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SkyMaker: astronomical image simulations made easy

E. Bertin

Institut d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre & Marie Curie, 98bis bd Arago, F-75014 Paris, France, e-mail: bertin@iap.fr

Abstract. SkyMaker is a software package for creating artificial astronomical images. I show how such a tool could be used in the framework of the Virtual Observatory to generate virtual observations from simulation data.

Key words. Methods: numerical – Techniques: image processing

1. Introduction

Realistic data simulations are an essential component of all modern astronomical survey experiments, in particular those that deal with images. Detection efficiencies in microlensing studies, or star/galaxy separation and surface brightness selection effects in galaxy surveys are examples of critical issues relying on realistic image simulations.

The science of large imaging surveys requires large numerical simulations and huge datasets. Suitable datasets, such as ”toy universes” from n-body simulations, consisting of particle attributes at various epochs, are readily available (see e.g. the contributions by Volker Springel or Hervé Wozniak, this conference). Unfortunately the data volumes are much too large to be directly publishable through the Virtual Observatory. A more consistent approach, as proposed by G. Lemson, is to set up a VO-compliant "virtual telescope" webservice, generating on-the-fly images from the numerical simulations[1].

Contemporary observations of astronomical sources are often conducted over of a wide range of electromagnetic wavelengths to get a comprehensive understanding of physical processes. The image generator should ideally be flexible enough to offer the possibility to simulate data at wavelengths ranging from radio waves to γ−rays. Hopefully this is not as difficult as it may seem, at least to first order, as most modern imagers share many common characteristics. Image data are generally arranged as a rectangular grid of pixels with close-to-linear behaviour over a dynamic range of 10,000 or more. The image formation process provided by the focusing system is largely translation-invariant up to some cutoff angular frequency over large parts of the focal-plane, and can be described by a point spread function slowly variable over the field of view. Noise may essentially be decomposed into a Poissonian component from the photon-noise

Send offprint requests to: E. Bertin

[1] www.ivoa.net/cgi-bin/twiki/bin/view/IVOA/VirtualTelescopeConfiguration

and an additive, Gaussian component from the electronics.

In the following I present a versatile astronomical image simulation software package called SkyMaker[2] which relies on this set of features. SkyMaker is distributed under the GNU Public license[3]. It started out as a testing tool for the SExtractor source extraction software (Bertin & Arnouts 1996). It has since been used in various studies: weak lensing (e.g. Erben et al. 2001, Heymans et al. 2006), preliminary instrument/pipeline design (e.g. Babusiaux 2005, Réfrégier et al. 2006) or rendering of n-body simulations (e.g. Cattaneo et al. 2005, Blaizot et al. 2005). The organisation of this paper follows that of the main computation steps in SkyMaker: §2 describes the modelling of the different point spread function components; §3 explains how sources are rendered; §4 presents the final stages of the simulation process; §5 gives some performance numbers; §6 focuses on some issues with input data; finally, §7 takes a look at features that may be implemented in future versions.

2. The point spread function

SkyMaker uses a tabulated Point Spread Function (PSF) model, which may be loaded from a FITS file or internally generated. The SkyMaker PSF is tabulated at a considerably higher resolution than the final image (typically $3-11\times$) to provide a faithful reproduction of aliasing effects in conditions of undersampling. The purpose of the internal generator is to be able to represent with decent accuracy the PSF of typical astronomical instruments. It is assumed to be the convolution of five components:

- atmospheric blurring (for ground-based instruments),
- telescope motion blurring (jitter and guiding errors),
- instrument diffraction and aberrations,
- optical diffusion effects,
- intra-pixel response.

[2] `terapix.iap.fr/soft/skymaker`
[3] `www.gnu.org`

In practice, the first three steps are conducted in pupil space, the final PSF being the Fourier transform of the autocorrelation of the pupil.

