REDUCTION OF CCD OBSERVATIONS OF DOUBLE AND MULTIPLE STARS

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Abstract. The method used at the Royal Observatory to extract photometric and astrometric information from CCD images of visual double stars with a separation in the range 1.5 to 20 arcsec is described. Since standard methods are not applicable, a short history of the technique selection process is given. Finally direct profile fitting was used and the adopted point spread function is a modified Moffat profile, corrected for ellipticity of the isophotes. The problems related to the technique are described, some results are given and preliminary errors are estimated.

1. Introduction

In recent years the Royal Observatory was involved in several observational programmes of wide visual double stars (Argue et al., 1992; Oblak et al., 1992; Sinachopoulos et al., 1995). Besides classical photometry also CCD imaging of double stars was done (see Figure 1 for an example).

Extracting accurate photometric and astrometric information of bright visual double stars on CCD images is not straightforward. When bright stars are involved, mostly none or very few additional stars are recorded on the image and, as a consequence, crowded field packages for CCD reduction cannot be used in a proper way. It is also not clear whether a profile derived from stars further away from the components will give the accurate information on the double or multiple star contained in the CCD image.

If there is overlap between the images of the components (even under good seeing conditions stars separated by 10 arcsec and more still show some overlap in 1 m telescopes), a classical approach (aperture photometry and centering routines) cannot be used.

Consequently, direct profile fitting was used, since this is a method were the information can be extracted sufficiently accurately.

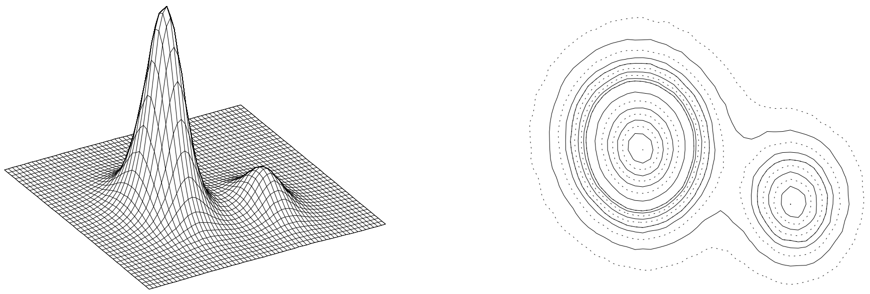

Figure 1. Example of a double star image on CCD (3D view and contour plot): HIC 24366 ($\rho = 7.8$", $magA = 10.5, \Delta mag = 1.7$)

2. Choosing a profile

After some experiments with one-dimensional projections of the images (inspired by Rakos et al., 1982 and Sinachopoulos, 1988) a two-dimensional approach was adopted. The point spread function (PSF) is given as a function of the two spatial coordinates x and y.

Several profiles were tested to fit to an image of a single star. For the fitting process a least-squares approach was used, where minimization was done with a modified Gauss-Newton algorithm with numerical derivatives (as implemented in the ESO-MIDAS configuration with use of the numerical subroutines of the NAG library).

A simple Gaussian

$$f(x, y) = h_A e^{-br^2},$$

or Lorentz-like profiles

$$f(x, y) = \frac{h_A}{(1 + (r_A b)^2)^t} \qquad \text{(with } t \text{ fixed at 1, 2, \ldots)}$$

where

$$r_A = \sqrt{(x - x_A)^2 + (y - y_A)^2}$$

and the unknowns are x_A, y_A, h_A and b, were clearly not sufficient to describe the core and the wings of the images accurately.

