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Automated Morphometry with SExtractor and PSFEx

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Abstract. Variable blurring of astronomical images by seeing and the instrumental Point Spread Function (PSF) makes it challenging to obtain accurate photometric and morphometric measurements under changing observing conditions. I show how the new PSFEx PSF modeling software and the latest version of the SExtractor source extraction tool can be combined to perform fully automated, PSF-corrected source measurements. An implementation of these techniques in the Dark Energy Survey Data Management (DESDM) pipeline is presented.

1. Introduction

The purpose of the SExtractor software package (Bertin & Arnouts 1996) is to create lists of sources in astronomical images in an efficient and fully automated way. Until recently, measurements of features detected by SExtractor has been limited to rather basic quantities, partly because of processing time constraints. Recent increases in computer performance now allow for more sophisticated measurements to be carried out in a reasonable amount of time,

One of these features is two-dimensional model-fitting. The fitting of two-dimensional models of galaxies convolved with a model of the instrumental Point Spread Function (PSF) has been proposed as an effective way of measuring shape parameters of faint galaxy images (see, e.g. Peng et al. 2002, and references therein). Several efforts have recently been made to automate the process on the scale of complete images (Barden et al. 2009; Vikram et al. 2010). These tools have the disadvantage of relying on a heterogeneous collection of codes, which impacts their efficiency. In the following, I introduce the PSFEx companion software and describe an optimized, fully automated, two-dimensional model-fitting code implemented in C directly within SExtractor. I also describe the extra step taken in the Dark Energy Survey Data Management (DESDM) pipeline, to homogenize PSFs prior to image stacking and model-fitting.

2. Modeling the PSF with PSFEx

The modeling of the PSF itself is performed by the newly released software package PSFEx.[1] Briefly, PSFEx starts by identifying detections that are likely to be point-

[1] Available at `http//astromatic.net`.

sources using an empirical recipe which includes finding the position of the stellar locus in a magnitude *vs* half-light-radius diagram (Kaiser et al. 1995). PSFEx models the PSF as a linear combination of basis vectors. The basis vectors are rendered as small images at a resolution chosen to minimize aliasing, which makes it possible to recover the PSF even with severely undersampled data. The vector basis may be the pixel basis, the Gauss-Laguerre basis (Massey & Refregier 2005), the Karhunen-Loève basis derived from a set of actual point-source images, or any user-provided basis. PSFEx fits the image of every point-source $\vec{p}_s$ with a projection on the local pixel grid of the linear combination of basis vectors $\vec{\psi}_b$ by minimizing the χ^2 function of the coefficient vector $\vec{c}$:

$$\chi^2(\vec{c}) = \sum_s \left(\vec{p}_s - f_s\mathbf{R}(\vec{x}_s)\sum_b c_b\vec{\psi}_b\right)^T \mathbf{W}_s \left(\vec{p}_s - f_s\mathbf{R}(\vec{x}_s)\sum_b c_b\vec{\psi}_b\right), \qquad (1)$$

where f_s is the flux within some reference aperture, and $\mathbf{W}_s$ the inverse of the pixel noise covariance matrix for point-source s. $\mathbf{R}(\vec{x}_s)$ is a resampling operator that depends on the image grid coordinates $\vec{x}_s$ of the point-source centroid:

$$\mathbf{R}_{ij}(\vec{x}_s) = h\left(\vec{x}_j - \eta.(\vec{x}_i - \vec{x}_s)\right), \qquad (2)$$

where h is a 2-dimensional interpolating function, $\vec{x}_i$ is the coordinate vector of image pixel i, $\vec{x}_j$ the coordinate vector of model sample j, and η is the image-to-model sampling step ratio (oversampling factor). PSFEx is able to model smooth PSF variations by making the c_b coefficients (equation 1) themselves a linear combination of polynomial functions of the source position within the image (Fig. 1).

χ^2 minimization is fast, but restricts the current modeling process to images with noise in the Gaussian regime. The point-source selection and modeling process is iterated several times to minimize contamination of the sample by image artifacts, multiple stars and compact galaxies. More details about the working of PSFEx can be found in Bertin et al. (in preparation).

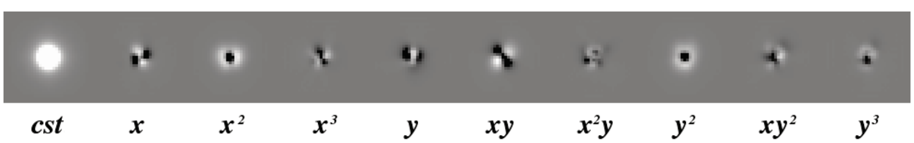

Figure 1. Examples of PSF image components recovered using PSFEx on a CCD image. PSF variations are modeled as a 3rd degree polynomial in image coordinates. The final PSF at a given position is the sum of all image components, each of which is weighted by the associated polynomial term.

