# Photometry of supernovae (transient point sources)

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*Pierre Astier*
*LPNHE / IN2P3 / CNRS , Universités Paris 6&7.*

# Two types of (SN) photometry

## Real Time :

- Used for detection and allow for real time follow-up decisions.
- Performed on image subtractions.

## After the fact :

- Performed using the whole image sequence (even after the SN has faded away).
- Meant to be optimal in some sense (see later), mostly for distance estimation.

# Framework

- Wide field camera, CCD mosaic.
- Large ditherings between visits, possibly with rotations.
- Images are affected by a whole suite of instrumental effects.

# Instrumental effects

Optics

- Distortions
- PSF chromaticity
- Vignetting
- Non uniformity of filters
- Differential chromatic refraction

Sensors

- Non-linearity of video chains
- Brighter-fatter

# After-the-fact photometry

- "scene modeling": fit a forward model to an image sequence describing a time-variable point source (SN) sitting on a static background (galaxy).
- It is different from photometry on image subtractions:
  - It does not require a deep "template" from good-seeing SN-free images.
  - No image resampling.
  - It delivers a covariance matrix of measured fluxes.
- With an infinite set of images, the two techniques are identical.
- The scene modeling is optimal (regarding shot noise), not just asymptotically optimal.

# How to (1)

$$M_{i,p} = \left[f_i \times \phi_i(\vec{x}_p - T_i[\vec{x}_{obj}]) + G\left(T_i^{-1}(\vec{x}_p)\right) \otimes K_i + S_i\right] R_i$$

- Coordinate mapping
- Photometric ratio
- Flux in Image i
- PSF of Image i
- Coordinate Of pixel p
- Supernova position (same for all images)
- Galaxy Model (best PSF)
- Convolution Kernel, Best→ i
- Sky

G is a pixelized model of the galaxy, at the ref image quality (i.e. the best).

$K_i$ is determined from PSF's.

For images free of SN light, $f_i$ is forced to 0.

One $S_i$ has to be 0.

# How to (2)

$$M_{i,p} = \left[f_i \times \phi_i(\vec{x}_p - T_i[\vec{x}_{obj}]) + G\left(T_i^{-1}(\vec{x}_p)\right) \otimes K_i + S_i\right] R_i$$

Prerequisites:

- $T_i$ : astrometric mappings between images (both ways)
- $R_i$ : photometric mappings between images
- PSFs for all images
- A rough idea of an SN-free image set.
- A rough SN position (~ 1 pixel or so).

For the least-squares fit, the computing time depends mostly on the number of parameters of the galaxy model, and the number of images.

# What are we measuring ?

- Supernova fluxes ?
- Not exactly: we want the ratio of SN fluxes to fluxes of neighboring stars,
- Measured using the same technique, in the same images.
- Then, SN magnitudes are derived from magnitudes of neighboring stars….
- Usually obtained using aperture photometry

# What are we measuring?

$$m_{SN} = -2.5\ log_{10}\left[\frac{\phi_{SN}}{\phi_{star}}\frac{\phi_{star}}{\phi_{standard}}\right] + m_{standard}$$

PSF Aperture

$$m_{SN} = -2.5\ log_{10}\left[\frac{\phi_{SN}}{\phi_{star}}\right] + m_{star}$$

PSF

Averaged over
stars around the SN

# Least squares

$$\chi^2 = \sum_i \sum_p w_{i,p}(M_{i,p} - I_{i,p})^2$$

- $w_{i,p} = 1/I_{i,p}$ ?
  - Bad because the weighted residuals are biased by shot noise because $I_{i,p}$ appears twice.
- $w_{i,p} = 1/(V_i + f_i * phi_{i,p})$ ? $V_i$ : sky shot noise
  - Arguable because it renders the flux estimator non linear. Unbiased only if the PSF is accurate.
- $w_{i,p} = 1/V_i$ : ← With this scheme, the shot noise contribution to SN distances is ~1% suboptimal
  - OK for faint sources, sub-optimal for bright sources. Unbiased for any PSF shape.

# Technicalities of scene modeling

- It is worth to provide derivatives to the minimizer. The problem is “semi-sparse”, and almost linear.
- For the galaxy model, splines are a good option, 1knot per pixel is OK for well-sampled images
- Kernels can be computed right away from PSF’s evaluated at the SN location.
- If the SN is very faint in some band, the position should be fixed to the position in other bands.
- Lightcurves of neighboring stars can dominate the CPU budget (depending on SN density)

# The “prerequisites”: PSF

- The difficult part is to accommodate the BF effect, but the shape fidelity is not an issue for this application, at variance with shear.
- We assume that the video chain non-linearity correction has been determined and applied.

# The “prerequisites”: astrometry

- Jointcal was built to fit a relative solution (without any reference to an external catalog). Not clear if it is useful in the Gaia era.
- All available astrometry codes miss the ability to rotate the instrument distortion model w.r.t the focal plane. This is needed if one relies on an (empirical) instrumental solution.
- It is probably useful to account for chromatic differential refraction (jointcal has the code).
- However, the accuracy of the astrometric solution is a mild issue since it affects both SNe and neighboring stars in the same way.

# The "prerequisites" : photometry

- One needs a uniform photometric response across the focal plane, preferably for PSF photometry. This is sometimes called a "star flat", because it can be determined from dithered observations of a semi-dense stellar field.
- This does not come trivialy from SNe observations (low star density)
- Even when the photometric response is uniform, one should allow for a scale per exposure or even something more flexible.

# Performance assessment

- Almost trivial on an equatorial mount. Using real images:
  - pickup a (bright) star
  - copy a scaled down version not too far, shifting by an integer number of pixels
  - Compare the recovered flux ratio to the scale-down factor
- On an alt-az mount, with varying position angle? with BF-affected CCDs ?
  - Not easy to avoid relying on the PSF model…

# Actual performance on SNLS@CFHT

1306.5153

- Based on star shift-and-scale.
- Equatorial mount, small dithers (<< 1CCD)
- Thin CCDs : negligible brighter-fatter effect
- → O(0.1%) accuracy (below other systematics)
- For LSST, the context is less favorable (sensors, ditherings, rotator … ), and the requirements are stronger. But there is no show-stopper.