Therefore, a Moffat profile (Moffat, 1969) was used, written as:

$$f(x, y) = \frac{h_A}{(1 + (r_A b)^2)^q}$$

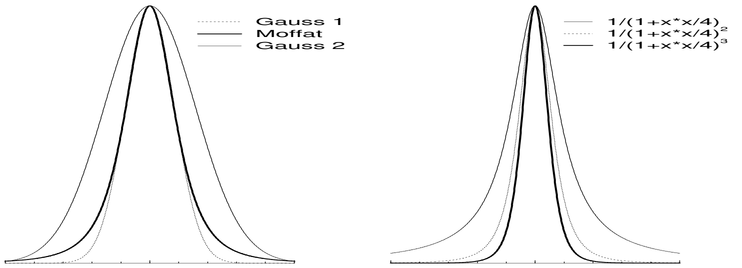

Figure 2. Gaussian and Moffat profiles compared

The extra unknown parameter q makes it possible to fit the core and the wings as well (see Figure 2). In all profiles (x_A, y_A) gives the central position and h_A is the height at that position. Remark that b is related to the Full Width at Half Maximum : $FWHM = 2\sqrt{\{\sqrt[q]{2}-1\}}/b$. In this modified form the fitting proces was usually more "stable", then when written otherwise. Other profiles, such as two-dimensional analogues of the Franz profile (Franz, 1973) and those suggested for use with the one-dimensional area scanner (Rakos et al., 1982), were also tested. An additional unknown describing the dependency on distance in the exponent should make it possible to fit even better the observed profiles, but a lot of numerical instabilities, especially in the derivatives, are introduced. Moreover, the important quantities to be derived (height and central position of the profile) did not change significantly compared to the results obtained with the Moffat profile (E. Ruymaekers, unpublished annex thesis, 1994).

In a lot of cases it was necessary to use elliptical isophotes. This was done by replacing r_A with the expression:

$$r_A = \sqrt{(x-x_A)^2 + e(x-x_A)(y-y_A) + (1+f)(y-y_A)^2}$$

with two additional unknowns e and f.

3. Fitting multiple components

When a small number of stars is present on the CCD frame a sum of profiles with identical shapes has to be fitted. The two components model will be:

$$f(x,y) = \frac{h_A}{(1+(r_A b)^2)^q} + \frac{h_B}{(1+(r_B b)^2)^q} + sky,$$

where A and B refer to the two components and b, q, h and r are defined as above. From the results of the fit, one can derive the differential position and magnitude of B with respect to A.

For N components this becomes:

$$f(x,y) = \sum_{i=1}^{N} \frac{h_i}{(1+(r_i b)^2)^q} + sky,$$

where, as above,

$$r_i = \sqrt{(x-x_i)^2 + e(x-x_i)(y-y_i) + (1+f)(y-y_i)^2}$$

A few tests (Lampens and Seggewiss, 1995) indicated that at least ten components can be fitted with this method.

4. The programme in the MIDAS environment

The fitting proces was done within the ESO-MIDAS environment. This was done for reasons of availability when the observations started (most sets of data resulted from ESO) and tradition. The treatment of the "raw" data could be done in the same environment as well.

The CCD images were bias subtracted and flat-fielded with MIDAS commands. Since almost all the stars observed so far had very bright components, and, therefore, only very short exposure times were used, a simple sky subtraction, based on the mean of the three smallest values of small squares in the corners of the images was used. In the subsequent analysis it was assumed that the sky background was equal to zero.

Initial values for the parameters could easily be estimated: the parameter b is directly related to the seeing, q is usually in the range 2 to 3. For e and f (if used), zero is the starting value. A good guess for the position of the main component are the coordinates of the maximum of the frame and the position of the other component(s) can be estimated directly on the frame (mouse clicking) or from an astrometric list (e.g. Hipparcos Input Catalogue). Special attention is necessary when the magnitude differences between the components have different signs in different filters.

5. Tests and estimates of errors in the astrometry

For synthetic data the fitting routines perfectly reproduced the profiles. On single, isolated, well observed stars, remaining residuals were only slightly above the photon noise. It is clear that when the isophotes do not have a perfect elliptical shape, residuals will be larger. In those cases the largest residuals where five to ten times the photon noise, but the influence on the derived photometric and astrometric parameters, was very small.

