Psfmeasure/Starfocus: IRAF PSF Measuring Tasks

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Abstract.

This paper describes two new IRAF tasks `psfmeasure` and `starfocus` for measuring parameters of the point-spread function in astronomical images and estimating the best focus from images with multiple focus settings.

The IRAF[2] tasks `psfmeasure` and `starfocus` measure the point-spread function (PSF) width of stars or other unresolved objects in digital images. The measured width is based on the circular radius which encloses a specified fraction of the background subtracted flux. The algorithmic details of this are described in another paper of these proceedings. The two tasks use the same source code and differ only in whether multiple focus values are analyzed. For data from a single focus setting extraneous input parameters are eliminated. `Psfmeasure` can measure a single object or analyze variations in PSF widths and shapes from multiple images and multiple positions. `Starfocus` analyzes one or more objects at multiple focus settings. When there are multiple objects spatial variations can be examined and compromise best focus values estimated. This paper concentrates on the more complex case of multiple focus values but much of the discussion also applies to the PSF measuring task.

The tasks have three stages; selecting objects and measuring the PSF width and other parameters, an interactive graphical analysis, and a final output of the results to the terminal and to a logfile. The input begins with a list of images. The list may consist of explicit image names, wildcard templates, and @files. The images may consist of a single exposure at some focus setting or multiple exposures in which the telescope or detector are shifted between the exposures at a sequence of focus settings. The multiple exposures can be shifted on the image along lines or columns and there may be a double step at either end of the sequence (a standard focus pattern used at many observatories).

Focus values are associated with each image. The focus values may be specified in several ways; a list of values, an @file, or an image keyword.

Identifying the object or objects to be measured may be accomplished in several ways. One may tell the tasks to automatically look for an object near the center of the image. This does not require any user input. Alternatively

[1] National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation

[2] Image Reduction and Analysis Facility, distributed by the National Optical Astronomy Observatories

one may select objects with the image cursor. This is usually taken from an image display (and the program can display the image automatically if desired) though a file containing the positions can be substituted. The latter is useful if an automatic finding task is used. The selection of objects with an image cursor or file has two variants; objects are selected in the first image of a sequence and other images are assumed to have objects in the same positions or the selection can continue independently for all images. In the former case only one image needs to be displayed and interactively marked.

The tasks accumulate PSF data for each object selected. These are all analyzed together when all the objects have been selected. However, one may also graphically examine the PSF information for each object as it is marked. The PSF information measured is described in a separate paper. The graphical examination and analysis features of these tasks in described in the next section.

When the task finishes it prints the results to the user's terminal and also to an optional log file. The tabulated results may be previewed during the execution of the task with a colon command. The results begin with a banner and the overall estimate of the best focus and PSF size. If there are multiple stars measured at multiple focus values the best focus estimate for each star is printed. A star is identified by it's position (the starting position for multiple exposure images). The average size, relative magnitude, and best focus estimate are then given. If there are multiple focus values the average of the PSF size over all objects at each focus are listed next. Finally, the individual measurements are given. The columns give the image name, the column and line position, the relative magnitude, the focus value, the PSF size as either the enclosed flux radius or the FWHM, the ellipticity, and the position angle.

The task estimates a value for the best focus and PSF size at that focus for each star. This is done by finding the minimum size at each focus value (in case there are multiple measurements of the same star at the same focus), sorting them by focus value, finding the focus value with the minimum size, and parabolically interpolating using the nearest focus values on each side. When the minimum size occurs at either extreme of the focus range the best focus is at that extreme focus; in other words there is no extrapolation outside the range of focus values.

The overall best focus and size when there are multiple stars are estimated by averaging the best focus values for each star weighted by the average flux of the star as described above. Thus, when there are multiple stars, the brighter stars are given greater weight in the overall best average focus and size. This best average focus and size are what are given in the banner for the graphs and in the printed output.

The log output also includes an average PSF size for all measurements at a single focus value. This average is also weighted by the average flux of each star at that focus.

Interactive Graphics

The graphics part of `starfocus` and `psfmeasure` consists of a number of different plots selected by cursor keys or window buttons and menus. The available plots depend on the number of stars and the number of focus values. The various plots are a spatial plot at a single focus, a spatial plot of best focus values, enclosed flux for stars at one focus and one star at all focuses, size and ellipticity vs focus for all data, size and ellipticity vs relative magnitude at one focus, radial profiles for stars at one focus and one star at all focuses, size and ellipticity vs radius from field center at one focus, and a *zoom* plot of a single measurement.

