that of the SIMLIB, and avoids the need to create a new SIMLIB for each sequence of exposure times. The sim-input syntax is

```
EXPOSURE_TIME:      2.0          # global increase for all filters
EXPOSURE_TIME_FILTER: g    3.0    # x3.0 more exposure in g-band
EXPOSURE_TIME_FILTER: r    4.6    # x4.6 more exposure in r-band
EXPOSURE_TIME_FILTER izY 8.0    # x8 more exposure in izY bands
```

Since the global EXPOSURE\_TIME multiplies the filter-dependent exposure times, the net exposure-time increase for the above example is 6 and 9.2 for *g* and *r*, respectively, and 16 for the *izY* filters. The default exposure-time increase is one.

This option is equivalent running each exposure longer by the specified amount, or increasing the aperture or efficiency. Technically, the simulation does the following for each filter:

```
ZPT(SIMLIB)  -> ZPT + 2.5*LOG10(EXPOSURE_TIME)
SKYSIG       -> SKYSIG * sqrt(EXPOSURE_TIME)
CCDNOISE     -> CCDNOISE * sqrt(EXPOSURE_TIME)
```

The changes in the ZPT and SKYSIG are unambiguous for a given EXPOSURE\_TIME, but the CCDNOISE should not change if the EXPOSURE\_TIME is assumed to increase the efficiency without increasing the number of times that the CCDs are read out. There is an option-mask to control which parameters to modify,

```
EXPOSURE_TIME_MSKOPT:  7  # bits 1,2,3 => ZPT, SKYSIG, CCDNOIST
```

The default is to modify all three SIMLIB parameters. To modify ZPT and SKYSIG while leaving the CCDNOISE fixed, set “EXPOSURE\_TIME\_MSKOPT: 3”

## 4.21 Simulating Galactic Extinction

The following sim-input parameters control MilkyWay (MW) Galactic extinction:

```
RV_MWCOLORLAW:      3.1    # default
OPT_MWCOLORLAW:      94     # default: CCM89+ODonnel94
OPT_MWEBV:           1      # default: MWEBV key in SIMLIB file
GENSIGMA_MWEBV_RATIO: 0.16  # default: smear by sig(MWEBV) = .16*MWEBV

APPLYFLAG_MWEBV: 1    # correct FLUXCAL for MWEBV (e.g., for PLASTICC)

# for systematic tests:
GENSIGMA_MWEBV:      0.0    # smear by fixed sig(MWEBV)
GENSHIFT_MWEBV:      0.0    # fixed shift relative to dust map
GENSCALE_MWEBV:      1.0    # scale MWEBV
GENRANGE_MWEBV:      xxx yyy # genrate flat distrib between xxx and yyy
```

The first four keys control the  $R_V$  value, color law, source of  $MWEBV = E(B - V)$ , and the fractional uncertainty on  $E(B - V)$ . The remaining keys are intended for additional systematic tests. In `MWgaldust.c`, the function ‘`GALextinct`’ applies the selected color law (based on `OPT_MWCOLORLAW`) to compute the extinction at arbitrary wavelengths, and ‘`modify_MWEBV_SFD`’ determines  $E(B - V)$  according to `OPT_MWEBV`. To turn off Galactic extinction, set either `OPT_MWCOLORLAW` or `OPT_MWEBV` to zero. Analogous control keys exist in the fitting programs (§5.6), and thus systematic tests can be performed using both simulations and fitting.

Since options may change over time, a robust way to see the current options is to grep the definition keys,

```
grep OPT_MWCOLORLAW $SNANA_DIR/src/MWgaldust.h
#define OPT_MWCOLORLAW_OFF      0 // No Extinction applied.
#define OPT_MWCOLORLAW_CCM89    89 // Clayton,Cardelli,Matheson, 1989
#define OPT_MWCOLORLAW_ODON94   94 // O'Donnel 1994 update
#define OPT_MWCOLORLAW_FITZ99   99 // Fitzpatrick 1999

grep OPT_MWEBV $SNANA_DIR/src/MWgaldust.h
#define OPT_MWEBV_OFF          0 // no extinction
#define OPT_MWEBV_FILE         1 // FILE value (simlib or data header)
#define OPT_MWEBV_SFD98        2 // use SFD98 value
#define OPT_MWEBV_Sch11_PS2013 3 // PS1-2013 implementation of Schlafly 2011
```

The default keys are indicated above, and these defaults are trivially implemented by running the simulation without specifying any of the `MWEBV` keys in the sim-input file. With the default `OPT_MWEBV=1`, the value of  $E(B - V)$  is taken from the simlib “`MWEBV: xxx`” key. If this key is missing, or the entry value is zero, then `MWEBV` is calculated internally using the dust maps from [11], which is equivalent to `OPT_MWEBV=2`. `OPT_MWEBV>2` are intended for SFD98 recalibrations such as in Schlafly 2011. For each simulated SN, the nominal map-value of  $E(B - V)$  and its uncertainty are written to the header, and this value is used in the fitting programs (§5.6). `GENSIGMA_MWEBV_RATIO` controls the  $E(B - V)$  scatter relative to the nominal map value, and the smeared values are used

to redden the true magnitudes in the simulation. If the smearing for a given SN results in negative extinction, the extinction is set to zero.

Finally, the reported `FLUXCAL` are corrected for `MWEBV` if `APPLYFLAG_MWEBV` is set, as was done for the PLASTICC classification challenge. Use caution with this flag to avoid double-correcting in both the simulation and in the analysis.

#### 4.21.1 Some Details on Galactic Extinction Computations

The implementation of Galactic extinction is quite different for observer-frame and rest-frame models, although the sim-input keys work the same for both. The discussion here is relevant for both the simulation and fitting programs.

For observer-frame models (e.g., SALT2, S11DM15) the extinction is computed exactly for each filter-wavelength bin in the flux integrals. For rest-frame models that require K-corrections (e.g., mlcs2k2, snoopy) the Galactic extinctions are stored in the `kcor/calib` file; the resulting lookup improves CPU speed. In the `kcor/calib` file, the extinction is computed and stored for  $E(B - V) = 0$  and  $E(B - V) = 0.1$  mag, and interpolation is used to compute the extinction for arbitrary  $E(B - V)$ . The treatment of `RV` and `OPT_MWCOLORLAW` is more subtle. These two keys in the sim-input file are also used in the `kcor`-input file to define the Galactic extinction values. If `RV` and/or `OPT_MWCOLORLAW` are varied in the sim-input file or in the fit-input namelist (§5.6), i.e., are different than what was used to generate the `kcor/calib` file, an extinction correction is computed at the central wavelength of the observer-frame filter.<sup>10</sup> The correction is the extinction difference between using the sim-input (or fit-input) parameters and those used to generate the `kcor/calib` file. With this strategy, a new `kcor/calib` file is *not* required to use a different `RV` value or color law. However, for large variations it would be prudent to make an explicit crosscheck by re-generating another `kcor/calib` file.

WARNING: `EXTINC_MILKYWAY` is obsolete and will cause the simulation to abort.

#### 4.21.2 Correcting `FLUXCAL` for Galactic Extinction

By default, the reported `FLUXCAL` and uncertainties in the data files include the effect of Galactic extinction. The analysis codes must therefore account for this effect. In some cases it is convenient to provide de-reddened data files. Simulated `FLUXCAL` in the data files can be internally corrected by setting `OPT_MWEBV` to be negative: e.g., “`OPT_MWEBV: -2`” will apply a smeared SFD98 map to redden the observed fluxes, and then correct the observed fluxes (`FLUXCAL`) using the SFD98 map value and central wavelength of each filter. Although the fluxes are `MWEBV`-corrected, the SNR is degraded from the reduced photo-statistics. Because of `MWEBV` uncertainty, the true extinction differs from the map value and this true value is used to correct `SIM_MAGOBS` (each epoch) and `SIM_PEAKMAG`.

---

<sup>10</sup>See function `GET_MWXT8` in `snana.car`.

## 4.22 Simulating the Host Galaxy

The simulation includes a host-galaxy package designed to model the following effects:

- select host galaxy based on arbitrary user-function of host properties; see `WGTMAP` (§4.22.4).
- Generate SN properties (e.g., stretch & color) correlated with host properties; see `VARNAMEs` list.
- two methods to shift SN magnitudes (coherent for all epochs and wavelengths) based on host properties; add `SNMAGSHIFT` to `VARNAMEs` list or use `WGTMAP`.
- host-galaxy photo-z to use as photo-z fitting prior (§ 5.12); include `ZPHOT` & `ZPHOT_ERR` in `VARNAMEs` list.
- select random SN location (near host galaxy) weighted by surface brightness; see Sersic params and set `HOSTLIB_MSKOPT += 8`.
- host-galaxy contribution to [SN] Poisson noise at each epoch; set `HOSTLIB_MSKOPT += 2`.

The host-galaxy information is stored in a library, hereafter denoted “HOSTLIB”. An example HOSTLIB is shown in Fig. 11. This self-documented file contains a list of “VARNAMEs,” and there are two mandatory variables: `GALID` and true heliocentric redshift `ZTRUE` (or `ZTRUE_CMB`; see §4.22.14); the simulation will abort if either variable is missing. The integer `GALID` must be the first element, but `ZTRUE` can be anywhere on the `VARNAMEs` list. The library need not be sorted by `ZTRUE` since the simulation internally sorts the library by redshift.

In principle a HOSTLIB needs to contain only `GALID` and `ZTRUE`, but such a library would not be useful to simulate interesting effects. The remaining `VARNAMEs` in Fig. 11 are optional, and enable different effects based on `HOSTLIB_MSKOPT`. The `ZPHOT` and `ZPHOTERR` specify an externally-computed photometric redshift, and “[filt]\_obs” are the observer-frame galaxy magnitudes needed to compute the Poisson noise. The coordinate variable names can be `RA`, `RA_GAL` or `RA_HOST`, and similarly for `DEC`; one of the latter two is recommended to avoid potential conflict with the `RA,DEC` of the SN in one of the output tables.

The galaxy shape is described by an arbitrary sum of Sersic profiles using the following `VARNAMEs`:

```
a0_Sersic - a9_Sersic   # half-light radius, major axis
b0_Sersic - b9_Sersic   # half-light radius, minor axis
n0_Sersic - n9_Sersic   # Sersic index; 0.5, 1, 4 -> Gauss, exp, deVauc
w0_Sersic - w9_Sersic   # weights (if 2 or more profiles per galaxy)
```

The `a` and `b` are major- and minor-axis half-light sizes (arcseconds) for up to 10 Sersic components. There are two options for defining the the Sersic index `n0_Sersic - n9_Sersic`: 1) include in `VARNAMEs` list (e.g., see `n0_Sersic` in Fig. 11) to allow a different Sersic index for each host galaxy, and 2) define a fixed Sersic index for all host galaxies using a key after the `VARNAMEs` list as shown in Fig. 11. The first Sersic-index method is recommended because the 2nd method may break python readers. Commonly used Sersic indices are  $n = 0.5, 1, 4$  for Gaussian, exponential and deVaucouleurs, respectively. If there are 2 or more Sersic profiles per galaxy, weights (`w0_Sersic-w9_Sersic`) are needed; the sum of Sersic weights is 1.

Finally, “`a_rot`” is the rotation angle (in degrees) of the major axis w.r.t. the +`RA` coordinate. If North is up and East is to the right, `a_rot` is measured clockwise, from the East toward the South.

Figure 11: Example HOSTLIB for the SNANA simulation.

```

VARNames: GALID RA_GAL DEC_GAL ZTRUE ZERR  u_obs g_obs r_obs i_obs z_obs
          r_ABS n0_Sersic  a0_Sersic  b0_Sersic  a_rot  ZPHOTFLAG

n0_Sersic: 0.5      # optional: fix sersic index for each host
                  # Note that n0_Sersic can be defined only once;
                  # either among the VARNames or here.

GAL:   2940448741  52.67432  -27.17716  0.3964  0.0828  99
       22.06580   20.99990  20.65600  20.33090  -21.43 0.50  0.99290
       0.73811   154.40625  1
GAL:   2940535300  52.67437  -28.42170  0.7860  0.0580  99
       25.78030   23.14940  22.0693   21.4904  -22.98 0.50  1.14660
       0.51003    77.85583  1
etc ...

```

Figure 12: Example HOSTLIB\_WGTMAP\_FILE for the SNANA simulation.

```

VARNames_WGTMAP: LOGMASS  LOG_SFR  WGT  SNMAGSHIFT
WGT:  4.50 -12.5  9.119e-04  0.
WGT:  4.50 -12.3  1.114e-03  0.
WGT:  4.50 -12.1  1.360e-03  0.
etc ...

```

The host-galaxy selection starts by finding a “near- $z$ ” subset of host galaxies, where sim-input `HOSTLIB_DZTOL` (§4.22.1) defines the `zSN-zGAL` tolerance. A random host among this near- $z$  subset is picked based on the weight map. A `HOSTLIB` should have adequate statistics to densely cover the redshift range and parameter space used by the weight map.



### 4.22.1 HOSTLIB Options

The following HOSTLIB options can be set in the sim-input file (or via command-line override):

```

HOSTLIB_FILE:          DES.HOSTLIB # required
# optional
HOSTLIB_MSKOPT:        8           # default=0
HOSTLIB_WGTMAP_FILE:   xxxx        # default=none
HOSTLIB_WGTMAP_EXTRAP: 1           # default=0
HOSTLIB_ZPHOTEFF_FILE: xxxx        # default=none
HOSTLIB_SPECBASIS_FILE: xxxx       # default=none
HOSTLIB_SPECDATA_FILE: xxxx       # default=none
HOSTLIB_MAXREAD:       10000       # default=billion
HOSTLIB_MNINTFLUX_SNPOS: .20       # default=0.0
HOSTLIB_MXINTFLUX_SNPOS: .97       # default=0.99
HOSTLIB_SNR_DETECT:    xxx         # default=0 SNR>xxx for detection (see below)
HOSTLIB_MAG_DETECT:    xxx         # default=99 MAG>xxx for detection
HOSTLIB_MAXDDLRL:      xxx         # default=4 (for host matches)
HOSTLIB_MAXDDLRL2:     xxx         # default=7 (for HOST_CONFUSION calculation)
HOSTLIB_SBRADIUS:      xxx         # default=1.2 arcsec
HOSTLIB_GENRANGE_RA:   xxx yyy     # default= -999 to +999
HOSTLIB_GENRANGE_DECL: xxx yyy     # default= -999 to +999)
HOSTLIB_STOREPAR:     var1,var2,var3 # default = ''
HOSTLIB_MINDAYSEP_SAMEGAL: xxx     # default=99999999
HOSTLIB_DZTOL:        a0,a1,a2,,,aN # default=0.002,0.040
HOSTLIB_GALID_PRIORITY: xxx yyy    # default= 0 0
HOSTLIB_GALID_UNIQUE: 0            # default=0; 1-> assign unique GALID
HOSTLIB_VARNAME_ZPHOT: ZPHOT_xxx  # use this column for ZPHOT[_ERR]
HOSTLIB_GENZPHOT_FUDGEMAP: 'z0:rms0,z1:rms1,z2:rms2,etc..' #no pad spaces
HOSTLIB_GENZPHOT_FUDGEPAR: a0 a1 a2 bprob b1 # default = all -9
HOSTLIB_GENZPHOT_BIAS:   b0 b1 b2 b3 # 3rd order poly(ztrue)
HOSTLIB_SCALE_SERSIC_SIZE: xxx      # default= 1.0
HOSTLIB_SCALE_LOGMASS_ERR: xxx      # default= 1.0 (Legacy key)
HOSTLIB_SCALE_PROPERTY_ERR: 0.8(LOGMASS),0.9(LOGSFR),0.1(LOGsSFR)
                                # default= 1.0 for all properties
# debug options
HOSTLIB_GALID_FORCE:    ####       # forced GALID
HOSTLIB_FIXRAN_RADIUS:  #.##       # fix radial random number (0-1)
HOSTLIB_FIXRAN_PHI:     #.##       # fix phi random number (0-1)
HOSTLIB_FIXSERSIC:      a b n a_rot # a,b in arcsec, a_rot in deg
HOSTLIB_ABMAF_FORCE:    #.##       # force mag for galmag and host spectrum

```

Only the HOSTLIB\_FILE key is required, while the other keys are optional. Ideally all surveys would use the same HOSTLIB\_FILE, but in practice each survey will have its own HOSTLIB with a specific focus. Also note that there is no standard method for creating a HOSTLIB. The optional WGTMAP\_FILE overrides the default weight map embedded in the HOSTLIB file. HOSTLIB\_ZPHOTEFF\_FILE specifies a 2-column file with true redshift and efficiency of finding a host photo-z. For very large HOSTLIB files, the MAXREAD key may be useful to reduce the initialization time or limit memory usage. The



next options (`MNINTFLUX_SNOPOS`, `MXINTFLUX_SNPOS`) sets the fraction range of total galaxy flux used to generate the SN position; this option truncates extreme galaxy-SN separations, and can be used to keep events away from the core. `HOSTLIB_STOREPAR` is a comma-separated list of parameters (case-insensitive, but no blank spaces before or after each comma) to store in the data files; these “STOREPAR” parameters are automatically propagated into the `SNTABLES` and `ascii_fitres` file. `HOSTLIB` variables defined in `SEARCHEFF_ZHOST_FILE`, `GENPDF_FILE`, and `WGTMAP` are automatically included in the `HOSTLIB_STOREPAR` list.

`HOSTLIB_SNR_DETECT` works only if both mags and mag-uncertainties are defined in the `HOSTLIB` as `[band]_obs` and `[band]_obs_err`. Setting “`HOSTLIB_SNR_DETECT: 5`” requires at least one band with  $\text{SNR} > 5$ ; an argument of ‘5,5’ requires two bands to satisfy  $\text{SNR} > 5$ ; ‘5,5,3’ requires at least two bands with  $\text{SNR} > 5$  and a 3rd band with  $\text{SNR} > 3$ . If the true host fails the SNR cut, the event will either be host-less (no matches), or matched to a different nearby galaxy that passes SNR cut.

`HOSTLIB_MINDAYSEP_SAMEGAL` specifies the minimum `PEAKMJD` separation (in days) for re-using a galaxy. This option can be useful, for example, in multi-year surveys with long seasonal gaps, and in very low- $z$  simulations that have a limited number of galaxies.

A redshift tolerance,  $dz_{\text{tol}} \equiv \max|z_{\text{SN}} - z_{\text{GAL}}|$ , sets a limit on the max difference between the SN redshift and the redshift of the host galaxy picked from the `HOSTLIB`. This tolerance is needed because for each generated SN redshift there is no host with the exact same redshift. Requiring stricter  $z$ -tolerance (and allowing only 1 SN per host) generally requires a larger `HOSTLIB` to avoid running out of hosts and aborting. The input key `HOSTLIB_DZTOL` defines  $dz_{\text{tol}}$  as a polynomial function of redshift:  $a_0 + a_1z + a_2z^2 + \dots + a_Nz^N$ , where  $a_{0,1,2,\dots,N}$  are  $N+1$  comma-separated parameters following the `HOSTLIB_DZTOL` key. The default is 0.002,0.040 so that  $dz_{\text{tol}} = 0.002$  at  $z = 0$  and increases to  $dz_{\text{tol}} = 0.042$  at  $z = 1$ . To require a fixed 0.01  $z$ -dif tolerance at all redshifts set “`HOSTLIB_DZTOL: 0.01`.” To monitor  $z_{\text{SN}} - z_{\text{GAL}}$ , include `GALZDIF` in the `SIMGEN_DUMP` list (§4.37.2). The legacy syntax of space-separated  $a_i$  values is allowed, but only for a 2nd-order polynomial: `HOSTLIB_DZTOL: a0 a1 a2`.

`HOSTLIB_GALID_PRIORITY` allows giving priority to a subset specified by a `GALID` range. For example, if there only a few real host galaxies with `GALID > 0`, and the majority are fake galaxies on random sky with `GALID < 0`, then setting “`HOSTLIB_GALID_PRIORITY: 0 99999999`” will preferentially select the real galaxies before picking the fake galaxies.

`HOSTLIB_GALID_UNIQUE` sets a unique `GALID` for every event, even if the same `HOSTLIB` galaxy is re-used many times. This feature is useful, for example, in simulated data challenges. The algorithm uses the already unique `CID`<sup>11</sup> and computes

$$\text{GALID} = 57 * \text{CID} + \text{int}[\text{ran}(0:1) \times 57]$$

If there are multiple hosts per event and a duplicate `GALID`, another random `GALID` is selected. To avoid possible confusion with duplicate host-galaxy mags (e.g., `r_obs` column), each mag is shifted by a Gaussian-random fluctuation based on the mag-uncertainty (e.g., `r_obs_err` column).

`HOSTLIB_GENZPHOT_FUDGEPAR` specifies an analytic description of the host photo- $z$  profile and its error. This `FUDGEPAR` implementation does not require `ZPHOT` and `ZPHOTERR` keys in the `HOSTLIB`; if these keys exist in the `HOSTLIB`, their values are overwritten by the `FUDGEPAR` description. The `ZPHOT-ZTRUE` profile is described by a sum of two Gaussian profiles. The first Gaussian (G1) has a width described by the first 3 `FUDGEPAR` parameters:  $\sigma_1 = a_0 + a_1(1+z) + a_2(1+z)^2$ . The second Gaussian (G2) is described by the remaining two parameters: 1) `bprob` is the probability of selecting from G2, and  $1-\text{bprob}$  is the prob of selecting from G1, and 2)  $\sigma_2 = b_1(1+z)$  is the width of G2. G2 is intended to be broader than G1, and to account for outliers and wrong-host

<sup>11</sup>To ensure unique CIDs, set “`RESET_CID: 2`” in the `sim-master-input` file for `submit_batch_jobs`.

matches. The reported ZPHOTERR is  $\sigma_1$ , and thus G2 introduces non-Gaussian outliers which are not described by the reported uncertainty.

To avoid negative photo-z with FUDGEPAR, the Gaussian distribution is internally modified to an asymmetric Gaussian if the true redshift is less than  $3\sigma$  away from 0.01. Defining  $\sigma_-$  and  $\sigma_+$  to be bifurcated Gaussian sigmas, and  $z_{\text{peak}}$  to be the redshift with max probability, these 3 quantities are constrained by

$$z_{\text{peak}} = 0.01 + 3\sigma_- \quad (20)$$

$$\text{ZTRUE} = z_{\text{peak}} + \left[ (\sigma_- - \sigma_+) \sqrt{2/\pi} \right] \quad (21)$$

$$\text{ZPHOTERR}^2 = \left[ (\sigma_+ + \sigma_-)^2 + (\sigma_+ - \sigma_-)^2 (1 - 2/\pi) \right] / 4 \quad (\text{variance}) \quad (22)$$

Although an exact solution exists for this quadratic equation, the solution for  $z_{\text{peak}}, \sigma_-, \sigma_+$  is found numerically. If ZPHOTERR/ZTRUE ratio is too large, a solution cannot be found. In this case of no solution, the mean ZTRUE is preserved while the variance will be smaller than the requested ZPHOTERR<sup>2</sup>. The reported ZPHOTERR reflects the calculated variance on the r.h.s of Eq. 22.

If  $b_1 \geq 10$ , the G2 distribution is flat over the redshift range of the HOSTLIB. To specify a different outlier photo-z range (e.g.,  $0.01 < z_{\text{phot}} < 2.5$ ), set the **b1** (5th) element to the following string: 'FLAT(.01:2.5)'

HOSTLIB\_GENZPHOT\_BIAS introduces a z-dependent bias on ZPHOT. The parameters **b0, b1, b2, b3** describe a 3rd order polynomial function of true redshift. This bias applies to HOSTLIB\_GENZPHOT\_FUDGEPAR or to the ZPHOT[ERR] columns in the HOSTLIB.

HOSTLIB\_SCALE\_SERSIC\_SIZE scales the a0 and b0 half-light radii to make the galaxy sizes bigger or smaller.

HOSTLIB\_SCALE\_LOGMASS\_ERR scales the LOGMASS uncertainty.

HOSTLIB\_SCALE\_PROPERTY\_ERR scales the error of the property in parenthesis as illustrated above.

The HOSTLIB\_MSKOPT options can be viewed with the grep-command

```
grep MSKOPT $SNANA_DIR/src/sntools_host.h
```

- MSKOPT += 2 : compute the host-galaxy Poisson noise within an aperture of radius  $2\sigma_{\text{PSF}}$  (added to total error per epoch), and also compute the local surface brightness.<sup>12</sup> This option requires defining HOSTLIB header keys “f\_obs” for each filter (see VARNAMES in Fig. 11), where ‘f’ is the one-character filter representation. These observer-frame HOSTLIB mags should be corrected for MW Galactic extinction and correspond to the entire galaxy flux.
- MSKOPT += 4 : apply SN mag shift from WGTMAP. Does not control SNMAGSHIFT in VARNAMES list.
- MSKOPT += 8 : replace originally selected SN coordinates (i.e., randomly selected in field or from SIMLIB) by SN coordinates near the host galaxy (i.e., randomly selected from the surface brightness profile). This option is useful to generate SNe for image simulations. SN-generated  $z_{\text{cmb}}$  is preserved;  $z_{\text{hel}}$  is updated to account for new coordinates and generated  $v_{\text{pec}}$ . Generated distance ( $\mu$ ) is also updated.
- MSKOPT += 16 : adjust the SN redshift, SN mags, and  $\mu$  to galaxy redshift, ZTRUE (useful for image simulations).  $z_{\text{hel}} = \text{ZTRUE}$ ;  $z_{\text{cmb}}$  and  $\mu$  are updated to account for new  $z_{\text{hel}}$  and generated  $v_{\text{pec}}$ .

<sup>12</sup>see “HOSTGAL\_SB\_FLUXCAL” key in data header: units are FLUXCAL per arcsec<sup>2</sup>.

- MSKOPT += 32 : allow only one SN per host galaxy (results in abort if library is too small)
- MSKOPT += 64 : use SN properties in hostlib to override default generation: c, x1, Delta, AV, RV. Case-insensitive so that x1 and X1 both work. Sim aborts if no SN parameters are found.
- MSKOPT += 128 : set ZTRUE = ZPHOT (e.g., study impact of HOSTLIB based on photo-z).
- MSKOPT += 256 : increase init verbosity to screen.
- MSKOPT += 512 : use peculiar velocity columns in HOSTLIB (VPEC,VPEC\_ERR). Overrides sim-input keys GENSIGMA\_VPEC and VPEC\_ERR.
- MSKOPT += 1024 : detailed screen dump for each event (for small tests only)
- MSKOPT += 32768 : force Gaussian PDF (debug test) for quantiles with mean,sigma = ZPHOT,ZPHOTERR. Overwrite quantile values in HOSTLIB, or force 10 quantile redshifts.

Options can be combined, such as HOSTLIB\_MSKOPT=10 will transfer the SN redshift and coordinates to that of the galaxy, and compute the galaxy noise.

#### 4.22.2 Poisson Noise from Host

If the 2-bit of HOSTLIB\_MSKOPT is set, the noise covariance from the host ( $C_{\text{host}}$ ) is computed as the PSF-convolved galaxy flux contained within the noise-equivalent-area (NEA) centered on the Supernova, as illustrated in Fig. 13;

$$C_{\text{host}} = \int_{\text{host}} \left[ \int_{\text{NEA}} F_{\text{host}}(\rho_g, \theta_g) \text{PSF}(x - x_g, y - y_g) dx dy \right] \rho_g d\rho_g d\theta_g \quad (23)$$

where  $\rho_g$  is the reduced radius<sup>13</sup>  $\theta_g$  is the azimuthal angle, and  $F_{\text{host}}$  is the host Sersic profile flux at coordinate  $\{\rho_g, \theta_g\}$  (w.r.t. center of host). The inner PSF integral is over the circular NEA region; for computational speed, the Gaussian-PSF integrals are pre-computed and stored on a grid as a function of  $R = \sqrt{(x - x_g)^2 + (y - y_g)^2}$ , where  $\{x_g, y_g\}$  are Cartesian coordinates converted from polar coordinates. The outer integral is over the entire host galaxy with 100  $\rho_g$  bins and 36  $\theta_g$  bins. To avoid computing this integral for each observation per event,  $C_{\text{host}}$  is pre-computed on a grid of about 10 PSFSIG values at the start of each generated event, and interpolated at the PSFSIG value of each observation.

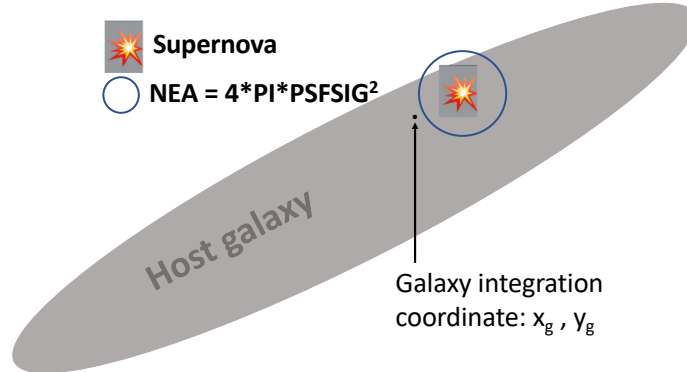


Figure 13: Diagram of host galaxy, SN, NEA and coordinates used to compute Poisson noise.

<sup>13</sup> $(\rho_g \equiv R/R_{1/2}$ , where  $R_{1/2}$  is the half-light radius.

### 4.22.3 Hostgal properties

In the HOSTLIB columns you can define true, observed, and error for up to four properties;

LOGMASS	LOGMASS_TRUE	LOGMASS_OBS	LOGMASS_ERR
LOGSFR	LOGSFR_TRUE	LOGSFR_OBS	LOGSFR_ERR
LOGsSFR	LOGsSFR_TRUE	LOGsSFR_OBS	LOGsSFR_ERR
COLOR	COLOR_TRUE	COLOR_OBS	COLOR_ERR

Item in the left column is the “BASENAME,” and defining a HOSTLIB column as BASENAME is interpreted as BASENAME\_TRUE. If BASENAME\_ERR is specified, BASENAME\_OBS is computed as `Gauss(BASENAME_TRUE,BASENAME_ERR)`. Non gaussian errors can be simulated with BASENAME\_OBS instead of BASENAME\_ERR. BASENAME\_ERR can be rescaled using the sim-input key

HOSTLIB\_SCALE\_PROPERTY\_ERR: 0.0(LOGMASS),0.0(LOGSFR) # set errors to zero

or

HOSTLIB\_SCALE\_PROPERTY\_ERR: 0.8(LOGMASS),0.9(LOGSFR),0.5(LOGsSFR)

where the first example sets errors to zero so that observed property equals the true value, and second example scales the error on 3 properties. These host-property values are automatically propagated to the simulated data files, and after light-curve fitting they are propagated to output tables (e.g. SNANA, FITRES).

### 4.22.4 HOSTLIB Weight Map (WGTMAP)

Ideally the simulation would select a random galaxy in the universe, and then select SN properties based on the host galaxy properties. In practice, however, the reverse is more practical: SN properties are picked from a measured population, and after the SN is selected a host galaxy is assigned. Using the HOSTLIB properties, an optional “weight map” (WGTMAP) defines a relative probability for assigning a host galaxy. The redshift is matched based on a tolerance (see HOSTLIB\_DZTOL key), and the WGTMAP is applied among all galaxies within the redshift tolerance. An example HOSTLIB\_WGTMAP\_FILE is shown in Fig. 12. Any HOSTLIB parameter may appear before the WGT column, and the map dimension can be arbitrarily high provided that your computer has sufficient memory to hold the entire weight map. An important constraint is that binning in each dimension must be uniform.

Following the VARNAMES\_WGTMAP key, the first “ $N - 2$ ” variables must be from the VARNAMES list in Fig. 11, which describe an arbitrary dependence on host properties. The last two variables must be WGT and SNMAGSHIFT, where the latter is applied to the generated magnitudes if the 4-bit is set in HOSTLIB\_MSKOPT. All WGTMAP variables are automatically included in the data files, equivalent to internally appending these variables to HOSTLIB\_STOREPAR. While there is no need to specify the same variable in both the WGTMAP and HOSTLIB\_STOREPAR list, there is no harm in doing so.

If no weight map is provided, the simulation will assign a weight of unity to each host galaxy, with zero mag-shift. Starting with SNANA version v10\_70, the “NVAR:” and “NVAR\_WGTMAP:” keys are obsolete, although leaving them in the HOSTLIB file will not cause any harm.

To include WGTMAP correlations with SALT2 stretch (x1) and color (c), simply include x1 and/or c in the WGTMAP. These are the only WGTMAP variables that are not required to be in the HOSTLIB VARNAMES list. If x1 and c are not in the HOSTLIB, the generated value is snapped to the nearest WGTMAP grid point so that the simulation runs more efficiently. For example, consider a WGTMAP color grid from  $-0.3$  to  $+0.5$  in bins of  $0.1$ ; for a generated color of  $c = 0.12$ , the weight is the pre-computed value at the grid point  $c = 0.1$ .

If a `HOSTLIB` value is beyond the defined range of the `WGTMAP`, the simulation aborts by default. To avoid the abort and fix out-of-range values to the `WGTMAP` edge,

```
HOSTLIB_WGTMAP_EXTRAP: 1
```

**MEMORY WARNING:** To maintain simulation speed, the `WGT` and `SNMAGSHIFT` are precomputed and stored in memory for each galaxy and each `x1,c` grid point; beware that this memory storage can be large. For example, consider a `HOSTLIB` with a million galaxies and a `WGTMAP` that includes a  $20 \times 20$  “`x1 \times c`” grid. The `WGT` and `SNMAGSHIFT` are stored for  $20 \times 20 \times 10^6 = 400$  million values, consuming 4 Gb of memory.<sup>14</sup> Check memory usage in the stdout from this output:

```
Interpolate WGTMAP for each galaxy (68.47 MB)
```

---

<sup>14</sup>While `WGT` is stored as 8-byte double, `SNMAGSHIFT*20000` is stored as 2-byte short int to reduce memory.

### 4.22.5 Generating Host Spectra

Host spectra are generated with the SPECTROGRAPH feature, and with several inputs as follows:

- `HOSTLIB_SPECBASIS_FILE` points to a file with spectral basis such as PCA. The header keys must include  
`VARNames: ROW WAVELENGTH SPECBASIS00 SPECBASIS01 SPECBASIS02 ... etc,`  
 where each vertical `SPECBASIS` column is an SED basis. Following `VARNames`, a `ROW:` key specifies  $\lambda$  and  $dF/d\lambda$  for each wavelength bin.  
 Optional keys before the header are:  
`FLAM_SCALE: 1.55E-30 # global flux norm.`  
`FLAM_SCALE_POWZ1: -2 # z-norm: 1/(1+z)**2`  
 If using EAZY SED templates, reformatting to SNANA-table format can be avoided with key `“EAZY_TEMPLATES_LIST_FILE: <list_file>”` that points to the template-list file in the EAZY repository. With this EAZY-direct read, leave out the `VARNames` and `ROW` keys.
- `HOSTLIB_SPECDATA_FILE` points to a file with spectral data. The header keys must include  
`VARNames: ROW WAVELENGTH SPECDATA00 SPECDATA01 ... etc,` where each vertical column is an SED. Optional keys before the header are the same as for `SPECBASIS`.
- `HOSTLIB_FILE` that includes columns `COEFF_SPECBASIS00`, `COEFF_SPECBASIS01`, etc.. or for `specdata` there is a single `IDSPECDATA` column to pick a specific `specdata` column from the `SPECDATA_FILE`.
- `TAKE_SPECTRUM` key with `HOST` argument as shown in §4.25.2.

For a given `hostlib` entry, each basis spectrum `“specbasis[nn]”` is multiplied by `coeff_specbasis[nn]`, and all of the `spec-basis` terms are summed. The sum is multiplied by `FLAM_SCALE` and the `z-norm` term.

### 4.22.6 Computation of DDLR (SNSEP/DLR)

The Sersic parameters in the `HOSTLIB` are assumed to represent the true galaxy profile, without PSF smearing, and this profile is used to overlay a true SN location near the host galaxy. To compute `DDLR=SNSEP/DLR`, a default `DLR` is computed from the true Sersic profile, which does not account for PSF smearing. There are two approximate methods to account for PSF smearing in the `DLR` computation:

1. define `HOSTLIB` columns `a_DLR` and `b_DLR` based on measured half-light radii. These quantities are used only to compute `DLR`, but are not used to overlay a true SN location.
2. Use sim-input `“HOSTLIB_SMEAR_SERSIC: 1.0”` which is loosely interpreted as FWHM (arcsec) for average PSF. This parameter does not impact placement of SN near galaxy, but it affects `DLR`; defining  $ab_{\text{smear}} \equiv \text{HOSTLIB\_SMEAR\_SERSIC}/2$ ,

$$a \rightarrow \sqrt{a^2 + ab_{\text{smear}}^2} \quad b \rightarrow \sqrt{b^2 + ab_{\text{smear}}^2} \quad (24)$$

where  $a, b$  are the semimajor/minor half-light radii.



#### 4.22.7 Generating HOST-less Events

The following sim-input keys control the fraction of simulated events reported by `HOSTGAL_NMATCH=0`; i.e., “host-less.”

```
# keys that require Sersic profile in HOSTLIB
HOSTLIB_MAXDDLRL:      4.0      # SEP/DLR
HOSTLIB_MXINTFLUX_SNPOS: 0.94    # default=0.99

# keys that require [band]_obs and [band]_obs_err in HOSTLIB
HOSTLIB_SNR_DETECT:    5      # or 5,5 -> 2 bands with SNR>5
HOSTLIB_SNR_SCALE:     0.5    # reduce by 2 -> impacts SNR_DETECT
    or
# PEAKMJD-dependent SNR_SCALE
HOSTLIB_SNR_SCALE(53000:53365): 0.3
HOSTLIB_SNR_SCALE(53365:53720): 0.5
HOSTLIB_SNR_SCALE(53720:54050): 0.7
```

The first key (`MAXDDLRL`) defines host-less events based on the separation from the host. Very broad profiles (e.g., de Vaucouleur with  $n = 4$ ) can lead to excessive host-less fractions from large `DDLRL`. To truncate the galaxy profile, `MXINTFLUX_SNPOS` removes the high-probability region at large radii.

The last two keys simulate host-less events by excluding nearby galaxies which fail a user-defined SNR cut. Galaxy mags and uncertainties are required in the `HOSTLIB` for this feature. In the example above, at least one band must satisfy  $\text{SNR} > 5$ .

A `HOSTLIB` is often based on the full depth of a survey, and is thus not appropriate for simulating samples before the end of the survey. For example, consider a `HOSTLIB` based on a 4-year co-add depth; to simulate a 1 year co-add depth, set `SNR_SCALE: 0.5` to reduce the galaxy SNR by a factor of  $\sqrt{1/4} = 1/2$ . An optional `PEAKMJD`-dependent `SNR_SCALE` can be given by providing `PEAKMJD`-ranges as parenthetical arguments.

#### 4.22.8 Generating Host Galaxy Photometric Redshifts

Photometric redshifts are read from the `HOSTLIB`. The  $z_{\text{phot}}$  values are not used in the simulation for calculations, but are simply written to the data files for analysis. There are two ways to provide photo- $z$  information into the `HOSTLIB`. First, provide `ZPHOT` and `ZPHOTERR` columns. The second method is to provide 11 quantile redshift columns corresponding to integrated (CDF) probabilities of 0, 10%, 20%, ... 100%:

```
ZPHOT_Q000  ZPHOT_Q010  ZPHOT_Q020  ZPHOT_Q030 ... ZPHOT_Q100
```

One or both methods may be provided in the same `HOSTLIB`. A more general framework for arbitrary quantiles may be developed in the future. The corresponding output data variables are

```
HOSTGAL_ZPHOT_Q000  HOSTGAL_ZPHOT_Q010
HOSTGAL_ZPHOT_Q020  HOSTGAL_ZPHOT_Q030 ... HOSTGAL_ZPHOT_Q100
NZPHOT_Q
```

where `NZPHOT_Q=11`.

To select photo- $z$  in the light curve fitting program, set `&FITINP` namelist variable `OPT_PHOTOZ=4` (§5.12). To override photo- $z$  information in the data files (real or sim), see (§5.28.1). Note that quantile overrides are unique because they can be appended even if the original data files do not have quantile data.



#### 4.22.9 Compute Synthetic HOSTLIB Magnitudes (+HOSTMAGS)

Using HOSTLIB\_SPECBASIS\_FILE, synthetic galaxy mag is computed for each band in “GENFILTERS:” key using the command-line option

```
snlc_sim.exe <inputFile> +HOSTMAGS
```

A new HOSTLIB file is created with [band]\_obs columns appended, and then the simulation stops execution. Note that +HOSTMAGS is not read from the sim-input file, and thus can be specified only as a command-line argument. This new HOSTLIB can be used to generate with galaxy mags, compute additional Poisson noise, and model anomalous flux-scatter as a function of local surface brightness.

#### 4.22.10 Generate List of HOSTLIB Neighbors (+HOSTNBR)

To simulate the effect of matching SN to the wrong galaxy with the DLR method, a list of true galaxy neighbors is needed for each HOSTLIB entry. For a HOSTLIB that includes sky coordinates, a supplemental column with a comma-separated list of neighbors can be created with

```
snlc_sim.exe <inputFile> +HOSTNBR
or
snlc_sim.exe <inputFile> +HOSTNBR SEP_NBR_MAX 10.0 NNBR_WRITE_MAX 10
```

The sim-input file must include a HOSTLIB\_FILE key, but no other sim-input keys are required. The optional command-line arguments are 1) SEP\_NBR\_MAX, the maximum angular separation between galaxies (default: 10”), and 2) NNBR\_WRITE\_MAX, the max number of neighbors to include (default: 10). These commands work only on the command line, and do not work as sim-input keys. A new HOSTLIB is created with +HOSTNBR extension, and the simulation quits without generating events. If Sersic profiles are included, running the simulation again with the newly-created HOSTLIB results in computing DLR for the true galaxy and each neighbor galaxy, and ordering the galaxy matches by DDLR = DLR/Angsep, even if the smallest DDLR is the wrong match.

To find the galaxy neighbors quickly when using the output HOSTLIB+NBR in a simulation, the galaxy identifiers are HOSTLIB row numbers (start at row 1) rather than GALID. To allow for easy verification, the +HOSTNBR option includes a screen-dump for several entries, where the dump includes both row number and GALID.

SIM\_HOSTLIB\_GALID is the true galaxy ID, and is in output data files and output tables created by analysis codes. An incorrect host-match is flagged by SIM\_HOSTLIB\_GALID≠HOSTGAL\_OBJID; in this case, it is likely that SIM\_HOSTLIB\_GALID = HOSTGAL2\_OBJID. To reject host-matches with a DDLR cut (§4.22.1), set sim-input key “HOSTLIB\_MAXDDLRL: <cutval>.” For analysis, host information can be added to TEXT-formatted tables (§12.1) using

```
SNTABLE_LIST = 'SNANA(text:host) FITRES(text:host)'
```

#### 4.22.11 Append Arbitray Columns to HOSTLIB (+HOSTAPPEND)

Contents from a supplemental HOSTLIB file can be appended to a primary HOSTLIB with

```
snlc_sim.exe <inputFile> +HOSTAPPEND <hostlib_append_file>
```

The sim-input file must include a `HOSTLIB_FILE` key, but no other sim-input keys are required. The supplemental `hostlib_append_file` must include a `VARNAMES` key that begins with `GALID`, and the `GALID` values should match those in the primary `HOSTLIB`. Each row should begin with “`GAL:`” key. The sim program ends after writing a new `HOSTLIB`, and warnings are printed for the number of missing `GALIDs`.

#### 4.22.12 Treatment of LOGMASS

To propagate effects of host-galaxy mass uncertainty, the simulation treats the following `HOSTLIB` columns:

<code>LOGMASS_TRUE</code>	# true $\log_{10}(M/M_{\text{solar}})$
<code>LOGMASS</code>	# same as above
<code>LOGMASS_ERR</code>	# Gaussian uncertainty
<code>LOGMASS_OBS</code>	# measured $\log_{10}(M/M_{\text{solar}})$

If `LOGMASS_OBS` is not included, then the measured mass is determined from a random Gaussian fluctuation using `LOGMASS_ERR`. `LOGMASS_OBS` is propagated to the output and used in cosmology fitting. The sim-input parameter `HOSTLIB_SCALE_LOGMASS_ERR` scales the uncertainty (see Table near top of §4.22.1).

#### 4.22.13 Notes on CPU Resources

The CPU generation time per host galaxy is dominated by the noise calculation that includes a convolution of the galaxy flux within a separate PSF-aperture for each epoch. The generation time is about 3 msec per host for a single Sersic profile, and 5 msec for a sum of 2 Sersic profiles. The main tool to minimize the generation time is to pre-compute integral tables for 2-dimensional Gaussians, and for Sersic profiles. Defining a reduced radius  $\rho \equiv R/R_{1/2}$  in terms of the half-light radius  $R_{1/2}$ , the dimensionless Sersic integrals

$$\mathcal{S}_n(\rho) = 2\pi \int_0^\rho \exp[-B_n(x^{1/n} - 1)] x dx \quad (25)$$

are tabulated and stored on a uniform grid as a function of  $1/n$  ( $n = 0.3 - 5$ ) and as a function of  $\log_{10}(\rho)$  ( $\rho = 10^{-4}$  to 100). The  $B_n$  coefficients are chosen such that  $\mathcal{S}_n(1)/\mathcal{S}_n(\infty) = 1/2$ . The galaxy flux ( $F$ ) at local galaxy coordinates  $x_{\text{gal}}$  and  $y_{\text{gal}}$  is the sum over Sersic components,

$$F = \sum_n w_n \frac{\exp[-B_n(\rho^{1/n} - 1)]}{a_n b_n \mathcal{S}_n(\infty)} \quad (26)$$

where  $w_n$  is the Sersic weight such that  $\sum_n w_n = 1$ ,  $a_n$  and  $b_n$  are the major and minor half-light axes, respectively, and  $\rho^2 = (x_{\text{gal}}/a_n)^2 + (y_{\text{gal}}/b_n)^2$  is the reduced radius.

#### 4.22.14 Ensuring Host PhotoZ in Fitting Program

To ensure that the light-curve fitter cannot cheat when doing photoZ fits on simulated SNe, there is an option to replace the output `REDSHIFT_FINAL` with the host-galaxy (photoZ) redshift so that the spectroscopic redshift is not available in the data file; this option is invoked by setting `GENSIGMA_REDSHIFT`  $\geq 1$ . If there is no host-galaxy photo-z, `GENSIGMA_REDSHIFT`  $\geq 1$  results in undefined `REDSHIFT_FINAL` =  $-9 \pm -9$ .

#### 4.22.15 ZTRUE\_CMB Column instead of Heliocentric ZTRUE

The HOSTLIB redshifts can be specified in the CMB frame using a ZTRUE\_CMB column instead of the default ZTRUE column. For this ZTRUE\_CMB feature, the HOSTLIB coordinates (RA\_GAL, DEC\_GAL) are used to transform ZTRUE\_CMB back to heliocentric ZTRUE during initialization. Therefore, this CMB-frame feature works only with the HOSTLIB\_MSKOPT += 8 option to use HOSTLIB coordinates instead of SIMLIB coordinates. If ZTRUE\_CMB is specified without also using the HOSTLIB-coordinate option, the simulation aborts.

#### 4.22.16 Connecting SIMGEN\_DUMP to HOSTLIB

Consider this example in the sim-input file:

```
GENVERSION: MYTEST
SIMGEN_DUMP: CID,ZCMB,ZHELIO,GALID,GALZTRUE,GALZPHOT,GALZPHOTERR,GALZDIF
etc ...
```

The simgen-dump file can be examined with command

```
get_fitres_values.py \
-f $SNROOT/SIM/MYTEST/MYTEST.DUMP \
-v ZCMB,ZHELIO,GALID,GALZTRUE,GALZPHOT,GALZPHOTERR,GALZDIF \
--nrow 1
```

CID	ZCMB	ZHELIO	GALID	GALZTRUE	GALZPHOT	GALZPHOTERR	GALZDIF
2	0.732063	0.733324	328788	0.7359	0.736324	0.0155	-0.002576

The original HOSTLIB information is extracted using the GALID:

```
get_fitres_values.py \
-f <HOSTLIB_FILE_NAME> \
-g 328788 -v ZTRUE,ZPHOT,ZPHOTERR
```

GALID	ZTRUE	ZPHOT	ZPHOTERR
328788	0.7359	0.7389	0.0155

Here a few comments on how these two sets of variables are related to each other:

- ZCMB is randomly selected SN redshift (cmb frame) from rate model.
- ZHELIO is the SN helio-redshift, transformed from ZCMB.
- GALZTRUE is the original true helio-redshift of the selected host with GALID=328788.
- $\text{GALZTRUE}(\text{SIMGEN\_DUMP}) = \text{ZTRUE}(\text{HOSTLIB}) = 0.7359$
- $\text{ZHELIO} - \text{GALZTRUE} = 0.733324 - 0.7359 = -0.002576$  is the difference between the SN redshift and randomly selected host based on HOSTLIB\_DZTOL; this difference is GALZDIF.
- $\text{GALZPHOT}(\text{SIMGEN\_DUMP}) - \text{ZPHOT}(\text{HOSTLIB}) = 0.736324 - 0.7389 = -0.002576 = \text{GALZDIF}$ .
- The original ZPHOT(HOSTLIB) can be computed as  
 $\text{ZPHOT}(\text{HOSTLIB}) = \text{GALZPHOT}(\text{SIMGEN\_DUMP}) - \text{GALZDIF}(\text{SIMGEN\_DUMP})$

#### 4.22.17 Miscellaneous

##### HOSTLIB Variables for SIMGEN\_DUMP file:

The SIMGEN\_DUMP option is described in §4.37.2. Here is an example showing the HOSTLIB variables:

```
SIMGEN_DUMP: 7 CID Z GALZTRUE GALZPHOT GALSNDM GALWGT r_obs
```

The GAL\* quantities can always be added, along with the subset of variables used to define the weight map.

