Photometry of Stars on Uneven Backgrounds

S. Spännare

Lund Observatory, Box 43, S-221 00 Lund, Sweden; Email: stefans@astro.lu.se

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Abstract. The program POLYFIT has been developed to perform photometry of well sampled stars on luminous uneven backgrounds consisting of nebulae or galaxies. The program can also be used to remove stars from galaxy images, if the galaxy itself is the relevant object. The program uses empirical PSFs defined from the stellar image. POLYFIT performs a simultaneous least squares fit of the PSF to the image of the star and a two-dimensional polynomial (of degree ≤ 5) to the background. Detection and approximate positions of the stars in the image are made available by a separate routine. As a rule of thumb a fitting radius of $1.5 \cdot \mathrm{FWHM}$ of the image of the star and a polynomial degree of 2 or 3 give the best results. Comparative tests using simulated and observed well sampled stellar images added to observed galaxy backgrounds show that POLYFIT gives photometric results superior to those produced by some major photometry packages widely available. Photometric errors smaller than 0.05 magnitudes are obtained for most stars in these images.

1. Introduction

Modern detectors i.e. Charged Coupled Devices (CCD), and increasing power of computers, have stimulated development of many, more or less automatic, methods for detection and photometry of stars in astronomical images. Common to all of the methods is that they fit an empirical or analytical Point Spread Function (PSF) to the stellar images. The background is usually estimated from the surrounding of the stars or simultaneous with the PSF fit.

Examples of reduction packages are RICHFLD (Tody 1980), the Aurière & Cordoni (1981) package, ROMAFOT (Buonanno et al. 1980, 1983), Blecha's (1984) software, STARMAN (Penny & Dickens 1986), WOLF (Lupton & Gunn 1986), DAOPHOT (Stetson 1987), HAOPHOT (Gilliland & Brown 1988), PAWSPHOT (Mighell 1989), The Lund package (Linde 1989) and CAPELLA (Debray et. al. 1994). Some of them, for instance ROMAFOT and PAWSPHOT, use the analytical Moffat function for the shape of the PSF (Moffat 1969). Blecha uses a modified Gaussian profile and STARMAN a combination of a Gaussian and a Lorentzian function. RICHFLD, WOLF, the Lund package and CAPELLA employ an empirical PSF. DAOPHOT and HAOPHOT use a semi empirical PSF constructed from an analytical profile corrected by an array of differences between the instrumental and modeled profiles. Two other packages, INVENTORY (West & Kruszewski 1981, Kruszewski 1989) and DoPHOT (Mateo & Scheechter 1989), perform stellar photometry, and in addition, provide information on the nature (stellar or extended) of the object. INVENTORY uses a radial one-dimensional empirical PSF and DoPHOT a modified Gaussian for the PSF.

Some projects in progress at Lund Observatory deal with chemical evolution of globular clusters and the Hubble constant, the latter program through investigations based on supergiant stars in galaxies. This has prompted the development of the computer program POLYFIT, for photometry of stars on luminous uneven backgrounds.

2. Basic data reduction

Of great importance to all photometric work with CCD images is careful basic data reduction, i.e. bias subtraction, dark signal subtraction and flat fielding. For long exposure times removal of cosmic ray hits usually is necessary. For a more detailed discussion see for example Gilliland (1992) and Debray et al. (1994).

3. Derivation of the PSF from the image

The PSF of an image is the light distribution of a point light source on the detector. Thus the PSF obtained from a ground based astronomical observation is the image of a star. The star can be regarded as a point light source. The light is convolved by the turbulence in the atmosphere (the seeing) and instrumental profile of the telescope. The image can also be affected by tracking errors of the telescope. In the case of a digital (CCD) image the resulting digital PSF is the continuous PSF convolved with the pixel window.

For all photometric methods that use PSF fitting, careful derivation of the PSF is of great importance. An erroneous PSF usually gives rise to systematic photometric errors. There are three ways to obtain the PSF, empirical, analytical and semi empirical, i.e. the analytical profile is corrected by an array of differences between the instrumental and the modeled profiles. Usually stars are located at fractional pixel positions, which makes interpolation (such as bicubic spline interpolation) necessary when fitting empirical and semi empirical PSFs. This works fine in the Nyquist range, which for astronomical images typically translates to the condition $\mathrm{FWHM} \geq 2.4$ pixels (Debray et. al. 1994). For semi empirical PSFs the interpolation errors can be made considerably smaller by interpolating only the differences between the instrumental profile and the analytical function (Stetson 1987).

