PRAIA Photometry Task

Version 3.0.4

- User Guide -

Marcelo Assafin

Universidade Federal do Rio de Janeiro - Observatório do Valongo, Brazil

(Federal University of Rio de Janeiro - Valongo Observatory, Brazil)

First V3 release (version 3.0.0): 11 January 2019

Last V3 release (version 3.0.4): 11 January 2023

Copyright (c) 2023 PRAIA Marcelo Assafin

==========
PRAIA Software License
==========

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the Software), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

Note

1. THE SOFTWARE IS PROVIDED AS IS, WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.

2. SOFA SOFTWARE USED BY PRAIA IS UNDER SOFA SOFTWARE LICENSE

3. NUMERICAL RECIPES SOFTWARE USED BY PRAIA IS UNDER NUMERICAL RECIPES SOFTWARE LICENSE

Correspondence concerning PRAIA software should be addressed as follows:

Internet email: massaf@ov.ufrj.br (insert the word "PRAIA" in the subject)

Postal address:

Marcelo Assafin - PRAIA
Observatorio do Valongo
Ladeira do Pedro Antonio 43 - Saude
20.080-090 Rio de Janeiro, RJ, Brazil

Contents

1 Introduction **5**

2 Differential Aperture Photometry with PRAIA **5**

3 PRAIA Photometry **6**
3.1 Pixelized Circular Aperture Photometry . . . 6
3.1.1 Flux and area equalization . . . 7
3.2 Guide, Calibrators, Targets and Ghosts . . . 9
3.3 Object detection and location in the images; aperture optimization with BOIA . . . 10
3.4 Object centring . . . 11
3.5 Object tracking . . . 11
3.6 Photometry modes . . . 12
3.6.1 Photometry mode 0 . . . 12
3.6.2 Photometry mode 1 . . . 12
3.6.3 Photometry mode 2 . . . 12
3.6.4 Photometry mode 3 . . . 13

4 PRAIA Light Curves **14**
4.1 Building light curves from photometry measurements . . . 14
4.1.1 Multi-layered filtering of outlier LC points . . . 14
4.2 Removing intruding flux in light curves . . . 16
4.2.1 Method 1: using occultation images and the occultation star flux from calibration images . . . 16
4.2.2 Method 2: directly using the body flux from calibration images fraction LC (FLC) 17
4.2.3 Method 3: directly using the body flux from calibration images separate LCs for body and occultation star . . . 17
4.2.4 Output information for methods 1, 2 and 3 . . . 17

5 Creating the Executable Code and Running the Task **18**

6 Configuring the PRAIA Photometry Task **20**

7 Configuring the Task for Photometry Measurements **20**
7.1 Input list of FITS images for photometry . . . 20
7.2 Reference image . . . 21
7.3 Range of FITS images for photometry . . . 21
7.4 Pixel mask of bad rectangle regions . . . 22
7.5 Pixel mask of bad circular regions . . . 22
7.6 Pixel mask of bad ADU counts . . . 22
7.7 Output photometry file name . . . 23
7.8 Output ds9 batch movie file name . . . 23
7.9 Output astrometry file name . . . 23
7.10 Module: FITS header keys for image information extraction . . . 23
7.11 Module: Input time information . . . 25
7.12 Module: User time . . . 26
7.13 Fix hot/cold pixels . . . 26
7.14 Signal-to-noise ratio computation setup . . . 26
7.15 Pixel scale . . . 26
7.16 Aperture flux equalization . . . 27
7.17 Module: Automatic object identification (photometry mode 3 only) . . . 27
7.18 Guide identification: range of the FOV . . . 27
7.19 Module: Guide . . . 28
7.19.1 Module: Guide - photometry mode 0 . . . 28
7.19.2 Module: Guide - photometry mode 1 . . . 28
7.19.3 Module: Guide - photometry mode 2 . . . 29
7.19.4 Module: Guide - photometry mode 3 . . . 30
7.20 Module: Calibrators . . . 30

7.20.1 Module: Calibrators - photometry mode 0 . . . 31
7.20.2 Module: Calibrators - photometry mode 1 . . . 31
7.20.3 Module: Calibrators - photometry mode 2 . . . 32
7.20.4 Module: Calibrators - photometry mode 3 . . . 33
7.21 Module: Targets and ghosts . . . 33
7.21.1 Module: Targets and ghosts - photometry mode 0 . . . 34
7.21.2 Module: Targets and ghosts - photometry mode 1 . . . 34
7.21.3 Module: Targets and ghosts - photometry mode 2 . . . 35
7.21.4 Module: Targets and ghosts - photometry mode 3 . . . 35
7.22 Module: Best fixed aperture time window and flux ratio setup (mode 1 only) . . . 36
7.23 Target in low count regime; Module: Time windows for target events . . . 37

8 Configuring the Task for Building a LC from Photometry Measurements 38
8.1 Output file names: PPT LCs, User-defined LC module . . . 38
8.2 MLF keys and cutoff values and factors for FWHM and flux ratio errors . . . 39
8.3 Module: User time . . . 40
8.4 Module: Selection of best calibrators . . . 40
8.5 Module: Smoothing calibration flux . . . 41
8.6 LC smoothing and binning . . . 41
8.7 Target flux contamination correction . . . 42
8.8 Flattening and normalization of calibration, target and flux ratios . . . 42
8.9 Module: Time windows for target events . . . 43
8.10 Flux offsets for plotting/analysis purposes . . . 43
8.11 Input photometry measurements . . . 43
8.11.1 Module: Time instants of input photometry file . . . 44
8.11.2 Module: Input photometry file format . . . 44

9 Configuring the Task for Eliminating the Intruding Flux in a LC 45
9.1 Label, input/output LCs, report file names . . . 46
9.2 Input times, time modules and fluxes in the input LCs; polynomial fittings . . . 47

10 Output PPT photometry file formats 48
10.1 Output PPT photometry file format . . . 48
10.2 Output PPT (x,y) astrometry file format . . . 50

11 Output PPT light curve building file formats 51
11.1 Output PPT main light curve file format . . . 51
11.2 Output PPT quick look light curve file format . . . 53
11.3 Output PPT User-defined light curve file format - Module User-defined output LC file . . . 53

12 Output PPT light curve intruding flux file formats 54
12.1 Output report with intruding flux ϕ_o solutions . . . 54
12.2 Output "compact" sanity-check LCs . . . 56

13 Running the Task - Examples 56
13.1 Example 1: running PPT photometry block . . . 56
13.2 Example 2: running PPT LC building block . . . 58
13.3 Example 3: running PPT LC intruding flux block . . . 59

1 Introduction

This document presents the functionalities of the PRAIA photometry task, release version 3.0.4. In any publication that made use of the PRAIA photometry task, please insert the sentence "This work made use of the PRAIA package." in the Acknowledgements. Please also cite in your publication the following article that describes in detail the PRAIA photometry task, its concepts and essentials: Assafin (2023a).

PRAIA stands for "Package for the Reduction of Astronomical Images Automatically". It is a standalone package fully developed in FORTRAN with no graphic interfaces. It is composed of multiple independent tasks. Each task is characterized by its source/executable code and its input text file (ASCII format) with editable input parameters. The tasks can be run in scripts for the astrometry and photometry of observations in (standard or not) Flexible Image Transport System (FITS, Wells et al. 1991) format. PRAIA allows full control by the user to manipulate input and output data with his/her own preferred external statistical, plotting and visualization tools. The tasks of the PRAIA package are publicly available at https://ov.ufrj.br/en/PRAIA/.

An important task of the package used in photometric works is the PRAIA photometry task – hereafter PPT. The PPT usage is twofold: do differential aperture photometry over digitized (FITS) images and build light curves. This task is suited for (but not limited to) the treatment of differential photometric observations of solar system bodies (asteroids, Centaurs and transneptunian objects, natural satellites, planets and dwarf-planets) for the analysis of rotation, stellar occultations and mutual phenomena.

2 Differential Aperture Photometry with PRAIA

In differential aperture photometry we only need the relative variation of fluxes rather than measuring absolute fluxes in a standard photometric system. If observations are made with a sufficiently small Field-Of-View (FOV) which is usually the case one can profit from the differential photometry technique and measure relative flux variations with high internal accuracy and precision. In differential photometry, any non-photometric-standard stars or even any Solar System bodies can be used as photometric calibrators. Since the same systematic effects affect the target and calibrator fluxes in small FOVs, systematic errors are canceled out after the calibration procedure, resulting in high-precision, highly accurate relative flux measurements. No calibration images are needed in differential photometry, simplifying telescope observations and data treatment without any concession to accuracy/precision.

Differential photometry has been successfully applied, particularly in Solar System studies involving the observation of rotational light curves, stellar occultations and mutual phenomena. Rotational light curves are used in the determination of the proportion of axes and eventually in the limits of the density of Solar System bodies. Stellar occultations serve to obtain highly accurate and precise sizes and shapes for the occulting bodies, mostly if combined with rotational data. Mutual phenomena furnish highly accurate and precise relative positions in the sky plane between the involved bodies.

PPT is thus particularly suited for the treatment of such Solar System observations. Due to the nature of stellar occultations and mutual phenomena observations, we avoid Point-Spread-Function (PSF) photometry. In stellar occultations the target is made of two mixed PSFs those of the body and of the star to be occulted. The apparent distance between these objects vary along the event and at some point the body may only partially obstruct the star. A similar situation arises in mutual phenomena with two bodies at play. The resulting PSF model in these cases is unclear and the use of Gaussian or Moffat profiles may yield to biased results. Even if an empirical PSF can be numerically obtained, the procedure is highly computer-time consuming, with no guarantee of satisfactory results. In stellar occultations, short exposure times let objects in a low signal-to-noise ratio regime for better time/spatial resolution, and the target star may be totally occulted, making it very difficult or impossible to fit a PSF.

PPT only uses aperture photometry. Aperture photometry techniques are more flexible and can successfully measure the light of targets in all situations described above, even in the cases of partial or total flux drop during a stellar occultation. In particular, PPT uses a new aperture photometry procedure that we call "Pixelized Circular Aperture Photometry" (PCAP), improving photometry measurements with respect to standard procedures.

PPT performs photometry measurements and separately builds a light curve (LC). Photometry measurements can be made with PPT in running modes 0 to 3. Modes 0 and 1 regard to fixed aperture photometry. In mode 0 the user manually setups the aperture and sky background ring sizes of all objects. In mode 1, the aperture and ring sizes of all objects are sampled with a bisection method in order to automatically find the best set of fixed apertures and sky background rings for all objects. Modes 2 and 3 regard to varying aperture photometry. In mode 2, the user indicates which objects are calibrators

and which ones are targets. In mode 3, PPT automatically finds the target(s) - the one(s) with the most varying flux, with the rest of the objects (from brightest to faintest) taken as calibrators - the user only sets the numbers of targets and calibrators. In modes 2 and 3, the best aperture and sky background sizes are obtained for each object after sampling the aperture/ring sizes and searching for the set with the best signal-to-noise ratio (S/N). A flux equalization procedure is performed for all objects in modes 2 and 3 in order to compensate for the different aperture sizes. In all photometry modes, the location of object apertures - even for fast moving objects - is determined with precision and accuracy, without the need of identification and (α, δ) reductions with reference catalogue stars, or the use of Word Coordinate System (WCS) FITS header keys.

The building of a LC is performed by PPT with mode 4. Usually, a LC is the result of the ratio between the flux of the target with respect to the calibration flux from calibrators. PPT also has a special LC building procedure performed with mode 5, on which the intruding flux of an occultator can be determined and eliminated from the LC of an occultation.

Prior to proceeding for the next sections of this User Guide, we strongly recommend that the reader gets familiar with the concepts and essentials of PPT, the photometry modes 0 to 3, and the building of LCs with modes 4 and 5 described in detail in Assafin (2023a).

Together with PPT, we strongly recommend the use of a supporting visualization FITS image tool such as the image display program ds9[1].

3 PRAIA Photometry

In this section, we describe the novel aperture photometry procedure used by PPT called "Pixelized Circular Aperture Photometry" (PCAP). We present the PPT categories of objects, and briefly describe how the task identifies and track/locate objects in connection with the optimization of apertures. We also summary the four PPT photometry modes available for photometry measurements.

3.1 Pixelized Circular Aperture Photometry

Care must be taken with the circular (or any non-rectangular) shape of apertures due to the square form of pixels encompassed by object profiles in CCD or digitized images. It is computer-time expensive to calculate for all measurements the partial area of pixels intersected by the aperture circumference, be it made numerically by pixel sub-sampling or with analytical formulae linked to complicated geometrical schemes – see for instance Gendler et al. (2018). Besides, there are no satisfactory extrapolation schemes that can precisely enough furnish the true flux under a given partial pixel area, unavoidably resulting in a net flux error propagation in the measurements.

Bickerton & Lupton (2013) give a good summary of this known and unsolved problem in classical circular aperture photometry work. Nevertheless, they present a way to measure the exact flux within the exact circular area of a given circular aperture, under few assumptions, by the use of sinc functions. The procedure involves Fast Fourrier Transformation computations and predefined indexing of parameters for a wide range of aperture radii. The method can be extended to elliptical apertures and will be applied on LSST aperture photometry. Unfortunately, their method involves heavy computations at some stages, being only suited for a single and quite stable instrument/detector, as is the LSST case. This condition is opposed to the huge variety of instruments/detectors and observations that PPT is designed to be used for.

All this motivated us to find a new approach for doing circular aperture photometry, which we call Pixelized Circular Aperture Photometry (PCAP). This is not to be confused with pixel mask photometry. PPT uses circular aperture radii only in a nominal basis, and does not try to compute or make extrapolations to obtain the flux that would be encompassed by an exact circular area.

The photometric principle is to only measure an integer number of pixels which corresponds as close as possible to the area of a circular aperture with a given nominal radius, thus avoiding any kind of pixel sub-sampling, intersection area calculations or flux extrapolation schemes. PCAP was developed and implemented by us in the last PPT version 3, proving to be quite fast an precise.

The total area of a circular aperture is not the sum of pixels internal to the circle, since the pixels are square in size. Only as the aperture size grows, the internal pixels will form figures with areas more and more similar to the total area of the circular aperture. Most importantly, for the same nominal aperture radius, mostly for small apertures, the number of pixels internal to the circle by any criterion may vary

[1] ds9 (SAOImageDS9): http://ds9.si.edu/site/Home.html

as the centre of the aperture lays on distinct parts of the central pixel – a pixel-centring effect that may occur in mask-based photometry if integer pixel photometry is carried out without proper care. Thus, depending on the centring, even using the same nominal aperture radius, the number of internal pixels contained inside the circular aperture could vary, even for the same object (from image to image, as the object centre varies even slightly in the FOV).

Thus, even when using fixed apertures, and certainly in the equalization of flux with variable apertures, if we take pixels internal to an aperture to measure flux, we still may be unwarily sampling different numbers of pixels for the same nominal aperture radius, i. e. taking different areas, and thus different fluxes. If we do not take this into account, we are ultimately adding noise to the measurement of the variation of the flux with time. It is not uncommon to find targets in rotation light curves, stellar occultations or mutual phenomena with small circular aperture sizes, when the problem gets worse.