2.1. Atmospheric blurring

The effects of the atmosphere are modelled as isotropic phase fluctuations on the pupil. Assuming that the turbulent structure of the atmosphere follows a Kolmogorov model, the optical transfer function of atmospheric blurring in long exposures may be written as (see, e.g. Roddier 1981)

$$\mathrm{OTF}(||\boldsymbol{f}||) \propto \exp -3.442\left(\frac{\lambda||\boldsymbol{f}||}{r_0}\right)^{5/3}, \qquad (1)$$

where $||\boldsymbol{f}||$ is the angular frequency (in rad^{-1}), λ the observation wavelength, and r_0 the Fried (1965) parameter representing the coherence scale of phase fluctuations. r_0 may itself be written as a function of λ and the Full-Width at Half-Maximum (FWHM) of the resulting "atmospheric" PSF:

$$r_0 \approx 0.976\frac{\lambda}{\mathrm{FWHM}}. \qquad (2)$$

Removing the first-order component of phase fluctuations ("image wander"), either by combining many very short exposures, or using a fast tip-tilt mirror (e.g. Christou 1991), or an orthogonal transfer detector (Tonry et al. 1997) can bring significant improvement to the image quality on small telescopes. SkyMaker offers the possibility to simulate images with perfect tip-tilt-correction by removing the image wander contribution, which is assumed to be Gaussian and independent of wavelength:

$$\mathrm{OTF}(||\boldsymbol{f}||) \propto \exp \quad -3.442\left(\frac{\lambda||\boldsymbol{f}||}{r_0}\right)^{5/3} \times\left(1-\left(\frac{\lambda||\boldsymbol{f}||}{d_{M_1}}\right)^{1/3}\right), \qquad (3)$$

where d_{M_1} is the diameter of the primary mirror.

2.2. Telescope motion blurring

Jitter and guiding errors can be a significant source of image degradation; both effects are available in SkyMaker, as a convolution of the PSF with a Gaussian (jitter) and/or a one-dimensional door function (trailing).

2.3. Instrument diffraction and aberrations

The SkyMaker PSF simulator reproduces the effects of diffraction and aberrations in the Frauhofer regime of Fourier optics by manipulating a virtual entrance pupil function $p(\rho, \theta)$. The amplitude part of p is a mask driven by the limits of a primary mirror M_1 and the possible obscuration by spider arms and a secondary mirror or primary focus. A set of numbers – the diameters of M_1 and the central obscuration (disk shapes are assumed for both), and the number, position angle and thickness of the spider arms – makes it possible to simulate with reasonable accuracy the diffraction pattern of most common telescope configurations.

Optical aberrations may be added by introducing changes of phase $\phi(\rho, \theta)$ throughout the complex pupil (Fig. 1). The following low-order phase terms can be linearly combined within SkyMaker to simulate a wide range of aberrations:

- defocus: $\phi_{\rm defoc} \propto \rho^2$,
- astigmatism: $\phi_{\rm asti} \propto \rho^2 \cos 2(\theta - \theta_{\rm asti})$,
- coma: $\phi_{\rm coma} \propto \rho^3 \cos(\theta - \theta_{\rm coma})$,
- spherical: $\phi_{\rm spher} \propto \rho^4$,
- tri-coma: $\phi_{\rm tri} \propto \rho^3 \cos 3(\theta - \theta_{\rm tri})$, and
- quad-ast: $\phi_{\rm quad} \propto \rho^4 \cos 4(\theta - \theta_{\rm quad})$.

Phase terms are individually normalised following the ESO d80 convention (Fouqué and Moliton 1996, private communication): phase coefficients represent the diameter of a circle enclosing 80% of the total energy (flux) of an aberrated spot on the focal plane.

2.4. Diffusion

The wings of instrumental PSFs become dominated by diffusion beyond a few FWHMs from the centre. This so-called “aureole” component is experimentally found to follow a somewhat “universal” r^{-2} profile (King 1971), with a surface brightness generally close to 16 mag.arcsec^{-2} at 1’ from a 0$^{\rm th}$ magnitude star. The exact formation process of the aureole is not well understood, although dust, scratches and micro-ripples on optical surfaces, as well as atmospheric aerosols, are most likely the major contributors (see, e.g. Racine 1996 and references therein).

The aureole of bright sources can be traced out to large angular distances from their centre. To avoid manipulating exceedingly large PSFs in SkyMaker, the aureole is generated at a later stage of the processing, and convolved with the image in the final resolution.

2.5. Intra-pixel response

SkyMaker convolves the oversampled optical PSF with the intra-pixel response, and therefore makes the implicit assumption that the latter does not vary on small scales. In the current version, the intra-pixel response function is simply the door function with a width equal to the sampling step, and effects such as charge diffusion are ignored.

3. Source rendering

After generating the PSF model, SkyMaker reads the input catalogue and renders sources at the specified pixel coordinates in the frame. Sources are rendered “on-the-fly”; hence there is no memory limitation to the number of sources that can be added to an image. The current version of SkyMaker supports two types of sources: point-sources and galaxies.