##### HOSTGAL vs. SIM\_HOSTLIB variables in Data Files:

There are two sets of HOST-related parameters in the output. The first set, HOSTGAL\_XXX, corresponds to observables which can appear in real data files. These observables include OBJID, ZPHOT, ZPHOT\_ERR, LOGMASS\_TRUE. Additional observables may be added later. The second set, SIM\_HOSTLIB\_XXX, corresponds to the user-selected parameters from the sim-input key HOSTLIB\_STOREPAR. If this user-list includes an observable such as ZPHOT, then HOSTGAL\_ZPHOT and SIM\_HOSTLIB\_ZPHOT will both appear in the data files and in the analysis output (SNTABLEs and ascii fitres file).

##### HOSTLIB\_ZPHOTEFF\_FILE vs. SEARCHEFF\_zHOST\_FILE:

The former determines the probability (vs. redshift) for finding a host galaxy photo- $z$ , and it has no impact on setting SIM\_SEARCHEFF\_MASK. This option also requires ZPHOT in the HOSTLIB file. The latter determines the probability (vs. redshift) for finding a *spectroscopic* galaxy redshift, and it sets the 4-bit of SIM\_SEARCHEFF\_MASK. This option does not depend on the HOSTLIB.

##### Visual Testing with HOSTLIB\_FIXRAN :

To verify the “a\_rot” convention, it is useful to fix the radius and angle to known values and visually inspect the location on a real image with the HOSTLIB galaxies. A relative galaxy position and Sersic profile can be selected with

- HOSTLIB\_FIXRAN\_PHI is a random number ( $0 < r < 1$ ) that fixes the azimuthal angle to  $r \times 360$ :  $r = 0, 0.5, 1$  correspond to the major axis ( $0^\circ, 180^\circ, 360^\circ$ );  $r = 0.25$  and  $0.75$  correspond to the minor axis ( $90^\circ, 270^\circ$ ).
- HOSTLIB\_FIXRAN\_RADIUS is a random number ( $0 < r < 1$ ) where the reduced radius contains a fraction ‘ $r$ ’ of the total flux.
- HOSTLIB\_FIXSERSIC fixes the Sersic parameters  $a, b, n$ , and also the galaxy major axis angle (a\_rot) w.r.t. Right Ascension.

#### 4.22.18 Anomalous Flux-Scatter on Bright Galaxies

This is a near-obsolete utility, and it is recommended to use FLUXERRMAPs in §4.14. With this legacy model, the true flux uncertainty is increased as a function of surface brightness, while the nominal uncertainty is reported in the data file. The sim-input key word is

```
HOSTNOISE_FILE: <fileName>
```

and the file syntax is

```
NOISEMODEL_NAME: SB_ERRSCALE

# SBMAG      = mag/arcsec^2 in template at SN location
#            = 27.5 - 2.5*log10(FLUXCAL_SB)
# ERRSCALE: fluxerr -> fluxerr x ERRSCALE

LIBID: 1
BAND: g      FIELD: E1+E2+S1+S2+C1+C2+X1+X2
#           SBMAG  ERRSCALE
HOSTNOISE: 20.50  4.60
HOSTNOISE: 21.50  2.70
HOSTNOISE: 22.50  1.78
HOSTNOISE: 23.50  1.40
HOSTNOISE: 24.50  1.09
HOSTNOISE: 25.50  1.02
HOSTNOISE: 26.50  0.99
HOSTNOISE: 27.50  1.00
HOSTNOISE: 28.50  0.99

and repeat for each band and group of fields.
```

In the analysis, the data-file errors can be increased with the same model using

```
&SNLCINP
FUDGE_HOSTNOISE_FILE = '<fileName>'
```

#### 4.22.19 Simulating Mis-Matched Host Galaxy

WARNING: the recommended mis-match method is to use HOSTLIB neighbors (§4.22.10) and DDLR matching. The WRONGHOST method here pre-dates the +HOSTNBR feature, and should only be used for rapid testing.

For surveys that do not have SN spectroscopic confirmation and instead rely on a host galaxy spectroscopic redshift, there is the issue of matching each SN candidate to the correct host galaxy. This effect can be simulated by specifying a “WRONGHOST” model with sim-input key

```
WRONGHOST_FILE: <file>
```

and the WRONGHOST model is defined in the file with

```

#
# PROB_WRONGHOST_POLY: 0.065  0.015  -0.066  0.0544  [hard-code 3rd order]
#           or
# PROB_WRONGHOST_POLY: 0.065,0.015,-0.066           [arbitrary order]
#
# ZTRUE ZMATCH
0.921  1.019
0.875  1.455
0.517  0.499
0.174  0.1674
0.995  0.7651
0.325  0.861
etc ...

```

The key `PROB_WRONGHOST_POLY` specifies a 3rd order polynomial function of redshift to compute the wrong-host probability; first term is a constant, 2nd term is linear in redshift, etc. For incorrectly matched host galaxies, the remainder of the file gives a list of the true SN redshift (`ZTRUE`) and the redshift of the incorrectly matched galaxy (`ZMATCH`). `WRONGHOST` entries are rejected if either `ZTRUE` or `ZMATCH` is outside the `HOSTLIB` redshift range.

For a given SN redshift ( $z_{\text{SN}}$ ), the `WRONGHOST` library is searched for nearby `ZTRUE` values within 0.01 of  $z_{\text{SN}}$ ; a random `ZTRUE` is selected among these nearby values. The host redshift is computed as

$$z_{\text{host}} = z_{\text{SN}} + (Z\text{MATCH} - Z\text{TRUE}).$$

Note that the `WRONGHOST` model is created outside of the `SNANA` environment. Ideally, this model is based on matching simulated SN locations to galaxies in a catalog generated from the survey.

There are two ways to identify mis-matched hosts from the data files. First is an explicit flag, `SIM_ZFLAG=4` (see § 4.36.7 for details). Second, `REDSHIFT_FINAL - SIM_REDSHIFT_CMB` should show a tail from wrong-host matches. In the output tables (`SNANA,FITRES`) from `snana-analysis`, examine `zCMB-SIM_zCMB`, and extract `SIM_ZFLAG` using the `APPEND_TABLE_TEXT` feature in `split_and_fit`.



#### 4.22.20 Correlating SIMLIB and HOSTLIB with GROUPID

The default use of SIMLIB and HOSTLIB libraries assumes no correlation between instrumental cadence and host properties. While this assumption is largely correct, it fails for simulating large scale structure (LSS) because the host properties (e.g., peculiar velocity) may depend on sky location and thus the cadence and host properties are correlated. To efficiently connect the SIMLIB sky location to a host at the same (within user tolerance) sky location, use the **GROUPID** feature.

For each SIMLIB entry, the header can include an optional **GROUPID** key such as

```
LIBID: 24
HOSTLIB_GROUPID: 45,46
RA: <RA>          DEC: <DEC>
etc ...
```

With sim-input key

```
USE_SIMLIB_GROUPID: 1 # enable GROUPID feature
```

the simulation selects a host with **GROUPID** = 45 or 46. The HOSTLIB must include a **GROUPID** column to use this option of forcing an {RA,DEC}-match between the SIMLIB and HOSTLIB. This **GROUPID** feature is compatible with **WGTMAP** so that host property distributions are preserved.

Beware of defining an {RA,DEC}-match tolerance that is too strict, otherwise a **GROUPID** match will not be found and the simulation will abort. If the sim aborts with “Unable to select GALID”, try one of the following: i) create larger HOSTLIB, ii) relax {RA,DEC} match tolerance between SIMLIB and HOSTLIB, or iii) relax redshift match tolerance (see **HOSTLIB\_DZTOL** key).

## 4.23 Simulating Rate vs. Redshift: Volumetric and per Season

To simulate a constant volumetric rate at all redshifts, include one of the following sim-input options:

```
DNDZ: HUBBLE
```

and to simulate a redshift-dependent rate that depends on a power of  $1 + z$ ,

```
DNDZ: POWERLAW 2.6E-5 1.5 # rate=2.6E-5*(1+z)^1.5 /yr/Mpc^3
```

Note that setting the second POWERLAW argument to zero is equivalent to the HUBBLE option of a constant rate. Finally, to simulate multiple power laws in different redshift ranges,

```
#          R0      Beta  Zmin Zmax
DNDZ: POWERLAW2 2.2E-5 2.15 0.0 1.0 # rate = R0(1+z)^Beta
DNDZ: POWERLAW2 9.76E-5 0.0 1.0 2.0 # constant rate for z>1
```

where  $R0$  is the rate ( $/\text{yr}/\text{Mpc}^3$ ) at  $z = 0$ ,  $Beta$  gives the  $z$ -dependence ( $Beta=0$  for constant rate), and the last two entries give the min/max redshift range. The output README file includes a dump of the SN volumetric rate in redshift bins of 0.1 (grep “MODEL-RATE”).

To read and interpolate a table of  $R(z)$ ,

```
DNDZ_FILE: <myrate.dat>
```

containing two columns, redshift  $z$  and volumetric rate (no keys). Comment lines with  $\#$  are allowed.

Highly distorted redshift distribution for special tests can be obtained with

```
DNDZ: FLAT # dN/dz = constant
or
DNDZ: ZPOLY a0,a1,,,aN # dN/dz = N'th-order polynom
DNDZ: ZPOLY a0 a1 a2 a3 # LEGACY dN/dz = 3rd order polynom
or
DNDZ: CC_S15 # CC-Rate(z) from Strolger 2015 (Fig 6, green line)
or
DNDZ: CC_S15*.3 # 30% of S15 rate
or
DNDZ: MD14 Rate(z=0) # Rate(z) from Madau & Dickenson 2014
or
DNDZ_ZEXP_REWGT: -2.0 # dN/dz *= 1/z^2
or
DNDZ_ZPOLY_REWGT: a0,a1,,,aN # dN/dz *= [N'th prder polynom]
DNDZ_ZPOLY_REWGT: a0 a1 a2 a3 # LEGACY dN/dz *= [3rd prder polynom]
```

The “FLAT” command results in a flat redshift distribution, and the ZPOLY option specifies the redshift distribution with an  $N'$ th-order polynomial function of redshift. CC\_S15 is the HST-measured CC rate. MD14 is the Star-formation rate, and there is one user-input parameter to define the rate ( $\text{yr}^{-1}\text{Mpc}^{-3}$ ) at  $z = 0$ . The next two examples re-weight the distribution defined by the DNDZ key above. The example with “DNDZ\_ZEXP\_REWGT: -2” re-weights by  $z^{-2}$ . The last option allows the user to multiply the “DNDZ” redshift distribution by an arbitrary 3rd-order polynomial function of the redshift.

As a convenience, the absolute number of SN per season within your survey ( $N_{\text{season}}$ ) is written into the output README file as follows:

Number of SN per season = 12345

This value does not depend on `NGEN_LC` or `NGENTOT_LC`,<sup>15</sup> and it is not used in the simulation. This calculated value depends on the MJD range (`GENRANGE_PEAKMJD`), redshift range (`GENRANGE_REDSHIFT`), `DNDZ` option above, and coordinate ranges (`GENRANGE_RA` and `GENRANGE_DECL`). The sky area specified by the RA and DECL ranges can be overwritten by explicitly defining a solid angle in your sim-input file using

```
SOLID_ANGLE: 0.0204 # solid angle (steradian) for SN/season estimate
```

The `SOLID_ANGLE` option is useful when the survey consists of several dis-connected patches of sky, thereby requiring the RA and DECL ranges to represent a solid angle that is much larger than that of the survey.  $N_{\text{season}}$  can be used generate an arbitrary number of SN seasons. For example, to simulate 3 seasons set the following:

```
NGENTOT_LC: 37035 # 3*12345 = 3 seasons
or
NGEN_SEASON: 3.0
```

To scale the rates,

```
DNDZ_SCALE:      xx yy # xx= SNIa-scale; yy=scale for NON1A/SIMSED
or
DNDZ_SCALE_NON1A: yy # scale NON1A and SIMSED rates (scaleIa=1.0)
or
DNDZ_ALLSCALE:  xx # scale rate for all models
```

This option is also useful for `submit_batch_jobs.sh`: e.g., to add a large Ia-biasCor sample, “`GENOPT: DNDZ_SCALE 10 1.0E-8`” scales the Ia sample by a factor of 10 while turning off the NON1A. Beware that the NON1A scales apply specifically to NON1ASED and NON1AGRID models. SIMSED models can be either Ia or NON1A, and thus `DNDZ_ALLSCALE` applies to all models.

---

<sup>15</sup>`NGEN_LC` is the number of SNe generated after trigger cuts and `NGENTOT_LC` is the total number generated regardless of the trigger and cuts (§4.29).

## 4.24 Simulating Rate vs. Galactic Coordinates

For the LCLIB model, the relative rate is defined as a function of Galactic  $b$ -coordinates,

```

DNDB:  COSBPOLY  b0,b1,b2,,,bN      # Nth order polynomial in cos(b)
DNDB:  COSBPOLY  b0 b1 b2 b3 b4 b5   # legacy input for 5th order polynom
      or
DNDB:  BPOLY      b0,b1,b2,,,bN      # Nth order polynomial in b
DNDB:  BPOLY      b0 b1 b2 b3 b4 b5   # legacy input for 5th order polynom

# ----- examples -----
DNDB:  COSBPOLY   1                # isotropic
DNDB:  COSBPOLY   1,0.3            # 1 + 0.3*cos(b)

```

which defines the  $b$ -dependence with an  $N'$ th-order polynomial function of  $\cos(b)$  or  $b$ . The absolute number of generated events is given by NGENTOT\_LC. *Beware* of the following:

- DNDB is a re-weight function applied to the SIMLIB distribution.
- For isotropic SIMLIB and highly anisotropic DNDB reweight, set SIMLIB\_NREPEAT  $\gg 1$  for efficient generation.

With default “SIMLIB\_NREPEAT: 1,” the simulation randomly selects/rejects each SIMLIB entry based on the input DNDB function. This procedure is efficient for nearly isotropic DNDB, but for more realistic DNDB with a very large anisotropy, the simulation spends most of the time reading and skipping SIMLIB entries, and is thus very inefficient.

To reduce reading of SIMLIB entries, and thus reduce processing time, use the SIMLIB\_NREPEAT feature (§4.7.1). While SIMLIB\_NREPEAT is fixed for isotropic rate models that depend on redshift (§4.23), here it is multiplied by the relative rate for each SIMLIB entry  $i$ :

$$\text{SIMLIB\_NREPEAT}(i) = \max(\text{SIMLIB\_NREPEAT}) * \text{DNDB}(b) / \max[\text{DNDB}(b)]$$

The  $b$ -weight is implemented by how many times each SIMLIB entry is read. Since SIMLIB\_NREPEAT( $i$ ) is a float, the floating remainder is compared with random number to determine whether to use NREPEAT=int(SIMLIB\_NREPEAT) or int(SIMLIB\_NREPEAT)+1. If NREPEAT=0, the SIMLIB entry is skipped.

As an example consider a  $\cos^5(b)$  profile,

```
DNDB:  COSBPOLY  0,0,0,0,0,1
```

With default “SIMGEN\_NREPEAT: 1” using each SIMLIB entry once, only  $\int_0^1 x^5 = 1/6$  of the (isotropic) SIMLIB entries are processed. However, with “SIMGEN\_NREPEAT: 100”, SIMLIB entries with  $|\cos(b)| > 0.4$  (60%) have SIMLIB\_NREPEAT( $i$ )  $> 1$  and thus are processed. A caveat is to generate enough events to sample most of the SIMLIB; e.g., if NGENTOT\_LC = 100 then only a few SIMLIB entries are sampled in this example.

The DNDB-rate feature specifies a relative re-weight vs.  $b$ , but the simulation has no mechanism to normalize separate simulations of different sky regions. Here we describe how to determine the relative normalization using the SIMLIB\_DUMP feature (§4.37.1). Consider three sky regions, S1, S2, S3, with solid angles  $\Omega_1$ ,  $\Omega_2$ ,  $\Omega_3$ , and each with a separate SIMLIB-cadence file. Running the simulation with an LCLIB model and the SIMLIB\_DUMP option results in a calculation and screen-dump of the average weight over the SIMLIB:  $\bar{w}_1 = [\sum_i \text{DNDB}_i] / \text{NLIBID}_1$ , and similarly for  $\bar{w}_2$  and  $\bar{w}_3$ . The sum over  $i = 1, \text{NLIBID}$  runs over each entry in the SIMLIB file. The NGENTOT\_LC values to generate are

$$\text{NGENTOT\_LC} = N\Omega_1\bar{w}_1 \quad (\text{S1})$$

$$\text{NGENTOT\_LC} = N\Omega_2\bar{w}_2 \quad (\text{S2})$$

$$\text{NGENTOT\_LC} = N\Omega_3\bar{w}_3 \quad (\text{S3})$$

where  $N$  is an arbitrary number setting the global normalization.

## 4.25 Simulating a SPECTROGRAPH

As described in §3.2, a SPECTROGRAPH instrument can be defined in a text file and then ingested into a kcor file. While the photometric (broadband) fluxes and SNR are computed from observational information (ZP,PSF,SKY), spectral SNR-vs- $\lambda$  are stored in the kcor file and read by the simulation. Thus, users must estimate spectral SNR properties with an external calculator. There are two methods for simulating spectra. First, the SPECTROGRAPH can be included in the SIMLIB file as described in §4.7.2. This method results in spectra at fixed MJD values regardless of the explosion date. Since spectroscopic programs tend to target SNe based on the time of peak brightness ( $t_0$ ), there is a second method to simulate spectra within arbitrary time windows with respect to  $t_0$  (§4.25.2).

Here are few warnings:

- works for the following models: SALT2, NON1ASED, FIXMAG, BYOSED (WARNING: does not work for SIMSED)
- if true flux is negative, it is suppressed in the output. So beware of spectroscopic wavelength holes, particularly at early epochs and the UV. To replace negative fluxes with zero, set GENMODEL\_MSKOPT=16.
- there are no SNANA programs which read the simulated spectra.
- Units:  $dF/d\lambda$  , erg/s/cm<sup>2</sup>/Å.

For TEXT formatted data files (FORMAT\_MASK: 2), the spectra are appended to the ascii file for each SN; search for “SPECTRUM\_” keys. For FITS format (FORMAT\_MASK: 32), a separate \*SPEC.FITS file is created with two tables as follows:

TableName	Ncol	column names
-----		
SPECTRO_HEADER	9	SNID MJD Texpose SNR_COMPUTE LAMMIN_SNR LAMMAX_SNR
		NBIN_LAM PTRSPEC_MIN PTRSPEC_MAX
SPECTRO_FLUX	5-6	LAMMIN LAMMAX FLAM FLAMERR SIM_FLAM SIM_WARP

The SPECTRO\_HEADER table provides a one-row summary for each spectrum: 1) SNID is the object ID, 2) MJD is the spectrum date, 3) Texpose is the exposure time (sec), 4) SNR\_COMPUTE is computed SNR, or -9 if SNR-option not used, 5,6) LAMMIN\_SNR, LAMMAX\_SNR is the observed  $\lambda$ -range whose flux-sum corresponds to SNR\_COMPUTE, 7) NBIN\_LAM is the number of  $\lambda$  bins (see comment above about suppressing negative fluxes), 8,9) PTRSPEC\_MIN, PTRSPEC\_MAX are pointers to extract the spectrum from the SPECTRO\_FLUX table.

The SPECTRO\_FLUX table contains information for every spectral bin for every SN: min and max wavelength, FLAM ( $dF/d\lambda$ ), its uncertainty FLAMERR, and the generated (true) flux, SIM\_FLAM. If a WARP\_SPECTRUM key is used, there is an extra SIM\_WARP column; it is multiplied by 1000 and stored as short int. After the last wavelength bin of a spectrum in the SPECTRO\_FLUX table, the next row is an end-of-spectrum marker containing “777 -777 -777 0”; this marker should be checked to ensure correct parsing.

The first table is small, and should read quickly and stored in memory for quick access. The 2nd (SPECTRO\_FLUX) table can be very large (few GB), so beware of memory storage. To avoid memory issues, each spectrum can be read quickly from SPECTRO\_FLUX table using pointers in the SPECTRO\_HEADER table.

#### 4.25.1 Spectral MJD-Windows or Sequences

Spectra can be generated within MJD windows or with a cadence:

```
TAKE_SPECTRUM:  MJD(59400:59407)    TEXPOSE_ZPOLY(1200)    # random within week
TAKE_SPECTRUM:  MJD(59400:59600:20) TEXPOSE_ZPOLY(1200)    # every 20 days

# define different exposure time in each field
TAKE_SPECTRUM(SHALLOW): MJD(59400:59407)  TEXPOSE_ZPOLY(800)
TAKE_SPECTRUM(DEEP):    MJD(59400:59407)  TEXPOSE_ZPOLY(1600)
```

The MJD argument defines either i) a pre-defined calendar window from which to select a random MJD, or ii) a pre-defined calendar sequence; e.g., MJD(59400:59600:20) defines 11 spectra, one every 20 days. The TEXPOSE\_ZPOLY key defines a 1200 sec exposure time; see §4.25.2 for more details.

The latter two keys define field-dependent exposure times for SHALLOW and DEEP fields. Beware that an invalid field name (e.g., typing mistake) results in no spectra without any warnings.

#### 4.25.2 Spectral Time-Windows Relative to Peak Brightness

In the sim-input file, spectroscopic exposure times can be assigned with TAKE\_SPECTRUM keys as follows:

```
TAKE_SPECTRUM:  TREST(-12:-10) TEXPOSE_ZPOLY(2000,500)
TAKE_SPECTRUM:  TOBS(-7:7)     TEXPOSE_ZPOLY(600,200,-3)
TAKE_SPECTRUM:  TREST(0:2)     TEXPOSE_ZPOLY(1000)
TAKE_SPECTRUM:  TREST(10:12)   TEXPOSE_ZPOLY(1500:2500,500)
TAKE_SPECTRUM:  HOST           TEXPOSE_ZPOLY(1200)

# field-dependent exposure time
TAKE_SPECTRUM(SHAL): TREST(0:2)    TEXPOSE_ZPOLY(1000)
TAKE_SPECTRUM(DEEP): TREST(0:2)    TEXPOSE_ZPOLY(2000)
```

Each TREST argument defines a 2-day rest-frame window from which to randomly select a spectroscopic MJD. The TOBS argument defines a 2-week observer-frame window from which to randomly select a spectroscopic MJD. The TEXPOSE\_ZPOLY key defines the exposure time (seconds) as a polynomial function of redshift. The TREST exposure times are  $2000 + 500z$  sec (10-12 days before peak),  $600 + 200z - 3z^2$  sec (7 days before peak), 1000 sec (near-peak),  $[1500 : 2500] + 500z$  sec (10-12 days after peak).

The values in parentheses can be float or integer: e.g., TREST(-2.5:2.5). Beware that no blank spaces are allowed inside the (). The colon separates a range, while commas separate a list; if you use the wrong punctuation, the simulation will abort. A range for a polynomial coefficient (4th example above) results in a randomly selected coefficient. Arbitrary polynomial orders are specified with comma-separated values; 1st value is constant term, 2nd value is linear term, etc ... Finally, the HOST argument results in a host spectrum based on HOSTLIB\_FILE and HOSTLIB\_SPECBASIS\_FILE. HOST spectra have MJD = -9 in the data files.

The template exposure time is defined in the SIMLIB file with the key TEMPLATE\_TEXPOSE\_SPECTROGRAPH.



Rather than pre-defining exposure times, the exposure time can be computed from a requested SNR value. The `TREST` and `TOBS` arguments are the same as in the previous example. `SNR_ZPOLY` specifies the requested SNR as a polynomial function of redshift. In the first pre-peak example,  $\text{SNR} = 20 - 5z$ , allowing the SNR to degrade with increasing redshift in order to reduce exposure time. The third argument, `SNR_LAMREST`, specifies the rest-frame wavelength range for which SNR is defined: for each event, the observer wavelength range is  $5000(1+z) \text{ \AA}$  to  $6000(1+z) \text{ \AA}$ . The third block of arguments shows that SNR can be defined for observer-frame  $\lambda$ -ranges using `SNR_LAMOBS`.

When `SNR_ZPOLY` keys are defined, the SNR and  $T_{\text{expose}}$  information is automatically added to the `SIMGEN_DUMP` file (§4.37.2). This allows checking  $T_{\text{expose}}$  vs. redshift, or vs any other quantity allowed in the one-row-per-SN summary.

```
# 1) rest-frame epoch, rest-frame SNR def
TAKE_SPECTRUM:  TREST(-12:-10) SNR_ZPOLY(20,-5)  SNR_LAMREST(5000:6000)
TAKE_SPECTRUM:  TREST(0:2)      SNR_ZPOLY(20)     SNR_LAMREST(5000:6000)
TAKE_SPECTRUM:  TREST(10:12)    SNR_ZPOLY(20,-2)   SNR_LAMREST(5000:6000)

# 2) obs-frame window, rest-frame SNR def
TAKE_SPECTRUM:  TOBS(-7:7)      SNR_ZPOLY(20)     SNR_LAMREST(5000:6000)

# 3) rest-frame epoch, obs-frame SNR def
TAKE_SPECTRUM:  TREST(-3:3)     SNR_ZPOLY(20)     SNR_LAMOBS(8000:10000)
TAKE_SPECTRUM:  TREST(-3:3)     SNR_ZPOLY(20)     SNR_LAMOBS(13000:15000)

#4) host spectrum
TAKE_SPECTRUM:  HOST            SNR_ZPOLY(20)     SNR_LAMOBS(3000:5000)
TAKE_SPECTRUM_HOSTFRAC:  0.1  # add 10\% of FLAM(host) to each SN spectrum
TAKE_SPECTRUM_HOSTSNFRAC: 0.1  # scale FLAM(HOST) so Sum(HOST)/Sum(SNPEAK) = 0.1

TAKE_SPECTRUM:  TEMPLATE_TEXPOSE_SCALE(1.2)
```

There are two methods to introduce host contamination in SN spectra. The first method, `TAKE_SPECTRUM_HOSTFRAC`, adds a specific fraction of host spectrum to the SN spectrum; this option depends on correct normalization of host spectrum. The 2nd method (`TAKE_SPECTRUM_HOSTSNFRAC`) scales the host normalization relative to the SN at peak brightness; the correct host normalization is not necessary because  $dF_{\text{host}}/d\lambda$  is scaled by  $S_{\text{host}}$  such that

$$\text{HOSTSNFRAC} = \frac{S_{\text{host}} \int d\lambda [dF_{\text{host}}/d\lambda]}{\int d\lambda [dF_{\text{peak}}/d\lambda]}, \quad (27)$$

where  $dF_{\text{peak}}/d\lambda$  is the SN spectrum at peak brightness, and the integration is over the spectrograph wavelength range in which both  $F_{\text{host}}$  and  $F_{\text{peak}}$  are defined.

There are two methods to define the template exposure time. First is to defined a fixed exposure time in the `SIMLIB` file with the key `TEMPLATE_TEXPOSE_SPECTROGRAPH`. The second option is defined in the example above with

```
TAKE_SPECTRUM:  TEMPLATE_TEXPOSE_SCALE(1.2)
```

which sets the template exposure time to be 20% longer than that used at the epoch nearest peak brightness. The template exposure time and noise are computed for each SN along with the search exposure times. While the search exposure time varies with each epoch to acquire the specified SNR, the template exposure time is the same for all epochs. This key overrides the `TEMPLATE_TEXPOSE_SPECTROGRAPH` key in the `SIMLIB` file.

To turn off all spectra without commenting or removing all of the `TAKE_SPECTRUM` keys,  
`snlc_sim.exe <inputFile> TAKE_SPECTRUM NONE`

WARNING: can use either the `TAKE_SPECTRUM` keys in sim-input file, or the `SPECTROGRAPH` keys in the `SIMLIB` file; using both results in an abort.

### 4.25.3 Calibration Warp vs. Wavelength

Smooth spectral mis-calibration can be defined as a polynomial function of wavelength using the sim-input `WARP_SPECTRUM` key as follows:

```
WARP_SPECTRUM:  LAMPOLY(1,1.0E-5)
TAKE_SPECTRUM:  TREST(-12:-10)  TEXPOSE_ZPOLY(2000,500,-20)
TAKE_SPECTRUM:  TREST(0:5)  SNR_ZPOLY(20:30,-5)  SNR_LAMREST(5000:6000)

WARP_SPECTRUM:  LAMPOLY(1,-1.0E-5:1.0E-5)
TAKE_SPECTRUM:  TREST(10:12)  TEXPOSE_ZPOLY(2000,500)
```

The first `LAMPOLY` argument above is a multiplicative calibration warp of  $dF/d\lambda \rightarrow dF/d\lambda \times (1 + 10^{-5}\lambda)$ , and it is applied to the first two `TAKE_SPECTRUM` keys. The 2nd `LAMPOLY` argument specifies a warp range with a slope ( $dWARP/d\lambda$ ) randomly selected between  $-10^{-5}$  and  $+10^{-5}$ ; this random warp is applied to the 3rd `TAKE_SPECTRUM` key. Analogous to the `TEXPOSE_ZPOLY` and `SNR_ZPOLY` arguments, the `LAMPOLY` argument can include an arbitrary polynomial order defined with more comma-separated terms. The warping is applied only to the measured  $dF/d\lambda$  (`FLAM` column in output); the true  $dF/d\lambda$  is not warped (`SIM_GENFLAM`).

#### 4.25.4 Field-Dependent PreScale for SN Spectra

Since SN spectra are typically limited to a subset of events, field-dependent pre-scales for SN spectra can be specified in two distinct ways. First is a global prescale per field, such as:

```
# SN spectra for half of SHALLOW events
  TAKE_SPECTRUM_PRESALE: SHALLOW/2

# SN spectra for 1/4.2 of shallow and 1/2.05 of deep
  TAKE_SPECTRUM_PRESALE: SHALLOW/4.2+DEEP/2.05
```

The prescale is applied per event, not per spectrum. Thus if 6 SN spectra are defined per event, the prescale results in each event having either 6 SN spectra, or none. While there is no host spectrum prescale, there is a zHOST efficiency file (§4.18.3).

The second prescale method allows controlling the prescale as a function of phase and exposure time (or SNR), even for the same field:

```
TAKE_SPECTRUM(DEEP/4):   TREST(-3:3)      TEXPOSE_ZPOLY(1000)
TAKE_SPECTRUM(DEEP/8):   TREST(-3:3)      TEXPOSE_ZPOLY(2000)
TAKE_SPECTRUM(DEEP/10):  TREST(-10:-5)    TEXPOSE_ZPOLY(2500)
TAKE_SPECTRUM(DEEP/15):  TREST(-10:-5)    TEXPOSE_ZPOLY(3500)

TAKE_SPECTRUM(SHALLOW/2): TREST(-3:3)     TEXPOSE_ZPOLY(500)
TAKE_SPECTRUM(SHALLOW/5): TREST(-3:3)     TEXPOSE_ZPOLY(800)
```

The TREST and TEXPOSE\_ZPOLY keys can be replaced with other valid keys at that location, and the integer prescales shown here can be replaced with floats (e.g., DEEP/4.23). This option is useful to study multiple spec-follow up strategies with a single generation of the simulation, provided that the FIELD-dependent exposure times are unique for each TAKE\_SPECTRUM key.

#### 4.25.5 SPECTROGRAPH Options

The SPECTROGRAPH\_OPTMASK key in the sim-input file can be used as follows:

```
SPECTROGRAPH_OPTMASK: 1   # turn off lambda smearing
SPECTROGRAPH_OPTMASK: 2   # double LAMSIGMA smearing
SPECTROGRAPH_OPTMASK: 4   # flux only in center lambda bin (delta function)
SPECTROGRAPH_OPTMASK: 8   # SNR -> SNR x 100
SPECTROGRAPH_OPTMASK: 16  # TREF -> TREF x 100 (template expose time)
SPECTROGRAPH_OPTMASK: 32  # only template noise
SPECTROGRAPH_OPTMASK: 64  # for SNR_REQUEST, extrap TEXPOSE if needed
SPECTROGRAPH_OPTMASK: 2048 # skip spectra
SPECTROGRAPH_OPTMASK: 32768 # turn off all noise in spectra
SPECTROGRAPH_OPTMASK: 6   # flux only in center bin & LAMSIGMA**=2

SPECTROGRAPH_SCALE_TEXPOSE: 2.4 # scale exposure times by 2.4
SPECTROGRAPH_SCALE_SNR:      0.9,0.02,-.003 # SNR *= [0.9 + 0.02*lam - 0.003*lam^2]
```

Multiple options can be combined by adding values as illustrated by the last option above with SPECTROGRAPH\_OPTMASK=6. The default is SPECTROGRAPH\_OPTMASK=0, and the options above are intended for testing and debugging.

OPTMASK+=64 is a little tricky, so here is added explanation. By default, the exposure time is bounded by the min and max `TEXPOSE_LIST` values in the spectrograph table (Fig. 3). For example, suppose `SNR_MAX=20` at the max exposure time of `TEXPOSE=2000`, and the user requests `SNR_REQUEST=40` (via `TAKE_SPECTRUM` key); the default behavior is to return `TEXPOSE=2000` and `SNR=20` to avoid exposing for longer than what has been defined. With `OPTMASK+=64`, however, the exposure time is extended to give the requested SNR:

$$\text{TEXPOSE} = \text{TEXPOSE\_MAX} + [\text{SNR\_REQUEST}/\text{SNR\_MAX}]^2 \quad (28)$$

and a similar equation is used for requested SNR below the minimum-defined `SNR_MIN`.

The last option (`SCALE_TEXPOSE`) is a continuously tunable knob to scale the exposure times (for search and template).

#### 4.25.6 Simulating a Single High-S/N Spectrum

A single high-S/N spectrum (rest-frame) can be simulated at arbitrary redshift using the `NON1ASED` model (§9.6), and defining sim-input key `PATH_NON1ASED` to use a private `NON1ASED` directory. Instead of defining an SED time series covering a few-month range of epochs, the `NON1ASED` file can contain a single spectrum at one epoch. The `DAY` column can have any value since internally the simulation will shift the SED times such that `DAY=0` at max flux. Hence by definition, a single epoch will have `DAY=0`. Recall that uniform wavelength binning is required.

To generate one spectrum, the sim-input key `GENRANGE_PEAKMJD` should be defined as a  $\delta$ -function landing exactly on any `SPECTROGRAPH` MJD in the `SIMLIB` file. See §4.7.2 for how the `SPECTROGRAPH` is defined in the `SIMLIB`. It is also recommended to set “`GENRANGE_TREST: -1 1`” to remove photometry output from epochs with an undefined model. The simulated spectrum and photometry is artificially defined to appear at “peak,” but they really correspond to the epoch from which the input spectrum was extracted. As a sanity check, the simulated mag should be compared with that from the input light curve.

Several spectra can be included in the `NON1ASED` model. For example, if there are 8 SEDs, then setting “`NGENTOT_LC: 8`” will generate each spectrum once. If several spectra come from the same SN, each spectrum should be defined as a separate SED file.

#### 4.25.7 Output Observer-Frame Model SED

To output the true observer-frame model SED at each observation to the data files (`TEXT` for `FITS` format), set the following sim-input key

```
LAMBIN_SED_TRUE:      10                # wavelength bin size (Å) for true SED output
LAMRANGE_SED_TRUE:    <lammin> <lammax> # optional; defaults explained below
VERIFY_SED_TRUE:      1                # diagnostic dump
```

This option is unique because a spectrograph need NOT be defined in the `kcor/calib` file. The simulation internally defines a spectrograph with `LAMBIN_SED_TRUE` Å bin size and `SNR~105`. The simulation creates an ideal spectrum, corresponding to the true SED, for each observation that occurs at least 1 hr later than the previous observation. BEWARE: to avoid excessively large output data files, define reasonable `GENRANGE_TREST`, `NGENTOT_LC`, and `LAMBIN_SED_TRUE`.

The default true-SED wavelength range is as follows. Min-wave is minimum of blue edge for bluest filter or model-SED. Max-wave is maximum of red edge for reddest filter or model-SED. The default range can be overwritten by sim-input key `LAMRANGE_SED_TRUE`, and this range can only extend the wavelength range beyond that defined by the bluest & reddest filter edge; if `LAMRANGE_SED_TRUE` defines a more strict wavelength range, the sim will abort.

## 4.26 Simulating Rise-Time Variations

The rise-time for any model can be adjusted using the following sim-input parameters:

```
GENPEAK_RISETIME_SHIFT:  2.3      # shift at -18 days
GENSIGMA_RISETIME_SHIFT: 0.6 0.6
GENRANGE_RISETIME_SHIFT: -4. 4.
```

In the above example, the rest-frame rise-time at each epoch is increased by  $2.3 \times T_{\text{rest}}/18$  days with a Gaussian sigma of 0.6 days, and shifts past  $\pm 4$  days are excluded. The rise-time adjustments can be used, for example, to generate a double-stretch model by simulating two separate samples, each with a different rise-time shift.

## 4.27 Simulating Atmosphere Effects

The simulation of atmospheric effects includes differential chromatic refraction (DCR) and its effect on measured coordinates and magnitudes. The impact on spectra is not included. The DCR effects are enabled with sim-inputs

```
ATMOSPHERE_OPTMASK: 1  # simulate DCR effect on coordinates
ATMOSPHERE_OPTMASK: 2  # simulate DCR effect from PSF shape
ATMOSPHERE_OPTMASK: 3  # simulate both DCR effects
ATMOSPHERE_OPTMASK: 513 # 1+512: 512-> write [VERSION].DCR summary file

ATMOSPHERE_SEDSTAR_FILE: [sed_fileName]
ATMOSPHERE_DCR_COORDRES_POLY: a0,a1,... # poly for coordRes(asec) vs. PSF_FWHM/SNR
ATMOSPHERE_DCR_MAGSHIFT_POLY: a0,a1,a2,.. # poly for magShift vs. fracPSF shift
racPSF
```

The geo-location (degrees) and mountain elevation (meters w.r.t. sea level) of the instrument must be specified in the \$SNDATA\_ROOT/SURVEY.DEF file; e.g.,

```
SURVEY:  LSST    12    geo:-30.244639,-70.749417,2647  # lat,long,elevation
```

The sim aborts if `ATMOSPHERE_OPTMASK > 0` and the geolocation is not provided.

While the default simulation defines the measured RA,DEC to be their exact values without measurement noise, `ATMOSPHERE_OPTMASK > 0` changes the sim to determine the following for each observation: i) measured RA,DEC using coordinate-smear based on a polynomial function of `PSF_FWHM/SNR` (`ATMOSPHERE_DCR_COORDRES_POLY`), and ii) calculated mag-shift based on a polynomial function of fractional PSF-shift (`ATMOSPHERE_DCR_MAGSHIFT_POLY`). These polynomial functions are computed externally from SNANA, such as from studies using `GALSIM`.

The average reference star SED (`ATMOSPHERE_SEDSTAR_FILE`) is used to compute a reference SED-weighted wavelength in each filter band ( $\bar{\lambda}_{\text{refStar}}$ ), and DCR coordinate shifts are defined as the shift-difference between the SN SED-weighted wavelength and  $\bar{\lambda}_{\text{refStar}}$ . The RA,DEC shift for each observation is defined w.r.t. the filter-averaged RA,DEC over all observations with `SNR > 3`.

The simulation of atmosphere effects automatically appends the following columns in the photometry table per observations:

```
dRA          # RA - RA_AVG_FILTER (arcsec)
dDEC         # DEC - DEC_AVG_FILTER (arcsec)
AIRMASS      # uses telescope geo-location in SURVEY.DEF file
SIM_DCR_dRA  # calculated RA shift from DCR (arcsec)
SIM_DCR_dDEC # calculated DEC shift from DCR (arcsec)
SIM_DCR_dMAGOB # calculated mag shift from fractional PSF-shift
```

The 512-bit of `ATMOSPHERE_OPTMASK` results in writing an extra auxiliary table file, `[VERSION].DCR`, that contains a summary for each observation of DCR-related information that is easier to access compared to data files.

## 4.28 Altering Input SEDs

The options in this section work for NON1ASED and SIMSED models.

### 4.28.1 Simulating PEAKMJD or Time of Explosion

For all models, the default light-curve time window is defined by its time of peak brightness, or PEAKMJD. In particular, the sim-input key

```
GENRANGE_PEAKMJD: <MJDmin> <MJDmax>
```

specifies an MJD window to randomly generate PEAKMJD.

For triggered events, such as from gravity waves (LIGO) or neutrinos (ICECUBE), it is more practical to simulate sources based on time of explosion instead of PEAKMJD. For NON1ASED and SIMSED models, a time of explosion can be specified with

```
MJD_EXPLODE: <MJD>
OPTMASK_TOSHIFT_EXPLODE: 0 # no shift: model T=0 at explosion (default)
or
OPTMASK_TOSHIFT_EXPLODE: 1 # T_explode at .01*FLUXMAX
or
OPTMASK_TOSHIFT_EXPLODE: 2 # T_explode at .001*FLUXMAX
```

Note that the time of explosion is not always observed, and thus can be ambiguous for data-derived template models. For models with well-defined time of explosion at DAY=0, the default OPTMASK=0 adds no shift. OPTMASK=1 computes explosion time to be the epoch when the rest-frame SED flux, in any wavelength bin, falls below 1% of the maximum flux. OPTMASK=2 requires less than 0.1% of max flux. Other options based on rise-time shape fits may be added later.

### 4.28.2 Extrapolating UV Flux

At sufficiently high redshift, broadband fluxes in UV filters are not defined and thus not included in the output data files. For example, consider a UV filter spanning 3000-4000Å, and input SEDs starting at 2000 Å. For redshifts  $z > 3000/2000 - 1 = 0.5$ , the UV flux depends on the undefined SED range below 2000 Å, and therefore this band is suppressed in the output. Missing UV bands are usually harmless, but this artifact can potentially fool classifiers training on data, or provide un-intended clues in a data challenge.

Since far-UV fluxes are typically well below the sky noise, simply reporting a random sky noise would be good enough. The simulation includes a somewhat better option, which is to extrapolate the UV flux down to arbitrary wavelength. The sim-input key is

```
UVLAM_EXTRAPFLUX: 500 # extrapolate SED flux down to 500 Å.
```

Defining  $F_\lambda$  to be the flux at a particular wavelength,  $F_{2000}$  is the edge-flux at 2000Å. The UVLAM option above will extrapolate the flux to be linearly decreasing so that  $F_{500} = 0$ . This option extends the valid UV-filter redshift range from 0.5 to  $3000/500 - 1 = 5$ . Finally, users are cautioned to check that the UV flux is indeed negligible at high redshifts.



## 4.29 NGEN keys

There are three “NGEN” keys to control the number of generated events:

```
NGEN_LC:      1000  ! default is zero
or
NGENTOT_LC: 1000  ! default is zero

NGEN_SCALE: 3          ! scale all models: default is 1
NGEN_SCALE_SCALE: 3    ! scale NON1A and SIMSED models: default is 1
```

The first key, `NGEN_LC`, specifies the number of SN generated and written out after trigger and selection cuts. Thus if the simulated efficiency is 10% and `NGEN_LC` = 1000 as shown in the example above, the simulation will generate 10,000 SNe in order to get 1000 SN written out. In short, SNe are generated until 1000 are written out, regardless of the efficiency. The sim-input key `EFFERR_STOPGEN` prevents an infinite loop if the efficiency is near zero (§4.19).

The second key, `NGENTOT_LC`, specifies the total number of SNe to generate regardless of the efficiency. Thus in the example above with `NGENTOT_LC` = 1000 and a 10% efficiency, only about 100 SNe are written out. If the efficiency is very low, it is possible that zero events are written out. This option is useful to generate statistics corresponding to a particular SN rate and survey length (§4.23). Only one of the `NGEN_LC` or `NGENTOT_LC` keys can be set; if both are set the simulation will abort.

Finally, `NGEN_SCALE` can be used to scale whichever `NGEN` key is set. This feature is useful, for example, to change the statistics on several independent simulated samples while preserving the relative ratios between samples.

## 4.30 “Perfect” Simulations

To make detailed numerical crosschecks, there is a “perfect” option to simulate light curves with  $\times 10^4$  nominal photostatistics, no galactic extinction (Milky Way and host), and no intrinsic mag-smearing. The light curve fitter should determine the shape and color parameters with very high precision, and the cosmology fitter should determine cosmological parameters that agree well with the input. This option is invoked with

```
GENPERFECT: 1
```

and it automatically overrides the relevant parameters so that you need not change your sim-input file. The top of the sim-README file summarizes the modified quantities. You can also unselect some of the “PERFECT” options by specifying a bit-mask as the `GENPERFECT` argument. To see the bit-mask options,

```
snlc_sim.exe mysim.input GENPERFECT -1
```

will list the current bit-mask options and then quit without generating any SNe. You can then run, for example,

```
snlc_sim.exe mysim.input GENPERFECT 6 # = 2+4 (bits 1 & 2)
```

which selects the  $\times 10^4$  exposure-time option (bit 1) and turns off intrinsic mag-smearing (bit 2), but leaves Galactic and host-galaxy extinction as defined in your sim-input file.

### 4.31 Generating Redshift ( $z_{\text{hel}}$ , $z_{\text{cmb}}$ ) and Distance

An overview of redshift-related inputs are as follows:

```

GENRANGE_REDSHIFT:  0.01 1.0  # ZCMB-gen range
GENSIGMA_REDSHIFT:  0.001      # Gaussian z-error      (default=0)
GENBIAS_REDSHIFT:   1.0E-4     # global redshift bias  (default=0)
VEL_CMBAPEX:        370        # CMB dipole, (default = 370 km/sec)

```

The CMB redshift is generated first, and then the RA & DEC from the SIMLIB file is used to compute  $z_{\text{hel}}$  with  $\ell = 264.14$  deg,  $b = 48.26$  deg, and default VEL\_CMBAPEX=370.

To generate  $z_{\text{hel}} = z_{\text{cmb}}$  (sometimes useful for debugging), set GENSIGMA\_VPEC (§4.31.1) and VEL\_CMBAPEX to zero in the sim-input file, or use the command-line override “VEL\_CMBAPEX 0 GENSIGMA\_VPEC 0”.

The simulated/true  $z_{\text{cmb}}$  range is defined by GENRANGE\_REDSHIFT, and the probability vs. redshift is defined by the rate model (§4.23). The true  $z_{\text{hel}}$  is transformed from  $z_{\text{cmb}}$  using the sky coordinates and a peculiar velocity ( $v_{\text{pec}}$ , §4.31.1). The measured  $z_{\text{hel}}$  (REDSHIFT\_HELIO in data files) includes measurement noise drawn from a Gaussian with  $\sigma_z = \text{GENSIGMA\_REDSHIFT}$ . The measured  $z_{\text{cmb}}$  (REDSHIFT\_CMB in data files) is computed from the measured  $z_{\text{hel}}$  using the sky coordinates. The true quantities (without measurement noise) are stored in the data files as SIM\_REDSHIFT\_CMB and SIM\_REDSHIFT\_HELIO. Note that SIM\_REDSHIFT\_HELIO includes the peculiar velocity, and therefore the SIM\_REDSHIFT\_XXX quantities will not transform under the usual cmb $\leftrightarrow$ heliocentric transformations unless  $v_{\text{pec}} = 0$ .

It is important to pay attention to redshift ranges in different parts of the analysis. While the simulation generates a  $z_{\text{cmb}}$  range, the analysis programs (snana.exe and snlc\_fit.exe) select a redshift range based on  $z_{\text{hel}}$  because  $z_{\text{hel}}$  is used for lightcurve fitting (see &SNLCINP namelist parameter CUTWIN\_REDSHIFT). Finally, the cosmology fitting program is likely to apply cuts on the observed  $z_{\text{cmb}}$ . To be on the safe side, one should generate a slightly larger  $z_{\text{cmb}}$ -redshift range compared to the anticipated analysis cuts. The extended generation range should allow for  $v_{\text{pec}}$  variations<sup>16</sup> and measurement noise.

Finally, rather than simulating a  $z$ -bias with GENBIAS\_REDSHIFT, a  $z$ -bias can be added in the analysis/fitting program (data or sim) with &SNLCINP parameters shown in § 5.24.

The simulated luminosity distance is computed as

$$D_L = (1 + z_{\text{hel}})r(z_{\text{cmb}}), \quad r(z_{\text{cmb}}) \equiv (c/H_0) \int_0^{z_{\text{cmb}}} dz/H(z). \quad (29)$$

To override either min or max redshift,

```

snlc_sim.exe <inputFile> GENRANGE_REDSHIFT .05 -1 # (a) increase zmin if < 0.05
or
snlc_sim.exe <inputFile> GENRANGE_REDSHIFT -1 1.3 # (b) decrease zmax if > 1.3

```

and setting the  $-1$  value in a sim-input file results in abort. Note that the half-range update is applied *only* if it is more strict than the original value. For example, if  $z_{\text{min}}=0.06$  in the sim-input file, the first example above makes no change; but if  $z_{\text{min}}=0.04$  in the sim-input file, then  $z_{\text{min}}$  is increased to 0.05. A usage example is a new HOSTLIB with min galaxy redshift above the minimum defined by GENRANGE\_REDSHIFT. To avoid abort, add global command (a) in either the command-line override, submit\_batch\_jobs, or pippin.

<sup>16</sup>Beware that the maximum  $v_{\text{pec}}$ -redshift variation is  $(1+z)370/c$  and not just  $370/c$ .

### 4.31.1 Generating Peculiar Velocity

There are two methods to simulate peculiar velocity. The first method is to define a Gaussian sigma for the true profile and for the measured precision in the sim-input file,

```
GENSIGMA_VPEC:  300    # true sigma(v_pec), km/sec  (default=0)
VPEC_ERR:       150    # error on measured/computed VPEC (default=0)
```

A Gaussian-random peculiar velocity ( $v_{\text{pec}}$ ) is defined by `GENSIGMA_VPEC`,<sup>17</sup> and corresponds to the true scatter. `VPEC_ERR` is the error on a  $v_{\text{pec}}$  estimate (see §5.29) used for analysis. The true peculiar-velocity value is

```
SIM_VPEC = GENSIGMA_VPEC * GaussRan
```

and the “measured VPEC” reported in the data file is

```
VPEC = SIM_VPEC + VPEC_ERR*GaussRan  # VPEC_ERR <  GENSIGMA_VPEC
VPEC = 0                             # VPEC_ERR >= GENSIGMA_VPEC
```

For high- $z$  samples that do not provide a  $v_{\text{pec}}$  estimate, set `VPEC_ERR = GENSIGMA_VPEC` as a flag to skip the VPEC estimation,

The estimated `VPEC` and `VPEC_ERR` are written to the data files for analysis, but they are not used by the sim to modify the reported redshift; this is analogous to providing Galactic extinction `MWEBV` without correcting the reported fluxes. The lightcurve fitting program (`snlc_fit.exe`) outputs a Hubble diagram redshift `zHD` that includes a VPEC correction, and the uncertainty `zHDERR` includes `VPEC_ERR`.