`PCAP` does not parameterize the photometry by the nominal radius R of the aperture, not even by the corresponding nominal circular area. It parameterises the flux with respect to the *area* defined by an integer number of pixels that corresponds to the round off of the nominal area of the circular aperture of nominal radius R. For an aperture with nominal radius R=3.3 p (p = 1 pixel length), the total nominal area is $TA = \pi R^2 = 34.212$ p^2, while the round off area is $RA = 34$ p^2, or $RA = 34$ pixels, taking 1 pixel $\equiv$ p^2 as unit for area. Thus, the round off area RA associated to an aperture of radius R=3.3 pixels to be used in `PCAP` is $RA = N = 34$ pixels, where N is the number of actual pixels to be used in the aperture flux measurements. The pixels are sorted in accord to their distance to the objects centre. This properly takes into account the pixel-centring effects of mask-based photometry - for any given nominal aperture radius value R, there is always an unique number N of pixels associated to it, from the round off of the total aperture area in pixel units. `PCAP` can also be easily adapted for elliptical or irregular aperture shapes.

3.1.1 Flux and area equalization

`PCAP` allows for a robust equalization of the fluxes and areas of the apertures. The equalization is made in two ways depending whether the apertures are fixed or not.

For fixed apertures, `PCAP` equalizes areas straightforwardly. Each object i is measured on each image with its fixed respective aperture size R_i with associated pixel number (area) N_i. The sampled pixels are sorted in crescent distance order from the object centre, so that the resulting N_i pixels always covers the same area from image to image, but also adapts its form to essentially cover the same objects portions in the images, regardless of pixel-centring effects. In this way, by force, we are always measuring flux over exactly the same effective area around the object centre, for each object in all images.

For varying apertures, `PCAP` equalizes fluxes and areas simultaneously by constructing a Light Growth Curve (LGC). LGCs are suited here because of the usually wider range of aperture sizes that must be equalized. In varying aperture photometry, `PCAP` computes the flux F_i of each object i for the optimum aperture radius (and associated pixel area) found, based on the S/N of the flux, and register the radius R_i and the associated number of pixels N_i. The aperture radius R_i may vary considerably from image to image. We cope with this wide variation by constructing LGCs after sampling the brightest object in each image, as described next.

The observed LGC is obtained by sorting pixels in crescent distance from the brightest object centre and accumulating the flux as a function of the number of pixels (area). If not imposed by the user, `PCAP` arbitrarily fixes as reference the aperture radius R of the faintest target in the reference image, which corresponds to a number of pixels N related to the round off area of the aperture. Then, for each object i on each subsequent image, we use the observed LGC to deduce the ratio $F(N)/F_i(N_i)$, which represents the flux correction factor to take F_i to the corrected flux F of the object for an equalized area of N pixels. Since the accumulation of flux grows smoothly only for pixels within the same distance from the centre, we only use the pixels of the observed LGC that are within a ring of 1 pixel width and same radius as that of the objects aperture. Since we want to use as much information as possible, instead of computing the factor $F(N)/F_i(N_i)$ from $F(N)$ and $F_i(N_i)$ directly available from the observed LGC, we fit the observed LGC by a polynomial P and get $F(N)/F_i(N_i)$ from $P(N)/P_i(N_i)$. Empirical tests showed that a polynomial P of degree 2 fits well any observed LGC, when we take F as a function of the the number of pixels N_p. Fig. 1 displays an example of a polynomial fit to an observed LGC, where we display the number of pixels N_p used in the fitting. The (O-C) residuals (LGC P) is also plotted as a percentage of the LGC. The equivalent radius shown in the residual's plot is the radius of a circle with the same area as the number of pixels N_p. The plots indicate that P represents quite well the observed LGC within less than 0.15 per cent.

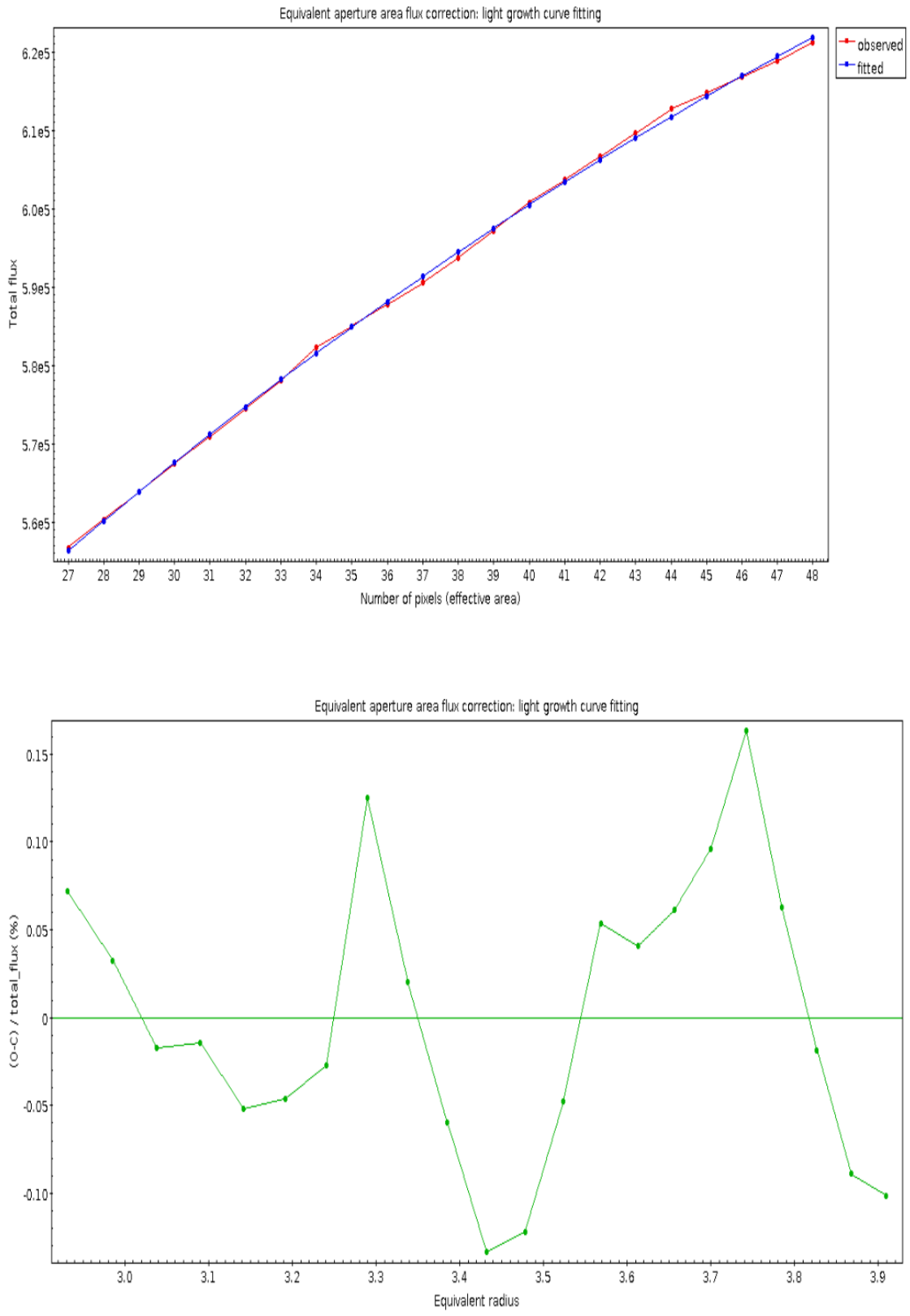


Figure 1: Top panel: Observed Light Growth Curve (LGC) (red) with accumulated pixel flux as a function of the number N of pixels sorted by distance from the centre of the brightest object on a FOV; a polynomial P of degree 2 (blue) was fitted as a function of N. Lower panel: (O-C) residuals = LGC $-$ P as a percentage of LGC; the equivalent radius in the plot is the radius of a circle with the same area as the number of pixels in the top panel. The polynomial model represents well the LGC within less than 0.15 per cent.

LGCs are evaluated for each object in the image to find the flux factor that will equalize each area (number of pixels) to the reference area. PCAP allows the user to set the reference aperture radius R for each object. This is equivalent to setting fixed apertures for each object for all images, but with the benefits of the varying aperture photometry. Unlike apertures, the sky background level and dispersion are completely insensitive to flux correction issues. Internally, PPT works directly with sky background level and dispersion in ADU/pixel units, so that sky background corrections can be easily applied when dealing with flux/pixel units, as is the case with PCAP. Also, for saving computer time, PPT only works internally with integer pixel units for the sky background ring radius and width.

PCAP proved to be more precise and faster than the method of pixel sub-sampling and/or internal/external ring extrapolation procedures used in previous task versions. That is probably because no interpolation or extrapolation for computing partial ADU flux counts of partial pixels is done anymore only entire integer number of pixels are considered and manipulated straightforwardly.

We do not use fixed masks - masks with a fixed geometry layout form with a fixed area or number of pixels. Fixed masks force the sampling of inappropriate border pixels with distinct flux levels from image to image, depending on the location of the object centre within the central pixel, resulting on higher flux dispersion along the images. In PCAP, the pixels are naturally added by their distance from the object centre, and do not form a fixed mask with a predefined geometric format. The object is sampled from one image to the other by the same number of pixels, distributed as homogeneously as possible around the object centre, resulting on masks of variable geometric formats with the same fixed number of pixels that sample more coherent flux levels from image to image, resulting on a smaller flux dispersion in the measurements.

3.2 Guide, Calibrators, Targets and Ghosts

PPT works with 4 categories of objects: the guide, calibrators, targets and respective ghosts. The guide object serves to automatically locate the calibrators and targets in the FOV of all images. The calibrators serve to calibrate the flux of targets in the ways of differential photometry. The targets are the objects of most scientific interest at hand being measured. The ghosts serve for sky background comparisons with their respective targets. A ghost should present fluxes varying around zero, since in principle it is the clean flux of the local sky background. For each target, its ghost is a nearby empty-object centered at a fixed relative distance to its target, sampling a region dominated by the local sky background, with the same aperture and sky background ring sizes of its target. A target or a calibrator may also be the guide object. The guide, the calibrators and the targets may or may not be moving objects in the FOV.

It is well known that in most cases the FITS headers of images lack sufficient information for the identification of objects by their right ascension and declination, even when the FOV contains enough reference stars. Also, sometimes the FOV does not contain enough reference stars, preventing pixel reduction to spherical coordinates even in the presence of some WCS keys. That is why the PPT does not identify objects by their right ascension and declination positions, or by some sort of positioning from the FITS header keys in compliance with the Word Coordinate System (WCS). Thus, in what concerns the identification of calibrators and targets in all images, the complete absence of any WCS information in the headers of the FITS images is of no importance at all to this task.

PPT locates the calibrators and targets in all images by the use of a guide object. The ghosts are located by their fixed relative distances with respect to the coordinates of their respective targets. The guide must be the brightest object in a fixed region of the FOV for all the images set for processing. The fixed region "dominated" by the guide can have any size; it can even be the entire FOV. The guide is automatically searched and identified in all the images.

For the correct location of calibrators and targets (and their ghosts), it is mandatory that: a) the guide be always present within the furnished fixed region in all images; b) the calibrators and targets be always present within the FOV in all images; c) the sky in the images being processed have the (x, y) axis orientation and pixel scale fixed or varying in a way that can be modeled by a polynomial of degree N (N<21) with time. One can easily set up the guide object search because, usually, the set of images come from a run with the same instrument set up.

The pixel coordinates of calibrators, targets and ghosts can be directly set up by the user. They are later automatically referred to the guide coordinates by the task. This is done by setting the coordinates of these objects on the FOV of a chosen reference image (see comments in the next paragraph). In particular, one usually wants that at least some of the brightest objects available in the FOV can be used as calibrators because of their signal-to-noise ratio (S/N). PPT may also be set up so as to automatically detect and locate the best calibrators alone, or best calibrators and targets (and their ghosts), in the chosen

reference image. Or PPT can even be set up to fully automatic mode. In this case, PPT automatically searches for and select the best reference image, then automatically searches for, detect and locate the best calibrators and the targets (and their ghosts). In this case, the pixel coordinates of the calibrators and targets (and their ghosts) relative to the guide are also computed automatically.

The reference image shall contain all the four types of objects: the guide, the calibrators, the targets and their ghosts. The user should avoid by all means choosing a reference image in which one or all targets have low S/N, such as during a stellar occultation or a mutual event, or (to a lesser extent) in the minimum phase of a rotation light curve. It is recommended, although not mandatory, that the reference image be one of the best sampled images in terms of the S/N of the targets. The criteria used for defining the reference image when PPT is set up to fully automatic mode is to pick up the image containing an object - actually the guide with the highest S/N among all images, withing the region of search of the guide. The region can be a limited one or encompass the whole FOV. It is up to the user to be sure that the object found in automatic mode fulfills all the previously stated requirements to be the guide.

The maximum allowed number of calibrators, as well as targets (and thus ghosts) that can be input and output by PPT is 20. It is not caused by any drawbacks in the search algorithm. It is rather a numeric computer overflow imposition due to an advanced functionality of PPT in the automatic selection of the best calibrators, among all available, at the building stages of a light curve. The limitation for targets and ghosts are related to computer overflow memory issues.

Note that these limitations do not apply during the automatic search of objects. A much higher number of candidate objects are stored and analyzed, prior to the final classification and registration of calibrators and targets (ghosts). Virtually all objects in the FOV of the reference image above a certain S/N threshold input by the user are stored and analyzed at this stage. Targets may or may not be among the faintest candidate objects this poses no problem for their automatic identification. Even so, the user may still want to secure the target(s) and let the job of automatically finding only the calibrators to PPT. When this is the case, the user manually sets up the targets coordinates in the reference image and let the best calibrators (the remaining objects with the highest S/N available) be searched automatically. In this case, the reference image must be set by the user.

In the automatic selection, all objects get provisional aperture sizes and are probed in all images. Objects for which the aperture radius falls outside of the FOV, even if for one image only, are excluded. Only the candidate objects that survive all these filters pass the automatic selection of calibrators and targets.

When PPT automatically searches for targets, it does so among all the objects picked up in the (automatically or not) selected reference image. The automatic search works for any number of targets, but in the majority of cases, there is only 1 target in the FOV. The calibrators are objects with the most steady flux along the images. The targets are the objects that shall have the highest flux variation in the series of images, if we are dealing with one of the following cases: rotation light curve, stellar occultation, mutual phenomena, variable stars and transient events in general. PPT searches for the objects with the highest flux variation along the series of images and sets them up as the targets. The remaining objects are set up as calibrators. Then, all images are processed again for the final photometry, but now the target (or targets) and calibrators are processed in accord to the parameters set up separately for calibrators and targets. It is at this definite stage of the photometry processing that we limit to 20 the number of targets and calibrators.

3.3 Object detection and location in the images; aperture optimization with BOIA

Frequently in most tasks setups, PPT must detect, then locate an object (guide, calibrator, target) on the FOV of an image. Here, we briefly summarize how it is done. We call this procedure BOIA (Browsing Objects: Identification and Analysis, see Assafin 2023a).

Since the detection implies in locating the object, and since we want to locate the object with the highest possible precision and accuracy, BOIA also incorporates, in a natural way, the search for the best aperture and sky background ring in terms of S/N.

In BOIA, the FOV is recursively scanned and candidate objects are found. The procedure then searches for the best aperture and sky background ring radius and width. It tests (x, y) centres, aperture sizes, sky background radii and widths and selects the set that furnishes the best S/N ratio. The sky background ring width is tested in bins of 1 pixel, with a maximum size furnished by the user. The aperture radius is tested by incrementing values in bins between 0 and 1 pixels set by the user. In the case of the sky background ring, the bin for increments is 1 pixel. The (x, y) centre is obtained by a 2D Gaussian fit or from the Photogravity Center Method (PGM, see Assafin 2023a).

