

SUN/45.16

Starlink Project
Starlink User Note 45.16

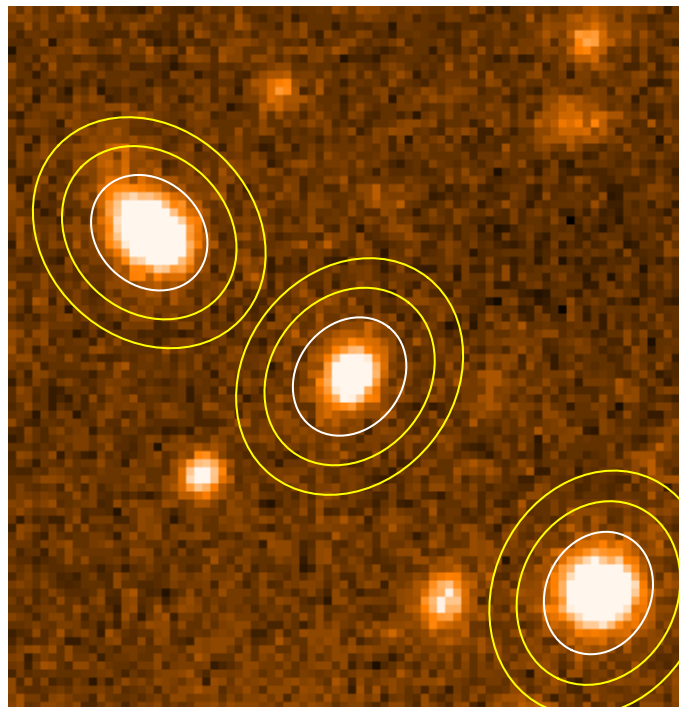
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27th November 2009

PHOTOM — A Photometry Package

Version 1.12-0

User's Manual



Abstract

PHOTOM is a package for measuring the sky corrected magnitudes and fluxes of astronomical objects, within circular and elliptical apertures, using either the aperture or optimal extraction algorithms.

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1 Introduction

PHOTOM is a package for performing photometry of digitized images. It has two basic modes of operation: using an interactive display to specify the positions for the measurements, or obtaining those positions from a file. In both modes of operation PHOTOM allows you to perform photometry using either the traditional aperture method or via optimal extraction. When using the traditional aperture extraction method the target aperture can be circular or elliptical and its size and shape can be varied interactively on the display, or by entering values from the keyboard. Both methods allow the background sky level to be either sampled interactively by the manual positioning of an aperture, or automatically from an annulus surrounding the target object.

PHOTOM is also used by the Graphical Astronomy and Image Analysis tool (GAIA – SUN/214) which integrates the tasks of photometry with an image display tool. This allows the detailed inspection of objects and their environments and provides a highly interactive environment for placing, rotating and resizing apertures.

2 New to aperture photometry?

If you are new to aperture photometry then you should read the section on techniques of aperture photometry in appendix B. You should also read the Starlink Cookbook “CCD Photometric Calibration” (SC/6). If you have any questions beyond what these offer (which are elementary texts) then you should get friendly with a local expert or be prepared to delve into the literature.

3 New to optimal photometry?

If you are going to be using the optimal extraction features of PHOTOM then it is recommended that you should read the MNRAS paper “An optimal extraction algorithm for imaging photometry” (MNRAS, 1998, 296, 339) which discusses this algorithm in depth. However, a brief discussion of the algorithm is given later in appendix C.

4 Running the photom software

To initialize the PHOTOM package so that you can run its programs from the C-shell you use the command:

```
% photomstart
```

(after setting yourself up to run Starlink software - see ‘Setting up your environment’ in SUN/145).

Similarly to set up PHOTOM to run from within ICL use:

```
ICL> photomstart
```

4.1 Getting help

On-line help is available for all the PHOTOM programs using the command:

```
% photomhelp
```

from the C-shell, or by using the command:

```
ICL> help photom
```

when running ICL. Help can also be found by specifying ? or ?? as the reply to any program prompt.

As an alternative to these approaches this document may also be viewed on-line using a hypertext browser. To do this use the command:

```
% showme sun45
```

If you come across any bugs or problems when using PHOTOM then e-mail a description to: starlink@jiscmail.ac.uk.

5 Performing interactive analyses

Interactive measurement is performed in PHOTOM using a program which is also called PHOTOM¹. Alternatively, if it is available on your system, you can use the photometry toolbox which is part of the GAIA (SUN/214) display tool. In the following discussion it is assumed that you are using the PHOTOM program.

The first thing you need to do is display your image. Although PHOTOM can work using a display that does not have an overlay, it is best to have one. This is so that any line graphics which PHOTOM draws can be erased. Without this ability the display becomes quickly confused, particularly when setting the size and orientation of the aperture.

You can create a GWM X-windows display with an overlay using the command:

```
% xmake xwindows -overlay -ovcolour green
```

and can display an image in this window either using the KAPPA (SUN/95) DISPLAY program, or if this isn't available the PHOTGREY program.

You can now start up the main PHOTOM program by typing the command:

```
% photom
```

¹At one time this program was the only application in PHOTOM, hence the now slightly confusing terminology.

this could be from the C-shell or ICL.

The first response from this program is a request for the name of the image you have just displayed. This image remains open until you exit from PHOTOM. If you need to measure objects in another image then you should exit PHOTOM, display the new image and then restart PHOTOM.

The next request should be for a parameter “COMMAND” which indicates that you are now in the main command loop of PHOTOM. Your response to this prompt should be a single character. To see a menu of the possible commands return a ‘h’ (or ‘H’).

The first time one of the interactive graphical options: I – interactive shape (aperture photometry only); or M – interactive measurement is selected the name of the display device is requested. If you are using an image display with overlay capabilities then remember that the overlay device is not the same as the device you displayed your image in, e.g. if you displayed on an X-windows device ‘xw’, then the overlay device is called ‘xov’.

Typically the cursor position is controlled by the mouse and the mouse button meanings are indicated by three menu boxes drawn on the screen. If you use an unusual display device without a mouse then the graphics are controlled by the keyboard. A message from PHOTOM shows which of these options applies to you.

5.1 The PHOTOM menu options

The following section describes each of the menu items that you can use at the COMMAND prompt.

5.1.1 A — annulus

This is a toggle switch which alters the way in which the background level is measured. There are two methods available. The first is interactive, and uses an aperture identical in size and shape to the object aperture. The aperture is positioned manually to select the region of sky to measure. The message ‘Interactive aperture in use’ will signify that this has been chosen.

When using the interactive aperture, several sky areas can be sampled to improve the estimate of the sky. The sky estimates from each aperture are simply summed, and the mean of these is used when the object is measured.

The alternative is to use an aperture which is a concentric annulus around the object aperture. In this mode the sky is measured automatically every time a measurement is made. The message ‘Concentric aperture in use’ signifies this choice. The size of the sky aperture is specified by the INNER and OUTER parameters. These are defined as multiplying factors of the object aperture size, or in optimal extraction mode of the clipping radius, e.g. if INNER were 2 and OUTER 3 then the sky aperture would start at two radii from the centre and end at three radii.

When starting PHOTOM one of these modes will be chosen as the default. This choice is controlled by the CONCEN parameter. If the positions of the objects is entered by a file of positions (command F), then the background is automatically taken with the concentric annulus, whatever the default value of CONCEN.

5.1.2 C — centroid

This is a toggle switch which alters whether the object is centered in the aperture before doing the measurement. Centroiding is controlled by the parameters SEARCH, POSITIVE, MAXSHIFT, MAXITER and TOLER. These cannot be changed from within the program, and if alternative values are required they should be given on the command-line when starting PHOTOM. For instance:

```
% photom positive=f
```

would make PHOTOM centroid on objects whose signal was negative (not a very likely choice).

The choice of mode is indicated by the messages ‘Centroiding in stellar aperture’, or ‘No centroiding’. When starting PHOTOM one of these modes will be chosen as the default. Centroiding cannot be turned off when using optimal extraction.

Unless the field under investigation is very crowded, or there are other special conditions, it is probably best to leave the centroiding option on all the time. This is more important if the measurements are being made in non-interactive mode (command F); unless you’re certain that the positions are accurate for all images.

5.1.3 E — exit

This command exits PHOTOM.

5.1.4 F — file of positions

This command causes the measurements to be done automatically. A file containing the positions is requested, and the photometry is performed with the current parameters.

The name of the file containing the positions is requested through the POSFILE parameter. If the file cannot be found or is not in a suitable format then no action is taken.

