

Two-dimensional CCD photometric data reduction

Excellent papers on reduction of CCD photometry are in a Astronomical Society of the Pacific publication "Astronomical CCD observing and reduction techniques" ed Steve B. Howell.

Some Chapter titles are: Basic Photometry Techniques G.S. DaCosta; Details of Noise Sources and Reduction Processes R.L. Gilliland Introduction to Differential Time Series Astronomical Photometry using CCDs. S.B Howell; Two Dimensional Imagery C.A. Gullixson; Image Processing, Data Analysis Software and Computer Systems for CCD Data Reduction and Analysis. G.S. Kutter

Some basic facts of CCD photometry

Pixel scale. Because of **intra-pixel sensitivity variations** and the sampling theorem, it is best to have at least 2 pixels per FWHM (full width half maximum) of an unresolved stellar image. Photometry to better than 0.05 mags is then easily attainable to fainter than 20th magnitude with a 1m telescope.

Preliminary steps

Before attempting photometry, CCD frames must be **bias subtracted, dark count subtracted, non-linearity corrected, flat field corrected and cleaned of cosmic rays** (if necessary). The recorded data values also need to be turned into electron numbers by multiplying by the **gain factor** (the number of electrons per adu) to enable the correct statistical analyses. At the time of observation the length of exposure and airmass also need to be recorded as does the Standard Solar Time for variable stars.

Bias frames are exposures with zero exposure time or often they are derived from the average pixel value in the "overscan" region comprising blind pixels or virtual pixels. **Read-out noise** (RON) is usually measured by calculating the rms of the bias in the overscan region.

Dark frames are taken with the same exposure as the image, but with the shutter closed.

Non-linearity correction

The relation between the total light incident on a pixel and the digital data units measured at the output stage of the CCD is generally not linear with a slope of 1 over the whole range from the level of the sky to the saturation limits of the potential well. Texas Instruments suggest a gamma of 0.98 for points near saturation in a TC241. The linearity should be measured occasionally from a range of integrated light levels. This can be done by taking a series of different length exposures of a constant light source so that the longest exposure almost reaches saturation and the shortest is close to the sky value. The technique is to take 2 exposures at each selected exposure time from shortest to longest and then immediately repeat from longest to shortest. In this way any variation in the intensity of the lamp can be corrected for.

The slope gamma is defined as $(\text{Intensity } 2 / \text{Intensity } 1)^{\text{gamma}} = (\text{Output Count } 2 / \text{Output Count } 1)$. Any non-linearity needs to be corrected for to get the number of detected photons from the output counts.

The **gain G** can also be checked at the same time. This is done by selecting pairs of exposures with count levels above about half the well depth and after subtracting the biases, divide one frame of each pair into the other frame and examine the root mean square deviation (RMS) of the divided frame. By dividing the frames in this way one removes any pixel-to-pixel variation and the remaining RMS should reflect the Poissonian statistics of the total number of electrons measured (multiplied by $\sqrt{2}$ as 2 frames were used). That is, if N is the average adu count in each of the exposure pairs and G is the gain (the number of electrons in each adu), then S the RMS of the divided frame should be given by $S = \sqrt{2} \times \sqrt{(G \times N)}$.

Flat fielding.

A raw CCD image shows a brightness variation across the field due to a combination of pixel-to-pixel sensitivity variation and illumination variation due to optical shadowing (vignetting). This must be corrected for. Exposures of the inside of the illuminated dome or of the twilight sky are usually used. This correction is usually the limitation on the precision of photometry, in particular for stars fainter than the level of the sky. Obtaining a uniform calibration flat-field accurate to 1 part in 1000 or better is extremely difficult.

The best vignetting (flat field) correction is obtained using a flat field obtained from median filtering a whole night's data. This can be smoothed and divided into a dome flat which will have more counts but may not correctly account for the vignetting because of improper baffling of the telescope and scattered light. So essentially you get the pixel-to-pixel variation correction from the dome or twilight sky flat exposures and impose the correct shape of the vignetting correction from the "real" sky, the median filtered set of all the night's images through each filter. For the median filter to work correctly there needs to be a random distribution of stars. Images of galaxies and globular clusters is not good for this purpose. If you observe the same field all night simply remove the stars from the final median filtered image.

See Gilliland above for discussion of bias (including preflash), flat fielding and non linearities.

Cosmic ray removal.

Software packages enable cosmic rays to be removed by hand or automatically by the fact that they are sharper than stars (if a star has a fwhm of at least 2 pixels) and many times brighter than surrounding pixels. They are replaced by some average of the surrounding pixels. Usually works well but occasionally makes spectacular mistakes. Check the cosmic ray removal program by dividing the before and after removal images then you can hand correct any mistakes. BCLEAN and CLEAN in Figaro are very good.

A better way – Many people take at least 3 exposures of any field and **median filter** them. That is, they compare each pixel with the corresponding pixel in the other frames and replace any that are more than 3 or 4 sigma different by the median value. Some packages also reject excessively bright pixels automatically during the photometry, although this is usually only in the sky apertures.

Photometric reduction

Don't divide the total electron counts by the exposure time before running the data reduction programs as the statistics calculated by most program needs to know the total number of electrons not the number of electrons per second. Of course the exposure time is needed to get the correct magnitude.

CCD point source photometry is done either using aperture photometry or profile fitting.

Aperture photometry is similar to that used in photoelectric photometry with the important difference that many different apertures can be used and very accurate results obtained for aperture sizes down to the FWHM of the image with significant improvement in the S/N for faint images.