The first method has the advantage of simplicity, but does not account for large-scale correlations and bulk flows. To account for such effects, the second method reads a `VPEC` column from the `HOSTLIB` if the 512-bit is set in `HOSTLIB_MSKOPT` (§4.22.1). The associated uncertainty can be defined in two ways: 1) a separate `VPEC_ERR` column defining a distinct uncertainty for each host, or 2) fixing the uncertainty with `HOSTLIB` header key “`VPEC_ERR: <vpecErr>`.” The output `README` includes summary information as follows:

```
!!!!!! TO DO: fix this to account for README refactor !!!!!!!
```

Note that mixing the two methods is not allowed; e.g, the sim will abort if the 512-bit is set for `HOSTLIB_MSKOPT` while `GENSIGMA_VPEC` or `VPEC_ERR` is defined in the sim-input file.

---

<sup>17</sup>SNANA users would be grateful if somebody provides code to compute  $v_{\text{pec}}$  based on RA, DEC, and  $z_{\text{cmb}}$ .

## 4.32 Population Parameters: Stretch, Color, Dust

For SNIa models, the stretch and color parameters are each drawn from a probability distribution function (PDF), also called a parent population. The PDF is a best estimate of the complete population without selection biases. Examples: for SALT2, a PDF is needed for color ( $c$ ), stretch ( $x_1$ ), and possibly host-galaxy dust parameters  $A_V$  and  $R_V$ ; MLCS2k2 needs  $A_V$ ,  $R_V$ , and shape-parameter ( $\Delta$ ); SNCC models need  $A_V$  and  $R_V$ .

There are two methods for describing each PDF: i) analytical function using asymmetric Gaussian (AG) or exponential, and ii) multi-dimensional map including arbitrary dependence on HOSTLIB parameters. AG sim-inputs are shown in §9.3 for the SALT2 model, and exponential models for extinction ( $A_V$ ) are shown in §9.1.

An illustration of a map with SALT2x1 dependence on host-galaxy mass is shown in Fig. 14. Multiple maps can be defined in the same file, where a new VARNAMES key is the start of each map. Any HOSTLIB parameter(s) can be included in the map. The first variable (e.g., SALT2x1) is name of the variable to be generated by the simulation; the last variable must be PROB to indicate “probability.” The simulation internally normalizes the PDF so that the max PROB value is 1.0; however, it is recommended to create properly normalized maps to simplify debugging if visual inspection of the maps is needed. A combination of AG and PDF maps can be used; e.g., AG for  $R_V$ , and PDF maps for  $x_1$  and  $c$ .

VARNAMES:	SALT2x1	LOGMASS	PROB
PDF:	-3.000	7.00	0.00387
PDF:	-3.000	7.20	0.00388
PDF:	-3.000	7.40	0.00389
etc	...		

Figure 14: Example PDF map for simulating distribution of SALT2x1 parameter.

Sim-input keys controlling PDF maps are as follows:

GENPDF_FILE:	<fileName>
GENPDF_IGNORE:	<comma-sep list of map(s) to ignore>
GENPDF_OPTMASK:	<optMask>
GENPDF_FLAT:	SALT2x1(-4:4),SALT2c(-0.4:0.5)
or	
GENPDF_FLAT:	SALT2x1(-4:4),SALT2c(-0.4:0.5),RV(1:4),AV(0:2)

Only one map-file can be specified, so all maps must reside in this file. GENPDF\_IGNORE disables a map, and allows for using an AG without creating a separate map file which excludes the relevant map. For example,

```
snlc_sim.exe <inputFile> GENPDF_IGNORE RV \
GENPEAK_RV 2.2 GENSIGMA_RV .2 .3
```

disables the RV-PDF map, and instead uses an AG for  $R_V$ : peak at 2.2,  $\sigma_{-/+} = 0.2/0.3$ . If both the analytical AG and PDF map are defined for the same parameter, the simulation will abort.

GENPDF\_FLAT forces a flat distribution for an arbitrary set of SALT2-related (x1,c) and dust-related (RV,AV,EBV) variables. Variable names are comma-separated, and the colon-separated numbers in parentheses are the min & max generated value for each variable. This option overrides other PDF options based on maps, asymmetric Gaussians (x1,c,RV), and exponential (EBV,AV).

GENPDF\_OPTMASK options:

- += 1: for HOSTLIB parameters outside map range, extrapolate instead of abort.

In addition to specifying population maps in the GENPDF\_FILE, an analytical AG map can be specified for SALT2  $\alpha$  and  $\beta$  using the same keys as in the sim-input file:

```
GENPEAK_SALT2BETA:  2.1
GENSIGMA_SALT2BETA: 0.22 0.22
GENRANGE_SALT2BETA: 0.4  3.0
```

```
GENPEAK_SALT2ALPHA:  0.15
```

The  $\beta$  distribution here is a symmetric Gaussian, and the  $\alpha$  distribution is a delta-function since the  $\sigma$  and range are not specified. Internally, the simulation sets  $\sigma_\alpha = 0.15 \times 10^{-6}$ , and the range to be  $0.15 \pm 2\sigma_\alpha$ . Both  $\alpha$  and  $\beta$  Gaussians are converted into maps as if they had been read from the GENPDF\_FILE; thus all PDF maps are processed using the same grid-interpolation code.

To use a command-line override to change the Gaussian function in the GENPDF\_FILE, the relevant map must be disabled using the GENPDF\_IGNORE key:

```
snlc_sim.exe <inputFile> GENPDF_IGNORE SALT2ALPHA  GENPEAK_SALT2ALPHA 0.16
```

### 4.33 Redshift-Dependent Parameters

Although the default simulation parameters are independent of redshift, you can specify an arbitrary  $z$ -dependence for SN-related parameters such as dust parameters  $R_V$  &  $\tau_V$ , SALT-II parameters  $\alpha$  &  $\beta$ , and the population parameters for shape, color, etc ...

The  $z$ -dependence is specified as an additive shift. If the function is simple, you can specify a polynomial function of redshift with arbitrary order. More complex functions can be specified in a file with a  $z$ -dependent map. Examples for specifying both types of parameter-shift functions are given in this file,

```
$SNDATA_ROOT/sample_input_files/SALT2/SIM_ZVARIATION.PAR .
```

To get a complete list of parameters that can have a  $z$ -dependence, type the command

```
> snlc_sim.exe mysim.input ZVARIATION_FILE 0
```

Next, copy the `SIM_ZVARIATION.PAR` above to your working area, and modify as desired. Then add the following keyword to your sim-input file,

```
ZVARIATION_FILE: SIM_ZVARIATION.PAR
```

or use the command-line override (§12.2.3). You can also change the name of the “ZVARIATION” file.

The polynomial option can be specified in the sim-input file (without a separate file) to define redshift-dependent parameters with

```
ZVARIATION_POLY: GENPEAK_VARNAM1      a0,a1,a2      # 2nd order poly
ZVARIATION_POLY: GENPEAK_VARNAM2      a0,a1,a2,a3    # 3rd order
ZVARIATION_POLY: GENSIGMA[0]_VARNAM3  a0,a1          # lo-side sigma,linear
ZVARIATION_POLY: GENSIGMA[1]_VARNAM3  a0,a1          # hi-side sigma,linear
ZVARIATION_POLY: GENSKEW[0]_VARNAM3   a0,a1,a2,a3,a4
ZVARIATION_POLY: GENSKEW[1]_VARNAM3   a0,a1,a2

# hard-coded [LEGACY] 3rd order poly still supported:
ZVARIATION_POLY: GENPEAK_VARNAM1      a0 a1 a2 a3
ZVARIATION_POLY: GENPEAK_VARNAM2      a0 a1 a2 a3
etc ...
```

Note that either the `ZVARIATION_POLY` key or the `ZVARIATION_FILE` key is allowed; specifying both results in an abort. Since populations are defined by two `GENSIGMA` values and two `GENSKEW` values, the redshift dependence is specified separately using the index in `[]` as shown above.

Beware that the function must give a shift of zero at  $z = 0$ , otherwise the simulation will abort: this ensures that the sim-input parameters are clearly defined at  $z = 0$ . For example, suppose we want `GENPEAK_SALT2c` to have the form  $-0.10 + 0.01z$ . The following illustrates the incorrect and correct sim-inputs:

```
GENPEAK_SALT2c: 0.0
ZVARIATION_POLY: GENPEAK_SALT2c -0.1,0.01 # ==> results in abort

GENPEAK_SALT2c: -0.1
ZVARIATION_POLY: GENPEAK_SALT2c 0.0,0.01 # ==> valid
```

## 4.34 Estimating PEAKMJD

The SNANA analysis & fitting programs include options for estimating PEAKMJD from the measured fluxes (§5.5.1, Fig. 15), and these options can be applied to both data and the simulation. For non-SNANA analysis codes, it may be useful to include a PEAKMJD estimate in the simulated data files, and thus alleviate the need to run `snana.exe` to extract a PEAKMJD estimate. The PEAKMJD-estimate options are

```
OPT_SETPKMJD:    16    # Fmax-clump method (default)
OPT_SETPKMJD:     8    # naive Fmax over all epochs
GENSIGMA_PEAKMJD: 3.0   $ Gauss smear (days)
```

If no options are given, the default “Fmax-clump” method is used. Other OPT\_SETPKMJD options using Bazin fits (Fig. 15) are implemented in the analysis codes, but are not supported in the simulation. Backward compatibility issue: if both GENSIGMA\_PEAKMJD and OPT\_SETPKMJD are defined, GENSIGMA\_PEAKMJD is used and OPT\_SETPKMJD is ignored. See output README file to verify method.

To check residuals with SIMGEN\_DUMP feature, add variables PEAKMJD (true value) and PEAKMJD\_SMEAR (estimate).

## 4.35 Generating Efficiency Maps

An efficiency map as a function of SN parameters may be needed as part of a fitting prior, or as part of an MC-based correction such as correcting the SN rate for the selection efficiency. The simulation can be used to generate an arbitrary efficiency map using the command

```
SIMEFF_MAPGEN.pl <SIMEFF input file>
```

and examples of the SIMEFF input file are in

```
$SNDATA_ROOT/sample_input_files/simeff_mapgen/
```

“`sntools.c`” contains functions read the generated efficiency map (`init_SIMEFFMAP`) and to evaluate the efficiency for an arbitrary set of SN parameters (`get_SIMEFF`). The efficiency is determined by multi-dimensional interpolation. Since the generation of a multi-dimensional efficiency map can be CPU intensive, this script distributes jobs on several nodes defined by the NODELIST key, and the simulation runs in a mode where there are no output files, and hence no secondary SNANA jobs are needed. Your sim-input file (specified inside the SIMEFF input file) must apply selection cuts as described in § 4.19. It is assumed that the selection efficiency does not depend on the result of the light curve fit.

The critical part of the SIMEFF input file is shown below,

#				out			
#	sim-input key			key	NBIN	MIN	MAX
#	-----						
GENVAR:	LIN	GENRANGE_MWEBV	MWEBV	2	0.0	0.3	
GENVAR:	LIN	GENRANGE_REDSHIFT	Z	23	0.05	1.15	
GENVAR:	LOG	GENRANGE_AV	AV	19	-3.0	0.6	(0.001 < AV < 4)
GENVAR:	LIN	GENRANGE_DELTA	DELTA	14	-0.5	2.1	
GENVAR:	INV	GENRANGE_RV	RV	3	0.25	0.75	(4 > RV > 1.33)



Each **GENVAR** key specifies one dimension of the multi-dimensional efficiency map. Following each **GENVAR** key is a key defining whether that variable is stored linearly (LIN), logarithmically-base10 (LOG), or as the inverse (INV). For example, the efficiency is quite linear as a function of  $1/R_V$  and hence fewer  $R_V$  bins are needed to describe the efficiency as a function of  $1/R_V$  compared to using  $R_V$ . The **GENRANGE\_XXX** key is the simulation key used to specify that particular parameter. For example, a specific value of **DELTA** is simulated using

```
snlc_sim.exe <sim-input file>  GENRANGE_DELTA -0.1 -0.1
```

All of the **GENRANGE\_XXX** commands are catenated and given as input to the simulation. The output-key is the name given in the output efficiency-map file. Any output key-name is valid, but to use this map for a fitting prior the key-names must correspond to one of the following: (i) any fit-parameter name in **snlc\_sim.exe** such as **AV**, **DELTA**, **x1**, **c**, (ii) **REDSHIFT** or **Z**, (iii) **MWEBV**.

The last three entries are the number of bins to define the efficiency map in each dimension (**NBIN**), and the min/max range for each dimension. In the above example,  $1/R_V$  is generated for values 0.25, 0.50, and 0.75 corresponding to  $R_V = 4, 2, 1.33$ , respectively. When the resulting efficiency map is used as part of a fitting prior, fit-values outside the min/max range are pulled to the edge for evaluating the efficiency. For example, if the fitting program tries to evaluate the  $\chi^2$  for **DELTA**= 2.4, the efficiency is evaluated at the boundary **DELTA**= 2.1.

Finally, one must be careful allocating appropriate resources since the computing time can be long. In the above example the total number of bins in this efficiency map is  $2 \times 23 \times 19 \times 14 \times 3 = 36708$ . If the efficiency-uncertainty (see **SIMGEN\_EFFERR** key) is set so that each simulation job takes 10 seconds, then the total computing time needed for this map is 4.2 CPU-days, or about 10 wall-clock hours with 10 cores.

## 4.36 Light Curve Output Formats

Each simulated light curve is written to the directory

```
$SNDATA_ROOT/SIM/[GENVERSION]    # default
```

or to argument of `PATH_SNDATA_SIM`, where `GENVERSION` is the user-supplied version name. For FITS format, two FITS files are created: i) a “HEADER” file containing global information for each SN (SNID, redshift, RA, etc ...) and ii) a “PHOT” file containing all of the light curves. Pointers in the HEADER file are used to extract the appropriate light curve from the PHOT file. These FITS files can be visually examined with the product “fv.” For text-output options each light curve is written to a separate file, `[GENVERSION]_SN#####.DAT`, where “#####” is a six digit identifier; the text-option is useful for testing small samples and debugging.

The output format is controlled by the sim-input keyword `FORMAT_MASK`, and the various options are described below. Note that `FORMAT_MASK` is a bit-mask so that multiple format options can be included. Either TEXT or FITS format can be selected, but not both. TEXT format is allowed only for interactive jobs; FITS format must be used for batch jobs. Here is a quick summary of the bit-mask format options,

FORMAT_MASK:	2	# TEXT format
FORMAT_MASK:	18	# 2(TEXT) + 16(RANDOM CID)
FORMAT_MASK:	26	# 2(TEXT) + 8(BLIND) + 16(RANDOM CID)
FORMAT_MASK:	32	# FITS format (default for version >= v9_82)
FORMAT_MASK:	48	# 32(FITS) + 16(RANDOM CID)
FORMAT_MASK:	+64	# compact PHOT table (remove GAIN,RDNOISE,SKYSIG_T,PSF_SIG2,PSF_RATIO,ZP_ERR)
FORMAT_MASK:	288	# 32(FITS) + 256(write filterTrans files)
FORMAT_MASK:	2080	# 32(FITS) + 2048(no SPEC.FITS, but keep VERSION.SPEC)

and the sub-sections below give more details.

### 4.36.1 FITS Format

“**FORMAT\_MASK: 32**” uses the compact binary-FITS format that is processed using the `cfitsio` library. The advantage of this format is that there are very few files to manage, reading is much faster compared to the TEXT options, FITS files are portable to any computing platform, and there are public fits-viewing utilities such as “fv.”

For data version VVV, the file `VVV.LIST` points a set of HEAD files with a one-row summary for each SN. The summary info includes the SNID, sky coordinates, redshift, Galactic extinction, host-galaxy information, and many other quantities. Each HEAD file also contains the name of the second “PHOT” file which contains the photometric light curves. All of the light curves are written sequentially to the PHOT-tables, and pointers in the HEAD file (see `PTROBS_MIN` and `PTROBS_MAX`) are used to select the appropriate rows from the PHOT table. To help catch pointer mistakes, `MJD = -777` is written after each light curve to clearly indicate the end of the light curve.

If `submit_batch_jobs` is used to generate simulations on mutiple cores, there will be one HEAD and one PHOT file per core, all gzipped. Reading a gzipped FITS file requires the memory of the entire unzipped FITS file; therefore the FITS files are not merged to reduce memory. For example, 40 1GB FITS files requires only 1GB of memory to read, while merging into one file would require 40 GB memory.

The PHOT table columns are:

```

TTYPE1  = 'MJD      '      / MJD
TTYPE2  = 'BAND     '      / single-char band label
TTYPE3  = 'FIELD    '      / name of FIELD
TTYPE5  = 'PHOTFLAG'      / bit-mask from photometry pipeline
TTYPE6  = 'PHOTPROB'      / float FoM from photometry pipeline
TTYPE7  = 'FLUXCAL  '      / MAG = 27.5 - 2.5*LOG10(FLUXCAL)
TTYPE8  = 'FLUXCALERR'    / error on FLUXCAL
TTYPE12 = 'PSF_SIG1'      / central Gaussian PSF (sigma, pixels)
TTYPE12 = 'PSF_SIG2'      / 2nd Gaussian PSF (sigma, pixels)
TTYPE13 = 'PSF_RATIO'     / PSF2/PSF1 at origin
TTYPE14 = 'SKY_SIG  '      / Search image sky sigma (ADU/pixel)
TTYPE15 = 'SKY_SIG_T'     / Template sky sigma (ADU per pixel)
TTYPE16 = 'RDNOISE  '      / image read noise (pe/pixel)
TTYPE17 = 'ZEROPT   '      / image zero point (ADU)
TTYPE18 = 'ZEROPT_ERR'    / error on above
TTYPE19 = 'GAIN     '      / ADU per pe
TTYPE21 = 'SIM_MAGOBS'    / True model mag (sim only)

```

#### 4.36.2 TEXT Light Curve Output

“**FORMAT\_MASK: 2**” This option results in a simplified one-line-per-observation output for the light curves. Header information includes RA, DEC, redshift, etc ... This output is recommended for testing with small interactive jobs. Below is a sample of the output.

```

# TEXT LIGHT CURVE OUTPUT:
#
NVAR: 9
VARLIST:  MJD  FLT FIELD  FLUXCAL  FLUXCALERR  SNR   MAG    MAGERR  SIM_MAG
OBS: 49562.316  Y 1694  -1.333e+03  5.891e+02  -2.26  128.000    0.000  27.313
OBS: 49572.430  z 1694   6.500e+01  1.708e+02   0.38   26.628  101.372  25.385
OBS: 49590.422  Y 1694   1.492e+02  1.635e+02   0.91   24.236  103.764  24.064
OBS: 49591.387  i 1694   3.733e+03  4.644e+02   8.04   23.970    0.144  24.198
OBS: 49591.414  z 1694   1.644e+03  3.271e+02   5.03   23.850    0.241  24.200
...

```

It is recommended to use the fluxes instead of mags because the mags are not defined for negative fluxes, and are ill-defined for very small fluxes. The **FIELD** is given for each measurement to properly label overlapping fields, **SNR** is the signal-to-noise ratio ( $\text{FLUXCAL}/\text{FLUXCALERR}$ ) and **SIM\_MAG** is the exact magnitude (without noise fluctuations) computed from the SN model.

#### 4.36.3 Suppress SIM\_XXX Info

“**FORMAT\_MASK: 8**” Suppress **SIM\_XXX** header info. This option is useful for things like blind-testing photometric classifiers.

#### 4.36.4 Random CID

“**FORMAT\_MASK: 16**” Generate random (integer) CID from 1-300,000,000 instead of the default sequential generation. The purpose of this option is that mixing different SN samples (Ia,II,Ibc) cannot be sorted by CID. Any random subset of the combined SN sample will contain similar fractions of each SN type.

Note that the keyword **CIDOFF** plays the role of selecting a unique set of random CIDs so that combined SN samples will not have overlapping CIDs. For example, suppose you generate 1000 type Ia SNe with **CIDOFF: 0**. The CIDs will be the first 1000 randomly selected (and non-repeating) integers between 1 and 300,000,000. Now suppose you generate 1000 type II with **CIDOFF: 1000**. The simulation will generate 2000 CIDs, but only use the last 1000 on the list (i.e., skip the first 1000). When the type Ia and type II SNe are combined (see **submit\_batch\_jobs**), the CIDs will not overlap and the SN types (Ia and II) will be perfectly mixed with no correlation between type and CID. It is up to the user to pick the correct **CIDOFF** value for each SN type, although **submit\_batch\_jobs** will automatically assign the appropriate **CIDOFF** values. After combining the SN samples, a useful unitarity check is to do `‘ls *.DAT | wc’` and verify that the total number of files matches the expected sum from the simulation jobs.

#### 4.36.5 Suppressing Spectra Output

To avoid excessive disk volume output for spectra, there are two methods to suppress output without affecting the **VERSION.SPEC** summary table. The first method is to suppress all spectra by adding 2048 to **FORMAT\_MASK**. The second method is to pre-scale the number of output spectra with **sim-input**

```
WRSPEC_PRESCALE: 5 # write 1 of 5 spectra
```

#### 4.36.6 PHOTFLAG Mask

The **PHOTFLAG** data column is a 4-byte integer mask containing the following user-requested information:

```
# override mask(s) in SEARCHEFF_PIPELINE_EFF_FILE
PHOTFLAG_DETECT: <MASK> # set for each detection
PHOTFLAG_TRIGGER: <MASK> # set for epoch satisfying trigger

# override mask(s) in SIMLIB global header
PHOTFLAG_SATURATE: <MASK> # saturation, see NPE_SATURATE in SIMLIB
PHOTFLAG_SNRMAX: <MASK> # set for epoch with max SNR
PHOTFLAG_NEARPEAK: <MASK> # set for epoch closest to peak
```

These **PHOTFLAG** masks can be specified in either an input table file, or the **sim-input** file; latter has priority if both are specified. Setting **PHOTFLAG** no impact on the simulation; it simply provides additional information to the analysis programs.

#### 4.36.7 Source of Each Redshift

The output data files include `REDSHIFT_FINAL`, the best redshift to use for Hubble diagrams. However, the source of this best redshift can be from the SN, from a host-spectrum, from a host photo- $z$ , or from a wrong host. An integer flag, `SIM_REDSHIFT_FLAG`, is written to the data files, and the interpretations can be found with the following `grep` command:

```
grep REDSHIFT_FLAG $SNANA_DIR/src/snlc_sim.h | grep define
#define REDSHIFT_FLAG_NONE      0
#define REDSHIFT_FLAG_SNSPEC    1
#define REDSHIFT_FLAG_HOSTSPEC  2
#define REDSHIFT_FLAG_HOSTPHOT  3
#define REDSHIFT_FLAG_WRONGHOST 4
```

In the output tables (SNANA, FITRES), this flag is called `SIM_ZFLAG`; it is written to `TEXT`, `ROOT`, and `HBOOK` files.

## 4.37 Simulation Dump Options

### 4.37.1 SIMLIB\_DUMP Utility

To quickly check global properties of a SIMLIB, a screen-dump summary is obtained with the command:

```
snlc_sim.exe mysim.input SIMLIB_DUMP 1
or
snlc_sim.exe NOFILE SIMLIB_FILE <simlib_file> SIMLIB_DUMP 1

*****
SIMLIB_DUMP

LIBID  MJD-range      NEPOCH(all,gri) GAPMAX(frac) <GAP>
-----
001    53616-53705    126,42 42 42    11.0(0.12)  2.2
002    53622-53700    51,17 17 17    19.0(0.24)  4.9
003    53622-53705    69,23 23 23    10.1(0.12)  3.8
004    53622-53705    54,18 18 18    15.0(0.18)  4.9
...
050    53622-53705    57,19 19 19    15.0(0.18)  4.6

Done reading 496 SIMLIB entries.

LIBRARY AVERAGES PER FILTER:
          <PSF>
      <ZPT-pe> FWHM  <SKYSIG>  <SKYMAG>          Cadence
FLT  (mag)  (asec) (ADU/pix) (asec^-2) <m5sig> <Nep>  FoM
-----
u   30.86   0.866      9.0    22.65    19.99   2.86   0.036
g   34.31   0.828    117.8    20.75    19.99  29.71   0.123
r   35.04   0.820    173.5    20.50    19.99  29.71   0.130
i   34.81   0.829    216.2    19.74    19.99  31.43   0.128
z   34.18   0.823    205.7    19.20    19.99  32.14   0.135

LIBRARY MIN-MAX RANGES:
      RA:    -59.994  to    58.766 deg
      DECL:  -1.253  to     1.257 deg
      MJD:   53616.2  to   53705.4
```

The sim-input file must contain the SIMLIB\_FILE key; no other keys are needed. To avoid creating a sim-input file, the NOFILE argument ignores the sim-input file and reads all arguments on the command line.

GAPMAX and <GAP> are the maximum and average gaps (days) between epochs in the SIMLIB. The “frac” after GAPMAX is the fraction of the MJD-range consumed by the largest gap. The LIBRARY MIN-MAX RANGES show you the ranges needed to include all SIMLIB entries. The CUT-WARNINGS shows how many SIMLIB entries are excluded by the selection ranges in your sim-input file. CUT-WARNINGS are checked for RA, DECL and PEAKMJD.

In addition to the screen-dump, a one-line summary for each LIBID is written to DUMP\_LIBID-[simlib] where [simlib] is the name of the SIMLIB file that you specify. This file is self-documented like the “fitres” files, and can be converted into an ntuple using the “combine\_fitres.exe” program (§12.1.2).

A one-line dump per MJD, which includes ZP in photoelectrons, sky noise converted into mag/arcsec<sup>2</sup>, and 5 $\sigma$  limiting mag calculation, can be obtained by setting the 2nd bit of the SIMLIB\_DUMP mask,

```
snlc_sim.exe mysim.input SIMLIB_DUMP 2
or
snlc_sim.exe NOFILE SIMLIB_FILE <simlib_file> SIMLIB_DUMP 2
```

and the corresponding output file is DUMP\_MJD-[simlib]. To obtain both the LIBID and MJD dump-files, set the SIMLIB\_DUMP argument to 3.

#### 4.37.2 Creating SIMGEN\_DUMP File

To quickly analyze generated distributions, there is an option to write generated quantities to a table file in TEXT format. For example, to check the generated redshift and SALT-II parameters, add the following to your sim-input file:

```
# dump same SN that are written to data files
SIMGEN_DUMP: 5 CID ZCMB SALT2x0 SALT2x1 SALT2c
or
# dump all SN, even those rejected by trigger and cuts
SIMGEN_DUMPALL: 6 CID ZCMB SALT2x0 SALT2x1 SALT2c SIM_SEARCHEFF_MASK
or
# no need to specify NVAR with comma sep list
# SIMGEN_DUMP: CID,ZCMB,SALT2x0,SALT2x1,SALT2c

# optional pre-scale (e.g., to limit output from DUMPALL)
SIMGEN_DUMP_PRESCALE: 10
or
PRESCALE_SIMGEN_DUMP: 10
```

SIMGEN\_DUMP[ALL] produces an auxiliary file [VERSION].DUMP in the same directory as the data files. The dump-file looks like:

```
VARNAMES: CID ZCMB SALT2x0 SALT2x1 SALT2c
SN: 50001 1.3820e-01 3.8970e-04 1.0906e+00 -1.5431e-01
SN: 50002 3.1260e-01 1.0278e-04 1.8671e-01 -3.9044e-01
SN: 50003 2.4248e-01 1.9417e-04 8.8190e-01 -3.8711e-01
SN: 50004 2.5666e-01 8.3385e-05 -6.7122e-01 -1.5304e-01
```

To list all valid SIMGEN\_DUMP variable names to stdout, either specify zero variables or intentionally list an invalid variable name,

```
snlc_sim.exe mysim.input SIMGEN_DUMP 0
snlc_sim.exe mysim.input SIMGEN_DUMP CID,BAD
```



After printing the valid variable names, the program quits.

To switch from `SIMGEN_DUMP` (in the input file) to `SIMGEN_DUMPALL` via command line arg, use the “SWITCH” option,

```
snlc_sim.exe mysim.input SIMGEN_DUMPALL SWITCH
```

To append dump variables on the command line (or `GENOPT` using `submit_batch_jobs`),

```
snlc_sim.exe mysim.input SIMGEN_DUMPADD SALT2c,SALT2x1
```

The ADD-list argument must be a comma-separated list, and using this key in the sim-input file will trigger an abort.

To dump the noise components in photo-electrons (source, sky, host, readout):

```
SIMGEN_DUMP_NOISE: 1 # dump noise for obs closest to peak per event & band
SIMGEN_DUMP_NOISE: 2 # dump noise for every obs with defined source flux
```

which outputs a table file (`[VERSION].NOISE`) in the output data folder.

### 4.37.3 Model Dump

Model magnitudes can be dumped with the sim-input key

```
GENRANGE_DMPREST: -20 60 # dump model for this Trest range, 1 day bins
```

This option will dump model magnitudes for a grid of

1. 1-day  $T_{\text{rest}}$  bins
2. each observer-frame band
3. hard-wired range of shape-parameter values for the selected model (e.g.,  $x_1$  for SALT2,  $dm_{15}$  for SNOOPY, etc ..).
4. color parameter ( $c$  or  $A_V$ ) is set to zero.

and the first generated redshift is used for the dump. The `GENRANGE_DMPREST` option results in an output text file and then the simulation stops. The name of the output file is `DUMP_GENMAG_[MODELNAME].TEXT` and it contains the generated observer-frame model mag for a grid of `{Trest,band,shapePar}`.

Instead of generating model mags on a grid, a model mag can be generated for fixed values of `{Filter,Trest,ShapePar,Redshift}` with the following sim-input keys,

```
GENFILTERS:      V          # pick filter
GENRANGE_DMPREST: 4.3  4.3  # pick Trest (this key flags the dumpFile)
GENRANGE_SALT2x1: 0.36 0.36 # pick SALT2x1
GENRANGE_REDSHIFT: 0.13 0.13 # pick redshift
```

The SALT2x1 parameter can be replaced with the appropriate model-dependent parameter. To dump rest-frame mags, set the redshift to 2.335E-9 (10 pc).

## 4.38 Including a Second Sim-Input File

A sim-input file can be split into two files using the keyword

```
INPUT_FILE_INCLUDE:  my2nd.input
```

which instructs the simulation to read and parse “my2nd.input” in exactly the same way as the original sim-input file. To see why this might be useful, consider the `NON1ASED` model that has many “NON1ASED:” keywords. The `NON1ASED` keys can be stripped out into a separate file such as `NON1ASED_keys.input`, and then included in many sim-input files. Thus a dozen sim-input files can each include `NON1ASED_keys.input`. To modify or add a `NON1ASED` key for all of the sim-input files, only one file needs to be modified.

## 4.39 Multi-dimensional GRID Option

Instead of generating random distributions in the variables describing each SN (redshift, shape parameter, color, etc ..), the simulation can generate SNe on a well-defined grid for each parameter using the following sim-input options,

```
GENSOURCE:      GRID      # replaces RANDOM option
NGRID_LOGZ:      20      # log10(redshift)
NGRID_SHAPEPAR:  10      # x1, Delta, stretch,dm15 ...
NGRID_COLORPAR:  2       # AV or SALT2 color
NGRID_COLORLAW:  1       # RV or BETA
NGRID_TREST:     56      # rest-frame epoch
GRID_FORMAT:     FITS     # TEXT or FITS

GENRANGE_REDSHIFT: 0.01  1.2      # redshift range
GENRANGE_TREST:   -20.0  90.0     # test epoch relative to peak (days)
GENFILTERS:       griz

# ----- Use one of the following models below -----
# for mlcs2k2
GENRANGE_DELTA:   -0.4    1.8      # delta-range (mlcs only)
GENRANGE_RV:      2.2    2.2      # range of CCM89-RV
GENRANGE_AV:      0.0    2.00     # AV range

# for SALT2
GENRANGE_SALT2x1: -3.0    3.0
GENRANGE_SALT2c:  -0.3    0.5
GENRANGE_SALT2BETA: 3.2    3.2

# for SIMSED model
SIMSED_SHAPEPAR:  DM15      # replace SIMSED_PARAM key to identify SHAPEPAR
GENRANGE_DM15:   0.6    1.59
SIMSED_COLORPAR:  AV        # replace SIMSED_PARAM key to identify COLORPAR
GENRANGE_AV:     -1.0    2.8
SIMSED_COLORLAW:  RV        # replace SIMSED_PARAM key to identify COLORLAW
GENRANGE_RV:     2.2    2.2
```

and explicit examples of complete sim-input files are in

`$SNDATA_ROOT/sample_input_files/GRID`

Also see the `sim_SNgrid.pl` utility in §8.1.1. This GRID option allows external (non-SNANA) fitting programs to use the SNANA models. The original motivation is for the photometric SN id program (§8.1). Each `NGRID_XXX` value divides the corresponding `GENRANGE_XXX` range into the specified number of bins for the grid. The “`GRID_FORMAT: TEXT`” option produces a human-readable file intended only for visual inspection. The “`GRID_FORMAT: FITS`” option produces a platform-independent file to be read by external programs. To save memory for programs reading the FITS tables, the magnitudes and errors have been multiplied by 1000 and stored as 16-bit (2-byte) integers. Magnitudes

dimmer than 32 are written as 32000, and undefined model magnitudes are stored as  $-9000$  (i.e,  $\text{mag} = -9$ ).

The GRID file is written in the same directory as the auxiliary files

`$SNDATA_ROOT/SIM/MY_VERSION/MY_VERSION.GRID`

where “GENVERSION: MY\_VERSION” is specified in the sim-input file. Note that only the GRID file is written; no light curve files are written out.

The FITS tables can be visually examined using a utility such as “fdump” or “fv.” SNANA has a “fits\_read\_SNGRID” utility to read in the generated GRID; to use this utility the following code-lines must be included,

```
#define SNGRIDREAD // use only the read utilities in sngridtools.c
#ifdef SNGRIDREAD
#include "fitsio.h"
#include "sngridtools.h"
#include "sngridtools.c" // fits_read_SNGRID is in here
#endif
```

The read-back utility fills the following global arrays/structures in `sngridtools.h`,

```
GRIDGEN_INFO
GRIDGEN_SURVEY  GRIDGEN_MODEL  GRIDGEN_FILTERS
PTR_GRIDGEN_LC  I2GRIDGEN_LCMAG I2GRIDGEN_LCERR
```

Also note that `genmag_snoopy.c` illustrated how to read and access the GRID.

Here is a brief description of the FITS tables and how to look up the correct magnitude and error from a set of SN parameters. Technically only the first (SNPAR-INFO) and last (I2LCMAG) tables are needed; the intermediate tables provide additional information that you would otherwise have to compute on your own. The SNPAR-INFO columns NBIN, VALMIN and VALMAX are simply copied from the sim-input parameters. The BINSIZE is calculated from the previous parameters, and the ILCOFF are used to determine the absolute light curve index (ILC) as a function of the SN parameters as follows:

$$\text{ILC} = 1 + \sum_{i=1}^4 \text{ILCOFF}_i \times (\text{INDX}_i - 1) \quad (30)$$

The parameter index  $i = 1, 4$  runs over (1) redshift, (2) color ( $A_V$  or  $c$ ), (3) color law ( $R_V$  or  $\beta$ ) and (4) shape parameter. Each integer index  $\text{INDX}_i$  runs from 1 to  $\text{NGRID}_i$  for parameter  $i$ . Do NOT extend the summation to include the filter and epoch indices. While the physical grid-values corresponding to each  $\text{INDX}_i$  can be computed from the SNPAR-INFO table, these grid values have been store in the intermediate tables that have a GRID suffix (and include FILTER-GRID and TREST-GRID).

Note that the  $\text{ILCOFF}_i$  are fixed, while the  $\text{INDX}_i$  depend on the set of SN parameters. For example, consider a redshift range of 0.01 to 1 and 200 bins; in  $\log z$  space we have  $-2 \leq \log_{10}(z) \leq 0$  and a  $\log z$  binsize of 0.01. For  $z = 0.1$ ,  $\log_{10}(z) = -1$  and the GRID-index is  $\text{INDX}_1 = 100$ .

Now we have an ILC index corresponding to a Supernova described by the four parameters above. Each SN light curve is written out in all of the GENFILTERS, and all of the SNe are strung together in the I2LCMAG table. This table contains one column of model magnitudes and another

column of model errors, each multiplied by 1000 to maintain millimag precision in 2-byte integer storage. The starting location in the I2LCMAG table is given in a separate 'pointer table' by PTR\_I2LCMAG(ILC). Note that you could compute this pointer as

$$\text{PTR\_I2LCMAG[ILC]} = 1 + ((\text{NGRID\_FILT} * \text{NGRID\_TREST}) + \text{NWDPAD}) * (\text{ILC}-1);$$

where NGRID\_FILT is the number of "GENFILTERS" and NWDPAD= 4 is the number of pad-words. Starting at the specified pointer location for ILC, the first word is a pad-word (−1111) and the second word is the first 8 bits of ILC; read-programs should verify these words to avoid getting lost. The next NGRID\_TREST words are the magnitudes ( $\times 1000$ ) for the first filter (g), the next NGRID\_TREST words are the magnitudes for the second filter (r), etc.. Finally, after reading all of the light curve magnitudes there are two end-of-lightcurve pad-words with values of −9999.

The I2LCMAG storage for a single SN light curve is illustrated below:

```
pad1 = -1111 <== start I2LCMAG address is PTR_I2LCMAG(ILC)
pad2 = first 8 bits of ILC
I2LCMAG(g,ep1) = mag * 1000
I2LCMAG(g,ep2)
I2LCMAG(g,ep3)
...
I2LCMAG(g,NGRID_TREST)
I2LCMAG(r,ep1)
...
I2LCMAG(r,NGRID_TREST)
...
...
I2LCMAG(z,NGRID_TREST)
pad3 = -9999
pad4 = -9999
```

While pointers are provided to compute ILC and to determine the starting I2LCMAG address from ILC, you are on your own to find the sub-index corresponding to the filter and epoch.

For the NONIASED GRID, there is no physically meaningful shape parameter; this parameter is therefore used to store a sparse index that runs from 1 to the number of NONIASED templates that are specified with the "NON1ASED:" keyword in the sim-input file. The FITS file includes an additional NONIA-INFO table that gives the SNANA index, a character-string type (e.g., II, Ib, Ibc), and a character-string name of the underlying SN used to create the template (e.g., 'SDSS-002744').

## 4.40 TGRIDSTEP: Linear Interpolation of Model Flux

It is sometimes useful to simulate with linear interpolation between model points. An example is to reproduce fakes overlaid on images, where each fake model flux is linearly interpolated from a pre-computed model grid. The sim-input key is

```
TGRIDSTEP_MODEL_INTERP: 4
```

which will compute the model flux on a 4-day grid, and then use linear interpolation to compute the flux at each MJD.

## 4.41 Marking Sub-Samples

Sometimes it is useful to generate many statistically independent samples. Rather than generating separate versions, there is less bookkeeping to generate one large sample and mark subsamples with sim-input

```
NSUBSAMPLE_MARK: 20
```

which will mark 20 sub-samples with an integer index. This index is automatically included in the output tables for all tables formats.

## 4.42 Applying Systematic Errors (RANSYSTPAR)

While systematic variations are typically evaluated in the analysis stage, it may be useful to simulate a large number of data-sized samples, each with a different random set of systematic errors applied. In principle, one can define each set of variations in a brute-force manner: e.g., picking random zero points offsets for each simulated version, and specifying “GENOPT: GENMAG\_OFF\_ZP <list>” for each GENVERSION (see §12.2.1).

Instead of the brute-force approach, it is simpler to use the RANSYSTPAR\_XXX input parameters so that the simulation picks random errors. Here are examples of available options for the sim-input file:

```
#      systematics that are 100 percent correlated among samples
RANSYSTPAR_SIGSCALE_MWEBV:    0.05      # scale MWEBV
RANSYSTPAR_SIGSHIFT_MWRV:     0.2       # shift RV
RANSYSTPAR_SIGSHIFT_REDSHIFT: 1E-4      # shift measured redshift
RANSYSTPAR_SIGSHIFT_zPHOT_HOST: 0.01    # shift zPHOT of host galaxy
RANSYSTPAR_SIGSHIFT_WO:       0.1       # shift w
RANSYSTPAR_SIGSHIFT_OMEGA_MATTER: 0.1   # shift OM

RANSYSTPAR_RANGESHIFT_WO:      -0.5 0.5  # flat shift range for w
RANSYSTPAR_RANGESHIFT_OMEGA_MATTER: -0.2 0.4 # flat shift range for OM

RANSYSTPAR_GENMODEL_WILDCARD: "/path/to/genmodels*"
      # pick random model out of globbed list

RANSYSTPAR_GENPDF_FILE_WILDCARD: "/path/to/genpdf_files*"
      # pick random GENPDF_FILE out of globbed list
```

```
#      systematics that depend on survey
GENFILTERS:  griz
RANSYSTPAR_SIGSCALE_FLUXERR:  0.02      # scale true & measured flux-errors
RANSYSTPAR_SIGSCALE_FLUXERR2: 0.04      # scale measured flux-errors
# filter-dependent variants:
RANSYSTPAR_SIGSHIFT_ZP:       .01 .02 -0.01 .03      # sigma per band
RANSYSTPAR_SIGSHIFT_ZP(g,r,i,z): .01 .02 -0.01 .03  # idem
RANSYSTPAR_SIGSHIFT_ZP(gr,iz): 0.01 0.02      # sig(g&r)=0.01, sig(i&z)=.02
RANSYSTPAR_SIGSHIFT_ZP(g,riz): 0.01 .03      # sig(g)=0.01, sig(r&i&z)=.03

RANSYSTPAR_SIGSHIFT_LAMFILT:   8 7 19 9   # sigma per band
RANSYSTPAR_SIGSHIFT_LAMFILT(g,r,i,z): 8 7 10 9 # idem
```



```

# misc control parameters

# use this random to select sytematic shifts; then switch back to
# user-define RANSEED, or RANSEED_GEN above. submit_batch_jobs uses
# this key to define correlated syst for each of the N samples.
RANSYSTPAR_RANSEED_SYST: 12345

# after ransyst params are picked, reset randoms with fixed seed
# to suppress random fluctuations between GENVERSIONS
RANSYSTPAR_RANSEED_GEN: 12345

# if different surveys use same instrument, force the same
# IDSURVEY-dependent randoms for systematics such as ZP and FilterWave.
RANSYSTPAR_IDSURVEY: 15 # e.g, same shifts for Found and PS1

```

SIGSCALE\_XXX parameters are interpreted as follows. A Gaussian sigma is defined as  $\sigma = \text{SIGSCALE\_XXX}$ , and then a random Gaussian number,  $r$ , is picked. The FUDGESCALE used in the simulation is  $1 + r$ . The SIGSHIFT\_XXX variables define a Gaussian sigma used to determine a random shift. Finally, RANGESHIFT\_XXX define a random shift with uniform probability over the defined range of shifts.

- RANSYSTPAR\_SIGSCALE\_FLUXERR applies a scale to the true and measured flux-uncertainties to either over- or under-estimate the uncertainties.
- RANSYSTPAR\_SIGSCALE\_FLUXERR2 applies a scale to the measured flux-uncertainties, but NOT to the true uncertainty used to smear the fluxes.
- RANSYSTPAR\_SIGSCALE\_MWEBV applies a scale to Galactic extinction.
- RANSYSTPAR\_SIGSHIFT\_MWRV applies a random shift to Galactice RV.
- RANSYSTPAR\_SIGSHIFT\_ZP parameters are Gaussian sigmas, not ZP shifts.<sup>18</sup> The simulation uses these sigmas to select a random set of ZP offsets. Changing RANSEED results in a different random set of ZP offsets, and there is no need for the user to pick random offsets.
- RANSYSTPAR\_SIGSHIFT\_LAMFILT applies a Gaussian-random shift to each filter bandpass.
- RANSYSTPAR\_RANSEED\_SYST is a flag for `submit_batch_jobs.sh` to select the same random for each split job. For exampe, consider 50 random data samples for LOWZ,PS1,DES. Split-sample 1 gets the same RANSYSTPAR\_RANSEED\_SYST value for each survey, split-sample 2 gets a different value, etc...
- RANSYSTPAR\_RANSEED\_GEN allows fixing the generation seed after systematic variations are selected. This removes statistical fluctuations from multiple GENVERSIONS.

---

<sup>18</sup>GENMAG\_OFF\_ZP key can be used to explicitly define ZP shifts.

## 4.43 Auto-Generated README (valid starting Jan 7 2022)

The simulation produces an auto-generated README file in the same directory as the data files,

```
$SNDATA_ROOT/SIM/[GENVERSION]/[GENVERSION].README
```

where [GENVERSION] is the argument of the GENVERSION key. The README content is a yaml-compliant DOCUMENTATION block that includes 4 sub-blocks:

```
DOCUMENTATION:
  OVERVIEW:      # survey, genmodel, node, username, snana_version ...
  ...
  INPUT_KEYS:    # collection of all user input keys and args
  ...
  INPUT_NOTES:   # computed quantities & subtle explanations
  ...
  OUTPUT_SUMMARY: # summary stats
  ...
```

The first 3 blocks are created during initialization and can therefore be viewed while the simulation is running. The OUTPUT\_SUMMARY block is created at the end of the job. The simulation input can be distributed among several INCLUDE files and command-line overrides, and thus tracking the input can be difficult. To enable checking the inputs more easily, the INPUT\_KEYS block lists all of the user-inputs in one location regardless of their origin. The INPUT\_KEYS can be converted into a single sim-input file with quick-command (§12.2.4)

```
quick_commands.py -v [GENVERSION] --extract_sim_input
  (creates sim_input_[GENVERSION].input)
```

## 5 The SNANA Fitter: `snlc_fit.exe`

### 5.1 Getting Started Quickly

Here you will perform lightcurve fits, hopefully in under a minute. To get started,

```
> cp $SNDATA_ROOT/sample_input_files/mlcs2k2/snfit_SDSS.nml .  
    or  
> cp $SNDATA_ROOT/sample_input_files/SALT2/snfit_SDSS.nml .
```

(Edit `.nml` file and put in correct `VERSION_PHOTOMETRY = 'xxx'`)

```
> snlc_fit.exe snfit_SDSS.nml >! snfit_SDSS.log &
```

When the unix command “ps” shows that the job has finished, congratulations ! You have fit your lightcurves with CERNLIB’s MINUIT program.<sup>19</sup> To create a pdf file showing the light curve fits, see §5.10.1.

### 5.2 Finding Data Folders

For SNANA analysis codes (`snlc_fit.exe`, `snana.exe`, `psnid.exe`), data folders are specified with

```
&SNLCINP  
    VERSION_PHOTOMETRY = 'folder_name'  
    or  
    VERSION_PHOTOMETRY = 'folder1, folder2, folder3'  
    or  
    VERSION_PHOTOMETRY = 'folder/subfolder'
```

Multiple folders are useful, for example, when data from a survey are separated into seasons. However, folders from different surveys *cannot* be analyzed together. The SNANA codes automatically search for data folders in

```
# real data  
$SNDATA_ROOT/lcmerge           # public data release  
$SNDATA_ROOT/lcmerge/PREFIX    # public compilation  
argument of PRIVATE_DATA_PATH  # optional/proprietary data location  
  
# sims  
$SNDATA_ROOT/SIM               # default sim output  
paths in $SNDATA_ROOT/SIM/PATH_SNDATA_SIM.LIST # alternate sim output
```

`$SNDATA_ROOT/lcmerge` is the default location for public data releases. Compilations consisting of many folders can be under a main folder; e.g., `$SNDATA_ROOT/lcmerge/JLA2014` contains 6 sub-folders corresponding to the 6 data samples in this compilation. More generally, for any `VERSION_PHOTOMETRY` input of the form “PREFIX\_SUFFIX,” the snana codes search under `lcmerge/` and `lcmerge/PREFIX`. Note that the following `&SNLCINP` inputs are equivalent,

---

<sup>19</sup><http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html>

```

VERSION_PHOTOMETRY = 'JLA2014_CSP'           ! auto-search under JLA2014
VERSION_PHOTOMETRY = 'JLA2014/JLA2014_CSP'   ! explicit reference

```

Since proprietary data are not under `$SNDATA_ROOT/lcmerge`, `&SNLCINP` key `PRIVATE_DATA_PATH` specifies an arbitrary location (see §6.3).

The default simulation output is under `$SNDATA_ROOT/SIM`. However, disk quotas may require alternate sim output locations. The file

```
$SNDATA_ROOT/SIM/PATH_SNDATA_SIM.LIST
```

lists alternate sim-output directories, and the `SNANA` codes search each directory in this file. Alternate directories are typically in scratch locations with higher (short-term) quotas. `PATH_SNDATA_SIM.LIST` should list only a few directories, such as per survey, or major projects. Do not use this file to list a directory for each user. Using environment variables is recommended to work on multiple platforms.

### 5.3 Discussion of Lightcurve Fits

Before reading this section, make sure you have successfully run the commands described in §5.1. Let's start the discussion by checking the end of the log-file,

```
> tail snfit_SDSS.log
```

The very last line should be “ENDING PROGRAM GRACEFULLY.” If you do not see this, check that your namelist variable `VERSION_PHOTOMETRY` is really pointing to an existing version in `$SNDATA_ROOT/SIM`. If you still have trouble, contact an expert for help.