The file of positions is an ordinary text file and should specify an index number and the x and y positions in pixel coordinates. For every x and y pair in the file an measurement is made, sampling the sky with the concentric annulus, whose size is specified by the current values of the INNER and OUTER parameters. Centroiding in the object aperture is, or is not done, depending on the current value of the CENTRO parameter, which is selected with command C. When the input file is exhausted PHOTOM returns to the command level.

If optimal extraction is enabled the first entry in the the POSFILE should have index 0 and x and y co-ordinates corresponding to the chosen PSF star.

Results of the measurements are shown on the terminal as well as output to the file named by the RESFILE parameter. Results are identified by the index number associated with the x and y position in the input file.

A previous results file can be used as the input file of positions, but it should not have the same name as the results file otherwise the program will fail when it tries to open a new results file.

The format of the input and the results files are given with the full PHOTOM description in appendix A.

5.1.5 H — help

This displays a brief line of help for each command. For more extensive information refer to this manual or the on-line help.

5.1.6 I — interactive shape

This allows the size and shape of the aperture to be adjusted interactively on the screen to best suit the objects. When using optimal extraction this command is disabled, the clipping radius can be changed using the O menu option.

The size and shape of the aperture is governed by the three ellipse parameters, the semi-major axis (in pixels), eccentricity and position angle. The semi-major axis and eccentricity are as usually defined for an ellipse. An eccentricity of 0 gives a circular aperture with a radius equal to the semi-major axis. The orientation of the ellipse is given in degrees and specifies the orientation of the semi-major axis of the ellipse anti-clockwise with respect to the vertical axis of the screen.

When this option is chosen five boxes appear on the graphics display. The upper two show the parameter that will be changed and its current value. The lower three boxes show the functions that are performed by the mouse buttons (or keys if your device doesn't support a mouse). Mouse button 1 (or key 1) changes the parameter to one of SEMI-MAJOR, ECCENTRICITY or ORIENTATION. Mouse button 2 (or key 2) changes the value of the parameter and finally mouse button 3 (or key 0) completes defining the aperture shape and returns you to the COMMAND prompt.

The parameters only have a limited number of preset values which can be cycled through by repeated presses of the middle mouse button (key 2). If the range or interval of the values associated with a parameter aren't suitable then you can override these by setting a specific value using the N menu option.

When a parameter value is changed, the aperture displayed at the cursor position is updated to reflect this. The aperture is also redisplayed whenever the first mouse button is pressed (or key 1). As this only changes the current parameter rather than any of the actual values, you can use this function to reposition the aperture to inspect its suitability on more than one object (but remember to return to the aperture parameter that you want to change before attempting to alter a value).

The initial values of the three parameters are just the current ones. The semi-major axis can be changed from a maximum of double to a minimum of a half of the current value (with steps of a tenth or fifth of this interval). The possible values of the eccentricity and orientation are limited, to a number of preset values. The value initially displayed is taken to be the member of the preset table which is closest to, but lower than, the current value of that parameter.

5.1.7 M — measure

This performs interactive measurements of objects individually selected from the displayed frame. If using aperture extraction the size and shape of the cursor should be set-up in advance using the I or N commands, while the clipping radius should be set (using the 0 command) when using optimal extraction.

There are two basic methods for measurement of background. Either the background is sampled from an annulus around the object aperture, or from a separately chosen area of sky (see command A). The two cases can be distinguished at this stage from the on-screen display.

In the case of the manual sky measurement the middle box is labelled with SKY, while for automatic sky measurement it will remain empty. The left-hand box will either be labelled STAR, in the case of aperture extraction, or PSF when optimal extraction is selected. The remaining right-hand box will be annotated RETURN TO KEYBOARD.

To perform the measurements with the automatic sampling of the sky, the cursor is positioned over the chosen object and the left-hand mouse button (or key 1) is pressed. If optimal extraction is selected the first measurement will define the point spread function (PSF) for the technique. It is important to pick a bright star which is unsaturated for this task. After this measurement has been taken, if you are using a terminal capable of erasable line graphics such as an `xoverlay`, then the left-hand box label will change to read STAR to denote that further measurements will be photometric.

For further measurements using optimal extraction, or all measurements using the older aperture method an aperture is displayed where the measurement was made. For optimal extraction this “aperture” will be the size of the clipping radius (the CLIP parameter). If centroiding is being done (command C), automatic enabled for optimal extraction, then the displayed aperture may not be centered on the cursor position. The results of the measurement are printed on the terminal and recorded in the results file. Measurements can be continued until the third mouse button (key 0) is pressed.

When using manual selection of the background the middle mouse button (key 2) is also used. Selecting this button records the sky estimate in an aperture identical in size and shape to the object aperture, at the position specified by the cursor. On the screen an aperture is displayed at that position. No centroiding is done in this aperture, even if the centroiding option is on. When the measurement of the object is made, the most recent value of the sky is used. This means that the sky has to be sampled BEFORE the measurement of the object. Having a correct background estimate is crucial for optimal extraction to such an extent that PHOTOM will not allow you to make a star or PSF measurement using this method until a background measurement has been provided. If the background needs to be sampled in several places around an object, to minimise the noise or take account of a sloping background, then a sky aperture can be selected a number of times and the mean of these values is used. The calculation of the mean is only cleared when an object is measured, so if a mistake has been made in estimating the mean of the skies then an object measurement has to be made, and a note made that the measurement was in error, before going back to the estimation of the sky. Control stays with the interactive menu until the third mouse button (key 0) is pressed.

The results of the measurements are displayed on the terminal and sent to the file accessed by the RESFILE parameter.

5.1.8 N — non-interactive shape

The size and shape of the aperture can be specified from the keyboard by entering values for the semi-major axis (in pixels), the eccentricity and the orientation of the ellipse defining the aperture. When using optimal extraction this command is disabled, the clipping radius can be changed using the V menu option.

An eccentricity of 0 gives a circular aperture with a radius equal to the semi-major axis. The orientation of the ellipse is given in degrees and specifies the rotation of the semi-major axis of the ellipse anti-clockwise with respect to the vertical axis of the pixel array.

5.1.9 O — options

This allows changes of the values of some of the non-aperture shape related parameters.

The INNER and OUTER parameters define the size of the annulus to be used in the automatic sampling of the sky. The annulus has the same elliptical shape as the object aperture, but is larger by the factors given by INNER and OUTER. These two parameters are given in terms of multiplicative factors of the semi-major axis of the object aperture. Thus an INNER radius of 1 means that the sky annulus starts where the object aperture ends. The annulus thus grows and shrinks with changes to the object aperture.

The PADU parameter defines the number of photons for each interval of the data. Multiplying the data value in each pixel by PADU gives the number of photons recorded (after correcting for BIASLE). If this parameter is unknown then leave it at 1. It is **necessary to provide an estimate of this number** if optimal extraction is to be carried out correctly.

The SKYMAG parameter specifies the magnitude to be given to the sky when calculating the magnitude of the object. The magnitude of the object is calculated from $mag = SKYMAG - 2.5 \log_{10}(signal)$ where signal is the brightness of the object minus sky in photons. This parameter is not used if USEMAGS is set to FALSE (in this case the output is not in magnitudes).

The BIASLE parameter gives the level in data units of any offset in the bias level per pixel. This is needed if there is any non-photon source of background, and proper photon statistics are required. If this parameter is unknown then leave it at 0.

The SATURE parameter is the saturation level for the image in data units. If there are any pixels in the object aperture with values greater than the saturation level then this is indicated by an error code 'S' in the final column of the output table. The object magnitude is calculated with the saturated pixel **included** in the result. So changing the value of this parameter will not change the results but will alter the number of objects flagged in the output file.

The CLIP parameter is clipping radius of the weight mask used in optimal extraction. This is needed if optimal extraction is enabled and defaults to 5 pixels. If optimal extraction is not enabled (using the X command) then the CLIP parameter will not appear in the list when the options command is issued.

The SEE parameter is a rough estimate of the seeing in the CCD image in pixels. This is used by the optimal extraction algorithm for an initial estimate of the FWHM of the point spread function (PSF) during fitting. This parameter defaults to 2 pixels, and again if optimal extraction is not enabled then this parameter will not appear in the list when the options command is issued.

5.1.10 P — photon statistics

This is used to choose between the different ways in which the errors are calculated. There are three possible choices selected by the integers 1 to 4 which have the following meanings :

- (1) Errors from photon statistics.
- (2) Errors from variations in the sky aperture.
- (3) Errors from data variance.
- (4) Gaussian errors from variations in the sky aperture.

The first works out the errors from photon statistics in the sky and signal apertures. This requires you to know and set-up the parameters PADU and BIASLE which convert the data values to numbers of photons. The message ‘Errors from photon statistics’ will signify that this has been chosen.

