# VAPHOT − A Package for Precision Differential Aperture Photometry

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## Abstract

The aperture photometry package `vaphot´ was developed to perform reliable and precise time−series photometry of uncrowded fields. This package works within the IRAF environment and is built upon the standard aperture photometry task `phot´ from IRAF. The design goal of `vaphot´ was a simple−to−use photometry task with relatively few input parameters that performs precise aperture photometry, using optimum sized apertures. The derivation of optimum sized apertures is outlined; the calculation of these sizes is performed by a subroutine `apcalc´ within the `vaphot´ package. We also outline the derivation of signal−to−noise values for differential photometry, when the flux reference is constituted by an ensemble of reference stars. A comparison of vaphot against normal aperture photometry shows, that the sizing of apertures with the psf of the CCD images greatly isolates against changes in the size of the psf during an observing run. The use of apertures sized individually to each star on the field does not greatly improve photometry against the use of similar−sized apertures. However, the use of photometry with previously determined optimum aperture sizes ensures that this photometry will be of the best quality that can be obtained.

## Introduction

Differential time−series photometry has been used in many fields of astronomy to obtain information about temporal varying phenomena. The paper by Young et al (1991) demonstrates how photo−tube measurements can obtain precisions of a few parts in $10^4$. Many of its aspects regarding the diminution of potential sources of errors can be applied to photometry based on CCD imagery as well. CCDs have meanwhile become more available then phototubes on most telescopes, and their instrumental precision for differential photometry is competitive, with theoretical limits on the order of 1 part in $10^5$ (Robinson et al., 1995). For the 'Transits of Extrasolar Planets' (TEP) project (Deeg et al., 1997, 1998; Doyle et al., 1996, 2000), for which the software described here has been developed, the task was to measure the brightness evolution of *one* star (the program star) with a high precision against a set of reference stars. For precision time−series photometry with CCDs, this measurement task can be broken up into two steps: (i) The extraction of flux count values from the stars on the CCD frames, and (ii) the creation of a flux−standard from the reference star(s), against which the brightness of the program star is measured.

Optimized data−extraction techniques have been addressed for aperture photometry by Howell (1989), and by Kjeldsen & Frandsen (1992) for a package that uses a 'mixed' approach between aperture and point spread function (psf) fitting. We note that photometry programs that depend purely on psf fitting, such as 'daophot' (Stetson, 1987) or 'dophot' (Schechter et al., 1993) are *not* optimized for high precision photometry of bright stars, which is generally associated with time−series photometric projects. On point (ii), techniques for the creation of flux standards, as well as evaluations of their stability, have been addressed by Howell et al. (1988), Gilliland & Brown (1988) and Kjeldsen & Frandsen (1992). The general consensus is that CCD photometry does have advantages over single−channel and multichannel photo−tubes, the major one being that the program star *and* several reference stars can be measured simultaneously.

This communication is aimed at introducing a software package '*vaphot*'[1] for differential time−series photometry, using optimized data extraction, and introducing a way to create and to evaluate reference flux standards. These methods have been developed for the TEP project, whose major goal is the monitoring of the eclipsing binary star CM Draconis for the presence of planetary transits. These transits would express themselves as brightness dips with amplitudes of 0.1 − 1% of the star's quiescent brightness, and would have a duration of typically one hour (Borucki & Summers, 1984; Schneider & Chevreton, 1990). In the course of this project, a very large number ( > 30000) of CCD frames has been obtained of CM Draconis and of some neighboring stars. These observations were taken at several observatories, and due to manpower restrictions, had to be reduced by the observers at their sites. It has therefore been necessary to obtain software packages that can deal efficiently with large numbers of CCD frames, are relatively easy to use, and deliver reliable and precise photometry. Preference was given to the IRAF environment due to its availability at the various sites and due to the observers' acquaintance with it. We found the standard tasks supplied in the IRAF−'ccdred' package fully sufficient for the basic image−reduction steps. The situation was more difficult with software to perform the differential photometry. Distributed within IRAF are two photometry packages: the 'apphot' package for aperture photometry, which can be adapted to be used for large numbers of frames, but only allows the use of same−sized apertures for all stars within a CCD frame, and the 'daophot' package, which employs psf fitting, and is intended for crowded field photometry rather then for differential precision photometry. It is also relatively complicated to use, especially for consistent reductions of large numbers of frames.