3. Morphometry Measurements with SExtractor

Like GalFit, SExtractor's two-dimensional model-fitting procedure relies on the Levenberg-Marquardt minimisation algorithm. It uses a modified version of the LevMar library (Lourakis 2004). Minimization is carried out on a modified χ^2 of the residuals:

$$\chi^2_g(\vec{q}) = \sum_i g^2\left(\frac{p_i - m_i(\vec{q})}{\sigma_i}\right), \qquad (3)$$

where $\vec{q}$ is the vector of parameters to fit, p_i the background-subtracted value of galaxy image pixel i, $m_i(\vec{q})$'s the associated model sample (2-D galaxy model convolved with the local PSF model and resampled to image resolution), σ_i the uncertainty, and $g(u)$ a derivable function that reduces the influence of large deviations:

$$g(u) = \begin{cases} u_0 \log\left(1 + \frac{u}{u_0}\right) & \text{if } u \geq 0, \\ -u_0 \log\left(1 - \frac{u}{u_0}\right) & \text{otherwise.} \end{cases} \quad (4)$$

Setting $u_0 \approx 10$ makes the solution more immune against occasionally large non-Gaussian deviations such as contamination by neighbor sources or artifacts, while essentially preserving the convergence properties for regular objects.

Galaxy models tested so far include linear combinations of concentric Sérsic (1963), exponential and delta functions. Best fitting parameters, as well as estimates of uncertainties derived from the approximate Hessian matrix, are directly available as standard SExtractor measurements, both in pixel or world coordinates. Figure 2 shows examples of galaxy models fitted on deep imaging data.

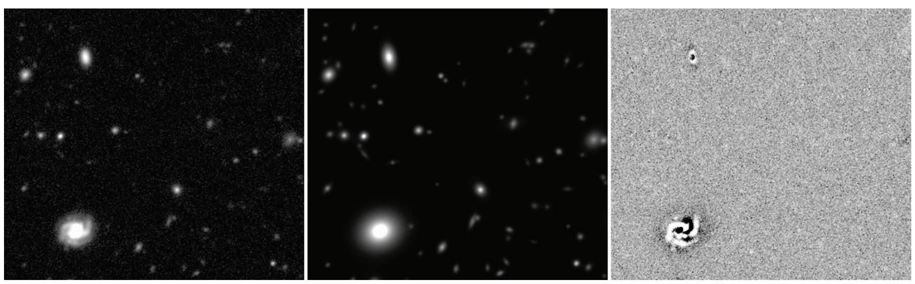

Figure 2. Examples of bulge+disk galaxy models fitted to deep imaging data. *Left*: $1' \times 1'$ fragment of an image (CFHTLS D1-deep field, i-band). *Middle*: best-fitting galaxy models, convolved with the local PSF model. *Right*: residuals of the fit; residual features in late-type galaxies are dominated by spiral arms and star formation regions.

4. PSF Homogenization

One of the challenges faced by the Dark Energy Survey data management (Mohr et al. 2008) is to provide homogeneous photometry and morphometry for 300 million galaxies over 5000 square degrees of imaging data. Observations are ground-based and use a large, regular tiling pattern. Image stacks involve several tiles and therefore images with different shifts and different PSFs. A PSF homogenization procedure has been set up to avoid "jumps" in the PSF from tile to tile (Darnell et al. 2009). The procedure generates variable noise correlations at the scale of about 1 arcsec, but these are much easier to track than composite PSF variations. Briefly, PSFEx computes a set of convolution kernels $\vec{\kappa}_l$ which, when applied to the variable model PSF $\vec{\phi}(\vec{x})$, minimizes (in the χ^2 sense) the difference with a constant target PSF. The resulting PSF $\vec{\phi}^{(H)}$ is:

$$\vec{\phi}^{(H)} = \sum_l X_l(\vec{x})\vec{\kappa}_l * \vec{\phi}(\vec{x}), \quad (5)$$

where the $X_l(\vec{x})$'s are terms of a polynomial in pixel coordinates $\vec{x}$. The kernels $\vec{\kappa}_l$ are computed as combinations of the first $\sim$ 60 vectors of the Gauss-Laguerre basis (e.g. Massey & Refregier 2005). All overlapping images, each convolved with its own combination of kernels, now deliver the same well-defined PSF everywhere and can be stacked before applying model-fitting.

4.1. Current Developments

I am currently concentrating my efforts on adding new model ingredients in SExtractor and allowing multiple sources to be fitted simultaneously in order to improve the photometric and morphometric accuracy in dense environments such as galaxy clusters.

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