If the stars in the image are well sampled it may be possible to choose a bright, unaffected and isolated star and use its im-

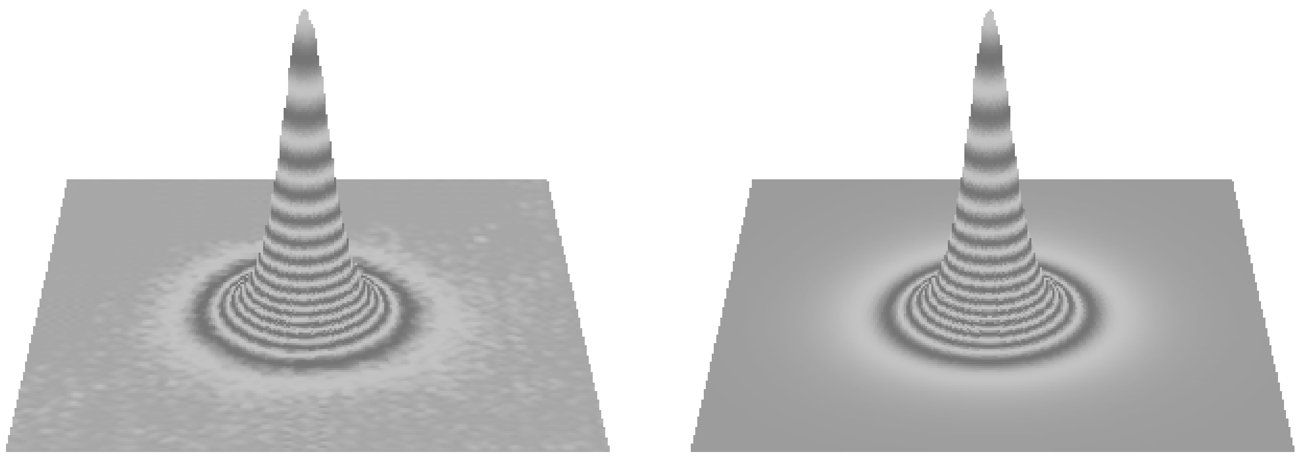

Fig. 1. a) Left: A bright PSF star (FWHM 7.8 pixels) from the galaxy NGC 672 is shown. b) Right: The fitted Moffat function (using MOFFIT) is shown. Both the star and the Moffat function are over sampled a factor 4 for display purposes.

age as a PSF. The background must be carefully estimated and subtracted. The empirical PSF can be improved by averaging a number of individual stellar images.

Another possibility is to least squares fit an analytical function to a bright, unaffected and isolated star in the image. Such a program (MOFFIT), that fits an elliptically symmetric Moffat function (Moffat 1969) to the star, has been developed. The formula for such a function is:

$$m(x,y) = (c_5x^2 + c_4y^2 + c_3xy + c_2x + c_1y + c_0)^{-\beta}$$

The coefficients $c_0, \ldots, c_5$ are constants to be fitted. The shape of the PSF and especially the width of the "wings" depends on the β value. It is difficult numerically to make an automatic fit of β, why an interactive improvement is performed. For most stars $2 \leq \beta \leq 4$. In Figure 1 a, a bright PSF star (FWHM 7.8 pixels) from the galaxy NGC 672 is shown. In Figure 1 b the fitted Moffat function (derived using MOFFIT) is shown. Both the star and the Moffat function are over sampled a factor 4 for display purposes.

4. Description of POLYFIT

The computer program POLYFIT, written in C, was developed to give accurate photometry of well sampled stars also on uneven luminous backgrounds consisting of galaxies or nebulae. The program can also be used to remove stars from galaxy images, if the galaxy itself is the relevant object.