BOIA is used in its full form in the automatic search for calibrators and targets in the reference image. It is also recurrently used in the search for the guide object alone, when only part of the FOV may be used, and just the first (brightest) object is picked up, after which the process is stopped. BOIA is also recurrently used in photometry modes 2 and 3 in the measuring of calibrators and targets.

If any problem arises in the BOIA when the reference image is being processed, then PPT emits a warning and then stops. It is mandatory that the guide, all the calibrators and targets pass the BOIA procedure when the reference image is being processed. The problems that cause the task to stop are an insufficient number of objects detected, centring failure and flux and/or sky background computation failures.

For the remaining images, if the problems above occur with the guide or with any one of the calibrators and targets, the image is simply skipped and the processing continues to the next image.

It is important to notice that the procedure that searches for the best aperture and sky background ring radius and width in terms of S/N is further used in subsequent stages of the photometry, after all objects have already been identified. In particular, the procedure may be only partially used. For instance, the optimization of the S/N may be done by using a fixed (x, y), when only the aperture and sky background ring are improved. Conversely, the optimization of the S/N may be done for finding the best (x, y) alone, by using a fixed aperture and sky background ring.

3.4 Object centring

We do not need to stress the importance of a good aperture centring in order to take the best out of aperture photometry. When it is needed, PPT performs astrometry, or more specifically, high-precision object centring. There are currently two centering algorithms in PPT for determining the (x, y) centre of objects in the FOV: the Photogravity Center Method (PGM, see Assafin 2023a) and the 2D Gaussian fitting. The user sets which centring method is to be used (it can even be both) for each one of the object types: guide, calibrators and targets.

On any of the centering methods, only pixels within a given circular region are effectively evaluated and eventually used.

PPT performs object centring on many instances, for example in the objects of the reference image, on the automatic detection and location of objects, in the updating of the (x, y) centres of moving objects in all images or when the tracking option is set "0", or in the procedures related to finding the best aperture and sky background ring in the reference image and/or in all images.

If any problem arises in the centring of any object when the reference image is being processed, then PPT emits a warning and then stops. It is mandatory that the guide object, all calibrators and targets pass the centering procedure when the reference image is being processed. For the remaining images, if any centering problems occur with the guide or with any one of the calibrators or targets, the image is simply skipped and the processing continues with the next image.

3.5 Object tracking

There is no restriction about the guide, calibrators or targets being moving objects (Solar System bodies of any kind) in the FOV. PPT tracks moving objects relative to the guide (which can in turn be itself a moving object). As the object-guide relative distances (dx, dy) change with time from image to image, they are fitted by (dx, dy) polynomials in time of degree N (N defined by the user). In this way, the relative position of each object with respect to the guide is projected to the mid-instant of the next image to be processed, so that the (x, y) location in the FOV is foreseen and each object can be correctly identified. The tracking function option "+1" of PPT is used in such cases. The user can set up parameters for the elimination of outliers in the (dx, dy) polynomial fittings by a sigma-clip procedure in order to improve the fittings.

When the object does not change its relative position with respect to the guide, the user has 4 tracking options with the tracking function, each one affecting in distinct forms the way that the final (dx, dy) relative distance object-guide will be computed and, thus, the final (x, y) location of the object in the FOV of each image.

The first tracking option is "-1". This makes the task use always the same object-guide relative distances (dx, dy) for all images. The fixed (dx, dy) relative distances are setup from the (x, y) centre measurements made for the object and the guide in the reference image.

The second tracking option is "-2". This also fixes the object-guide relative distances (dx, dy) for all images. The difference is that the fixed (dx, dy) relative distances for the object and the guide come from their input (x, y) coordinates furnished by the user in photometry modes 0, 1 and 2 - in mode 3, these

input (x, y) coordinates are automatically computed in the objects detection and location step. This option is useful in the case of nearby objects which prohibits any (x, y) centre updating, even for the reference image.

The third tracking option is "0" which allows for (x, y) object position updates. This makes the task assume that the object-guide relative distances (dx, dy) are fixed, but at each image the (x, y) center of the object is updated, so that the (dx, dy) distances are also updated, and used for the next image to be processed. In this way, the (dx, dy) relative distances are always updated from one image to the other, based on the (x, y) object update of the last processed image.

The forth tracking option is "+1", but using a trick in the polynomial fittings. Setting up tracking option "+1" but with degree N=0 actually implies that the object-guide relative distances (dx, dy) are fixed with respect to time, but at each image the (dx, dy) are updated by the new polynomial fit from all past images processed, and not from the update of the last image only as in option "0". In a sense, this gives a more robust determination for the (dx, dy) relative distances. The (x, y) centre of the object is thus updated, and so are the (dx, dy) distances, used for the next image to be processed. In this way, the (dx, dy) relative distances are always updated from one image to the other, based on the (dx, dy) fits of all the past processed images.

3.6 Photometry modes

We describe here the four photometry measuring modes carried out by `PPT`.

3.6.1 Photometry mode 0

In mode 0, photometry measurements are made with fixed apertures and sky background rings (fixed radii and widths) manually setup by the user.

3.6.2 Photometry mode 1

In mode 1, photometry measurements are still made with fixed apertures and sky background rings (fixed radii and widths), but `PPT` automatically finds the best aperture/ring set for each object. The user sets up the aperture and sky background ring radius and width search ranges and bins. The best set of fixed apertures and sky background rings and widths for the guide, each calibrator and target are those for which a provisional flux ratio target/calibration presents the least dispersion at the given time window sections defined by the user. There are two methods to find the best set of apertures and sky background rings: brute force and the bisection method. The bisection method works as follows. Given two limit values V_1 and V_3 for a certain LC parameter (aperture, sky background ring radius or width), we compute the middle value V_2. Now we take the middle values between V_1 and V_2 and V_2 and V_3 - V_{12} and V_{23} - and produce 2 provisional LCs using parameter values V_{12} and V_{23} (keeping the other LC parameters fixed). The LC presenting the least dispersion is kept. It is associated to parameter value V. Now we pick up the two nearest values to V, with V as the middle value, and set them as the new two limit values. For instance, if $V = V_{12}$, then the new limits would be V_1 and V_2. We repeat the procedure until the difference between the previous and current LC parameter value V converges. The procedure is then repeated for other LC parameters. The bisection method allows for a much wider sampling of apertures, ring widths and radii without precision loss. Due to the nature of the method, its rapid convergence for the best set of values dramatically improves the speed of the processing with respect to the standard brute force search method. In general, we recommend the use of the bisection method instead of the brute force procedure in mode 1.

3.6.3 Photometry mode 2

In mode 2, the user still explicitly indicates the calibrators, targets and ghosts by manually furnishing their (x,y) coordinates on the reference image. But much fewer parameters must be furnished with regard to modes 0 and 1. And the photometry measurements are made with variable apertures and sky background rings. Above all, the aperture sizes and the radius and width of the sky background rings are automatically found by `PPT`, when the best S/N ratios are obtained for the guide, calibrators and targets. The obtained clean fluxes can be equalized (due to the use of variable apertures) for each image only, or they can be equalized for all images (recommended option). There is also an option (option 3) that allows for the user to select the best apertures and sky background rings for each object in the reference

image, then fix these apertures and rings and use them for all remaining images. Finally, the user can also choose not to equalize fluxes/apertures at all.

The user can also set a limit for the radius size of the apertures of each object. This avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images.

Effective on mode 2 only, the user can now also set the reference aperture radius for each calibrator and target, to be used in the equalization of apertures/fluxes. Otherwise, the automatic default setup is to use the smaller aperture among targets in the reference image. The corresponding entry is now included in calibrator and target modules for mode 2 only.

3.6.4 Photometry mode 3

In mode 3, all the photometry can be made fully automatically. And we mean it! The user does not need to explicitly indicate what are the guide, calibrators, and even the targets (!!) and ghosts (!). There is no need to manually inputting their (x,y) coordinates on the reference image. Even the reference image can be automatically selected by `PPT`! Actually, there is an option for the user to manually indicate the targets by their (x,y)s only, if that is needed. But the guide and, specially, the calibrators are all fully automatically found. The photometry measurements are carried out with variable apertures and sky background rings in exactly the same way as for mode 2.

The identification of the guide and the definite photometry of the found calibrators, targets and ghosts in all images (including the reference image) are setup apart and performed in sequence. After the automatic identification of candidate objects, a second step eliminates objects which present problems in the (x, y) centring in the reference image. Finally, with provisional apertures set for each object, all images are verified and further objects are eliminated if the aperture radius gets outside the FOV, even if for one image only. Then, we segregate the surviving objects as calibrators and targets. For that, we conduct a provisional astrometry/photometry on all the images. The centring is made with the fast PGM method (Assafin, 2023a). Object tracking along the images is performed, according to the users set up. Then, we obtain a provisional raw light curve for each object, based on their clean fluxes (no calibration is available at this step, of course). Each light curve is then normalized by the highest fluxes found for each object. The targets are selected as the objects with the higher flux dispersions among all objects. Indeed, this is always the case when working with rotation light curves, stellar occultations, mutual phenomena, variable stars and transient events in general. The remaining objects are then set as calibrators.

In the automatic identification of objects, the guide is automatically found on each image. Using the reference image, all the other objects detected by `BOIA` have their input (x, y) coordinates automatically computed and referred to the guide coordinates. As usual, the objects are then identified in all the other images by their relative coordinates to the guide, following the (x, y) tracking option setup in this module. Here, the useful `PPT` tracking option "-2" (fixed distance from user-input coordinates) is of course not available, as no such coordinates are input by the user in mode 3. Tracking option "-1" fixes the relative coordinates found with the reference image for that object with respect to the guide for all images. Option "0" also fixes the relative distance to the guide, but allowing for small corrections by the update of the object (x, y) centre from image to image. Tracking option "+1" is suited for moving objects. The (x, y) centre is always updated for the next image, but with larger (x, y) corrections, based on proper motions in (x, y) taken with respect to the guide, and computed with polynomials of degrees nx and ny for x and y, using all images processed so far. In particular, setting degree zero will have the same effect of tracking option "0", but with the small (x, y) corrections taken over all past-processed images and not in an image-to-image basis. Outliers are eliminated in the polynomial fits with a sigma-clip procedure. If the tracking option is set to "0", "-1" or "-2", the tracking information regarding to polynomial fittings in the respective lines in the module input data file must still be present, but are ignored.

Thus, regarding to the tracking option in the automatic procedure, we recommend that option "+1" and polynomials of degree higher than 0 (usually N=1 will suffice) be set only if at least one of the targets or calibrators are known to be a moving object. If this is not the case, we recommend the use of option "0", or option "+1" with a polynomial of degree N=0. By "moving" object, we mean an object which movement in the FOV along the images is actually detectable, or measurable, within (x, y) errors.

One last comment about the automatic selection of calibrators and targets of mode 3. The user must be sure that the automatic setup will actually allow for the detection of the targets. This is easily accomplished when there are few objects in the FOV or when the targets have similar brightness to the calibrators. But when the targets are very faint with respect to the calibrators, the user must pay attention to the S/N threshold, in order to effectively allow faint objects to be detected, with the targets

among them. Once detected, it is relatively easy for PPT to identify the targets by their larger flux variations with respect to the more steady fluxes of the calibrators.

Once the automatic selection of calibrators and targets is finished, they have their (x, y) coordinates referred to the guide coordinates in the reference image. From this point on, PPT is ready to proceed with the definite astrometry/photometry procedures for all the images, starting by the reference image.

As in mode 2, the user can set a limit for the radius size of the apertures of all objects. This avoids problems in the BOIA method due to crowded FOVs, nearby objects or features (like FOV borders) in the images.

4 PRAIA Light Curves

We strongly recommend the user to read Assafin (2023a) for more detailed information.

PPT can create LCs from previously made photometry measurements. And it can eliminate intruding flux in a LC. Creation of LCs are made with PPT in mode 4, with a specific LC block in the PPT main input data file (Section 8). This is by far the most commonly used PPT feature in terms of LCs. Another much more rarely used PPT feature is the elimination of intruding flux in a furnished LC, made in mode 5 with another specific LC block (Section 9).

4.1 Building light curves from photometry measurements

A light curve (LC) from PPT presents target/calibration flux ratios as a function of time. Often, we flat and normalize the flux ratio by taking portions of the photometry measurements as reference. The task works with 1 target per run, and every procedure applied to the target is also applied to its ghost.

LC building is performed by PPT in mode 4. PPT works best with photometry measurements from PPT itself (modes 0 - 3), when all metadata is available for fine-tuning the LC. But the task also works with photometry measurements from other packages. In this case, the user sets up the task to find the necessary basic data – object fluxes, time instants, reference time. If flux errors are not available, PPT uses the $\sqrt{flux}$ Poisson approximation. Other quantities such as the FWHM of objects are desirable, but not mandatory.

LC points may or may not be eliminated during the LC building process, and may or may not be used in certain steps of the procedures, in accord to the Multi-Layered Filtering (MLF) sophisticated filtering/elimination PPT scheme setup by the user (see Section **??**). PPT starts by marking target and calibrator outliers by FWHM above a given threshold. Calibrator outliers are also marked by a sigma-clip procedure in accord to their flux errors. A provisional LC with the flux ratio of target and calibrators is made and outlier points with large errors in magnitude are marked. A sigma-clip procedure also finds outliers with discrepant provisional flux ratio errors.

PPT then computes the calibration flux from calibrators. It can automatically select the best combination of calibrators based on the dispersion of the resulting provisional LCs with the flux ratio of target and calibrators. This is done outside specified event time windows when the target flux is expected to vary. PPT can also smooth the calibration flux by averaging the flux of the point and its neighbours with equal weights. The number of neighbours can be set by the user or found by sampling and analysing the dispersion of provisional LCs with the flux ratio of target and smoothed calibration flux.

The flattening and normalization of the calibration and target fluxes can be done separately by polynomial fittings. Sigma-clip procedures mark outliers for each fit. Event time windows are avoided in the fitting of targets. PPT then computes the flux ratio of the target and calibration fluxes. Next, it performs flattening and normalization to the flux ratio. This is done with polynomial fittings, avoiding event time windows. A sigma-clip procedure then marks outliers.

The resulting flux ratio points at this stage constitute the final LC. But the LC can be further smoothed by using points within a given time bin. This can be done to compare it with other LCs obtained with the same cadence of the time bin. The LC can also be binned by setting a time bin for the same reason. PPT can output the flux ratio of the LC with a given offset in ADU/ADU ratio or in magnitudes, which is useful for plotting purposes.

4.1.1 Multi-layered filtering of outlier LC points

Some PPT procedures may be directly or indirectly linked to each other. At each step, a parameter/value related to a LC point may not pass a quality control criteria that may jeopardize the execution of some – but not all – future procedures. In that case, it is desirable to filter out the LC point, but only from these

Table 1: Multi-Layered Filter (MLF). Position 1 indicates if the LC point must be dropped. Positions 2 to 11 refer to 10 critical LC procedures.

MLF position	LC production step
1	"+" (maintain) or "−" (drop) LC point
2	Calibration flux error sigma-clip elimination
3	Flattens/normalizes calibration flux
4	Smooths calibration flux with neighbor calibrators: the point is the current central point in the smoothing
5	Smooths calibration flux with neighbor calibrators: the point is a neighbor point in the smoothing
6	Flattens/normalizes target flux
7	Flattens/normalizes LC flux ratio (target/calibration)
8	LC flux ratio (target/calibration) error sigma-clip elimination
9	Smooths the (target/calibration) flux ratio: the point is the current central point in the smoothing
10	Smooths the (target/calibration) flux ratio: the point is a neighbor point in the smoothing
11	Averages LC points in time window bins

specific procedures. To cope with these needs and allow for the user to take full control of the quality of the LC production, making it possible to get the best results out of the photometry measurements, `PPT` has an exquisite set of filters and filtering procedures that can account for a variety of practical situations that arise in (but are not limited to) rotational light curves, stellar occultations and mutual phenomena photometry.