The second method of calculating the errors is from the measured variance in the sky aperture. This method assumes that the measured variance is due to photon statistics and scales the measurement in the object aperture accordingly. This method still requires the parameter PADU to be known, but does not need the BIASLE parameter to be known. The message ‘Errors from sky variance’ will signify that this has been chosen. If neither the PADU or BIASLE parameters are known, then it is best to use this method to indicate the reliability of the measurements, but not to take the quoted error values as absolute since this method will be wrong by a factor \sqrt{PADU} , where *PADU* is the unknown conversion factor.

The third method of calculating the errors is from the data errors that are stored with the image (one per pixel). This method of calculating the errors also requires the parameter PADU to be known. The message ‘Errors from data variance’ will signify that this has been chosen. A variance component may not always be present in data file along with the data array (indeed this can only be true if you are storing your images in NDFs, see section §8), and if this is the case then PHOTOM will issue the warning ‘Data does not have a variance component’ if this method is selected.

The fourth method of calculating the errors is like the second and uses the measured variance in the sky aperture. This method assumes that the measured variance is due to some gaussian source and doesn’t require any knowledge of the PADU and BIASLE values (which are unknown when dealing with data that has been combined using a mean, say from a CCD Mosaic dithered on the sky), but clearly this can only measure an upper limit as the actual noise in the object will be (fractionally) less than in the sky. The best way to avoid such uncertainty is by propagating data variances through all the stages that produced the combined data and using method three. Appendix D gives a full discussion of the calculation of the errors assuming photon statistics.

5.1.11 S — sky

This is used to choose between the different methods of estimating the background level in the sky aperture. There are four possible choices selected by the integers 1 to 4 which have the following meanings :

- (1) Simple mean.
- (2) Mean with 2 sigma rejection.
- (3) Mode.
- (4) A constant.

The simple mean uses all the values in the sky aperture. The mean with 2 sigma rejection excludes all those points which are more than 2 standard deviations from the mean. Because one or more wayward outliers can affect the size of the standard deviation, the mean and standard deviation are recalculated after each stage of clipping up to a maximum of three times. The mode is superficially calculated from the empirical relation $mode = 3 * median - 2 * mean$, but because

this can be fooled by excessive skewness in the histogram there are rejection and averaging schemes in the algorithm to ensure stability. The final option is to supply a constant for the sky which is used for all subsequent measurements. This value is used until either a new value is chosen or one of the other methods of estimation is selected. The sky variance is also requested so that if the errors are calculated from the sky variance (command P) then a realistic error can be assigned. Both the sky value and variance should be given in data units.

When using a concentric background aperture it is recommended that the mode or mean with 2σ rejection is used as these offer protection against contamination from other objects in the sky aperture.

For optimal extraction it is currently recommended that you use the modal sky estimate.

5.1.12 V — values

This summarizes the current settings of the significant parameters on the terminal.

5.1.13 X – eXtraction

This is a toggle switch which alters the way in which the photometry is carried out. There are two methods available, aperture extraction is the default.

5.2 Defaulted parameters

A number of parameters can only be defined when the PHOTOM program starts. They all have reasonable defaults, but if required can be changed before running the program. The way to set a new value for one of these is to use the keyword (the name by which the parameter is always referred to) on the command line, as in :

```
% photom usemags=f resfile=flux.dat
```

This outputs the values in photon counts (i.e. as modified by the BIASLE and PADU parameters) and writes the results of the analysis to the file `flux.dat`.

5.2.1 resfile

This specifies the name of the results file which makes a permanent record of the measurements.

5.2.2 maxshift, maxiter, search and toler

There are a number of parameters that control the centroiding algorithm. SEARCH defines the size of the search box to be used in locating the centroid in pixels. MAXITER defines the maximum number of iteration steps. MAXSHIFT gives the maximum allowable shift in pixels between the initial, rough, position and the calculated centroid. TOLER defines the position accuracy in pixels that will terminate the centroiding iterations.

5.2.3 exsource and etime

These two parameters control how a value for the image exposure time is determined. The exposure time is used to scale the results as in:

$$mag = SKYMAG - 2.5 \log_{10}(signal / exposure\ time)$$

This affects the output values for the measured signal in the object and the resultant magnitude or flux, but it does not change the reported value for the sky in each pixel, or the error in the measurement.

There are three methods for getting an exposure time:

- (1) supply a floating point value
- (2) supply the name of a FITS keyword (which must decode into a floating point value)
- (3) supply the name of an HDS object that exists somewhere in your data file that can be decoded as a floating point value (this presumes that you're storing your images in NDFs).

So for instance if you've got an image with a FITS-type header and the exposure time of the image is recorded in the record with name EXPOSURE, then you'd use a command like:

```
% photom exsource=header etime=exposure
```

A simple floating point value (600) is indicated by:

```
% photom exsource=constant etime=600
```

An HDS object `ext_time` in the CCDPACK extension of an NDF is indicated by:

```
% photom exsource=hds etime=more.ccdpack.ext_time
```

The structure of an NDF can be viewed using the HDSTRACE (SUN/102) utility. The default exposure time is 1.0.

5.2.4 usemask

This parameter is a logical flag which indicates whether a mask is to be used when estimating the background. The purpose of the mask is to block out contaminating objects from the background aperture. In this way bright stars can be excluded from the estimation of the sky, which would otherwise introduce contamination. Note that the sky estimators that perform clipping of the pixel histogram, the mode and the mean with 2σ rejection, also exclude contaminating pixels, but using the mask along with the mean estimator allows this to be done in a controlled way.

If the USEMASK flag is TRUE then a file containing a list of positions is requested (MASKFILE). The format of the file is the same as for inputting a list of positions to measure (command F), namely an index number followed by an x and y position. The given coordinates define the centres of circles and any pixel with its centre within a circle will be excluded from the sky estimation. The radius of the masking circle is defined by another parameter (MASKRAD).

The mask only affects pixels in the background aperture, it does not exclude any pixels from the measurement aperture. This means that identical lists can be used to create the mask and to provide a source for measurement. The output from an automatic object finding package could be used in this way.

It is important not to confuse this mask with the point spread function masks discussed as part of the optimal extraction algorithm.

Other ways of masking out pixels are to use the KAPPA (SUN/95) facilities ARDGEN and ARDMASK, or the ARD and PATCH toolboxes of the GAIA (SUN/214) image display tool.

6 Automated photometry

PHOTOM provides two methods to perform the photometry of objects in a non-interactive fashion. There are typically two reasons why you would want to do this:

- (1) There are far too many objects on your images, so a statistical approach with some measurements in error is a necessity.
- (2) You just want to use PHOTOM as an engine for other interactive or script based tools.

The second case is covered by the program AUTOPHOTOM, which is used by the photometry mode in the GAIA (SUN/214) image display tool. The first case by the PHOTOM program in a special mode.

You can use PHOTOM in 'batch' mode either interactively or by controlling it from an ICL command procedure or from a C-shell script. If you use a script of some kind then you'll also need another file that contains the commands you would have used interactively. It may be necessary to run the program by hand first to verify the order of the prompts. An example input file (photom.in say) could contain the following commands:

```
FRAME
N
5.0
0.0
0.0
F
POSITIONS.DAT
E
```

In this example the image data is assumed to be in a file FRAME in the default directory. The size and shape of the aperture is set using the non-interactive command, N and the command F instructs the program to take the initial positions from the file POSITIONS.DAT. The E command ends the program.

The program could then be run in the background with the command

```
% photom < photom.in > photom.out &
```

Using AUTOPHOTOM requires that a file with a specified format is created, the details of which are described in in appendix A. Basically this describes each aperture and also allows information about the sky region associated with it to be given. The sky region can be defined in a single annulus (each aperture can have a different inner and outer scale) or can be defined as a series of other apertures. The easiest way to create such a description of the apertures on an image is to use the GAIA display tool. This description can then be run on other frames non-interactively (say for different colours, or repeat measurements).

7 Altering program parameters

When a PHOTOM application is started, the initial selection of most of the parameters is taken from the previous run of the routine. The parameter values are stored in the `GLOBAL.sdf` or `application_name.sdf` files in the `~/adam` directory at the end of a run. The current values can be examined using the HDSTRACE facility (SUN/102). To clear these values, and to revert to the start-up defaults the `GLOBAL.sdf` and `application_name.sdf` files have to be deleted.