4.1. Algorithm

In POLYFIT the background of the star is modeled with a two-dimensional polynomial of a degree that can be set to 0, 1, 2, 3, 4 or 5. A polynomial of degree 0 corresponds to a flat plane while degree 1 corresponds to a tilted plane. Higher order polynomials correspond to more complicated shapes allowing higher spatial frequencies. There is no special theoretical argument for polynomials as background estimators (other functions can be used as well) but they are easy to implement and experiments show that they give quite accurate results if the parameters are properly tuned.

The PSF and the background polynomial are least squares fitted simultaneously to the star and the background in the image. A circular mask is created for all $n_{\rm fit}$ pixels with positions (x, y) inside the fitting radius $r_{\rm fit}$ counted from the center of the star (x_0, y_0). The linear equation system then has $n_{\rm fit}$ rows of the form:

$$\sum_{\substack{i,j \\ 0 \leq i+j \leq d}} c_{ij}x^iy^j + c \cdot \mathrm{PSF}(x,y) = \mathrm{I}(x + x_0, y + y_0)$$

for $x^2 + y^2 \leq r_{\rm fit}^2$

and for different degrees $(d)$of the polynomial. This equation system is solved using a standard least squares fit to obtain the coefficients c_{ij}. c is the intensity of the star when the PSF is normalized to an integrated intensity of unity. $\mathrm{I}(x+x_0, y+y_0)$ is the image in the position $(x + x_0, y + y_0)$. Obviously at least as many equations (i.e. points in the mask) as there are coefficients c_{ij} in the equation (i.e. $\pi r_{\rm fit}^2 \approx n_{\rm fit} \geq n_{\rm coeff}$) are needed. It is possible to reject pixels from the fit, pixels that deviates more than a pre-defined number of standard deviations (σ) from the mean. In the case of a two-dimensional polynomial of degree 5, 22 coefficients have to be determined, 21 for the polynomial and 1 for the PSF. To have enough equations this requires a fitting radius $r_{\rm fit} > \sqrt{22/\pi} \approx 2.6$ pixels. In practice the radius must be much larger for a proper fit. For a polynomial of degree 0 (i.e. a constant) the radius can be as small as 1 pixel. In the least squares fit the $n_{\rm fit}$ equations are equally weighted, but other weighting functions such as $1/(r+1)$ or $1/(r^2+1)$ have been tested. Here r is the radius $\leq r_{\rm fit}$ from the center of the stellar image. However, brief experiments show that equal weighting works best in most cases, which is in agreement with a theoretical discussion by Mighell (1989).

To be able to obtain a sub-pixel position for the star the PSF is bicubically spline-interpolated to fractional pixel positions. This interpolation works well for well sampled stars. To obtain the best value of the stellar magnitude and the position of the star, a simple "grid-search" is performed to find the local residual minimum. This grid-search means that the least squares fit is performed in every point in a grid ($n \times n$ points, normally $n = 5$) of a pre-defined size around the initial position of the star. This initial position must be fed to the program and can be obtained for example by using FINDSTARS (described in section 5.3). The improved position of the star is then the grid-point where the standard deviation of the residuals has the lowest value. The position can be further improved by decreasing the grid size in more than one step. This grid-search works well in practice but requires substantial computer time. POLYFIT has some capabilities to make a simultaneous fit of many stars (in a group) at the same time, which is important when the target star is affected by bright neighbors. POLYFIT is not optimized for speed, as it is usually used only for a small number of stars with large fitting radius. The output from the program contains the (improved) x and y position, intensity, magnitude, background level, square sum and computation time for each star in the input file.

5. Programs for comparison

Short descriptions are given of the photometric programs DAOPHOT, PLUCY and FINDSTARS that are compared to POLYFIT.

5.1. DAOPHOT

DAOPHOT (Stetson 1987) is one of the most popular photometry packages available. It is well adapted for crowded field photometry and includes separate routines for star detection, aperture photometry and PSF-fitting. The PSF-fitting routine use positions from the detection routine and a semi empirical PSF constructed from an analytical profile corrected by an array of differences between the instrumental and modeled profile. The instrumental PSF is obtained from the image in a nice interactive way. To make the code efficient the stars are divided into small groups before the least squares fit is performed. The background is estimated from the surrounding of the stars.