If there is only one object at a single focus the only available plot is the zoom plot. This plot may be selected with the cursor for any object from any other plot. It has three graphs; a graph of the normalized enclosed flux verses scaled radius, a graph of the intensity profile verses scaled radius, and the equivalent Gaussian full width at half maximum verses enclosed flux fraction. The latter two graphs are derived from the normalized enclosed flux profile as described in the algorithms paper. An example of this plot is shown in figure 1.

There are three types of symbol plots showing the measured PSF size (either enclosed flux radius or FWHM) and ellipticity. These plot the measurements verses focus (see figure 2), relative magnitude, and radius from the field center. The focus plot includes all measurements and shows dashed lines at the estimated best focus and size.

Grids of enclosed flux vs. radius, intensity profile vs. radius, and Gaussian FWHM vs. enclosed flux fraction give a visual overview of PSF changes with focus or star. Any of the graphs with enclosed flux or intensity profiles vs radius may have the profiles of the object with the smallest size overplotted.

The final plots give a spatial representation. These require more than one object. One gives a spatial plot at a single focus. The space bar can be used to advance to another focus. This plot has a central graph of column and line coordinates with symbols indicating the position of an object. The objects are marked with a circle (when plotted at unit aspect ratio) whose size is proportional to the measured PSF size. In addition an optional asterisk symbol with size proportional to the relative brightness of the object may be plotted. On color displays the circles may have two colors, one if the object size is above the average best size and the other if the size is below the best size. The purpose of this is to look for a spatial pattern in the smallest PSF sizes.

Adjacent to the central graph are graphs with column or line as one coordinate and radius or ellipticity as the other. The symbols are the same as described previously. These plots can show spatial gradients in the PSF size and shape across the image.

The second type of spatial plot shows the best focus estimates for each object. This requires multiple objects and multiple focus values. As discussed previously, given more than one focus a best focus value and size at the best focus is computed by parabolic interpolation. This plot type shows the object positions in the same way as the other plot except that the radius is the estimated best radius. Instead of adjacent ellipticity plots there are plots of best focus verses columns and lines. Also the two colors in the symbol plots are selected depending on whether the object's best focus estimate is above or below the overall best focus estimate. This allows seeing spatial trends in the best focus. An example of this type of plot is shown in figure 2.

In addition to the keys and buttons which select plots there are other keys which do various things such as print help, delete or undelete a star or stars, print information about one measurement, adjust the normalization of the enclosed flux profile, and change parameter values. There is, of course, also a key to exit the program.

The deletion of bad measurements, usually due to being too faint or too near another object, is an important feature. When an object is deleted it is not included in any averages or output. Objects may be deleted individually, by image, or over all focus values and they may be undeleted as well.

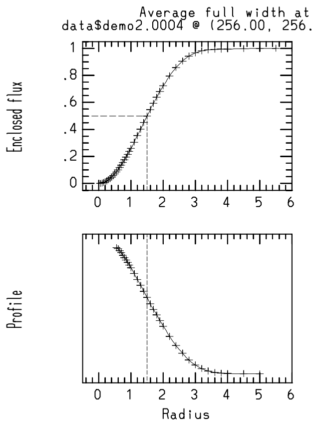

Figure 1. Plots of the enclosed flux vs radius, pixel flux vs radius, and equivalent Gaussian FWHM vs enclosed flux for a single PSF measurement. The dashed lines mark the radius enclosing 50% of the flux.

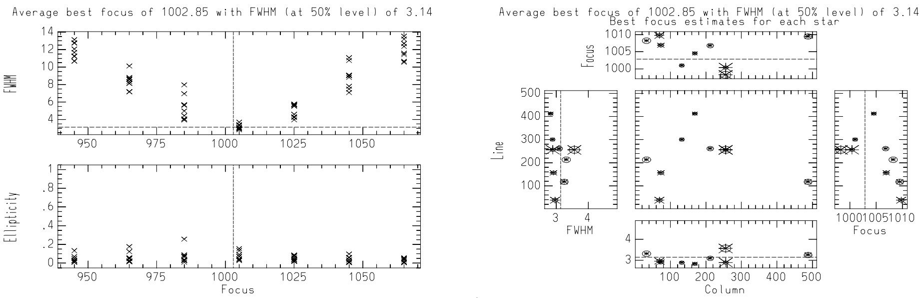

Figure 2. Two plots from `starfocus`. The left plot shows the FWHM and ellipticity vs focus value for all measurements. The right plot shows the position, relative best focus size, magnitude, best FWHM, and best focus as a function of object position in the image. The size of the circles represent the FWHM and of the asterisks the relative magnitude.

Psfmeasure/Starfocus: PSF Measuring Algorithms

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Abstract.

This paper describes algorithms used in the IRAF tasks `psfmeasure` and `starfocus` for accurately measuring parameters of the point-spread function in astronomical images.