Since the field of CM Dra is uncrowded, aperture photometry techniques should in principle be able to obtain the best precision. We evaluated the stand−alone MOMF package (Kjeldsen &Frandsen, 1992), whose photometry has been optimized for time−series CCD photometry. This package delivers results with excellent precision but is quite complicated to use, and its large number of output files with generic file names is not well adapted to the needs of the TEP project. We used this package however for reference evaluations. The program that is the topic of this paper, 'vaphot', was then developed as a task for IRAF. 'vaphot' is built on the reliable aperture−photometry task 'phot' from IRAF, but employs apertures that are sized to obtain optimum Signal−to−Noise ratios for *each* star in a CCD frame. It also fulfills the requirements of simple use, and creates for each night of observations just one output file which contains all needed data (instrumental magnitudes for all stars, sky−brightness, tracings of FWHM, airmass, etc.), as well as a record of all relevant parameter settings that have been used. This output file is in straight ASCII text, to facilitate its interpretation by further reduction routines. Besides the TEP project, 'vaphot' has been used in a project to measure rotation curves of low−mass stars from their brightness variations (Martín & Zapatero−Osorio, 1997) and is used in an ongoing survey of minimum times of eclipsing binaries (Doyle et al., 1997). It is expected that this program will be of use for those investigators, who need to perform precision time−series photometry of bright stars in uncrowded fields where aperture photometry is feasible.

The points addressed in the following sections are:

· The aperture optimization used in vaphot

· Overview of the vaphot package

· The use of multiple reference−stars as the flux basis. Considerations about inclusion/exclusion of stars into flux basis.

· Photometric performance of vaphot

1 The programs 'vaphot', 'apcalc' and associated routines are available as part of the software distribution for the TEP project, at ftp://ftp.iac.es/pub/hdeeg/tep_dist/

## Calculation of the signal−to−noise for aperture photometry and derivation of an optimum sized aperture

For time−series photometry based on CCD aperture photometry, the choice of the correctly−sized aperture is of importance in obtaining lightcurves with the lowest possible noise. Clearly, in apertures too small, light from a star is wasted at the fringes of the psf, whereas in apertures too big, unwanted noise − but no signal − is contributed from the inclusion of unnecessary sky background. The right−sized aperture therefore depends mainly on the size and the amplitude of the stellar point−spread−function (psf) and on the level of background−noise on the CCD. The flexibility in sizing the optimum aperture onto a CCD at the reduction stage can be considered an advantage over photometer−tube photometry, where the aperture has to be fixed before performing the observations. Finding this optimum sized aperture for stellar CCD photometry in a simple to use photometry package is now outlined.

For the sake of clarity, signal and noise is expressed in units of electrons on the CCD; the conversion to CCD−counts (ADU) is trivial. Also, the aperture radius r is assumed to be in units of pixel−side−length. On the CCD, the signal, $S$, is the number of photons, $N_{ph}$, from the star inside a aperture with radius $r$, which is under the assumption of a Gaussian psf with width $\sigma_{psf}$ given by:

$$S = N_{ph}(r) = N_{ph,tot}\left(1 - \exp\left(\frac{-r^2}{2\sigma_{psf}^2}\right)\right) \tag{1}$$

where $N_{ph,tot}$ is the total number of photons from the star in the limit of an infinite aperture. The total noise inside the radius r is given by the error−sum:

$$N = \sqrt{\sigma_{N_{ph}}^2(r) + \sigma_{BG}^2(r) + \sigma_{scin}^2} \tag{2}$$

where $\sigma_{Nph}(r) = \sqrt{N_{ph}(r)}$ is the photon noise from the star inside radius $r$, and where $\sigma_{BG}(r)$ is the uncertainty in the contribution of the sky−background to the total count within the aperture. If the average noise of one background pixel (from photon noise of the sky−background and from CCD read−noise), is $\sigma_{1pix}$, then $\sigma_{BG}(r)$ is given by:

$$\sigma_{BG}(r) = \sigma_{1pix} r \sqrt{\pi} \tag{3}$$

The scintillation noise $\sigma_{scin}$ is a constant, which is independent of the stars' magnitudes or the aperture used. Except for extremely short exposure times or with very small telescopes, $\sigma_{scin}$ will be much smaller then $\sigma_{Nph}$ or $\sigma_{BG}$, and can therefore be neglected in Equation (2). The ratio of Equations (1) and (2) gives then the S/N, and is also known as the "CCD equation" (Howell, 1989). Fig 1. shows the graph of S/N for a test−image of CM Dra taken at the Mees Telescope of the Univ. of Rochester. It is of course desirable that aperture photometry will be performed with apertures sized so that the S/N reaches a maximum. The programs to do this are the subject of the next section.

## The photometry routines 'apcalc' and 'vaphot'

The major programs ('tasks' in IRAF lingo) of the `vaphot´ package are 'apcalc', which calculates optimized apertures, and the main vaphot task, which performs the photometry on a time−series of CCD images, using the apertures calculated by apcalc. The package also provides an improved version of the IRAF task 'imalign', called 'imal2', which is intended for the aligning of large numbers of CCD frames.

Apcalc finds the optimum aperture sizes from a simple iteration that searches for the zero−point in the derivative $\partial(S/N)/\partial r$. The only user input required is a CCD image containing the stellar field, a list of x−y coordinates of the stars on this field, and a value for the CCD gain. The program then measures the values $\sigma_{psf}$, $N_{ph,tot}$ and $\sigma_{1pix}$ on the stars in this field, and finds the optimum aperture size for each star. Lastly, apcalc writes a file that contains the stars' x−y coordinates and their optimum aperture diameter in units of the FWHM of the psf (assuming a uniform psf across a CCD image). This file can be used as an input to the photometry routine vaphot. 'Apcalc' is normally used on only one image per night (or per observing run) for each stellar field observed. This reference image should be typical for the observing run in terms of seeing and sky brightness.

Vaphot performs aperture photometry on a time series of CCD frames, with apertures sized individually for each star. An example of the vaphot input specifications is shown in Fig 2. Items that need to be specified are the CCD images, a file for the results, a file with the stars' position and aperture−sizes (normally this is produced by apcalc), initial settings for psf fitting, and the names of header keywords for exposure time and duration. Also given is the option to include two more auxiliary image−header keywords in the results file, which allows to keep track of changing parameters (like airmass) that are being logged in the image header. Also, if the images have previously been aligned with the 'imal2' task, a header keyword describing the X and Y shifts was created, which can subsequently be logged to the results file.

```
TASK = vaphot
images  =          @imlist   Images to do photometry on
result  =          940519c   Output file
stapcor =     stapcor940519   File with object star coordinates and
                             apertures
psfcoord=     stapcor940519   File with psf star coordinates
(fwhmini=               5.)   Initial FWHM for psf fitting
(obstime=              HJD)   Time of observation image header
                             keyword
(exptime=         EXPOSURE)   Exposure time image header keyword
(keyw1 =           AIRMASS)   1st auxiliary header keyword (i.e.
airmass)
(keyw2 =           IMSHIFT)   2nd auxiliary header keyword
(verbose=              yes)   verbose output
```

*Fig. 2 Relevant input parameters for the 'vaphot' task. For explanation, see text.*

While this is not intended as a manual for vaphot (detailed instructions are available at the same location as the software), we give here a short overview on the working of vaphot: On each image, vaphot measures the psf on one representative star (if not oversaturated, the brightest stars would be suitable). The FWHM of this psf is used as a basis to scale the apertures for each star by the value that has been calculated by apcalc.