5.2. PLUCY

A new method that is well adapted for photometry on irregular backgrounds is "multiple channel photometric image restoration" (Lucy 1993). The program code is called PLUCY by Lucy. The method splits the image in two parts - one consisting of the stars and one of the background. The stars are represented as delta functions. An iterative optimization is performed which maximizes the normal likelihood function for the point sources. This improves the accuracy of the measured star magnitudes. Initial values of these magnitudes must be given, as well as the positions and the PSF of the stars.

5.3. FINDSTARS

FINDSTARS is a new program developed by the author for detection and photometry of stars in crowded fields. FINDSTARS was initially developed to *find* stars in crowded fields. However the photometric results were rather good, comparing well with other crowded field programs (for example DAOPHOT). Two features make FINDSTARS unique. Firstly it performs a linear least squares fit of the PSF and a constant background for all pixels inside the fitting radius around each sub pixel position in the image. The sub pixel step size is normally 1/2, 1/4 or 1/8 pixels. This is equivalent to a fit with POLYFIT with degree 0 of the background polynomial. Secondly the output file from FINDSTARS (with positions of most local maxima) is sorted with a special program (FSORT) to avoid multiple detection of the stars. This is a simple concept that makes the program fast if the fitting radius is reasonably small. FINDSTARS normally uses bicubic spline interpolation to interpolate an empirical PSF to fractional pixel positions. For under sampled images an analytical Moffat function can be used to avoid interpolation.

6. Experiments

It is a complicated task to make simulated images of galaxies. Therefore, to test POLYFIT on realistic backgrounds, simulated stars have been added to observed galaxy images with no or very few real stars present. This has been done for the three galaxies NGC 672, NGC 1637 and NGC 925, all CCD images taken with the V color filter with the Nordic Optical Telescope (NOT). In addition tests have been made with stars from the image of the globular cluster NGC 7790 are added to the image of the galaxy NGC 1637. The photometric results with POLYFIT are compared to those of DAOPHOT, PLUCY and FINDSTARS. It is difficult to assure optimal performance of external software. Therefore suggestions from experienced DAOPHOT and PLUCY users have been adopted to optimize the parameters of these programs.

6.1. Simulated stars added to galaxies

Images of the galaxies NGC 672, NGC 1637 and NGC 925 are shown in Figures 2 a, 4 a and 6 a. In Figures 2 b, 4 b and 6 b the same galaxies are shown with simulated (Moffat shaped) stars added. The simulated stars are marked with dark rings. Data for the simulated stars and the images are shown in Table 1. The simulated stars have approximately the same shape as real stars in the images, obtained by fitting a Moffat function to real stars in the images using the program MOFFIT. The small areas inside the grey frames, in Figure 2 b, 4 b and 6 b, are shown in magnified scale to the left in the Figures 3 a, 5 a and 7 a. The grey scales in these figures are different from those of the large figures to emphasize details. The magnified areas contain both simulated and real stars. In Figures 3 b, 5 b and 7 b the resulting background images are shown after the stars have been measured and subtracted using POLYFIT. Only some faint residuals are seen. A fitting radius of $1.5 \cdot \mathrm{FWHM}$ of the stars and a polynomial degree of 2 was used for POLYFIT. In Figures 3 c, 5 c and 7 c the original image (with real stars) are shown for comparison.

Table 1. Data for the simulated stars added to the galaxies NGC 672, NGC 1637 and NGC 925. The image sizes, number of stars (n), intensity of the stars, FWHM and Moffat β are given.

Galaxy	Image size	n	Intens (ADU)	FWHM (pixels)	FWHM (")	β
NGC 672	512^2	22	100000	9.0	0.99	2.5
NGC 1637	1000^2	78	25000	8.0	0.88	3.0
NGC 925	1000^2	30	25000	19.0	2.09	2.2

6.1.1. The accuracy of POLYFIT

The simulated stars added to NGC 672, NGC 1637 and NGC 925 were measured using POLYFIT for different fitting radii and different degree of the background polynomial. The fitting radius was varied in the range $1/2 \cdot \mathrm{FWHM} \leq r_{\mathrm{fit}} \leq 2 \cdot \mathrm{FWHM}$ and the polynomial degree was varied between 0 and 5. For the PSFs Moffat functions with data from Table 1 were used. As seen from Table 1 all the simulated stars in each galaxy have the same intensity. The results for the different galaxies are shown in Figures 8, 9 and 10. In the upper diagrams (a) the average magnitude offsets as function of fitting radius and degree of the polynomial are shown. Here also the different line types for different degree of the polynomial (0–5) are shown. In the middle diagrams (b) the standard deviations (σ) in magnitude of the stars as function of fitting radius and degree of the polynomial are shown. Finally, in the lower diagrams (c) the maximum magnitude errors (both positive and negative) as function of fitting radius and degree of the polynomial are shown.