This paper describes the major algorithms used to measure the point-spread function, PSF, in astronomical images using the IRAF[2] tasks `psfmeasure` and `starfocus`. The functionality of these tasks is described in another paper in these proceedings. The algorithms are designed to provide accurate measures of various properties of the PSF, such as width, extending into the difficult regime of marginally sampled images where the PSF width is of order of a single pixel.

The PSF is characterized by the azimuthally symmetric enclosed flux profile of objects such as stellar images. To measure the enclosed flux profile requires algorithms for determining the center of an object, determining the background, accurately sampling the profile and image pixel values, defining the normalization, and measuring radial flux profiles and widths. There are additional algorithms for measuring relative magnitudes, ellipticities, position angles, and combining multiply measurements at varying positions and focuses which are given in the technical documentation for the IRAF tasks

1. Center Determination

The center of a PSF object is determined starting with an initial estimate. In the tasks this is either given by the user as an image cursor coordinate (either interactively or from a cursor coordinate file) or assuming the object is near the center of the image. A subraster containing the object is extracted. The half size of this subraster is set by a fitting radius, plus a background region buffer distance, plus a background region annulus width. The lines and columns of the subraster are summed to form marginal distributions. The mean value of each distribution is computed and then the centroid of the data above this mean defines a new estimate of the object center. If the center moves to a different

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pixel the process is repeated using a raster about the new center. The iterations continue for a maximum of three times.

2. Background Determination

A constant background is determined from an annulus centered on the object with inner edge given by a specified fitting radius plus a buffer distance. The outer edge is then specified by a annulus width. All pixels with pixel center radii within the annulus limits are sorted by value into a one dimensional array using the *qsort* algorithm. The point of minimum slope in this array, using a numerical derivative length of 50% of the pixels, defines the background level. For integer valued images this algorithm is modified by first adding a uniform random dither value between -0.5 and 0.5 in order to avoid multiple regions of constant values; i.e. slope of zero. This algorithm is a bin-free method of measuring the mode.

3. Enclosed Flux Profile and Intensity Profile

The background subtracted, azimuthally symmetric enclosed flux profile is determined at a set of nonuniformly spaced radial intervals, dr. Similarly, the image pixels are subsampled with different subsample sizes, dx and dy, depending on the radius of the pixel center. The sampling intervals and sizes are given by

$$\left.\begin{array}{l} dr \\ dx \\ dy \end{array}\right\} = \left\{\begin{array}{ll} 0.05 & r < 1 \\ 0.10 & r < 2 \\ 0.20 & r < 4 \\ 0.50 & r < 9 \\ 1.00 & r > 9 \end{array}\right.$$

This nonuniform sampling is done to give fine profile resolution near the PSF center, particularly for narrow PSFs, but avoid increased memory and computation time requirements for very large PSFs.

Bi-cubic spline image interpolation is used for evaluating the pixel value at each subpixel. This value is background subtracted and added to all points in the enclosed flux profile which contain the pixel. Even with pixel subsampling there are points where a subpixel straddles a particular radius in the enclosed flux profile. When this happens the fraction of the subpixel with radius interior to the enclosed flux radius is used to define the fraction of the subpixel value included in the enclosed flux.

Because of errors in the background determination due to noise and contaminating objects it is sometimes the case that the enclosed flux is not completely monotonic with radius. The enclosed flux normalization is the maximum of the enclosed flux profile even if it occurs at a radius less than the maximum radius. It is possible to change the normalization and subtract or add a background correction interactively.

A cubic spline function is fit to the normalized enclosed flux profile at the measured sample radii. This interpolation function is then used for such things as determining the radius enclosing a specified fraction of the flux.

The intensity radial profile, $P(R)$, is related to the enclosed flux radial profile, $F(R)$, as given below. The derivative is estimated using simple numerical differentiation.

$$\begin{aligned} F(R) &= \int_0^R P(r) r dr \\ P(R) &= (dF/dR)/R \end{aligned}$$

4. PSF Radii and FWHM

One of the key measures of the PSF is a radius or width. The width is determined at a specified fraction, f, of the enclosed flux; for example the width enclosing 50straightforwardly from the continuous interpolation function of the enclosed flux profile. Another common measure used in the literature for characterizing the PSF width is the full width at half maximum, $FWHM$, of the intensity radial profile. This is also often determined by assuming a Gaussian profile. Making this assumption the radius at the specified fraction can be converted to an equivalent Gaussian $FWHM$ using the equation

$$FWHM(f) = 2R(f)\sqrt{\ln(2)/\ln(1/(1-f))} \tag{1}$$

By varying f one can also make plots of $FWHM$ verses f. This gives an interesting way to see departures of the PSF from Gaussian. A Gaussian PSF will have a constant $FWHM$. Increasing or decreasing $FWHM$ will indicate wings, sharp cores, out of focus, or other shapes.