3.1. Point sources

SkyMaker renders point-sources by simply scaling in flux and interpolating the PSF on the final pixel grid at the specified position. Interpolation is carried out using a 6×6-tap Lánczos-3 filter (e.g. Wolberg 1994), which represents a good compromise between flatness of the spatial frequency response and processing speed.

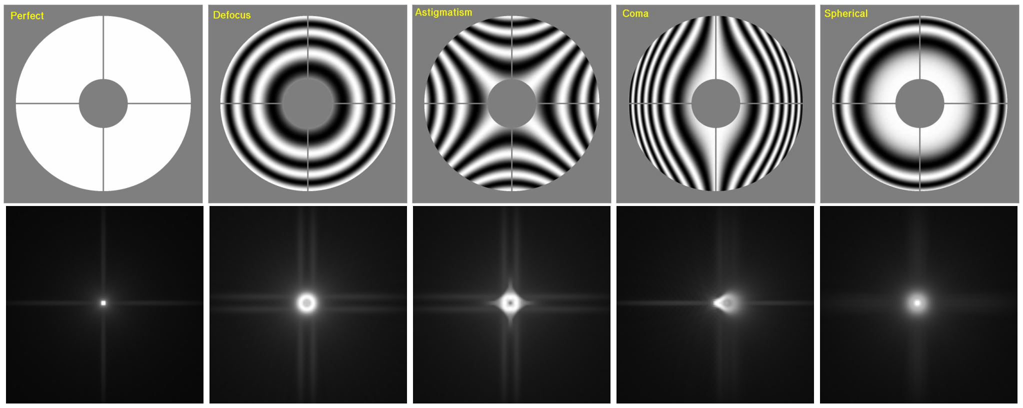

Fig. 1. Real part of the pupil functions and their respective PSFs in the perfect case (left), and in the presence of 1” (d80) of defocus, astigmatism, coma, and spherical aberrations. The PSFs are free of seeing effects and convolved with a 0.2” square-shaped pixel footprint.

3.2. Galaxies

Galaxies are modelled as a sum of a spheroid (bulge) and a disk components. Spheroids follow a de Vaucouleurs profile:

$$\mu_S(r) = m - 2.5\log(B/T) + 8.3268\left(\frac{r}{r_{\rm eff}}\right)^{1/4} + 5\log r_{\rm eff} - 4.9384. \quad (4)$$

μ_S is expressed in units of mag.arcsec^{-2}, m is the apparent galaxy magnitude, B/T the apparent bulge-to-total ratio, and $r_{\rm eff}$ the effective radius of the spheroid in arcseconds (see e.g. Graham & Driver 2005). Disks are given an exponential profile

$$\mu_D(r) = m - 2.5\log(1 - B/T) + 1.0857\left(\frac{r}{r_{\rm h}}\right) + 5\log r_{\rm h} + 1.9955, \quad (5)$$

where $r_{\rm h}$ is the disk scalelength in arcseconds. m, B/T, $r_{\rm eff}$, $r_{\rm h}$ as well as independent aspect ratios and position angles for both components are read from the catalogue.

Galaxy models are generated at a higher resolution than the final image to minimise aliasing effects. To speed up computations, galaxy images are framed around a limiting isophote which depends on galaxy surface brightness and background noise level. After convolution with the PSF, galaxy images are downsampled to the final resolution using Lánczos-3 interpolation and added to the image.

4. Sky background, noise, saturation and quantization

The current version of SkyMaker renders the sky background simply as a constant added to all pixel values. Up to this stage, all pixel values are expressed in “expected” numbers of photo-electrons (detector events), that is, not as integers. Next, two noise processes are applied independently to the data: each pixel value p is replaced with a random number of events drawn from a Poisson distribution with mean p, and Gaussian read-out noise is added. No correlation of the noise is introduced between adjacent pixels.

Charge-coupled devices (CCDs) are used extensively for wide-field imaging. CCDs are known to “bleed’ (or “bloom”) when the number of photo-electrons exceeds the full well capacity of a pixel. Bleeding/blooming on a bright star results in an intense, saturated streak extending in opposite directions along the axis of charge transfer. SkyMaker reproduces this feature by spreading photo-electrons in excess of the pixel full well capacity, symmetrically along the y direction (Fig. 2).