In `PPT`, the user sets up some cutoff values and some sigma-clip parameters to detect (not exclude) outliers at some steps in the LC processing. The detected outliers are not eliminated. Instead, the user sets up what to do with them at each step, by configuring multi-layered filters related to critical procedures in the production of the LC. It is the multi-layered filter status of each point, at each critical step of the LC production, that defines if the point is to be used or not, or even dropped. Some LC points may behave as outliers at some steps and yet not be bad LC points - even the contrary may be true. An example is the detection of rings around bodies in stellar occultations. Due to the pronounced but short and unexpected flux drop caused by the ring, the few isolated and flux-discrepant associated LC points are natural outliers in the LC normalization, regardless of their extreme importance. Thus, `PPT` grants the user with much more flexibility in deciding what to do with LC outliers.

`PPT` defines the Multi-Layered Filter (MLF) of a LC point as a string with 11 positions. The first position is "+" or "-", indicating the "maintain" or "drop" status of the LC point. If a LC point MLF presents status "-" at position 1, the point is immediately eliminated from the LC. It will not be used in further steps and procedures and will not be output in the LC. The remaining 10 positions indicate the status of a LC point with regard to 10 critical procedures in the LC production. The 11 positions of the MLF and the corresponding 10 critical procedures in the LC production are listed in Table 1.

The initial MLF of all LC points is "+0000000000". The MLF is then continuously updated as the task proceeds from one step to the other. A MLF position with "0" indicates that the respective procedure status of that LC point was not changed since the beginning of the processing. Otherwise, the status value will change to either "1" or "2". Status value "1" means "use" and value "2" means "do not use" the LC point for that specific LC procedure.

The 10 critical steps controlled by MLF involve FWHM limits, flux ratio errors, calibration and flux normalization issues. When the task reaches each one of these 10 steps, the MLF of a detected outlier is updated in accord with the MLF setup by the user. If the new MLF position 1 is "-", all the outliers detected in that step are dropped immediately from the LC. The remaining 10 positions of the old MLF of the outliers are updated only if the new value is higher than the older one. For instance, if the old MLF of one of the outliers was "+0100000002" and the new MLF setup by the user for the current step is "+0000100000", then the updated MLF of this LC point will be "+0100100002". Consulting Table 1 for this example, value "2" in position 11 of the updated MLF indicates that the LC outliers will not be used on the averaging of LC points in time window bins. Value "1" in the positions 3 and 6 mean that the outliers at the current step can still be used in the flattening/normalization procedures of calibration

and target fluxes (see Table 1).

4.2 Removing intruding flux in light curves

Sometimes it is necessary to eliminate the intruding flux contaminating a light curve. For example, in stellar occultations sometimes the intruding body flux ϕ_o should be determined and eliminated from measurements to get the clean flux ratio of the occultation star alone during the light drop. This is specially recommended when the occulting body is relatively bright and has an atmosphere, so pressure and temperature profile models can be found from the LC without using ϕ_o as parameter, improving profile fittings.

Although the intruding flux elimination in a LC fits to any general observation case, here we will focus on stellar occultation observations and nomenclature to facilitate the comprehension by the reader.

There are 3 methods for computing the intruding body flux ϕ_o with `PPT`. In all cases, besides occultation observations, calibration images are used, preferably made at a height (air mass) near (ideally at) that of the occultation images. The apertures of each target and calibrator must be the same for all occultation and calibration observations.

4.2.1 Method 1: using occultation images and the occultation star flux from calibration images

The intruding body flux ϕ_o can be computed from the contaminated non-flatted and non-normalized target/calibrator flux ratio F measured from occultation images outside of the occultation time window, and from the non-flatted and non-normalized occultation star/calibrator flux ratio f measured from calibration images. By fitting F and f with polynomials of degree n (usually n=1 or 2) in time and extrapolating for $F_0 = F(t_0)$ and $f_c = F(t_c)$, where t_0 is the mid-instant of occultation and t_c is the instant at which calibration observations are at the same occultation air mass at t_0, then ϕ_o can be expressed by equation 1. The occultation star/calibrator flux ratio cleaned from the intruding body flux for the mid-instant of the occultation is thus $F_0(1 - \phi_o)$.

$$\phi_o = \frac{F_0 - f_c}{F_0} \tag{1}$$

The mean error $\sigma(\phi_o)$ of the intruding body flux ϕ_o is given by equation 2. It comes from equation 1 by taking the mean errors (sigmas) of F_o and f_c, which are in turn determined from the sigma of the respective polynomial fittings. Notice the third (correlation) term in the square root in equation 2, due to the linear relation between F_o and f_c because of the implicit presence of the occultation star flux on both F_o and f_c. The uncertainty of ϕ_o comes from a similar formula, with the sigmas of F_o and f_c divided by the square root of the respective number of points used for computing F_o and f_c.

$$\sigma(\phi_o) = \phi_o \sqrt{\left(\frac{\sigma(f_c)}{f_c}\right)^2 + \left(\frac{\sigma(F_o)}{F_o}\right)^2 - 2\frac{\sigma(f_c)\sigma(F_o)}{f_c F_o}} \tag{2}$$

One advantage of Method 1 is that unlike Methods 2 and 3, we do not use measurements of the body flux from calibration images. Thus, we do not need to assume a fixed brightness for the intruding body, which may vary in some cases. In Method 1, we just need to assume that the relative brightness of the occultation and calibrator stars does not vary over the time span between occultation and calibration observations a demand also needed for Methods 2 and 3.

Another advantage of Method 1 is that it is not limited to short exposure times in the calibration images, regardless of the nature of the body (for instance, a satellite nearby a bright planet). This is because only the occultation star is measured in calibration images. In this case, the exposure times of calibration images are only limited by saturation or by objects close to the occultation star. The attained S/N ratios are as high as possible. This may not be possible with Method 2 and 3, depending on the nature of the body.

Using a planet as calibrator in ϕ_o computations for its usually high S/N ratio flux is risky and not recommended, due to the usually strong intrinsic brightness variations in the surface of giant planets in the optical domain. This is true for all cases, Method 1, 2 and 3.

4.2.2 Method 2: directly using the body flux from calibration images fraction LC (FLC)

In Method 2, the amount ϕ_o of the intruding body flux is directly computed from calibration images only, where the body is isolated from the occultation star. The fluxes are calibrated by taking the same calibrator star used in the occultation observations. We measure the fluxes of the isolated body B and occultation star S and construct a fraction light curve $\frac{B}{B+S}$ (FLC). The fraction flux ratio of this FLC gives the direct evolution in time of the body flux B with respect to the total amount of body plus occultation star fluxes $B+S$. We fit the FLC with a polynomial in time of degree n (usually n=1 or 2), and extrapolate the fraction flux ratio for the time t_c for which we get the same air mass (height) as that of the occultation. For this time t_c we then get ϕ_o as in equation 3:

$$\phi_o = \frac{B}{B+S} \ (t = t_c \equiv t_0) \tag{3}$$

The error of ϕ_o is the sigma of the polynomial fit. The uncertainty is this error divided by the square root of the number of points of the FLC. Here, we assume that the relative brightness of both the body and occultation star doesnt change between calibration and occultation times t_0 and t_c, although the body brightness may vary in some cases. The relative brightness of the calibrator star must also not change with respect to the body and the occultation star. Thus, the application of Method 2 is more restricted than for Method 1.

One great advantage of Method 2 is that unlike Method 1, we only deal (in principle) with high S/N ratio fluxes. This is because only calibration images are used, and their exposure times can be high, only limited by saturation or by the presence of objects close to the body or occultation star. On the other hand, the S/N ratio of occultation fluxes used in Method 1 are usually limited by short exposure times for better spatial resolution. In this way, we can get excellent S/N ratios for the FLC and consequently much smaller errors in the determination of ϕ_o. However, in natural satellite occultations such as with Triton, the S/N ratio advantage vanishes, as even for calibration images the exposure times must be short too, due to saturation or contamination by the planets flux over the satellite. In such cases, digital coronagraphy (Assafin, 2023b) can help to mitigate these effects to some extent, allowing for a little bit larger exposure times.

4.2.3 Method 3: directly using the body flux from calibration images separate LCs for body and occultation star

Method 3 follows the same principles of Method 2. The idea is again to directly measure the amount B of body flux with regard to the total flux $B + S$ from calibration images. The difference is that we construct the LC of the body flux and the LC of the occultation star separately. We fit each light curve by a polynomial in time and extrapolate the flux B_c and S_c for $t = t_c$ at the same air mass of the occultation height. The amount of intruding body flux ϕ_o is then obtained straightforwardly from equation 4:

$$\phi_o = \frac{B_c}{B_c + S_c} \tag{4}$$

The error (sigma) of ϕ_o is computed from the errors of B_c and S_c, which come from the sigmas of the respective polynomial fittings. Again as in Method 1, we must consider the linear relation of the numerator and denominator (the presence of B_c) in the expression above for ϕ_o in order to correctly derive its error.

The same comments made for Method 2 apply. The results of Method 2 and 3 are usually similar. However, one possible advantage of Method 3 over Method 2 is in the detection of outliers in the separate polynomial fittings of each of the body and occultation star LCs, which could otherwise be masked and maintained in the fraction LC fit. In this way, it is expected that the errors in Method 3 be somewhat smaller than in Method 2.

4.2.4 Output information for methods 1, 2 and 3

`PPT` generates a complete report of results using all 3 methods, including alternative results from weighted mean values for ϕ_o (with weighted sigma and uncertainties) from Method 1 with Method 2 and 3. It lists and compares many quantities (with errors) besides the ϕ_o solutions (F_o, F_c, S_c, B_c, etc). Auxiliary LCs besides the FLC (Fraction Light Curve) are also generated for sanity checking purposes. The meaning of all output quantities and auxiliary LCs generated from the ϕ_o computations are in the `PPT`'s User Guide.

The occultation LC corrected from the intruding body flux is obtained by running `PPT` in mode 4 and furnishing the ϕ_o value (see Section **??**). Once ϕ_o is determined, a clean occultation LC corrected from the intruding body flux ϕ_o can be obtained regardless of the use of any object as calibrator. Even a giant planet can be used, with gain in S/N ratio – the brightness variation mentioned before can be neglected during the short time span of an occultation.

The values obtained for ϕ_o may vary by the use of distinct sets of instruments/observations, or even by using distinct methods (1, 2 or 3) with the same instrument and observation sets, because of: instrument size, filters, seeing, photometry setup (apertures, etc). For consistency on the amount of measured flux of the objects involved, we must use the same fixed aperture for the calibrator, and another same fixed aperture for the occultation target (body + occultation star) and for the body and occultation star in the calibration images.

In terms of error (sigma), Method 1 performs better than Method 2 or Method 3 when the calibration images are made of short exposures. This is because in Method 1 less objects are involved in the measurements (less photometric error propagation) and the smaller S/N ratios of observations used in Method 2 and 3 are more similar to those of the observations from occultation LCs used by Method 1. Longer exposures for calibration images favor Method 2 and 3 because of the better S/N ratio of the observations used to compute ϕ_o in comparison to the observations used by Method 1.

For natural satellites of giant planets, such as Triton, care must be taken to avoid the contamination of flux by the bright planet. Observers should acquire two sets of calibration images, one with short exposure times which favors Method 1, and another with long exposures suited for Method 2 and 3. In this way, the determination of ϕ_o can be done by all 3 methods in ideal conditions.

The use of a planet as calibrator in ϕ_o computations for its high S/N ratio is not recommended, due to usually strong intrinsic brightness variations in the surface of giant planets in the optical along the time span encompassing calibration and occultation observations. However, once ϕ_o has been computed by any of the 3 methods, there is no restriction for using giant planets as calibrators for obtaining the LC free from the intruding body flux. Actually, the high S/N ratio of the planet favors the photometry and the precision of the derived LC, and the brightness variation can be neglected due to the short time span involved in the acquisition of occultation images.

5 Creating the Executable Code and Running the Task

Currently the task executable runs only under MacBook and debian-based Linux operation systems. It was thoroughly tested with Ubuntu distributions 16.04–22.04. The task consists of 1 FORTRAN source code, the main input data file and a number of auxiliary module files that setup the task:

- `PRAIA_photometry_3_0_04.f` - The FORTRAN source code
- `PRAIA_photometry_3_0_04.dat` - Main `PPT` input data file
- PRAIA_photometry_3_0_04_FITS_header_keys.dat - Module of FITS header keys (all photometry modes)
- PRAIA_photometry_3_0_04_input_time.dat - Module of time instants (all photometry modes)
- PRAIA_photometry_3_0_04_user_time.dat - Module of User time (all photometry and LC modes)
- PRAIA_photometry_3_0_04_automatic_obj_id.dat - Module of automatic object identification (photometry mode 3)
- PRAIA_photometry_3_0_04_guide_mode0.dat - Module of guide (photometry mode 0)
- PRAIA_photometry_3_0_04_guide_mode1.dat - Module of guide (photometry mode 1)
- PRAIA_photometry_3_0_04_guide_mode2.dat - Module of guide (photometry mode 2)
- PRAIA_photometry_3_0_04_guide_mode3.dat - Module of guide (photometry mode 3)
- PRAIA_photometry_3_0_04_calibrators_mode0.dat - Module of calibrators (photometry mode 0)
- PRAIA_photometry_3_0_04_calibrators_mode1.dat - Module of calibrators (photometry mode 1)
- PRAIA_photometry_3_0_04_calibrators_mode2.dat - Module of calibrators (photometry mode 2)

- PRAIA_photometry_3_0_04_calibrators_mode3.dat - Module of calibrators (photometry mode 3)
- PRAIA_photometry_3_0_04_targets_mode0.dat - Module of targets (photometry mode 0)
- PRAIA_photometry_3_0_04_targets_mode1.dat - Module of targets (photometry mode 1)
- PRAIA_photometry_3_0_04_targets_mode2.dat - Module of targets (photometry mode 2)
- PRAIA_photometry_3_0_04_targets_mode3.dat - Module of targets (photometry mode 3)
- PRAIA_photometry_3_0_04_best_fixed_aperture_tw.dat - Module for best fixed aperture time window and flux ratio setup (photometry mode 1)
- PRAIA_photometry_3_0_04_events_time_windows_Ph.dat - Module of time windows for target events (all photometry and LC modes)
- PRAIA_photometry_3_0_04_select_calibrators.dat - Module for selection of best calibrators (LC mode 4)
- PRAIA_photometry_3_0_04_smooth_calibration.dat - Module for smoothing calibration flux (LC mode 4)
- PRAIA_photometry_3_0_04_events_time_windows_LC.dat - Module of time windows for target events, and for target flux and flux ratio flattening/normalization (LC modes 4 and 5; same format as PRAIA_photometry_3_0_04_events_time_windows_Ph.dat; can even be the same file for photometry, or have different internal values for the LCs in modes 4 and 5)
- PRAIA_photometry_3_0_04_input_time_photometry.dat - Module for definition of input time instants of input photometry file (LC, modes 4 and 5)
- PRAIA_photometry_3_0_04_format_photometry.dat - Module with input photometry file format (LC, mode 4)
- PRAIA_photometry_3_0_04_LC_user.dat - Module with User-defined output LC file format (LC, mode 4)

To create the executable task file `PRAIA_photometry_3_0_04`, execute the following command in the prompt line:

gfortran -O3 `PRAIA_photometry_3_0_04.f` -o `PRAIA_photometry_3_0_04`

Here, gfortran is the native FORTRAN compiler. To run the task, as in the usual style of `PRAIA` tasks, simply execute the following command in the prompt line:

`PRAIA_photometry_3_0_04` < `PRAIA_photometry_3_0_04.dat`

Some information is output on the screen. To store it on file (e.g. on `screen_output.txt`), execute the following command in the prompt line:

`PRAIA_photometry_3_0_04` < `PRAIA_photometry_3_0_04.dat` > `screen_output.txt`

The name of input data file ("`PRAIA_photometry_3_0_04.dat`" in the example) can be freely modified by the user. However, it is recommended that the user keeps track of the released versions being used, as the entries of the input data file may vary from version to version. Avoid using mixed versions of executables and input data files, as crashing or wrong outputs may result.