Inside the input file `snfit_SDSS.nml`, the namelist variable

```
FITRES_DMPFILE = 'snfit_SDSS.fitres'
```

results in a dump of the fit parameters for each SN in a self-documented “fitres” file. Go ahead and “more `snfit_SDSS.fitres`” to see the results. The header keywords `NVAR` and `VARNames` specify the columns. The `SNANA` library includes a utility called `RDFITRES` to read these files. You can “cat” multiple fitres files together and add comments, and still read them with the same parsing code.

To figure out what you did, you need to check the namelist options in `snfit_SDSS.nml`. There are two separate namelists:

- `&SNLCINP`: defines selection of SNe and epochs by specifying criteria for the number of epochs, earliest & latest times relative to peak, maximum signal-to-noise, etc ... All namelist options are defined and commented inside `SNANA_DIR/src/snana.car`.
- `&FITINP`: defines fitting options such as priors, marginalization, and range of  $T_{\text{rest}}$  in the second fit-iteration. All namelist options are defined and commented inside `SNANA_DIR/src/snlc_fit.car`.

In the sample namelist file, a prior on  $A_V$  is used by setting `PRIOR_AVEXP = 0.40`, which translates into a prior of the form  $\exp(-A_V/0.4)$ . There is no marginalization so that your first fits run much faster. To marginalize, set the number of integration bins per variable, `NGRID_PDF = 11`. Since the marginalization is over four fit variables ( $t_0, A_V, \Delta, \mu$ ), the CPU-time goes as the fourth power of `NGRID_PDF`; previous studies indicate that 11 bins per fit-variable is a good compromise between accuracy and CPU time.

## 5.4 Methods of Fit-Parameter Estimation

There are three methods that can be used to estimate light curve fit-parameters:

1. **MINIMIZATION** based on CERNLIB's MINUIT program<sup>20</sup>. `&SNLCINP` namelist parameter `NFIT_ITERATION` specifies the number of iterations (2 or 3 recommended). You must always use this option, even if you use the options below. For very high-SNR SNe the first fit-iteration can sometimes fall into a false minimum, leading to pathological fits on successive iterations. This problem can be alleviated with `&FITINP` namelist variable `FUDGEALL_ITER1_MAXFRAC` (set to few percent); on the first fit-iteration this option adds an extra error equal to its value  $\times$  the peak flux, thus reducing the chance of finding a false minimum. Consider using `FUDGEALL_ITER1_MAXFRAC` for final fits, or at least as a crosscheck, along with `NFIT_ITERATION=3`.
2. **MARGINALIZATION** using multi-dimensional integration in `SNANA` function `MARG_DRIVER`. `&FITINP` namelist parameter `NGRID_PDF` controls the number of grid-points per fit-parameter (11 is recommended). You must run the minimizer first (`NFIT_ITERATION=2`) to get starting values and integration ranges. After marginalizing, the following crosschecks are performed: probability at the boundaries and number of bins with zero probability; if either is too large, the integration ranges are adjusted and the marginalization repeats.
3. **Monte Carlo Markov Chain (MCMC)**: See `&MCMCINP` namelist parameters. **WARNING**: this option has not been used for years, so it may be broken.

### 5.4.1 MINUIT Covariances

As described in the MINUIT manual, each MINUIT fit returns a covariance status, `MNSTAT_COV`, with one of the following values:

```
MNSTAT_COV = 0 -> not calculated
MNSTAT_COV = 1 -> Diagonal approximation only, not accurate
MNSTAT_COV = 2 -> Full matrix, but forced positive-definite
MNSTAT_COV = 3 -> Full accurate covariance matrix (normal convergence)
```

After the last fit iteration, if `MNSTAT_COV < 3` then the fit is repeated to try getting a better evaluation of the covariances. The final `MNSTAT_COV` value is included in the `FITRES` table.

Roughly  $\sim 1\%$  of light curve fits with the SALT2 model result in a covariance matrix,  $\text{COV}(m_B, x_1, c)$ , that is not invertible. The reason is subtle and related to how COV is determined. MINUIT-computed COV is approximated from second derivatives, while the MINUIT errors are determined from better methods (MIGRAD or MINOS). The COV diagonals are thus sometimes different than the error-squared. The FITRES output includes errors and off-diagonal COV terms, and analysis codes must therefore reconstruct COV diagonal terms using error-squared, which doesn't always correspond to the approximations used for the off-diagonal terms.

There has long been a hack in the SALT2mu.exe program (which implements BBC method) to fix non-invertible matrices. To apply the same hack-fix to the FITRES output of `snlc_fit.exe`, use the following input:

---

<sup>20</sup><http://wwwasdoc.web.cern.ch/wwwasdoc/minuit/minmain.html>

&FITINP

```
OPT_COVAR_LCFIT = 1    ! fix non-invertible COV with old method
OPT_COVAR_LCFIT = 129 ! idem, with one-row summary per fix
OPT_COVAR_LCFIT = 385 ! idem, with full COV dump

OPT_COVAR_LCFIT = 2    ! newer COV fix using reduced corr.
```

Note that `OPT_COVAR_LCFIT` is a bit-mask; 1 fixes non-invertible matrix, 128 gives one-row dump per fix, and 256 gives full COV dump per fix. A newer option (`OPT_COVAR_LCFIT=2`) preserves the reduced correlations ( $\rho_{ij}$ ) from the MINUIT-computed COV, and uses the errors and  $\rho_{ij}$  to determine COV.

### 5.4.2 Tricks to Avoid Pathological Fits

As samples have grown as large as  $\sim 10^7$  for bias-corrections, extremely robust light curve fitting methods are needed to avoid rare pathological fits or code crashes. Here is a list of &FITINP tricks that have been developed over the years (and might be useful with other fitting codes):

- `PRIOR_MJDSIG = 10.0` :  
Apply Gaussian prior using pre-fit estimate of `PEAKMJD`, where estimate is from data file, or one `OPT_SETPKMJD` options (Fig. 15). `OPT_SETPKMJD=16` is recommended because i) there is no fitting, and ii) it is insensitive to catastrophic outlier fluxes.
- `PRIOR_SHAPE_RANGE = -4.0, +4.0` :  
Apply flat prior on shape parameter (e.g.,  $-4 < x_1 < 4$ ), with half-Gaussian roll-off at edges to preserve continuity in the derivative (beware that discontinuous derivatives can wreak havoc with MINUIT).
- `PRIOR_SHAPE_SIGMA = 0.1` :  
Width of half-Gaussian roll-off for `PRIOR_SHAPE_RANGE`.
- `PRIOR_COLOR_RANGE` and `PRIOR_COLOR_SIGMA`  
Analogous of `PRIOR_SHAPE_XXX` above.
- `TREST_REJECT = -15.0, 45.0` :  
Apply rest-frame phase cut. There is under-the-hood logic to ensure that observations do not migrate in/out as `PEAKMJD` varies with each fit-iteration.
- `DELCHI2_REJECT = 16.0` :  
on 2nd fit-iteration, reject observations that contribute  $\chi^2 > 16$  (e.g., for preliminary/search photometry that has rare pathologies).
- `FUDGEALL_ITER1_MAXFRAC = 0.05` :  
For very high-SNR events (e.g., low redshift) the initial  $\chi^2$  can be very large, and sometimes MINUIT is not able to converge. To avoid extremely large initial  $\chi^2$ , this `FUDGEALL` parameter adds flux-uncertainty on the first fit-iteration only; the extra uncertainty here is 5% of the maximum flux. A more complete set of `FUDGE` parameters to downweight/exclude epochs is in §5.13.
- `OPT_COVAR_LCFIT = 1 (2)` :  
See §5.4.1 for fixing covariances among SALT2-fitted parameters.

- **USE\_MINOS = T :**  
Default fit errors use MIGRAD (USE\_MINOS=F). Enabling MINOS gives better error estimates, but also increases the CPU time by a factor of few.
- **Avoid Negative Variance in  $\chi^2$  Function:**  
Since variance  $V = V_0 + V_1 x_1^2 + (2x_1 V_{01})$ , large-negative  $x_1$  can result in  $V < 0$ ; hence the minimizer function needs protection requiring  $V > 0$ .

## 5.5 Initial Parameter Estimates

Before minimization, there are two stages for initializing light curve fit parameters. First is a rough estimate of peak MJD (§5.5.1). The second step is a refined peak MJD estimate and an estimate for the amplitude parameter (§5.5.2).

### 5.5.1 Rough Estimate of Peak-MJD ( $\tilde{t}_0$ )

Many light curve fitting programs rely on an approximate estimate of peak-MJD ( $\tilde{t}_0$ ). In particular, the SALT-II fitting program won't work without  $\tilde{t}_0$ . &SNLCINP namelist variable OPT\_SETPKMJD provides several SNANA options to estimate  $\tilde{t}_0$ . Options are based on analyzing fluxes, and/or a light curve fit in each pass-band using a generic Bazin function.

The  $\tilde{t}_0$  value can be determined prior to a SALT-II fit within `snlc_fit.exe` so that only one program is run for both, or  $\tilde{t}_0$  can be extracted into a TEXT-formatted table (column PKMJDINI) for a non-SNANA code as follows:

```
snana.exe NOFILE \
  VERSION_PHOTOMETRY <VERSION> \
  SNTABLE_LIST 'SNANA(text:key)' \
  TABLEPREFIX_TEXT <PREFIX> \
  OPT_SETPKMJD <OPT_SETPKMJD> > stdout.log
```

For simulations, plot residuals with PKMJDINI-SIM\_PKMJD.

A summary of the &SNLCINP bit-mask options is given in Fig. 15.

OPT\_SETPKMJD=8 does a naive search for max flux and sets  $t_0$  to be the corresponding MJD. This estimate, however, is subject to catastrophic errors if there is just a single outlier flux. To limit impact from outliers, the “Fmax-clump” method (OPT\_SETPKMJD=16 or 32) finds max flux in the densest clump of SNR-detections. Each SNR-detection is defined by user-input SNRCUT\_SETPKMJD, and MJDWIN\_SETPKMJD defines the size of the time window to search for detections. The window is analyzed in sliding steps of 10 days throughout the duration of the survey; e.g., for a 1000-day survey, 96 10-day windows are analyzed, and each window 50 days long. The last 4 windows (97-100) are skipped because they contain no additional information. The window containing the maximum weight-sum among SNR-detections is used to determine max flux, and  $t_0$  is MJD of the max flux observation. Each weight is 1.0 per detection for OPT\_SETPKMJD=16, and weight is  $\log_{10}(SNR)$  for OPT\_SETPKMJD=32. If there are no observations with  $SNR > SNRCUT\_SETPKMJD$ , the process is repeated with  $SNRCUT\_SETPKMJD \rightarrow 3$ . The CPU time for this max-flux method is  $\sim 10$  milliseconds per event.

OPT\_SETPKMJD=64 sets  $\tilde{t}_0$  to the MJD when the survey trigger is satisfied; e.g., MJD of the 2nd detection for a trigger requiring two detections. This option requires that the survey sets a PHOTFLAG mask for the observation when the survey trigger is satisfied; &SNLCINP input PHOTFLAG\_TRIGGER



specifies this PHOTFLAG trigger mask. To date, no public data sets include a PHOTFLAG trigger mask. However, the simulation can include this information as shown in Fig. 8.

The Bazin fit options are based on the SNLS CC rate paper (Bazin et al, 2008),

$$f(t) = A[1 + a_1(t - \bar{t}) + a_2(t - \bar{t})^2] \times \frac{\exp[-(t - \bar{t})/T_{\text{fall}}]}{1 + \exp[-(t - \bar{t})/T_{\text{rise}}]}, \quad (31)$$

where the fitted parameters are  $A, a_1, a_2, \bar{t}, T_{\text{fall}}, T_{\text{rise}}$ . `OPT_SETPKMJD=1` sets  $a_1 = 0$  and  $a_2 = 0$ , while `OPT_SETPKMJD=2` floats both  $a_1$  and  $a_2$ . The time at peak is obtained by setting the derivative equal to zero:  $\tilde{t}_0 = \bar{t} + T_{\text{rise}} \ln(T_{\text{fall}}/T_{\text{rise}} - 1)$ . Each filter is fit independently and the final  $\tilde{t}_0$  is the filter-weighted average. A filter's  $\tilde{t}_0$  is dropped from the average if: (1) its max-flux measurement has the smallest  $S/N$  ratio among filters and has  $S/N < 3$ , or (2) its  $\tilde{t}_0$  value is more than 30 days away from the average of the other filter- $\tilde{t}_0$  values (tested only if there are 3 or more filters). The max-flux epoch must have  $S/N > 3$  to make an estimate of  $\tilde{t}_0$ . The CPU time is  $\sim 170$  msec per event.

The Bazin fit needs an initial  $\tilde{t}_0'$  estimate, which by default is the MJD at maximum flux, `MJD(Fmax)`. However, the Fmax-clump method can be used instead by combining bit-mask options,

```
OPT_SETPKMJD = 17 # 16(Fmax-clump) + 1(Bazin)
```

Once `MJD(Fmax)` is determined, user-input `CUTWIN_TOBS` defines an optional MJD-range to select observations for the Bazin fit: the MJD-range is

$$\text{MJD(Fmax)} + \text{CUTWIN\_TOBS}(1) < \text{MJD} < \text{MJD(Fmax)} + \text{CUTWIN\_TOBS}(2)$$

If  $\tilde{t}_0$  cannot be determined, SNANA programs abort by default. To avoid aborts, `OPT_SETPKMJD += 4`, or `OPT_SETPKMJD=21` for the example above. The Bazin fit parameters for each band can be included in output tables with `OPT_SETPKMJD += 512`. Users should compare the  $\tilde{t}_0$  estimate (`PKMJDINI` in output tables) to the final  $t_0$  from a light curve fit (e.g., from SALT-II) and check for outlier  $\tilde{t}_0$  values.

Outlier  $\tilde{t}_0$  estimates can be identified by visual inspection of the light curve, but the SNANA options may not be sufficient to fix the outliers. The most robust solution is to set the `SEARCH_PEAKMJD` keyword in the data files, and then run SALT-II fits with `OPT_SETPKMJD=0`, which sets  $\tilde{t}_0 = \text{SEARCH\_PEAKMJD}$ . The advantage of this method is that outlier  $\tilde{t}_0$  values can be manually fixed. For simulations, see §4.34 on how to leave a  $\tilde{t}_0$  estimate in the output data files.

### 5.5.2 Refined Estimate of Peak-MJD and Amplitude Parameter

After  $\tilde{t}_0$  is determined, a coarse `PEAKMJD` grid is searched from  $-4$  to  $+4$  days (2 day bins) w.r.t, `PKMJDINI`, and `PEAKMJD` from minimum  $\chi^2$  is used as the initial value. Next, the data/model ratio is used to estimate the amplitude parameter:  $x_0$  for SALT2, or distance modulus for MLCS. For very high-SNR events, the initial parameter estimate may not be good enough to prevent catastrophic fits; in this case, try inflating the first-iteration flux uncertainties using `FUDGEALL_ITER1_MAXFRAC` (§5.13).

Figure 15: &SNLCINP options to estimate PEAKMJD

```

OPT_SETPKMJD  = 0      # use SEARCH_PEAKMJD value in data file
OPT_SETPKMJD += 1      # Bazin fit
OPT_SETPKMJD += 2      # Bazin fit with 2nd order poly (see below)
OPT_SETPKMJD += 4      # do NOT abort when PKMJD cannot be found
OPT_SETPKMJD += 8      # PKMJD -> MJD at max-flux (no fit)
OPT_SETPKMJD += 16     # Fmax-clump method, wgt=1 per obs (see below)
OPT_SETPKMJD += 32     # Fmax-clump method, wgt=log10(SNR) per obs (see below)
OPT_SETPKMJD += 64     # PKMJD = MJD_TRIGGER (must set PHOTFLAG bit)
OPT_SETPKMJD += 512    # save fit-PKMJD params (each band) in SNANA table
OPT_SETPKMJD += 1024   # DUMP info for each SN

SNRCUT_SETPKMJD  = 5    # for Fmax-clump method only (default=5)
MJDWIN_SETPKMJD  = 60   # for Fmax-clump method only (default=60)
PHOTFLAG_TRIGGER = MASK # for MJD_TRIGGER method (MASK set by survey)
CUTWIN_TOBS     = -999,999 # Find MJD(Fmax), then apply TOBS cut for Bazin fit.

SHIFT_SETPKMJD = 5.0    # syst test to shift initial PKMJD by 5 days (default=0)

```

## 5.6 Galactic Reddening

In the fitting programs, Galactic extinction is applied to the model; i.e., the data are NOT de-reddened. For `snlc_fit.exe`, the extinction is computed at each filter-wavelength bin in the flux-integrals. In `psnid.exe` the Galactic extinction is approximated by the value at the central wavelength. The Galactic extinction covariance is controlled with the `&FITINP` namelist option

```
OPT_COVAR_MWXTERR = 1 ! default: full covariance matrix
```

The reduced  $N_{\text{obs}} \times N_{\text{obs}}$  covariance matrix is 1 everywhere, and each diagonal element is the MWEBV uncertainty at the central wavelength of the observer-frame passband. The covariance matrix is computed and inverted between fit iterations. For each SN the MWEBV value and uncertainty are read from the header. For data, if MWEBV or its uncertainty are zero (or do not exist), then they are internally set to the SFD98 value and  $0.16 \times \text{MWEBV}$ , respectively. To allow for arbitrary tests in simulations, any value of MWEBV and its uncertainty are accepted. For fitting both data and simulations, Galactic extinction can be disabled by setting either of the namelist parameters `OPT_MWCOLORAW` or `OPT_MWEBV` to zero.

Starting at snana version v10\_29n, the Galactic reddening law and source of  $E(B - V)$  are determined by the `&SNLCINP` namelist parameters

```
&SNLCINP
RV_MWCOLORLAW = 3.1 ! default
OPT_MWCOLORLAW = 94 ! default: CCM89+ODonnel94 (default)
OPT_MWEBV      = 1   ! default: read E(B-V) from data header

MWEBV_SCALE = 1.0 ! default: scale all MWEBV values
MWEBV_SHIFT = 0.0 ! default: shift all MWEBV values
USE_MWCOR = F ! default: do NOT correct data, include in fit-model
```

A similar set of parameters controls reddening in the simulation, and additional option-values for these parameters is illustrated in §4.21. If no reddening law is specified (`OPT_MWCOLORLAW`), the default CCM89+ODonnel94 model is used in all programs with the exception of fitting simulations; in this case the default reddening model is that used in the simulation. Similarly, if `OPT_MWEBV` is not specified, the data-header values are used for both data and simulation. In the fitting programs (`snlc_fit.exe` and `psnid.exe`), specifying `OPT_MWCOLORLAW` or `OPT_MWEBV` explicitly in the `&SNLCINP` namelist will override the simulation default.

See §4.21.1 for a description of the Galactic extinction calculation for observer-frame models, and for rest-frame models that require K-corrections.

Finally, `&SNLCINP` namelist parameter `USE_MWCOR` controls whether the data or fit-model is corrected. The default `USE_MWCOR=F` does *not* correct the data, and instead MW reddening vs. wavelength is included in the fit-model. `USE_MWCOR=T` corrects the data approximately, using the extinction at the central wavelength of each filter band, and is then ignored in the fitting model. We recommend using the default, except for special cases such as building de-reddened templates.

## 5.7 Selecting Filters

By default the snana codes read and store epochs from all defined filters. The fitted filters must be specified in the `&FITINP` namelist variable

```
FILTLIST_FIT = 'ugriz'
FILTLIST_DMPFUN = 'gri' ! debug dump for SN model function
FILTLIST_DMPFCN = 'gri' ! debug dump for chi2 function
```

The debug-dump options should be used only in special cases to debug a fit problem, and only 1 or 2 SN should be fit to limit the size of the stdout.

The filters in `FILTLIST_FIT` must be defined in the `kcor/calib` file and in the `SURVEY` filters defined in the data files. Any undefined filter results in an `ABORT`. To estimate peak-mags in non-survey filters (e.g., 'abc'), these extra filters must be defined in the `kcor/calib` file; to prevent the fitting program from aborting, the non-survey filters must be explicitly defined via the `&SNLCINP` namelist variable

```
NONSURVEY_FILTERS = 'abc'
```

Finally, filters can be selected based on the mean wavelength in the rest-frame ( $\lambda_{\text{rest}} = \lambda_{\text{obs}}/(1+z)$ );

```
&SNLCINP
  CUTWIN_RESTLAM = 4000, 8000.
  CUTWIN_LAMREST = 4000, 8000. ! same as above
  CUTWIN_LAMOBS  = 4000, 8000. ! cut on <LAMOBS> instead of <LAMREST>
  ...
or
&FITINP
  RESTLAMBDA_FITRANGE = 4000. , 8000.
  ...
```

Note that `RESTLAMBDA_FITRANGE` can be used only to reduce the  $\lambda_{\text{rest}}$  range of the SN model; i.e., you cannot use this parameter to arbitrarily increase the wavelength range. If you really want to increase the  $\lambda_{\text{rest}}$  range, then you must define your own model and modify the corresponding parameters in one of the model-info files.

## 5.8 Fitting Priors

The fitting prior options in `snlc_fit.exe` are mainly designed to prevent catastrophic fits. There are also options related to the host-galaxy extinction. Photo- $z$  priors are described in §5.12, and a brief description of the other `&FITINP` namelist prior options are given below.

- **PRIOR\_MJDSIG**: sigma on Gaussian prior for MJD at peak brightness. Default is 20 days.
- **PRIOR\_SHAPE\_RANGE(2)**: range of flat prior for shape parameter to prevent crazy values. Typical prior-range values are  $\{-0.5, 2.0\}$  for the `MLCS2k2` parameter  $\Delta$ , and  $\{-5, +3\}$  for `SALT-II` parameter  $x_1$ . Default range is  $\{-9, +9\}$ . The parameter below defines a smooth roll-off at the edges.

- **PRIOR\_SHAPE\_SIGMA**: sigma of Gaussian roll-off at edge of flat prior defined above. Default is 0.1.
- **PRIOR\_DELTA\_PROFILE(4)**: Used only for MLCS2k2  $\Delta$ , the first two elements are  $-\sigma$  and  $+\sigma$  for the asymmetric Gaussian prior, the 3rd element is the  $\Delta$  value at the Gaussian peak, and the 4th element is the minimum 'flat' probability for all  $\Delta$  values within **PRIOR\_SHAPE\_RANGE**. A flat  $\Delta$  prior is obtained by simply setting the 4th element to 1.0. Setting the 4th element to  $\sim 0.1$  results in a Gaussian prior with a flat tail for large  $\Delta$  values; this tail prevents the suppression of very fast decliners (91bg-like).
- **OPT\_PRIOR**: Default is 1  $\rightarrow$  use priors. Setting to zero turns off ALL priors regardless of their values.
- **OPT\_PRIOR\_AV**: Used only for MLCS2k2 model, default is 1  $\rightarrow$  use  $A_V$  priors. Setting to zero turns off  $A_V$ -related priors.
- **PRIOR\_AVEXP(2)**: For MLCS2k2 only, defines up to two exponential slopes for  $A_V$  prior.
- **PRIOR\_AVWGT(2)**: For MLCS2k2 only, defines weight for the two  $A_V$ -exponential terms.
- **PRIOR\_AVRES**: Since the  $A_V$  prior has a sharp boundary at  $A_V = 0$  and therefore a discontinuity in the fitting function, this **PRIOR\_AVRES** option allows a Gaussian smearing of the prior function that results in a continuous function. Recommended values are .001 to 0.01.

### 5.8.1 Initial Values from Existing FITRES file

For the **SNCID\_LIST\_FILE** option (§5.20.1), the file can contain one of two formats: 1) list format with list of CIDs and nothing else, or 2) **FITRES** (keyed) format that includes CID in first column. For the **FITRES** format, the fit-par columns (PKMJD, x1, c, zHD) are automatically used as initial values to the fit. Using the uncertainties as a prior requires a code update.

## 5.9 Selecting an Efficiency Map for a Fitting Prior

The light curve fitting prior includes an optional simulated efficiency as a function of redshift, Galactic extinction (MWEBV) and model-dependent parameters that describe the SN brightness. For example, the MLCS2k2 model parameters are shape ( $\Delta$ ), extinction ( $A_V$ ), and color law ( $R_V$ ). The fitting prior and efficiency map can be applied to other models too. An efficiency map can be generated using the SNANA script **SIMEFF\_MAPGEN.pl** (§4.35), and a map is selected via the **&FITINP** namelist:

```
! Select file name explicitly. Will first check YOUR current working
! directory; if not there, then fitter checks public area
! $SNDATA_ROOT/models/simeff/mysimeff.dat
SIMEFF_FILE = 'mysimeff.dat'
```

The efficiency map is defined on a multi-dimensional grid, and interpolation is used to determine the efficiency for any set of SN model parameters. Note that these maps depend on the selection requirements and are therefore analysis-specific; these maps should therefore not be considered as general purpose files such as those describing K-corrections (§7) or search-efficiencies (§4.18).

## 5.10 Plot Utilities

### 5.10.1 Viewing Lightcurve Fits: `plot_snana_lightcurves.py`

To view light curves,

```
plot_snana_lightcurves.py -v <version> -i <snid1,snid2,snid3,etc...>
```

where `-v` is the data version with FITS (or TEXT) files, and `-i` specifies a comma-separated list of SNIDs to show. Optional arguments include `-p` for private data path, and `-f` for fit-input file to overlay light curve fit. Typing `plot_snana_lightcurves.py` with no arguments gives a help menu.

### 5.10.2 1D and 2D plots for table: `plot_table.py`

To make 1D plots, 2D plots, and overlays among multiple samples (e.g., data and sim), `plot_table.py` operates on (i) FITRES files produced by the light curve fitting program (`snlc_fit.exe`), (ii) HOSTLIB files (need to copy and remove DOCUMENTATION block), or (iii) any table with similar keyed format. Extensive help on syntax is obtained with

```
plot_table.py @@HELP  
or  
plot_table.py @H
```

Each plot is viewed in a pop-up window by default, or saved to pdf or png file using `SAVE` option.

### 5.10.3 Plot peakmag vs. redshift: `plot_peakmag_redshift.py`

To quickly compare brightness among many different models, `plot_peakmag_redshift.py` plots peakmag vs. redshift for each band and sim-data folder specified by path wildcard argument. Simulations must be run with `SIMGEN_DUMP` feature and include the `PEAKMAG_[band]` variables.

## 5.11 Tracking SN versus Cuts

Typically the final number of processed SN is smaller than the number read in, and thus it is often useful to track the losses, particularly if there seem to be too few (e.g., zero) SNe. At the end of each snana job, the stdout includes a statistics summary for each SN “Type” showing the number of SN vs. incremental cut. An example is shown here,

CUT NAME	ITYPE=	Number of SN passing incremental cut for		
		118	119	120
-----				
CID		8	37	502
Trestmin		5	36	476
Trestmax		5	34	374
NFILT(SNRmax)		4	31	370
FIT + CUTS		4	30	369

The last row labeled 'FIT+CUTS' is shown for the `snlc_fit.exe` job, and the previous rows are shown for both the `snana.exe` and `snlc_fit.exe` jobs. Additional information is given by the following snana table<sup>21</sup> variables

CUTFLAG_SNANA	= 0	-> failed snana cuts
CUTFLAG_SNANA	bit0	-> passed snana cuts
CUTFLAG_SNANA	bit1	-> passed fit & cuts
ERRFLAG_FIT	= -9	-> no fit done (i.e., CUTFLAG_SNANA=0 or snana.exe job)
ERRFLAG_FIT	= 0	-> no fitting errors
ERRFLAG_FIT	> 0	-> see error codes with
		grep 'ERRFLAG_' \\${SNANA_DIR}/src/snlc_fit.car   grep '&'

where this table is created with `LTUP_SNANA=T` (§12.1) and the variables can be extracted into text format using the `sntable_dump.py` utility (§12.1.3). `CUTFLAG_SNANA= 1` means that the snana cut-requirements were satisfied, but the fit either failed or was not attempted. `CUTFLAG_SNANA= 3` means that the SN satisfied the snana cuts and has a valid fit whose results are stored in the `fitres` file and the `fitres` ntuple.

`ERRFLAG_FIT` is zero if the fit is valid and the fit-cuts are satisfied. A positive flag indicates an error; grep the source code for error definitions. `ERRFLAG_FIT= -9` means that the fit was not attempted; this occurs if the snana cuts fail (`CUTFLAG_SNANA= 0`) or when running `snana.exe`.

<sup>21</sup>The snana table id is 7100 for hbook or SNANA for root.



## 5.12 PhotoZ Fits

Here we describe light curve fits that determine the SN Ia redshift ( $z$ ) from photometry, called “SN-photoZ” fits. There are two fundamental methods to perform photoZ fits. The first method, called a “constrained photoZ fit,” is designed to identify SNe Ia that do not have a spectroscopic redshift: uses include SN rates and targeting host-galaxy redshifts for unconfirmed SN Ia. For MLCS2k2 photoZ fits, there are four floated parameters:  $z$ ,  $t_0$ ,  $\Delta$ , and  $A_V$ . For SALT-II photoZ fits, the four floated parameters are  $z$ ,  $t_0$ ,  $x_1$ , and  $c$ . The distance modulus is constrained (calculated) assuming a particular cosmology:  $\mu = \mu(z, \Omega_M, \Omega_\Lambda, w)$  where  $z$  is floated in the fit, and  $\Omega_M, \Omega_\Lambda, w$  are fixed by the user. The cosmology can be specified with &SNLCINP namelist parameters HO\_REF, OMAT\_REF, and OLAM\_REF. For SALT-II photoZ fits, the distance modulus is converted into the  $x_0$  parameter, and therefore SALT2alpha & SALT2beta must be specified as &FITINP namelist parameters.

The second method, called a “cosmology-photoZ” fit, involves floating five parameters:  $\mu$ ,  $z$ ,  $t_0$ ,  $\Delta$ , and  $A_V$  for MLCS2k2, and  $x_0$ ,  $z$ ,  $t_0$ ,  $x_1$ , and  $c$  for SALT-II. This method is designed to use large photometric samples to measure distance moduli that can be used to measure cosmological parameters. One of the difficulties with the 5-parameter fit is CPU time: the marginalization takes a few minutes per fit, so studying the bias on a sample of  $10^4$  simulated SNe Ia requires about a CPU-month of resources.

In addition to the two main methods above, there are variations that involve using the host-galaxy photoZ (host-photoZ) as a prior to help constrain the redshift. A distance-modulus prior can be applied to the second method (5-parameter fit); this is essentially a constrained-photoZ fit, but the photoZ errors will include uncertainties from the cosmological parameters. Needless to say, *never* run a cosmology fit on output where a distance-modulus prior is used !

There are five &FITINP namelist parameters that control photoZ fits. The default values are set so that photoZ fits are turned off,

DOFIT_PHOTOZ	= F	
OPT_PHOTOZ	= 0	! 1=>hostgal photZ prior; 2=> specZ prior
INISTP_DLMAG	= 0.1	! 0=> constrain DLMAG; non-zero => float DLMAG
PRIOR_ZERRSCALE	= 100.0	! scale error on host-photoZ prior
PRIOR_MUERRSCALE	= 100.0	! scale error on distance modulus prior

Setting DOFIT\_PHOTOZ=T and INISTP\_DLMAG=0.0 results in a 4-parameter constrained-photoZ fit. Since PRIOR\_ZERRSCALE=100.0 by default, the host-photoZ errors are multiplied by 100 and therefore have no impact on the fits. Setting PRIOR\_ZERRSCALE = 1.0 results in using the host-photoZ prior described by a Gaussian distribution<sup>22</sup>.

To switch from a constrained-photoZ fit to a 5-parameter cosmology-photoZ fit, set INISTP\_DLMAG to any non-zero value such as 0.1. The use (or non-use) of the host-photoZ prior is controlled by the value of PRIOR\_ZERRSCALE. The parameter OPT\_PHOTOZ controls the source of the redshift prior as follows:

```

OPT_PHOTOZ = 1    ! use host zPhot mean and Gauss sigma
OPT_PHOTOZ = 2    ! use best-z (spec or host photo-z)
OPT_PHOTOZ = 4    ! use photo-z PDF unpacked from quantiles; cubic interp
OPT_PHOTOZ = 8    ! use photo-z PDF unpacked from quantiles; Steffan interp
OPT_PHOTOZ = 10   ! use accurate zSpec, otherwise use quantiles.
OPT_PHOTOZ = 16   ! CHEAT: set initial zPhot=zSpec and skip grid search (for debug)

```

<sup>22</sup>Depending on user interest, non-Gaussian tails may be added later.

```
OPT_PHOTOZ += 32 ! compute INISTP = STD(zPDF)/3.0 (ignore INISTP_PHOTOZ)
```

Setting `OPT_PHOTOZ=1` forces using host photo- $z$  Gaussian prior, even if spec- $z$  is available. `OPT_PHOTOZ=2` uses the best redshift (spec or photo- $z$ ) as a Gaussian prior, and is useful for samples with a mix of spec- $z$  and photo- $z$  redshifts. `OPT_PHOTOZ=4` uses zPDF from quantiles, and ignores subset with accurate spec- $z$ . `OPT_PHOTOZ=6` (2+4) uses accurate spec- $z$  Gaussian prior if available; else it uses quantiles.

For quantile option, existence of spec- $z$  is determined as follows. The most robust method is data variable `MASK_REDSHIFT_SOURCE` set by the survey team creating the data files, and automatically set for simulations. The mask values are as follows: 1: host spec- $z$ , 2: SN spec- $z$ , 4: host photo- $z$  point estimate, 8: host photo- $z$  quantiles. Thus, for example, `MASK_REDSHIFT_SOURCE=9` means that both spec- $z$  and quantiles are available. If this mask is not available, an alternative (less robust) method is to define `&SNLCINP` input `QUANTILE_ZERRMIN = 0.01`; this identifies spec- $z$  if redshift uncertainty is below 0.01.

If `PRIOR_MUERRSCALE` is 100 or larger (the default), then there is no prior applied to the distance modulus ( $\mu$ ). Setting `PRIOR_MUERRSCALE = 2` will apply a  $\mu$ -prior using a Gaussian profile of width  $\sigma = 2\sigma_\mu$ , where  $\sigma_\mu$  is calculated from the user-specified uncertainties in the cosmological parameters. Note that `OMAT_REF`, and `WO_REF` are two-dimensional arrays that specify both the value and error. For example,

```
OMAT_REF = 0.3, 0.03
WO_REF   = -1.0, 0.1
```

would use  $\sigma_w = 0.1$  and  $\sigma_M = 0.03$  to calculate the  $\mu$ -error for the photoZ at each fit-iteration.

To get going quickly, some useful examples of setting the namelist options are given below in Fig. 16.

A few other photoZ-related issues are:

- To test the photoZ methods in simulated SN Ia samples, the simulation includes an option to include host-galaxy photoZs based on an externally-supplied library (§ 4.22). To test SN-only photoZ fits (without host), increase `GENSIGMA_REDSHIFT` so that the initial redshift estimate is poor.
- To test the photoZ sensitivity to the initial redshift estimate, see § 5.24.

Figure 16: Examples of setting photoZ options within the &FITINP namelist.

```

! constrained photoZ fit, ignore host-galaxy photoZ:
DOFIT_PHOTOZ      = T
PRIOR_ZERRSCALE   = 100.0 ! inflate error on photoZ prior
INISTP_DLMAG      = 0.0    ! fix MU = MU(zphot,cosmology)

! equivalent way to do the above
OPT_PHOTOZ        = 1
PRIOR_ZERRSCALE   = 100.0 ! inflate error on photoZ prior
INISTP_DLMAG      = 0.0    ! fix MU = MU(zphot,cosmology)

! constrained photoZ fit using host-galaxy photoZ:
DOFIT_PHOTOZ      = T
PRIOR_ZERRSCALE   = 1.0
INISTP_DLMAG      = 0.0    ! fix MU = MU(zphot,cosmology)

! constrained photoZ fit, host-galaxy photoZ errors inflated by 1.3
DOFIT_PHOTOZ      = T
PRIOR_ZERRSCALE   = 1.3
INISTP_DLMAG      = 0.0    ! fix MU = MU(zphot,cosmology)

! cosmology photoZ fit, ignore host-galaxy photoZ:
DOFIT_PHOTOZ      = T
PRIOR_ZERRSCALE   = 100.0 ! inflate error on photoZ prior
INISTP_DLMAG      = 0.1    ! float DLMAG

! cosmology photoZ fit using host-galaxy photoZ:
DOFIT_PHOTOZ      = T
PRIOR_ZERRSCALE   = 1.0
INISTP_DLMAG      = 0.1    ! float DLMAG

! cosmology photoZ fit with priors on both distance & host-galaxy photoZ:
DOFIT_PHOTOZ      = T
PRIOR_ZERRSCALE   = 1.0    ! use host-galaxy photoZ errors
PRIOR_MUERRSCALE  = 3.0    ! use x3 mu-error calculated from dw & dOM
INISTP_DLMAG      = 0.1    ! float DLMAG

! spec-z fit or host photo-z fit, for mixed spec+photo-z sample
OPT_PHOTOZ        = 2      ! use REDSHIFT_FINAL as prior
PRIOR_ZERRSCALE   = 1.0    ! use REDSHIFT_FINAL_ERR in prior
INISTP_DLMAG      = 0.1    ! float DLMAG

```

### 5.12.1 Redshift-Dependent Selection in PhotoZ Fits

There is a subtle fitting issue concerning the usable observer-frame filters for which  $\lambda_{\text{obs}}/(1+z)$  is within the valid  $\lambda_{\text{rest}}$ -range of the light curve model, and for which  $T_{\text{rest}} = T_{\text{obs}}/(1+z)$  are valid. In addition, requirements on quantities such as the min & max  $T_{\text{rest}}$  are ambiguous before the photoZ fit has finished, yet it is useful to make such cuts before fitting to prevent fitting pathological light curves and to reduce processing time. Here we discuss how to select filters and how to make cuts on  $T_{\text{rest}}$ -dependent quantities.

For regular cosmology fits using spectroscopic redshifts, a list of usable filters & the  $T_{\text{rest}}$ -range is made before the fit starts. For a photoZ fit, however, it is not clear which filters & epochs are valid until the fit has finished. For example, consider a *gri* photoZ fit using SALT-II: when  $z_{\text{phot}} < 0.072$ , *i*-band maps to rest-frame wavelengths greater than the 7000 Å cutoff in SALT-II. Including *i*-band in the fit results in using an unphysical region of the model, while dropping *i*-band measurements results in a discontinuous drop in the  $\chi^2$ . In the latter case, the minimizer is trapped in this low- $\chi^2$  well, and quite often the minimum occurs at the drop-out boundary  $z_{\text{phot}} = 0.072$ . Another example is in DES & LSST, where *g*-band maps below 3000 Å at redshifts above about 0.5.

To make initial  $T_{\text{rest}}$ -dependent cuts before the photoZ fit has started, the cuts are loosened by a factor of “ $1 + Z_{\text{max}}$ ”, where  $Z_{\text{max}} = \text{PHOTOZ\_BOUND}(2)$  is the maximum allowed redshift (specified in &FITINP). The  $T_{\text{rest}}$ -cuts are therefore loosened to be valid for any redshift in the range specified by PHOTOZ\_BOUND. For example, consider PHOTOZ\_BOUND = 0,1 and a requirement that the min- $T_{\text{rest}}$  is before  $-4$  days; the initial cut would be a requirement of an epoch before  $-2$  days using whatever REDSHIFT\_FINAL is in the data file, and the  $-4$  day requirement is applied after the photoZ fit has finished. Similarly, a max- $T_{\text{rest}}$  requirement of 30-60 days is loosened to 15-120 days before the photoZ fit. If a filter is dropped after the first fit-iteration (see below), the loose  $T_{\text{rest}}$ -cuts are re-applied before fitting again.

To select observer-frame filters, the basic strategy is to perform the first-iteration photoZ fit with all filters except for those in the UV with  $\lambda < 4000$  Å. A reasonable analytical extrapolation of the model beyond the defined wavelength range is required. This possibly biased photoZ is then used to determine which filters to exclude (or add in case of UV filter) in the next iteration. Technically, when one more more filters is excluded, the first-iteration is repeated so that two complete fit-iterations are performed with the correct filters. The basic assumption in this strategy is that it does not matter if there is an unknown bias in choosing the redshift to drop a filter ... as long as the fit, with or without the filter in question, is unbiased. As an example, consider photoZ fits with *griz* filters. For  $z > 0.49$ , *g*-band should be excluded. As a safety margin, one might exclude *g*-band when the 1st-iteration photoZ value is above 0.43, or 0.44, or 0.45 ... the cut does not matter as long as we are confident that when *g*-band is used, it is within the valid range of the model.

The redshift safety margin is controlled by &FITINP namelist parameters

PHOTOZ_ITER1_LAMRANGE	= 4000, 25000 ! 1st-iter obs-frame lambda range
PHOTOZ_BOUND	= 1.0E-6, 1.4 ! hard MINUIT bound
PHOTODZ_REJECT	= 0.05 ! dz cut
PHOTODZ1Z_REJECT	= -99. ! dz/(1+z) cut; default is no cut

The default PHOTOZ\_ITER1\_LAMRANGE cut is set to exclude any UV filter on the first iteration since this filter is used only at the lowest redshifts. Note that the excluded UV filter can be added back after the first fit-iteration if the photoZ value is low enough. PHOTOZ\_BOUND is a hard MINUIT bound to prevent crazy excursions during the minimization, and is also used to loosen the  $T_{\text{rest}}$ -related cuts before the fit has started.

The next two cut-parameters define the redshift safety margin, and can be defined as a cut on  $dz$  and/or  $dz/(1+z)$ . The SNANA default is to use only the cut on  $dz$ , so we use this for discussion, noting that the other cut works in a similar manner. In principle it would be better to cut on the number of fitted  $\sigma_z$ , but on the first iteration the MINUIT errors are sometimes pathological; it is therefore safer to make a fixed cut.

The  $dz$  cut is illustrated here using  $g$ -band and the MLCS2k2 model for which the valid wavelength range is 3200-9500 Å. Since the mean filter wavelength is  $\lambda_g = 4790$  Å, the valid rest-frame redshifts are given by  $Z_{\min} = \lambda_g/9500 - 1 = -0.50$  and  $Z_{\max} = \lambda_g/3200 - 1 = +0.50$ . The  $g$ -band is excluded if the 1st-iteration photoZ satisfies  $z_{\text{phot}} > Z_{\max} - \text{PHOTODZ\_REJECT}$ ; in this example,  $z_{\text{phot}} > 0.45$ . For Y-band ( $\lambda_Y = 10095$  Å),  $Z_{\min} = 0.062$  and this filter is excluded if  $z_{\text{phot}} < Z_{\min} + \text{PHOTODZ\_REJECT}$ , or  $z_{\text{phot}} < 0.11$ . Note that PHOTODZ\_REJECT is defined to be positive when adding a safety margin, regardless of whether a blue or red band is being tested. Setting PHOTODZ\_REJECT to a large negative value (i.e., -99) disables the cut. Finally, the PHOTODZ\_REJECT cut is applied to all observer-frame filters, and often more than one filter (i.e.,  $ugr$ ) is rejected.

A quick list of dropped filters can be viewed from the log-file with the following 'grep' command:

```
grep "DROPPED" myjob.log
WARNING for SN 40002 : DROPPED obs-filter=g
WARNING for SN 40002 : DROPPED obs-filter=r
```

and similarly grepping for “ADDED” will find any (UV) filters that were added.

To study filter dropouts in more detail, five variables are include in the fitres-ntuple (ntid 7788):

- NEARDROP: index of filter that is closest to being dropped. Positive (negative) value indicates that this filter was included (excluded) after the first fit-iteration.
- DZMIN1: redshift safety margin for filter NEARDROP after 1st iteration. Positive value always indicates that it is within the valid region of the model; negative value indicates invalid region.
- DZMIN2: same as above, but after 2nd fit-iteration.
- DZ1ZMIN1 & DZ1ZMIN2: same as above, but for  $dz/(1+z)$ .

## TRAINING & TUNING CUTS:

SNe with spectroscopic redshifts ( $z_{\text{spec}}$ ) should be use to train the filter-selection cuts. For each filter labeled by index “IFILT,” plot  $z_{\text{spec}}$  when NEARDROP = IFILT and check that there are no (or very few) entries in the undefined redshift-region of the model. Also plot  $z_{\text{spec}}$  when NEARDROP = -IFILT, and you will see entries in the undefined region, but this is OK since the filter was dropped.  $z_{\text{spec}}$  values in the defined region indicates that this dropped filter could have been safely used, but was rejected based on its photoZ value from the first fit-iteration. Users will have to decide the trade off between including a particular filter more often in the defined region versus using that filter more often in the undefined region.

### 5.12.2 Initial Parameter Estimate

For SN-only photo- $z$  fits, MINUIT is likely to find a local minimum, rather than the global minimum. It is therefore important to provide initial parameter estimates before the MINUIT stage. After using the recommended OPT\_SETPKMJD=21 (Fmax-clump+BazinFit) to estimate PEAKMJD, there are two user-options for estimating initial parameters:

&FITINP

ISCALE\_COURSEBIN\_PHOTOZ = 1 # multi-dim grid search (default)

! or

NEVAL\_MCMC\_PHOTOZ = 300 # MCMC burn-in with 300 evaluations

The default option performs a multi-dimensional grid-search over redshift (0.04 bin-width), color (4 bins) and stretch/shape (3 bins). The distance parameter is estimated analytically as follows. For each grid point (photoZ, color, shape) the model fluxes are first evaluated using the distance (SALT2- $\bar{x}_0$  or distance modulus  $\bar{\mu}$ ) calculated from a reference set of cosmological parameters. To minimize the  $\chi^2$  w.r.t. the distance parameter, a distance-scale is determined as

$$d_{\text{scale}} = x_0/\bar{x}_0 \quad \text{or} \quad 10^{0.4(\mu-\bar{\mu})} = \sum_i (F_{\text{data}}^i F_{\text{model}}^i / \sigma_i^2) / \sum_i (F_{\text{model}}^i / \sigma_i)^2 \quad (32)$$

where  $\sigma_i$  is the quadrature sum of data and model errors and 'i' is the epoch index.<sup>23</sup> The resulting  $x_0$  or  $\mu$  value is used to re-evaluate the  $\chi^2$  at this grid-point. After finding these four parameter estimates, PEAKMJD is searched in 0.5 day bins (−2 to +2 days).

The second option (MCMC) processes all 5 parameters simultaneously. Initial STEP sizes are 1/3 of the range, and every 20 evaluations the STEP size is multiplied by 0.90. For each evaluation, the parameters are shifted by  $\text{STEP} \times (R_{01} - 0.5)$ , where  $R_{01}$  is a random number between 0 and 1. For each trial  $z_{\text{phot}}$ , a random distance shift (dmu) is added to the cosmology-constrained distance (−4 to +4 mag). To ensure reproducibility, the same random seed is used to initialize the random sequence for each event.

Cheater option: OPT\_PHOTOZ = 16 sets initial photoZ to spectroscopic redshift and skips the redshift grid-search. This option is for debugging only.

### 5.12.3 Smooth Model Error Transition Across Filter Boundaries

For rest-frame models such as MLCS2k2, the model error changes abruptly when a photoZ variation results in an observer-frame filter mapping into a different rest-frame filter. This abrupt change in the model error causes a small kink in the  $\chi^2$ , and can cause fitting pathologies. This pathology is treated by smoothly transitioning the model error between  $\pm 200$  Å of the transition wavelength ( $\bar{\lambda}$ ). The 200 Å range can be modified with the namelist parameter LAMREST\_MODEL\_SMOOTH. The transition weight-function is an arc-tangent that is scaled to equal 0 at  $\bar{\lambda} - 200$  and 1 at  $\bar{\lambda} + 200$ . (see function RESTFILT\_WGT for more info).

### 5.12.4 Don't Fool Yourself when PhotoZ-Fitting Simulations

When studying photoZ fits with simulations, avoid fooling yourself with simulations outside the valid wavelength range. If you use the default light curve model in the simulation, measurements outside the valid wavelength range are excluded, and therefore the fitter has the same “initialization” advantage in picking filters as using a spectroscopic redshift. For testing photoZ fits, a “wavelength-extended” model should be used as explained in §5.14. Even with a wavelength-extended model, you can fool yourself because the same model is used in both the simulation and in the fit; hence even if the extrapolated model (i.e, below 3200 and above 9500 Å for MLCS2k2) is wrong in reality, it is by definition correct when fitting the simulation. This forced correctness of the extrapolated model means that the 1st fit-iteration using all of the filters is guaranteed to give good results. A better test is to fit with a light curve model that deviates from the simulated model in the extrapolated regions.

<sup>23</sup>See R4SN\_FFSUM\_XXX variables in snlc\_fit.car.



The 1st fit-iteration should then produce biased photoZ estimates, and ideally the filter-exclusion cut will work well enough so that there is no bias after the 2nd fit-iteration.

### 5.12.5 Including the $\log(\sigma)$ Term in the $\chi^2$

The default fits minimize the usual function  $\chi^2 = \sum_i \Delta F_i / \sigma_i^2$  where  $\Delta F_i$  is the data-model flux-difference for observation  $i$ , and  $\sigma_i^2$  is the quadrature-sum of the measurement plus model errors. If the model error depends on one or more fit parameters, there is a namelist option (DOCHI2\_SIGMA = T/F) to add in the extra term,  $2 \ln(\sigma_i)$ . To avoid adding or subtracting large values to the  $\chi^2$ , the actual term added is  $\Delta\chi_{\sigma_i}^2 = 2 \ln(\sigma_i / \sigma_i^{\text{last}})$  where  $\sigma_i^{\text{last}}$  is the uncertainty from the previous fit-iteration. Typically  $\Delta\chi_{\sigma_i}^2$  adds  $\sim 1$  to the total  $\chi^2$ , but sometimes  $\Delta\chi_{\sigma_i}^2$  can be very large (positive or negative) if a fitted uncertainty undergoes a significant change between fit iterations. Fits with a large  $\Delta\chi_{\sigma_i}^2$  value can be rejected using the &FITINP namelist variable FITWIN\_CHI2SIGMA, or using SIGCHI2 variable in output FITRES table. Values of  $\Delta\chi_{\sigma_i}^2$  can be visually examined with

```
grep MINUIT fit.log | grep SIGMA | more
```

DOCHI2\_SIGMA=F by default for fits with a fixed redshift. Currently (snana v9\_30) the only model affected by setting DOCHI2\_SIGMA=T is SALT-II because the model-error depends on the stretch/shape parameter. For the default fits with DOCHI2\_SIGMA=F, the stretch parameter in the error term is fixed to the value from the previous iteration; it is therefore recommended to set NFIT\_ITERATION=3 for SALT-II fits.