The starting values of the parameters can also be specified within the ADAM command language. The keyword facility allows the parameters to be given on the command line (see SG/4, the ADAM User's Manual). The keywords have the same name as the parameters; for example the search box for the centroiding can be changed using the command.

```
ICL> photom search=5
```

From the C-shell the keywords can be included on the command line.

```
% photom search=5
```

8 Using different image formats

Little has been said so far about the image data format that PHOTOM programs will work with. The native format that these use is the Starlink NDF (see SUN/33). Files that contain an NDF are identified by the extension `.sdf` and are accessed by PHOTOM programs when you just give the filename without an extension. So for instance if you have a file `image.sdf` that contains an NDF then you just supply the response `image` when prompted for an input image.

In addition to the NDF PHOTOM programs can also be made to use images in other formats, such as disk FITS, old-style FIGARO and IRAF, using the 'on-the-fly' conversion abilities of the NDF library. To make this work for you, you need to setup the CONVERT (SUN/55) package and then pass images to PHOTOM programs together with their file extensions. So if you wanted to work on the IRAF image `pix.imh` you'd use a command sequence like:

```
% convert
% kappa
% xmake xwindows -overlay -ovcolour green
% display in=pix.imh device=xw
% photom in=pix.imh device=xov
... enter interactive command loop ...
```


In this case the file extension “tells” PHOTOM and the KAPPA program DISPLAY that they have an IRAF image. You should look at the CONVERT document (SUN/55) to see the list of formats that can be processed.

9 Acknowledgements

Thanks go to Nial Tanvir for his helpful comments on the sky background estimation section in Appendix C, and a number of people for suggestions for improvements to PHOTOM over the years. The optimal extraction algorithm used in PHOTOM originated with Tim Naylor, and thanks should go to him for his help during its incorporation into the code.

10 Acknowledging this software

Please acknowledge the use of this software in any publications arising from research in which it has played a significant role. Please also acknowledge the use of any other Starlink resources (hardware or software) in such publications. The following is suggested as a suitable form of words:

The authors acknowledge the data analysis facilities provided by the Starlink Project which is run by CCLRC on behalf of PPARC. In addition, the following Starlink packages have been used: PHOTOM, ...

A Full routine descriptions

AUTOPHOTOM

Do aperture photometry on a list of objects

Description:

This program performs photometry of a list of objects. It is designed to be used non-interactively (i.e. by the GAIA - SUN/214- photometry tool or script). It provides more flexibility than the automated mode of the PHOTOM program by allowing the specification of sky regions other than in annular regions. The results of the measurements are recorded in another file which has the same format as the input file (and can therefore be passed back to this routine and the same measurements can be repeated on a new frame). The format of this file is different for aperture and optimal extraction and is described in the relevant sections.

Usage:

```
AUTOPHOTOM IN INFILE OUTFILE
```

Parameters:**BIASLE = _REAL (Read)**

The level in data units per pixel of any constant offset in the image. This should be defined if the errors are to be calculated from photon statistics. If the true value is unknown then return 0.

CENTRO = _LOGICAL (Read)

Centre the object before measurement or accept the given position as the centre of the aperture. This parameter is forced to be true for optimal extraction.

If this is TRUE the aperture is centered around the object of interest before the measurement is taken. The position supplied to the program is taken as a starting point and the position of maximum flux is located within a search box of fixed size.

If this is FALSE the position supplied to the program is used as the centre of the aperture.

CLIP = _REAL (Read)

The clipping radius used for the weight mask if optimal photometry is selected. Not to be confused with the mask used to exclude regions from the background estimate (USEMASK parameter)

EXSOURCE = LITERAL (Read)

The "source" of the image exposure time supplied via the ETIME parameter. This can take one of the values, HDS, CONSTANT or HEADER, with the following meanings:

HDS: indicates that the exposure value is stored in an HDS object somewhere in the image (this presumes that the image is an NDF and corresponds to the original behaviour of PHOTOM, prior to the introduction of this parameter).

CONSTANT: indicates that a simple floating point value will be supplied for the image exposure time.

HEADER: indicates that the value to be used is stored in the image header (i.e. FITS headers).

[HDS]

ETIME = LITERAL (Read)

A string that, according to the value returned for parameter EXSOURCE, allows the exposure time of the image to be determined. If EXSOURCE is defined as:

HDS: then a fully qualified HDS path to the required object within the NDF should be given. For instance if the exposure time is stored in the CCDPACK extension of an NDF, under the item ETIME then a suitable return would be:

```
more.ccdpack.etime
```

The HDS structure of an NDF can be viewed using the HDSTRACE utility (see SUN/102).

CONSTANT: then a floating point value should be given.

HEADER: then the name of the associated item should be given (e.g. the FITS item EXPOSURE).

[!]

FIXANN = _LOGICAL (Read)

If TRUE then any annular regions in the input description file are interpreted as radii (in pixels) along the aperture major axis, otherwise they are interpreted as scale factors of the major axis. [FALSE]

INFILE = LITERAL (Read)

Name of the file containing the descriptions of the objects to measure and the positions and nature of any sky regions associated with them. See the notes section for the format of this file.

IN = IMAGE (Read)

Name of the image on which aperture photometry will be performed.

USEMAGS = _LOGICAL (Read)

If TRUE then the output values are converted into magnitudes. If FALSE the output values MAG and MAGERR are modified to be a mean photon count and the error in this count, the other values remain the same, i.e. the sum of sky corrected photons and the mean sky value. Note the SKYMAG value is not used when this is FALSE. [TRUE]

MASK = LITERAL (Read)

An ARD description of any regions to be excluded from the image before any calculations of sky and object are performed. The ARD language is described in SUN/183. A filename can be given using the indirection character “^”

MAXITER = _INTEGER (Read)

The maximum number of iteration steps to be used in locating the object centroid.

MAXSHIFT = _REAL (Read)

The maximum allowable shift in pixels between the initial object position and the calculated centroid.

OPTIMA = _LOGICAL (Read)

If this is TRUE then optimal rather than aperture extraction is used for photometric measurement. The default, for backward compatibility reasons, is FALSE.

OUTFILE = FILENAME (Read)

Name of the file to contain the updated descriptions of the measured objects. See the notes section for the format of this file.

PADU = _REAL (Read)

The number of photons for each interval of the data. If the true value is unknown use a value of 1, in which case the quoted measurement errors will be wrong by the unknown factor $\text{SQRT}(\text{PADU})$.

PHOTON = _INTEGER (Read)

Select the method for calculating the measurement errors. There are three possible choices selected by the integers 1 to 4 which have the following bindings:

- (1) The errors are estimated from the photon statistics in the sky and object apertures. The parameters PADU and BIASLE should be set to their appropriate values to convert the data units to photon numbers.
- (2) The errors are estimated from the measured variance in the sky aperture. This method assumes that the measured variance is due to photon statistics and estimates the error in the object aperture accordingly. The PADU parameter should be set to its appropriate value to convert the data units to photon numbers.
- (3) The errors are estimated from the variance component of the data array.
- (4) The errors are estimated from the measured variance in the sky aperture. This method assumes that the errors are Gaussian (same value per object and sky pixel), and thus requires no knowledge of the values of PADU and BIASLE, but can only be considered an upper limit on the error in a measurement.

POSITIVE = _LOGICAL (Read)

Find the object centroid for image features which are positive or negative with respect to the background. This should be set to TRUE.

SATURE = _REAL (Read)

The saturation level in data units for the image. If any pixels in the object aperture have values greater than this then the measurement is flagged with an 'S' in the output record.

SEARCH = _INTEGER (Read)

The size of the search box in pixels to be used in locating the object centroid.

SEE = _REAL (Read)

Approximate seeing in pixels, used to estimate the FWHM of the point spread function (PSF) by the optimal extraction algorithm.

SKY = _REAL (Read)

A constant value to be used as the sky estimate for subsequent measurements. This defines the sky level in data units per pixel. This value is used until another estimator is chosen.

SKYEST = _INTEGER (Read)

Select the estimator to be used to evaluate the background level in the sky aperture. There are four possible choices selected by the integers 1 to 4 which have the following bindings:

- (1) Mean. All pixels in the sky aperture are averaged.
- (2) Mean with 2 sigma rejection. All pixels with data values within 2 standard deviations of the mean are averaged.
- (3) Mode. The peak of the histogram of pixel values (the most likely value) in the sky aperture is estimated.

- (4) A constant. A single value to be used for all measurements. A sky variance (standard deviation) is also requested so that a realistic error can be assigned to the measurements if the error is calculated from the variance in the sky aperture.

SKYMAG = _REAL (Read)

The magnitude assigned to the sky level when calculating the magnitude of the object using the relation $OBJMAG = SKYMAG - 2.5 * LOG_{10}(SIGNAL)$ where SIGNAL is the brightness of the object minus sky in photons.

Not used if USEMAGS is FALSE.

