Comparison of the possible photometry packages for the STELLA 2 and Robotel telescopes

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1 Introduction

This document is continuation of the document "The automated data reduction pipeline for the imaging telescopes STELLA 2 and Robotel" written by A. Staude and A Schwope in April 2004 (document: *S2-reduc-concept*). In that document the whole reduction procedure is discussed, including few notes on the possible photometry packages. In this document the available photometry packages are discussed in more detail and their pros and cons are emphasised. The Section 2 gives a short description of the available packages and in Section 3 a comparison between the different packages is given.

2 Available packages

2.1 DoPHOT

DoPHOT is a photometry package originally written by Schechter & Caldwell (modified by many others) and described in detail by Schechter, Mateo & Saha (1993). It searches objects from an image and produces positions, magnitudes and crude classification for those objects. The programme is designed to run with minimum effort from the users side. The user has to provide rough estimate of the seeing and background sky, and of course some parameters concerning the instrument (e.g., gain and read-out noise). In the following the main idea behind DoPHOT is summarised (based on Schechter et al. 1993).

A central feature in DoPHOT is using models for describing different types of objects. Six parameters are associated with the models: x and y position, total or central intensity, and three shape parameters (height, width and tilt). More complex models can also be adopted, but that of course increases the computation time. The same model is used for both the detection of the object and the photometry for ensuring a well-defined completeness limit based on the signal-to-noise.

DoPHOT uses the user supplied seeing value to identify stars brighter than some fairly high initial detection value. After this a better estimate of the shape of a typical star on the image is obtained by fitting the model of a star to a number of subrasters centered on different detected objects. If an object is better fitted by other model than the model for a star, e.g., the model for a cosmic or a galaxy, the object is classified as such. A working image is obtained by subtracting detected object from the original image. The working image is then search for more objects using progressively fainter detection threshold. After each pass through the working image the model fit is also done to all the objects found on previous passes to derive improved estimates of the model parameters. For doing this the previous best fitting model is added back to the working image. Since neighbouring fainter objects have now been removed from the working image, the shape parameters and magnitude

is better fit. While finding the objects the DoPHOT also constructs and updates a noise image which provides weights for each pixel in its non-linear least squares fitting routine. The noise image is also used to check whether a potential object is significantly above the background.

Analytical point-spread functions (PSF) fail most noticeably with bright stars. Large positive residuals that are left over from the fitting can trigger false identifications. To avoid this DoPHOT adds noise to the noise image every time it subtracts a star from the working image. As a negative consequence of this likelihood of detecting weak sources close to bright targets is reduced. One would think that given the systematic patterns of residuals seen in the star subtracted images the fluxes derived from fitting the model PSF to the data would also have systematic errors. On the other hand, these systematic errors can be assumed - to the first order- to be the same for all the stars. As an aid for correcting for such systematics DoPHOT also calculates fluxes inside a suitably chosen subraster. These aperture magnitudes are more uncertain than the PSF fit magnitudes, because there is much more Poisson noise from the sky inside the aperture than there is under the model profile.

2.2 DAOPHOT II

DAOPHOT II is a computer programme for obtaining precise astrometric positions and photometry for stellar objects from already reduced CCD images. It has been written by P. Stetson and downloadable manuals exist for this programme. The following is largely based on the DAOPHOT II manual.

In DAOPHOT II the user has to supply the following a-priori information to the programme: the approximate size of the unresolved stellar objects in the frame, CCD gain, read-out noise and the saturation limit. When this information is known the DAOPHOT II will preform the following tasks:

1. Find stellar objects above a certain detection threshold. This routine rejects to some degree the bad pixels, rows and columns, and avoiding multiple hits to on individual bright objects. Anyhow, the programme has some problems with saturated objects.

2. Obtain concentric aperture photometry for the objects found by the first task. The local sky brightness for each star from a surrounding annulus of pixels is also determined.

3. Determine PSF for the frame from one star or from the average of several stars in an iterative process intended to fit and subtract faint neighbour stars which contaminate the profile.

4. Compute precise positions and magnitudes for the programme stars by fitting

the PSF to each star, either individually or in simultaneous multiple-profile fits to up to 60 stars at a time.

5. Erase stars from the picture by subtracting appropriately scaled PSF corresponding to the positions and magnitudes derived for the stars during the photometric reductions.