As is the case with many other `PRAIA` tasks, by construction, there are many ways of building automatic scripts with `PPT`. We leave it to the creative/experienced user the building of such scripts.

6 Configuring the PRAIA Photometry Task

The main input data file (say, "PRAIA_photometry_3_0_04.dat") is an ASCII text file. It comes in the zip file of PPT. Each photometry mode and LC mode is represented as a separate block of lines ending with "****" symbols. The first line of the block indicates the mode and the second line indicates if the block is active or not (execute or not the block). There can be any number of active or inactive blocks. The blocks must be placed one after the other without empty lines in between. The task resumes execution after it finds an empty line after the last processed block. After this empty line, there can be notes or backup blocks left by the user.

Frequently, we use two blocks: a block for one of the photometry modes (0 to 3), and another block for the LC building (mode 4). The first block performs the photometry and the second one produces a LC from the photometry measurements previously made with the first block. Usually, we only activate one block at a time. First, we do photometry measurements, make tests, run the photometry block some times, then run it for the last time to get the definite photometry. Then, we inactivate the photometry block and activate the LC building block. Again, we perform tests, run this LC block some times, then run it for the last time to get the definite LC.

Notice that the blocks in PRAIA_photometry_3_0_04.dat are processed independently from each other, and following the input order. The user can thus create scripts by setting up all kinds of blocks in a logical sequence. One or more sets of images from the same or from distinct observation runs, and/or one or more sets of previous photometric measurements from the same of distinct runs (derived or not with PPT) can be processed in one single task run. It is up to the user to create and edit the blocks in the input data file. The way to do scrips will get easier and easier as the user gains experience with the use of the task. Usually, the user will edit a previously existing file, or make a copy and edit the new input data file.

There are no limits to the number of input/output photometry measurements and LCs points in PPT. The same applies to the number of input images. There is also no limit regarding to the FOV sizes (e.g. the CCD pixel dimensions in x and y) - PPT automatically figures out the necessary amount of computer memory to allocate in all modes (0 to 5). Any extremely large values may however eventually result in computer memory overflow for machines with very small amounts of memory.

In the following sections, we describe each entry in the main input data file of PPT and the entries of the respective module input data files. In Section 7 we describe how to configure the photometry block, encompassing the 4 PPT photometry modes 0 to 3. In Section 8 we detail the configuration of the basic (more frequently used) LC building block mode 4. In Section 9 we describe how to configure the (more rarely used) advanced LC building block mode 5, which deals with the subtraction of intruding flux in previously obtained LCs.

7 Configuring the Task for Photometry Measurements

Photometry measurements are made with the PPT photometry block shown here. There are 4 possible photometry modes that the user can configure using the photometry block: modes 0, 1, 2 and 3 (see Section 3.6).

A typical block content of the main input data file PRAIA_photometry_3_0_04.dat for photometry measurements is shown in Fig. 2. The value in the first line of the block must be 0, 1, 2 or 3, indicating one of the 4 possible photometry measuring modes. The second entry must be 1 or 2, indicating respectively if the user wants or not to effectively activate (run) the block.

All entries in this block are common to all of the 4 photometry modes. However, the content of some of the modules are specific to the chosen modes 0 to 3, and are only effectively used if the specific mode was actually set. The modules for the guide, calibrators and targets have specific input entries, in accord to the photometry mode set (0 to 3). All the entries in this block are commented in the following sub-sections.

7.1 Input list of FITS images for photometry

On line 3 of the block, we furnish the input list file name. The list of input FITS images to be processed must be created and furnished by the user. Notice that PRAIA only accepts images in FITS format. The input filenames may or may not contain ".fits" or ".FITS" extensions.

Usually the user will run the task at the same directory where the input FITS images are. If not, the input list file must contain valid paths for the input images from the directory where the task is

```
2                                                | Aperture Photometry. Fixed: (0) manual setup, (1) automatic; Varying: (2) semi-automatic, (3) automatic setup
1                                                | Do photometry? (1) yes; (2) no
lista_ori                                        | List of FITS images for photometry
q_e_20171005_1_800_1_1.fits                      | Reference image (processed first): image name, order number in input list or automatic search (mode 3 only)
00000                                            | First image in the list to process: 0 = first in the list  .:. use numbers (image order or percentage
00000                                            | Last  image in the list to process: 0 = last  in the list  .:. with "%") or explicit image file names
bad_boxes.pix                                    | Mask of bad pixels: rectangle regions (xmin, xmax, ymin, ymax)
bad_circles.pix                                  | Mask of bad pixels: circular regions (xc, xc, radius)
bad_fluxes.pix                                   | Mask of bad pixels: ADU counting range (count_min, count_max) of bad pixels to be excluded
photometry72.dat                                 | Main output: photometry measurements file (read notes for the output format)
regions72.ds9                                    | ds9 batch movie
reg72|-------------------------------------------| ds9 region file extension
1                                                | display ds9 regions in movie? (1) yes ; (2) no
0000                                             | First frame for ds9 movie display: 0 = first processed image .:. use numbers (image order, xx.x%)
0000                                             | Last  frame for ds9 movie display: 0 = last  processed image .:. or explicit image names
xy72.dat                                         | output (x,y) astrometry file (read notes for the output format)
PRAIA_photometry_3_0_04_FITS_header_keys.dat     | Module: FITS header keys setup (aperture photometry, all modes 0-3, mode0=mode1=...=mode3)
PRAIA_photometry_3_0_04_input_time.dat           | Module: Input time information (aperture photometry, all modes 0-3, mode0=mode1=...=mode3)
PRAIA_photometry_3_0_04_user_time.dat            | Module: User-time reference instant (aperture photometry and LC, all modes, mode0=mode1=...=mode4)
2                                                | Fix hot/cold pixels? (1) yes; (2) no
2                                                | S/N ratio formula: 1-Classic (gain, rdnoise, dark current, pixel binning); 2-ADU-based (needs gain only)
0.50                                             | Dark current (e/pixel/hour) (default = 0)
2                                                | Pixel binning factor (1=1x1 pixels; 2=2x2 pixels; 3=3x3 pixels ; ...)
1                                                | Gain and readout noise: 1 = extract from image header; 2 = input by the user (below)
1.0                                              | CCD gain        given by the user (put 1.0 if not known)
1.0                                              | CCD read noise  given by the user (put 1.0 if not known)
1.000                                            | Pixel scale (arcsec/pixel) (put 1.0 if not known)
2                                                | Equalize variable apertures? (0) No; (1) on each image; (2) on all; (3) fixed from ref. image (modes 2 and 3 only)
PRAIA_photometry_3_0_04_automatic_obj_id.dat     | Module: automatic object identification setup (aperture photometry mode 3 only; ignored in other modes)
0365                                             | Guide: xmin of rectangular area for guide search (brightest object) .:. 0: from 1rst X pixel
0475                                             | Guide: xmax of rectangular area for guide search (brightest object) .:. 0: to last X pixel
0025                                             | Guide: ymin of rectangular area for guide search (brightest object) .:. 0: from 1rst Y pixel
0125                                             | Guide: ymax of rectangular area for guide search (brightest object) .:. 0: to last Y pixel
PRAIA_photometry_3_0_04_guide_mode2.dat          | Module: Guide setup (aperture photometry modes 0, 1, 2 and 3) (mode 2 = mode 3)
PRAIA_photometry_3_0_04_calibrators_mode2.dat    | Module: Calibrators setup (aperture photometry modes 0, 1, 2 and 3)
PRAIA_photometry_3_0_04_targets_mode2.dat        | Module: Targets (ghosts) setup (aperture photometry modes 0, 1, 2 and 3)
PRAIA_photometry_3_0_04_best_fixed_aperture_tw.dat| Module: Best fixed aperture time window and flux ratio setup (mode 1 only; ignored in other modes)
2                                                | Automatic detection of target low counts: (1) Do it; (2) Do not do it
PRAIA_photometry_3_0_04_events_time_windows_Ph.dat| Module: Time windows setup for target events (aperture photometry and LCs, all modes, mode0=mode1=...=mode5)
*************************************************************************************************************************************************************************
```

Figure 2: A photometry block sample in the input data file `PRAIA_photometry_3_0_04.dat` furnished in the zip file of `PPT` for version 3.0.4.

being run. For individual images, such as individual bad pixel masks and output `ds9` regions, files are read/generated at the same directory of the original FITS images. For overall results like photometry and (x, y) measurements, or `ds9` batches, files are stored at the same directory where the task is being executed.

7.2 Reference image

On line 4 in the block the user indicates the reference image. All input data, like the coordinates, related to the guide, calibrators, targets and ghosts refer to the reference image. The reference image is always the first image processed. It may or may not be the first image in the input list – there is no restriction for that. It is recommended that all the objects of interest, that is the guide, the calibrators and the targets, be well sampled in the reference image. Valid entries are the explicit reference image file name, or the reference image order number in the input list.

In mode 3 only, a third option is valid on setting up the reference image. If the user puts 0, `PPT` will automatically select the reference image. The task scans all images in the input list and selects the one which has the object with the highest S/N. The objects are searched within the (x, y) FOV limits set for the guide (see Section 7.18).

In mode 3, the user cannot manually set the targets and at the same time set up `PPT` to select the reference image automatically. The reason is that, when manually setting up the (x, y)s of the targets, these coordinates must be defined with regard to the FOV of the reference image.

7.3 Range of FITS images for photometry

On lines 5 and 6 in the block, the user defines the range of images to be submitted for processing by setting the first and the last images from the input list. The reference image may or may not be within this range of images. It may or may not be the first valid image in the range. There is no problem with that.

There are 4 ways of setting up the first and last images. The first and last images may be explicitly set by their FITS file names. They can also be set by the image order given in the input list. Also, they can be defined by percentages from the total number of images in the input list – in this case, the user furnishes values such as "15%" with the "%" symbol explicitly inserted. There is no need that the images in the input list be ordered in time. Actually, it is the chronological order of the images that are taken into consideration for processing, instead of the strict order in the input list. The user must then be aware about the way that the images are ordered in the input list, when setting the range of images to be processed. Finally, if "0" is set for the first and/or last images, then the first and/or last images are automatically set as the first and/or last images given in the input list.

PPT processes the images in the following sequence order. First, it orders all the images in the input list by time with respect to the reference image. The reference image is always the first image processed. After that, following the internally established processing sequence, only then PPT will start to process the other images in the input list, skipping images not included in the start/end image range indicated by the user.

The output of results follows the chronological order of images.

7.4 Pixel mask of bad rectangle regions

On line 7 of the block, the user furnishes the input file name of a file containing rectangular masks of pixels to be excluded from the photometry for all images. It is up to the user to create or edit such file. If the user dont want to use such mask, let this field empty in the block or delete the file if it exists in the running directory.

An unlimited number of rectangular mask entries may be furnished, one per line in this input file. For each line, or rectangular pixel mask, there must be listed the (xmin, xmax, ymin, ymax) pixel coordinates of the rectangular area and the inside/outside range key in free format. Positive keys (+1, +2, ...) mean mask pixels "inside" range, and negative ones (-1, -2, ...) mean mask pixels "outside" range. Ex.:

0001 0010 0023 0049 +1
0043 0055 0002 0003 +1
0100 0100 0124 0124 +1

For individual image masks, the user must furnish mask files at the same directory of the images. The filenames must be the same as the FITS filenames, omitting the ".fits" or ".FITS" extensions (if present) and using the following extension rule:

- `image_root_name.bbpx` - Rectangular (box) region mask

7.5 Pixel mask of bad circular regions

On line 8 of the block, the user furnishes the input file name of a file containing circular masks of pixels to be excluded from the photometry for all images. It is up to the user to create or edit such file. If the user dont want to use such masks, let this field empty in the block or delete the file if it exists in the running directory.

An unlimited number of circular masks may be furnished, one per line in this input file. For each line, or circular pixel mask, there must be listed the x and y centers, the radius of the circular area and the inside/outside range key in free format. Positive keys (+1, +2, ...) mean mask pixels "inside" range, and negative ones (-1, -2, ...) mean mask pixels "outside" range. Ex.:

0043 0055 5 +1
100.45 0234.33 5.65 +1

For individual image masks, the user must furnish mask files at the same directory of the images. The filenames must be the same as the FITS filenames, omitting the ".fits" or ".FITS" extensions (if present) and using the following extension rule:

- `image_root_name.bcpx` - Circular region mask

7.6 Pixel mask of bad ADU counts

On line 9 of the block, the user furnishes the input file name of a file containing ADU count-range masks of bad pixels to be excluded from the photometry for all images. It is up to the user to create or edit such file. If the user dont want to use such masks, let the file empty or simply erase the file from the running directory.

An unlimited number of ADU count-range masks may be furnished, one per line in this input file. For each line, or ADU count-range pixel mask, there must be listed the minimum and maximum counts, and the inside/outside range key in free format. Positive keys (+1, +2, ...) mean mask pixels "inside" range, and negative ones (-1, -2, ...) mean mask pixels "outside" range. Ex.:

100000 1000000 +1
-200 0 +1
65000.5 67000.3 +1

For individual image masks, the user must furnish mask files at the same directory of the images. The filenames must be the same as the FITS filenames, omitting the ".fits" or ".FITS" extensions (if present) and using the following extension rule:

- `image_root_name.bfpx` - ADU range mask

7.7 Output photometry file name

On line 10 of the block, the user furnishes the output file name with photometry measurements and complete information for the targets, ghosts, calibrators and guide object made for all images. It is the most important output of the task for this block. The content of this output file is given in Section 10.

7.8 Output ds9 batch movie file name

On line 11 of the block, the user furnishes the output `ds9` batch movie file name.

On line 12, the user sets the extension for naming the `ds9` region file of each individual image.

On line 13, the user indicates if `PPT` should or not load individual `ds9` region files in the `ds9` batch movie file.

On lines 14 and 15, the user indicates the range of images to be loaded by `PPT` onto the `ds9` batch movie file. The rules for setting the image range are the same as that of the input list (Section 7.3), including the commented chronological ordering issues.

After the processing, `PPT` produces a `ds9` batch movie file. This batch file can be used to call the `ds9` program and load all selected images with their respective region files (if this was set by the user). The batch movie can be used, for instance, to produce movies and analyse events such as stellar occultations.

The `ds9` region files are produced for each processed observation using the root name of the FITS image added with the extension. These files contain formatted information that `ds9` uses to display the apertures and sky background rings of guide, calibrators, targets and ghosts measured by `PPT` for each image. The user can set up the task to make the `ds9` batch movie file display or not the contents of these `ds9` region files. The sky background rings of the objects are set in blue. The color of the aperture circle of the guide is yellow; green is used for the calibrators, red for the targets and white for the ghosts. This tool is very useful in the photometry analysis of the objects in the FOVs.