SKYSIG = _REAL (Read)

A constant value for the sky variance. This is an estimate of the standard deviation in the sky level in data units and is used when SKYEST is 4.

TOLER = _REAL (Read)

The required positional accuracy in pixels to terminate the centroiding iterations.

USEMASK = _LOGICAL (Read)

Define a mask to exclude regions from the background estimate. If this is TRUE an ARD description is requested. Contaminating objects, such as bright stars, can thus be removed from the background estimate.

Notes:

- *Aperture Extraction* – The input/output file must contain one line per-object that has the following information:

```
INDEX XPOS YPOS MAG MAGERR SKY SIGNAL CODE MAJOR ECCEN ANGLE POSITIONS SHAPE
```

Where the fields have the following meaning:

INDEX = unique integer identifying this object.
 XPOS = X coordinate of object.
 YPOS = Y coordinate of object.
 MAG = current magnitude/mean count of object.
 MAGERR = current error in magnitude/mean of object.
 SKY = current estimate of sky value for object.
 SIGNAL = current estimate of the total count in object.
 CODE = current object status.
 MAJOR = length of semimajor axis of aperture.
 ECCEN = eccentricity of object aperture.
 ANGLE = position angle of object aperture.
 POSITIONS = how the sky regions are determined.
 SHAPE = shape of the aperture.

Values that are unknown initially (MAG, MAGERR, SKY, and SIGNAL) should be set to 0.0, the derived values will be used to replace these fields on exit. The CODE field should

be set to "OK" initially. The POSITIONS field should have one the values "annulus" or "regions", to indicate how the sky regions are determined (this is ignored if SKYEST is 4). The SHAPE field should be set to "circle" or "ellipse" to indicate the aperture shape.

Other lines in the file may be comments or definitions of the sky regions. Comment lines start with the "#" character, sky regions either with "#ANN" or "#SKY" (the # is used so that other programs can skip over this information). If the POSITIONS field of an object is set to "annulus", then at least one "#ANN" line must be present for this object, this defines the scales or sizes for the inner and outer loci of the sky region.

```
#ANN INDEX INNER_SCALE|SEMI_MAJOR OUTER_SCALE|SEMI_MAJOR
```

The INDEX value is the identifier of the related object. If POSITIONS is set to "regions" then as many lines starting with "#SKY" should be present as there are regions (circular or elliptical apertures) in which to estimate the sky value for this object.

```
#SKYn INDEX XPOS YPOS SHAPE MAJOR ECCEN ANGLE
```

The "n" added to the "#SKY" identifier indicates the number of the sky region being defined and is optional. The other fields are the same as for an object aperture.

- *Optimal Extraction* – Then the first star in the file must be the PSF. In this case the following information must be provided:

```
INDEX XPOS YPOS FWHM1 FWHM2 ROT CODE CLIP SEE POSITIONS
```

Where the fields have the following meaning:

```
INDEX      = For PSF star this MUST be 0.
XPOS       = X coordinate of object.
YPOS       = Y coordinate of object.
FWHM1     = FWHM of the PSF in the X-direction.
FWHM2     = FWHM of the PSF in the Y-direction.
ROT        = Rotation of the FWHM from strict X-Y orientation.
CODE       = current object status.
CLIP       = clipping radius
SEE        = estimate of the seeing in pixels
POSITIONS  = how the sky regions are determined.
```

Values that are unknown initially (eg FWHM1, FWHM2, ROT) should be set to 0.0, the derived values will be used to replace these fields on exit. The CODE field should be set to "OK" initially. The POSITIONS field should have one the values "annulus" or "regions", to indicate how the sky regions are determined (this is ignored if SKYEST is 4). Aperture must be circular for optimal extraction so no SHAPE field is provided.

Further stars should be entered with the following information:

```
INDEX XPOS YPOS MAG MAGERR SKY SIGNAL CODE POSITIONS
```

Where the fields have the following meaning:

INDEX	=	unique integer identifying this object.
XPOS	=	X coordinate of object.
YPOS	=	Y coordinate of object.
MAG	=	current magnitude/mean count of object.
MAGERR	=	current error in magnitude/mean of object.
SKY	=	current estimate of sky value for object.
SIGNAL	=	current estimate of the total count in object.
CODE	=	current object status.
POSITIONS	=	how the sky regions are determined.

Values that are unknown initially (MAG, MAGERR, SKY, and SIGNAL) should be set to 0.0, the derived values will be used to replace these fields on exit. The CODE field should be set to "OK" initially. The POSITIONS field should have one the values "annulus" or "regions", to indicate how the sky regions are determined (this is ignored if SKYEST is 4).

Note that the same clipping radius will be used for all stars (this is an entirely proper and necessary restriction under the algorithm).

Other lines in the file may be comments or definitions of the sky regions. Comment lines start with the "#" character, sky regions either with "#ANN" or "#SKY" (the "#" is used so that other programs can skip over this information). If the POSITIONS field of an object is set to "annulus", then at least one "#ANN" line must be present for this object, this defines the scales or sizes for the inner and outer loci of the sky region.

```
#ANN INDEX INNER_SCALE|SEMI_MAJOR OUTER_SCALE|SEMI_MAJOR
```

The INDEX value is the identifier of the related object. A good estimate of the inner radius of the sky box is about twice the FWHM of the PSF star

If POSITIONS is set to "regions" then as many lines starting with "#SKY" should be present as there are regions (circular or elliptical apertures) in which to estimate the sky value for this object.

```
#SKYn INDEX XPOS YPOS SHAPE MAJOR ECCEN ANGLE
```

The "n" added to the "#SKY" identifier indicates the number of the sky region being defined and is optional. The other fields are the same as for an object aperture.

It is VERY heavily recommended that annuli are used for sky measurement when using the optimal extraction algorithm unless there are obvious reasons for not doing so.

Pitfalls :

- The format of the object file must be correct.

PHOTGREY

Displays a grey scale image

Description:

Plots an image as a greyscale on a suitable device.

Usage:

PHOTGREY

Parameters:

IMAGE = IMAGE (Read)

Name of the image.

XSTART = _REAL (Read)

The first X pixel of the image to be displayed.

XEND = _REAL (Read)

The last X pixel of the image to be displayed.

YSTART = _REAL (Read)

The first Y pixel of the image to be displayed.

YEND = _REAL (Read)

The last Y pixel of the image to be displayed.

LOW = _REAL (Read)

The data value corresponding to black on the display.

HIGH = _REAL (Read)

The data value corresponding to white on the display

DEVICE = DEVICE (Read)

The image display device.

PHOTOM

Perform aperture photometry

Description:

PHOTOM performs photometry. It has two basic modes of operation; using an interactive display to specify the positions for the measurements, or obtaining those positions from a file. In both modes the user may perform photometry using either the traditional aperture method or using optimal extraction.

During aperture photometry the aperture can either be circular or elliptical and the size and shape can be varied interactively on the display, or by entering values from the keyboard or parameter system. During optimal extraction the mask clipping radius can also be varied from the keyboard or via the parameter system. The background sky level can be sampled interactively by manual positioning of the aperture, or automatically from an annulus surrounding the object.

PHOTOM is a menu driven application. The menu has been designed around single character entries, which hopefully have easily remembered mnemonics. Many of the options have counterparts in the parameter system, and so can be controlled outside the task by the environment.

Parameters:**ANGLE = _REAL (Read)**

The orientation of the ellipse defining the aperture. This is defined in degrees going anti-clockwise from the positive y-axis. This is equivalent to a position angle.

BIASLE = _REAL (Read)

The level in data units per pixel of any constant offset in the image. This should be defined if the errors are to be calculated from photon statistics. If the true value is unknown use a value of 0.

CENTRO = _LOGICAL (Read)

Centre the object before measurement or accept the given position as the centre of the aperture. This is forced to be true for optimal extraction.

If this is TRUE the aperture is centered around the object of interest before the measurement is taken. The position supplied to the program (interactively or from a file of positions) is taken as a starting point and the position of maximum flux is located within a search box of fixed size.

If this is FALSE the position supplied to the program is used as the centre of the aperture.