DAOPHOT II also includes ALLSTARS II programme which performs a much more sophisticated multiple-profile fit to all the stars in a frame simultaneously. Also many other routines are included in DAOPHOT II. These routines allow, e.g., estimate an average sky brightness for a frame and sorting the stars' output data according to specified criteria.

2.3 SExtractor

SExtractor (Source-Extractor) is a programme written by E. Bertin that builds a catalogue of objects from an astronomical image. It is mainly used for source extraction and astrometry, but it can also do photometry using 4 different approaches: ISO, ISOCOR, AUTO and APERTURE. In ISO the user defines a threshold above which the SExtractor should do photometry with the estimated background as the zero point. With ISOCOR SExtractor takes into account the fact that some of the flux from the object is in the wings outside the isophotal area used in ISO. SExtractor does only a crude correction to the flux by assuming a symmetric Gaussian profile for the object. In AUTO method SExtractor uses flexible elliptical aperture around every detected object and measures all the flux inside it. In APERTURES all the flux inside a user defined circular aperture is measured. In some SExtractor manuals also a possibility of fitting PSF to the objects is mentioned, but it seems that this feature is not yet fully implemented in SExtractor.

2.4 Multiple Object and Multiple Frame (MOMF) CCD photometry package

MOMF photometry package that has been developed and described by Kjeldsen & Frandsen (1992) can reduce time-resolved photometry in half crowded fields. MOMF preforms CCD photometry on reduced frames. It first creates fiducial frame for star identification and goes non-interactively through the following steps to preform the actual photometry: determination of the empirical PSF for each frame, subtraction of all identified stars, re-determination of sky background on star-subtracted frame, re-determination of PSF and again subtractions of all stars and aperture photometry correction on the residuals. The aperture radii for the aperture correction are specified by the user and scale with the seeing. Finally, the programme optimally

combines the data relative to a freely selected comparison stars for lowest possible point-to-point scatter in the object light-curve (some weighting is also possible).

MOMF also includes a special part, DEFOC, which has been designed to obtain photometry on defocused stars. It finds the center coordinates and diameter of the defocused stars and calculates the magnitudes. Three different ways are used for calculating the magnitude:

1. One image is chosen as a reference image. Based on the diameter of the defocused stars in the image, the programme calculates 30 concentric apertures which will be used on all stars and on all the frames. For each frame the sky background is first calculated, after which the coordinates for each star are found and the aperture photometry is done.

2. The same as the first point, except the individual stellar coordinates are not allowed to move. The coordinates are calculated from the offset values from a reference star. The offset values are found on the reference frame.

3. From the image diameter in the reference frame a best-guess image size is taken. This image size is then used on all the stars on all the frames for aperture photometry. When calculating the magnitude, the coordinates for each star are allowed to move, and the magnitude for the star is taken when the light reaches a maximum for the moving center coordinate.

According to Kjeldsen and Frandsen (1992) the best way to do photometry on a defocused star depends on many things, e.g., the field, the CCD chip and the amount of defocusing. So, all three methods described above are used in order to reduce the reduction noise.

2.5 Image subtraction method

This method is also sometimes called difference image analysis (DIA, see Woźniak 2000). In image subtraction one image is matched against another by using a convolution kernel. Differences in these two images are used to detect and measure the variable objects. The first successful implementation of this method was by Tomaney & Crotts (1996). The method was further developed by Alard & Lupton (1998) who eliminated the division in Fourier space and created the fast Optimal Image Subtraction method which solves the full least-squares problem. This method can produce subtracted images and light-curves with an accuracy approaching the photon noise limit. The method was further improved by Alard (2000) who generalised the result for spatially variable kernels.

The first step in the image subtraction is to re-map all the images to the same grid. After this, the reference image to which all the other images ("science" images)

are compared to is chosen. Usually, the image with the best seeing is chosen as the reference image. If many images of similar (good) quality are available these matched images can also be stacked to produce the reference image. Using several images in creation of the reference image improves the result as the seeing variation and noise are reduced. After the creation/selection of the reference image the reference image and the "science" image need to be matched to exactly the same seeing for a perfect subtraction. This is done by convolving the seeing in the reference image to the seeing of each "science" frame. The images are subtracted and the resulting images can be analysed for variation. This method is particularly well suited for crowded fields.