7.9 Output astrometry file name

On line 16 of the block, the user furnishes the output file name with the (x, y) astrometry measurements and errors of the target, calibrators and guide object made for all images. The content of this output file is given in Section 10.

7.10 Module: FITS header keys for image information extraction

On line 17 the user furnishes the file name of the FITS header keys module, furnished as `PRAIA_photometry_3_0_04_FITS_header_keys.dat` in the zip file of `PPT`.

A series of standard FITS header keys must be furnished by the user in order to enable `PPT` to correctly extract meta-data from the observations (time, air mass, etc), if available, and to be able to correctly retrieve the ADU pixel counts from the FITS images. This is done by setting up the FITS Header Keys module, that is, the furnished `PRAIA_photometry_3_0_04_FITS_header_keys.dat` input data file. A typical example of this input data file content is shown in Fig. 3.

Notice that there are some redundant keys in the definition of image dimensions and of time. Usually only one or other group of keys is available in the FITS headers. But there are occasions on which both groups of keys are present, or partially present. For avoiding confusion, `PPT` adds the so-called "stamp keys", for image dimensions and for time, which define what group of correct keys are to be actually used.

The stamp key for image dimensions may have values "1" or "2" according to the following situations:

- 01 - x and y axes dimensions furnished in separate keys (usually "NAXIS1" and "NAXIS2" for x and y respectively).

```
BITPIX  |--------------------------------------| FITS header key: Bitpix of CCD
EXTEND  |--------------------------------------| FITS header key: FITS header extension key
01|--------------------------------------------| Axes stamp key for (x,y) axes dimensions: (1) NAXIS1, NAXIS2 keys for (x,y); (2) WINSEC key for (x,y)
WINSEC1 |--------------------------------------| FITS header key: dimension of axes (1,2;x,y) together: windows section key
NAXIS1  |--------------------------------------| FITS header key: dimension of axis 1 (x)
NAXIS2  |--------------------------------------| FITS header key: dimension of axis 2 (y)
BSCALE  |--------------------------------------| FITS header key: Scale of pixel counts (bscale)
BZERO   |--------------------------------------| FITS header key: zero level of pixel counts (bzero)
GAIN    |--------------------------------------| FITS header key: CCD gain
READNOIS|--------------------------------------| FITS header key: CCD read noise
AIRMASS |--------------------------------------| FITS header key: Air mass
01|--------------------------------------------| Time stamp key
JD      |--------------------------------------| FITS header key: Julian Date
MJD-OBS |--------------------------------------| FITS header key: Modified Julian Date
DATE-OBS|--------------------------------------| FITS header key: Observation Date, UTC
UTSTART |--------------------------------------| FITS header key: Start instant of exposure, UT
LTEND   |--------------------------------------| FITS header key: End instant of exposure, UT
TIME    |--------------------------------------| FITS header key: Start and End exposure instants, UT
EXPTIME |--------------------------------------| FITS header key: Exposure Time (seconds)
0                                              | little-endian x big-endian byte-swap: (0) automatic; (1) don't swap ; (2) = swap bytes
1                                              | little-endian x big-endian byte-swap check: display counts of center pixel of 1rst image? 1=yes ; 2=no
-99                                            | bitpix (-99 = read from image header)
0                                              | Pixel physical counts: 0 = from image header or 1 = input by the user (below)
1.d0                                           | Pixel physical counts: bscale;  Pixel = bscale * matrix + bzero
0.d0                                           | Pixel physical counts: bzero ;  Pixel = bscale * matrix + bzero
```

Figure 3: A sample of the FITS header keys module `PRAIA_photometry_3_0_04_FITS_header_keys.dat` furnished in the zip file of `PPT` for version 3.0.4.

- 02 – x and y axes dimensions furnished together in one key (usually ”WINSEC”), in the form [N1_1:N1_2,N2_1:N2_2], where:

  NAXIS1 = N1_2 - N1_1 + 1
  NAXIS2 = N2_2 - N2_1 + 1

Time stamp keys may have values from “01” to “06” according to one of the following options:

- 01 – Date and start time furnished together in one key: yr mo day (day mo yr) and hh mm ss.sss (usually at ”DATE-OBS” key).
- 02 – Date and start time furnished together in one key: yr day mo (mo day yr) and hh mm ss.sss (usually at ”DATE-OBS” key).
- 03 – Date and start time in separate keys: yr mo day (day mo yr) usually furnished in ”DATE-OBS” key:

  – if the exposure time is given, only the UTC start time (usually hh mm ss.sss) is needed, and given in a separate key (usually ”UT” or ”TIME-BEG” keys).

  – if the exposure time is not given, then the UTC start and end exposure times must be furnished. They can be evoked by separate keys (usually ”UT”/”TIME-BEG” and ”TIME-END” keys), or evoked by the same key (user-defined, usually ”TIME”), usually in the hh mm ss.sss format.

  – the start and end times may be also furnished in hh mm.mmm or even in sss.sss format.
- 04 – Date and start time in separate keys: yr day mo (mo day yr) usually furnished in ”DATE-OBS” key:

  – if the exposure time is given, only the UT start time (usually hh mm ss.sss) is needed, and given in a separate key (usually ”UT” or ”TIME-BEG” keys).

  – if the exposure time is not given, then the UT start and end exposure times must be furnished. They can be evoked by separate keys (usually ”UT”/”TIME-BEG” and ”TIME-END” keys), or evoked by the same key (user-defined, usually ”TIME”), usually in the hh mm ss.sss format.

  – the start and end times may be also furnished in hh mm.mmm or even in sss.sss format.
- 05 – Start time in Julian Date (JD): the date is computed from the JD (usually furnished by the ”JD” key); the exposure time must be also furnished.
- 06 – Start time in Modified Julian Date (MJD): the date is computed from the MJD (usually furnished by the ”MJD” key); the exposure time must be also furnished.

Depending on the architecture of the machine/system from which the FITS image is first created, the numbers (pixel raw counts) may (or may not) be written with bytes swapped (Littleendian or Bigendian

structure). Use option "0" (recommended) to let PPT automatically detect the correct byte-swap option, or give the option explicitly: "1" (dont byte-swap numbers) or "2" (byte-swap numbers).

The user can set up PPT to output on the screen the counts that it finds for the central pixel of each image. Thus, the user can check if this value is correct by comparing it with the output of another program or image software, such ds9. If the value is not the same as that displayed by ds9, odds are that the BITPIX value or the chosen byte-swap option ("1", "2" or much more rarely even "0") or both are wrong. These entries must thus be changed until the correct pixel count value is extracted by PPT. Only then, one can be sure that the correct pixel counts are being used in the photometry, otherwise unpredictable outputs may result.

The standard BITPIX FITS header key indicates how the pixel counts where written in the FITS file (integer, fluctuation point, simple, double precision). This key is usually correctly furnished in the FITS header of the images. Set -99 to make the task use the value directly furnished in the FITS header. Otherwise, insert the correct value. Valid values are 8, 16, -32, +32, -64, +64.

The pixel physical counts fields in this module indicate how to retrieve the correct ADU pixel counts from the actual data written in the FITS image files. Use "0" to extract this information directly from the FITS header, or "1" to extract the scale and zero level of the pixel counts from the two corresponding lines in the module file. Before choosing "0", the user must be sure that the FITS header of the images do contain the BSCALE and BZERO FITS keys. If any one of these keys are missing in the FITS header, the user must set "1", and furnish both scale and zero level values explicitly. Notice that these two lines must always be present in the module file, even if the option is set to "0" (in which case the furnished values are simply ignored).

7.11 Module: Input time information

On line 18 the user furnishes the file name of the Input Time Information module, furnished as PRAIA_photometry_3_0_04_input_time.dat in the zip file of PPT.

This PPT module gifts the user with more time options to cope with a series of situations that (more than we wished for) arise in photometry work (rotation light curves, stellar occultations, mutual phenomena, microlensing, transits, variable stars, etc), when observations are carried out under non-ideal instrumental and/or acquisition-software conditions (or even when this is not the case). This is the case, for instance, when no information at all is given in the FITS headers about the timing of the observations.

A typical example of this module input data file is shown in Fig. 4.

```
2                                       | Time unit of Exposure Time: (1) minutes; (2) seconds; (3) milliseconds
0000.000d0                              | Time instant offset (Julian years)
00.000d0                                | Time instant offset (Julian months of 30.5 days)
000.000d0                               | Time instant offset (days)
+00                                     | Time instant offset (hours)
00                                      | Time instant offset (minutes)
00.000                                  | Time instant offset (seconds)
00                                      | Exposure time correction (seconds) (put zero if no correction needed)
0                                       | 0 = extract time information from image header (start time, exposure); 1 = time input by user (* below)
2018                                    | * year    of starting time of 1rst image in the input list
10                                      | * month   of starting time of 1rst image in the input list
05                                      | * day     of starting time of 1rst image in the input list
06                                      | * hours   of starting time of 1rst image in the input list
14                                      | * minutes of starting time of 1rst image in the input list
06.815                                  | * seconds of starting time of 1rst image in the input list
00.500                                  | * Exposure time (seconds)
00.500                                  | * Cycle time (seconds) (cycle = time interval between start times of consecutive exposures)
```

Figure 4: A sample of the Input Time Information module PRAIA_photometry_3_0_04_input_time.dat furnished in the zip file of PPT for version 3.0.4.

The exposition time in standard FITS headers should be in seconds of time. Nevertheless, there are cases when the registered values are in other units. PPT thus allows the user for setting the unity of time of the exposures. Options are minutes, seconds and milliseconds.

The user is also allowed for offsetting the instants of time extracted from the FITS headers. The offsets may be given in Julian years, months, days, hours, minutes or seconds, or by a combination of these.

It is also allowed for the user to add a correction to the exposure time extracted from the header. This has many utilities. For instance, if the exposure time is the only time quantity not available from the FITS image (header), the user can set it by putting the integral exposure time here. The corrections may be positive or negative values. They are added to the exposure times stamped in the FITS headers in order to get the correct value.

Finally, it is often the case when no time information at all is available on the FITS headers of the images. Or simply the information there may not be trustful. In such occasions, the user can setup PPT

to ignore the time information given in the FITS headers and, instead, directly setup the mid-instants of the images. In this case, the user must set the starting time (when the shutter opens) of the first image listed in the input file list, then set the exposure time and the cycle time (time interval between start times of consecutive exposures). In this case, PPT assumes that the images are ordered in chronological order in the input list file.

If the option for the extraction of time information from header on line 9 of the module is set as "1", then the user must furnish the correct values mentioned in the previous paragraph for all the module lines marked with *. On the other hand, for option "0", all information on these lines are ignored.

7.12 Module: User time

On line 19 the user furnishes the file name of the Input User Time module, furnished as `PRAIA_photometry_3_0_04_user_time.dat` in the zip file of PPT.

This module allows the user to setup a time scale that better suits to his/her own taste, being an important and flexible tool for plotting and analysis purposes. The module User Time, setup with the input data file `PRAIA_photometry_3_0_04_user_time.dat`, is used in all photometry modes (0, 1, 2, 3), in the LC block (mode 4) and in the Intruding body flux block (mode 5). Indeed, for the same set of observations, one usually takes the same module setup to run all these modes (modes 0 to 5). A typical example of this module input data file is shown in Fig. 5.

```
1                                       | User-time unit: 1=ss 2=mm 3=hh 4=dd (JD) 5=mm 6=yrs
1                                       | User-time reference instant type: 1 = Gregorian date; 2 = JD; 3 = MJD
23                                      | User-time reference instant: hours   (user-time type 1)
30                                      | User-time reference instant: minutes (user-time type 1)
00.000                                  | User-time reference instant: seconds (user-time type 1)
05                                      | User-time reference instant: day or JD or MJD (user-time types 1, 2 or 3 respectively)
10                                      | User-time reference instant: month   (user-time type 1)
2017                                    | User-time reference instant: year    (user-time type 1)
```

Figure 5: A sample of the Input User Time module `PRAIA_photometry_3_0_04_user_time.dat` furnished in the zip file of PPT for version 3.0.4.

The user defines the reference instant and the time unity used to count time from the reference instant.

7.13 Fix hot/cold pixels

On line 20 of the photometry block the user sets if PPT should ("1") or not ("2") correct pixel counts for hot/cold pixel defects.

It is often the case when the images present lots of hot/cold pixels. This may jeopardize the automatic identification of objects, and even the photometry (sky background computations, etc.). PPT offers the option to correct the ADU counts of such pixels. By scanning all image pixels and applying Student-t tests (Press et al., 1982) on the surrounding pixels, the ones with significant difference in the counts with respect to their neighbors are corrected. After elimination of the higher and lower pixel counts, following quartile statistic principles, the average value of the surrounding pixels replace the value of the hot/cold pixel.

The user has the option to fix or not hot/cold pixels. We warn the user that the operation may introduce noise and, sometimes, spurious signals in the photometry measurements of objects, as any pixel in the image (including those encompassed by objects) are corrected. We do not recommend this correction when the images do not present significant levels of cold/hot pixels.

7.14 Signal-to-noise ratio computation setup

From lines 21 to 26 in the photometry block input file the user sets up the way that PPT shall compute the S/N of measurements: by the "classical" or "ADU-based" formula (Assafin, 2023a). In the case that the classical formula is chosen, then the pixel binning, detector gain and readout noise must be known. Otherwise, only the gain is actually used (put values 1.0 for gain and read noise, if they are not know). The pixel binning index is "1" for no binning (1x1 pixel binning), "2" for 2x2 pixel binning, "3" for 3x3 pixel binning, etc.

7.15 Pixel scale

On line 27 of the photometry block, if known, the pixel scale shall be furnished in arcseconds per pixel. The (x, y) centring errors (if available) are scaled with this value furnished by the user and output in

milliarcseconds (mas). The FWHM is also set in arcseconds using the pixel scale. If not know, put 1.0 for the pixel scale. In this way, the user knows that the output quantities mentioned here are in milli-pixels (errors) and pixel (FWHM) unities, so that conversion may be done in the future when the pixel scale information becomes available.

7.16 Aperture flux equalization

On line 28 of the photometry block, the user sets the option for variable aperture flux equalization in the case that the photometry be performed in modes 2 or 3. Option "0" means no equalization at all. Option "1" equalizes aperture area/flux on each image individually, that is, the reference aperture - applied for all objects - will be defined for each image, and can be different from image to image. Option "2" is the most common choice: the reference aperture is set in the reference image (or input by the user in mode 2 only) and kept fixed for all images and objects. Option "3" is actually not an equalization: it defines the aperture radius (and sky background radius and width) for each object in the reference image, and then fixes them for the rest of the images.

7.17 Module: Automatic object identification (photometry mode 3 only)

On line 29 of the photometry block the user furnishes the file name of the Automatic Object Identification module, furnished as `PRAIA_photometry_3_0_04_automatic_obj_id.dat` in the zip file of `PPT`. This module is only activated in photometry mode 3, being ignored in all other modes. A typical example of this module input data file is given in Fig. 6.

```
+1                                      | Automatic obj. id. (provisory photometry): +1=track; 0=no; -1=fixed (except ref. image); -2=fixed (all)
0                                       | Automatic obj. id.: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       | Automatic obj. id.: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     | Automatic obj. id.: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     | Automatic obj. id.: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
+6.0                                    | Automatic obj. id.: Maximum aperture radius (pixels) => input negative value for no radius limit
20.0                                    | Automatic obj. id.: minimum S/N ratio
```

Figure 6: A sample of the Automatic Object Identification module `PRAIA_photometry_3_0_04_automatic_obj_id.dat` furnished in the zip file of `PPT` for version 3.0.4.