Looking at Figures 8, 9 and 10 it is interesting to note that the curves for different polynomial degrees follow each other in the pairs (2,3) and (4,5) for σ and the maximum error. The reason for this is that the PSF represents an even function (with respect to the center of the star) and the polynomials with odd degrees represent odd functions. Thus the correlation coefficients between the intensity of the star (i.e. the coefficient c in the PSF term) and the coefficients of the odd polynomial terms are small. This means that the coefficients of the odd polynomial terms can have large values without affecting the intensity significantly. The result is the observed effect that the polynomials with even and odd degree, in the pairs (2,3) and (4,5), give approximately the same intensity values. The residuals however decrease with higher polynomial degree, which does not imply that the intensity values improve. The pair effect is seen also for the simulated stars added to the image of NGC 672 for polynomial degree 0 and 1 (Figure 8 b and c). For NGC 1637 and NGC 925 one or a few simulated stars have been erroneously measured for these polynomial degrees because the stars are located on very uneven backgrounds. Thus σ and the maximum error show large deviations in these cases (Figure 9 b and d and Figure 10 b and d). The positive maximum error curve for NGC 1637 is above the diagram limits (Figure 9 c). The diagrams show that the errors are significantly smaller for higher order polynomials.

Some general conclusions can be drawn from inspection of Figures 8, 9 and 10. The errors for higher order polynomials are large for small fitting radii and decrease for larger radii. The reason for this is that there are too few points n_{fit} to make a proper fit if the radius is small. The errors for polynomial degrees 0 and 1 increase with the fitting radius depending on difficulties to fit to an uneven background. Looking at σ it seems possible to use a low order polynomial and a small fitting radius to get a good fit. However the maximum errors are smaller if a higher order polynomial and a larger fitting radius are used. For the well sampled PSFs used here a good rule of thumb is to use a fitting radius $r_{\mathrm{fit}} = 1.5 \cdot \mathrm{FWHM}$ and a background polynomial of degree 2 or 3.

6.1.2. Comparison with other programs

POLYFIT was compared with DAOPHOT, PLUCY and FINDSTARS for the simulated stars in the three galaxy images mentioned above. The parameters for POLYFIT (i.e. the fitting radius for the stars and degree of the background polynomial) are shown in Table 2. For comparison two different measurements with POLYFIT have been performed for each galaxy. The first measurement (labeled POLYFIT 1) use optimal parameters from Figures 8, 9 and 10. The second measurement (labeled POLYFIT 2) use the rule of thumb $r_{\mathrm{fit}} = 1.5 \cdot \mathrm{FWHM}$ of the stars and a polynomial degree of 2. The other programs should be compared to the POLYFIT 2 measurements, which corresponds to realistic cases when no optimization is possible. The fitting radius for FINDSTARS was equal to FWHM of the stars.

The photometric results, magnitude offset, σ and maximum error, for POLYFIT, DAOPHOT, PLUCY and FINDSTARS for the simulated stars in the three galaxy images are shown in Table 3. The magnitude offsets for DAOPHOT are floating and could not be determined. It was not possible to directly measure the simulated stars added to NGC 925 with DAOPHOT because of the large FWHM (19 pixels) of the PSF. Therefore the image was sub sampled a factor of 2 before measurement with this program. The measurements with POLYFIT using the rule of thumb $r_{\mathrm{fit}} = 1.5 \cdot \mathrm{FWHM}$ of the stars agree very well with the optimal cases for NGC 1637 and NGC 925. For NGC 672 a fitting radius of approximately $1.0 \cdot \mathrm{FWHM}$ of the stars gives better result.