For photoZ fits DOCHI2\_SIGMA=T is automatically set because the model errors change as the photoZ sweeps through different rest-frame epochs and wavelengths for each observation. If a filter is added after the first fit-iteration then  $\sigma_i^{\text{last}}$  is undefined and  $\Delta\chi_{\sigma_i}^2$  is set to zero for this filter. In this case, LREPEAT\_ITER is set to force a repeat fit-iteration with the added filter; this logic ensures that  $\Delta\chi_{\sigma_i}^2$  is defined for each filter in the last fit-iteration.

### 5.12.6 Avoiding Filter Drop-outs at High PhotoZ

A potential problem with photo- $z$  fitting is that low-redshift events can result in high-redshift  $z_{\text{phot}}$  due to filter drop-outs. For example, if the  $u$  and/or  $g$  band are outside the SED model range at high redshift, these bands are dropped and the resulting  $\chi^2$  is artificially small because it ignores the rest-frame UV region. An approximate fix is to use the same UV-extrapolation feature used in the simulation (§4.28.2),

```
&FITINP
  UVLAM_EXTRAPFLUX      = 500
  RESTLAMBDA_FITRANGE = 2000, 13000
```

In this example, the model flux at the bluest wavelength (at each phase) is linearly extrapolated to zero flux at  $\lambda = 500 \text{ \AA}$ . The RESTLAMBDA\_FITRANGE should be set so that all bands are defined at the highest allowed  $z_{\text{phot}}$  set by the PHOTOZ\_BOUND input.

### 5.12.7 4-Parameter Fit Using Host Galaxy Photo- $z$

To run a 4-parameter light curve fit with the host-galaxy photo- $z$  (instead of spectroscopic redshift), run `snlc_fit.exe` with

```
&SNLCINP
  USE_SNHOST_ZPHOT = T
```



Note that this will *not* perform a 5-parameter photo- $z$  fit, but instead uses the already determined host-galaxy photo- $z$  as a fixed redshift in the fit. If any photo- $z$  fit flags are set with `USE_SNHOST_ZPHOT=T`, the code will abort.

### 5.13 Excluding/Downweighting Filters and Epoch Ranges

Here we discuss options to exclude or down-weight data in the light curve fitter. The filter selection is based on rest-frame wavelength so that a uniform cut can be applied to different filter systems. To globally exclude the rest-frame ultraviolet (UV) region, for example, set \$SNLCINP namelist variable

```
CUTWIN_RESTLAM = 3900. 20000.
```

which excludes filter(s) whose central wavelength satisfies  $\lambda_{\text{obs}}^{\text{rest}}/(1+z) < 3900 \text{ \AA}$ . This option excludes data as if it were not part of the data file; hence the corresponding passband is not used for spectral warping,  $T_{\text{rest}}$  cuts, etc ...

One problem with the above option is that there is no way to extrapolate the model back to excluded filter and check data-model fit residuals. To visually monitor data-model residuals for the excluded region, it is better to simply down-weight rather than exclude a particular range in wavelength or epoch. A set of FUDGE\_FITERR\_XXX variables allow the user to down-weight arbitrary wavelength and epoch ranges. These &FITINP namelist variables are illustrated in the following example:

FUDGE_FITERR_TREST	= -20., 100.	! rest-frame range (days)
FUDGE_FITERR_RESTLAM	= 1000., .3900.	! wavelength range (A)
FUDGE_FITERR_PASSBANDS	= 'UBVRI'	! observer filters
FUDGE_FITERR_MAXFRAC	= 100.	! error -> 10*maxFlux

This example does essentially the same thing as the above example using “CUTWIN\_RESTLAM = 3900., 20000.” However, using the FUDGE\_FITERR\_XXX variables means that filters mapping onto the rest-frame UV region are used in the spectral warping for K-corrections, and these filters are also used in the  $T_{\text{rest}}$  sampling requirements. In evaluating the lightcurve fit- $\chi^2$ , an additional uncertainty of  $100\times$  the maximum flux (FUDGE\_FITERR\_MAXFRAC=100) is added in quadrature to each epoch-uncertainty that satisfies the RESTLAM and TREST windows, and hence such epochs are effectively excluded from the fit. Note that FUDGE\_FITERR\_PASSBANDS specifies the observer-frame filters for which the other criteria apply. If you set the observer passbands to 'U', then the RESTLAM and TREST criteria are applied only for observer-U and not the other filters. One can therefore choose to down-weight data based on filters or based on rest-frame wavelength ranges.

Here is another example in which epochs before  $-5$  days and after  $+50$  days are excluded for all filters:

FUDGE_FITERR_TREST	= -99, -5.0, +50., 999.
FUDGE_FITERR_RESTLAM	= 1000., 20000.
FUDGE_FITERR_PASSBANDS	= 'UBVRI'
FUDGE_FITERR_MAXFRAC	= 100

Two sets of “RESTLAM” windows can be defined in the same that the two “TREST” window are defined above. To downweight all measurements more easily there are two global options,

FUDGEALL_MAXFRAC	= 0.3 # all epoch, all fit-iterations
FUDGEALL_ITER1_MAXFRAC	= 0.3 # all epochs, 1st fit-iter only

where the “ITER1” option inflates the errors only on the first fit-iteration. These options may be useful in cases where the data uncertainties are smaller than the model errors, resulting in unstable fits. Inflating the errors generally results in more stable fits. The “ITER1” option is intended to gives a reliable initial-parameter estimate for the 2nd fit-iteration that uses the nominal uncertainties.

## 5.14 Rest-Frame Wavelength Range

Each SN model includes a function that returns the valid rest-frame wavelength range ( $\lambda_{\text{rest-range}}$ ) to the fitting program. There are two different ways to change the  $\lambda_{\text{rest-range}}$ , but note that you can only make the  $\lambda_{\text{rest-range}}$  *more restrictive*; i.e., you cannot arbitrarily loosen the  $\lambda_{\text{rest-range}}$  for a SN model. The two equivalent namelist options to change the  $\lambda_{\text{rest-range}}$  (Å) are

```
&SNLCINP
  CUTWIN_RESTLAM = 2000 , 25000
&END

&FITINP
  RESTLAMBDA_FITRANGE = 3500 , 9500
&END
```

The first option rejects measurements as part of the pre-fitting selection, and is useful if you want to apply this requirement without running the fit; i.e., using only the `snana.exe` program. The second option is applied during the fitting stage.

The  $\lambda_{\text{rest}}$ -ranges appear in your log-file as follows,

```
CUTWIN_RESTLAM = 2000. 25000.
SN-MODEL LAMBDA RANGE: 3200. - 9500.
USER-FIT LAMBDA RANGE: 3500. - 9500.
```

and again note that the *most restrictive* range is used. If you specify a wide open range such as 1000 to 30000, this simply tells the fitting program to use the default range.

Finally, if you really insist on changing the default  $\lambda_{\text{rest-range}}$  for a particular SN model,<sup>24</sup> you can modify the default range by editing the file

```
$SNDATA_ROOT/models/[model-subdir]/RESTLAMBDA_RANGE.DAT
```

Such changes should be used with great caution because this change affects all users. Before making such a change, consider creating a private model-version (i.e., `mlcs2k2.LAM2800`).

---

<sup>24</sup>All maintenance warranties are null & void if you change the default  $\lambda_{\text{rest-range}}$ .

## 5.15 Better peak Flux Estimate

While the flux values are from the data, the estimate of the peak flux (peakFlux) is based on the best-fit model. The peakFlux estimate can be significantly off, particularly for multi-band light curves that fit one of the colors poorly. Such peakFlux errors are evident for light curves in which the data points in a given filter lie well above or below the best-fit model. To get a better estimate of the peakFlux, one can correct for the average data/model ratio in a particular epoch-range. This correction is implemented using the `$FITINP` namelist variable

```
TREST_PEAKRENORM = -10.0, +20. # rest-frame days
```

which specifies the rest-frame range for which to include epochs in the data/model correction. The default values are 0,0  $\rightarrow$  no correction. A data/model weighted-average is taken over the epochs within `TREST_PEAKRENORM`. The weight ( $w_i$ ) at each epoch “ $i$ ” is defined to be

$$w_i \equiv [\sigma_i^2 \times (|T_{\text{rest}}| + 1)]^{-1}, \quad (33)$$

where  $\sigma_i$  is the data/model flux-ratio uncertainty based on the data-flux error (i.e., ignores the model error), and “ $|T_{\text{rest}}| + 1$ ” is an arbitrary factor (in days) used to downweight epochs away from peak.

## 5.16 Landolt $\leftrightarrow$ Bessell Color Transformations

As explained in the first-season SDSS–II results paper (Appendix B of arXiv:0908.4274), the nearby SNe Ia magnitudes are reported in the Landolt system, but there are no *UBVRI* filter responses for this system. We therefore define color transformations between the Landolt system and synthetic *UBVRI* magnitudes using Bessell (1990) filter response functions (See Eqs. B1-B2 in above reference). These color transformations can be implemented in the fitter with the `&FITINP` namelist flag

```
OPT_LANDOLT = 1 ! transform rest-frame Landolt model mags -> Bessell90
OPT_LANDOLT = 2 ! transform obs-frame Bessell90 mags -> Landolt
OPT_LANDOLT = 3 ! both of the above
```

For example, to analyze the JRK07 sample with MLCS2k2, set `OPT_LANDOLT=3`; to analyze with SALT-II, set `OPT_LANDOLT=2`. To analyze ESSENCE data with MLCS2k2, `OPT_LANDOLT=1`. In the last case, the ESSENCE *RI* filter response functions are well known, so there is no need to use Bessell90 filter responses. Note that the 2nd bit should be used only when the *UBVRI* filter response is not known. Thus, for example, do not set the 2nd bit for CFA3 & CFA4.

All of the above use BD17 as the primary reference. To use Vega, add 4 (3rd bit) to each `OPT_LANDOLT` value. You are also responsible for using the appropriate K-correction file with the matching primary reference.

## 5.17 Interpolating Fluxes and Magnitudes

There are two methods for interpolating the SN flux at a particular observation time (MJD). The first method is to use the generic 'any-LC' function from §5.5.1, and the second method is to use an SN Ia light curve model. For either method prepare a two-column file that lists each SNID and MJD to interpolate. To interpolate all SN at a particular MJD replace the SNID with the keyword 'ALL'. In the following example of a two-column input file,

```
1      53616.0
2      53610.0
2      53626.0
ALL    53640.0
```

one epoch (MJD 53616) is interpolated for SNID=1, two epochs (53610,53626) are interpolated for SNID=2, and one epoch (53640) is interpolated for all SNe. Specify input and output files with the following &SNLCINP namelist variables,

```
SNMJD_LIST_FILE = 'KECK-SDSS.LIST'
SNMJD_OUT_FILE  = 'KECK-SDSS.OUT'
```

Errors on the interpolated fluxes account for the errors and covariances among the fitted parameters. The interpolated results are dumped into a human-readable output file with keywords to simplify parsing. To interpolate the flux at peak brightness, specify  $\text{MJD} = 0$  in the `SNMJD_LIST_FILE`.

The “any-LC” function is recommended in most cases since each filter is fit separately and since a more general class of light curve shapes can be accurately fit. Note that you must run `snana.exe` instead of `snlc_fit.exe`! The &SNLCINP namelist parameters are

```
OPT_SETPKMJD = 1 # fit with any-LC function
```

Filters can be ignored, for example, setting `EPCUT_SNRMIN = 'g 99999 r 99999'` to skip the *g* and *r* bands.

When fitting with an SNIa model (2nd method) it is recommended to fit a single passband by either specifying one passband with the &FITINP namelist variable `FILTLIST_FIT`, or by downweighting the other passbands using the `FUDGE_FITERR_XXX` options (§5.13). The latter is recommended because some SNIa models return garbage if only one filter is included. Thus, to interpolate the flux in each of the *griz* passbands, four separate fits should be done. The &FITINP namelist parameters to interpolate *g*-band by downweighting the other bands are as follows:

```
FILTLIST_FIT = 'griz'
FUDGE_FITERR_TREST      = -20. 80. 0. 0.
FUDGE_FITERR_PASSBANDS = 'riz'
FUDGE_FITERR_MAXFRAC    = 100.
```

Note that you can use command-line arguments (§12.2.3) to write a wrapper that loops over the filters,

```
snlc_fit.exe myfit.nml FUDGE_FITERR_PASSBANDS riz SNMJD_OUT_FILE g.OUT
snlc_fit.exe myfit.nml FUDGE_FITERR_PASSBANDS giz SNMJD_OUT_FILE r.OUT
snlc_fit.exe myfit.nml FUDGE_FITERR_PASSBANDS grz SNMJD_OUT_FILE i.OUT
snlc_fit.exe myfit.nml FUDGE_FITERR_PASSBANDS gri SNMJD_OUT_FILE z.OUT
```

## 5.18 Fitting Rest-Frame Peak-Magnitudes and Colors

There are two ways to define rest-frame peak magnitudes ( $M^*$ ): 1) from the best-fit model and 2) the true mag. While the former is trivial to obtain after fitting a light curve, the resulting rest-frame colors are simply pegged to the SNIa model and may not reflect variations from intrinsic scatter. The true  $M^*$  and associated colors include intrinsic variations. This section focuses on obtaining the true  $M^*$  and colors by specifying the following &FITINP options for `snlc_fit.exe`,

```
FILTLIST_FITRESTMAG = 'UBV'
LAMEXTRAP_FITRESTMAG = 250 ! (A) allow this much rest-frame extrapolation
SHAPEFIX_FITRESTMAG = -0.2 ! => fix SHAPEPAR for PEAKMAG calc
DLAMTOL_FITRESTMAG = 100 ! include obs bands with 100 A of closest bands
```

The `kcor/calibration` file must include these extra (UBV) filters in addition to the observer-frame filters. Each  $M_{U,B,V}^*$  is determined by fitting only the two nearest observer-frame bands that bracket the rest-filter in wavelength. `LAMEXTRAP_FITRESTMAG` allows wavelength slop in defining the observer-frame filters, and increases the redshift range for which all of the  $M_{U,B,V}^*$  can be determined. For example, suppose that the bluest observer-frame filter is  $g$  band with a central wavelength of  $\lambda_g = 4800 \text{ \AA}$ , and the rest-frame  $U$  band has  $\lambda_U = 3600 \text{ \AA}$ . If `LAMEXTRAP_FITRESTMAG`= 0 (default) then the minimum redshift for which  $M_U^*$  can be determined is  $z_{\min} = 4800/3600 - 1 = 0.333$ ; with `LAMEXTRAP_FITRESTMAG`= 250  $\text{\AA}$  we have  $z_{\min} = 4800/(3600 + 250) - 1 = 0.247$ . Similar logic is applied to the reddest filter.

`DLAMTOL_FITRESTMAG` allows the inclusion of multiple bands with similar central wavelengths. For example, consider a survey with G and g bands, and central wavelengths of 4800  $\text{\AA}$  and 4840  $\text{\AA}$ , respectively. If g is the closest band to the desired rest-frame band, then G is excluded by default. However, with `DLAMTOL_FITRESTMAG`=100 both G and g are included.

The fitting for each SN proceeds as follows. The first “`NFIT_ITERATION`” fit-iterations are used to determine the time-of-peak ( $t_0$ ) and stretch parameter ( $s_0$ ) from a fit to all of the observer-frame bands. One additional fit-iteration is then performed for each  $M^*$  using only the two nearest bands, holding  $t_0$  and  $s_0$  fixed from the global fit. The floated color and distance parameters provide the flexibility to fit both observer-frame bands. After each two-band fit  $M^*$  is computed as follows,

$$M_X^* \equiv \text{modelMag}(T_X, t_0, s_0, \text{color}, \text{distance}) - \mu_z \quad (34)$$

where  $T_X$  is the filter-transmission for filter  $X = U, B, V$ , and  $s_0$  is replaced by `SHAPEFIX_FITRESTMAG` if this namelist parameter is set. The Galactic extinction `MWEBV` is set to zero for this rest-frame `modelMag` calculation.  $\mu_z$  is the calculated distance modulus using the known redshift and an assumed cosmology. The subtraction of  $\mu_z$  is done so that the  $M_X^*$  have reasonable values ( $\sim -19$ ), but it has no impact on the rest-colors since the same  $\mu_z$  is subtracted for each (UBV) filter. After all of the two-band fits are done, a final fit-iteration is performed using all of the filters so that the analysis variables (`Ndof`, `SNRMAX`, `FITPROB`, etc ...) correspond to the global fit.

The rest-mags are written to the `fitres`-file as `MO_X` and `ERRMO_X` where X are the rest-filter character names (e.g., U,B,V). For each filter in a 2-band fit, the maximum S/N is required to satisfy the &SNLCINP namelist cut-variable `CUTWIN_SNRMAX2`. If both bands fail `CUTWIN_SNRMAX2`, the rest-mags are not evaluated and `MO_X`=999.

## 5.19 Peak-Mag Crosschecks: FITMAGDIF

To check the best-fit model magnitudes there is an option to compute a given observer-frame magnitude in two independent ways : 1) fitting only the one band, and 2) fitting the other bands

and extrapolating the model. An example of this FITMAGDIF option is as follows,

```
FILTER_FITMAGDIF = 'u'
FILTLIST_FIT      = 'ugr'
```

The first NFIT\_ITERATION fits are done with all of the FILTLIST\_FIT (ugr) filters so that the time of peak brightness ( $t_0$ ), stretch and color parameters are well determined and fixed for the fit-iterations that follow. The next fit-iteration is done only with filter “FILTER\_FITMAGDIF” (u) in which the flux-scale ( $x_0$  or  $\mu$ ) is the only floated parameter. The final fit-iteration is done with all of the FILTLIST\_FIT (ugr) filters, but with u-band deweighted so that it contributes nothing to the  $\chi^2$  and only the g & r bands are included in the fit. The quantity MAGDIF\_u and its errors are computed as

```
MAGDIF_u = peakMag(u, extrapolate gr) - peakMag(u only)
          = peakMag(predicted)         - peakMag(measured)
```

The MAGDIF variable is in the fitres table (ntuple 7788) and also in the fitres-text output.

## 5.20 Selecting SNID(s), Field(s), and Telescope(s)

All namelist variables discussed here are in &SNLCINP.

### 5.20.1 Selecting/Ignoring SNID

By default all candidate IDs (CID) are processed. Here are some examples on how to select a range of CIDs or a list of CIDs, and to ignore a list of CIDs:

```
CUTWIN_CID      = 700, 2000      ! CID integer-range to process
or
SNCID_LIST      = 5944, 10550    ! integer list of SN to process
or
SNCCID_LIST     = '5944', '10550' ! same as above, using strings
or
SNCID_LIST_FILE = 'myCIDs.list'  ! file with list of CIDs to process;
                                ! separated by space or <CR>

or
SNCID_IGNORE    = 4524, 8151, 7017 ! list of SN to ignore
SNCCID_IGNORE   = '4524', '8151', '7017' ! same as above with strings
SNCID_IGNORE_FILE = 'reject.list'  ! list of CIDs to ignore;
                                ! separate CIDs by space or <CR>

OPT_SNCID_LIST = 1      ! ignore SN cuts & process all CIDs in list
OPT_SNCID_LIST = 2      ! if FITRES format, use SALT2 params as initial values in LCFIT
OPT_SNCID_LIST = 3      ! both of the above

MXEVT_PROCESS   = 20      ! stop processing after 20 events
MXEVT_CUTS      = 5       ! stop processing after 5 events pass cuts
```



Internally all CIDs are strings. If the CIDs are integers then you can use `SNCID_LIST` and `SNCID_IGNORE`, otherwise you must use the character-CID variables “`SNCCID_`” and put each CID in quotes. A zero or blank acts as a terminator. For example, `SNCID_LIST = 5944, 0, 1032, 10550` would process SN 5944 and ignore the rest.

`CUTWIN_CID` gives the integer range. For CIDs that are integers, you can specify the integer range without worrying about the internal string conversions. For CIDs that are strings, `SNANA` internally assigns integer CIDs that are sequential starting from 1. For example, consider the SNLS CIDs that are strings (e.g., 04D1cc); `CUTWIN_CID = 1,10` would process the first 10 SNe. However, for a survey using integer CIDs that start at 1000, `CUTWIN_CID = 1,10` would discard all SNe.

Using any of the “`_LIST`” options (e.g., `SNCID_LIST`), the analysis codes internally set `CUTWIN_CID=0,0` so that only the list CIDs are processed. Setting the 1 bit of `OPT_SNCID_LIST` ignores cuts and forces all CIDs to be processed; example use is for systematics tests with small calibration shifts that could migrate events in and out of SNR cuts. Beware that while SN-select cuts are ignored, epoch-select cuts are still applied. The 2 bit of `OPT_SNCID_LIST` reads and uses SALT2 parameters as initial values for LC fit. If `&FITINP` namelist input `INISTP_COLOR=0`, the SALT2 color parameter from the FITRES file is fixed for all fit iterations, and similarly for the other `INISTP` inputs.

Finally, `MXEVT_PROCESS` stops processing after this many events, regardless of how the other “CID” inputs are set.

### 5.20.2 Selecting SNID List with Command Line Override

To select a few CID values on the command-line, use a comma-separated list:

```
snana.exe <myInputFile>  SNCID_LIST 5,19,184
or
snana.exe <myInputFile>  SNCCID_LIST 5,19,184
or
snana.exe <myInputFile>  SNCCID_LIST 2004cx,2002cx,2005he
or
snana.exe <myInputFile>  MXEVT_PROCESS 5
or
snana.exe <myInputFile>  MXEVT_CUTS 5
```

and this syntax also works for the `snlc_fit.exe` and `psnid.exe` programs. `SNCID_LIST` works only for integers, so it is safer to always use the character-string `SNCCID_LIST`, and there is no need to use quotes for command-line options.

### 5.20.3 Selecting Fields and Overlapping Fields

By default all fields and overlapping fields are used. Using SDSS 82N and 82S fields as an example, fields are selected by

```
SNFIELD_LIST = '82S'    ! select only 82S pointings (ignore 82N)

CUTWIN_NFIELD = 1, 1    ! select only SN with no 82N/82S overlap
or
CUTWIN_NFIELD = 2, 2    ! select only SN with 82N+82S overlap
```

SNFIELD\_LIST determine which field-pointings to use for lightcurves; these fields must be specified in SURVEY.DEF, otherwise the code aborts. In the first example above, only 82S pointings/epochs are used, and overlap pointings on 82N are discarded. SNe that overlap 82S and 82N are used, but only the subset of 82S pointings are selected. Similarly, SNFIELD\_LIST='82N' would select the epochs with an 82N pointing.

CUTWIN\_NFIELD=1,1 picks out SNe in which all observations are on the same pointing; i.e., no overlaps. CUTWIN\_NFIELD=2,2 picks out only those SNe that overlap 82N and 82S.

Another example of selecting multiple fields is as follows:

```
SNFIELD_LIST = 'C1', 'C2', 'C3'
or
SNFIELD_LIST = 'C1+C2', 'C3'
or
SNFIELD_LIST = 'C1+C2+C3'
or
SNFIELD_LIST = 'C1 C2 C3'
```

where the above three commands are equivalent. Either of the last two commands can be used as a command-line override with an arbitrary number of fields.

Even if you don't use the selection options above, there are table variables (§12.1) that can be used to apply some of these selections after the fitting: NFIELD\_OVP is the number of overlapping fields for each SN, and FIELD is the name of the field(s). For SN on overlapping fields, such as 82N and 82S, FIELD = '82N+82S'. The order of the overlapping fields in the FIELD string is the same as that in SURVEY.DEF. The 'append' option in the sntable-dump utility (§12.1.3) can be used to add NFIELD\_OVP into the text-fits file. Note that the FIELD string cannot be appended to the text-fits file (sorry!).

#### 5.20.4 Selecting MJD Ranges

There are three &SNLCINP CUTWIN parameters to define MJD ranges:

```
CUTWIN_MJD          = 53600, 53700  ! use obs only in this MJD range
CUTWIN_MJD_EXCLUDE  = 53622, 53628  ! exclude obs in this MJD range
CUTWIN_MJD_INCLUDE  = 53630, 53660  ! require at least 1 MJD in this range
```

The first two CUTWIN parameters define epochs to select. The last cut (CUTWIN\_MJD\_INCLUDE) does not pick epochs, but rejects the entire light curve if there is no observation in the defined window.

#### 5.20.5 Quickly Analyzing a few SNe from a Large Sample

This section is for the text-output option only (FORMAT\_MASK = 1 or 2).

It is often useful to select a few SNe for fitting and analysis, such as for debugging a particular problem. From §5.20 above, the namelist variable SNCID\_LIST can be used to select an arbitrary subset, but the snana.exe and snlc\_fit.exe programs must read every SN data file up to the point where each SN in the list has been found. The time to simply read these data files can be relatively slow (~ minute) if a large number of data files must be screened. To read in the data files more quickly, a temporary DEBUG\_XXX version can be created where XXX are your initials or some other identifier. Just three files need to be created:

```
$SNDATA_ROOT/lcmerge/DEBUG_XXX.README
$SNDATA_ROOT/lcmerge/DEBUG_XXX.IGNORE
$SNDATA_ROOT/lcmerge/DEBUG_XXX.LIST
```

and for simulations replace “lcmerge” with “SIM” and create a sub-directory SIM\_DEBUG\_XXX with the appropriate files. The IGNORE and README files can be blank. The LIST file contains the name of each data file to analyze. You can then analyze this debug version by specifying \$SNLCINP namelist variables

```
VERSION_PHOTOMETRY = 'DEBUG_XXX'
CUTWIN_CID = 1, 100000
```

and there is no need to specify SNCID\_LIST.

## 5.21 Mag-Shifts in Zero Points and Primary Reference Star

The `snlc_fit.exe` program provides an interface to modify zero-point (ZP) offsets as well as the primary magnitudes. The primary mags can be individually adjusted using &SNLCINP namelist options

```
MAGOBS_SHIFT_PRIMARY = 'B .02 V .01'
MAGOBS_SHIFT_PRIMARY = 'B .01 V .01 R 0.01'
MAGOBS_SHIFT_PRIMARY = 'BVR 0.01'      # same as above
MAGREST_SHIFT_PRIMARY = 'B .02 V .01'
```

which shifts the primary mags by 0.02 and 0.01 for *B* and *V*, respectively. Note that separate strings are used for the observer-frame and rest-frame to allow for the same filter-character to be used in each reference frame. This option is equivalent to re-generating the K-correction tables with these shifts, but the MAG[OBS,REST]\_SHIFT\_PRIMARY option is more convenient since you can use the same K-correction tables.

There are two ways to introduce ZP shifts. First, specify ZP offsets in a file, ZPOFF.DAT, located in the `filters` sub-directory. For the SDSS AB-offsets, the file location is

```
> more $SNDATA_ROOT/filters/SDSS/ZPOFF.DAT
u -0.037 g 0.024 r 0.005 i 0.018 z 0.016
```

If ZPOFF.DAT does not exist, the ZP shifts are zero. This method is used for standardized shifts.

The second option is designed to probe the uncertainty in the zero-point offsets; an arbitrary shift can be specified with the &SNLCINP namelist string

```
MAGOBS_SHIFT_ZP = 'g .02 r .01 i .008'
MAGOBS_SHIFT_ZP = 'g .01 r .01 i .01'
MAGOBS_SHIFT_ZP = 'gri .01'      # same as above
```

Note that the MAGOBS\_SHIFT\_ZP shifts are added to those in ZPOFF.DAT.

Wavelength-dependent shifts can be applied with polynomial parameters in &SNLCINP,

```
MAGOBS_SHIFT_ZP_PARAMS      = 0, 0.02, -0.01
MAGOBS_SHIFT_PRIMARY_PARAMS = 0, 0.01, 0
```

which applies a ZP shift of  $0.02\lambda_{\text{obs}} - 0.01\lambda_{\text{obs}}^2$ , and a PRIMARY mag shift of  $0.01\lambda_{\text{obs}}$ . Note that  $\lambda_{\text{obs}}$  is the central wavelength in MICRONS, not Å, so that the **PARAMS** coefficients are about the size of the mag-shift.

## 5.22 Fudging the FLUXCAL Offsets and Uncertainties

Filter-dependent offsets and errors can be added to the calibrated fluxes and errors using the following **&SNLCINP** namelist variables,

```
FUDGE_FLUXCAL_OFFSET = 'u -0.6 g 0.4   r 1.2   i -3.7 z 2.2'
FUDGE_FLUXCAL_ERROR  = 'u 24   g -12   r 44    i 19    z -22'
FUDGE_MAG_ERROR      = 'u .01   g .011  r .009 i .01   z .018'
FUDGE_MAG_ERROR      = 'ALL 0.02'      ! add .02 mag err to all bands
FUDGE_FLUXERR_SCALE  = 'g 1.04 r 1.02'  ! scale fluxerr in g,r bands
FUDGE_FLUXERR_SCALE  = 'ALL 1.03'      ! scale all bands by 1.03
```

These fudges are intended for systematic studies; permanent changes should be made in the data files. The error fudges are added/subtracted in quadrature based on the sign of **FUDGE\_FLUXCAL\_ERROR**.

## 5.23 Updating the Filter Transmission for each SN

In 2009 the SNLS reported that their filter transmission depends on the focal plane position.<sup>25</sup> While their transmission function depends only on the radius from the center, in general the SN filter transmission can be unique for each SN. Using the **SNANA** fitting program, an SN-dependent filter transmission can be specified, although it is assumed that each transmission function is the same for all epochs. This feature is invoked by specifying an 'update' directory from the **\$SNLCINP** namelist as follows:

```
FILTER_UPDATE_PATH = 'MYPATH'
```

**MYPATH** can be a subdirectory under **\$SNDATA\_ROOT/filters**, or **MYPATH** can be the full directory name; both directories are checked, with the former having priority. This directory must contain an instruction file called '**FILTER.INFO**', along with a filter transmission text-file for each SN. Rather than giving an explicit list of filter-transmission filenames, the **INFO** file specifies the naming conventions for the filter-transmission directories and files:

```
FILTER_SUBDIR: filters-{SNID}
FILETRANS_SN:  SNtrans_*.dat
FILETRANS_REF: REFtrans_*.dat
```

The first key specifies the sub-directory name for each set of filter transmissions, and the directory name depends on the name of each SN. The next two keys specify the transmission filenames residing within each **FILTER\_SUBDIR**. The star (\*) represents the 1-letter representation for each filter. For example, the SNLS filenames would be **SNtrans\_g.dat**, **SNtrans\_r.dat**, etc. The filter

<sup>25</sup>Regnault et al., **A&A** **506**, 999 (2009).

transmission can be different for the SN and for the primary references (REF). However, if only one set of transmissions is specified (either SN or REF), then these transmissions are used for both the SN and the primary reference.

WARNING: currently this filter-update feature works only for the SALT2 model; perhaps a future SNANA version will work for rest-frame models that use K-corrections.

## 5.24 Redshift Shifts

The following &SNLCINP inputs apply systematic shifts to redshifts:

```
REDSHIFT_FINAL_SHIFT = 0.0001 ! 1. global shift to all redshifts
HOSTGAL_SPECZ_SHIFT  = 0.0002 ! 2. apply only to host specz
HOSTGAL_PHOTOZ_SHIFT = 0.003  ! 3. apply only to host photoz
```

The first option is applied globally to all redshifts, regardless of how they are measured. For a mix of host-galaxy spectroscopic and photometric redshifts, options 2 and 3 apply to the respective z-shift method. For spec-confirmed SNe that have no host-galaxy information, only the 1st option applies. All z-shifts are applied before light curve fitting.

## 5.25 Shifting the Mean Filter Transmission Wavelength

Each band can be independently shifted via &SNLCINP input

```
FILTER_LAMSHIFT = 'g -3.4 r 5.6 i 12.3'
```

## 5.26 Monitoring Fit-Jobs with “grep”

If you pipe the fitter screen dump to a log file, the unix “grep” command can be used to quickly monitor progress during the fits, as well as after the fits have completed. This is particularly useful when many fit-jobs are run in parallel so that you can monitor progress and catch aborts. Many screen outputs are explicitly designed to help monitor the job status. Below are some examples of useful grep-commands to run. A dagger (†) indicates those commands that work only when the fit-job has finished. Note that adding “| wc” to the end of a grep command will count the number of entries.

- `grep GRACE fit*.log` †  
lists the unique string ENDING PROGRAM GRACEFULLY to identify and count jobs that have finished.
- `grep " ABORT " fit*.log` †  
identifies jobs that have aborted. Note the blank space before and after ABORT to distinguish from namelist variables that include ABORT as part of the name.
- `grep "after snana" fit*.log` †  
shows the number of SN before and after SNANA cuts.
- `grep "after fit" fit*.log` †  
shows the number of SN after fitter cuts.

- `grep "PROCESS TIME" fit*.log`<sup>†</sup>  
shows total processing time.
- `grep "PASSES FIT" fit*.log`  
lists each SN that passes fit cuts.
- `grep "Cuts REJECT" fit*.log`  
lists each SN rejected by SNANA cuts.
- `grep "FAILED FIT" fit*.log`  
lists each SN rejected by fitter cuts.
- `grep ":DLMAG" fit*.log | grep pdf`  
lists the marginalized distance-modulus for each fitted light curve. Works for any fit-parameter: AV, DELTA, PEAKMJD, PHOTOZ. Include the colon, or you will be overwhelmed by the screen dump.
- `grep ":x0" fit*.log | grep fitpar`  
lists the SALT2 amplitude for each fitted light curve.

## 5.27 User SN Tags

User-defined SN tags can be specified with the `&SNLCINP` namelist variable

```
&SNLCINP
  USERTAGS_FILE = 'mytags.dat'
  ...
&END

more mytags.dat
SN:  1032  1
SN:  2033  1
SN:  2490  1
SN:  3088  2
etc ...
```

and these `USERTAG` indices will appear in the analysis ntuples. These tags may be useful, for example, to label SNe confirmed by a particular telescope.

## 5.28 Over-Riding Information in Data Files

### 5.28.1 Over-Riding Header Information: HEADER\_OVERRIDE\_FILE

For SNANA analysis programs (`snana.exe`, `snlc_fit.exe`, `psnid.exe`), here we describe how to over-ride header information in the data files without re-making the data files. This feature is useful to study the impact of data changes (e.g., redshifts and host matches) without altering a released data set. Beware that this feature is intended only for internal use by analysis teams, and should not be part of a publicly released data set; see Sec. 5.28.3 on updating data files with override information.

The header information includes host properties, peculiar velocities, redshifts (spec- $z$  and photo- $z$ ), and Galactic extinction, all of which can be modified for a particular study. To see a complete list of data keys, search any `*HEAD.FITS` data file. The input key for the analysis programs is

```
&SNLCINP
  HEADER_OVERRIDE_FILE = 'myUpdates.dat'  ! real data only
    or
  HEADER_OVERRIDE_FILE = 'myUpdates1.dat,myUpdates2.dat  ! real data only
    or
  SIM_HEADER_OVERRIDE_FILE = 'sim_overrides.dat'  ! sim data only
```

```
more myUpdates.dat
VARNAMES: CID  REDSHIFT_HELIO  REDSHIFT_HELIO_ERR  MWEBV
SN:      1346137      0.246      0.001      0.021
SN:      1346387      0.533      0.0011     0.038
etc ...
```

In the first example (`muUpdates.dat`), three header values are updated: helio redshift, the uncertainty, and Galactic extinction. For SNe missing from the update file, the original values in the data file header are preserved. This override feature does NOT work on epoch-dependent quantities, but mag and flux corrections can be applied as described below in Sec. 5.28.2. The second example illustrates a comma-separated list of table files; beware that the variables in each override file must be unique (except for CID).

Data-override variables must exist in the original data file, with the exception of photo- $z$  quantiles (§4.22.8). Thus quantiles can be overwritten if they already exist in the original data files, or appended if the original data files do not include quantile information. For quantile overrides using `HOSTGAL_ZPHOT_Qppp` (where `ppp=000, 010, ... 100`), make sure to also include an `NZPHOT_Q` column with each value set to 11.



The header-override list may include variables that are used later in BBC or cosmology fitting, but not used in light curve fitting; e.g., host-galaxy properties and peculiar velocity. To avoid losing time re-running identical light curve fits for such variable changes, it can be more efficient to make substitutions at the BBC/SALT2mu.exe stage using BBC-input

```
datafile_override=over1.dat,over2.dat,etc
```

Any variable in the input table (see `datafile` arg) can be included in an override table. For VPEC (VPEC\_ERR) changes, the Hubble diagram redshift (zHD, zHDERR) is internally re-computed by subtracting the original  $v_{\text{pec}}$  and adding the override value. To update host matches, make sure to include the following variables in the header-override file:

- All of the HOSTGAL\_XXX, except for HOSTGAL\_SB\_FLUXCAL\_[band]  
(because SB depends on SN coordinates rather than host-match)
- All of the HOSTGAL2\_XXX
- REDSHIFT\_HELIO and REDSHIFT\_HELIO\_ERR
- REDSHIFT\_FINAL and REDSHIFT\_FINAL\_ERR
- possibly VPEC

### 5.28.2 Epoch-Dependent Mag Corrections

Since photometry is typically performed separately for each passband, SED-dependent corrections are often missing for internal data releases. If SED-based corrections are computed as an after-burner task, it may be convenient to avoid re-making data files and instead read a supplemental `MAGCOR` file until a final data release is ready.

External epoch-dependent mag-corrections are applied to the `FLUXCAL`, but not to `FLUXCAL_ERR`, and thus there is an implicit assumption that changes are small ( $\sim 1\%$ ). For large changes, the data files should be re-made with the new errors as well. The syntax is

```
&SNLCINP
  MAGCOR_FILE      = 'magCor.dat'    ! data only (not for sims)
  SIM_MAGCOR_FILE = 'magCor.dat'    ! force on sims (not data)
```

```
more magCor.dat
NVAR: 5
VARNAMES:      ROW          DUM1  MAGCOR  DUM2    DUM3
ROW:  1346137-56542.271-g    23    0.0123  10.23   22.456
ROW:  1346137-56542.272-r    33    0.0094  10.12   24.679
ROW:  1346137-56542.274-i    67   -0.0025  11.98   21.023
etc ...
```

The `SNID`, `MJD` and `BAND` are glued together to form a unique `ROW`-string identifying the correction. Only the `MAGCOR` column is used, and other optional columns (`DUM1`, `DUM2`, `DUM3`) are ignored. Each `FLUXCAL` is internally multiplied by  $10^{(-0.4 \cdot \text{MAGCOR})}$ .

For public data releases, such corrections may be included in the data files. To avoid accidentally applying these corrections twice, the `MAGCOR_FILE` should include the header key

```
VERSION_ADD:  <VERSION>
```

for the data version that has the corrections included. The `SNANA` analysis codes will abort if `MAGCOR_FILE` is specified for a data version that already includes these mag-corrections. If mag-corrections have been applied to data, the corrections can be removed with

```
&SNLCINP
  MAGCOR_FILE = '-magCor.dat'
```

where the minus sign in front is a command to subtract. This subtract option works only with the `VERSION_ADD` key.

### 5.28.3 Create New Data Files with `OVERWRITE` Updates

While the data override features in § 5.28.1 and § 5.28.2 are useful for quick testing, it is not always practical to analyze data with multiple sets of data-override files, and public data releases should never use this feature. To update data files with the override information, use the `OVERWRITE` feature(s) above and also use the `REFORMAT` feature in §12.4.2. Although reformatting is typically for translating `TEXT` to `FITS` (and vice-versa), it preserves the override values and it works for `TEXT`→`TEXT` and `FITS`→`FITS`.

## 5.29 Peculiar Velocity Corrections

By default, the CMB redshifts are used for the Hubble diagram analysis. Although **SNANA** has no explicit code to compute peculiar-velocity corrections ( $v_{\text{pec}}$ ), such corrections can be made with external codes and be included in the data files with **VPEC** and **VPEC\_ERR** keys. The  $v_{\text{pec}}$  values can also be read from an external file as described in §5.28.1. The light curve fitting program (**snlc\_fit.exe**) reads  $v_{\text{pec}}$  and computes a corrected CMB redshift,

$$z_{\text{HD}} = (1.0 + Z_{\text{CMB}}) / (1.0 + V_{\text{PEC}}/c) - 1.0$$

which is written to the output tables and used by the **SNANA** program **SALT2mu.exe**.

## 5.30 SIMCHI2\_CHEAT

For simulations, the  $\chi^2$  is automatically computed in which the fitted parameters are replaced by the exact simulated parameter values. The resulting  $\chi^2$  variable is called **SIMCHI2\_CHEAT** and it is stored in the table output (ntuple for hbook, tree for root).

There is no ambiguity for fits with fixed redshifts. For photo-z fits, however, the defined filter bands based on the fitted photo-z may be incorrect for the true redshift. For example, a fitted photo-z of 0.4 would include the  $z$ -band filter for the SALT2 model, but if the true redshift is 0.1 then trying to evaluate the  $z$ -band model-mag would result in an abort because it is too red for the SALT2 model in the rest-frame. When undefined filters are detected, **SIMCHI2\_CHEAT** is set to **-NFILT\_UNDEFINED** and the  $\chi^2$  calculation is skipped to avoid the abort.

## 5.31 Cuts on true SIM\_XXX Parameters

To apply cuts on generated (true) parameters,

```
&SNLCINP
SIMVAR_CUTWIN_STRING = 'SIM_c -0.1 0.1 SIM_REDSHIFT_CMB .1 .2'
! and/or
SIM_TEMPLATE_INDEX_LIST = 202,203
! and/or
SIMVAR_CUTWIN_STRING = 'NEP_SIM_MAGOBS 3 9999' ! >=3 obs with trueFlux>0
! and/or
CUTWIN_TREST_TRUEFLUX = -20, 100 ! require trueFlux>0 in this range
```

The first option requires the true SALT2-color (for SALT2 model only) and true redshift (for any model) to satisfy the above cut-windows. Also works on **SIM\_x1**. The second option is for **NON1ASED**, **SIMSED**, and **LCLIB** models; it selects a user-defined list of template indices.

The 3rd option requires at least 3 observations with true flux > 0. The last option (**CUTWIN\_TREST\_TRUEFLUX**) requires a true positive flux in the specified **TREST** range (days). For fakes overlaid on image, these last two options are useful to avoid pathologies from missing fake overlays that leave unphysical zero-flux observations.

### 5.32 IDEAL Fits with True Flux (Sim only)

To determine the intrinsic scatter matrix from simulations ( $\Sigma_{\text{int}}$ ), this section describes how to perform “IDEAL” light curve fits that use 1) true fluxes instead of the reported fluxes with Poisson fluctuations, 2) true Galactic extinction value for MWEBV, and 3) fixes peak-MJD to its true value. The flux uncertainties are not modified with the options presented here. There are two methods for running IDEAL fits:

```
&SNLCINP                                or                                &FITINP
  USESIM_TRUEFLUX = T                      SIMFIT_IDEAL_PRESCALE = 4
```

The first option (USESIM\_TRUEFLUX) prepares IDEAL fits and works with `psnid`, `snlc_fit` or any user analysis. The second option (PRESCALE) works only with `snlc_fit`, but it performs both the IDEAL and nominal fit in the same job, thus simplifying higher-level pipelines. For example, fitting with the SALT2 model results in the following fit parameters store in the same FITRES table (TEXT,HBOOK,ROOT):

```
PKMJD c x1 x0 mB                                # Nominal
PKMJD_IDEAL c_IDEAL x1_IDEAL x0_IDEAL mB_IDEAL # IDEAL
```

The difference between IDEAL-fitted parameters and the true generated parameters can be used to compute  $\Sigma_{\text{int}}$ . For example, the mB-c element of  $\Sigma_{\text{int}}$  is compute with FITRES table elements as follows:

$$\Sigma_{\text{int}}(mB, c) = N^{-1} \sum [(mB\_IDEAL - SIM\_mB)(c\_IDEAL - SIM\_c)]$$

Since fitting every event twice doubles the CPU time, this option is enabled with an explicit pre-scale to allow reducing the CPU time if a smaller sample of IDEAL fits is adequate. In the example above, 1/4 of the events are fit twice (IDEAL plus nominal), thus increasing the CPU time by 25%. Events which do not have an IDEAL fit have their IDEAL parameter values set to 999.

## 6 Private Options

### 6.1 Creating Your Private Code

Here we describe how to create a private code version for the snana program (`snana.exe`) or the light curve fitting program (`snlc_fit.exe`). This feature is useful to write your own analysis package without the overhead of reading data files and applying selection cuts, and also to make small modification to the existing analysis codes. Modifications include writing out specific information to a file, calculating a quantity that is not available, or testing variations on algorithms in the public code. This feature is available for the fortran analysis codes, but is not available for the simulation.

There are two steps to creating your own private executable:

```
> cp $SNANA_DIR/src/snana_private.cra .
> snmake.pl snana_private
    or
> cp $SNANA_DIR/src/snlc_fit_private.cra .
> snmake.pl snlc_fit_private
```

should result in a private executable file in your directory: `snana_private.exe` or `snlc_fit_private.exe`. Now run your private version,

```
./snana_private.exe myinput.nml
    or
./snlc_fit_private.exe myinput.nml
```

You can edit your private version of `snlc_fit_private.cra` and modify `USRINI`, `USRANA` and `USREND`. The sample `USRANA` shows how to access fit results, and how to access information for each epoch used in the fit. You can also re-name the code to any other name, such as ‘myfit.cra’, and then compile an executable with the command “`snmake.pl myfit`” to produce the executable file `myfit.exe`.

In addition to adding private code into the `USR[INI,ANA,END]` routines, you can also modify the official public code. Copy any subroutine from `$SNANA_DIR/src/snana.car` or `snlc_fit.car`, paste it into your private `snlc_fit_private.cra`, and then make modifications. Once these changes are fully tested, you can request that the modified routine(s) be installed into the next public release of `SNANA`. Your changes may be included as the default, or they may be available to other users via input namelist flags. Note that modifications can also be made by checking out the entire `SNANA` product from CVS. You are welcome to check code out of CVS (`cvs co`), but please do NOT check code in without contacting the `SNANA` manager. Working with `snlc_sim_private.cra` should be much easier than working with the entire `SNANA` product.

#### WARNINGS:

- Do not trap yourself into an obsolete version of `SNANA` if you have lots of private code that is not integrated into the public `SNANA`.
- If you find yourself doing lots of cutting & pasting as part of your analysis, this is a bad sign: ask for help!
- If you find that you are doing lots of tedious/redundant operations, ask for help. Often adding just a few lines of code into `SNANA` can greatly simplify your analysis procedure.

## 6.2 Private Sim Path: PATH\_SNDATA\_SIM

By default, the simulation creates a “GENVERSION” sub-directory under `PATH_SNDATA_SIM = $SNDATA_ROOT/SIM`.

The simulated data files can be re-routed to a user-defined path with sim-input key

```
PATH_SNDATA_SIM: <path>
```

This key works in the sim-input file with interactive `snlc_sim.exe`. To submit batch jobs with the `submit_batch_jobs.sh` script (§12.2.1), this key must be in the sim-master-input file. This output re-route feature is *not* recommended, except for special reasons such as insufficient disk space under `$SNDATA_ROOT`.

The simulation automatically stores use user-defined path names in

```
$SNDATA_ROOT/SIM/PATH_SNDATA_SIM.LIST
```

so that analysis programs (`snana.exe`, `snlc_sim.exe`, `psnid.exe`) know where to check for simulated samples without user input. If a simulation needs to be moved out of `$SNDATA_ROOT/SIM`, the file above (`PATH_SNDATA_SIM.LIST`) can be manually edited.

## 6.3 Private Data Path for Analysis: PRIVATE\_DATA\_PATH

After creating or translating a new version of light curves, it is useful to run tests before copying these files to the public/official area `$SNDATA_ROOT/lcmerge`. SNANA and fitter jobs can read data (not simulations) from a private directory as follows:

```
&SNLCINP
  VERSION_PHOTOMETRY = 'myVersion'
  PRIVATE_DATA_PATH  = 'myDir'
  .
  .
&END
```

The version “myVersion” will be read from “myDir” in exactly the same way that it would have been read from `$SNDATA_ROOT/lcmerge`. Users are cautioned to use this feature only for testing, and not as long-term data storage for your analysis. For simulations, `PRIVATE_DATA_PATH` is ignored.

## 6.4 Private Model-Path: \$SNANA\_MODEL\_PATH

For a given SN model in the simulation (`GENVERSION`) or in the fitter (`FITMODEL_NAME`), the model parameters are assumed to reside in

```
$SNDATA_ROOT/models/SALT2/*
$SNDATA_ROOT/models/mlcs2k2/*
$SNDATA_ROOT/models/snoopy/*
$SNDATA_ROOT/models/SIMSED/*
etc ...
```

While these public directories are intended for stable models, a private “`setenv SNANA_MODELPATH`” directory can be defined for testing models that are not suitable for public release. If this user-defined environment variable exists, then the model is assumed to be under this path. For example, `SALT2.Guy07` would be read from

```
$SNANA_MODELPATH/SALT2.Guy07
```

## 6.5 Private Variables in Data Files

Private variables can be included in data file headers as illustrated by the following example,

```
PRIVATE(HOST_PROPERTY): 43.22
PRIVATE(PHOTOFLAG):    439
PRIVATE(SEARCH_TYPE):  27
```

These ‘PRIVATE’ keys must appear in the header before the light curve (MJD) observations. These variables are included in the FITS-translated data files (§12.4.2). Using a private fitter option (§6.1), the value of any private variable can be accessed from the function

```
REAL*8 GET_PRIVATE_VALUE  ! declare function
DVAL = GET_PRIVATE_VALUE(varName,0) ! do not abort on error
DVAL = GET_PRIVATE_VALUE(varName,1) ! abort on error
```

where `varName` is the name of any private variable. Note that `varName` can be simply `HOST_PROPERTY` or it can be ‘PRIVATE(HOST\_PROPERTY)’.