In photometry mode 3, the user furnishes the S/N threshold below which all objects (if any) to be automatically identified by the `BOIA` procedure (Assafin, 2023a) will be discarded. All candidate objects found must pass some validation steps, which includes making a provisional photometry of all images. For that, it is necessary to setup the (x, y) tracking options for the candidates, and this is done here. The user has the option to limit the radius size of the apertures of the candidates (useful for crowded FOVs, for instance) put negative values for setting no radius limit.

In photometry mode 3, calibrators and targets are automatically found by `PPT`. There is no need of furnishing (x, y) values or aperture and sky background ring sizes for these objects in this mode. However, the user has the option of securing the targets (only, not calibrators) by defining their coordinates. Once the targets are defined, their ghosts are also set automatically.

Regarding to the tracking option in the automatic procedure, we recommend that option "+1" and polynomials of degree higher than 0 (usually N=1 will suffice) be set only if at least one of the targets or calibrators are known to be a moving object. If this is not the case, we recommend the use of option "0", or option "+1" with a polynomial of degree N=0. By "moving" object, we mean an object which movement in the FOV along the images is actually detectable, or measurable, within (x, y) errors.

One last comment about the automatic selection of calibrators and targets of mode 3. The user must be sure that the automatic setup will actually allow for the detection of the targets. This is easily accomplished when there are few objects in the FOV or when the targets have similar brightness to the calibrators. But when the targets are very faint with respect to the calibrators, the user must pay attention to the S/N threshold, in order to effectively allow faint objects to be detected, with the targets among them. Once detected, it is relatively easy for `PPT` to identify the targets by their larger flux variations with respect to the more steady fluxes of the calibrators.

7.18 Guide identification: range of the FOV

On lines 30-33 of the photometry block the user furnishes the rectangular region with $(x_{min}, x_{max}, y_{min}, y_{max})$ pixel coordinates indicating where the guide must always be located in the FOV of all images.

The guide must always be the brightest object inside these limits. If this is the brightest object in the entire FOV of all the images, the user has the option of setting $(x_{min}, x_{max}, y_{min}, y_{max})$ = "0 0 0 0" in which case the search is carried out automatically over the entire image. This is particularly suited for cases in which the location of the brighter source varies a lot over the FOV, but without leaving it. However, for less computer-time consuming, it is recommended that the user sets the rectangular region $(x_{min}, x_{max}, y_{min}, y_{max})$ as small as possible, within safe margins.

Warning: failing to correctly setup the rectangular region $(x_{min}, x_{max}, y_{min}, y_{max})$ limits will result in a wrong identification of the guide in some or all images, rendering unusable wrongly photometry results. It is entirely up to the user to check the validity of the $(x_{min}, x_{max}, y_{min}, y_{max})$ limits.

7.19 Module: Guide

On line 34 the user furnishes the file name of the Guide module.

The setup of the guide is made with the Guide module. There is one specific module input data file for each one of the photometry modes 0, 1, 2 and 3. The modules are self-explanatory.

It is up to the user to use/setup the correct module input data file in correspondence with the photometry mode being used.

It is up to the user to setup what kind of centring method is best suited for the guide. Notice that if the centring option is set to "0" (mix of PGM and 2D Gaussian PSF), and since by default the centre of the guide is always fitted, the (x, y) centre that results in the best S/N is always the one used/stored.

When the 2D Gaussian fit fails because of insufficient number of pixels or for other causes, and/or when the PGM centring also fails, the processing of the image is aborted and the task moves for the next image. In the case that this happens with the reference image, the task issues an alert and then stops.

A Student-t test is applied to compare the pixel counts of the aperture with those of the sky background ring. If the mean of both distributions are not significantly different, then we have a situation in which the guide is too faint. This can be due to passing clouds or some instrumental issue. The image is then skipped and `PPT` goes on to the next image. If it happens with the reference image, the task displays a warning and then stops.

The guide is a fundamental object in the procedures carried out by `PPT`. Thus, if the guide does not pass the astrometry or the photometry filters above, the image is skipped. The reference image is also central in the task procedures. Thus, if this happens with the reference image, the task stops.

7.19.1 Module: Guide - photometry mode 0

The Guide module for photometry mode 0 is given by the input data file `PRAIA_photometry_3_0_04_guide_mode0.dat`. A typical example of this module input data file is shown in Fig. 7.

```
04.5                                    | Guide: flux aperture radius (pixels) (also astrometry aperture radius)
12.0                                    | Guide: sky background ring radius (pixels)
2.0                                     | Guide: sky background ring width (pixels) (suggestion = 5 pixels)
0423.0                                  | Guide: x coordinate on the reference image
0063.5                                  | Guide: y coordinate on the reference image
0                                       | Guide: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 7: A sample of the Guide module for photometry mode 0 `PRAIA_photometry_3_0_04_guide_mode0.dat` furnished in the zip file of `PPT` for version 3.0.4.

In the photometry mode 0, the astrometry and photometry aperture location and sizes, and the radius and width of the sky background ring of the guide are fixed and defined by the user. These values, specially the (x, y) coordinates, must be set using the reference image. The use of an image visualization software like `ds9` is mandatory, in order to set up these quantities "as good" as possible. Notice that `PPT`, as well as other `PRAIA` tasks, takes as (x=1,y=1) the geometric center of the respective corner pixel in the images.

If tracking option is "on", the final centre of the apertures is computed with the pixels inside the input circular region. Notice that the aperture and sky background ring sizes are furnished by radius (not by diameter).

7.19.2 Module: Guide - photometry mode 1

The Guide module for photometry mode 1 is given by the input data file `PRAIA_photometry_3_0_04_guide_mode1.dat`. A typical example of this module input data file is shown in Fig. 8.

```
03.5                                    | Guide: flux aperture radius (pixels) .:. minimum value
04.5                                    | Guide: flux aperture radius (pixels) .:. maximum value
00.1                                    | Guide: flux aperture radius (pixels) .:. bins
12.0                                    | Guide: sky background ring radius (pixels) .:. minimum value
12.0                                    | Guide: sky background ring radius (pixels) .:. maximum value
01.0                                    | Guide: sky background ring radius (pixels) .:. bins
2                                       | Guide: sky background ring width (pixels) .:. minimum value (suggestion = 1 pixel)
2                                       | Guide: sky background ring width (pixels) .:. maximum value (suggestion = 5 pixels)
1                                       | Guide: sky background ring width (pixels) .:. bins (suggestion = 1 pixel)
0423.0                                  | Guide: x coordinate on the reference image
0063.5                                  | Guide: y coordinate on the reference image
0                                       | Guide: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 8: A sample of the Guide module for photometry mode 1 `PRAIA_photometry_3_0_04_guide_mode1.dat` furnished in the zip file of `PPT` for version 3.0.4.

In mode 1, the fixed aperture size and sky background ring radius and width of the guide, calibrator and targets are automatically set by `PPT`, instead of being furnished by the user as in mode 0.

In mode 1, a range of aperture radii, radii and widths of sky background rings for all objects guide, calibrators and targets are sampled in order to get the best overall set of values in an automatic fashion by `PPT`. Given variation bins and minimum-maximum values for the aperture radii and ring radii and widths, for all objects, the task performs provisional photometry for all objects in a selected set of images, computes provisional flux ratios (target/calibration flux) for all possible centers (PGM and 2D Gaussian, if mix option is set on), aperture radius and ring radius/width combinations among all objects, searches for the provisional flux ratio with the least dispersion in a given time window and stores the aperture radius and sky background ring radius and width of each object that furnished the best flux ratio, and finally performs the photometry measurements of all objects with the found apertures and sky background rings.

There are two methods to find the best set of apertures and sky background rings in mode 1: brute force and bisection (binary search) method. The bisection method, due to its faster convergence, allows for a much wider sampling of apertures, ring widths and radii without precision loss. The bisection method dramatically improves the speed of the processing with respect to the standard brute force search method. In general, we recommend the use of the bisection method instead of the brute force procedure in mode 1.

Notice that the best set of apertures and rings for each object individually are determined with some kind of interdependence among the objects. In the brute force option the user must setup the bins and value ranges in as much a realistic basis as possible, because the number of provisional photometry runs (or loops) that must be done for testing each aperture and ring set of values may easily increase to prohibitive figures, making the task work for hours or even days unnecessarily. (`PPT` displays the expected number of loops to be performed). This is not a problem with the bisection method, with which very elastic ranges can be probed for apertures and rings.

In the example, looking only at the guide, using the brute force procedure, `PPT` will test apertures with radius 3.5, 3.6, 3.7, , 4.5 with 0.1 bins (all in pixels). The sky background ring radius (in pixels) is set to 12 and will not be tested (minimum value is equal to maximum). Finally, the ring width is also fixed in 2 pixels. If the bisection method is chosen, aperture radii between 3.5 and 4.5 pixels will be sampled, with convergence given by the bin = 0.1 pixels. Notice that, by default, for speeding computations, only integer values are used in the case of the ring widths, and ring radius bins.

The method to be used for all objects in mode 1 brute force or bisection method is setup in the Best Fixed Aperture Time Window and Flux Ratio module described in Section 7.22 (this module is only active in photometry mode 1).

7.19.3 Module: Guide - photometry mode 2

The Guide module for photometry mode 2 is given by the input data file `PRAIA_photometry_3_0_04_guide_mode2.dat`. A typical example of this module input data file is shown in Fig. 9.

```
+6.0                                    | Guide: maximum aperture radius (pixels) => input negative value for no radius limit
0.1                                     | Guide: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
5                                       | Guide: maximum sky background ring width (pixels) (suggestion = 5 pixels)
0                                       | Guide: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 9: A sample of the Guide module for photometry mode 2 `PRAIA_photometry_3_0_04_guide_mode2.dat` furnished in the zip file of `PPT` for version 3.0.4.

These are all the parameters that must be set by the user to setup the guide photometry and astrometry

measurements in photometry mode 2. Following the procedure that searches for the best aperture and sky background ring radius and width in terms of S/N described in Section 3.3, the best (x, y) centre of the guide is determined for the reference image as well as for all the other ones. The user can set a limit for the aperture radius of the guide. This avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images. Put negative values for setting no radius limit.

7.19.4 Module: Guide - photometry mode 3

The Guide module for photometry mode 3 is given by the input data file `PRAIA_photometry_3_0_04_guide_mode3.dat`. It is identical as the module of the guide for photometry mode 2. A typical example of this module input data file is shown in Fig. 10.

```
+6.0                                    | Guide: maximum aperture radius (pixels) => input negative value for no radius limit
0.1                                     | Guide: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
5                                       | Guide: maximum sky background ring width (pixels) (suggestion = 5 pixels)
0                                       | Guide: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 10: A sample of the Guide module for photometry mode 3 `PRAIA_photometry_3_0_04_guide_mode3.dat` furnished in the zip file of `PPT` for version 3.0.4.

These are all the parameters that must be set by the user to setup the guide photometry and astrometry measurements in mode 3. Following the procedure that searches for the best aperture and sky background ring radius and width in terms of S/N ratio described in Section 3.3, the best (x, y) centre of the guide is determined for the reference image as well as for all the other ones. The user can set a limit for the aperture radius of the guide. This avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images. Put negative values for setting no radius limit.

7.20 Module: Calibrators

On line 35 the user furnishes the file name of the Calibrators module.

The setup of the calibrators is made with the Calibrators module. There is one specific module input data file for each one of the photometry modes 0, 1, 2 and 3. The modules are self-explanatory.

The maximum allowed number of calibrators is 20. In the photometry mode 0, the astrometry and photometry aperture location and sizes, and the radius and width of the sky background ring of each calibrator are fixed and defined by the user. These values, specially the (x, y) coordinates, must be set with the reference image. The use of an image visualization software like `ds9` is again mandatory. It is up to the user to set up what kind of centring method is best suited for each calibrator.

After processing the reference image and getting precise relative calibrator coordinates with respect to the guide, tracking option "-1" fixes the relative coordinates of a calibrator to the guide for all images. Option "-2" freezes relative coordinates from the inputs by the user (see previous section for the special case of photometry mode 3). Option "0" also fixes the relative distance to the guide, but allowing for small corrections by the update of the calibrator (x, y) centre from image to image. Tracking option "+1" is suited for "fast moving" objects like natural satellites or asteroids. The (x, y) centre of the calibrator is always updated for the next image, but with larger (x, y) corrections, based on proper motions in (x, y) taken with respect to the guide, and computed with polynomials of degrees nx and ny for x and y separately, using all images processed so far. In particular, setting degree nx and ny equal to zero will have the same effect of tracking option "0", but with the small (x, y) corrections taken over all images and not in an image-to-image basis. Outliers are eliminated in the polynomial fits with a sigma-clip procedure. If the tracking option is set to "0", "-1" or "-2", the tracking information (polynomial degrees, sigma-clip factors) in the respective lines in the input data file must still be present, but are ignored.

It is up to the user to use/setup the correct module input data file in correspondence with the photometry mode being used.

The user must also choose the centring method best suited for the calibrators. If the centering option is set to "0" (mix of PGM and 2D Gaussian PSF), and the tracking options set to "+1" or "0", the (x, y) centre that results in the best S/N is always the one used/stored.

Even if for only 1 poor calibrator among many good ones, if the 2D Gaussian fit fails because of insufficient number of pixels or for other causes, and if the PGM centring also fails (with mix option "0"), the processing of the image is aborted and the task moves for the next image. In the case that this happens with the reference image, the task issues an alert and then stops.

For each calibrator, a Student-t test is applied to compare the pixel counts of the aperture with those of the sky background ring. If the mean of both distributions are not significantly different, then we have a situation in which that calibrator is too faint. This can be due to passing clouds or some instrumental issue. The image is then skipped and PPT goes on to the next image. If it happens with the reference image, the task displays a warning and then stops.

Any of the calibrators are fundamental objects in the procedures carried out by the PPT. Thus, even if only one of them does not pass the astrometry or the photometry filters above, the image is skipped. The reference image is also central in the task procedures. Thus, if this happens with the reference image, the task stops.