In Figure 11 logarithmic magnitude error diagrams are shown for comparison between POLYFIT and the other programs (DAOPHOT, PLUCY and FINDSTARS) for simulated stars added to the galaxies NGC 672 (a, b and c), NGC 1637 (d, e and f) and NGC 925 (g, h and i). The stars are represented by circles in the diagrams. Stars with errors above the diagonal lines give better fits for POLYFIT and stars with errors below the diagonal line give better fits for the other programs. As mentioned above a fitting radius of $1.5 \cdot \mathrm{FWHM}$ and a polynomial degree of 2 were used for POLYFIT. It seems obvious that POLYFIT performs better than the other programs for most stars. As men-

Table 2. The parameters for POLYFIT (i.e. the fitting radius (in pixels) and the degree of the background polynomial (deg)) for the simulated stars in the three galaxy images are shown. POLYFIT 1 shows the optimal parameters obtained from the Figures 8, 9 and 10 and POLYFIT 2 shows the parameters given by the rule of thumb $r_{\rm fit} = 1.5 \cdot {\rm FWHM}$ of the stars and a polynomial degree of 2. The FWHM (in pixels) of the stars and $r_{\rm fit}/{\rm FWHM}$ are also given.

Galaxy	Program	FWHM	$r_{\rm fit}$	$\frac{r_{\rm fit}}{\rm FWHM}$	deg
NGC 672	POLYFIT 1	9.0	8.0	0.89	2
NGC 672	POLYFIT 2	9.0	13.0	1.44	2
NGC 1637	POLYFIT 1	8.0	14.0	1.75	3
NGC 1637	POLYFIT 2	8.0	12.0	1.50	2
NGC 925	POLYFIT 1	19.0	29.0	1.52	2
NGC 925	POLYFIT 2	19.0	28.0	1.47	2

Table 3. Photometric results from measurements with POLYFIT, DAOPHOT, PLUCY and FINDSTARS of simulated stars added to the galaxies NGC 672, NGC 1637 and NGC 925. The offset, σ, maximum and minimum errors (max and min) are given in magnitudes. POLYFIT 1 shows results from measurements with optimal parameters obtained from the Figures 8, 9 and 10 and POLYFIT 2 shows results from measurements with parameters given by the rule of thumb $r_{\rm fit} = 1.5 \cdot {\rm FWHM}$ of the stars and a polynomial degree of 2. The offset for DAOPHOT is floating and could not be determined. It was not possible to directly measure the simulated stars added to NGC 925 with DAOPHOT because of the large FWHM (19 pixels) of the PSF. Therefore the image was sub sampled a factor of 2 before measurement with this program.

Galaxy	Method	Offset	σ	Max	Min
NGC 672	POLYFIT 1	0.001	0.034	0.054	−0.061
NGC 672	POLYFIT 2	−0.009	0.056	0.077	−0.152
NGC 672	DAOPHOT	—	0.106	0.151	−0.292
NGC 672	PLUCY	0.034	0.092	0.156	−0.230
NGC 672	FINDSTARS	−0.009	0.071	0.092	−0.188
NGC 1637	POLYFIT 1	−0.002	0.027	0.069	−0.054
NGC 1637	POLYFIT 2	−0.005	0.028	0.078	−0.062
NGC 1637	DAOPHOT	—	0.080	0.204	−0.456
NGC 1637	PLUCY	0.039	0.050	0.162	−0.079
NGC 1637	FINDSTARS	−0.001	0.028	0.080	−0.065
NGC 925	POLYFIT 1	0.005	0.071	0.170	−0.133
NGC 925	POLYFIT 2	0.011	0.072	0.179	−0.128
NGC 925	DAOPHOT	—	0.360	0.873	−0.942
NGC 925	PLUCY	0.066	0.367	1.251	−0.649
NGC 925	FINDSTARS	0.015	0.079	0.154	−0.171

tioned above the image of NGC 925 was sub sampled a factor of 2 before measurement with DAOPHOT.