5. Gaussian Subtraction Algorithm

Even with fine pixel subsampling, using an image interpolation function, and partial pixels at the boundaries, the enclosed flux profile has significant errors when the PSF is narrow. This is because the image interpolation function may only have a few pixels to fit and determine a shape that is very rapidly varying. The solution to this is to use a physically realistic analytic function to model the rapid variation.

The analytic model is an azimuthally symmetric Gaussian. The Gaussian width is estimated using equation (1) with a fraction of 80normalization is set such that the integral of the model over the central pixel is equal to central pixel value. The model is then subtracted from the image subraster and the cubic spline interpolation function is fit to the residuals which are now much more slowly varying. The enclosed flux profile is then reevaluated with subpixel values given by the sum of the model at that point plus the interpolation function value from the residuals.

This Gaussian subtraction is only done if the first $FWHM$ estimate is less than 4 pixels. If the $FWHM$ is less than 2 pixels even the Gaussian model subtraction is not adequate since the initial $FWHM$ is significantly biased to broader values. What is done in this case is that an empirical correction is applied to this measured $FWHM$. The correction is determined from simulations with known $FWHM$ by comparing the true $FWHM$ with the measured

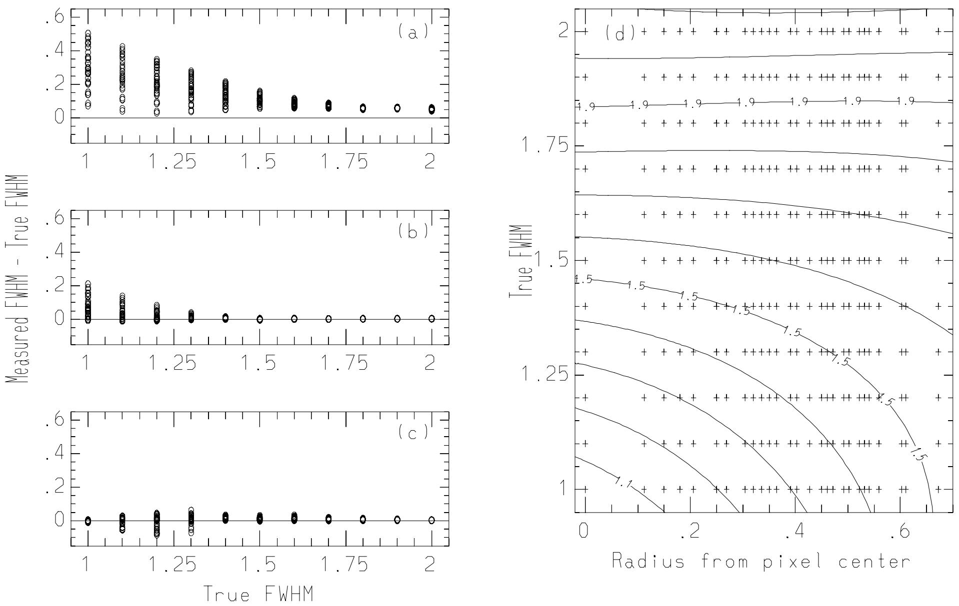

Figure 3. Results of simulations with noisefree Gaussian profiles at varying $FWHM$ and center. (a) The $FWHM$ error without model subtraction. (b) The $FWHM$ error with model subtraction but no empirical $FWHM$ correction. (c) The $FWHM$ error with both empirical $FWHM$ correction and model subtraction. (d) The correction surface showing the measured uncorrected $FWHM$ as a function of true $FWHM$ and pixel center. The symbols mark the simulated profiles.

$FWHM$. The correction is actually a function of the measured $FWHM$ and the center of the object relative to a pixel center. This is because a narrow PSF centered on a pixel will appear sharper than those centered near the boundary with other pixels. This algorithm allows accurately recovering PSF widths down to a $FWHM$ of 1 pixel.

In the figures a series of Gaussian profiles with varying $FWHM$ and center are sampled as a noisefree image (each point at the same true $FWHM$ has a different subpixel center). Figure 1a shows the error in the $FWHM$ as a function of the true $FWHM$ when the Gaussian subtraction algorithm is not used. In figure 1b the algorithm is applied without correction to the initial $FWHM$ estimate. Figure 1c shows the result with the correction to the $FWHM$ applied. The correction surface is shown in figure 1d where the marks are the simulated objects and the contour lines are at constant initial measured $FWHM$. This is basically a surface fitted to the points of figure 1a. The surface shows that the greatest correction is needed at the smallest true $FWHM$ and for centers furthest from a pixel center.