### 6.5.1 CUTWIN-selection on Private Variables

Arbitrary cuts on private variables can be applied. Using the private variable example above, cuts are defined using the `&SNLCINP` namelist string

```
PRIVATE_CUTWIN_STRING = 'HOST_PROPERTY 20.4 100.', 'PHOTOFLAG 1 600'
or
PRIVATE_CUTWIN_STRING = 'AGN_SCAN != 2' ! veto cut
```

where the first example requires values within the specified ranges, and the second example shows how to reject (veto) based on a value.



## 7 Adding a New Survey

Starting with `SNANA v6_00` you can add a new survey without modifications to the software. Primary SEDs, primary magnitudes and filter transmissions are defined via K-correction files, even for models like `SALT-II` that do not use K-corrections (but still use primary SEDs and magnitudes). A filter is defined by a single character to simplify the handling of a wide variety of output variable names that append the filter string (i.e, `MAGT0_[filter]`), and to simplify output formatting. While the `SNANA` filter definition is limited to the 1-character strings above, arbitrary filenames can be used to define the filter transmissions. There are 62 allowed filter-characters: A-Z, a-z, and 0-9. `SNANA` versions prior to `v9_00` allowed only the legacy filters *ugriz*, *UBVRI*, *YJHK*, along with 0-9. Additional filter-characters will be allowed when we all switch to using Chinese keyboards. Here are the steps for adding a new survey:

1. Add your survey and telescope to the file `$SNDATA_ROOT/SURVEY.DEF`. Check if your survey and/or telescope is already defined before making changes.
2. Add new filters in `$SNDATA_ROOT/filters`. The wavelength spacings for the filter transmissions must be uniform. If the wavelength spacings are large (several hundred Å) you should prepare a finer-binned filter set using an appropriate interpolation algorithm.
3. Generate K-correction tables using `kcor.exe`,<sup>26</sup> and see §7.1 for rules about filter names. You can leave your private K-correction table(s) in your directory where you run other jobs, or you can share official K-correction tables in `$SNDATA_ROOT/kcor/`. For initial testing, use a very coarse grid so that the tables are built quickly. Once the simulation and fitter are working, you can generate the K-correction tables with a finer grid. The grid is controlled by `REDSHIFT_BINSIZE` and `AV_BINSIZE`. WARNING: you must generate a K-correction file even if you plan to run an observer-frame fitter such as `SALT-II` that does not use K-corrections; in this case do “`kcor.exe mykcor.input SKIPKCOR`” so that the K-corrections are skipped, but the filters and primary SED are included. Finally, for rest-frame models that use K-corrections, there is a limit of 10 rest-frame filters and 62 observer-frame filters. For observer-frame models such as `SALT-II`, the limit is 62 observer-frame filters.
4. If you want to generate simulated samples, you need to prepare a simulation library. See examples in `$SNDATA_ROOT/simlib`. This is usually the most difficult part of setting up a new survey.
5. Check for an adequate rest-frame model to describe the supernova light curve.
6. If you plan to add new data files, use an existing data version as a template. To see existing versions do “`cd $SNDATA_ROOT/lcmerge ; ls *.README`”. The light-curve fitter uses `FLUXCAL = 10(11-0.4m)`. The scale-factor of  $10^{11}$  is arbitrary; you can change it, but then your distance moduli will all have a common offset, although the final cosmological parameters are not affected by the choice of scale-factor. Use a well-measured data point in each filter to get the `FLUXCAL/FLUX` ratio, and then convert `FLUX → FLUXCAL` for each measurement. If you try to convert magnitudes to `FLUXCAL`, you will have problems for small & negative fluxes.
7. Modify a sim-input and fitter-input file by substituting your survey and filters. Good luck. And don't forget to send me a post-card about your experience.

---

<sup>26</sup>Sample `kcor`-input files are in `$SNDATA_ROOT/sample_input_files/kcor`.

## 7.1 Filter Names and Rules for K-corrections

The filter names defined in the K-correction input file can be anything, but only the last character (A-Z,a-z,0-9) is propagated into the simulation and fitting program. Thus, the following filter-names are all translated into 'g': SDSS-g, SDSSg, SDSS2.5m-g.

Filters are identified and stored separately for rest-frame and observer-frame. The reference frame is implicitly defined by KCOR entries such as

```
KCOR:  Bessell-B    SDSS-g    K_Bg
```

which defines  $B$  as a rest-frame filter and  $g$  as an observer-frame filter. If a filter is not used in a KCOR entry (such as for the SALT-II model), then it is assumed to be an observer-frame filter.

Each rest-frame filter must have a unique last character, and each observer-frame filter must have a unique last character; however, the same last character can be used in both the rest and observer frames. For example, consider filter sets CSP-[ugri] and SDSS-[ugri]. These two sets cannot both be defined as observer-frame filters in the same K-correction file, but one set can be used for rest-frame filters that describe a light curve model, and the other set can be used for the observer-frame. The K-corrections defined after the "KCOR:" keyword define which filters are used for rest/observer-frame.

Consider the following example that uses the same filter character 'B'.

```
MAGSYSTEM:  VEGA      (define mag system for filters below)
FILTSYSTEM: COUNT
FILTER:     ACS_WFC_F435W-B      ACS_WFC_F435W.dat
etc  ...

MAGSYSTEM: VEGA
FILTSYSTEM: ENERGY  (('ENERGY' => Trans -> Trans/lambda)
FILTER: Bessell-B    Bessell90_B.dat    0.021
etc  ...
```

If no K-corrections are defined, then  $B$  is defined twice as an observer-frame filter and the `snlc_fit.exe` fitting program will abort because of the ambiguity. However, if a K-correction is defined using Bessell-B as a rest-frame filter, then ACS\_WFC\_F435W-B is the unambiguous observer-frame  $B$  band filter.

## 7.2 Combining Surveys

For SNIa-cosmology analyses, there are many low- $z$  samples consisting of different surveys, and different filter systems within a survey. Because of duplicate filter names (e.g., UBVR appear in multiple samples), *SNANA* requires fitting each low- $z$  sample separately, which can complicate analysis pipelines. In addition, low- $z$  samples do not include meta-data (SKY,PSF,ZP) needed create *SIMLIB* files for simulations (§4.7). To simplify analysis, and produce a *SIMLIB* file for simulations, data samples can be combined with the following example based on hypothetical low- $z$  samples:

```
combine_dataVersions.py  myVersions.input

more myVersions.dat
VERSION:  LOWZ_SET1    LOWZ/kcor_LOWZ_SET1.input    # UBVRT
VERSION:  LOWZ_SET2    LOWZ/kcor_LOWZ_SET2.input    # UBVRi
VERSION:  LOWZ_SET3    LOWZ/kcor_LOWZ_SET3.input    # uBVRgri
SURVEY_OUT:  LOWZ_COMBINED
```

The input file contains a list of data versions, and associated kcor-input file (§3) for each data version. Note that kcor-INPUT files are specified, not the fits files. The filters are listed in the comment field, but not required since the filters are read from the kcor-input files. Each kcor-input file is checked locally, and under `$SNDATA_ROOT/kcor`. The script ‘`combine_dataVersions.py`’ performs the following tasks:

- merge all kcor-input files into a combined kcor-input file. Each original filter is mapped alphabetically to “abcde...xyzABCDE...XYZ01..89.” For the example data versions above, the filter remapping is

```
LOWZ_SET1:    UBVRT    -> abcde
LOWZ_SET2:    UBVRi    -> fghij
LOWZ_SET3:    uBVRgri  -> klmnop
```

These 3 samples include 16 unique filter bands, which are mapped to 16 unique characters: “abcdefghijklmnop.” To help preserve the original filter name, the auto-generated combined kcor-input file defines filters as follows,

```
FILTER:  LOWZ_SET1-U/a  LOWZ_SET1_U.dat  9.69
FILTER:  LOWZ_SET1-B/b  LOWZ_SET1_B.dat  9.82
FILTER:  LOWZ_SET1-V/c  LOWZ_SET1_V.dat  9.77
FILTER:  LOWZ_SET1-R/d  LOWZ_SET1_R.dat  9.44
FILTER:  LOWZ_SET1-I/e  LOWZ_SET1_I.dat  9.23
```

Thus we can still see the original filter name before the slash; *SNANA* only needs the last character in the filter string, which is a,b,c,d,e for the above FILTER keys.

- produce combined data set with filter names replaced as indicated in the kcor-input files. The combined survey name is specified by the SURVEY\_OUT key in the `myVersions.dat` file above. Input data versions must be in TEXT format.
- create *SIMLIB* file from data. For samples without meta-data (SKY,PSF,ZP), such as low- $z$ , some assumptions are needed. First, the PSF is fixed to 1” FWHM. Second, SKYMAG vs. wavelength is taken from an old LSST-DEEP simulation. For space-based surveys (HST,JWST,WFIRST), the assumptions are modified: PSF is 0.2”, and SKYMAG vs. wavelength is from WFIRST simulation. The zeropoint (ZP) for each observation is computed in order to match the measured S/N in the data.

To run light-curve fitting on the combined version, use the auto-generated kcor file and specify all bands in the `&FITINP` name-list with

```
FILTLIST_FIT = 'abcdefghijklmnop'
```

Similarly, run the simulation using the same kcor file and sim-input key

```
GENFILTERS:   abcdefghijklmnop
```

The SALT2-fitted parameters do not depend on how the filters are named and neither does the cosmology fitting step. The main inconvenience with the remapped bands is defining the spectroscopic selection function for the simulation. For example, defining  $\epsilon_{\text{spec}}$  as a function of the original *B*-band is really a function of the newly-defined *b, g, l*- bands in the combined data file. There are a few SNANA features to overcome this inconvenience:

1. For simulations, the  $\epsilon_{\text{spec}}$  map can be defined as a logical-or of bands,

```
NVAR: 2 # obsolete key starting v10_70
VARNAME: b+g+l SPECEFF # peakMag for B band
SPECEFF: 12.10 1.0000
SPECEFF: 12.30 1.0000
SPECEFF: 12.50 1.0000
SPECEFF: 12.70 0.998
etc ...
```

which is equivalent to defining 3 identical maps, each with a different band.

2. for the output SNANA and FITRES tables, the filter band names can be re-mapped back to their original names using the following `&SNLCINP` namelist input:

```
SNTABLE_FILTER_REMAP =
'afk->U bgl->B chm->V n->g di->r ej->i'
```

This feature has no effect on fitting, as the fit still uses all 16 distinct bands. However, the output tables are only a function of the re-mapped bands “UBVgri”. Thus instead of output peak-mag table columns ‘m0obs\_b, m0obs\_g, m0obs\_l,’ the REMAP feature results in just one column, ‘m0obs\_B,’ to replace the original 3 bands.

3. While the combined data version has a new name (e.g., ‘LOWZ\_COMBINED’), each original survey name is stored as a `SUBSURVEY_NAME`. `IDSURVEY` in the output tables is based on the sub-survey (`LOWZ_SET1`, `LOWZ_SET2`, `LOWZ_SET3`), allowing for studies to correlate with each input sample.

In principle, this script can be used to combine all data samples (e.g., low-*z* + SDSS + SNLS + PS1 + DES + ...). The kcor-file and light-curve fitting would be fine. However, the auto-generated SIMLIB file is based on rough guesses for missing meta-data. For surveys that provide the meta-data, it is better to use a proper SIMLIB with random sky locations.

## 8 Photometric Classification

### 8.1 psnid.exe

A separate program called “psnid.exe” (Photometric SN id) performs photometric classification using light curve templates. This program has the same `&SNLCINP` namelist as the `snana.exe` and `snlc_fit.exe` programs so that reading light curves and applying selection requirements is done the same way. Instead of defining a `&FITINP` namelist for the `snlc_fit.exe` program, there is a `&PSNIDINP` namelist with declarations and definitions in `$SNANA_DIR/src/psnid.car`. The `psnid.exe` architecture allows for arbitrary methods based on SNIa and CC templates. The templates are created with the simulation program (`snlc_sim.exe`) as described in §4.39. The current `psnid.exe` method is based on [12], and is called “Bayesian Evidence with Supernova Templates” (BEST); other methods can be added in `psnid.exe` using either C or fortran functions. Example namelist files are in

```
$SNDATA_ROOT/sample_input_files/psnid
```

and the main namelist keys are as follows

```
&PSNIDINP
  METHOD_NAME      = 'BEST'
  FILTLIST_FIT    = 'griz'
  OPT_ZPRIOR      = 0          ! 0=flat, 1=Zspec, 2=Zphot(HOST)
  FITRES_DMPFILE  = 'PSNID_DES.fitres' ! text-output (one row per SN)
  PRIVATE_TEMPLATES_PATH = 'myDir' ! optional private path for templates
  TEMPLATES_SNIa  = 'GRID_DES_SALT2.FITS'
  TEMPLATES_NONIa = 'GRID_DES_NONIA.FITS'
  FILTLIST_PEAKMAG_STORE = 'ri'      ! store peakmag for each model

etc ...
```

The default template location is “`$SNDATA_ROOT/models/psnid`” unless `PRIVATE_TEMPLATES_PATH` is specified. In addition to these control keys, there are many variables (see `psnid.car`) to control the detailed behavior of the classification algorithm.

The multi-CPU distribution script (`submit_batch_jobs.sh` ; see §12.2.1) can be used in the same manner as for `snlc_fit.exe` by specifying an additional key

```
JOBNAME: psnid.exe
```

at the top of the namelist file.

### 8.1.1 Preparing Photometric Templates for psnid.exe

SN templates for both Ia and NONIASED are prepared with standard sim-input files. The script

```
$SNANA_DIR/util/sim_SNgrid.pl
```

is convenient for processing multiple sim-jobs and organizing the output. See top of script for usage instructions.

The simulation input file (for `snlc_sim.exe`) is the same as for a normal simulation job, but with the following additional keys:

GENSOURCE:	GRID	# make sure to remove RANDOM GENSOURCE
NGRID_LOGZ:	50	# logarithmic redshift bins
NGRID_SHAPEPAR:	10	# Delta or x1 or dm15 ...
NGRID_COLORPAR:	2	# AV or color
NGRID_COLORLAW:	1	# RV or Beta
NGRID_TREST:	56	# GENRANGE_TREST
GRID_FORMAT:	FITS	# TEXT or FITS

The standard `GENRANGE_XXX` keys give the range for each parameter.

### 8.1.2 Redshift Priors for psnid.exe

There are three choices for a redshift prior in psnid using the `&PSNIDINP` namelist parameter `OPT_ZPRIOR`:

OPT_ZPRIOR		data header
Value	prior	keyname
-----		
0	flat/default	---
1	best/spectro	REDSHIFT_FINAL
2	host photo-z	HOSTGAL_PHOTOZ

where the above table shows which redshift key from the data header is used. Note that `REDSHIFT_FINAL` should correspond to the best available redshift, usually a spectroscopic redshift of either the SN or the host. However, if only a host photo-z is available then `REDSHIFT_FINAL = HOSTGAL_PHOTOZ` and `OPT_ZPRIOR` values of 1 and 2 will give the same result. For `OPT_ZPRIOR=1` you can select the redshift precision with namelist variable “`CUTWIN_ZERR= zmin,zmax.`”

The photo-z result implicitly assumes that the redshift prior information is independent of the SN light curve. Thus beware when setting `REDSHIFT_FINAL` to the SN photo-z; in this case setting `OPT_ZPRIOR=1` results in a photo-z that is strongly correlated with the input [SN] redshift, and hence the photo-z error is likely to be underestimated.

### 8.1.3 Rate Priors for psnid.exe

By default there is a flat rate prior such that the evidence is  $\exp^{-\chi_i^2/2}$ , where  $\chi_i^2$  is the best-fit chi-squared for the  $i$ 'th template (SNIa or SNCC). A rate prior can be used to compute the evidence as  $W_i \times \exp^{-\chi_i^2/2}$ , where  $W_i$  is the relative rate. The rate prior options can be defined in the `&PSNIDINP` namelist as

```
OPT_RATEPRIOR = 1  ! default is 0 (OFF)
ZRATEPRIOR_SNIA  = 2.6E-5, 2.2, 1.0  ! alpha, beta, Zmax (default)
ZRATEPRIOR_NONIA = 6.8E-5, 3.6, 2.0  ! alpha, beta, Zmax (default)
```

where `ZRATEPRIOR_XXX` define the redshift-dependent rate model as

$$R(z) = \alpha(1 + z')^\beta \quad (35)$$

with  $z' = z$  for  $z < Z_{\max}$  and  $z' = Z_{\max}$  for  $z > Z_{\max}$ . The  $Z_{\max}$  option allows giving a flat rate at high redshift where the rate-uncertainty is large. In general one needs to specify only `OPT_RATEPRIOR=1` since the default `ZRATEPRIOR_XXX` parameters are reasonable.

For SNIa,  $W_i = R(z)$ . For SNCC we have  $W_i = R(z) \times f_i$ , where  $f_i$  is the NONIA fraction (i.e., weight) defined in the sim-input file used to generate the GRID. The  $f_i$  are internally renormalized so that  $\sum_i f_i = 1$ .



## 8.2 Nearest Neighbor Method

This method follows that used in [13]. For this discussion we consider SN classification based on nearest-neighbor (NN) distances defined by redshift ( $z$ ), color ( $c$ ) and shape ( $s$ ), where  $c$  and  $s$  are fitted parameters from `snlc_fit.exe`. However, parameters from any light curve fitting program (e.g., `psnid.exe`) can be used. The NN distance ( $d_i$ ) between a SN from the data (real or mock) and the  $i$ 'th SN in the simulated training sample is

$$d_i^2 = \frac{(z - z_i)^2}{\Delta z_{\max}^2} + \frac{(c - c_i)^2}{\Delta c_{\max}^2} + \frac{(s - s_i)^2}{\Delta s_{\max}^2} \quad (36)$$

where  $\Delta z_{\max}$ ,  $\Delta c_{\max}$ ,  $\Delta s_{\max}$  are parameters optimized in the NN-training process described below. We count neighbors in the training set as the number of SN with  $d_i < 1$ ; hence the  $\Delta_{\max}$  parameters are the maximum allowed deviations to be included as a neighbor.

The simulation-based training procedure can be executed with

```
$SNANA_DIR/util/NEARNBR_pipeline.pl
```

and the input-file instructions are given at the top of this perl script. This script executes 5 serial stages: 1) simulate two large MC samples, REF and TRAIN, 2) fit the MC-REF sample, 3) fit and train using the MC-TRAIN sample, 4) determine optimal NN parameters ( $\Delta z_{\max}$ ,  $\Delta c_{\max}$ ,  $\Delta s_{\max}$ ) to maximize purity $\times$ efficiency. 5) apply training to data and simulation. While the `NEARNBR_pipeline.pl` script executes all of these stages, it may be useful to run the steps manually at least once to better understand the procedure. These five steps are described below in more detail:

1. Generate TWO large simulated samples, each including a mix of SNIa and SNCC. Use best estimates of redshift-dependent rates to get the correct CC/Ia ratio. One simulation serves as the training sample, while the other serves as a mock data sample. In principle one simulated sample could serve both purposes, but using two independent samples avoids odd statistical artifacts.
2. Run fitting program on the simulated training sample, and save the output `ascii/FITRES` file. If using `split_and_fit` on multiple simulated versions, the key “COMBINE\_ALL\_FLAG: 1” is useful to catenate all of the `ascii/fitres` files.
3. Run fitting program on simulated mock data sample with the following snana namelist,

```
&NNINP
  NEARNBR_TRAINFILE_PATH = 'path'
  NEARNBR_TRAINFILE_LIST = 'ascii/fitres file from previous step'
  NEARNBR_SEPMAX_VARDEF =
    'z .005 .14 .005   c .02 .30 .01   x1 .30 .80 .02'
  NEARNBR_TRUETYPE_VARNAME = 'SIM_TYPE_INDEX'
  !NEARNBR_SEPMAX_IGNORE = 'z x1'  ! optional disable list
&END
```

Note that `NEARNBR_SEPMAX_VARDEF` specifies a 3-dimensional grid of  $\Delta z_{\max}$ ,  $\Delta c_{\max}$ ,  $\Delta s_{\max}$ . For example,  $\Delta c_{\max}$  runs from 0.02 to 0.30 with a bin-size of 0.01. The total number of

bins in the above example is  $27 \times 28 \times 25 = 18,900$ . Be careful not to define outrageously large grids that cause memory problems. Either `HFILE_OUT` and/or `ROOTFILE_OUT` is required to define an output hbook and/or root file. The `NNINP` namelist turns on special NN tables needed to optimize the  $\Delta_{\max}$  parameters. See `sntools_earnbr.c[h]` for more details. `SEP_MAX` variables can be disabled with `NEARNBR_SEP_MAX_IGNORE`. This disable feature is convenient for using the batch script `split_and_fit` to run multiple trainings with different size `VARDEF` lists; specify the complete list in `NEARNBR_SEP_MAX_VARDEF` and then use the command-line override `NEARNBR_SEP_MAX_IGNORE` to disable one or more variables. In the above example, `z` and `x1` would be disabled leaving only 1 variable (`c`) for training. In addition to redshift, color and shape parameters, rest-frame peak-mags (§5.18) can also be specified in `NEARNBR_SEP_MAX_VARDEF`; e.g., `'MO_B .3 0.8 0.05'`.

4. Use output tables from previous step to maximum the Figure-of-Merit defined by

$$\text{FoM} = \text{Efficiency} \times \text{Purity} = \frac{N_{\text{true}}^{\text{Ia-tag}}}{N_{\text{all}}^{\text{Ia}}} \times \frac{N_{\text{true}}^{\text{Ia-tag}}}{N_{\text{true}}^{\text{Ia-tag}} + W_{\text{false}} N_{\text{false}}} \quad (37)$$

where  $N_{\text{true}}^{\text{Ia-tag}}$  is the number of correctly classified SNIa, and  $N_{\text{false}}$  if the number of incorrectly classified SNIa. This optimization is done with the `snana` program

```
earnbr_maxFoM.exe <HFILE_OUT argument from previous stage>
or
earnbr_maxFoM.exe <ROOTFILE_OUT argument from previous stage>
```

You will get a screen dump showing the optimized  $\Delta_{\max}$  values, each with a  $W_{\text{false}}$  grid of 1, 3, 5. A classified SNIa from the mock data sample requires that a majority of nearest neighbors (with  $d_i < 1$ ) in the training sample are true SNIa. To avoid statistical problems with few neighbors, the SNIa-fraction must be  $1\sigma$  above 50%. For example, 3 SNIa among a total of 5 neighbors has a majority-significance of  $(0.6 - 0.5)/(\sqrt{3}/5) = 0.3\sigma$ ; this is below the  $1\sigma$  requirement and is hence flagged as “unclassified.” Generating larger training samples reduces the number of unclassified SNe.

5. To apply the trained  $\Delta z_{\max}$ ,  $\Delta c_{\max}$ ,  $\Delta s_{\max}$  values on data, use the same `NNINP` namelist above, but input the trained values as follows,

```
NEARNBR_SEP_MAX_VARDEF = 'z .10   c 0.13   x1 0.62'
```

The output `ntuple/tree` will include the following variables:

```
NN_ITYPE      ! best integer type (corresponding to SIM_ITYPE_INDEX)
NN_NCELL      ! number of training SN in cell with d_i < 1
NN_PROB_IA    ! Type Ia  fraction in cell
NN_PROB_II    ! Type II  fraction in cell
NN_PROB_IBC   ! Type Ibc fraction in cell
```

## 9 Light Curve Models

Here we discuss the available light curve models *classes* for the simulation and light-curve fitting program. This is brief a technical discussion on how to use the models in SNANA; a reference for each model is provided for more details. While each model class described below can be used for simulations, only the semi-analytic SNIa models can be used for light-curve fitting with the `snlc_fit.exe` program; these fitting models (MLCS2k2, SALT-II, SNooPy) include `&FITINP` namelist information in addition to `sim-input` keys. Simulated output data from any model class can be fit with the `snlc_fit.exe` program.

GENMODEL specification is based on a directory path (class=SALT-II,SIMSED,NONIASED,BYOSED<sup>27</sup>) or a file (class=NONIAGRID,LCLIB). Examples are

```
# models based on directory: model class name is between slash and dot
GENMODEL:  [PATH]/SALT2.JLA-B14
GENMODEL:  [PATH]/SIMSED.SNII-MOSFIT
GENMODEL:  [PATH]/NONIASED.UV2IR

GENMODEL:  BYOSED [AnyPathName]    # option without PATH name restriction
GENMODEL:  BAYESN [AnyPathName]    # idem

# models based on file; no restriction on PATH or fileName
GENMODEL:  LCLIB      [PATH]/fileName
GENMODEL:  NONIAGRID  [PATH]/fileName
GENMODEL:  SIMLIB     # use MAG column in SIMLIB_FILE argument
```

An environment variable can be used as part of the [PATH]; e.g.,

```
GENMODEL: $DES_ROOT/models/SIMSED.TEST
```

Note that the model class must be specified between the last slash and a dot so that both class the path are parsed from a single argument. The BYOSED class has an option to remove path-name restriction as shown above.

Many model parameters are described by Gaussian or asymmetric Gaussian distributions. For parameter “XXX” the following input keys specify the distribution:

```
GENPEAK_XXX:  <PEAK>      (or legacy key GENMEAN_XXX)
GENRANGE_XXX: <MIN> <MAX>
GENSIGMA_XXX: <SIGNEG> <SIGPOS>
GENSKEW_XXX:  <SKEW>
```

The GENRANGE values truncate the distribution. The GENSIGMA key has two values to specify an asymmetric (or symmetric) Gaussian distribution. GENSKEW is used to define a value-dependent sigma,  $\sigma \rightarrow \sigma \times |\text{skew} \times (x - \text{Peak})|$ , where the sign of GENSKEW determine which side of the peak to add the longer tail. GENSKEW typically results in a larger tail compared with an asymmetric Gaussian.

---

<sup>27</sup><https://byosed.readthedocs.io/en/latest>

## 9.1 Host Galaxy Extinction

The following host-galaxy extinction parameters can be included with any of the SN models below. RV and AV specifications are required for MKCS2k2 and SNooPy, and optional for the other models. The color law (e.g., SFD98, Fitzpatrick99) is the same as that chosen for Galactic extinction (see OPT\_MWCOLORLAW in §4.21).

Simulation input keys for `snlc_sim.exe` :

```
GENPEAK_RV:      xxx      # peak prob dust parameter
GENRANGE_RV:     xxx  xxx  # min and max limits for RV generation
GENSIGMA_RV:     xxx  xxx  # lo & hi Gaussian sigmas

GENRANGE_AV:     xxx  xxx  # CCM89 V-band extinction
GENTAU_AV:       xxx      # dN/dAV = exp(-AV/xxx)
GENSIG_AV:       xxx      #      += Guass(AV,sigma)
GENRATIO_AVO:    xxx      # Gauss/exp ratio at AV=0

# instead of selecting AV from distribution, here E(B-V)
# is randomly picked so that AV = RV*E(B-V)
GENRANGE_EBV_HOST: xxx  xxx
GENTAU_EBV_HOST:  xxx
GENSIG_EBV_HOST:  xxx
GENRATIO_EBV_HOST: xxx
```

## 9.2 MLCS2k2

Reference: Jha, Riess, Kirshner, **AJ 659**, 122 (2007). Note that host-galaxy extinction parameters (for AV,RV) are required from §9.1.

Simulation input keys for `snlc_sim.exe` :

```
GENPEAK_DELTA:    xxx          # shape  parameter
GENRANGE_DELTA:   xxx   xxx
GENSIGMA_DELTA:   xxx   xxx
```

&FITINP namelist variables for `snlc_fit.exe` :

```
OPT_SNXT          = 1    ! Use CCM89 + ODonnell94 update
SCALE_COVAR       = 4.1  ! scale cov matrix
OPT_LANDOLT       = 1    ! 1=>transform Bessell90 <=> Landolt with color transf.
                   ! 3=> same for mlcs model & nearby-Landolt mags

OPT_PRIOR_AV      = 1    ! 0=> switch off AV prior
NGRID_PDF         = 11   ! marginalize NGRID per variable (0 => fit min only)
NSIGMA_PDF        = 4    ! initial guess at integration range: +- 4 sigma
OPT_SIMEFF        = 1    ! use simulated eff as part of prior
PRIOR_AVEXP       = 0.3   ! tau of exponential AV prior
PRIOR_AVRES       = 0.005 ! smooth Gauss rolloff for AV<0.
PRIOR_MJDSIG      = 10.   ! Gauss prior on MJD at peak

INISTP_RV         = xxx   ! 0 => fix RV to INIVAL_RV
INIVAL_RV         = 2.2   !
INISTP_AV         = xxx   ! 0 => fix AV = INIVAL_AV in fit; else float
INIVAL_AV         = xxx
INISTP_SHAPE      = xxx   ! 0 => fix DELTA to INIVAL_SHAPE; else float
INIVAL_SHAPE      = xxx

PRIOR_DELTA_PROFILE = xxx, xxx, xxx, xxx ! grep snlc_fit.car for details
```

### 9.3 SALT-II (J. Guy et al., A&A 466, 11, 2007)

Simulation input keys for `snlc_sim.exe` :

```
GENPEAK_SALT2x1:   xxx           ! peak PDF for shape parameter
GENSIGMA_SALT2x1:  xxx  xxx       ! sigma-lo and sigma-hi
GENRANGE_SALT2x1:  xxx  xxx       ! generation range

GENPROB2_SALT2x1:  xxx           ! optional PROB(2nd peak)/All
GENPEAK2_SALT2x1:  xxx           ! optional 2nd peak PDF
GENSIGMA2_SALT2x1:  xxx  xxx       ! optional sigmas

GENPEAK_SALT2c:    xxx           ! peak PDF for color parameter
GENRANGE_SALT2c:    xxx  xxx
GENSIGMA_SALT2c:    xxx  xxx

# mag = mB* + alpha*x1 - beta*color
GENPEAK_SALT2BETA:  3.2          ! color coeff
GENSIGMA_SALT2BETA: 0 0          ! default is no beta smearing
GENRANGE_SALT2BETA: 0 5          ! restrict if SIGMA is non-zero
SALT2BETA_cPOLY:    b0,b1,b2 ! polyFun of c; overrides GENPEAK_SALT2BETA

GENPEAK_SALT2ALPHA: 0.14         ! x1 coeff
GENSIGMA_SALT2ALPHA: 0 0.0       ! default is no alpha smearing
GENRANGE_SALT2ALPHA: 0 0.3       ! restrict if SIGMA is non-zero
```

and special grid keys for BBC are described in §10. Note that host-galaxy extinction parameters (AV,RV) are optional from §9.1.

To avoid transcription errors, `x1` and `c` populations can be selected from a list of asymmetric-Gaussian models as follows,

```
GENPOP_ASYMGAUSS: $SNDATA_ROOT/models/SALT2/POPULATIONS.DAT SK16_G10_HIZ
```

and `SK16_G10_HIZ` can be replace with other models in this file. For testing, a private `POPULATIONS.DAT` file can be used. For population models that depend on other variables (e.g., host mass), or cannot be described by an asymmetric Gaussian, use the more general `GENPDF_FILE` option (§ 4.32).

&FITINP namelist variables for snlc\_fit.exe :

```

INISTP_COLOR    = xxx    ! 0 => fix color to INIVAL_COLOR; else float
INIVAL_COLOR    = xxx
INISTP_SHAPE    = xxx    ! 0 => fix x1 to INIVAL_SHAPE; else float
INIVAL_SHAPE    = xxx

PRIOR_MJDSIG    = xxx          ! Gaussian prior on MJD at peak
PRIOR_SHAPE_RANGE = xxx, xxx    ! flat prior on x1 (prevents crazy values)
PRIOR_SHAPE_SIGMA = xxx          ! Gauss rolloff at edges of flat prior

OPT_COVAR = 0    ! 0 => COV-diag only
                ! 1 => COV fixed during fit
                ! 2 => COV re-calculated for each chi2 in fit

SALT2alpha      = xxx    ! to compute approx mu-resid; does not affect fit
SALT2beta       = xxx    ! idem

```

Note that the INISTP\_XXX and INIVAL\_XXX parameters are specified only to fix these parameters in the fit. If not specified, these parameters are floated in the fit.

### 9.3.1 Simulating $\alpha, \beta, \gamma$ Grid for SALT2mu/BBC

For SALT2mu-BBC, the “biasCor” sample is generated on a grid of  $\alpha, \beta, \gamma$  in order to dynamically interpolate the bias-correction at each fitting step. The sim-input keys are as follows:

```

BIASCOR_SALT2ALPHA_GRID:  0.10  0.20
BIASCOR_SALT2BETA_GRID:   2.50  3.50
BIASCOR_SALT2GAMMA_GRID:  0.0   0.10

# or ... below is legacy method requiring 4 keys per variable
GENPEAK_SALT2ALPHA:    0.14
GENSIGMA_SALT2ALPHA:   1E8   1E8
GENRANGE_SALT2ALPHA:   0.10  0.20
GENGRID_SALT2ALPHA:    2      # <=== only 2 allowed for BBC

GENPEAK_SALT2BETA:     3.2
GENSIGMA_SALT2BETA:    1E8   1E8
GENRANGE_SALT2BETA:    2.5   3.5
GENGRID_SALT2BETA:     2      # <== only 2 allowed for BBC

```

BIASCOR\_SALT2ALPHA\_GRID and BIASCOR\_SALT2BETA\_GRID specify  $2 \times 2$  grid for BBC interpolation. If  $\gamma$  were implemented the same way as for  $\alpha$  and  $\beta$ , BBC could only fit a step function with a  $M_{\text{host}}$ -split at exactly the same value used in the biasCor sample. To allow for an arbitrary standardization function of  $M_{\text{host}}$  in the BBC fit, the  $\gamma$  parameter is treated in a different manner compared with  $\alpha$  and  $\beta$ . BIASCOR\_SALT2GAMMA\_GRID specifies two grid-points to randomly generate mag-offsets. This is not quite  $\gamma$  because it has no  $M_{\text{host}}$  dependence, but in the BBC fit these mag offsets are associated with  $\gamma$  and  $M_{\text{host}}$ , where  $\gamma$  is the maximum SNIa mag-splitting.



### 9.3.2 Propagating Calibration Systematics from SALT2 Training

The batch-submit script (`submit_batch_jobs.sh`) includes TRAINOPT options to apply calibration systematics for the SALT2 training process; these calibration shifts (primary mag and filter wavelength) are recorded in the `SALT2.INFO` file as follows:

```
MAGSHIFT:  SDSS g  0.01
MAGSHIFT:  SDSS z -0.01
MAGSHIFT:  CFA2 B  0.01
WAVESHIFT: SDSS r  10   # Angstroms
```

Starting with SNANA version v11\_02b, the SNANA simulation (`snlc_sim.exe`) and light curve fit program (`snlc_fit.exe`) read and propagate these shifts. This feature captures the coherent effect of calibration errors in data samples used in both training and cosmology. The `MAGSHIFT` and `WAVESHIFT` keys are enabled by default; to disable these keys,

```
# fit-input file
&FITINP
  ENABLE_MAGSHIFT_SALT2 = F  ! disable MAGSHIFT
  ENABLE_WAVESHIFT_SALT2 = F  ! disable WAVESHIFT
  ALLOW_NEGFLUX_SALT2   = F  ! if Flam<0; Flam=0 (test only)

# sim-input file
GENMODEL_OPTMSK:  4  ! disable MAGSHIFT
GENMODEL_OPTMSK:  8  ! disable WAVESHIFT
GENMODEL_OPTMSK: 12  ! disable both
GENMODEL_OPTMSK: 16  ! if Flam<0; Flam=0 (test only)
```

## 9.4 SNooPy

Reference: C. Burns et al., arXiv:1010.4040. Note that host-galaxy extinction parameters (for AV,RV) are required from §9.1.

Simulation input keys for `snlc_sim.exe` :

```
GENPEAK_DM15:    xxx          # shape parameter
GENRANGE_DM15:   xxx  xxx
GENSIGMA_DM15:   xxx  xxx
```

&FITINP namelist variables for `snlc_fit.exe` :

```
OPT_PRIOR_AV     = 1    ! 0=> switch off AV prior
NGRID_PDF        = 11   ! marginalize NGRID per variable (0 => fit min only)
NSIGMA_PDF       = 4    ! initial guess at integration range: +- 4 sigma
OPT_SIMEFF       = 1    ! use simulated eff as part of prior
PRIOR_AVEXP      = 0.3   ! tau of exponential AV prior
PRIOR_AVRES      = 0.005 ! smooth Gauss rolloff for AV<0.
PRIOR_MJDSIG     = 10.   ! Gauss prior on MJD at peak
PRIOR_SHAPE_RANGE = 0.7, 2.0 ! constrain DM15 in this range
PRIOR_SHAPE_SIGMA = 0.7, 2.0 ! Gauss roll-off sigma for DM15 prior
INISTP_RV        = xxx   ! 0 => fix RV to INIVAL_RV
INIVAL_RV        = 2.2   !
INISTP_AV        = xxx   ! 0 => fix AV = INIVAL_AV in fit; else float
INIVAL_AV        = xxx
INISTP_SHAPE     = xxx   ! 0 => fix DELTA to INIVAL_SHAPE; else float
INIVAL_SHAPE     = xxx
```

Without a tuned ATLAS library (for gsl), the SNooPy generator is very slow such that a single light curve fits takes several minutes. To speed up the generator, the SNooPy model can be parameterized on a three-dimensional grid (filter, epoch,  $\Delta M_{15}$ ) using the GRID option from §4.39. This grid is specified by the GRIDFILE keyword in the SNooPY.INFO file that resides in the same directory as the model templates; both the simulation and fitter interpolate the GRID for each set of parameters. Also note that SNooPy returns a relative flux normalized to one at peak; the conversion to absolute magnitude is given for each filter in the SNooPY.INFO file.

## 9.5 SIMSED

A SIMSED model is an ensemble of SED time series, where the ensemble spans an arbitrary set of parameters characterizing the object. SIMSED models can be derived from specialized explosion-model codes (e.g., MOSFIT, Sedona, Pheonix ...), or determined from high-resolution spectroscopic data. The SIMSED model is implemented in the SNANA simulation, but is not included in a fitting code. However, simulated data using SIMSED can be fit with SNANA fitting codes (`snlc_fit.exe`, `psnid.exe`) the same way as for real data. SIMSED models tend to be much larger than SCDATA\_ROOT and are thus available through specialized releases such as PLAsTiCC.<sup>28</sup> A few examples in the public SCDATA\_ROOT are here,

```
$SCDATA_ROOT/models/SIMSED/SIMSED.SNANA_tester      # GCD explosion
$SCDATA_ROOT/models/SIMSED/SIMSED.KNovae_BarnesKasen2013 # theory KN
$SCDATA_ROOT/models/SIMSED/SIMSED.GW170817_AT2017gfo  # GW170817 KN
```

Each directory above includes an “SED.INFO” file listing each SED and the corresponding parameters. The only limit to the number of parameters (and SEDs) is the amount of memory on your computer. An example of an SED.INFO file is as follows:

```
# optional keys:
FLUX_SCALE:      1.000      # global flux scale (e.g., to fix units)
RESTLAMBDA_RANGE: 2500 15000 # valid range of <lamObs>/(1+z)
OPTMASK_TOSHIFT_PEAKMAG: 0   # do NOT time-shift PEAKMAG to DAY=0
MAG_ERR:         0.1        # not used
MINSLOPE_EXTRAP_LATE: 0.05  # force min mag/day slope for late-time extrap
LOGZBIN: 0.05          # force logz bins to reduce storage

# required keys
NPAR: 6
PARNAMES: SN_INDEX MNI COSANGLE MBSED DM15SED TEXPL
SED: GCD2D_Ni0.47_Pre80_1.SED 1 0.47 -0.967 -18.350 0.571 -21.628
SED: GCD2D_Ni0.47_Pre80_8.SED 2 0.47 -0.500 -18.413 0.574 -20.977
SED: GCD2D_Ni0.47_Pre80_1.SED 3 0.47 -0.033 -18.426 0.654 -21.398
SED: GCD2D_Ni0.47_Pre80_2.SED 4 0.47 +0.500 -18.400 0.767 -21.385
etc ...
```

Users prepare the SED.INFO file, along with each SED time-series file with format

```
epoch(days)    wavelength(A)    flux(erg/cm^2/s/A at 10pc) .
```

The wavelength binning must be uniform, but the epoch binning can be non-uniform. If the fluxes have incorrect units, the FLUX\_SCALE key can be used to make a global unit conversion. For each SED, there is a default internal time-shift applied such that the bolometric flux is maximum at  $T = 0$ , and this rest-frame epoch corresponds to PEAKMJD in the data header.

In cases where the explosion time is well defined (e.g., triggered event from LIGO or ICE-CUBE), it may be useful to leave the original  $T = 0$  definition in each SED file by specifying “OPTMASK\_TOSHIFT\_PEAKMAG: 0” in the SED.INFO file. With this option, beware that input

<sup>28</sup><https://zenodo.org/records/6672739>

GENRANGE\_PEAKMJD and output PEAKMJD correspond to the explosion time, not the time of maximum brightness.

MINSLOPE\_EXTRAP\_LATE forces extrapolated mags to get fainter with time; this feature is useful if late-time model fluctuations result in extrapolations that give brighter mags at later times.

The default redshift binning in log-space has LOGZBIN=0.02. For models consuming significant memory, LOGZBIN can be increased to reduce memory.

The first parameter with \_INDEX in the name can be used to select random indices as shown below. The next two parameters (MNI and COSANGLE) are the physical parameters for generation; the remaining three *baggage* parameters (see below) depend on the first two and they are inertly passed along to the output tables, just as a small pebble in your food is passed through the digestive system.

To simulate a SIMSED model, the distribution for each physical parameter must be specified in the sim-input file as follows,

```
SIMSED_PARAM:  MNI          # mass of Ni56
GENPEAK_MNI:   0.9          # mean of bifurcated Gaussian
GENRANGE_MNI:  0.47 1.26    # generation range
GENSIGMA_MNI:  0.4  0.25    # bifurcated Gaussian
    and/or
SIMSED_GRIDONLY:  COSANGLE      # cosine of viewing angle
GENPEAK_COSANGLE:  0
GENRANGE_COSANGLE: -0.96  0.96
GENSIGMA_COSANGLE:  1.E7  1.E7  # large sigmas => flat distribution

# optional covariances among parameters
SIMSED_REDCOR(MNI,COSANGLE): -0.26 # optional reduced covar; -1 to +1
    or
SIMSED_COV(MNI,COSANGLE): -1.34 # optional covar

# other GRIDONLY options=
SIMSED_GRIDONLY:  SEQUENTIAL  # sequential generation of grid values
    or
SIMSED_GRIDONLY:  SN_INDEX    # pick random SN_INDEX
    or
SIMSED_GRIDONLY:  SN_INDEX(3,5,6,9) # pick random among these SN_INDEX values

SIMSED_USE_BINARY:  1 # create binarys if they don't exist
SIMSED_USE_BINARY:  2 # force creation of SED.BINARY
SIMSED_USE_BINARY:  4 # force creation of flux-integral binary table
SIMSED_USE_BINARY:  6 # force creation of both binarys
SIMSED_PATH_BINARY:  <path for flux-table binary file>
```

Specify only those parameters that are used in the generation. For the SIMSED\_PARAM keyword (MNI), the simulation interpolates synthetic light curve magnitudes as a function of the explosion-model parameter MNI, resulting in a continuous distribution of the specified bifurcated Gaussian. For the SIMSED\_GRIDONLY keyword (COSANGLE), only values at the grid nodes are generated, and the specified bi-Gaussian distribution is respected; each randomly chosen parameter is 'snapped'

to the nearest grid value. If bi-Gaussian is not specified, a flat `COSANGLE` distribution is generated. This `GRIDONLY` option may be useful in cases such as a flag that specifies a random ignition point, and therefore continuous interpolation makes no sense. Un-specified parameters are treated as “baggage” parameters. These parameters are ignored in the generation, but the interpolated values are computed and stored along with the other parameters.

A correlation between any pair of parameters can be introduced with either a reduced correlation key (`SIMSED_REDCOR`) or a covariance key (`SIMSED_COV`). Default correlations are all zero, and correlations are allowed only for symmetric Gaussian profiles. If correlations between more than 2 parameters are specified, the full off-diagonal correlation must be specified, noting that `GENSIGMA_XXX` define the diagonal covariances. For example, correlations between 3 parameters require 3 correlation keys; correlations between 4 parameters require 6 correlation keys.

“`SIMSED_GRIDONLY: SEQUENTIAL`” steps through each grid-value sequentially, and there is no need to specify parameter names or their distributions. The first generated SN uses the first SED on the grid, the second SN uses the second value, etc. The number of generated SNe is internally set to be the number of SEDs.

While “`SIMSED_GRIDONLY: KN_INDEX`” selects a random `KN_INDEX` among the entire SED set, “`SIMSED_GRIDONLY: KN_INDEX(3,5,6,9)`” selects a random `KN_INDEX` among the subset 3,5,6,9. The subset feature works only if the column name includes an index sub-string (`INDEX` or `index` or `INDX`), and if the values are integers. Attempting the subset feature on `MNI`, for example, results in an abort.

All `SIMSED` parameters (“baggage” and for generation) are automatically included in the output table(s) and in the `SIMGEN_DUMP` list (§4.37.2). An explicitly defined `SIMSED` parameter in the `SIMGEN_DUMP` list will cause the simulation to abort because of a redundant parameter.

### 9.5.1 Arbitrary Distribution using `SIMSED` Weights

If the desired distribution is more complex than bifurcated Gaussian or picking a random SED, there are two mechanisms to assign an arbitrary selection weight for each SED. The first method is to include a `WGT` column in the `SED.INFO` file. The second method is to define a separate weight map in the sim-input file using key

```
SIMSED_WGTMAP_FILE: <wgtmap file>
```

The `WGTMAP` file has the same form as the `HOSTLIB_WGTMAP_FILE` in §4.22.4 and Fig. 12, except that there is no `SNMAGSHIFT` column for the `SIMSED_WGTMAP`. The weight map file works whether or not there is a `WGT` column in the `SED.INFO` file.

### 9.5.2 Binary `SIMSED` Files

The `SIMSED` initialization takes  $\sim 1$  sec per SED, and is somewhat time-consuming for 100’s or 1000’s of SEDs. About half the time is reading the SED text files, and the other half is doing the flux-integrals as a function of passband, redshift, Trest, and SED surface. To greatly speed up this slow initialization, two internal binary files are created the first time a new `SIMSED` model is simulated. The first simulation must be interactive; batch jobs abort to avoid multiple cores writing to the same binary file.

The first binary file contains the SEDs (`SED.BINARY`), and it is stored in the same model (`MMM`) directory as the SED text files, `$SNDATA_ROOT/models/SIMSED/MMM`. This `SED.BINARY` file is automatically used by any `SNANA` user who specifies the `MMM` version.

The second binary file is the filter-specific flux-integral table, and this survey-specific file is stored in the directory specified by `SIMSED_PATH_BINARY`. The validity of each binary file is verified internally; if there is an inconsistency between the two binary files and/or the requested survey parameters, the simulation will abort and recommend removing the old binary file(s) so that new ones can be created. A similar abort occurs if the binary flux-integral table has a time-stamp that is earlier than the SIMSED model or earlier than the K-cor file used to define the primary reference and filter transmissions.

To simplify creation of binary files for multiple SIMSED models,

```
make_simsed_binaries.py -H # get help on input config file
```

Beware that this script uses the force-create options.

If you are having problems with the binary files and just want to use the text files, the use of binary files can be switched off with

```
snlc_sim.exe mysim.input SIMSED_USE_BINARY 0
```

Finally, host-galaxy extinction parameters (for AV,RV) are optional from §9.1.

### 9.5.3 How to generate Spectra and True SED with SIMSED

The `SIMSED` model class pre-computes flux-integrals for each passband, phase and redshift, and does not hold the SEDs in memory. The advantage is that all of the model fluxes can be stored in memory, enabling more flexible selection algorithms among the SED templates. The disadvantage is that spectra and true SEDs cannot be generated.

For generating spectra or true SEDs for a `SIMSED` class, a simple work-around is to transform a `SIMSED` model into a `NONIASED` model (9.6) using utility

```
convert_SIMSED_to_NONIASED.py -h
```

which uses the same SEDs to define model class for both `SIMSED` and `NONIASED`, the latter of which can be used to generate spectra and true SEDs. Beware that the `NONIASED` model does not read the physical parameters and thus selection criteria is more limited compared to the original `SIMSED` model.

## 9.6 NONIASED

While the Type Ia light curve models are based on a parametric equation or photometric templates, the “NONIASED” models are based on smoothed light curves and spectral templates. A spectral template time-series corresponds to a particular (well-observed) SN where a composite spectrum is warped to match the observed photometry. In addition to non-Ia SNe, this feature can be used to simulate peculiar Ia, theoretical models, or any transient object.

The observer-frame “NONIASED” model assumes that each rest-frame SED has been warped to match the photometry of the underlying light curve. The observer-frame magnitudes are computed directly from the SED the same way as for SALT2, and in fact using the same software tools. The `KCOR_FILE` key is needed to read in the filters and primary reference. Optional host-galaxy extinction (from  $R_V$  and  $A_V$ ) is computed at  $\bar{\lambda}_{\text{obs}}/(1+z)$ , where  $\bar{\lambda}_{\text{obs}}$  is the central wavelength of each filter; this approximation is numerically accurate to about 0.01 mag. The distribution of  $R_V$  and  $A_V$  is controlled by the parameters described in §9.1 and §9.2.

Publicly available NONIASED templates are given in `$SNDATA_ROOT/models/NONIASED`. Each `NONIASED.XYZ` directory contains a `NON1A.LIST` file, and a sample `SIMGEN_INCLUDE_NON1A.INPUT` file that lists properties for each NONIASED as described below. You can include this file as-is using the `INPUT_FILE_INCLUDE` key, or copy it locally and make modifications.

