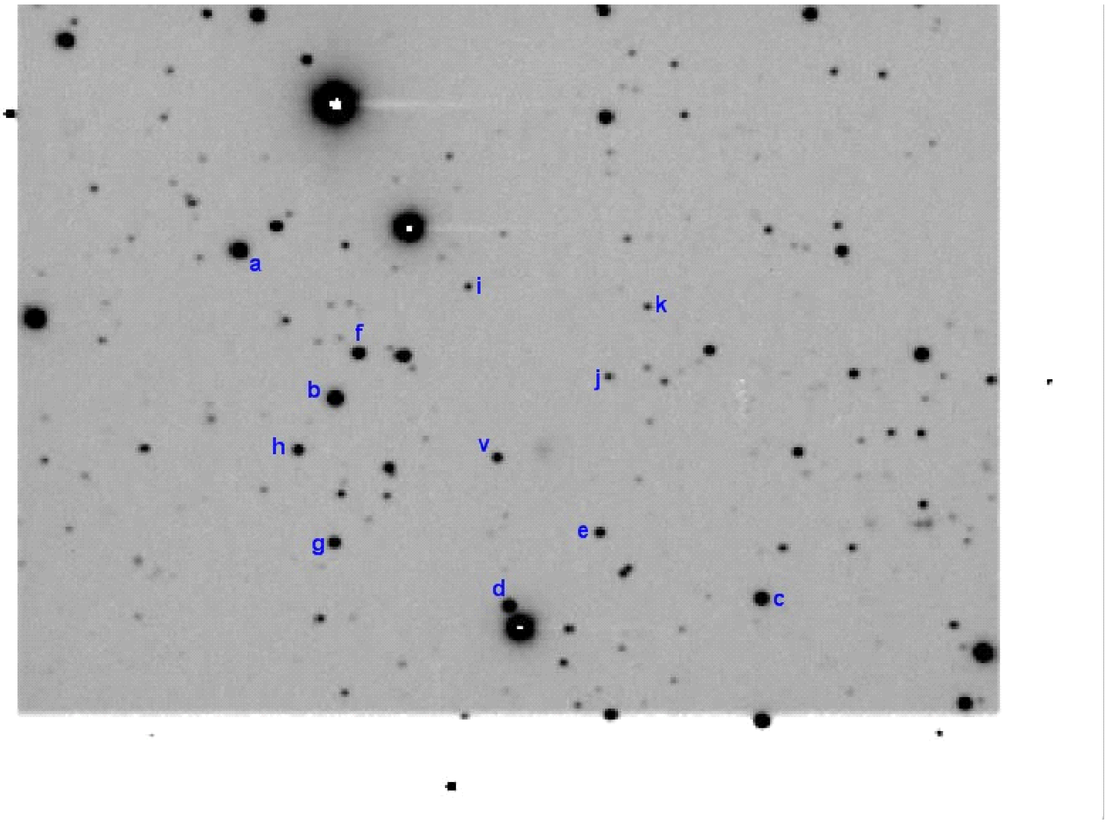
Optimal photometry in practice

The following data were obtained with on the night of 28-29 October 2008. There's nothing special about this dataset – it just happens to be one of the most recent from my observatory. The target was AI Tri.

The telescope was a 30 cm Meade SCT, used with a focal reducer to give f/6.3. The camera was a Starlight Xpress MX916, operated with 2x2 binning. No colour filter was used. The exposure time was 30 seconds.