CLIP = _REAL (Read)

The clipping radius used for the weight mask if optimal photometry is selected. Not to be confused with the mask used to exclude regions from the background estimate (USEMASK parameter)

COMMAND = _CHAR (Read)

The next action. The options are defined by single letter entries and should be one of the following:

- A**(nnulus) — This toggles between using an annular background aperture and an interactive aperture.
- C**(entroid) — This switches the centroiding of the object in the aperture on and off.
- E**(xit) — This command terminates the current PHOTOM session.
- F**(ile of positions) — This command takes positions from a file and performs photometry with the current aperture parameters.
- H**(elp) — This displays a brief line of help for each command.
- I**(nteractive shape) — This allows the size and shape of the aperture to be adjusted interactively on the screen.
- M**(easure) — This performs interactive measurements of objects individually selected from the screen.
- N**(on-interactive shape) — The size and shape of the aperture (in pixels) is entered from the keyboard.
- O**(ptions) — This allows some of the defaulted parameters to be changed from within the program.
- P**(hoton statistics) — This selects the method for calculating the errors: either from photon statistics, or from the measured variance in the sky aperture or from the variance component of the data array.
- S**(ky) — This selects between the different methods of estimating the background level in the sky aperture.
- V**(alues) — This summarizes the current settings of the programs parameters.
- (e)X**(traction) — Toggle between doing optimal and aperture photometry.

CONCEN = _LOGICAL (Read)

Find the sky automatically from a concentric aperture or select the sky regions interactively.

If this is TRUE the sky level is estimated from an aperture which is concentric about the object aperture. The shape and orientation of the sky aperture is the same as the object aperture and the size of the annular aperture is defined by the INNER and OUTER parameters. This mode is used if the measurement positions are being supplied from a file. This is the recommended mode for carrying out optimal extraction.

If this is FALSE the sky level is estimated from an aperture equal in size and shape to the object aperture, which is positioned manually on the image display. In this mode several consecutive sky measurements can be made around the object of interest and these are averaged to give the final sky estimate.

DEVICE = DEVICE (Read)

The name of the device to be used for interactive measurements on which the data has been displayed. If the device has an overlay plane then this should be selected.

ECCEN = _REAL (Read)

The eccentricity of the ellipse defining the aperture. For a circular aperture this should be set to 0.0.

EXSOURCE = LITERAL (Read)

The “source” of the image exposure time supplied via the ETIME parameter. This can take one of the values, HDS, CONSTANT or HEADER, with the following meanings:

HDS: indicates that the exposure value is stored in an HDS object somewhere in the image (this presumes that the image is an NDF and corresponds to the original behaviour of PHOTOM, prior to the introduction of this parameter).

CONSTANT: indicates that a simple floating point value will be supplied for the image exposure time.

HEADER: indicates that the value to be used is stored in the image header (i.e. FITS headers).

[HDS]

ETIME = LITERAL (Read)

A string that, according to the value returned for parameter EXSOURCE, allows the exposure time of the image to be determined. If EXSOURCE is defined as:

HDS: then a fully qualified HDS path to the required object within the NDF should be given. For instance if the exposure time is stored in the CCDPACK extension of an NDF, under the item ETIME then a suitable return would be:

```
more.ccdpack.etime
```

The HDS structure of an NDF can be viewed using the HDSTRACE utility (see SUN/102).

CONSTANT: then a floating point value should be given.

HEADER: then the name of the associated item should be given (e.g. the FITS item EXPOSURE).

[!]

IN = IMAGE (Read)

Name of the image on which the photometry will be performed.

INNER = _REAL (Read)

The radius of the inner edge of the annular sky aperture in units of the object aperture size. The actual dimension in pixels is obtained by multiplying this factor by the object aperture semi-major axis in pixels.

MASKFILE = FILENAME (Read)

Name of the file containing the positions to be used as centers for masking objects from the sky aperture. The file should contain a minimum of three columns the first of which contains an integer index number and the next two contain an x and y position.

MASKRAD = _REAL (Read)

The radius in pixels of the circles used to mask out objects from the background estimate. A pixel which is inside the sky aperture and inside a masked region is not included in the background estimate.

MAXITER = _INTEGER (Read)

The maximum number of iteration steps to be used in locating the object centroid.

MAXSHIFT = _REAL (Read)

The maximum allowable shift in pixels between the initial object position and the calculated centroid.

OPTIMA = _LOGICAL (Read)

If this is TRUE then optimal rather than aperture extraction is used for photometric measurement. The default, for backward compatibility reasons, is FALSE.

OUTER = _REAL (Read)

The radius of the outer edge of the annular sky aperture in units of the object aperture size. The actual dimension in pixels is obtained by multiplying this factor by the object aperture semi-major axis in pixels.

PADU = _REAL (Read)

The number of photons for each interval of the data. If the true value is unknown use a value of 1, in which case the quoted measurement errors will be wrong by the unknown factor $\text{SQRT}(\text{PADU})$.

PHOTON = _INTEGER (Read)

Select the method for calculating the measurement errors. There are three possible choices selected by the integers 1 to 4 which have the following bindings:

- (1) The errors are estimated from the photon statistics in the sky and object apertures. The parameters PADU and BIASLE should be set to their appropriate values to convert the data units to photon numbers.
- (2) The errors are estimated from the measured variance in the sky aperture. This method assumes that the measured variance is due to photon statistics and estimates the error in the object aperture accordingly. The PADU parameter should be set to its appropriate value to convert the data units to photon numbers.
- (3) The errors are estimated from the variance component of the data array.
- (4) The errors are estimated from the measured variance in the sky aperture. This method assumes that the errors are Gaussian (same value per object and sky pixel), and thus requires no knowledge of the values of PADU and BIASLE, but can only be considered an upper limit on the error in a measurement.

POSFILE = FILENAME (Read)

Name of the file containing a list of positions for measurement. The file should contain a minimum of three columns the first of which contains an integer index number and the next two contain an x and y position.

POSITIVE = _LOGICAL (Read)

Find the object centroid for image features which are positive or negative with respect to the background. This should be set to TRUE.

RESFILE = FILENAME (Write)

Name of the file to receive the results of the measurements.

SATURE = _REAL (Read)

The saturation level in data units for the image. If any pixels in the object aperture have values greater than this then the measurement is flagged with an 'S' in the output record.

SEARCH = _INTEGER (Read)

The size of the search box in pixels to be used in locating the object centroid.

SEE = _REAL (Read)

Approximate seeing in pixels, used to estimate the FWHM of the point spread function (PSF) by the optimal extraction algorithm.

SEMIM = _REAL (Read)

The semi-major axis of the ellipse defining the aperture in pixel units. For a circular aperture this corresponds to the radius in pixel units.

SKY = _REAL (Read)

A constant value to be used as the sky estimate for subsequent measurements. This defines the sky level in data units per pixel. This value is used until another estimator is chosen.

SKYEST = _INTEGER (Read)

Select the estimator to be used to evaluate the background level in the sky aperture. There are four possible choices selected by the integers 1 to 4 which have the following bindings:

- (1) Mean. All pixels in the sky aperture are averaged.
- (2) Mean with 2 sigma rejection. All pixels with data values within 2 standard deviations of the mean are averaged.
- (3) Mode. The peak of the histogram of pixel values (the most likely value) in the sky aperture is estimated. This is the recommended choice when using optimal extraction.
- (4) A constant. A single value to be used for all measurements. A sky variance (standard deviation) is also requested so that a realistic error can be assigned to the measurements if the error is calculated from the variance in the sky aperture.

SKYMAG = _REAL (Read)

The magnitude assigned to the sky level when calculating the magnitude of the object using the relation $OBJMAG = SKYMAG - 2.5 * LOG_{10}(SIGNAL)$ where SIGNAL is the brightness of the object minus sky in photons.

SKYSIG = _REAL (Read)

A constant value for the sky variance. This is an estimate of the standard deviation in the sky level in data units and is used when SKYEST is 4.

TOLER = _REAL (Read)

The required positional accuracy in pixels to terminate the centroiding iterations.

USEMAGS = _LOGICAL (Read)

If TRUE then the output values are converted into magnitudes. If FALSE the output values MAG and MAGERR are modified to be a mean photon count and the error in this count, the other values remain the same, i.e. the sum of sky corrected photons and the mean sky value. Note the SKYMAG value is not used when this is FALSE. Note also that this value may only be set once when PHOTOM is started and must be set either on the command line (USEMAGS=TRUE or USEMAGS=FALSE) or in response to a forced prompt (command line argument PROMPT). [TRUE]

USEMASK = _LOGICAL (Read)

Define a mask to exclude regions from the background estimate. If this is TRUE a file of positions is requested which define the centres of circles used to block regions from the sky aperture. Contaminating objects, such as bright stars, can thus be removed from the background estimate.

Examples:

```
PHOTOM ARP199
```

Performs aperture photometry on image ARP199.

```
PHOTOM SEARCH=5 MAXSHIFT=2.0
```

Defines the centroiding search box to be 5 pixels wide and the maximum shift of the centroid from its initial, rough position to be 2 pixels.