The aperture sizes used on each $star_{s,k}$, where *s* denotes the number of the star, and *k* the number of the CCD frame, are now given by: $a_{s,k} = FWHM_k \times aopt_s$, where $aopt_s$ is the optimized aperture size calculated by apcalc for each star in units of FWHM, and $FWHM_k$ is in units of pixel−size. This way, changes in the FWHM throughout a night can be taken into account. If there are drastic variations of the FWHM throughout a night, the *sizes* of the apertures used may deviate from the optimum aperture sizes for a particular image, but the relative brightnesses measured among the stars will not change. The aperture photometry that is then performed (using the aperture sizes $a_{s,k}$) on each *individual* stellar image is similar to the standard IRAF 'phot' (vaphot is actually a ``cl script'´ –or macro– built around the `phot´ task). The only other major difference to the 'phot' task is the format of the results file, which is adapted to the needs of time–series photometry. All measured magnitudes, several parameters that change throughout an observing run (Julian date, exposure time, FWHM, and parameters specified by the auxiliary header keywords), as well as relevant fixed parameters (such as the stars' positions, aperture sizes and the zero–magnitude) are then written into *one* table in ASCII format, which is suitable to be plotted, or to be analyzed by programs outside of the IRAF environment.

As it is the case with all photometric methods, consistency of the results will degrade if the observing conditions undergo strong changes. Strong variations in the sky–brightness, in the seeing, or in the transparency will cause the use of apertures, that are not optimized for a particular image. In general, though, it is preferable to use only one set of optimized apertures for each night (or for each observing run, if brightness variations on times–scales of several nights need to be tracked). The S/N dependency of the aperture–radii close to the optimum size (Fig. 1) is very small, and sky–brightness changes from rising/setting of the moon, from normal seeing fluctuations or small (< 10%) transparency fluctuations do not deviate the apertures far from the optimum S/N. Changes in S/N as a result from a deviation from the optimum apertures are not very relevant relative to the variations to the S/N that are introduced by atmospheric fluctuations under marginal conditions.

## S/N in an ensemble of reference stars

One of the major advantages of CCD photometry is the possibility of measuring simultaneously more then the usual 1 or 2 reference stars taken with photomultiplier tubes. This section evaluates the photometric precision that is given if such an ensemble of several stars is providing the brightness reference in differential photometry. The signal of an ensemble of $n$ reference stars is given by:

$$S_{ens} = \sum_{s=1}^{n} N_{ph,s} \tag{4}$$

where $N_{ph,s}$ is the photon count of each star $s$ within its aperture of radius $r_s$. The ensemble S/N is now:

$$S/N_{ens} = \frac{\sum_s N_{ph,s}}{\sqrt{\sum_s \left(N_{ph,s} + \sigma_{BG,s}^2\right)}} \tag{5}$$

Although the background noise of each pixel, $\sigma_{1pix}$, can be assumed to be the same everywhere on the CCD, it should be noted that $\sigma_{BG,s}$ is not the same for all stars, if differing sizes of $r_s$ where used (see Eq. 3), as is done by vaphot. The signal to noise of the *differential* photometric measurement for the program star is now given by:

$$S/N_{diff} = 1/\sqrt{S/N_{pro}^{-2} + S/N_{ens}^{-2}} \tag{6}$$

where $S/N_{pro}$ is the S/N of the program star, and can be determined from the CCD equation for single stars (the ratio of Eq.(1) and Eq.(2)).

As an example, Table 1 shows the values of the optimized apertures and the S/N ratios from an image of the field of CM Dra, where 7 reference stars where used for the ensemble reference. The parameters used are the same ones as given in the caption to Fig. 1.