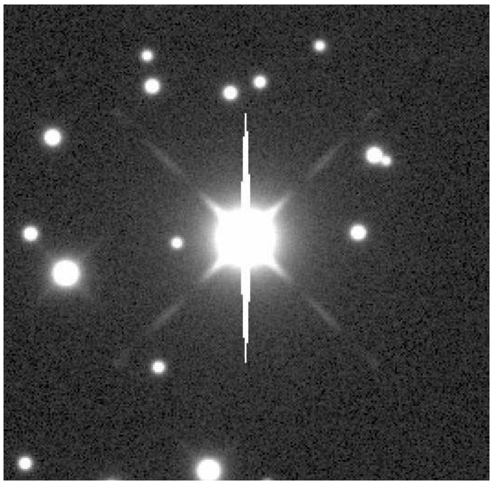

Fig. 2. Blooming artifact in a simulated CCD image of a bright star.

Finally, counts are converted to ADUs and clipped according to the gain factor and saturation values specified in the configuration file.

5. Performance

SkyMaker is written in C, and has been optimised to offer solid performance without sacrificing quality. Much of the code is multithreaded and therefore benefits from multicore CPUs and multiprocessor machines. Processing rates for typical deep field simulations (1024×1024 PSF model with $5\times$ oversampling) are ≈ 2000 sources/s with a 3GHz, quad-core CPU.

6. Input data

6.1. Input catalogues

Input catalogues may be created in a number of ways. Since they are ASCII files, they can be created or modified with any editor. They may consist only of particle coordinates and fluxes as in Fig. 3.

For studies of extragalactic survey systematics and applications such as advanced exposure time calculators, one has the possibility to generate galaxy catalogues with the Stuff[4] program. Stuff combines spectra, luminosity functions and physical parameters to generate artificial catalogues of the deep extragalactic sky in a standard universe driven by $(\Omega_M, \Omega_\Lambda)$. This is done simultaneously in many filters.

One should note that the current version of SkyMaker handles images in a purely monochromatic way. Simulating effects such as chromatic aberrations, differential chromatic refraction, or diffraction-limited images taken through wide bandpass filters requires running SkyMaker several times at different wavelengths and summing the resulting images. This might seem a cumbersome way of circumventing some limitation of the software. But it is actually in practice the simplest and most flexible approach; supporting full spectra directly within the renderer would bring a lot of complexity to the catalogue handling process without much performance benefit.

[4] terapix.iap.fr/soft/stuff

6.2. Mimicking survey data

SkyMaker offers the possibility to insert header information from an external FITS file into the header of the simulated image. This makes it straightforward to replace actual survey data with simulations in image analysis pipelines, for testing of scientific assessment purposes: completeness, reliability, crowding effects, effective area at a given depth, ... (Fig 4).

7. Future improvements to SkyMaker

A number of useful features are still waiting to be implemented, among which:

- PSF variability over the field of view, and full support for models derived with the PSFEx software (Bertin et al., in preparation),
- Additional galaxy features (bars, spiral arms, arcs),
- Additional image primitives (artifacts).

Support for new source features in catalogues will require a move to a more flexible input file format, such as XML, VO-tables and/or FITS binary tables.

