Calibrating Photo's PSF Magnitudes

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1 Photometric Calibration of Staring-Mode Data

Despite the fact that all of my gentle readers are intimately familiar with this topic, let me run through the details quickly, so as to illuminate the following discussion of TDI data.

In order to calibrate a CCD exposure, we first measure the number of counts in some target star using some favourite aperture $f(r)$, that is we calculate

$$C = \sum_i f(r_i) I_i \times \frac{\sum_i f(r_i)}{\sum_i f(r_i)^2}$$

where I_i is the value of the i^{th} pixel, a distance r_i from the centre of the object. One common choice for $f(r)$ is the PSF, leading to a PSF magnitude; another a top hat function, corresponding to an aperture magnitude (in this case the expression for C reduces to $\sum fI$). C's 'effective area' is $n_{\mathrm{eff}} \equiv (\sum_i f(r_i))^2 / \sum_i f(r_i)^2$ (i.e. the contribution of the sky S to C's variance is $S n_{\mathrm{eff}}$).

We then repeat exactly the same procedure on a standard star, and use the ratio of the two values to deduce the magnitude difference between the target star and the standard, and hence the magnitude of the target.

Note that there was no requirement that the aperture f contain all the light of the star — for real stellar profiles, with scattering wings and contributions from the pixel response function, it almost certainly won't — but providing that the same fraction of the light is lost in the two measurements the final answer will be correct. Our choice of the function $f(r)$ is made purely on the grounds of statistical efficiency, convenience, or worries about other effects (e.g. centering errors).

2 PSF Photometry

If we choose f to be the point spread function, for faint stars the resulting value of C is the maximum likelihood estimator (MLE), and has the lowest possible statistical error of any unbiased estimator (it attains the Cramér-Rao minimum variance bound).

There is a slight subtlety here; one might think that you should use the MLE for all stars, given by

$$\hat{C} = \frac{\sum_i f(r_i) \times \sum_i f(r_i) I_i/(S + I_i)}{\sum_i f^2(r_i)/(S + I_i)} \tag{1}$$

as the noise in the i^{th} pixel is $S + I_i$ (if I is measured in electrons). For stars much fainter than the sky S, this reduces to

$$\hat{C} = \frac{\sum_i f(r_i) \times \sum_i f(r_i) I_i}{\sum_i f^2(r_i)}$$

which is of the form given above.

If you use the result (1), however, you will create a magnitude-dependent photometric error if your assumed PSF doesn't exactly match the true PSF in the frame (as the discrepancies are weighted by the $1/(S+I_i)$ term differently for bright and faint objects). To avoid this, you should give up a little statistical efficiency for bright stars, where it doesn't matter anyway, and use an unweighted fit.

Consider for a moment a night when the seeing is Gaussian with standard deviation α and thus FWHM 2.35α. The PSF magnitude has $n_{\mathrm{eff}} = 4\pi\alpha^2$, so the sky's contribution to the noise is equal to that in an aperture of radius 2α, or about 0.8" for 1" seeing.

3 Photometric Calibration of TDI Data

For TDI data, we do not have the luxury of a standard star on each frame, and the PSF will in general have changed by the time that a frame with a standard arrives.

The solution that we intend to use in the photometric (more precisely, the PS) pipeline is in each frame to measure the counts for the postage-stamp stars (which may include MT stars) in two ways; using the adopted PSF for that frame and using an aperture with a radius of about 12 pixels (4.8"). This aperture magnitude will be used to transfer from frame-by-frame PSF magnitudes to the MT system (and will be referred to as a *transfer magnitude*), and the pairs of measurements for the PS stars in a frame define the conversion from PSF to transfer magnitudes.

Note that such a transfer magnitude is required. We cannot simply use the PSF magnitude at the time of the appearance of MT stars to determine the PSF–MT calibration, as the PSF will have changed by the time an MT star arrives; we cannot avoid this by using the frame-by-frame PSFs applied to the MT stars as the mismatch between the true and adopted PSF will have changed; the noise penalty of defining our magnitudes using such an aperture instead of the PSF is unacceptable (about two magnitudes).

This scheme can fail in two ways. Firstly, the wings of the PSF can change enough that the conversion from the transfer magnitude to the MT stars varies from frame to frame; the only solution to this is to use a larger aperture with an attendant noise penalty. Alternatively, the conversion from the PSF to the transfer magnitude may be sufficiently noisy to introduce significant photometric error. If this is the case, we may be forced to smooth the PSF—transfer conversion coefficients, which is probably desirable anyway.

If one of these failures cannot be avoided, we shall have to revisit the scheme.