**Table 1. Example of optimized apertures and S/N calculation for an ensemble of reference stars in the field of CM Dra.**

| Star | $R_{opt}$(1) | $N_{ph}$ | $\sigma$ Nph | $\sigma_{BG}$ | S/N(2) | mag(5) | magerr(6) |
|---|---|---|---|---|---|---|---|
| CM Dra | 2.23 | 1073271 | 1036 | 397 | 967 | 11.057 | 0.0011 |
| Ref *1 | 1.99 | 416501 | 645 | 354 | 566 | 12.085 | 0.0019 |
| Ref *2 | 1.75 | 141543 | 376 | 311 | 290 | 13.257 | 0.0037 |
| Ref *3 | 1.72 | 121210 | 348 | 306 | 261 | 13.425 | 0.0042 |
| Ref *4 | 1.68 | 96246 | 310 | 298 | 224 | 13.675 | 0.0048 |
| Ref *5 | 1.66 | 87339 | 296 | 295 | 209 | 13.781 | 0.0052 |
| Ref *6 | 1.58 | 52842 | 230 | 281 | 146 | 14.326 | 0.0074 |
| Ref *7 | 1.49 | 20345 | 143 | 265 | 68 | 15.363 | 0.0160 |
| Sum of Ref * | | 936027 | 967 | 801 | 745(3) | 11.206 | 0.0015 |
| CM Dra−(Sum of Ref *) | | | | | 590(4) | −0.149 | 0.0018 |

*Notes to Table 1:*

*(1)$R_{opt}$ is the optimum−sized apertures in units of FWHM of the psf.*

*(2)S/N for individual stars has been calculated by the ratio of Eqs.(1) and (2)*

*(3)S/N of the Ensemble of reference stars calculated with Eq. (5)*

*(4)S/N of the differential measurement calculated with Eq. (6)*

*(5)Magnitude, as converted from $N_{ph}$*

*(6)The magnitude error is calculated from S/N as follows: magerr=2.5 log (1+ N/S)*

One important consideration in the use of ensemble standards is, that more reference stars are not necessarily better. The inclusion of faint reference stars with a low S/N can have a deteriorating effect on the ensemble S/N! For example, excluding the faint reference star 7 of Table 1 would raise the differential S/N to 593.

Since this consideration cannot usually be taken into account at the moment of performing the photometry, for the vaphot package a dual path was chosen: The output file contains a value for the differential photometry ($mag_{Program\_star} - mag_{ensemble}$), but additionally, the magnitudes of all reference stars are recorded individually. This allows later removal of reference stars and a recalculation of the differential magnitudes, if reference stars are found to deteriorate the ensemble S/N due to their faintness, or due to variability. For these calculations a program was written which allows the evaluation of individual reference stars from vaphot output files, recalculation of the differential photometry, rejection of individual points based on unusual variations among the reference stars, and generation of a final lightcurve. This program, named 'vanaliz' and written in IDL, is included in the software distribution. There exists also a prototype version with limited capabilities for Microsoft Excel, which can be requested from H. Deeg.

## Photometric performance of vaphot

Since vaphot is entirely based on standard aperture photometry, its performance on *single* stellar brightness measurements will be identical to the IRAF 'phot' task. Where differences will occur is in the quality of measurements of ensembles of stars, and of sequences of CCD frames. A detailed comparison of vaphot to some other reduction packages is beyond the scope of this paper and is the subject of a forthcoming article. In the following, a comparison between optimized aperture photometry and conventional aperture photometry with similar−sized apertures (for all stars) and/or with constant sized apertures (independent of the psf) is outlined.

In Table 2, the noise of the differential photometry of a night (6 June 1999, observed at the Crossley 36" telescope at Lick observatory) of observations of CM Draconis is shown. This night was characterized by a strong change in the size of the psf, from variations in the seeing and possibly in the focusing of the telescope. The column 'rms' gives the standard deviation of the differential lightcurve against a nightly mean. The 'LF rms' indicates the low frequent noise, giving deviations over a longer time scale of about 1/2 hour, which was obtained by smoothing the resultant lightcurve with a boxcar with a length of 9 data–points. The 'HF rms' indicates the high–frequent or 'point–to–point' noise, and which was obtained by subtraction of the smoothed lightcurve from the original curve.