To evaluate the internal errors we compared the results of observations of the same double star, on images taken one after another on one night,

TABLE 1. Differential data of 1 night

HIC Nr	Filter	$\rho('')$	$\theta(^\circ)$	Δmag	Date
24366	V	7.787	106.687	1.725	1991 10 16 (1)
24366	V	7.775	106.657	1.725	1991 10 16 (2)
24366	V	7.778	106.601	1.718	1991 10 16 (3)
24366	V	7.803	106.860	1.712	1991 10 16 (4)
24366	V	7.782	106.711	1.724	1991 10 16 (5)
24366	V	7.782	106.671	1.718	1991 10 16 (6)

on different nights and in different seasons (see Tables 1 to 3 for a few examples). The agreement is excellent. Internal errors on separations are only a few milliarcseconds.

TABLE 2. Differential data of consecutive nights

HIC Nr	F.	$\rho('')$	Stdρ	$\theta(^\circ)$	Stdθ	Δmag	StdΔ	Date
25870	V	4.813	0.005	326.17	0.02	0.618	0.006	91.10.21
25870	V	4.814	0.005	326.24	0.02	0.624	0.001	91.10.22

The true (relative) apparent separation ρ between A and B, is function of the scale on the CCD image. If the same camera is used with the same instrument and filter, the scale will not change. The position angle θ changes with every dismount and remount of the camera. When observing a star near the equator in a "non-tracking" mode, a trace on the CCD is marked, but the precision of the extracted orientation is not much better than 0.4°, as repeated observations indicated.

In the range of expected precision (0.01-0.001 arcsecs in ρ and 0.1° in θ), there was not sufficient comparison material available. This will be possible when the definitive Hipparcos results are released. Comparisons with a few preliminary Hipparcos data, indicate that the scale factor can be obtained with a 0.05% precision and orientation with a 0.2° precision on a telescope of the 1m class, even in non-optimal conditions (badly focused images, no excellent seeing, ...). Remark that for large separations (>15 arcsec), the PSF is not necessarily identical for the different components and, therefore, an extra error will be introduced. At the very small separations (less than the $FWHM$) the quality of the results will degrade as well.

TABLE 3. Differential data in different seasons (no correction for scale and orientation)

HIC Nr	F.	$\rho('')$	Stdρ	$\theta(°)$	Stdθ	Δmag	StdΔ	Date
25436	I	12.005	0.005	251.34	0.01	0.704	0.004	91.10.23
25436	I	12.003	0.012	249.59	0.17	0.703	0.001	92.02.21

6. Towards standard magnitudes

The difference in magnitude between the components can be derived from the ratio of the heights of the fitted profile, as described above. It is difficult to give a reliable estimate of the errors on the differential magnitudes, since there exists almost no comparison material. Internal errors are very small, usually less than 0.005 mag (see Tables 1 to 3 for some examples).

If a total intensity can be extracted and the extinction is available, the total instrumental magnitude can be calculated. When the transformation to a standard system is known (e.g. from measurements of standard stars), there is sufficient information to calculate the standard magnitudes and colours of each component.

For the observing campaigns considered one tried to measure as many (single) standard stars as feasible and to use them as well for the calculation of the extinction. By combining the standard measurements per season, but with a different (calculated) extinction coefficient for each night, a reliable colour transformation could be done. Typical errors are around 0.01 magnitude (see Table 4). Combining all errors involved in the reduction proces of the double or multiple stars one arrives at an error of less than 0.03 mag in the standard magnitudes and colours of each component. For a detailed comparison of the magnitudes with other sources we refer to the paper presented by Lampens et al. at this meeting.

TABLE 4. Standard magnitudes in different seasons

HIC Nr	Filter	Mag A	Mag B	Δ Mag	Date
25436	V	8.260	9.102	0.842	91.10.23
25436	V	8.262	9.092	0.830	92.02.21
25436	I	7.765	8.469	0.704	91.10.23
25436	I	7.764	8.464	0.699	92.02.21

7. Conclusions

The procedure described here is adequate to extract photometric and astrometric information of double and multiple stars on CCD images. In view of the limited capacity of the telescopes used (< 1 m), the relatively few measurements taken of each star system and the non optimized CCD camera and acquisition system, a large quality improvement is still possible. Nevertheless, this procedure has produced data of unprecedented accuracy on individual components of a large group of "intermediate" visual double stars.

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