6.2. Open cluster stars added to a galaxy

The last experiment to test POLYFIT and to compare it with DAOPHOT, PLUCY and also FINDSTARS was to measure stars from the open cluster NGC 7790 added to the image of the galaxy NGC 1637, thus obtaining observed stars on a observed galaxy background. The open cluster is shown in Figure 12 a. In Figure 12 b, the measured stars are marked with white rings. The image of NGC 7790 was divided into four pieces of equal size. The pieces were then diagonally shifted to get more stars in the central part of the image, where the corresponding part of the galaxy image is more uneven. This is the reason why some star images are cut. The images were taken with the Nordic Optical Telescope (NOT) with the V color filter and 200 s exposure time. The image size is 1000 × 1000 pixels. To enable measurement of the statistical error three different exposures of NGC 7790 were added separately to the image of the galaxy NGC 1637. The FWHMs of the stars in the three images were 10.9, 10.9 and 12.5 pixels respectively. The stars in the three images were then measured using POLYFIT and the programs for comparison. The average of these three measurements, for each star, and each method, was then used as the resulting magnitude. The galaxy NGC 1637 is shown in Figure 12 c. In Figure 12 d, the galaxy with one of the open cluster NGC 7790 images added is shown. The measured open cluster stars are marked with white rings. The areas inside the small white frames (A–D) are shown in magnified scale in Figures 15–18. To get master data for comparison, the stars in the three open cluster images (without galaxy background) were measured using POLYFIT. These images are simple to measure, with well separated stars, resulting in good photometric accuracy. The initial positions of the 77 stars, for POLYFIT and PLUCY, were taken from earlier work with the open clusters images. These positions were applied to the combined images. The positions could equally well have been obtained by DAOPHOT or FINDSTARS. PSFs for POLYFIT, PLUCY and FINDSTARS were obtained from images of bright stars from the open cluster. The PSFs were centered and the background subtracted. The PSFs for DAOPHOT were obtained from the open cluster images and then used on the combined images.

6.2.1. Polynomial degree of POLYFIT

In the logarithmic magnitude error diagrams in Figure 13 a, c and e, POLYFIT is compared with itself for different degree (1–4) of the background polynomial for the 77 test stars in the open cluster superimposed on the galaxy images. The areas of the circles are proportional to the intensities of the stars. The best results from polynomials of degree 2 are compared to those from polynomials with degrees 1, 3 and 4 in Figure 13 a, c and e respectively. In the diagrams stars above the diagonal lines give better fits for polynomial degree 2 and stars below the diagonal lines give better fits for the other polynomial degrees. Polynomial degree 3 is equally good as 2 for most stars. This is due to the pair-wise effect described in Section 6.1.1. The fitting radius was 18 pixels ($\simeq 1.5 \cdot {\rm FWHM}$ of the stars). This is equal to the radius of the white rings around the stars in Figure 12 b and d. Polynomial degree 0 gives approximately the same result as 1, and degree 5 give approximately the same result as 4.

6.2.2. Comparison with some other programs

In the logarithmic magnitude error diagrams in Figure 13 b, d and f, results from POLYFIT (degree 2) are compared with those of DAOPHOT, PLUCY and FINDSTARS for the stars in the combined open cluster plus galaxy images. The areas of the circles are proportional to the intensities of the stars. In the diagrams stars above the diagonal lines give better fits for POLYFIT degree 2 and stars below the diagonal lines give better fits for the other programs. In all three cases POLYFIT gives better results for most stars. None of the programs with automatic star detection found all the 77 stars. DAOPHOT found 61 stars and FINDSTARS 70 stars, thus indicating that FINDSTARS is superior for detection of stars on irregular backgrounds. Measurement with FINDSTARS is equivalent to measurement with POLYFIT with degree 0 of the background polynomial. The fitting radii for POLYFIT and FINDSTARS were 18 pixels, which is $\simeq 1.5 \cdot \mathrm{FWHM}$ of the stars. The fraction of stars that have magnitude errors worse or better to POLYFIT (P) for the different programs (X) are shown in Table 5. One star was excluded from the measurement with POLYFIT and PLUCY because the stellar image overlap.

Table 4. The fraction of stars in the open cluster plus galaxy images that have magnitude errors worse $(P < X)$ or better $(P > X)$ to POLYFIT (P) for the different programs (X) are shown.