**Table 2 Comparison between different aperture photometry methods**

| Description | rms (mag) | LF rms (mag) | HF rms (mag) | apertures optimized for each star | apertures scale with FWHM |
|---|---|---|---|---|---|
| Vaphot (optimized apertures, scaling with FWHM of psf) | 0.0044 | 0.0029 | 0.0031 | Y | Y |
| Apertures of radius 2.5 x FWHM for *all* stars, and scaling with FWHM of psf | 0.0042 | 0.0026 | 0.0031 | N | Y |
| Optimized apertures for reference image, but apertures kept constant during night | 0.0068 | 0.0057 | 0.0032 | Y | N |
| Apertures of radius 16pixel[1] for *all* stars, and apertures kept constant during night | 0.0061 | 0.0047 | 0.0035 | N | N |

[1] *16 pixels corresponds to 2.5 times the FWHM of 6.5 pixels of the reference image.*

As can be seen, the major difference is in the 'rms' or 'LF rms' between photometry whose apertures scale with the psf, and photometry whose aperture don´t. This was caused by the strong changes in the size of the psf, which occur on slower time scales and do not affect much the 'point–to–point' noise (HF rms). The difference between apertures of optimum size for *all* stars and the use of a constant aperture of 2.5 x FWHM for all stars is not very profound. It should however be noted, that the optimized apertures for all stars are relatively close to 2.5 x FWHM (between 2.6 and 1.9 x FWHM) and that the dependence between S/N and size of aperture is not very strong near the optimum (see Fig. 1). The major advantage in the use of 'apcalc' and 'vaphot' is therefore, that the guesswork 'what is the best size for my apertures' is completely taken care of. This for any combination of observing conditions (brightness of stars, brightness of background, gain of camera, size of telescope etc), in a package that is straightforward to use, and will derive precise aperture photometry.

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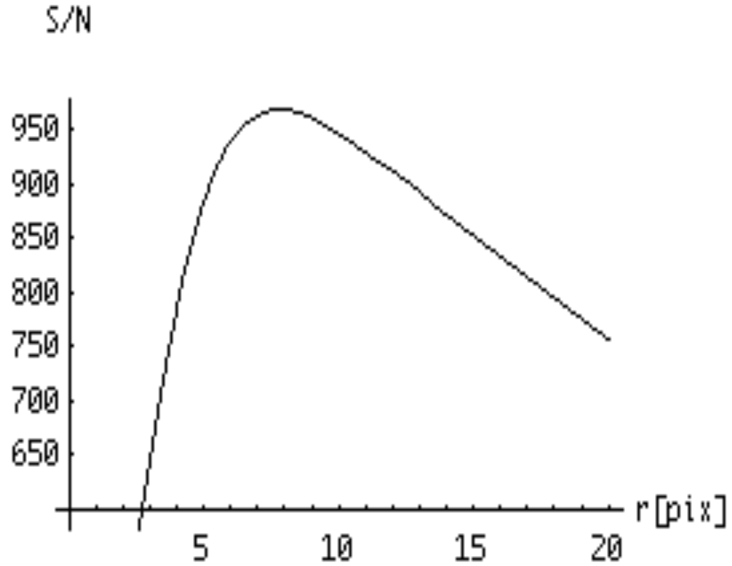


Fig. 1 The Signal−to−Noise ratio of aperture photometry of a stellar CCD image in dependence of the size of the aperture. The FWHM of the psf of the star was 7 pixels ($\sigma_{psf}$ = 2.97). The photon count from the star $N_{ph}$ was $1.1 \cdot 10^7$ electrons (at a gain of 4.1 $e^-$/ADU), and the noise of the background was 7 ADU. The radius of the optimum aperture is 7.8 pixels, corresponding to an aperture diameter of 2.23 times the FWHM)