As explained below, the user selects NONIASED templates using the integer indices in the `NON1A.LIST` file. As more NONIASED templates become available, the `NON1A.LIST` files should be updated by the relevant experts. The NONIASED model is specified with the following sim-input keys,

```
GENMODEL: $SNDATA_ROOT/models/NONIASED/NONIASED.V19_CC+HostXT

# or more generally for any path
GENMODEL: $PATH/NONIASED.[XYZ]

NONIASED_KEYS: 5 INDEX  WGT  MAGOFF  MAGSMEAR  SNTYPE
NONIASED:      2      0.2   0.0     1.2         2
NONIASED:      3      0.2  -0.2     0.8         2
NONIASED:      4      0.4  -0.6     0.9,0.5      3
etc ...
```

The `GENMODEL` base directory name must be of the form `NONIASED.[XYZ]` where `XYZ` is an arbitrary suffix. Following the `GENMODEL` specification, each SED template is assigned a weight (for relative rate), mag-offset (`MAGOFF`), and Gaussian mag-smear (`MAGSMEAR`). The legacy keys “NON1A” and “NON1A\_KEYS” have the same meaning as `NONIASED` and `NONIASED_KEYS`, respectively. The SED index is specified by “`SIM_TEMPLATE_INDEX`” in the data files and `fitres-tables`.

To process all SEDs with the same weight, magoff and mag-smear, set the first index to zero as follows:

```
NONIASED_KEYS: 5 INDEX  WGT  MAGOFF  MAGSMEAR  SNTYPE
NONIASED:      0      1.0   0.0     0.5         2
```

which automatically loops over all SEDs in the `NON1A.LIST` file.



The `NON1ASED_KEYS` are used to specify additional parameters that depend on `NON1ASED` type.

- **INDEX** is the index in the `NON1A.LIST` file.
- **WGT** are relative rates. Since the weights are re-normalized to sum to unity, the first 1/4 of the generated SNe use `INDEX = 2`, the second 1/4 use `INDEX = 3`, and the latter 1/2 use `INDEX = 4`.
- **MAGOFF** is a magnitude offset applied to all passbands, and enables adjusting the luminosity function to match data.
- **MAGSMEAR** is a Gaussian  $\sigma$  to generate coherent intrinsic mag fluctuations (i.e, equivalent to `GENMAG_SMEAR` for SNIa). Each random mag shift is stored in the data file (`SIM_MAGSMEAR_COH` key) and in the `SNTABLES`. Comma-separated values specify two sigmas for bifurcated Gaussian; `MAGOFF` is the distribution peak, not the mean.
- **SNTYPE** is a spec-confirmed typing-index that appears after the `SNTYPE` keyword in the `SNDATA` files (see §4.6 for `SNTYPE` details). In the above example, `NON1ASED` indices 2 & 3 are both assigned `SNTYPE=2`; `NON1ASED` index 4 is assigned `SNTYPE=3`.

Each `INDEX` is generated sequentially based on a pre-computed number of events per `INDEX`: *i.e.*, the `NON1ASED` indices are *NOT* randomly mixed. The sequential generation by `INDEX` is done for speed, and avoids re-initializing templates multiple times. It is therefore crucial to analyze the *entire* simulated sample in order to have the correct mixture of `NON1ASED` types. While the `NON1ASED` indices are processed sequentially, random SNIDs can be assigned as described in §4.36. With random SNIDs, any subset of the simulation is a truly random subset.

Since the SEDs are read into memory, this model class is compatible with `TAKE_SPECTRUM` keys (§4.25).

### 9.6.1 Peculiar SNIa

Peculiar SNIa (e.g., 91bg, 91T, Iax) are simulated the same way as `NON1A`, with an important caveat: the rate-vs-redshift for peculiar Ia is different than for `NON1A` (core collapse). There are three input modifications for peculiar Ia:

1. In the sim-input file, the `'NON1ASED:'` keys are replaced with `'PEC1ASED:'` (or `'PEC1A:'`)
2. In the `NON1A.LIST` file, the `'NON1A:'` keys are replaced with `'PEC1A:'` keys.
3. In the sim-input file, the rate-vs-redshift model for peculiar-Ia is defined with the `'DNDZ_PEC1A:'` key. The arguments following this key have the same meaning as the arguments following the `'DNDZ:'` key (§4.23) which defines the `NON1A` rate model.

### 9.6.2 Force Single NON1ASED Index

To select a specific `NON1ASED` index without modifying the sim-input file,

```
snlc_sim.exe <inputFile> NON1A_INDEX_FORCE 4 NGENTOT_LC 3
```

which will generate 3 events using only `NON1A` index 4. The `NON1A_INDEX_FORCE` key is allowed only as command-line override; if this key is found in a sim-input file, the simulation will abort.

## 9.7 NON1AGRID

This is a model of pre-computed observer-frame magnitudes on a grid of redshift, rest-frame epoch, and template index. Compared to the `NON1ASED` model, the advantages of the `NON1AGRID` model are 1) the input grid can be created by non-SNANA codes using more sophisticated models, and 2) the `NON1A` index is randomly picked for each event, instead of the sequential selection for `NON1ASED`. The syntax for this model is

```
GENMODEL:  NON1AGRID  <GRIDFILENAME>
```

where `GRIDFILENAME` can reside either in your current working directory, include a full path, or reside under

```
$SNDATA_ROOT/models/NON1AGRID
```

An input GRID file can be made from the `NON1ASED` model as described in §4.39; simply remove the `SN1a` model keys and add the `NON1A` keys from §9.6. The `MAGOFF` values are included in the mag calculations, but `MAGSMEAR` is not. When using the `NON1AGRID` model, the `MAGSMEAR` values are applied with a Gaussian random number per event.

## 9.8 FIXMAG and RANMAG

These flat-lightcurve models are not intended to reflect an astrophysical transient, but are instead intended for debugging or generating fake magnitudes to overlay on images. Examples are as follows:

```
GENMODEL:  fixmag  20      # every obs mag=20
GENMODEL:  fixmag  20:24   # random obs mag between 20 & 24
GENMODEL:  ranmag   20:24   # same as above

GENMODEL:  FIXMAG  -19     # obs mag = -19 + MU
GENMODEL:  FIXMAG  -19:-17 # obs mag = ran(-19:-17) + MU
```

In the first case, all observer-frame magnitudes are 20. The 2nd and 3rd cases are equivalent, where the observer-frame mag for each event is randomly selected between 20 and 24. The same mag is used at all epochs, but a different random mag is chosen for each event. The range of fixed-mag epochs is determined by the sim-input key `GENRANGE_TREST`. For these observer-frame models, `GENRANGE_REDSHIFT` is ignored.

The upper case `FIXMAG` specifies rest-frame mag for which the distance modulus is added. For this option, `GENRANGE_REDSHIFT` must be specified.

## 9.9 SIMLIB: Read True Mags from SIMLIB File

This model option does not compute true magnitudes, but instead reads the true magnitudes from the last column of the `SIMLIB` file. An example use of this feature is to simulate mags of “fake” SN overlaid on images. The redshift, peakMJD, and `GALID` are automatically read from the `SIMLIB` headers, and the original `GALID` is used to model host noise. Sim-input file syntax:

```
GENMODEL:  SIMLIB      # use MAG column in SIMLIB_FILE argument
```

## 9.10 LCLIB: Galactic Transients

### 9.10.1 Overview

Galactic transient models include three general classes:

1. RECURRING-NONPERIODIC (e.g., AGN)
2. RECURRING-PERIODIC (e.g., RRlyrae)
3. NON-RECURRING (e.g., micro-lens)

These models are simulated using a TEXT-file library and a list of template epochs specified in the sim-input file as

```
GENMODEL:  LCLIB  MYMODEL.TEXT  1+2+3+4
GENMODEL_MSKOPT:  <mask>
```

LCLIB (Light Curve LIBrary) is the generic model type in SNANA, MYMODEL.TEXT is the text-file library (Fig 17) and 1+2+3+4 is a list of relative epochs to average for the template magnitude. GENMODEL\_MSKOPT enable options described in §9.10.4.

### 9.10.2 Defining the Library

The TEXT library begins with a global header specifying the name of the SURVEY, and a list of broadband FILTERS. Since there is no redshifting, these LCLIB models are defined as pre-computed light curves (broadband magnitudes vs. time), and not as an SED time series. The SURVEY & FILTERS in the header are compared against the user-request to prevent accidental mixing (e.g., cannot use an LSST library to simulate DES). The global header also includes a model name and list of model parameters names (MODEL\_PARNAMES), for which floating-point (or integer) values are given for each LCLIB event. These model parameters are not used by the simulation, but they are written into the output data files to be used in offline analyses. A series of comment fields should be used to provide model references and to define the model parameters. An optional key NEVENT is used to re-use each event a total of  $\text{NUSE} = \text{NGENTOT} / \text{NEVENT}$  times in order to reduce read-time. Without the NEVENT key, the simulation would wrap around the library NUSE times, and waste time reading each event multiple times. Finally, the RECUR\_CLASS key specifies which of the three Galactic transient classes.

After the global header there is a list of LCLIB “events,” where each event includes an event header followed by a light curve in all filters. The event header contains the following information: 1) event ID (for debugging), 2) number of rows for the light curve, including T+S (NROW), 3) parameter values after PARVAL key, 4) optional coordinate, either RA&DEC or l&b, 5) optional angle-matching radius if event depends on Galactic coordinates.

Following the header, the light curve rows are defined with the keys “T:” (Template) and “S:” (Search). The LCLIB time steps can be non-uniform, and should be optimized to limit the library size. For example, the time step should be small during periods of rapid variation, and then increase during periods of slow change. Also note the recommended precision (%.3f for mags) to reduce file size.

For each of the three Galactic transient classes above, there are specific LCLIB features that must be included as described below:

1. **Recurring-NonPeriodic** events require explicit template (T:) epochs prior to the search (S:) epochs. The time-span of T-epochs should correspond to how templates are made in the survey, and the S-range must be at least as long as the survey. If the S-range is longer than the survey time, a random LCLIB start-time used. For example, consider a 3 year survey and a 5 year S-range: the simulation selects a random start-time within the first two years of the LCLIB event.
2. **Recurring-Periodic** events require search (S:) epochs covering exactly one cycle. Explicit template epochs are forbidden in the library because the simulation internally computes template epochs using the periodicity. The first and last S-epoch must have identical magnitudes, otherwise the simulation aborts.
3. **Non-Recurring** events require a single template (T:) epoch since all previous epochs must have the same quiescent magnitude. For the last S-epoch, the magnitudes should match the template epoch, indicating that the light curve has finished.

### 9.10.3 Implementation

Here are a few details about how the simulation interprets the library defined in §9.10.2. Note that "simulated event" (or generated event) refers to the light curve generated on the survey cadence, while "LCLIB event" refers to the library events illustrated in Fig. 17.

For each simulated light curve with duration  $\Delta T_{\text{survey}}$ , the corresponding range of the LCLIB event is extracted and interpolation is used to compute the true mag at each simulated epoch. For recurring-nonPeriodic, the LCLIB event duration must be greater than  $\Delta T_{\text{survey}}$  (if not, sim aborts). For recurring-periodic, the LCLIB event cycle is internally repeated until it spans  $\Delta T_{\text{survey}}$ . For non-recurring events that are shorter than  $\Delta T_{\text{survey}}$ , the undefined epochs are given template magnitudes.

#### LCLIB Event Probabilities

Each recurring event is assumed to have the same probability. Non-Recurring events are fundamentally different because any given event has an arbitrary start time. For example, an event with a 1,000 year duration can start any time within the previous 1,000 years and still leave a signal. To describe the implementation we first define

$$\Delta T_{\text{Tot}} \equiv \Delta T_{\text{survey}} + \Delta T_{\text{evt}} \quad (38)$$

where  $\Delta T_{\text{evt}}$  is the LCLIB event duration. A key assumption for the library is that the rate per unit time is the same for each LCLIB event, and thus an arbitrary rate of 1 per  $\Delta T_{\text{survey}}$  is assigned. The mean number of generated events is therefore  $\langle N_{\text{gen}} \rangle = \Delta T_{\text{Tot}} / \Delta T_{\text{survey}}$ . A Poisson generator picks  $N_{\text{gen}}$  and the LCLIB event is re-used  $N_{\text{gen}}$  times, each time with a different cadence and sky location. For a 3-year survey ( $\Delta T_{\text{survey}} = 3$ ), a 1 month event ( $\Delta T_{\text{evt}} = 0.083$ ) results in  $\langle N_{\text{gen}} \rangle = 1.028$ . For the same survey, a century-long event ( $\Delta T_{\text{evt}} = 100$ ) results in  $\langle N_{\text{gen}} \rangle = 34.33$ . Beware that including LCLIB events with vastly different  $\Delta T_{\text{evt}}$  values results in very large asymmetries in how many times each LCLIB event is used.

#### Template Mags

A template magnitude is determined for each simulated event and each band. The last argument after the `GENMODEL` key (§9.10.1) determines a list of user-requested template epochs to average, and the "T:" rows in the LCLIB are used to interpolate mag values at the user-requested template epochs. Each template mag is converted to flux, the flux values are averaged, and the average flux

is converted back into a template mag to use for subtraction. Variations in observing conditions are NOT included in template-mag computation.

For long-duration non-recurring events ( $\Delta T_{\text{evt}} \gg \Delta T_{\text{survey}}$ ) that start well before the survey, the true template mags are not observed. In this case, the event mags a few months prior to the survey are used to compute the template mags. For short-duration non-recurring events ( $\Delta T_{\text{evt}} \ll \Delta T_{\text{survey}}$ ), the true template mag is used. For intermediate cases ( $\Delta T_{\text{evt}} \sim \Delta T_{\text{survey}}$ ), the true template mag is used if the event starts after the survey begins; otherwise the template is computed from light curve mags shortly before the survey.

### Angle Matching

The optional `ANGLEMATCH` or `ANGLEMATCH_b` key in the event header specifies how close the simulated sky location must be to the LCLIB event. The simulation will keep reading LCLIB events until an angle-match is found. This option allows Galactic event profiles to depend on sky location. `ANGLEMATCH` specifies a radius (degrees), while `ANGLEMATCH_b` applies only to Galactic latitude ( $b$ ), and ignores the longitude coordinate.

To increase the efficiency for finding an LCLIB event satisfying `ANGLEMATCH_b`, a symmetry for events at  $-b$  and  $+b$  is used to require

$$| |b_{\text{SIM}}| - |b_{\text{LCLIB}}| | < \text{ANGLEMATCH\_b} \quad (39)$$

where  $b_{\text{SIM}}$  is for the simulated event and  $b_{\text{LCLIB}}$  is for the LCLIB event.

### Parameter Selection

To select a limited range of `PARVAL` values from the library, add the following key(s) to the sim-input file:

```
LCLIB_CUTWIN:  <PARNAME>  <CUTMIN> <CUTMAX>
```

Note that this option does not reduce the number of generated events; rather it reduces the LCLIB size by excluding LCLIB events.

#### 9.10.4 GENMODEL\_MSKOPT Options

- `GENMODEL_MSKOPT += 1`: ignore `ANGLEMATCH`.
- `GENMODEL_MSKOPT += 8`: After selecting RA,DEC from DNDB distribution, replace with RA,DEC in LCLIB, and also update MWEBV. This option is useful if DNDB rate model is inadequate, but *beware* that incorrect cadences are used with this option; i.e, the cadence from SIMLIB-{RA,DEC} is used even though the LCLIB coordinates are different. Note that a more accurate strategy is to create a SIMLIB cadence library with the correct RA,DEC distribution (and `GENMODEL_MSKOPT=0`).
- `GENRANGE_MJD: <MJDmin> <MJDmax>` : select MJD window

```

DOCUMENTATION:
  PURPOSE: model XXX galactic transient
  REF:
    - AUTHOR: A. Author et al 2020 (few word summary/reminder)
      ADS:    https://ui.adsabs.harvard.edu/abs/XXX
  USAGE_KEY: GENMODEL
  USAGE_CODE: snlc_fit.exe
  NOTES:
    - e.g., created from another code
    - e.g., model limitations
  PARAMS:
    - PAR1 is bla bla
    - PAR2 is bla bla
DOCUMENTATION_END:

# global header info
SURVEY: LSST
FILTERS: ugrizY
MODEL: MY_MODEL_NAME
MODEL_PARNAMES: PAR1,PAR2,PAR3 # comma-separated strings, no spaces
NEVENT: <NEVENT>
RECUR_CLASS: RECUR-NONPERIODIC (or RECUR-PERIODIC or NON-RECUR)

START_EVENT: <ID1> # internal integer ID
NROW: <NROW> RA: <RA> DEC: <DEC>
PARVAL: <VAL1>,<VAL2>,<VAL3> # comma-separated or space-separated
ANGLEMATCH: 10.0 # optional (deg) to match with cadence library
T: <DAY %7.4f> <mag_u %.3f> <mag_g> . . . . <mag_Y>
T: <DAY %7.4f> <mag_u %.3f> <mag_g> . . . . <mag_Y>
S: <DAY %7.4f> <mag_u %.3f> <mag_g> . . . . <mag_Y>
S: <DAY %7.4f> <mag_u %.3f> <mag_g> . . . . <mag_Y>
etc ...
END_EVENT: <ID1>

# ... continue next event

# Multiple key options
# NOBS: and NROW:
# MODEL_PARNAMES: and MODEL_PARAMETERS:

```

Figure 17: TEXT-library format for LCLIB model type.

### 9.10.5 Special MODEL\_PARNAMES Features

The MODEL\_PARNAMES are read and passed to output data files and simgen-dump file. These parameters are not used to generate events, except for two special features:

- **MWEBV (mwebv):** indicates that MWEBV has been computed and applied to the model light curves, perhaps using a 3D dust model. The simulation reports MWEBV based on OPT\_MWEBV (e.g., SFD98), but does not make a redundant MWEBV correction to the true magnitudes (SIM\_MWEBV=0). To avoid a MWEBV-naming conflict, the LCLIB-MWEBV is renamed MWEBV\_LCLIB for the data files and simgen-dump file.
- **REDSHIFT (redshift):** indicates a true non-zero redshift for the model light curve (default LCLIB redshift is  $z = 0$ ), and can be used with a HOSTLIB. This feature may be convenient for extraGalactic models such as AGN.



## 9.11 PySEDMODEL: Python SED models

To accomodate a broader class of SED models in the simulation, there is a C-python interface for python SED models (PySEDMODEL) to return i) rest-frame SED at requested phase, and ii) relevant internal parameters. The rest-frame SED is used by the simulation C-code<sup>29</sup> to compute broadband fluxes and noise in the same way as any other SED model (e.g., SALT2, NON1ASED ...). The internal parameters are not used by the C-code, but are passed to the output data files and/or SIMGEN\_DUMP file. There are currently 3 python models under development which can be called with the following syntax:

```
GENMODEL:  BYOSED  [path]  # Build-Your-Own SED
GENMODEL:  SNEMO   [path]  # based on SNFactory data
GENMODEL:  BAYESN  [path]  # optical+NIR

GENMODEL_MSKOPT: [mask] # integer option or mask
GENMODEL_ARGLIST: 'key0 val0 key1 val1 key2 x0,x1,x2,x3 etc ...'
```

The GENMODEL key is followed by a PySEDMODEL name and path. The path contains formatted information & instructions that are parsed by the init function in the python code.

The last two keys allow passing additional options to the python code, both in the form of an integer flag or char-string. These arguments can be passed on the command line to override default behavior, e.g.,

```
snlc_sim.exe <myInputFile> GENMODEL_MSKOPT 8
or
snlc_sim.exe <myInputFile> GENMODEL_ARGLIST 'TAU_AV 0.33 ZETA 4.3'
```

The simulation C code does not parse these argument, but simply passes these arguments to the python init function.

---

<sup>29</sup>PySEDMODEL does not connect with SNANA light curve fitting codes.

## 10 Computing Distance Moduli from BBC Method: `SALT2mu.exe`

The `SNANA` program `SALT2mu.exe` reads SALT-II fitted parameters, performs a global fit for  $\alpha, \beta, \gamma$ , which are SNIa standardization parameters associated with stretch ( $x_1$ ), color ( $c$ ), and host-galaxy mass ( $M_{\text{host}}$ ), respectively. `SALT2mu.exe` also fits for distance offsets in redshift bins, and the output includes binned distance moduli. The `SALT2mu` program can implement the “BEAMS with Bias Corrections” (BBC) method in [14, 15], to produce bias-corrected distances in redshift bins. To include bias corrections, `SALT2mu` reads SALT2-fitted parameters for the data and for a large “biasCor” simulation. The biasCor simulation should be generated on a grid of  $\alpha, \beta, \gamma$  as described in §9.3.1.

A sample `SALT2mu.exe`-input file is in

```
$SNDATA_ROOT/sample_input_files/SALT2/SALT2mu.default
```

and a description of all input-file options are given at the top of the code in `$SNANA_DIR/src/SALT2mu.c`.

## 10.1 Catenating FITRES Files from Multiple Samples

SN Ia-cosmology analyses include multiple samples (e.g., LOWZ, SDSS, PS1, SNLS, DES ...). While **SNANA** codes perform light-curve fitting and simulations separately for each sample, the **SALT2mu/BBC** program performs a global fit to all of the data samples combined. Through **SNANA** code versions v10\_76e, each **FITRES** table file (produced from `snlc_fit.exe`) was required to have the same columns so that a simple concatenate combines the data into a single file. Starting at v10\_77, input **FITRES** tables are allowed to have different columns, and the output **FITRES** table from **SALT2mu** is created with the following logic:

- column names appearing in each **FITRES** file are included, regardless of column locations.
- `varname_pIa` column is included; if missing (e.g., from LOWZ), then -9 values are substituted.
- the same “`varname_pIa`” logic is applied to variables specified with **SALT2mu**-input key `append_varnames_missing`. The default is **PROB\*** to include all classifier probabilities.

As an example, consider an analysis combining a spec-confirmed LOWZ sample and a photometrically-identified HIGHZ sample. The LOWZ sample contains several peculiar-velocity estimates (**VPEC1**, **VPEC2**, **VPEC3**) that are not in the HIGHZ table; the HIGHZ sample includes several classifier probabilities (**PROB\_A**, **PROB\_B**, **PROB\_C**) and **sSFR** that are not in the LOWZ table. All of these values are included in the **SALT2mu** output using the following **SALT2mu**-input key,

```
append_varnames_missing='PROB*,VPEC*,sSFR'
```

The wildcard (\*) picks up any column name containing **PROB** or **VPEC**. An exact **sSFR** column match is also selected. The **VPEC** values are set to -9 for the HIGHZ sample, and similarly the **PROB** and **sSFR** values are set to -9 for the LOWZ sample. The top of the output **FITRES** file includes comment-summary of i) input **FITRES** file names, ii) `append_varnames_missing`, and iii) column names that were discarded.

Combining **fitres** files with different columns may be useful for other (non-**SNANA**) codes, and therefore this **SALT2mu** “**FITRES**-combine” logic can be implemented as a utility without the overhead of fitting,

```
SALT2mu.exe cat_only \  
    datfile=LOWZ.FITRES,HIGHZ.FITRES \  
    append_varname_missing='PROB*,VPEC*,sSFR' \  
    catfile_out=CATFILE.FITRES  
or  
sntable_cat.py \  
    -i LOWZ.FITRES,HIGHZ.FITRES \  
    -a PROB*,VPEC*,sSFR \  
    -o CATFILE.FITRES
```

The `cat_only` argument (replacing input file) directs **SALT2mu** to skip fitting and perform only the catenation. Beware that the wildcard (\*) causes problems with unix; therefore use either single quotes as shown above, or use a backslash (`PROB\*`, `VPEC\*`, `sSFR`).

A python wrapper (`sntable_cat.py`) is also available with a more obvious code-name to search in `$SNANA_DIR/util`. This python wrapper can parse wildcards without single quotes. The `-i` and `-o` arguments are required; `-a` is optional (default is **PROB\***).

## 10.2 Blinding BBC Output from SALT2mu.exe

There are two methods for blinding results in the BBC output: 1) totally blind, and 2) blurry. For the totally blind method,

$$\text{MUDIF} \rightarrow \text{MUDIF} + \cos(10z) \quad (40)$$

where the cosine argument is  $10 \times \text{redshift}$ . The MUDIF ( $\mu$ -offsets) are  $O(1)$  and viewing these values provides no information about the true residuals; hence “totally blind.” The disadvantage is that the cosmology fitting program, which reads the BBC output, must subtract  $\cos(10z)$  from each blinded  $\mu$ . Also, the cosmology-fitting program must have its own blinding applied to the fitted cosmology parameters.

The blurry method adds unknown offsets to the reference cosmology parameters  $(\Omega_\Lambda, w_0)$ ,

$$\Omega_\Lambda^{\text{ref}} \rightarrow \Omega_\Lambda^{\text{input}} + A_L \cos(B_L) \quad (41)$$

$$w_0^{\text{ref}} \rightarrow w_0^{\text{input}} + A_w \cos(B_w) \quad (42)$$

where  $A_{L,w}$  and  $B_{L,w}$  are arbitrary. The cosmology fitting program need not modify any of the BBC outputs since all of the BBC outputs are correct.  $A_{L,w}$  and  $B_{L,w}$  can be modified separately for each user, or each analysis iteration, and there is no need to pass these blinding parameters to other colleagues or programs. However, the same blinding params must be used for systematic comparisons of the Hubble diagram. The blinding strategy is that the user does not know the reference-cosmology parameters, and therefore the output  $\mu$ -residuals (MUDIF) are offsets from an unknown cosmological model. However, if  $A_{L,w}$  are not too large, the  $\mu$ -residuals might still be somewhat close to zero. In this case, human inspection of the  $\mu$ -residuals provides some information; hence we call this method “blurry.”

By default, SALT2mu.exe will blind real data with the blurry method, and not apply blinding to simulated data. The following SALT2mu.exe inputs control blinding:

```
p9=0.7      # input Omega_L -> ref cosmology for MUDIF
p11=-1.0    # input w0      -> ref cosmology for MUDIF

blindflag=1      # totally blind, MUDIF += cos(10z)
blindflag=2      # blurry method (DEFAULT)
blindpar9=0.1,4400 # A_L,B_L: OL_ref = p9 + 0.10 * cos(4400)
blindpar11=0.2,3300 # A_w,B_w: w0_ref = p11 + 0.20 * cos(3300)

# add 64 to blind simulated data
blindflag=65 # 1+64 -> same as blindflag = 1 for real data
blindflag=66 # 2+64 -> same as blindflag = 2 for real data
```

It is highly recommended to practice blinding on simulated data before processing real data. Another useful feature is to generate simulations without the SIM\_XXX truth values, which checks if the analysis codes are mistakenly using some SIM\_XXX values. This sim option is invoked by adding 8 to FORMAT\_MASK. For example, “FORMAT\_MASK: 10” (2+8) produces text formatted data files that look like real data, and “FORMAT\_MASK: 40” (2+32) produces FITS-formatted data files that look like real data. If the simulated data has no SIM\_XXX keys, the default BBC output is blinded with the blurry method.

The output BBC tables include comment fields specifying SNANA\_VERSION, BBC\_VERSION, and a summary of the blinding parameters. For cosmology-fitting, the parsing/translation module should keep track of the integer BBC version to maintain backward compatibility in case of future modifications. If the BBC\_VERSION key is not included, set BBC\_VERSION=1.

# 11 Cosmology Fitting

State-of-the-art cosmology fitting tools include CosmoMC and CosmoSIS that are not included in SNANA. Within SNANA, `wfit.exe` is a fast cosmology fitting program that is not nearly as sophisticated as CosmoSIS, but is useful for systematics tests and forecasts. `wfit.exe` models  $w$ CDM ( $w, \Omega_M$ ) and CPL  $w_0w_a$ CDM model, both assuming a flat universe. The CMB prior is based the  $R$  parametrization using simulated cosmology parameters and  $\sigma_R = 0.007$  to reproduce the DES3YR uncertainties. The BAO prior is based on Alam 2020. Table 1 compares `wfit.exe` results to published DES3YR and Pantheon values using

```
wfit.exe [HubbleDiagram] -cmb_sim -sigma_Rcmb 0.007 -wsteps 101 -omsteps 101 \
-mucov_file [mucov_file] \
-bao_sim # only for DES w0waCDM only
```

where `HubbleDiagram` and `mucov_file` are from public data releases.

	$\Omega_m$	$\sigma(\Omega_m)$	$w_0$	$\sigma(w_0)$	$w_a$	$\sigma(w_a)$	FoM
DES3YR $w$ CDM SN+CMB	0.321	$\pm 0.018$	-0.978	$\pm 0.059$			
<code>wfit.exe</code>	0.326	$\pm 0.018$	-0.964	$\pm 0.059$			
Pantheon $w$ CDM SN+CMB	0.307	$\pm 0.012$	-1.026	$\pm 0.041$			
<code>wfit.exe</code>	0.308	$\pm 0.012$	-1.029	$\pm 0.041$			
DES3YR $w_0w_a$ CDM SN+CMB+BAO	0.316	$\pm 0.011$	-0.885	$\pm 0.114$	-0.387	$\pm 0.430$	46
<code>wfit.exe</code>	0.309	$\pm 0.012$	-0.965	$\pm 0.092$	-0.354	$\pm 0.442$	64
Pantheon $w_0w_a$ CDM SN+CMB	0.308	$\pm 0.018$	-1.009	$\pm 0.159$	-0.129	$\pm 0.755$	31
<code>wfit.exe</code>	0.305	$\pm 0.015$	-0.981	$\pm 0.159$	-0.302	$\pm 0.725$	32

Table 1: Comparison of published cosmology parameters to those obtained with `wfit.exe`. DES3YR results are from Table 2 in <https://arxiv.org/pdf/1811.02374.pdf>. Pantheon results are from Table 12 and 13 of <https://arxiv.org/pdf/1710.00845.pdf>. CMB prior in published results is from Planck 2016, and used in all four cases. CMB prior in `wfit.exe` uses  $R$ -parameter with  $\sigma_R = 0.007$  tuned to match DES3YR  $w$ -uncertainty. The `wfit.exe` BAO is based on <https://arxiv.org/abs/2007.08991>. All fits use redshift binned data.

## 11.1 Interpreting Redshift Variables in SNANA Tables

The following redshift variables are included in the output tables from the fitting programs (`snlc_fit.exe`, `SALT2mu.exe`):

- `zHEL`, `zHELERR`: heliocentric redshift.
- `zCMB`, `zCMBERR`: redshift transformed to CMB  
( $\ell = 264.14$  deg,  $b = 48.26$  deg,  $v_{\text{apex}} = 370$  km/s)
- `VPEC`, `VPECERR`: peculiar-velocity correction.  
If host galaxy is moving away from (toward) Earth, then `VPEC`<0 (`VPEC`>0).
- `zHD`, `zHDERR` =  $(1 + \text{ZCMB})(1 + \text{VPEC}) - 1$ . `zHDERR` is the quadrature sum of `zCMBERR` and  $(1 + \text{zCMB}) * \text{VPECERR}$ . This corrected CMB redshift, or “Hubble-diagram” redshift, should be used to compute the luminosity distance ( $D_L$ ) in cosmology-fitting programs.

To check that `VPEC` is used correctly with simulations, generate a large low- $z$  sample, analyze with `snana.exe` or `snlc_fit.exe` program, and then verify the following from the SNANA or FITRES table:

- 1) `zCMB` - `SIM_ZCMB` distribution has `RMS=GENSIGMA_VPEC` and `mean=0`
- 2) `zHD` - `SIM_ZCMB` distribution has `RMS=VPEC_ERR` and `mean=0`

where `GENSIGMA_VPEC` and `VPEC_ERR` are sim-input keys defined in §4.31.

## 11.2 Peculiar Velocity Covariances

The `wfit.exe` program has an option to account for peculiar velocity correlations (SNANA v8\_10 and later). First prepare a file with the following syntax

```
COV:  SN1  SN2  MUCOVAR(12)
COV:  SN1  SN3  MUCOVAR(13)
COV:  SN1  SN4  MUCOVAR(14)
etc ...
```

where `SN#` are the SN names used in the analysis (i.e, that appear in the `fitres` file), and `MUCOVAR(ij)` are the covariances between the distance moduli, with units of  $\text{mag}^2$ . Only off-diagonal terms from this file are used; diagonal terms are specified from the `-zerr` and `-snrms` options. The syntax is

```
wfit.exe <fitresFile> -mucovar <mucovarFile> <other options>
```

where “`mucovarFile`” is the name of the file specifying the off-diagonal covariances. The `wfit.exe` program will first check your current directory for this file; if not there `wfit` will check the public area, `$SNDATA_ROOT/models/mucovar/`. The covariances for the nearby sample have been computed by the authors in [16], and these are available in

```
$SNDATA_ROOT/models/mucovar/Hui_LOWZ_mucovar.dat
```

The minimization function is given by  $\chi^2 = \sum_{ij} [\Delta_i V_{ij}^{-1} \Delta_j] - B^2/C$ ,<sup>30</sup> where  $\Delta_i \equiv \mu_i^{\text{data}} - \mu_i^{\text{model}}$  is the distance-modulus residual for the  $i$ 'th SN,  $V_{ij}^{-1}$  is the inverse of the covariance matrix, and the term  $B^2/C$  accounts for the analytic marginalization over  $H_0$  as discussed in Appendix A of [17]. The  $B$  and  $C$  parameters are

$$B = \sum_i (\Delta_i / \sigma_i^2) \quad \longrightarrow \quad \sum_{i,j} (\Delta_i V_{ij}^{-1}) \quad (43)$$

$$C = \sum_i 1/\sigma_i^2 \quad \longrightarrow \quad \sum_{i,j} V_{ij}^{-1}, \quad (44)$$

where  $\sigma_i$  is the diagonal-uncertainty on the distance modulus. The expressions left of the arrows (Eqs. 43-44) are from [17], while the expressions right of the arrows show the `wfit` implementation that accounts for the off-diagonal covariance terms. The  $B^2/C$  term is equivalent to re-minimizing with the weighted-average distance-modulus residual subtracted from each distance-modulus residual;  $\Delta_i \rightarrow \Delta_i - \langle \Delta \rangle$ .

---

<sup>30</sup>We leave out the constant term  $\ln(C/2\pi)$ .



## 12 Miscellaneous Tools and Features

### 12.1 Analysis-Output: Files, Tables, Variables

For each analysis program (`snana.exe`, `snlc_fit.exe`, `psnid.exe`) the output results are stored in tables. The primary table-file formats are `ROOT` or `HBOOK`, which allow writing multiple structures in parallel and include a plotting interface. `TEXT`-tables are also available for a subset of the variables, and there is a separate utility (see `sntable_dump`, §12.1.3) to extract information from a `ROOT` or `HBOOK` file and convert into text format. The available output tables are

- **SNANA** (ID=7100): general variables for all SN before fitting
- **FITRES** (ID=7788): fit results for SN passing fit requirements. Fit residuals for each epoch can be optionally included with `FITRES+RESIDUALS`.
- **OUTLIER** (ID=7800): flux-outliers w.r.t. sim-truth for `snana.exe` job; w.r.t. fit model for `snlc_fit.exe` job. Default is  $> 3\sigma$ ; for `snana.exe`, default requires non-zero true flux.
- **SNLCPAK**: used by `mkfitplots.pl` (§5.10.1) to make light curve plots for data and best-fit model.

The **SNANA**, **FITRES**, **OUTLIER** tables are intended for continued analysis after the **SNANA** code finishes; the table name is assigned to a “tree” in `ROOT`, while the integer ID is assigned to an “ntuple” in `HBOOK`. The **SNLCPAK** table is for internal plotting scripts, and is not intended for general use. The user-selection of format(s) and table(s) is described below.

### COMPILATION FLAGS

The **SNANA** codes will compile with `HBOOK` if ENV `$CERN_DIR` is defined, and will compile with `ROOT` if ENV `$ROOT_DIR` is defined. To compile without `HBOOK` or `ROOT`, make sure that the associated ENV is not defined. Do not modify any files to adjust compilation with `HBOOK` or `ROOT`.

### SELECTING TABLE FORMAT(S)

The output table format is defined by the user in the `&SNLCINP` namelist,

<code>HFILE_OUT</code>	=	<code>'myout.hbook'</code>
<code>ROOTFILE_OUT</code>	=	<code>'myout.root'</code>
<code>TEXTFILE_PREFIX</code>	=	<code>'myout'</code>

Multiple output formats can be specified, including all 3 as shown above. For the `ROOT` and `HBOOK` formats, all tables are written to each `ROOT` and `HBOOK` file. For the `TEXT` format, however, each table is written to a separate file and thus a file *prefix* is specified rather than a file-name. The corresponding output-file names are “`myout.[tableName].TEXT`” where the *tableNames* are **SNANA**, **FITRES**, **OUTLIER**, and **LCPLOT**.<sup>31</sup>

### SELECTING TABLE(S)

The tables are selected by `&SNLCINP` namelist string `SNTABLE_LIST`,

---

<sup>31</sup>`LCPLOT` corresponds to the **SNLCPAK** table.

```

SNTABLE_LIST = 'FITRES'                                ! default
SNTABLE_LIST = 'SNANA FITRES OUTLIER LCPLOT'           ! select'em all

```

To protect memory and output file size for large jobs, the number of light curve plots (LCPLOT) is limited by &SNLCINP namelist variable MXLC\_PLOT=100: set to a higher value to get more plotted light curves.

If a ROOT file is specified via &SNLCINP namelist variable ROOTFILE\_OUT, then all SNTABLE\_LIST arguments are created under the ROOT structure. Similarly, all tables are created under the HBOOK structure if HFILE\_OUT is defined. For TEXT format with TEXTFILE\_PREFIX, only the FITRES table is created by default; to generate text output for other tables requires additional specifications such as

```

SNTABLE_LIST = 'SNANA(text:key)  FITRES(text:key)  LCPLOT(text:col)'
or
SNTABLE_LIST = 'SNANA(text:key)  FITRES              LCPLOT(text:col)'

```

where the available text formats are

- key : key before each row, plus keyed header.
- csv : comma-separated with header.
- col : space-separated columns with no header.

The two SNTABLE\_LIST strings above are equivalent because “text:key” is the default text format for the FITRES table. Also note that the SNTABLE\_LIST string is case-insensitive and thus the following are equivalent,

<pre> SNTABLE_LIST = 'snana(text:csv)  fitres(text:csv)  lcplot(text:csv)' SNTABLE_LIST = 'SNANA(text:csv)  FITRES(text:csv)  LCPLOT(text:csv)' SNTABLE_LIST = 'SNANA(TEXT:CSV)  FITRES(TEXT:CSV)  LCPLOT(TEXT:CSV)' </pre>
---

For the FITRES table, data-fit  $\chi^2$ -residuals can be included for each epoch using a feature of both ROOT and HBOOK that allows vector elements in tables columns. In addition to the data-fit chi-squared, the following are also included: PSF, sky-noise, zero point, best-fit model flux, etc ... Residuals can be included with

```

SNTABLE_LIST = 'SNANA  FITRES+RESIDUALS  LCPLOT'

```

There is no text-format option for the residuals, but the `sntable_dump` utility (§12.1.3) has an “outlier” option to extract the residual information into text format. Finally, be aware that defining FITRES+RESIDUALS results in a significantly larger output file.

For the SNANA table, an optional cut-mask on CUTFLAG\_SNANA can be defined to select the following subsets,

```

SNTABLE_LIST = 'SNANA(cutmask:0)'  ! write only events failing cuts
SNTABLE_LIST = 'SNANA(cutmask:1)'  ! write only events passing snana cuts
SNTABLE_LIST = 'SNANA(cutmask:2)'  ! write only events passing fit cuts
SNTABLE_LIST = 'SNANA(cutmask:3)'  ! default -> write all events

```

A few other miscellaneous table options are

```

SNTABLE_LIST = 'SPECPLOT'           # plot spectra
SNTABLE_LIST = 'SNANA+EPOCHS'       # include epoch info in SNANA table
SNTABLE_LIST = 'SNANA+SIM_MAGOBS'   # idem, but only MJD,IFILT,SIM_MAGOBS
SNTABLE_LIST = 'SNANA FITRES NOSIMVAR' # suppress SIM_xxx variables.
SNTABLE_LIST = 'SNANA FITRES MODELSPEC' # SALT2 model spectrum for each epoch
SNTABLE_LIST = 'SNANA(PS:10) FITRES' # pre-scale SNANA table by 10
SNTABLE_LIST = 'FITRES NOZPHOT'     # suppress ZPHOT variables
SNTABLE_LIST = 'SNANA(text:host)'    # include HOSTGAL info in text tables
SNTABLE_LIST = 'SNANA(text:host2)'   # include HOSTGAL & HOSTGAL2 in text table
SNTABLE_LIST = 'SNANA(text:key,text:host)' # same, with format spec
SNTABLE_LIST = 'OUTLIER(nsig:4)'     # table with >4sig outliers (default: 3sig)
SNTABLE_LIST = 'OUTLIER(nsig:4,ftrue:0.0)' # include obs with Ftrue=0

```

- SPECPLOT plots spectra (real or simulated); works with all formats. Note that SNANA has no spectral-analysis tools.
- SNANA+EPOCHS and MODELSPEC options work with HBOOK and ROOT format, but not with TEXT format.
- SNANA+SIM\_MAGOBS is a compressed table to contain only the model light curves. EPOCH is defined on a grid w.r.t.  $T_{\text{peak}}$ , and SIM\_MAGOBS is interpolated at each grid-EPOCH so that model colors can be easily examined.
- The NOSIMVAR option removes all simulated truth values, and is useful for *blind* challenges.
- The MODELSPEC table works for SALT2 light-curve fits only, and is filled for epochs ( $T_{\text{rest}}$ ) defined by the SALT2 model: includes scalars (CID,MJD,BAND,TOBS,etc) and a model spectrum (flux vs. wavelength). The MODELSPEC table may be useful for calibration corrections that require an SED. To save storage, each spectrum is stored within the wavelength range defined by the passband.
- The pre-scale option (PS:10) reduces table output for large simulated samples.
- NOZPHOT suppresses photo-z output so that photo-z and spec-z (4-parameter) light curve fits have the same FITRES table columns and can therefore be combined. Note that zHD contains the relevant redshift information so that ZPHOT is not needed. In addition, NOZPHOT results in adding OPT\_PHOTOZ (&FITINP input) to the FITRES table, allowing analysis programs (e.g., SALT2mu) to distinguish spec-z and photo-z events. For spec-z fits (i.e., NOT photo-z), NOZPHOT adds OPT\_PHOTOZ to the FITRES table, but does not remove anything.
- The OUTLIER table is useful to identify and characterize flux outliers from non-Gaussian tails. The recommended method is using the `snana.exe` program on samples where the true flux is known (i.e., data files which have a SIM\_MAGOBS column), such as fakes overlaid on image, or SNANA-simulated light curves. Running `snana.exe` with the OUTLIER table option will abort on real data because there is no true flux to compare. For real data (and sims), the OUTLIER table works with the lightcurve fitting program `snlc_fit.exe` by comparing fluxes to the best-fit model flux. This LC-fit option requires a high-confidence SNIa sample (e.g., spec-confirmed), otherwise some outliers may be artifacts of non-SNIa contamination.

An outlier-fraction summary (per band) is printed to stdout, and also to the top of TEXT formatted output. Finally, note that `snana.exe` is  $\sim 10^2$  faster than `snlc_fit`, and thus the former can typically run interactively while the latter should run in batch mode.

### 12.1.1 SNTABLE\_APPEND

An arbitrary column name and value can be added to output tables with command-line input

```
snlc_fit.exe <myInputFile> SNTABLE_APPEND MYVAR 0.03
```

which will include MYVAR column in all output tables with value 0.03. An example usage is measuring derivatives of SALT2 parameters w.r.t. changing the *i*-band zeropoint using the followig FITOPT options in the CONFIG yaml block,

FITOPT:

```
- MAGOBS_SHIFT_ZP 'i -0.03' SNTABLE_APPEND ZP_i -0.03
- MAGOBS_SHIFT_ZP 'i -0.01' SNTABLE_APPEND ZP_i -0.01
- MAGOBS_SHIFT_ZP 'i 0.01' SNTABLE_APPEND ZP_i 0.01
- MAGOBS_SHIFT_ZP 'i 0.03' SNTABLE_APPEND ZP_i 0.03
```

By concatenating the output FITRES files, it is easy to plot, for example, *c* vs. *ZP\_i* for individual events.

### 12.1.2 Combining Ascii “Fitres” Files: combine\_fitres.exe

As discussed in §5.3, the fit results are written to a self-documented “fitres” file. The simulation can also be used to dump generated variables into a file with the same format (§4.37.2). The utility ‘`combine_fitres.exe`’ is useful to combine (merge) multiple fitres files containing information about the same SNe. Note that fitres files with different SNe can be combined by simply using the unix “cat” command.

As an example, consider the following fitres files generated from different light curve fitters:

```

> more mlcs.fitres
NVAR: 2
VARNAMES: Z DLMAG
SN: 50001    0.1576  39.475
SN: 50002    0.2030  40.291

> more salt2.fitres
NVAR: 2
VARNAMES: x1 c
SN: 50001   -2.343  0.013
SN: 50002    0.893  0.235

> combine_fitres.exe mlcs.fitres salt2.fitres

> more combine_fitres.txt
NVAR: 5
VARNAMES: CID Z DLMAG x1 c
SN: 50001    0.157600001  39.4749985 -2.34299994  0.0130000003
SN: 50002    0.202999994  40.2910004  0.893000007  0.234999999

```

Although the SN candidate id (CID) is required after the “SN:” keyword, it is optional to specify CID in the VARNAMES list.

Fitres files with the same variable names can also be combined. The second repeated variable gets a “\_2” appended to the variable name, the third repeated variable gets a “\_3” appended, etc ... For example, consider two MLCS2k2 fits with slightly different options,

```

> more mlcs.fitres
NVAR: 2
VARNAMES: Z DLMAG
SN: 50001    0.1576  39.475
SN: 50002    0.2030  40.291

> more mlcs_test.fitres
NVAR: 2
VARNAMES: Z DLMAG
SN: 50001    0.1576  39.829
SN: 50002    0.2030  40.443

> combine_fitres.exe mlcs.fitres mlcs_test.fitres

> more combine_fitres.txt
NVAR: 5
VARNAMES: CID Z DLMAG Z_2 DLMAG_2
SN: 50001    0.157600001  39.4749985  0.157600001  39.8289986
SN: 50002    0.202999994  40.2910004  0.202999994  40.4430008

```

Up to ten fitres files can be merged together. If there are SNe in the second (3rd, 4th...) fitres file that are not in the first fitres file, then these extra SNe will be ignored. If there are SNe in the first fitres file that are not in the other fitres files, then values of  $-888$  are stored for the missing SNe. In addition to creating a merged fitres file, a merged Table file (`combine_fitres.hbook/root`) is also created in hbook and/or root format depending on the compile flag(s) in `sntools_output.h`. This table can be analyzed with PAW or ROOT, or using the `sntable_dump.py` utility (§12.1.3)

The default prefix for the output files is “`combine_fitres.`” This default can be changed using the argument `-outprefix`,

```
> combine_fitres.exe mlcs.fitres mlcs_test.fitres -outprefix mlcs
```

which produces the files ‘`mlcs.tup`’ and ‘`mlcs.txt`.’

### 12.1.3 SNTABLE Dump Utility: `sntable_dump.py`

The fitres text-file output from the light curve fitter contains a small fraction of the analysis variables. The entire set of analysis variables is stored in a more compact “SNTABLE” structure using HBOOK and/or ROOT based on the `&SNLCINP` namelist inputs

```
HFILE_OUT      = 'mjob.hbook'
ROOTFILE_OUT   = 'mjob.root'
```

Additional SNTABLE formats (e.g., HDF5, Pickle) can be added within the existing architecture. There are two primary SNTABLEs:

	snana	snlc_fit/psnid fit results	
HBOOK TABLE ID	7100	7788	(column-wise ntuples)
ROOT TABLE ID	SNANA	FITRES	(trees)

If you are fluent in PAW/HBOOK or ROOT, then you can analyze these tables directly without using text files. However, if you prefer a different analysis platform then `sntable_dump.py` can be used to extract table information into text format.

The script usage is explained at the top of `&SNANA_DIR/util/sntable_dump.py`, and here we illustrate its basic features:

1. Print list of SNTABLE variables:

```
sntable_dump.py myjob.root SNANA
sntable_dump.py myjob.root FITRES
```

2. For an arbitrary set of table variables, extract SN values into a fitres-formatted text file:

```
sntable_dump.py myjob.root SNANA -v RA,DEC,SNRMAX_r
sntable_dump.py myjob.root FITRES -v m0obs_g,m0obs_r
```

3. Append an existing text file with variables from a SNTABLE:

```
sntable_dump.py myjob.root SNANA -v RA,DEC,SNRMAX_r -a MYJOB.FITRES
sntable_dump.py myjob.root FITRES -v m0obs_g,m0obs_r -a MYJOB.FITRES
```

4. Dump epoch-list of dataFlux-fitFLux outliers:

```
sntable_dump.py myjob.root FITRES --outlier 3 99
sntable_dump.py myjob.root FITRES --outlier 3 99 -v FITPROB,SNRMAX3
(print epochs to ascii file with 3 < Nsigma < 99)
```

5. Dump epoch-list of dataFlux-simFLux outliers (sim only):

```
sntable_dump.py myjob.root FITRES --outlier_sim 3 99
sntable_dump.py myjob.root FITRES --outlier_Sim 3 99 -v FITPROB,SNRMAX3
(print epochs to ascii file with 3 < Nsigma < 99)
```

6. Dump observations & variables needed to compute flux-error maps in §4.14.1. Note that  $ERRTEST = \sigma_{SIM}/\sigma_F$ , where  $\sigma_{SIM}$  is the calculated error and  $\sigma_F$  is the reported error.

```
sntable_dump.py myjob.root FITRES --OBS
```

Using the append option (#3 above with --a), a new text file is created containing the original variables in MYJOB.FITRES plus the appended variables specified by the --v argument. The appended variables are extracted from the SNTABLE (2nd argument of sntable\_dump.py).