X	Nr of stars	$P < X$ %	$P > X$ %
DAOPHOT	61	70.5	29.5
PLUCY	76	81.0	19.0
FINDSTARS	70	70.0	30.0

6.2.3. Magnitude offsets and standard deviations

In Figure 14 the magnitude offset and the standard deviation σ for the three measurements for 59 stars in the combined open cluster plus galaxy images are presented for POLYFIT (degree 2) (a), DAOPHOT (b), PLUCY (c) and FINDSTARS (d). The zero-point for the magnitude scale is 100 ADU. This means that magnitude -5 corresponds to an intensity of approximately 10000 ADU. The magnitude offset for a star is the average of the three open cluster plus galaxy measurements subtracted with the average of the POLYFIT measurements of the open cluster images. The error bars represent $\pm\sigma$ for the three open cluster plus galaxy measurements for each star. All the 77 stars were measured with POLYFIT and PLUCY. As mentioned earlier the initial positions of the stars were obtained from earlier data. Not all the 77 stars were found by the automatic programs. 70 stars were found by FINDSTARS and 61 stars by DAOPHOT. Only the results from 59 stars that are common to all four programs are presented in Figure 14. The remaining stars would probably not be found at all in a case with no positions obtained from the open cluster image with flat background.

The magnitude offsets for POLYFIT (degree 2) show the best results, as found also from the logarithmic magnitude error diagrams. Regarding the standard deviations in the three measurements for each star, POLYFIT and FINDSTARS show relatively small σ (small error bars). The σ found by DAOPHOT and PLUCY are somewhat larger.

6.2.4. Some residual images

To give some examples of residual images obtained by POLYFIT, DAOPHOT, FINDSTARS and PLUCY, the four small white frames (A, B, C and D) in Figure 12 d are shown in magnified scale in Figures 15, 16 and 17 and 18. For these figures residual image means the galaxy plus open cluster image minus the measured star and the galaxy image. The frames have a size of 50×50 pixels. Every frame contains one measured star. All the three different open cluster plus galaxy images are shown for each frame. Counted from the left, in Figures 15–18, the first column shows the small open cluster plus galaxy frames (including the measured star). The second column shows the true galaxy background without the open cluster star. The third column represents the residual image obtained by POLYFIT (degree 2). The fourth column represents the residual images obtained by DAOPHOT. The fifth column shows the residual images obtained with FINDSTARS. Finally the sixth column shows the residual images obtained by PLUCY.

From inspection of Figures 15–18 some results seem clear. The measured target stars are relatively faint due to the large FWHM ($\approx$ 11 pixels). The backgrounds for the target stars are difficult (and affected by nearby stars). The residuals obtained by POLYFIT are small, indicating a good fit. DAOPHOT shows somewhat larger residuals than POLYFIT. FINDSTARS shows larger residuals than POLYFIT but smaller than DAOPHOT. The residual images obtained by PLUCY look noisy due to the fact that the program smoothes the background image using a Gaussian filter.

The intensity I (ADU) of each star and the magnitude errors obtained with the four programs are shown in Table 5.

Table 5. The intensity I (ADU) of each star (A–D in Figures 15–18) and the magnitude errors (Δm) obtained with POLYFIT, DAOPHOT, FINDSTARS and PLUCY are shown.

Star	I	POLYF Δm	DAOPH Δm	FINDS Δm	PLUCY Δm
A	15600	0.011	0.313	0.133	0.054
B	20000	-0.038	0.283	0.100	-0.235
C	23700	0.029	-0.261	-0.054	-0.104
D	37100	-0.035	0.143	0.010	-0.032

As seen from the residuals, the magnitude errors obtained with POLYFIT are smaller than those for the other programs in most cases.

7. Discussion

This paper has discussed the program POLYFIT for photometry of well sampled isolated stars on irregular backgrounds. The program can also be used to remove stars from galaxy images, if the galaxy itself is the relevant object. The program uses PSF-fitting and fits a two-dimensional polynomial of degree 0–5 to the background in the image. As a rule of thumb a fitting radius of $1.5 \cdot \mathrm{FWHM}$ of the image of the star and a polynomial degree of 2 or 3 give the best results. An interesting modification of the program would be to make an automatic optimization of the fitting radius and polynomial degree. Tests with simulated and observed well sampled stellar images added to observed galaxy backgrounds show that POLYFIT gives photometric results that are superior to those produced by DAOPHOT, PLUCY and FINDSTARS. Photometric errors smaller than 0.05 magnitudes are obtained for most stars in these images.

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