PHOTOM EXSOURCE=HDS ETIME=MORE.EXP_TIME

An exposure time for the frame will be found in the primitive component EXP_TIME which is a component of the structure MORE in the data file.

PHOTOM USEMASK=T

A mask file will be used to define regions to be excluded from the sky aperture.

PHOTOM USEMAGS=FALSE

This will output the photometry results in photon counts, so the MAG field will now have a mean photon count and MAGERR the error in this count (assuming poissonian statistics are valid).

Aperture Extraction – Format of Associated Files:

At present the file containing the positions of objects to be measured, given by the POSFILE parameter (command F), is read in in free format. The first three columns of the input file have to contain an index number (INTEGER), and the x and y positions (REAL) in that order. The index number is passed to the output to assist in identification of the objects.

The output on the screen contains column headers to indicate the content of each column of the results. These column headers do not appear in the output file given by the RESFILE parameter in order that this file can be accessed by database routines.

There are eleven columns in the output file containing the following information :

Column	Name	Description
1	INDEX	Index number of star.
2	XPOS	X position of centre of aperture in pixels.
3	YPOS	Y position of centre of aperture in pixels.
4	MAG	Magnitude or mean photon count of star.
5	MAGERR	Error in MAG.
6	SKY	Sky value in photons per pixel.
7	SIGNAL	Total number of photons in aperture due to star.
8	CODE	Error code flag.
9	SEMIM	Semi-major axis of aperture.
10	ECCEN	Eccentricity of aperture.
11	ANGLE	Orientation of aperture in degrees.

The magnitude (MAG) is calculated from $mag = SKYMAG - 2.5 \log_{10}(signal)$.

The error in the magnitude (MAGERR) is estimated using one of the methods expounded in appendix D (note this error is not transformed into magnitudes when USEMAGS is FALSE).

The error CODE can take on three possible values

- B One or more pixels in the object aperture is bad.
- S One or more pixels in the object aperture is above the saturation level.
- E The object aperture intersects the edge of the data array.
- ? There are other problems with the measurement.

If a bad pixel occurs in the object aperture then the pixel is not included in the calculation of the object signal. The bad pixel is not replaced by an estimate. If a saturated pixel occurs in the object aperture then it is included in the calculation of the object signal. If the aperture intersects the edge of the data array, the object signal is calculated for the reduced area of the aperture.

Only one of these code letters is displayed, even if more than one of the conditions has occurred. The codes are in an increasing hierarchy 'B', 'S', 'E', such that 'S' overrides 'B', and 'E' overrides 'S'.

Optimal Extraction – Format of Associated Files:

As for aperture extraction the file containing the position of objects to be measured (command F) is read in free format as above. However in the case of optimal extraction the first line of the file must have an index number (INTEGER) of 0 along with the x and y position of the PSF candidate star.

The output on the screen contains column headers to indicate the content of each column of the results. These column headers do not appear in the output file given by the RESFILE parameter in order that this file can be accessed by database routines.

The first line of the output file will contain the details of the PSF star, there will be seven columns in this line containing the following information :

Column	Name	Description
1	INDEX	Index number of star.
2	XPOS	X position of centre of aperture in pixels.
3	YPOS	Y position of centre of aperture in pixels.
4	FWHM1	1st FWHM of the point spread function.
5	FWHM2	2nd FWHM of the point spread function.
6	ROT	Rotation from perpendicular.
7	CODE	Error code flag.

The remaining lines contain details of the measurements, each of these lines will have eight columns with the following information :

Column	Name	Description
1	INDEX	Index number of star.
2	XPOS	X position of centre of aperture in pixels.
3	YPOS	Y position of centre of aperture in pixels.
4	MAG	Magnitude or mean photon count of star.
5	MAGERR	Error in MAG.
6	SKY	Sky value in photons per pixel.

7	SIGNAL	Total number of photons in aperture due to star.
8	CODE	Error code flag.

B Techniques of aperture photometry

In principle aperture photometry of digitized data is a straightforward procedure. Put down a computer generated aperture over the grid of data and add up the counts within the aperture. In astronomical applications the usual purpose of aperture photometry is to measure the brightness of an object without including possible contributions from contaminating sources such as bias levels, sky, defects or other stars and galaxies. Some if not all of these contaminants will always be present in a finite sized aperture and so this 'background' has to be accounted for. If it were possible the best place to estimate this background would be behind the object, i.e. in the object aperture with the object not there. As this is usually not possible to achieve, except for the case of moving objects or supernovae, the usual method is to estimate the background from other regions close to the object.

Estimating the contribution in this background is not always straightforward. In the simplest case the histogram of pixel values in the background will have an approximately Gaussian distribution, due to random fluctuations, and the best estimator is a simple mean. It is however common for real astronomical situations to be less straightforward than this. Other contributors are likely to be present, such as non-random noise, bad pixels, cosmic rays, and the presence of other objects in the background. Even when the possible contaminating objects are very faint compared to the object to be measured the histogram of pixel values can be sufficiently skewed to result in the mean giving an estimate of the sky too poor for high precision photometry. In this case it is usual to use some sort of clipping (or filtering) to remove the effects of such contamination.

There are conflicting interests at work here. On the one hand it is desirable to use a large background aperture to get good statistics, but on the other hand this increases the probability of introducing extra contamination or of sampling areas which are uncharacteristic of the background near the object.

Of course if there is contamination in the background aperture then there will almost certainly be some present in the object aperture. The effects of this on the measurement depend on the density of objects and the ratio of the sizes of the object and sky apertures. If the sky aperture is larger than the object aperture and the objects are randomly distributed, then there is a greater chance of having more contaminating objects in the sky aperture than in the object aperture. If the density of objects is large then the proportion in each aperture will be similar, but when the number of objects is small then the chances of the larger aperture being disproportionately endowed will increase. This is best seen by considering the limiting case of one contaminating object and its most probable location. In astronomical situations the smaller populations tend to be the brighter objects and thus have an even greater effect on the results.

An ideal filter would therefore include the many faint objects which inhabit each aperture equally, but exclude the rare bright objects, which are more likely to occur in the larger aperture. Unfortunately in reality the spectra of densities and brightnesses are continuous and a clean rejection scheme is difficult to construct.

The best scheme would seem to be to take many independent samples using the same sized aperture as for the object. A new population is made from the mean sky value in each aperture, and the peak of the histogram of values, here called the mode, is used as the sky value. The mode is a maximum likelihood estimator and this scheme ensures that the most likely sky value averaged over the aperture size is used. The problem in this case is to get sufficient independent

samples close to the object aperture and therefore individual pixel values are usually used to construct the sample population.

What these arguments are leading to is that there is no unique answer to the question which is the best estimate for the sky; it depends on the circumstances. PHOTOM offers a choice of three estimators, a simple mean, a mean with 2σ clipping and the mode. When running jobs non-interactively it is best to use one of the estimators that performs clipping: either the mode or the mean with 2σ rejection. In the presence of positive contamination the mode will, in general, provide the most rejection, the 2 sigma clipping the next and the mean will provide no rejection. If the you suspect that one of the estimators may be giving wrong results then try one of the others.

C Explaining optimal photometry

Optimal extraction offers several advantages over the normal aperture method of photometry. Formally optimal extraction is equivalent to profile fitting, however it offers more robust error estimation and a freedom of the bias introduced by mis-estimating the point spread function (PSF). It has been found to offer a gain of around 10 per cent in signal-to-noise over normal aperture photometry.

A general formula for summing flux (F) within an aperture is

$$F = \sum_{i,j} W_{i,j} (D_{i,j} - S_{i,j}),$$

where sum is over all the pixels i,j within the aperture, where the total count in a pixel is $D_{i,j}$, the estimated sky level is $S_{i,j}$ and $W_{i,j}$ is the weight given to each pixel. For normal aperture photometry this is one within the aperture, and zero outside it.

Finding the optimal value for $W_{i,j}$ for each i,j within the aperture is a two step process. Firstly a model profile is fitted to a nearby star (a 2-D Gaussian has proved adequate for this purpose), the resulting estimated stellar profile $P_{i,j}^E$ is normalised to one.

As shown by Horne (PASP, 1986, 98, 609) once the estimated profile is known the best signal-to-noise is obtained for

$$W_{i,j} = \frac{P_{i,j}^E / V_{i,j}}{\sum_{i,j} (P_{i,j}^E)^2 / V_{i,j}},$$

where $V_{i,j}$ is the variance for each pixel. Substituting this into our first equation we obtain the basic formula governing optimal extraction. However at this stage we make a further assumption, that the variance for each pixel is the same. For very faint stars this is clearly the case (since the counts in each pixel is dominated by the sky count), for brighter stars though this means that the extraction will be non-optimal. Hence we have that

$$F = \frac{\sum_{i,j} P_{i,j}^E (D_{i,j} - S_{i,j})}{\sum_{i,j} (P_{i,j}^E)^2}.$$

From this we note that if the PSF is wrong there will be no systematic bias in the results, provided one is interested in the relative brightness of one star with respect to another in the same frame.

