Photometry of Supernovae in an image series

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The photometry of SNe aims to construct the light curves of these faint objects. Contrary to the photometry of standard stars, this requires us to take into account the light emitted by the SN host galaxy. In order to remain below the uncertainty level of the calibration, we aim to construct a photometry method whose uncertainty does not exceed the per mil level.

1 Photometric Algorithm

1.1 PSF Photometry

SNLS employs direct simultaneous photometry. This consists of fitting a time-independent pixellised galaxy model and a time-variable point source to the image series, forcing the flux to zero in images where the SN is 'off'. Surrounding stars are measured similarly but without fitting a galaxy and without 'off' periods. This approach directly fits the model to the whole data set and is optimal from a statistical point of view (Gauss-Markov theorem). The point sources are fit to a PSF model obtained by fitting a spatially varying Moffat profile and pixellized correction to the stars in the image. The light curve itself can then be modeled as :

$$M_{i,p} = \{[f_i \times \phi_{ref}(\vec{x}_p - \vec{x}_{SN}) + gal_{ref}] \otimes K_i\}_p + s_i \tag{1}$$

Where f_i is the SN flux in image i, gal_{ref} is the galaxy pixel map in the reference image, K_i is the convolution kernel to the reference image, and s_i is the sky level in image i.

1.2 Relative Astrometry of the Image Series

Some field stars are found to move significantly over time. Our astrometric solution aims to take this into account. We therefore fit the proper motions of moving stars. For the star i, its expected position $\vec{P}_{ij}$ in image j is modeled as :

$$\vec{P}_{ij} = T_j(\vec{X}_i + \vec{\mu}_i(t_j - t_0)) \tag{2}$$

where T_j is the coordinate mapping from a reference system to pixels in image j, $\vec{X}_i$ refers to the coordinates of star i in this reference system, $\vec{\mu}_i$ the proper motion of this star, t_j the epoch of image j and t_0 some reference epoch. The parameters of the astrometric fit are T_j (one per image), $\vec{X}_i$ and $\vec{\mu}_i$ (one position and one proper motion per star).

1.3 Photometric Linearity

To test the linearity of our photometry, we employed a Monte Carlo simulation. Field stars are cut and pasted onto nearby galaxies while applying a dimming factor r. We then compare the photometry of the field stars and their corresponding fake star and test our ability to properly estimate r. Note that we expect a bias as a function of the S/N ratio, due to correlations between the flux and position estimators. Our simulation tests for deviations from this already expected bias. We find no significant deviation to well below the per mil level.

2 Calibration

2.1 Calibration Scheme

To calibrate photometric measurements, they need to be compared to stars with a known *Spectral Energy Density* (SED) through observations in similar conditions. This is only possible on photometric nights. To avoid losing observations on non photometric nights, we calibrate field stars which become local standards (or tertiary stars). The SN measurements are then compared to that of the tertiaries. Measurements of the primary standard are made using aperture photometry. The calibrated magnitudes of the tertiaries are therefore also obtained using **aperture** photometry. However, to compare SN fluxes to those of tertiaries, these aperture magnitudes must be converted to **PSF** fluxes.

2.2 Calibration Biases

Converting the **aperture** magnitudes of tertiary stars to **PFS** fluxes leads to significant biases (few per mil) due to systematic differences in the 2 methods. First, aperture photometry does not fit a sky level, this leads to a magnitude dependent bias. To correct for this, residual sky background is fit with the PSF photometry and is used to correct biased aperture photometry. Secondly, the actual shape of point sources depends on their colors, which is not modeled by the PSF, leading to a color dependent bias. The PSF color dependence is well mimicked by the addition of an effective linear filter with an adequately chosen slope. The bias is then interpreted as a difference between the aperture magnitude system and a newly defined PSF magnitude system.

3 Achieving Submillimag Accuracy

Table 1 summarizes the biggest contributions to photometric uncertainty, excluding calibration. It is important that these remain well below the per mil level, as calibration uncertainty can be as precise as 3 per mil in some bands.

Table 1: Dominant photometric uncertainties excluding calibration.

Effect	induced bias	determined using
linearity	2.72×10^{-4}	simulation
PSF color	1.30×10^{-4}	artificial filter
refraction	3.00×10^{-4}	comparison to direct fit

References

1. Astier, P. et al. :*Photometry of supernovae in an image series : methods and application to the Supernova Legacy Survey (SNLS)*, Astronomy & Astrophysics (2013)
2. Betoule, M. et al. : *Improved photometric calibration of the SNLS and the SDSS supernova surveys*, Astronomy & Astrophysics (2014)