Many large variability surveys, e.g., microlensing surveys, use this kind of algorithms for the photometry, thought the implementation itself varies. At least two packages using this method are available freely in the internet. The ISIS code has been written by C. Alard and is described in Alard (2000). The DIA code has been written by P.R. Woźniak (Woźniak 2000). Both of these packages are widely used. DIA is mainly used by the OGLE project (Optical Gravitational Lensing Experiment, see e.g. Udalski et al. 1997) and also in some other variability studies (see e.g. Wyrzykowski et al. 2002). ISIS code is used by many projects, e.g., HATnet (Hungarian-made Automatic Telescope network, see Bakos et al 2004), PISCES (Planets in Stellar Clusters Extensive Search, see e.g. Mochejska et al. 2002) and PSV (Princeton Variability Survey, Blake 2003). Slightly modified version of ISIS code is also used by several groups, e.g., CASE (Cluster Ages Experiment, Kaluzny et al. 2005) and PSST (Planet Search Survey Telescope, Dunham et al. 2004). Also other big microlensing experiments, MACHO (Massive Compact Halo Object, Alcock et al. 1993) and MOA (Microlensing Observations in Astrophysics, Bond et al. 2001), currently use image subtraction based on the paper by Alard (2000), but with slightly different implementation than ISIS or DIA.

3 Discussion

Some more specific points on some of the packages discussed in the previous Section are given in the following. Also, the pros and cons for each package/method are discussed in the end.

3.1 DoPHOT vs DAOPHOT

Ferrarese et al. (2000) give a nice comparison between the photometry obtained with DoPHOT and DAOPHOT ALLFRAME. They conclude that both packages work very well in non-crowded fields with limited variation in the background brightness across the image. In crowded fields problems arise from presence of confusion noise from crowding and rapidly varying background across the image. In this kind

of situations both programmes tend to overestimate the brightness of the objects: ALLFRAME by $\sim 5 - 10$ % and DoPHOT up to 25 %.

3.2 Comments on MOMF

Handler (2003) has done brief tests on MOMF and found out that the MOMF light-curves have about 10-20 % lower scatter than the light-curves produced by fitting an analytical PSF. Handler also lists few shortcoming of the programme, e.g., MOMF is not easy to learn and it cannot cope with field rotation.

3.3 Pros and cons

Above 5 different packages/methods for doing photometry were discussed. Here a short discussion in the pros and cons of all the methods/packages is given.

- *DoPHOT and DAOPHOT* seem to be very similar in their performance. They both work well in un-crowded fields, but start to have problems with increasing crowding.
- As far as could be determined *SExtractor* only uses aperture photometry, even though the possibility of PSF fitting is mentioned in some manuals. Anyhow, SExtractor is not recommended for high precision work, so it should not be used for photometry. On the other hand SExtractor is very good for astrometry and source extraction and can be used for that in the reduction pipeline.
- *MOMF* seems to produce very accurate photometry even with moderately crowded fields. And it can be used also on de-focused stars, a property that is important in case of STELLA II and Robotel. On the other hand, this programme is reportedly complicated and difficult to use. Also, the programme would have to be modified to run in a pipeline fashion.
- *The image subtraction method* produces very accurate light-curves and preforms well even in very crowded fields. On the other hand, this method only produces differential photometry, so for getting the magnitudes, some other programme should be used. Also, the image subtraction method gives the best results when using a reference image that has been stacked from several individual good quality images. This is feasible for long time series of a same field, but when only having few frames of the same target field, single reference frame has to be used, which of course would mean reduced accuracy in the photometry.

4 Summary

On the whole, MOMF and the image subtraction method seem to be able to produce the most accurate light-curves. So, most likely it would be recommendable to choose one of these methods for STELLA II and Robotel photometry. As we mostly work with semi-crowded fields and sometimes use also defocused star, MOMF seems to be the package that is more suited for us. Also, for optimal use of the image subtraction method several good quality images should be used in the creation of the reference frame. This would be difficult to obtain for some of the programmes envisioned for STELLA II and Robotel. Anyhow, practical tests on real data using at least MOMF and one (or maybe both) of the freely available image subtraction packages should be carried out to see how these methods perform in comparison to each other.

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