Difference-imaging photometry with pySIS3

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Aperture photometry

Add up the light from a star within a defined circular region called the aperture.

An outer annulus is used to measure the background light.
In crowded star fields, aperture photometry is usually unsuccessful, since it relies on stars being relatively isolated in order to get measurements of the stellar flux and sky flux that are not contaminated by other stars. PSF photometry involves fitting a model PSF to the flux recorded in each pixel. The model chosen can be an analytic function (such as a Gaussian) or can be some numerical representation. The stellar flux is determined by integrating the fitted model PSF.

Our fields are very crowded

OGLE 2005-BLG-390 image from PLANET Danish 1.5 m telescope, La Silla, Chile
Difference image photometry

This is a relatively new method for detecting and measuring variable stars in very crowded fields. The idea is to subtract two CCD images, taken at different times. All the constant-brightness objects should disappear, leaving behind things that have changed in brightness.

The major difficulty is that the images must first be processed so that they have the same PSF before doing the subtraction. Generally this involves convolving (blurring) the best-seeing image, R, to match the other one, T.
Difference-Imaging

If we have a reference image, $R$, and a series of target images, $T^\alpha$, then we define the difference image

$$D^\alpha \equiv R \otimes K^\alpha - T^\alpha$$

$K^\alpha$ is called a convolution kernel.
Convolution Kernel

Analytic - e.g. sum of a few fixed width gaussians multiplied by polynomials (Alard 2000). (Almost) complete image registration required.

Numerical - grid of pixels (Bramich 2008). Registration by integer-pixel shifts OK. Can cope with weird PSFs.

In either case the kernel can be allowed to vary smoothly across the image.

Convolution

First we will consider what happens in one dimension. The basic process is:
Convolution

An example:

```
original image: [ 10 10 10 90 90 90 90 90 90 ]

kernel: [ 0.25 0.5 0.25 ]

new image: [ 10 10 30 90 90 90 90 90 90 ]
```

In this case, a sharp transition in the original image is softened (blurred) by the kernel. This might represent the influence of the Earth's atmosphere.

On whiteboard:
```
10 \times 0.25 + 10 \times 0.5 + 90 \times 0.25 = 30
```

We nearly-always deal with symmetric kernels and in such cases the inverted order of the pixel-matching between the original image and the kernel can be ignored.

The identity kernel

Imagine we have an ‘image’
```
o = [ 0 0 100 0 0 ]
```

and we convolve it with a kernel
```
k = [ 0 1 0 ]
```

then
```
k \otimes o = [ 0 0 100 0 0 ]
```

[ 0 1 0 ] is an identity operator – all it does is make a copy of an image.
The kernel as a shift operator

Imagine we have an ‘image’

\[ o = \begin{bmatrix} 0 & 0 & 100 & 0 & 0 \end{bmatrix} \]

and we convolve it with a kernel

\[ k = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \]

then

\[ k \otimes o = \begin{bmatrix} 0 & 0 & 0 & 100 & 0 \end{bmatrix} \]

[0 0 1] is a shift operator – it makes a copy of an image with all pixels shifted one position to the right.
Original image

Classic sharpening kernel

Strong enhancement of fine-detail contrast

Crispening kernel

Milder degree of contrast enhancement

But note that it looks noisier

The Handbook of Astronomical Image Processing

Richard Berry
James Burnell

Includes AIP4WIN 2.0 Software
If we have a reference image, $R$, and a series of target images, $T^\alpha$, then we define the difference image

$$D^\alpha = R \otimes K^\alpha - T^\alpha$$

$K^\alpha$ is a convolution kernel computed to minimize

$$\chi^2 = \sum_{ij} \left( \frac{D_{ij}}{\sigma_{ij}} \right)^2$$
What do the kernels look like?

![Kernel Images]

- **good seeing (1.6")**
- **poorer seeing (2.0")**

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22"

Photometry

The microlens flux in the difference image is measured by optimal PSF photometry:

Compute the PSF of the reference image by coadding bright stars.

Convolve the reference PSF with the kernel.

Interpolate the convolved PSF at the subpixel lens coordinates.

Evaluate the flux as \( f = \sum_i \frac{pd}{p^2/\sigma^2} \)
Refining the lens coordinates

Use the pattern of photometric residuals.

Expand the PSF model:

\[ P = P_0 + \Delta x P_x + \Delta y P_y \]

After some arithmetic, the coordinate correction is given by

\[ \Delta x = \frac{\sum_j \Delta P \left( P - \Delta F P_0 \right) P_x - \left( \frac{P_x}{|P_y|^2} \right) P_y}{\sum_j (\Delta P)^2 \left( |P_x|^2 - \frac{P_x P_y^2}{|P_y|^2} \right)} \]

This depends on the flux, so the corrections must be iterated. Convergence to a few thousandths of a pixel usually takes only a few iterations.

Diagnostics

To verify the photometric performance, we always write out the photometric residual images and compare them with the difference images. e.g.

difference images
difference images after subtraction of fitted PSF