Here's the field – a stacked frame all 322 images:

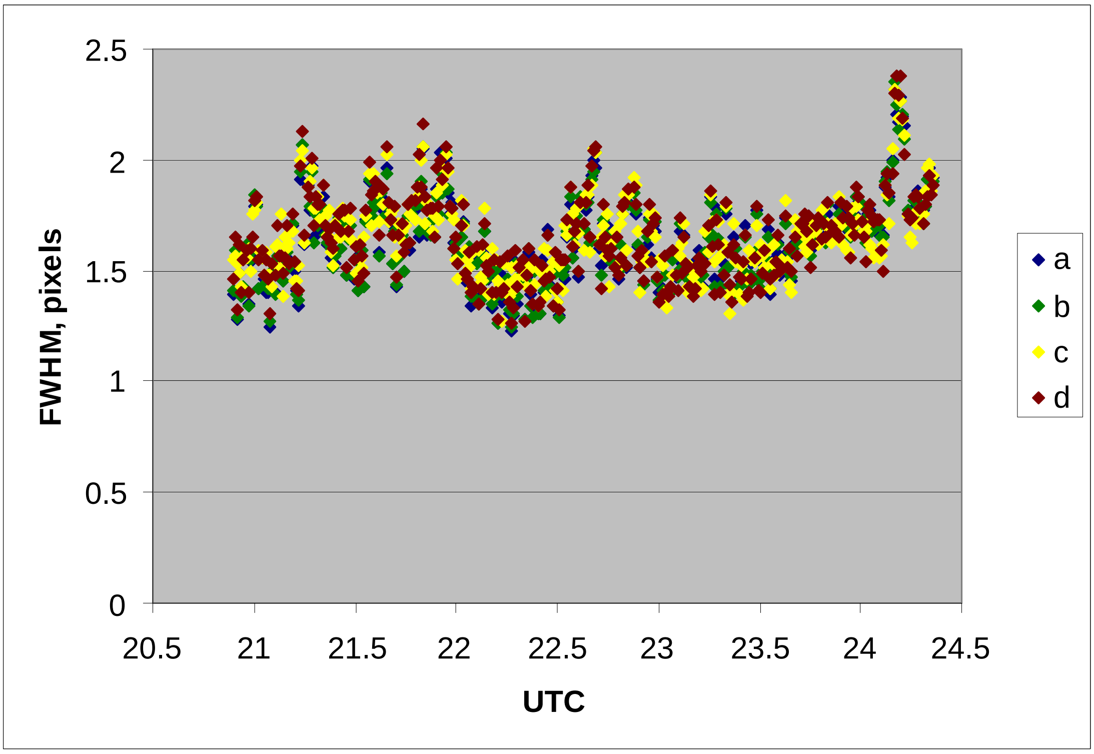


Data reduction followed my usual procedure: When the images were dark/flat corrected, a star search routine was used to find stars within the image, and the centroid positions written to a file. Four stars (a, b, c, d) were then chosen as fiducial stars, and a pattern recognition algorithm used to compute the offset for each image in the series, relative to the first. With this offset/rotation data, the positions from each frame were combined to give better positions. The positions were then further improved by PSF fitting for each lettered star (above) in individual images; star b was used to get the PSF shape (also used for the optimal extraction), then this PSF was used to refine the positions. Finally, the PSF positions for all the frames were combined, and the offset/rotation table was updated using these (best) PSF positions.

The reason for this elaborate position finding / image alignment exercise is that the photometry algorithm can use an exact, predetermined position obtained from many images, and does *not* have to recentre the star in each image. This is essential when working with very faint objects (for which one might determine the positions from a stacked image, although that was not necessary here).

Photometry was carried out for all the stars except d, using star b as the reference star. Sky backgrounds were obtained from a 60x60 pixel box centred on each star of interest

For the optimal extraction, star b was used as the PSF star. However, as a special exercise, PSFs for a, c and d were also determined, and here is a plot showing the PSFs versus time:



(Strictly, this is the north-south FWHM; the east-west FWHM is determined independently as the image may sometimes be elongated due to tracking errors).

In addition to optimal extraction photometry, I also carried out aperture photometry with apertures of 1.5, 1.7, 2.0, 2.5, 3.0 and 3.5 pixels radius.