Equation: $\text{mag} = ZP_{\text{ap}} - 2.5 \log (\sum I_{ij} - N_{\text{pix}} I_{\text{sky}})$

1. Determine centre of stellar image using gaussian fitting techniques or iterative method.
2. Determine sky value from annulus centred on star. Diameter of annulus should be at least 3 to 5 times the stellar FWHM. It should have a large enough area to minimise uncertainty. The mode of the values of the "sky" annulus is the correct value to use. Various techniques to estimate the mode by trimming the distribution.

3. Add up the signal contained inside the stellar aperture and subtract from it the normalised sky.

With small apertures, sub-pixels are often used to better approximate a circle.

Some programs use rectangles instead of circles. Most programs read and write disk FITS files but often use their own specially formatted files internally.

DAOPHOT and DoPhot (stand-alone programs but often found in IRAF) automatically find and measure all stars in the frame. The FIGARO aperture photometry programs FOTO requires you to roughly point out each star you wish to measure with CPOS and CENTERS then it finds precise positions. FOTO gives photometry from many concentric apertures at the one time. MIDAS (ESO) has similar programs. IRAF and MIDAS are available for PCs. FIGARO will soon be available for Macs and PCs.

Choice of aperture - aperture corrections - growth curves

A stellar profile goes on forever - almost. A decision has to be made on where to cut it off. The bigger the aperture the larger the contribution from the sky background. The fainter the star, the lower the S/N ratio gets as the aperture is increased. The **point spread function** (PSF) of a stellar image on a CCD at a properly corrected telescope focus is the same regardless of brightness and position in the frame. That is, the fraction of the total light in an aperture of a given size is the same regardless of the brightness of the star. Therefore, using bright stars (whose magnitudes are unaffected by the increased sky background in large apertures) construct an average relation between aperture magnitude and diameter, and calculate the aperture-magnitude correction for the small apertures relative to the asymptotic magnitude. These curves are called **growth curves**. Using an average of these bright star growth curves one can apply the aperture correction to the magnitudes of the faint stars measured through the small apertures. Do this for a few apertures around twice the FWHM of each star to assess the reliability of the values and their comparison to the theoretical error listed against each measured sky subtracted magnitude. As well as maximising S/N the smaller apertures also enables one to separate close companions as well.

Profile fitting:

Equation: $\text{mag} = ZP_{\text{psf}} - 2.5 \log(\text{scaling ratio})$

Aperture photometry is excellent for uncrowded fields and must be done for the brightest stars in any case to measure the total light or when using photoelectric standards that would have been measured through 15 arcsec apertures because even if you see other stars on the CCD frame within that aperture *they would have been included by the photoelectric observer*.

However, in very crowded fields or for large numbers of stars the best results can be obtained by using a **stellar profile fitting** routine. (It is often necessary to also distinguish between stars and galaxies and this can be done by comparing the shapes of the objects.). Some programs use an empirical PSF derived from selected isolated stars, others use a model PSF. Most enable the fitting of N multiple or overlapping images by deriving 3N parameters - the x,y centre and the scaling ratio for each of the N components.

A **Gaussian** function $G(r) \propto e^{-r^2/2\alpha^2}$ or a **Moffat** function $M(r) \propto 1/(1 + r^2/\alpha^2)^\beta$ are often used as the analytical profile. Some permit an elliptical fit, others use a symmetrical profile but keep a look-up table of residuals. The profile is fitted within a fixed aperture called the fitting radius using a least squares technique. The correction between the PSF zeropoint and the asymptotic aperture zeropoint must be derived from the brighter stars on the frame.

Relative magnitudes

Some photometric monitoring programs are greatly simplified by the use of CCDs. If the brightness of a particular star can be monitored relative to other stars on the same CCD frame there is often no necessity to correct for extinction or to worry about cloud as all stars in each frame are observed at the same time and at the same airmass. However, if the observations during the night run through a large range in airmass, differential extinction between stars with different colours must be corrected for. For some programs standard filters need not be used thus increasing the number of photons received in a given time, but for the highest precision work it is usual to use a standard filter and to correct for differential colour extinction or ensure that the comparison stars and the program star have similar colours.

Standard magnitudes

Reduction of CCD photometry into a standard system is done as for photoelectric data (described above) with the exception that magnitudes are usually reduced for each filter directly and not for colours that are more usual for photoelectric photometry. However, whereas tens of standard stars are often observed in a photoelectric program CCD observers are often not as conscientious because the observations and reductions are more time consuming. CCD observers would be greatly helped when standard fields are established with at least 5 stars with a range of colour if possible in a frame. Then only three different fields would provide more than 15 standard stars, comparable with most photoelectric work. I urge small telescope observers to coordinate the establishment of such standard fields based on the Cousins E and F regions and the Cousins and Landolt equatorial fields. Landolt has set up some good multiple standard fields but these generally contain stars of brightness better suited to 1 and 2m telescopes.

The colour terms in transformation equations should be quite stable over time for a given CCD and set of filters so need not be measured every night. Similarly with extinction at most sites in the absence of volcanic eruptions and bushfires. Standard or average extinction can be used provided the standards are observed at airmasses similar to and encompassing the range of extinctions over which the program stars are measured. Once the colour terms in transformation equations are known they can be adopted and only the zeropoints for each filter derived from the standard stars.

As commented above concerning relative magnitudes, standard magnitude photometry can also be gathered in non-photometric weather. Because cloud is essentially "grey", relative magnitudes can be derived from all frames obtained for any field. Eventually the field must be observed on a good photometric night and the uncrowded brighter stars in the frame can be used as local standards to correctly zero-point the data taken on the non-photometric nights. In this way very precise magnitudes can be measured by averaging many frames taken on non-photometric nights which would be lost to photoelectric photometry.

See Da Costa and other papers for more details.