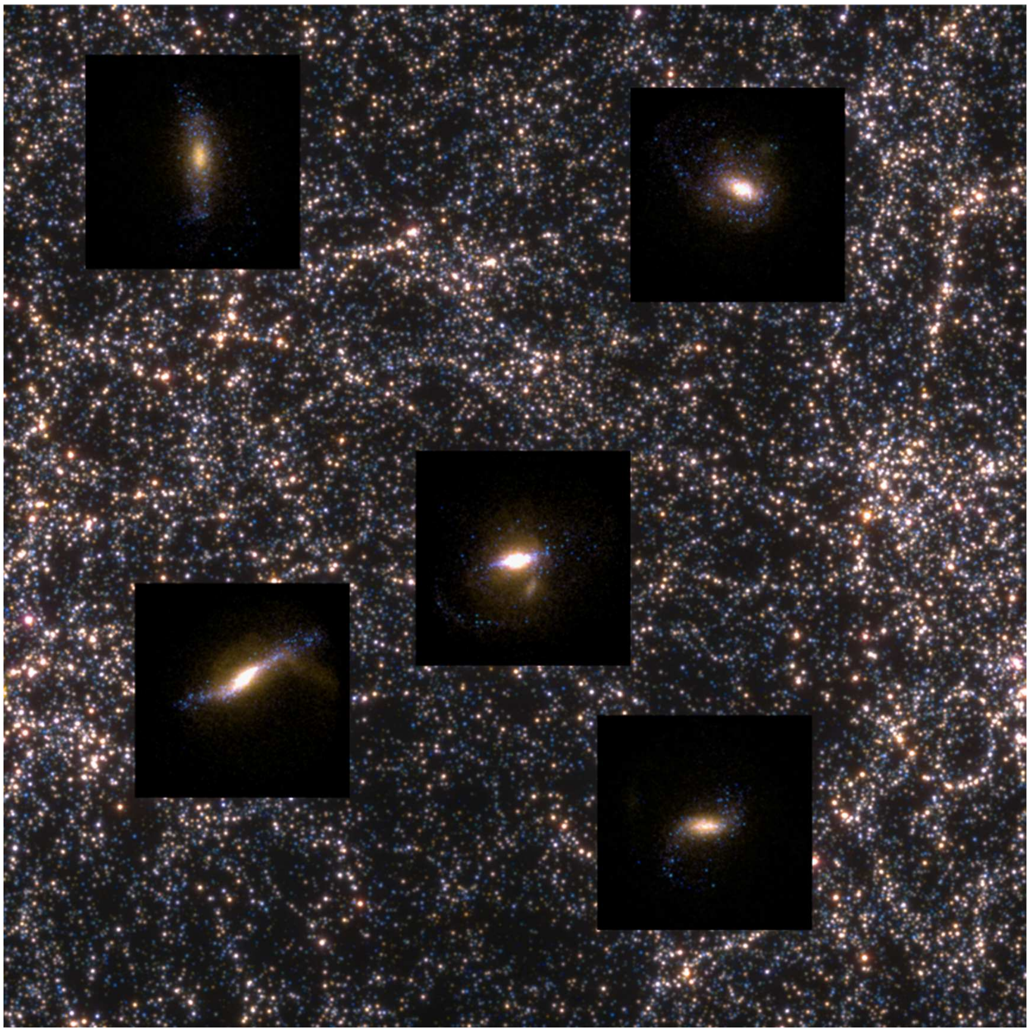

Fig. 3. A SkyMaker rendering of a section of the Mare Nostrum simulation at $z = 2.46$ (Ocvirk et al. 2008) "observed" in the I, K and IRAC-8 filters. Zooms on individual "galaxies" are shown in inserts. Particle data courtesy of C. Pichon, IAP.

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Fig.4 is based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii, and on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS.

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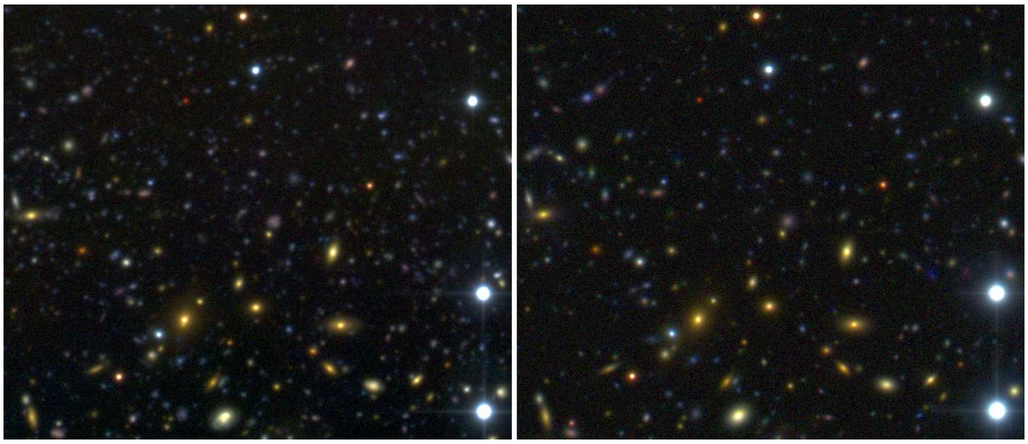

Fig. 4. *Left*: a small section of the CFHTLS "D1" deep field (e.g. Cuillandre & Bertin 2006) observed in the g,r,i filter set. *Right*: full reconstruction with SkyMaker from catalogues containing bulge+disk model parameters fitted using SExtractor 2.8.

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