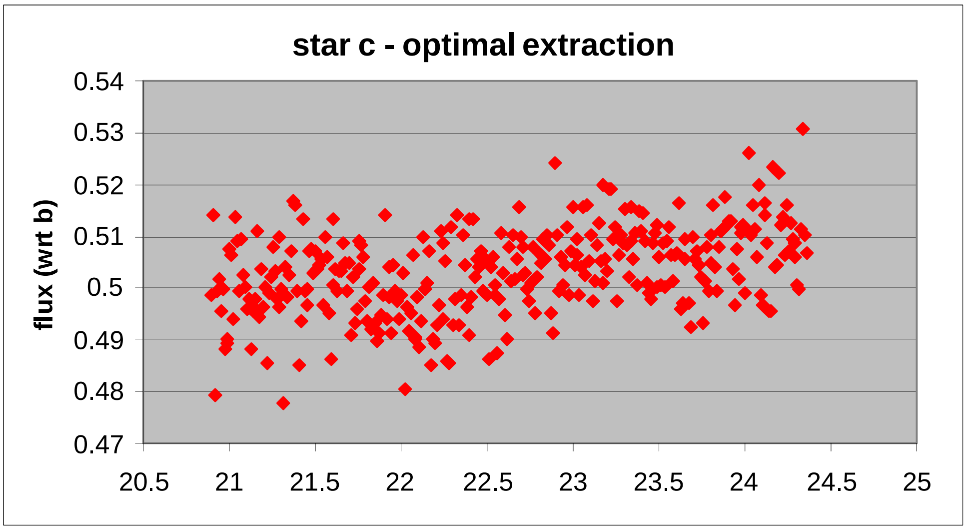
Here is a summary of the dispersions obtained with the various methods. ‘Best aperture’ refers to the best of the apertures listed above.

star	**a**	**c**	**e**	**f**	**g**	**h**	**k**	**i**	**j**
approx mag	**12.7**	**13.6**	**15.6**	**14.4**	**14.7**	**15.0**	**15.2**	**17.3**	**17.1**
best aperture radius	2.5	2.5	1.5	1.5	2.0	1.5	1.5	1.5	1.5
rms (mags)	**0.011**	**0.015**	**0.051**	**0.021**	**0.028**	**0.034**	**0.036**	**0.199**	**0.176**
optimal rms (mags)	**0.010**	**0.018**	**0.050**	**0.021**	**0.026**	**0.033**	**0.034**	**0.175**	**0.162**
ratio opt/aperture	0.983	1.214	0.974	0.980	0.932	0.963	0.956	0.881	0.920

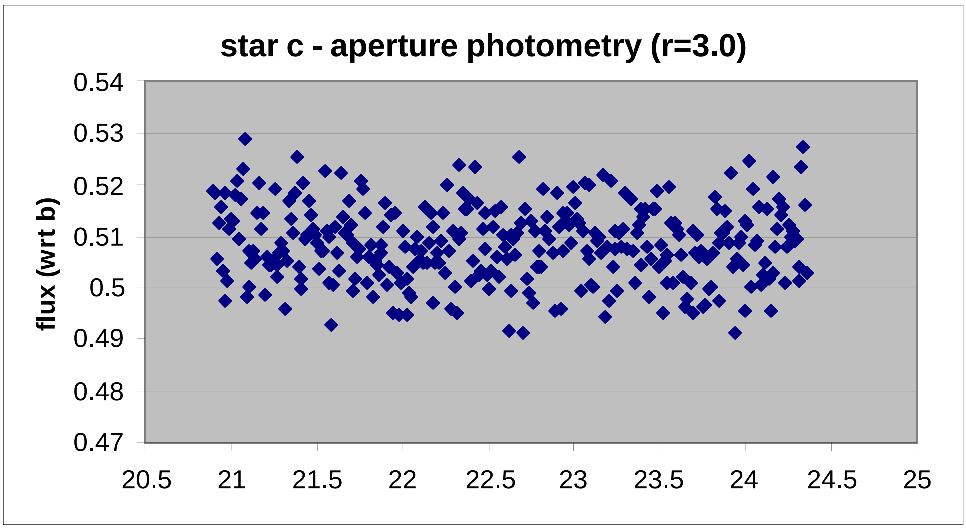
Things to note:

- For aperture photometry, fainter stars require a smaller aperture – although I did not try apertures smaller than 1.5 pixels radius.
- With one exception, optimal extraction gives better precision (less scatter) than aperture photometry, at least with the apertures tried. It seems to offer more improvement for fainter stars.
- Use of optimal extraction obtains the best precision at the first attempt, rather than having to try a series of apertures and then choose which works best.