A full treatment of optimal extraction can be found in Tim Naylor's MNRAS paper "An optimal extraction algorithm for imaging photometry" (MNRAS, 1998, 296, 339) to which the reader is directed for further information.

D Calculation of the errors

The errors are calculated in one of four ways, as discussed in the section on command P. The first method assumes true photon statistics and the error is calculated from the following definitions:

Number of pixels in object aperture = a_o
 Number of pixels in sky aperture = a_s
 Sum of data in object aperture = D_o
 Sum of data in sky aperture = D_s
 Offset in one pixel = $BIASLE$
 Number of photons per data unit = $PADU$

The contribution of the sky in the object aperture can now be calculated:

Number of photons in object aperture = $P_o = PADU * (D_o - a_o * BIASLE)$
 Number of photons in sky aperture = $P_s = PADU * (D_s - a_s * BIASLE)$
 Number of photons in object aperture due to sky = $P_{so} = PADU * (D_s - a_s * BIASLE) * (a_o / a_s)$

The signal due to the object is the difference of the total number of photons in the object aperture minus the number due to the sky:

$$\text{Object signal} = S_o = P_o - P_{so} = PADU * (D_o - D_s * (a_o / a_s))$$

The error on the object signal is the quadratic sum of the errors on the individual measurements. Using ϵ to signify the error:

$$\epsilon(S_o)^2 \sim \epsilon(D_o)^2 + \epsilon(D_s)^2 * (a_o / a_s)^2$$

Assuming the errors are solely from photon statistics then the error on the signal is:

$$\epsilon(S_o)^2 = \epsilon(P_o)^2 + \epsilon(P_s)^2 * (a_o / a_s)^2$$

The error from photon counting is the square root of the number of photons:

$$\epsilon(P_o) = \sqrt{P_o} \text{ and } \epsilon(P_s) = \sqrt{P_s}$$

Therefore:

$$\underline{\varepsilon(S_o)^2 = P_o + P_s * (a_o^2/a_s^2) = PADU * (D_o + D_s * (a_o^2/a_s^2) - BIASLE * a_o(1 + a_o/a_s))} \quad (1)$$

The second method of calculating the errors assumes that the variance in the sky aperture corresponds to the photon noise. This allows the photon errors to be calculated without knowing BIASLE. One additional definition has to be given:

$$\text{Standard deviation in sky aperture per pixel in data units} = \sigma_s$$

If the photon error $\sqrt{P_s}$ is equated to the standard deviation $PADU * \sigma_s$ then the total number of photons in the sky aperture is given by:

$$P_s = a_s * PADU^2 * \sigma_s^2$$

The offset in the sky aperture can now be calculated:

$$BIASLE = (D_s/a_s) - (PADU * \sigma_s^2)$$

Substituting this into the calculation of the error gives:

$$\varepsilon(S_o)^2 = PADU * (D_o - D_s * (a_o/a_s) + PADU * \sigma_s^2 * a_o * (1 + a_o/a_s))$$

or

$$\underline{\varepsilon(S_o)^2 = S_o + PADU^2 * \sigma_s^2 * a_o * (1 + a_o/a_s)} \quad (2)$$

The third method of calculating the errors sums the data variances from the variance component of an NDF. Two additional definitions have to be given:

$$\text{Sum of variance in object aperture} = V_o$$

$$\text{Sum of variance in sky aperture} = V_s$$

The error is then calculated from:

$$\underline{\varepsilon(S_o)^2 = PADU^2 * (V_o + V_s * (a_o/a_s)^2)} \quad (3)$$

The magnitude error is calculated from differentiating the magnitude equation:

$$m = -2.5 \log_{10} S_o$$

thus:

$$\underline{dm = \frac{-2.5}{\ln 10} * \frac{\varepsilon(S_o)}{S_o}}$$

The fourth method is like method two, but the sky variations are interpreted by a gaussian error source, so PADU and BIASLE are not required. With gaussian errors the source signal is effectively zero (since it has the same noise per pixel as the sky), so

$$\underline{\varepsilon(S_o) = PADU * \sigma_s * \sqrt{a_o}} \quad (4)$$

and

$$\underline{S_o = PADU * (D_o - D_s * (a_o/a_s))} \quad (5)$$

so the PADUs cancel out in the dm calculation.

E PHOTOPT - examining PHOTOM's performance

PHOTOPT is an auxiliary package to examine the performance of the various sky estimators used by PHOTOM. As indicated in section B the best choice of estimator depends on the circumstances. The idea behind PHOTOPT is to put down an aperture on a random piece of sky, estimate the background from a concentric aperture using one of the sky estimators offered by PHOTOM, and subtract this estimated sky from the flux in the central aperture. If the sky estimator correctly estimates the sky then the difference of the two will be zero. Since an automatic procedure cannot be certain of selecting a representative piece of sky, the procedure is repeated a number of times to increase the statistics.

PHOTOPT selects regularly spaced points within an image, puts down an aperture at each of the points and calculates the difference between the central aperture and the sky estimate from the surrounding annulus. Each of the three sky estimators offered by PHOTOM are tried in turn on the same set of points so that a comparison can be made between the three methods. The output is in the form of two graphs for each estimator. The first shows the difference between the central aperture and the sky estimator for each of the samples. The sample number forms the x-axis and the difference (object - sky) given in photons per pixel forms the y-axis. The second plot shows a histogram of the differences for the samples. The differences are binned into suitable intervals and form the x-axis of the histogram, with the y-axis giving the number of samples in each difference bin.

PHOTOPT has a number of parameters in common with PHOTOM: the aperture shape parameters, SEMIM, ECCEN and ANGLE, the scaling factors PADU and SATURE and the background annulus size INNER and OUTER. The two parameters unique to PHOTOPT are NP, the number of points to sample, up to a maximum of 100, and the RANGE, which defines the bounds of the data value used in the plot. The number of points sampled may not exactly equal the number requested as the program automatically positions the points to be on a rectangular grid which evenly covers the whole data array. The program also ensures that the density of points does not result in the central apertures overlapping.

PHOTOPT can be run from ICL or the C-shell. From ICL use :

```
ICL> photopt
```

From the C-shell use (assuming photomstart has been executed) :

```
% photopt
```

The full description of PHOTOPT follows.

PHOTOPT

Perform sampling experiments with different sky estimators

Description:

PHOTOPT examines the performance of the three different sky estimators used by PHOTOM on a particular frame. It does this by performing aperture photometry on random parts of the frame, subtracting the estimated sky level from a concentric aperture from the level in the central aperture. If the estimator is good then the expected result is zero, as long as there are no objects in the central aperture. This is repeated a number of times over the frame to ensure that a fair representation of the frames characteristics is obtained. The results are shown in graphical form as a set of difference graphs. The histogram of differences will indicate which is the best suited estimator for the frame.

Parameters:

ANGLE = _REAL (Read)

The orientation of the ellipse defining the aperture. This is defined in degrees going anti-clockwise from the positive y-axis. This is equivalent to a position angle.

DEVICE = DEVICE (Read)

The name of the device to receive the graphical output.

ECCEN = _REAL (Read)

The eccentricity of the ellipse defining the aperture. For a circular aperture this should be set to 0.0.

IN = IMAGE (Read)

Name of the image on which the sampling test will be performed.

INNER = _REAL (Read)

The radius of the inner edge of the annular sky aperture in units of the object aperture size. The actual dimension in pixels is obtained by multiplying this factor by the object aperture semi-major axis in pixels.

NP = _INTEGER (Read)

The number of points to sample in the image up to a maximum of 100. This number is factorised so that a regular grid of samples is taken. The actual number of samples is restricted to ensure that the central apertures do not overlap.

OUTER = _REAL (Read)

The radius of the outer edge of the annular sky aperture in units of the object aperture size. The actual dimension in pixels is obtained by multiplying this factor by the object aperture semi-major axis in pixels.

PADU = _REAL (Read)

The number of photons for each interval of the data. If the true value is unknown use a value of 1.

RANGE = _REAL (Read)

The limit of the plot in photon units (data units * PADU). This can be used to limit the range of the plot to the interesting region.

SATURE = _REAL (Read)

The saturation level in data units for the image.

SEMIM = _REAL (Read)

The semi-major axis of the ellipse defining the aperture in pixel units. For a circular aperture this corresponds to the radius in pixel units.