To see pre-explosion epochs with the outlier option, open the low-side of &FITINP namelist variable FITWIN\_TREST, such as “FITWIN\_TREST: -100, +45”

#### 12.1.4 Extract Value from Fitres File: get\_fitresValue.pl

See instructions at top of \$SNANA\_DIR/util/get\_fitresValue.pl

#### 12.1.5 Working with IAUC names

Data files contain a required SNID and an optional IAUC name. By default, only the SNID is used and propagated to the output tables as CID. However, using the IAUC name may sometimes be more practical. For example, SNID could be an integer that keeps changing as data are reprocessed, while the IAUC name remains fixed.

On the input side, &SNLCINP namelist inputs that specify CID strings will work with either SNID or IAUC names. These namelist inputs include

```
SNCCID_LIST
SNCCID_LIST_FILE
SNMJD_LIST_FILE
```



SNCCID\_LIST is an explicit list of SNIDs and/or IAUC names, and the list can contain a mix of SNID and IAUC names. The next two XXX\_LIST\_FILE inputs point to a file containing a list of SN names, and these can also be an arbitrary mix of SNID and IAUC names.

In the output tables, the CID column can be filled with the IAUC name by specifying an IAUC option in SNTABLE\_LIST,

```
SNTABLE_LIST = 'SNANA FITRES(iauc)'
or
SNTABLE_LIST = 'SNANA FITRES(text:key,iauc)'
or
SNTABLE_LIST = 'SNANA(iauc) FITRES(text:key)'
etc ...
```

If any one table has the IAUC specification then all tables will have IAUC written into the CID column.

### 12.1.6 MARZ Format for Spectra

After simulating host spectra, the spectra can be translated for analysis with the Marz utility<sup>32</sup> by specifying Marz output format for the snana.exe program,

```
&SNLCINP
  MARZFILE_OUT = '***marz***.fits'
  VERSION_PHOTOMETRY = 'XYZ'
&END
or
snana.exe NOFILE VERSION_PHOTOMETRY XYZ  MARZFILE_OUT '***marz***.fits'
```

The argument of MARZFILE\_OUT must include "marz" in the file name. Only the first spectrum per event (assumed to be HOST) is stored. SN spectra are not stored because Marz works only with host spectra.

## 12.2 General Misc. Tools

### 12.2.1 Batch Submit Script: submit\_batch\_jobs.sh

The SNANA script "submit\_batch\_jobs.sh" is a utility to run analysis codes in batch queue, and it includes preparation and post-processing. The script parses your input file and automatically determines which task to prepare and execute: snlc\_sim.exe, snlc\_fit.exe, SALT2mu.exe, SALT2-training code. Command line options are obtained with

```
submit_batch_jobs.sh -h
```

and detailed help on the config file for each task is given with

```
# detailed help on analysis programs
submit_batch_jobs.sh -H SIM           # simulation
submit_batch_jobs.sh -H FIT           # light curve fitting
submit_batch_jobs.sh -H BBC           # BBC: Beams with Bias Corrections
```

---

<sup>32</sup><http://samreay.github.io/Marz> (works with Chrome & Firefox, not with Safari)

```
submit_batch_jobs.sh -H TRAIN_SALT2    # SALT2-traing
```

```
# misc help
```

```
submit_batch_jobs.sh -H MERGE          # post-processing merge task
```

```
submit_batch_jobs.sh -H AIZ            # abort-if-zero logic
```

```
submit_batch_jobs.sh -H TRANSLATE      # translate input file for perl scripts
```

The misc help options provide explanations that may be useful for debugging or further script development. The MERGE task can include complex operations after all of the batch jobs have finished. AIZ explains the subtle logic to abort when jobs return zero events, but not abort on low-stat jobs (e.g., Kilonova sims) where a subset of jobs are expected to have zero events. Finally, TRANSLATE is a feature to automatically translate legacy input files used by the obsolete perl batch scripts.

Historical note: prior to SNANA version v11, three separate perl scripts ran batch jobs: `sim_SNmix.pl`, `split_and_fit.pl`, `SALT2mu_fit.pl`. After v11, these three scripts are replaced by an improved python script invoked with `submit_batch_jobs.sh`.

### 12.2.2 List Valid Input Keys

Each SNANA program has many input keys that are difficult to find and remember. For SALT2mu and simulation programs, the following results in a dump of all valid input keys and then quits:

```
snlc_sim.exe KEY_DUMP
```

```
SALT2mu.exe  KEY_DUMP
```

Using grep can help find keys related to a particular topic, although a decent guess is needed for a sub-string. Examples for the simulation are:

```
# to find peculiar-velocity keys in the sim
```

```
snlc_sim.exe KEY_DUMP | grep VPEC
```

```
VALID_KEYNAME: 124  GENSIGMA_VPEC:
```

```
VALID_KEYNAME: 125  VPEC_ERR:
```

```
# to find keys controlling SALT2x1 population.
```

```
snlc_sim.exe KEY_DUMP | grep SALT2x1
```

```
VALID_KEYNAME: 200  GENPEAK_SALT2x1:
```

```
VALID_KEYNAME: 201  GENMEAN_SALT2x1:
```

```
VALID_KEYNAME: 202  GENSIGMA_SALT2x1:
```

```
VALID_KEYNAME: 203  GENSKEW_SALT2x1:
```

```
VALID_KEYNAME: 204  GENRANGE_SALT2x1:
```

```
VALID_KEYNAME: 205  GENGRID_SALT2x1:
```

```
VALID_KEYNAME: 206  GENPROB2_SALT2x1:
```

```
VALID_KEYNAME: 207  GENPEAK2_SALT2x1:
```

```
VALID_KEYNAME: 208  GENSIGMA2_SALT2x1:
```

and here is a SALT2mu example to find file-related inputs,

```
SALT2mu.exe KEY_DUMP | grep file
VALID_KEYNAME:      1  catfile_out=
VALID_KEYNAME:      9  file=
VALID_KEYNAME:     10  datafile=      (same as file=)
VALID_KEYNAME:     11  simfile_bias=
VALID_KEYNAME:     12  simfile_biascor=
VALID_KEYNAME:     25  simfile_ccprior=
VALID_KEYNAME:     70  cid_select_file=
```

The KEY\_DUMP command-line option works for the C programs, but not for the fortran programs (snlc\_fit.exe, snana.exe, psnid.exe). Instead, the fortran programs have a built-in “name-list” (NML) feature, and the contents of each NML are printed to standard out. Therefore, use grep on stdout to find NML inputs; e.g.,

```
snlc_fit.exe SNFIT.NML | grep CUTWIN_TREST
CUTWIN_TRESTMIN= -99.000000      , -2.0000000      ,
CUTWIN_TRESTMAX=  10.000000      , 9999.0000      ,
CUTWIN_TRESTRANGE=-9.99999996E+11, 9.99999996E+11,
CUTWIN_TREST= -20.000000      , 80.000000      ,
CUTWIN_TREST_TRUEFLUX= 2*999.00000      ,
CUTWIN_TREST2=-9.99999996E+11, 9.99999996E+11,
```

The large range values ( $\pm 9.999\text{E}+11$ ) indicate that the NML input was not defined in the user-input file, but is a valid input.

### 12.2.3 Command-line Overrides

The simulation and light curve fitter described in the sections above are each driven by an input file that specifies instructions and parameters. For convenience, all input-file parameters can be specified on the command line. For example, if you have

```
GENMODEL: mlcs2k2.v006
GENTAU_AV: 0.35
```

in your simulation-input file, you can override these options on the command-line without editing the input file:

```
snlc_sim.exe mysim.input  GENMODEL mlcs2k2.v007  GENTAU_AV 0.45
```

These command-line overrides are useful for quick testing, and for writing wrappers that do many analysis variations without creating a new input file for each job. An invalid or unrecognized command-line option results in an immediate abort. The command-line options are printed to stdout, and therefore if you pipe your job to a log-file, you can rerun the same job as long as you have the original input file.

### 12.2.4 quick\_commands.py

Many useful/quick commands can be run from a python script

```
quick_commands.py -h    # standard python args help
quick_commands.py -H    # examples
```

Options include

- translate TEXT formatted data to FITS format
- extract a few events from FITS format to TEXT format
- create SIMLIB file from LOWZ data that has no metaData.
- make human-readable table of redshifts and vpec
- Create SNANA-formatted table(s) from data or sim
- extract info about a photometry version
- extract info about SNANA code

### 12.2.5 Bug-Catcher: the SNANA\_tester Script

To help verify that the SNANA code delivers the same results with each new version, there is a testing utility, `SNANA_tester.cmd` (no arguments), that runs a pre-defined list of jobs with two different versions of SNANA, and reports discrepancies. Typically this script is run just before releasing a new SNANA version, but users may want to run this script on other platforms. The goal is to catch and fix unanticipated changes (i.e, bugs) before releasing each new SNANA version. The top-level instruction file is here,

```
$SNDATA_ROOT/SNANA_TESTS/SNANA_TESTS.LIST
```

which specifies a series of test-jobs, input files, and log-file parsing instructions to extract results to compare between SNANA versions. The `SNANA_tester.cmd` script is written for the Fermilab ups product system; on other platforms, script modifications will be needed to setup the correct versions of SNANA. Users who use a particular feature of SNANA should check if the current test-jobs provide adequate protection; if not, you may request additional test-jobs.

### 12.2.6 Write List of Rejected Epochs

The most commonly used output of the `snlc_fit.exe` fitting program is the “FITRES” table, which includes summary information for each SN passing selection cuts. However, there may be analyses that require a list of selected epochs, such as the SuperNNova photometric classifier<sup>33</sup> that reads light curves instead of the summary FITRES file. To avoid duplicating epoch cuts in other codes, there is an SNANA utility to write a list of rejected epochs, with the assumption that writing rejected epochs results in a much smaller file compared to writing selected epochs. An example for the DES analysis is

```
&SNLCINP
PRIVATE_DATA_PATH = '$DES_ROOT/lcmerge'
VERSION_PHOTOMETRY = 'DESALL_forcePhoto_real_snana_fits'
PHOTFLAG_MSKREJ = 1016, 0      ! reject bits for PHOTFLAG column
CUTWIN_PHOTPROB = -999, 999    ! wide open -> not used here
```

---

<sup>33</sup><https://arxiv.org/abs/1901.06384>

```

CUTWIN_PSF      = 0.5, 2.75  ! PSF select window, arcsec
CUTWIN_ZPNPE    = 30.5, 100. ! zeropoint select window, Npe
OUT_EPOCH_IGNORE_FILE = 'DES_EPOCH_IGNORE.DAT'
&END

```

In this example there are four epoch-based cuts on PHOTFLAG, PHOTPROB,<sup>34</sup> PSF, and zeropt. The last user input, OUT\_EPOCH\_IGNORE\_FILE, writes every rejected epoch to the specified epoch-reject file. The output table columns are

```

VARNAMES: CID MJD BAND PHOTFLAG PHOTPROB ZP PSF CUTMASK

```

and the bottom of the epoch-reject file includes a commented statistics summary for all rejected epochs, and for each cut. To enable more detailed cut studies, the CUTMASK column indicates which cuts resulted in rejecting each epoch; see CUTMASK comments at top of epoch-reject file.

### 12.2.7 Restoring Bugs

Following the publication of an analysis, SNANA bugs are found and fixed, and algorithms are improved. While all SNANA code versions are archived for reproducibility, it may be convenient to include a flag to restore original code, including bugs. Such a flag allows using the same [current] code version to process data with & without the code changes. The first such flag is for the DES 3-year (DES3YR) cosmology results published Winter 2019:

```

RESTORE_DES3YR: 1  # sim-input

&SNLCINP
  RESTORE_DES3YR = T  # LC fit input

```

---

<sup>34</sup>Example PHOTPROB uses are machine-learning prob or PSF fit-chi2.

### 12.2.8 Crosscheck $z_{\text{hel}} \rightarrow z_{\text{cmb}}$ in Data Files

In some data files, the CMB-frame redshift has been evaluated using the additive approximation,  $z_{\text{cmb}} = z_{\text{hel}} + z_{\odot}$ , instead of the exact formula,  $1 + z_{\text{cmb}} = (1 + z_{\text{hel}})/(1 - z_{\odot})$ . If both REDSHIFT\_HELIO and REDSHIFT\_CMB are included in the data files, the snana code can run a crosscheck with the following input,

```
&SNLCINP
  ZTOL_HELIO2CMB = 0.001  ! abort if dz/zCMB > 0.001 (default=0.02)

or command-line arg:
  snana.exe <inpFile> ZTOL_HELIO2CMB 0.001
```

The SNANA code computes  $z_{\text{cmb}}$  from  $z_{\text{hel}}$  and compares with REDSHIFT\_CMB in the data file; if the difference (dz) satisfies  $\text{dz}/z_{\text{CMB}} > \text{ZTOL\_HELIO2CMB}$ , the code aborts. The default tolerance is 0.02, which may catch severe bugs, but will not catch the additive approximation.

### 12.2.9 K-correction Dump Utility: kcordump.exe

The K-correction tables are stored in HBOOK files, and accessing this information can be tricky even for those familiar with PAW. The utility kcordump.exe can be used to check a K-correction value for specific filter, epoch, and primary reference. If you type kcordump.exe with no arguments, the program will ask you for all needed arguments. You can also use command-line arguments, as illustrated here for SNLS  $K_{gU}$  at peak at  $z = 0.28$ :

```
> kcordump.exe KCOR_FILE Hsiao/kcor_SNLS_Bessell90_VEGA.fits \\  
                FILT_OBS g FILT_REST U Z .28 TREST 0.
```

The dump utility checks your current directory and \$SNDATA\_ROOT/kcor for the existence of the K-correction file (argument of KCOR\_FILE). All K-correction dumps are done with no spectral warping. To see K-corrections with warping, generate simulated SNe Ia and scroll through the data files for symbols containing “KCOR” and “WARP.” The slight disadvantage with using the simulation to check K-corrections is that you cannot specify which K-corrections to check, but you can only compare to whatever the simulation generates.

## 12.3 Misc. Simulation Tools

### 12.3.1 README and DASHBOARD Utilities

```
snlc_sim.exe mysim.input README      # write README file and quit
snlc_sim.exe mysim.input DASHBOARD   # print all map and library file names
```

The `README` argument forces the sim to write the standard `README` output file with the `OVERVIEW`, `INPUT_KEYS` and `INPUT_NOTES` yaml blocks, and then the sim quits. For speed, most initializations are skipped such as for `HOSTLIB` and transient model.

There are well over a dozen possible input files (maps, libraries ...) to the simulation, and keeping track can be difficult, especially with include files and command-line overrides. A brief summary of every input file can be displayed with the `DASHBOARD` command. Unused files are labeled `NONE`.

### 12.3.2 Co-Adding SIMLIB Observations on Same Night: `simlib_coadd.exe`

If a survey takes many exposures per filter in one night, the resulting `SIMLIB` can be quite large, and there may be no benefit to simulating each exposure within a night. Since one typically combines these exposures into a single co-added exposure, there is a utility to translate a `SIMLIB` so that there is just one effective co-added exposure per filter per night,

```
> simlib_coadd.exe MYSURVEY.SIMLIB
```

which produces an output `SIMLIB` called `MYSURVEY.SIMLIB.COADD`. By default, observations within 0.4 days are combined into a single co-added observation, and at least three observations are required to keep a sequence of observations (i.e, a `LIBID`). The `CCD` noise, sky-noise and zeropoint are calculated to reflect a single co-added exposure as follows,

$$\text{ZPT}(\text{COADD}) = 2.5 \log_{10} \left[ \sum_i 10^{(0.4 \cdot \text{ZPT}_i)} \right] \quad \text{NOISE}(\text{COADD}) = \sqrt{\sum_i \text{NOISE}_i^2} \quad , \quad (45)$$

where  $i$  is the exposure index. The co-added PSF is simply the average of the PSF values from the individual exposures.

There are additional options to change the requirement on the minimum number of observations, to change the time-separation for co-adding, and to determine the Milky Way Galactic extinction (`MWEBV`) from [11],

```
> simlib_coadd.exe MYSURVEY.SIMLIB MWEBV --TDIF .2 --MINOBS 5
```

When the “`MWEBV`” option is used, observation sequences with `MWEBV` > 2 are rejected. Read top of `$SNANA_DIR/src/simlib_coadd.c` for additional options.

### 12.3.3 Creating a SIMLIB from Data

Ideally, a `SIMLIB` is created from a library of observations containing PSF, sky-noise and zero-point. However, there may be cases where it is useful to create a `SIMLIB` directly from a data sample. A few examples are 1) low- $z$  sample which has no meta-data to construct a `SIMLIB` file, 2) simulating fake SNe that have already been overlaid on images.

The `snana.exe` program can create such a `SIMLIB` via the `&SNLCINP` input key(s)



```

&SNLCINP
  SIMLIB_OUT = 'mydata.simlib'

! for sims, or fake data with SIM_MAGOBS :
  OPT_SIMLIB_OUT = 1    ! write SIM_MAGOBS in last SIMLIB column, all obs
  OPT_SIMLIB_OUT = 2    ! idem, but only when true flux > 0

! for systematic tests only
  SIMLIB_OUT_TMINFIX = 5    ! force PEAKMJD = MJD_MIN - 5

! optional method to include SALT2x1 and SALT2c in header
! if fitted c and x1 are in the header-override file:
  HEADER_OVERRIDE_FILE = '[fileName with c and x1 cols]'

```

and the NOFILE feature can be used, e.g.,

```
snana.exe NOFILE VERSION_PHOTOMETRY [version] SIMLIB_OUT mydata.simlib
```

If the light curve data include meta data (PSF,SKY,ZP) for each epoch, these values are written out to the SIMLIB. If the meta data are not available (e.g., low- $z$  samples), then two assumptions are used to compute these values. First, the PSF(FWHM) is fixed to  $1''$ . Second, the sky brightness (mag/asec<sup>2</sup>) vs wavelength is taken from an old version of the LSST deep-drill cadence. For an arbitrary filter, the skyMag is interpolated as a function of the central wavelength of the filter. Fortran subroutine COMPUTE\_SIMLIB\_INFO computes the SKYSIG and ZP values using the above assumptions and the  $S/N$  from the data.

If there are no meta-data, the default ZPERR is 0.01, which imposes a true and/or reported SNR ceiling of 100 in the simulation (for ZPERR usage, see SMEARFLAG\_ZEROPT input in §4.7.1) Arbitrary ZPERR values can be input via &SNLCINP as shown in the following example:

```
SIMLIB_ZPERR_LIST = 'u .02 gri .01 z 0.015'
```

Any band not listed above gets the default ZPERR=0.01.

If spectra are included in data (e.g., SNIa training sample), a TAKE\_SPECTRUM key for each spectrum is automatically written to each LIBID header as follows

```
TAKE_SPECTRUM: TOBS(4.6)    SNR(1179)    SNR_LAMOBS(3590:7535)
```

The SNR and wavelength range (SNR\_LAMOBS) correspond to the full wavelength range of the spectrum, and each simulated spectrum (below) is truncated in wavelength to match that of the data. Beware that the average SNR of simulated spectra match the data, but the  $\lambda$ -dependence of SNR is from the spectrograph table (Fig. 3) and may not match the data.

The SIMLIB is updated for events passing cuts in the &SNLCINP namelist, and a SIMLIB row is written for each epoch. The SIMLIB header for each event includes the redshift, peak-MJD, and spectra-SNR info. When using this SIMLIB in the simulation, header values are selected with following sim-input keys (§4.7.1):

```

USE_SIMLIB_PEAKMJD: 1 # use peakMJD in header (if there)
USE_SIMLIB_REDSHIFT: 1 # use redshift in header (if there)
USE_SIMLIB_SPECTRA: 1 # use TAKE_SPECTRUM key(s) in header

```

A few warnings: 1) sim-input keys `GENRANGE_REDSHIFT` and `GENRANGE_PEAKMJD` are applied and therefore some `SIMLIB` entries can be rejected, 2) the simulation may generate more than `NGENTOT_LC` events so that `NGENTOT_LC` events are generated within the `GENRANGE_REDSHIFT[PEAKMJD]` windows, 3) `TAKE_SPECTRUM` keys are used from either the `SIMLIB` header or sim-input file, but not both; the simulation will abort if both are requested.

The `OPT_SIMLIB_OUT` feature writes the true (simulated) mags in the last column of the `SIMLIB` file. Beware that overlapping fields are not treated properly, so it is recommended to set `CUTWIN_NFIELD = 1,1`. The “SIMLIB” model feature in the simulation (§9.9) reads these mags.

### 12.3.4 Fudging Simulated Errors and Signal-to-Noise Ratio (S/N)

Errors and  $S/N$  can be fudged in the simulation as follows:

```
# 1. options to adjust exposure time (affects both SN flux and sky noise)
EXPOSURE_TIME: 20          # increase all exposure times by 20
EXPOSURE_TIME_FILTER: g 20  # increase g exposure by 20
EXPOSURE_TIME_FILTER: g,r 20,30  # band-dependent increase

FUDGESHIFT_ZPT: 0.03        # add 0.03 to ZPT in all bands
FUDGESHIFT_ZPT_FILTER: g 0.03 # add 0.03 to g-band ZPT only
FUDGESHIFT_ZPT_FILTER: gz 0.03 # add 0.03 to g and z-band ZPT
FUDGESHIFT_ZPT_FILTER: g,r,i,z 0.03,-0.02,0.01,0.04 # band-dependent ZPT

# 2. options to increase SKY-noise while leaving SN flux unchanged
FUDGESCALE_PSF: 2          # increase PSF
FUDGESCALE_NOISE_SKY: 3     # increases SKYNOISE (SKY *= 3^2)
FUDGESCALE_NOISE_TEMPLATE 0 # remove template noise

# 3. force nearest-peak S/N = 25 for all bands
FUDGE_SNRMAX: 25           # adjust exposure time
FUDGE2_SNRMAX: 25          # adjust sky-noise only (don't change SN flux)

# 4. force nearest-peak S/N in r-band; use same EXPOSURE time in other bands
FUDGE_SNRMAX: r=25         # adjust exposure time for r-band

# 5. add magErr to all epochs
FUDGE_MAGERR: 0.03         # add .03 magErr to all epochs and bands
FUDGE_MAGERR_FILTER: g .01  # add .01 magErr to g-band
FUDGE_MAGERR_FILTER: riz .02 # add .02 magErr to riz bands
FUDGE_MAGERR_FILTER: r,i,z .01,0.02,0.03 # band-dependent

# 6. add ZPTERR to all epochs
FUDGE_ZPTERR: 0.03         # add .03 ZPTERR to all epochs and bands
FUDGE_ZPTERR_FILTER: g .01  # add .01 ZPTERR to g-band
FUDGE_ZPTERR_FILTER: riz .02 # add .02 ZPTERR to riz bands
FUDGE_ZPTERR_FILTER: r,i,z 0.02,0.01,0.005

# 7. shift filter wavelength
FUDGESHIFT_LAM: 10.0        # add 10 A to all bands
FUDGESHIFT_LAM_FILTER: gr 7.2 # add 7.2A to g+r bands
FUDGESHIFT_LAM_FILTER: g,r,i,z 2.2,-3.3,4.4,1.1 # band-dependent
```

There are six classes of error-fudging: (1) adjust exposure time to change both the SN flux and sky-noise, (2) increase the sky-noise while leaving the SN flux unchanged, (3) force nearest-peak  $S/N$  to be the same fixed value in all bands, (4) force nearest-peak  $S/N$  for one band, then use computed, `EXPOSURE_TIME` in all bands, (5) add arbitrary mag-error at each epoch, (6) add zero point error for each epoch. The last two options (`MAGERR` and `ZPTERR`) are similar, but have a subtle

difference. `FUDGE_MAGERR` is applied to the model magnitudes regardless of the instrumental parameters. `FUDGE_ZPTERR` replaces the `ZPTERR` column in the `SIMLIB` file, which applies measurement scatter based on the `SMEARFLAG_ZEROPT` key. The 1-bit applies scatter to the true fluxes, the 2-bit includes `ZPTERR` in the reported flux-uncertainties, and “`SMEARFLAG_ZEROPT: 3`” does both.

`FUDGE2_SNRMAX` is useful for setting a nearly fixed error at all epochs, in contrast to a fixed  $S/N$ , or mag-error. For both options to fix the nearest-peak  $S/N$  ratio, the simulation processes each SN twice. The first iteration is done with nominal conditions and the resulting `SNRMAX`<sup>35</sup> is used to calculate the `EXPOSURE_TIME` for the second iteration. For option 3), the `EXPOSURE_TIME` is adjusted separately in each band to get the same fixed  $S/N$ , while in option 4) the `EXPOSURE_TIME` is the same in each band to fix  $S/N$  in just one band. The `EXPOSURE_TIME` value for each band is written to the header in each data file; see `SIM_EXPOSURE` key. Defining  $\text{SNR}_i$  to be the  $i$ 'th-iteration  $S/N$  where  $\text{SNR}_2$  is the requested `FUDGE[2]_SNRMAX` value, and  $\mathcal{R} \equiv \text{SNR}_2/\text{SNR}_1$ , the zeropoint and sky-noise are modified for each passband in the second iteration as follows:

$$\text{FUDGE\_SNRMAX} : \quad \text{EXPOSURE\_TIME}_2 = \mathcal{R}^2 \quad (46)$$

$$\text{FUDGE\_SNRMAX} : \quad \text{ZPT}_2 - \text{ZPT}_1 = 5 \log(\mathcal{R}) \quad (47)$$

$$\text{FUDGE\_SNRMAX} : \quad \sigma_{\text{sky},2}/\sigma_{\text{sky},1} = \mathcal{R} \quad (48)$$

$$\text{FUDGE2\_SNRMAX} : \quad \text{ZPT}_2 - \text{ZPT}_1 = 0 \quad (49)$$

$$\text{FUDGE2\_SNRMAX} : \quad \sigma_{\text{sky},2}/\sigma_{\text{sky},1} = \sqrt{[(1/\text{SNR}_2)^2 - 1/\hat{F}_{\text{SN}}] / [(1/\text{SNR}_1)^2 - 1/\hat{F}_{\text{SN}}]} \quad (50)$$

where  $\hat{F}_{\text{SN}}$  is the SN flux (photoelectrons) at the epoch with the maximum  $S/N$ .

Finally, `FUDGESHIFT_ZPT` and `FUDGESHIFT_LAM` can be used for systematic calibration shifts.

---

<sup>35</sup>`SNRMAX` is the maximum  $S/N$  ratio among all observations within a passband.

### 12.3.5 DOCANA: Documenting Input Maps

The simulation reads up to 20 different inputs maps and libraries (see **DASHBOARD** utility in §12.3.1), and thus documenting is a challenge. To enforce/remind about documentation, each map is required to include a yaml-compliant documentation block at the top of the file, which is called **DOCANA**. The **YAML** format enables higher-level pipelines to extract the **DOCANA** snippets and glue them together in a summary file. Examples can be found using `find` command, e.g.,

```
cd $SNDATA_ROOT/simlib
grep -rnw ./ -e 'DOCUMENTATION:'
```

and here is a generic illustration,

**DOCUMENTATION:**

```
PURPOSE: what is this for ?
REF:
- AUTHOR: Y. Astro et al 2017 (few-word reminder)
  ADS:    https://ui.adsabs.harvard.edu/abs/xxx
- AUTHOR: C. Telescope et al 2014 (few-word reminder)
  ADS:    https://ui.adsabs.harvard.edu/abs/xxx
INTENT:    Nominal or Test
USAGE_KEY: key name for input file
USAGE_CODE: snlc_sim.exe
VALIDATE_SCIENCE:
- figure(s) in published paper
- local/unpublished tests
- None ?
NOTES:
- odd reminder
- another odd reminder
VERSIONS:
- DATE: 2020-02
  AUTHORS: J. Cosmology, Y. Astro
```

**DOCUMENTATION\_END:**

While the **YAML** block is required to avoid a simulation abort, specific keys are not required. Thus the **REF** key could be absent during development (or point to internal collaboration memo), while other relevant **YAML** keys can be added as needed. The **INTENT** key indicates nominal analysis, or a generic test such as debug, systematic, etc. **VALIDATE\_SCIENCE** briefly indicates the level of validation; put **NONE** if there is no validation. For debugging or urgent/rare situations, the **DOCANA** requirement can be suppressed *interactively* with

```
snlc_sim.exe <myInputFile> REQUIRE_DOCANA 0
```

As of July 19 2021, **DOCANA** is required for

```
HOSTLIB_FILE  HOSTLIB_WGTMAP_FILE  SIMLIB_FILE
```

Additional maps will be gradually added over the next few months.

## 12.4 Misc. Fitting Tools

### 12.4.1 Translating SCDATA files into SALT-II Format

The `snana.exe` program can convert SNANA-formatted data (or simulation) files into SALT-II format needed to run the original (Guy07) SALT-II fitter code and the SALT-II training code. A sample namelist is as follows:

```
&SNLCINP
  VERSION_PHOTOMETRY = 'SDSS_HOLTZ08'
  OPT_REFORMAT_SALT2 = 2
  REFORMAT_KEYS      = '@INSTRUMENT SLOAN  @MAGSYS AB'
  SNFIELD_LIST       = '82N' , '82S'
  cutwin_cid         = 0, 100000
&END
```

Note that `OPT_REFORMAT_SALT2=2` is for the newer SALT-II format with one file per SN (`snfit` version 2.3.0 and higher), while `OPT_REFORMAT_SALT2=1` is for the original format with one file per passband.

### 12.4.2 Translating TEXT data-files into FITS Format; and vice-versa

For relatively large data samples, reading text files can be somewhat slow. A more efficient storage mechanism uses FITS format. TEXT-formatted data files can be translated into FITS format using `snana.exe` and an input file with the following,

```
&SNLCINP
  PRIVATE_DATA_PATH      = 'MYDATAPATH'
  VERSION_PHOTOMETRY     = 'MYSURVEY_TEXT'
  VERSION_REFORMAT_FITS  = 'MYSURVEY_FITS'
  OPT_SETPKMJD = 20      ! useful if there is no PEAKMJD estimate
  OPT_MWEBV      = 2      ! useful if there is no MWEBV in text files
&END
```

or use `NOFILE` option with no input NML file:

```
snana.exe NOFILE \
  PRIVATE_DATA_PATH      MYDATAPATH      \
  VERSION_PHOTOMETRY     MYSURVEY_TEXT   \
  VERSION_REFORMAT_FITS  MYSURVEY_FITS   \
  OPT_SETPKMJD 20        \
  OPT_MWEBV      2
```

This translation should be used only for data since the simulation is written in FITS format by default. In addition to translating the data into FITS format, the auxiliary files are also created: `MYSURVEY.LIST`, `MYSURVEY.IGNORE`, `MYSURVEY.README`. The output files are created under a newly created folder (`/MYSURVEY_FITS`) in your current directory.

If there is no `PEAKMJD` estimate in the TEXT formatted files, `OPT_SETPKMJD>0` provides a `PEAKMJD` estimate for the FITS files. Similarly, `OPT_MWEBV>0` modifies `MWEBV` and `MWEBV_ERR` for

the FITS output. Finally, updated redshifts and  $v_{\text{pec}}$  are included in FITS output; e.g., from header override, etc ... Beware that content of TEXT and FITS may differ in these header variables.

While FITS formatted data is efficient for analysis, it is not so useful for visual inspection. To enable visual inspection, TEXT-formatted data files can be extracted from FITS-formatted files (data or sim) as follows:

```
snana.exe NOFILE \
  VERSION_PHOTOMETRY      MYSURVEY_FITS \
  VERSION_REFORMAT_TEXT   MYSURVEY_TEXT \
  SNCID_LIST 8,1034,5944
```

where an explicit CID list or snana selection criteria can be applied. To avoid file-count quota issues, a max limit of 20 data files can be extracted.

Additional reformat options can be specified using SNLCINP input mask OPT\_REFORMAT\_FITS or OPT\_REFORMAT\_TEXT

```
OPT_REFORMAT_FITS = 2    ! include rejected epochs
OPT_REFORMAT_FITS = 64   ! exclude private variables
OPT_REFORMAT_FITS = 128  ! include spectra
OPT_REFORMAT_FITS = 256  ! exclude SIM truth to look like real data

OPT_REFORMAT_SPECTRA = 1 ! re-write only the spectra in text: lam Flam Flamerr
OPT_REFORMAT_SPECTRA = 2 ! write FLUX instead of FLam for astrodash
```

Here is an example command to convert a simulation into a data-like sample that has no truth information:

```
snana.exe NOFILE \
  VERSION_PHOTOMETRY      CHALLENGE_SNIa \
  VERSION_REFORMAT_FITS   CHALLENGE_SNIa_TRAIN \ # output data folder
  OPT_REFORMAT_FITS       256 \
  CUTWIN_SNTYPE 1 99
```

or the wildcard feature:

```
snana.exe NOFILE \
  VERSION_PHOTOMETRY_WILDCARD 'CHALLENGE_*' \
  VERSION_REFORMAT_FITS   CHALLENGE_TRAIN \ # output data folder
  OPT_REFORMAT_FITS       256 \
  CUTWIN_SNTYPE 1 99
```

The last input CUTWIN\_SNTYPE selects all spectroscopically-confirmed tags, and other CUTWIN options can be used as well. The output data folder contains no sim-truth which is useful for i) data challenges, and ii) test analysis codes to ensure they don't cheat using sim-truth.

OPT\_REFORMAT\_FITS[TEXT] applies to the entire event (header, photometry, spectra), while OPT\_REFORMAT\_SPECTRA applies only to spectra with the goal of re-formatting for spectral-analysis codes. This spectral-reformat writes a single file per spectrum in the cwd (i.e., does not create an output folder); the calling code should organize a folder structure.



### 12.4.3 Re-write Data Files with Flux Fudges

There are options in the analysis programs to modify the fluxes and flux-errors read from the data files. To re-write data files with these modifications,

```
&SNLCINP
  VERSION_PHOTOMETRY = 'DES-SN3YR_DES'
  MAGCOR_FILE        = '$DES_ROOT/lcmerge/DES3YR_DES_MAGCOR.DAT'
  FLUXERRMODEL_FILE  = '$DES_ROOT/simlibs/DES3YR_FAKE_ERRORFUDGES.DAT'
  VERSION_REFORMAT_FITS = 'NEW_VERSION_NAME' ! re-write in FITS format
&END
```

In this example, `MAGCOR_FILE` and `FLUXERRMODEL_FILE` are used to modify the fluxes and their uncertainties. `VERSION_REFORMAT_FITS` re-writes in FITS format with modified fluxes so that future analyses need not worry about using the SNANA flux-modify options. This option is particularly useful for data releases.

If the re-written data files include SNANA-computed flux/fluxErr fudges, a header variable in the data files is included,

```
MASK_FLUXCOR_SNANA: <MASK>
```

where `MASK+=1` if the fluxes include a correction, and `MASK+=2` if the flux-errors have been corrected. `MASK=3` means that both the fluxes and uncertainties have been corrected. When analyzing the re-written data files, `MASK` is an instruction to ignore SNANA fudges, thus allowing the same input `nameList` file to be used on original and re-written data files. When analyzing re-written data files that already include a correction, an additional correction can be “FORCED” as follows,

```
MAGCOR_FILE = '$DES_ROOT/lcmerge/DES3YR_DES_MAGCOR.DAT FORCE'
```

### 12.4.4 Fudging Fitting Errors

For the `snlc_fit.exe` fitting program there are the `FUDGE_FITTER_XXX` parameters described in detail in §5.13. The other fudge-option is the `&FITINP` namelist variable

```
FUDGE_MAGERR_MODEL = 0.1 # fix model mag-error in fitter
```

which replaces all model errors with 0.1 mag model-error at every epoch.

### 12.4.5 1/Vmax Method: Post-Fit Calculations

The 1/Vmax method can be used to compute  $Z_{\max}$  and the associated volume for each SN. These calculations are controlled with the following &FITINP namelist options,

```
MAGLIM_Vmax = 'r 21.5 i 21.0'
OPT_Vmax     = 0                      ! valid options: 0,1,2,3
```

MAGLIM\_Vmax defines a list of mag-limits and observer-frame filters to perform the 1/Vmax calculation. Only one mag-limit per filter can be defined, but a different mag-limit can be defined for each filter. OPT\_Vmax is a bit mask as follows.

- Bit0 controls how the SN magnitude is computed: OFF is for the brightest observed epoch (using best-fit mag) and ON is for the peak magnitude.
- Bit1 controls how  $Z_{\max}$  is computed: OFF is for the brightest observed epoch (using best-fit mag) and ON is for the peak magnitude.
- Bit7 (128) turns on verbose mode to see  $Z_{\max}$  at each iteration.

For example, OPT\_Vmax=0 means that both the SN magnitude and  $Z_{\max}$  are computed at  $T_{\text{rest}}$  corresponding to the brightest observed epoch. To avoid picking an epoch with an upward fluctuation, the best-fit fluxes are used to determine the brightest observed epoch rather than the observed fluxes. OPT\_Vmax=3 means that both the SN magnitude and  $Z_{\max}$  are computed at the best-fit epoch of peak brightness.

The following variables are automatically included in the fitres-text file and the SNTABLE (ntuple or Tree):  $T_{\text{rest}}$  where mag is computed, mag,  $Z_{\max}$ , volume.

### 12.4.6 FILTER\_REPLACE

For filters that are very similar, such as multiple filters overlapping a patch of sky, it is sometimes convenient to replace filter names. As an example, consider the SDSS filters *ugrizUGRIZ*, where the *UGRIZ* filters are defined for the small fraction of SN that land on overlapping CCD regions. To fit with the usual “`FITLIST_FIT = 'ugriz'`” input, we can replace the upper-case filters with the following `&SNLCINP` namelist variable,

```
&SNLCINP
  FILTER_REPLACE = 'UGRIZ -> ugriz'
```

This replacement is equivalent to modifying the data files with `U->u`, `G->g`, etc.

WARNING(v10\_28l): When there are no *UGRIZ* bands, we expect that fitting *ugrizUGRIZ* should give the same result as fitting *ugriz* with the `FILTER_REPLACE` command above. This test works perfectly except when `OPT_COVAR > 0`; hence something about using a model-error covariance matrix with off-diagonal elements introduces a very small (few millimag) discrepancy. It is not yet clear if this discrepancy is due to a bug, or if it is expected when using `OPT_COVAR`.

### 12.4.7 SNTABLE\_FILTER\_REMAP

This option is for a survey with many similar bands (e.g., low-*z*), and is used to remap the output bands. For example, suppose we have the following bands: *ab*(*U*-like), *cde*(*B*-like), *fghi*(*V*-like). The '*fghi*' bands are all *V*-like, and correspond to very small changes in telescope transmission, such as from a filter replacement. The output tables by default would include filter-dependent values for each band: *abcdefghi*. To simplify some analyses, it may be more convenient to work with *UBV* rather than with *abcdefghi*. This convenience is achieved in the output tables by remapping the filters with the command

```
&SNLCINP
  SNTABLE_FILTER_REMAP = 'ab->U  cde->B  fghi->V'
```

This command only affects the output tables, and has no impact on selection cuts or fitting: i.e., all 9 bands (*abcdefghi*) are still used in the light curve fit.

### 12.4.8 Selecting SNe

The SNANA analysis programs (`snana.exe`, `snlc_fit.exe`, `psnid.exe`) include a common set of cuts via the `&SNLCINP` namelist. Unfortunately these cut parameters are documented only within the code, e.g.,

```
grep cutvar_name $SNANA_DIR/src/snana.car | grep CUTBIT
```

and for each `CUTBIT_XXX` there is an associated `CUTWIN_XXX` for `&SNLCINP` or command line override. There are other non-`CUTWIN` inputs to select based on `CID` or `TYPE`,

```
SNCID_LIST      = 4,88,105          ! explicit list of integer CIDs
SNCCID_LIST     = 'Joe,Henry,Sam'   ! same for char string names
SNTYPE_LIST     = 1,18              ! select ITYPE = 1 or 18
MXEVT_PROCESS   = 10                ! process first 10 events
MXEVT_CUTS      = 4                 ! process until 4 events pass cuts
```

### 12.4.9 Selecting Observations

By default, all observations are selected. A subset of observations is selected with explicit `CUTWIN_XXX` inputs, and/or rejected via `PHOTFLAG` bits,

```
&SNLCINP
  CUTWIN_PSF     = 0.5, 2.75 ! FWHM, arcsec
  CUTWIN_ZPNPE   = 30.5, 100. ! cut on ZP in Npe

  PHOTFLAG_MSKREJ = 1016      ! reject if PHOTFLAG & 1016
    or
  PHOTFLAG_BITLIST_REJECT = 3,4,5,6,7,8,9 ! same as above (LSB=0)
```

If the `PHOTFLAG_MSKREJ` value is not stable (e.g., near start of analysis), the value can be included in the data `[VERSION].IGNORE` file as

```
# -----
PHOTFLAG_MSKREJ: 1016    # reject if PHOTFLAG & 1016
    or
PHOTFLAG_BITLIST_REJECT: 3,4,5,6,7,8,9 # LSB=0

# and optional list of specific epochs to ignore
#      SNID      MJD      band
IGNORE: 1032  53668.387    g
IGNORE: 1286  53773.291    r
IGNORE: 1785  53792.898    i
# -----
```

If `PHOTFLAG_MSKREJ` is defined in the `&SNLCINP` name-list or the command line, this value overrides the value in `[VERSION].IGNORE`.

### 12.4.10 Selecting Early Epochs

During a survey, light curves are fit with only a few epochs for monitoring or spectroscopic target selection. For testing on simulated data, however, the entire light curve exists because it is not practical to re-generate simulations that stop at each successive night. The following `&SNLCINP` inputs illustrate how to fit light curves (data or sim) using only a few epochs as if the latter epochs had not yet been observed:

```
&SNLCINP
  EARLYLC_STRING = 'MAXOBS 4  FILTERS riz  SNRMIN  4.5'      !1
    or
  EARLYLC_STRING = 'MAXOBS 4  FILTERS riz  PHOTPROBMIN .5'    !2
    or
  EARLYLC_STRING = 'MAXOBS 4  FILTERS riz  PHOTMASK 4096'     !3
    or
  EARLYLC_STRING = 'MAXNIGHT 2  FILTERS riz  PHOTMASK 4096'  !4
    or
  EARLYLC_STRING = 'MAXNIGHT 2  PHOTMASK 4096  NDAYADD 20'    !5
    or
  EARLYLC_STRING = 'MAXNIGHT 2  PHOTMASK_START 4096'          !6a
    or
  EARLYLC_STRING = 'MAXOBS 3  SNR_START 5'                    !6b
```

The `MAXOBS` key specifies the maximum number of `EARLYLC` observations to keep that satisfy the logical AND of cuts on filters, signal-to-noise (`SNRMIN`), photometry-probability (`PHOTPROBMIN`) and photometry-mask (`PHOTMASK`). The first example above (!1) keeps epochs until there are 4 observations in *r*, *i*, or *z* that have SNR above 4.5. In the second example (!2), the SNR requirement is replaced with the `PHOTPRPOBMIN` requirement. Third example (!3) requires four observations to have the 4096 bit of the photometry mask (e.g., detection). Epochs satisfying the `EARLYLC` requirements may not occur until well after explosion; thus all pre-`EARLYLC` (pre-explosion) epochs are kept. Once `MAXOBS=4` `EARLYLC` epochs are found, no additional epochs are kept.

The `MAXNIGHT` key (!4) includes all observations within a 12 hour period, or 1 night. For example, consider a night with observations in the *g*, *r*, *i*, *z* bands, and they all satisfy the “`PHOTMASK & 4096`” requirement. In the following night we have *i*, *z* observations which pass `PHOTMASK`. While this counts as 6 observations toward `MAXOBS`, it counts as 2 nights towards `MAXNIGHT`. Once the `MAXNIGHT` requirement is met with the first *i*-observation in the 2nd night, all observations in the 2nd night are included.

`NDAYADD` (!5) will add epochs for this many days after the last observation from the above keys.

Finally, `PHOTMASK_START` and `SNR_START` (!6a,6b) are requirements on when to start counting nights (for `MAXNIGHT`) or observations (for `MAXOBS`). In 6a, a single observation satisfying “`PHOTMASK_START & 4096`” starts the number-of-nights counter with no further requirements on successive observations. Similarly in 6b, a single observation with `SNR>5` starts the number-of-observation counter. This feature is useful for rapidly fading transients that may be detected on only 1 night, but still have useful observations in successive nights.

The default cuts are wide open, except for the default `NDAYADD=0`. Not specifying `FILTERS` will count all filters, not specifying `PHOTPROBMIN` will ignore `PHOTPROB` in counting early epochs, etc. Thus setting `EARLYLC_STRING='MAXOBS 4'` will select the first 4 observations in the data file, regardless of what is measured.

To avoid mistakenly using the entire light curve in some part of an analysis, the removed epochs are not stored in any arrays so that the internal arrays are filled as if the late epochs did not exist.

#### 12.4.11 Selecting Epoch Ranges for Fast Transients (REQUIRE\_EPOCHS\_STRING)

To help select transients whose duration is faster than Supernova, the time above threshold is a useful quantity that can be used with the following nameList input:

```
&SNLCINP
  REQUIRE_EPOCHS_STRING 'FILTERS riz SNRMIN 5 TOBS_RANGES 14 20 25'
```

SNRMIN defines the threshold. The three TOBS\_RANGES values specify time-window 1) before threshold is satisfied, 2) while SNR is above threshold, and 3) after SNR falls below threshold. More specifically, events are selected whose time above SNRMIN is less than 20 days. To avoid getting fooled at the start or end of a survey, an observation is required within 14 days prior to the first epoch with SNR>5, and another observation is required within 25 days after the last epoch with SNR>5. The pre- and post observation ensure that an above-threshold epoch would have been seen, and was not hidden by a dormant survey.

#### 12.4.12 Rejecting Outlier Fluxes for Fakes and SIM

If fakes overlaid on images have catastrophic outliers, outlier epochs can be rejected with

```
&SNLCINP
  CUTWIN_SIMPULL -3.0, +3.0 ! reject >3 sigma outliers
```

#### 12.4.13 Miscellaneous &SNLCINP Options

```
&SNLCINP
  USESIM_SNCC = F      ! ignore simulated CC (fit true Ia only)
    or
  USESIM_SNIA = F      ! ignore simulated IA (fit true CC only)

  SIM_PRESCALE = 4.0 ! fit 1/4 of sim sample, but still fit all data
```

## 12.5 Misc. SIMSED Utilities

### 12.5.1 SIMSED Spectrum Extraction: SIMSED\_extractSpec.exe

For a SIMSED model, the program `SIMSED_extractSpec.exe` can be used to extract a single spectrum for a particular SIMSED model version, epoch, and set of parameter values corresponding to the PARNAMES in the SED.INFO file. The current program uses the parameter values on the SED.INFO grid that are closest to the user-specified parameters; a future version may interpolate for better accuracy. See usage instructions at top of `$SNANA_DIR/src/SIMSED_extractSpec.c`.

### 12.5.2 SIMSED Fudge Afterburner: SIMSED\_fudge.exe

For a given SIMSED model (§9.5), an arbitrary color law can be applied to generate a new SIMSED version. The program syntax is

```
SIMSED_fudge.exe <inFile>
```

where an example input file is here:

```
$SNDATA_ROOT/sample_input_files/SIMSED/colorFudge.input
```

### 12.5.3 SIMSED Preparation for SNANA: SIMSED\_prep.exe

Translate native format of SED model into SNANA format.

## 12.6 Reading gzip'ed Input Files

To reduce disk usage and improve the speed in reading large input text files, SNANA will read any input file that is compressed with `gzip`. Always specify the uncompressed name (e.g., `mystuff.text`) and SNANA programs will check for both `mystuff.text` and `mystuff.text.gz`. If both the compressed and uncompressed files exist, the code will abort. Reading compressed files is faster, with the cost of a little added time ( $\sim 0.1$  sec) opening the file with `popen` instead of `fopen`. Gzipped inputs include the SIMLIB file (§4.7), HOSTLIB file (§4.22), SIMSED model files (§9.5), LCLIB model files, SALT2 model files, and text-formatted data files.

Be aware that two of these input files (SIMLIB & LCLIB) are rewound each time the EOF is reached. The “`popen`” command for gzipped files is not compatible with the “`rewind`” function, and thus rewinding a gzipped file requires an explicit close and re-open. For small input files that are re-read many times, the extra close-and-open overhead from a gzipped file may increase processing time. Thus it is recommended to *gzip only* the large unput files, and leave the small input files unzipped.

## 12.7 Program Return Codes

Program return codes are useful for higher-level pipelines. Each C and fortran program returns 0 on successful completion. An abort or error results in the following error codes that can be examined with unix command ‘`echo $?`’ :

Program	return error code
-----	-----
kcor.exe	10
snlc_sim.exe	11
SALT2mu.exe	12
combine_fitres.exe	13
sntable_dump.exe	14
wfit.exe	15
merge_root.exe	16
merge_hbook.exe	17
snana.exe	21
snlc_fit.exe	22
psnid.exe	23



## 13 SNANA Updates

The **SNANA** software is released in incremental versions, reflecting improvements, new code, and bug fixes. Users should periodically check for updated versions. Details of each release can be found by doing

```
tail -100 $SNANA_DIR/doc/README_UPDATES
```

Users should develop an automated “download & setup” script to easily maintain the most current version of **SNANA**, and to avoid getting trapped with an old or obsolete version. The **SNDATA\_ROOT** tarball is updated less frequently; **README\_UPDATES** will indicate if and why a new **SNDATA\_ROOT** is needed.

This manual (**\$SNANA\_DIR/doc/snana\_manual.pdf**) is updated mostly in response to questions from users. If you spot mistakes or obsolete information in the manual, please report it immediately !

## 14 Reporting Problems

Please don’t hesitate to report software problems or obsolete/incorrect information in the manual. If the problem is related to an abort or crash, please include a tarball that contains the input file(s) and data file(s) that reproduce the problem, as well as a log-file with the program’s screen-dump. Indicate which **SNANA** version was used, and try to isolate the problem in a single data file to avoid sending large numbers of data files. **WARNING: if you don’t provide enough information to reproduce the problem, we will not be able to provide assistance.**

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