The exception is star c. This is also the only star (except AI Tri!) for which optimal photometry suggests a significant change of brightness with time:



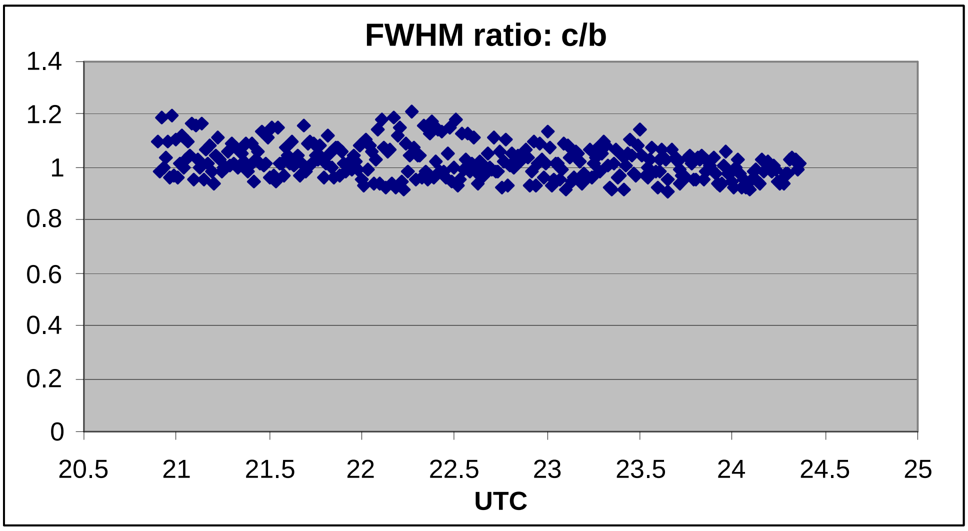
On the other hand, aperture photometry, using a large aperture, suggests the brightness is constant:



If one fits a straight line to the optimal extraction data, the dispersion from the line reduces to 0.016 mags. Nevertheless, there seems to be a problem associated with optimal extraction for this star.

A possible explanation for this difference is as follows: **It is a basic assumption of photometry that all stars must have the same PSF.** This assumption is more crucial if the aperture is small, so as not to transmit all the star's light (as is required to maximise S/N if the target is faint). Optimal extraction is particularly dependent on this assumption, since gives more weight to pixels in the core of the stellar image.

More careful examination of the PSF-fitting data suggests this may be the cause of the problem observed here. Plotting the *ratio* of FWHMs for stars c and b, indicates a steady change throughout the run. Star c appears to have a slightly wider image than than b in the early part of the run, which would be consistent with its appearing slightly fainter.



Why would the PSF ratio change with time? I don’t know, but possibly chromatic aberration combined with a slow shift in focus would cause this effect. My photometry is unfiltered – which is appropriate given the faintness of the targets – but consequently is more sensitive to any problems related to chromatic aberration.

On other datasets, I’ve also seen isolated stars which have different PSFs (perhaps suggesting chromatic aberration, or that the star is double) or the PSF change systematically across the field of view (indicating poorly collimated optics – I’ve since improved the collimation!).

Summary:

For data which is sampled as well, or better than, that shown here:

Optimal extraction is a useful technique for fainter targets, for which it gives precision better than, or at least as good as, aperture photometry.

It removes the need to try lots of different apertures to find which is best for a particular data set

For brighter stars, where the error from photon statistics is small, other sources of error may become significant. One then needs to be careful. In these cases aperture photometry may give better results than optimal extraction.

Methods which – based on photon statistics considerations - give particular weight to the core of the stellar image, are sensitive to the requirement that all stars must have the same PSF.