7.20.1 Module: Calibrators - photometry mode 0

The Calibrators module for photometry mode 0 is given by the input data file PRAIA_photometry_3_0_04_calibrators_mode0.dat. A typical example of this module input data file is shown in Fig. 11 for 2 calibrators.

```
1                                       | Number of calibrators
-1                                      | 01 calibrator: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   01 calibrator: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   01 calibrator: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   01 calibrator: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   01 calibrator: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
04.0                                    |   01 calibrator: flux aperture radius (pixels) (also astrometry aperture radius)
12.0                                    |   01 calibrator: sky background ring radius (pixels)
2.0                                     |   01 calibrator: sky background ring width (pixels) (suggestion = 5 pixels)
0423.0                                  |   01 calibrator: x coordinate on the reference image
0063.5                                  |   01 calibrator: y coordinate on the reference image
0                                       |   01 calibrator: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
+1                                      | 02 calibrator: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   02 calibrator: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   02 calibrator: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   02 calibrator: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   02 calibrator: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
05.0                                    |   02 calibrator: flux aperture radius (pixels) (also astrometry aperture radius)
15.0                                    |   02 calibrator: sky background ring radius (pixels)
5                                       |   02 calibrator: sky background ring width (pixels) (suggestion = 5 pixels)
0124.5                                  |   02 calibrator: x coordinate on the reference image
0034.0                                  |   02 calibrator: y coordinate on the reference image
0                                       |   02 calibrator: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 11: A sample of the Calibrators module for photometry mode 0 PRAIA_photometry_3_0_04_calibrators_mode0.dat furnished in the zip file of PPT for version 3.0.4.

In the photometry mode 0, the astrometry and photometry aperture location and sizes, and the radius and width of the sky background ring of the calibrators are fixed and defined by the user. These values, specially the (x, y) coordinates, must be set using the reference image. The use of an image visualization software like ds9 is mandatory, in order to set up these quantities "as good" as possible. Notice that PPT, as well as other PRAIA tasks, takes as (x=1,y=1) the geometric center of the respective corner pixel in the images.

If tracking option is "on", the final centre of the apertures is computed with the pixels inside the input circular region. Notice that the aperture and sky background ring sizes are furnished by radius (not by diameter).

7.20.2 Module: Calibrators - photometry mode 1

The Calibrators module for photometry mode 1 is given by the input data file PRAIA_photometry_3_0_04_calibrators_mode1.dat. A typical example of this module input data file is shown in Fig. 12 for 2 calibrators.

In mode 1, the fixed aperture size and sky background ring radius and width of the guide, calibrator and targets are automatically set by PPT, instead of being furnished by the user as in mode 0. All comments given in Section 7.19.2 apply here.

In the example, looking at calibrator 1, using the brute force procedure, PPT will test apertures with radius 3.5, 3.6, 3.7, , 4.5 with 0.1 bins (all in pixels). The sky background ring radius (in pixels) is set to 12 and will not be tested (minimum value is equal to maximum). Finally, the ring width is also fixed in 2 pixels. If the bisection method is to be used, aperture radii between 3.5 and 4.5 pixels will be sampled, with convergence given by the bin = 0.1 pixels. For calibrator 2, the sky background ring radius will also be sampled between 14 and 15 pixels with convergence of bin = 1 pixels. Notice that, by default, for speeding computations, only integer values are used in the case of the ring widths, and ring radius bins.

```
1                                       | Number of calibrators
+1                                      | 01 calibrator: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   01 calibrator: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   01 calibrator: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   01 calibrator: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   01 calibrator: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
03.5                                    |   01 calibrator: flux aperture radius (pixels) .:. minimum value
04.5                                    |   01 calibrator: flux aperture radius (pixels) .:. maximum value
00.1                                    |   01 calibrator: flux aperture radius (pixels) .:. bins
12.0                                    |   01 calibrator: sky background ring radius (pixels) .:. minimum value
12.0                                    |   01 calibrator: sky background ring radius (pixels) .:. maximum value
01.0                                    |   01 calibrator: sky background ring radius (pixels) .:. bins
2                                       |   01 calibrator: sky background ring width (pixels) .:. minimum value (suggestion = 1 pixel)
2                                       |   01 calibrator: sky background ring width (pixels) .:. maximum value  (suggestion = 5 pixels)
1                                       |   01 calibrator: sky background ring width (pixels) .:. bins (suggestion = 1 pixel)
0423.0                                  |   01 calibrator: x coordinate on the reference image
0063.5                                  |   01 calibrator: y coordinate on the reference image
0                                       |   01 calibrator: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
+1                                      | 02 calibrator: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   02 calibrator: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   02 calibrator: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   02 calibrator: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   02 calibrator: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
04.0                                    |   02 calibrator: flux aperture radius (pixels) .:. minimum value
06.0                                    |   02 calibrator: flux aperture radius (pixels) .:. maximum value
00.5                                    |   02 calibrator: flux aperture radius (pixels) .:. bins
14.0                                    |   02 calibrator: sky background ring radius (pixels) .:. minimum value
15.0                                    |   02 calibrator: sky background ring radius (pixels) .:. maximum value
01.0                                    |   02 calibrator: sky background ring radius (pixels) .:. bins
2                                       |   02 calibrator: sky background ring width (pixels) .:. minimum value (suggestion = 1 pixel)
2                                       |   02 calibrator: sky background ring width (pixels) .:. maximum value  (suggestion = 5 pixels)
1                                       |   02 calibrator: sky background ring width (pixels) .:. bins (suggestion = 1 pixel)
0124.5                                  |   02 calibrator: x coordinate on the reference image
0034.0                                  |   02 calibrator: y coordinate on the reference image
0                                       |   02 calibrator: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 12: A sample of the Calibrators module for photometry mode 1 `PRAIA_photometry_3_0_04_calibrators_mode1.dat` furnished in the zip file of `PPT` for version 3.0.4.

The method to be used in mode 1 for all objects brute force or bisection method is setup in the Best Fixed Aperture Time Window and Flux Ratio module described in Section 7.22 (this module is only active in photometry mode 1).

7.20.3 Module: Calibrators - photometry mode 2

The Calibrators module for photometry mode 2 is given by the input data file `PRAIA_photometry_3_0_04_calibrators_mode2.dat`. A typical example of this module input data file is shown in Fig. 13 for 2 calibrators.

```
1                                       | Number of calibration objects
-4.0                                    | * 01 calibrator: equalize variable apertures (option 2 only): reference aperture radius r (pixels) (r<0 for free value)
-1                                      |   01 calibrator: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   01 calibrator: tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   01 calibrator: tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   01 calibrator: tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   01 calibrator: tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
+6.0                                    |   01 calibrator: maximum aperture radius (pixels) => input negative value for no radius limit
0.1                                     |   01 calibrator: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
5                                       |   01 calibrator: maximum sky background ring width (pixels) (suggestion = 5 pixels)
422.688                                 |   01 calibrator: x coordinate on the reference image
63.996                                  |   01 calibrator: y coordinate on the reference image
0                                       |   01 calibrator: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
+4.0                                    | * 02 calibrator: equalize variable apertures (option 2 only): fixed aperture radius r (pixels) (r<0 for free value)
-1                                      |   02 calibrator: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   02 calibrator: tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   02 calibrator: tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   02 calibrator: tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   02 calibrator: tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
+6.0                                    |   01 calibrator: maximum aperture radius (pixels) => input negative value for no radius limit
0.1                                     |   02 calibrator: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
5                                       |   02 calibrator: maximum sky background ring width (pixels) (suggestion = 5 pixels)
0192.560                                |   02 calibrator: x coordinate on the reference image
0370.504                                |   02 calibrator: y coordinate on the reference image
0                                       |   02 calibrator: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 13: A sample of the Calibrators module for photometry mode 2 `PRAIA_photometry_3_0_04_calibrators_mode2.dat` furnished in the zip file of `PPT` for version 3.0.4.

These are all the parameters that must be set by the user to setup the photometry and astrometry measurements of calibrators in photometry mode 2. Following the procedure that searches for the best aperture and sky background ring radius and width in terms of S/N described in Section 3.3, the best (x, y) centres of the calibrators are determined for the reference image as well as for all the other ones. The user can set a limit for the aperture radius of each calibrator. This avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images. Put negative values for setting no radius limit.

7.20.4 Module: Calibrators - photometry mode 3

The Calibrators module for photometry mode 3 is given by the input data file `PRAIA_photometry_3_0_04_calibrators_mode3.dat`. It is identical as the module of the calibrators for photometry mode 2. A typical example of this module input data file is shown in Fig. 14 for 2 calibrators.

```
2                                       | Calibrators: maximum number of (best S/N ratio) calibrators (0 = use the limit of 20)
-1                                      | Calibrators: +1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       | Calibrators: tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       | Calibrators: tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     | Calibrators: tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     | Calibrators: tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
+6.0                                    | Calibrators: maximum aperture radius (pixels) => input negative value for no radius limit
0.1                                     | Calibrators: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
5                                       | Calibrators: maximum sky background ring width (pixels)
0                                       | Calibrators: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 14: A sample of the Calibrators module for photometry mode 3 `PRAIA_photometry_3_0_04_calibrators_mode3.dat` furnished in the zip file of `PPT` for version 3.0.4.

As explained in Section 3.6.4, in mode 3 all calibrators are automatically found. The input (x, y) coordinates of the calibrators are automatically computed in the reference image and may or may not be updated for the reference image and for the other images, depending on the tracking option setup. Tracking and centring options are set once for all calibrators. The best aperture and sky background ring radius and width are found in terms of the best S/N. The user sets the pixel binning for the apertures of all calibrators (greater than 0 and up to 1; suggestion: 0.1 pixels) and the maximum width value allowed for testing the ring widths (suggestion: 5 pixels maximum width). Bins for searching the best sky background ring radius and width are internally set to 1. The user can also set a limit for the aperture radius – it is the same for all calibrators. This option avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images. Put negative values for setting no radius limit.

Notice that in mode 3, the same centring method and tracking options are used for all calibrators. If the user needs to use different centring and/or tracking sets for different calibrators, mode 3 may not fit to the users needs. In this case, we recommend that the user chooses mode 2, where different sets for different calibrators can be setup.

Using tracking option "-2" in mode 3 will make `PPT` fix the relative distances (dx, dy) of calibrators with respect to the guide by taking as input the calibrators (x, y) coordinates computed for the reference image in the preliminary step of automatic object identification and location (see Section 3.6.4). Using tracking option -1 will use updated (x, y) coordinates from the reference image as input.

7.21 Module: Targets and ghosts

On line 36 the user furnishes the file name of the Targets and Ghosts module.

The setup of the targets and ghosts is made with the Targets module. There is one specific module input data file for each one of the photometry modes 0, 1, 2 and 3. The modules are self-explanatory.

The maximum allowed number of targets is 20. In the photometry mode 0, the astrometry and photometry aperture location and sizes, and the radius and width of the sky background ring of each target are fixed and defined by the user. These values, specially the (x, y) coordinates, must be set with the reference image. The use of an image visualization software like `ds9` is again mandatory. It is up to the user to set up what kind of centring method is best suited for each target.

After processing the reference image and getting precise relative target coordinates with respect to the guide, tracking option "-1" fixes the relative coordinates of a target to the guide for all images. Option "-2" freezes relative coordinates from the inputs by the user (see previous sections for the special case of photometry mode 3). Option "0" also fixes the relative distance to the guide, but allowing for small corrections by the update of the target (x, y) centre from image to image. Tracking option "+1" is suited for "fast moving" objects like natural satellites or asteroids. The (x, y) centre of the target is always updated for the next image, but with larger (x, y) corrections, based on proper motions in (x, y) taken with respect to the guide, and computed with polynomials of degrees nx and ny for x and y separately, using all images processed so far. In particular, setting degree nx and ny equal to zero will have the same effect of tracking option "0", but with the small (x, y) corrections taken over all images and not in an image-to-image basis. Outliers are eliminated in the polynomial fits with a sigma-clip procedure. If the tracking option is set to "0", "-1" or "-2", the tracking information (polynomial degrees, sigma-clip factors) in the respective lines in the input data file must still be present, but are ignored.

It is up to the user to use/setup the correct module input data file in correspondence with the photometry mode being used.

The user must also choose the centring method best suited for the targets. If the centering option is set to "0" (mix of PGM and 2D Gaussian PSF), and the tracking options set to "+1" or "0", the (x, y) centre that results in the best S/N is always the one used/stored.

Even if for only 1 poor target among many good ones, if the 2D Gaussian fit fails because of insufficient number of pixels or for other causes, and if the PGM centring also fails (with mix option "0"), the processing of the image is aborted and the task moves for the next image. In the case that this happens with the reference image, the task issues an alert and then stops.

Contrary to the case of guide or calibrators, no filter is applied to targets with respect to brightness. This is because target brightness is allowed/expected to eventually drop, even considerably, during some event, like in stellar occultations or mutual phenomena – the target counts may even get "null". That is, instead of discarding the image as bad, as would be the case with the guide or calibrators, in this case by the contrary we have a very worthy observation, and a special approach is taken, as shown in Section 7.23.

Any target is a fundamental objects in the procedures carried out by the `PPT`. Thus, only when it does not pass the astrometry filter (indicating that no secure measurement is possible), the image is skipped. The reference image is also central in the task procedures. Thus, if this happens with the reference image, the task stops.

7.21.1 Module: Targets and ghosts - photometry mode 0

The Targets module for photometry mode 0 is given by the input data file `PRAIA_photometry_3_0_04_Targets_mode0.dat`. A typical example of this module input data file is shown in Fig. 15 for 1 target.

```
1                                       | Number of targets
+1                                      | 01 target  : 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   01 target: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   01 target: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   01 target: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   01 target: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
03.4                                    |   01 target: flux aperture radius (pixels) (also astrometry aperture radius)
12.0                                    |   01 target: sky background ring radius (pixels)
2.0                                     |   01 target: sky background ring width (pixels)
0190.0                                  |   01 target: x coordinate on the reference image
0381.0                                  |   01 target: y coordinate on the reference image
0178.0                                  |   01 ghost : x coordinate on the reference image (sky background nearby target)
0404.0                                  |   01 ghost : y coordinate on the reference image (sky background nearby target)
0                                       |   01 target: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 15: A sample of the Targets module for photometry mode 0 `PRAIA_photometry_3_0_04_targets_mode0.dat` furnished in the zip file of `PPT` for version 3.0.4.

In the photometry mode 0, the astrometry and photometry aperture location and sizes, and the radius and width of the sky background ring of the targets are fixed and defined by the user. These values, specially the (x, y) coordinates, must be set using the reference image. The use of an image visualization software like `ds9` is mandatory, in order to set up these quantities "as good" as possible. Notice that `PPT`, as well as other `PRAIA` tasks, takes as (x=1,y=1) the geometric center of the respective corner pixel in the images.

If tracking option is "on", the final centre of the apertures is computed with the pixels inside the input circular region. Notice that the aperture and sky background ring sizes are furnished by radius (not by diameter).

Since the aperture radius and the radius and width of the sky background ring of ghosts are the same as those of their targets, the user must only set reference image (x, y) coordinates for ghosts.

7.21.2 Module: Targets and ghosts - photometry mode 1

The Targets module for photometry mode 1 is given by the input data file `PRAIA_photometry_3_0_04_targets_mode1.dat`. A typical example of this module input data file is shown in Fig. 16 for 1 target.

In mode 1, the fixed aperture size and sky background ring radius and width of the guide, calibrator and targets are automatically set by `PPT`, instead of being furnished by the user as in mode 0. All comments given in Section 7.19.2 apply here.

In the example, all aperture and sky background parameters are actually fixed and no search will be effectively conducted. Otherwise, the same rationale explained in the photometry mode 1 for calibrators apply for targets (see Section 7.20.2).

```
1                                       | Number of targets
+1                                      | 01 target  : 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   01 target: Tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   01 target: Tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   01 target: Tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   01 target: Tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
03.4                                    |   01 target: flux aperture radius (pixels) .:. minimum value
03.4                                    |   01 target: flux aperture radius (pixels) .:. maximum value
00.1                                    |   01 target: flux aperture radius (pixels) .:. bins
12.0                                    |   01 target: sky background ring radius (pixels) .:. minimum value
12.0                                    |   01 target: sky background ring radius (pixels) .:. maximum value
01.0                                    |   01 target: sky background ring radius (pixels) .:. bins
2                                       |   01 target: sky background ring width (pixels) .:. minimum value (suggestion = 1 pixel)
2                                       |   01 target: sky background ring width (pixels) .:. maximum value  (suggestion = 5 pixels)
1                                       |   01 target: sky background ring width (pixels) .:. bins (suggestion = 1 pixel)
0190.0                                  |   01 target: x coordinate on the reference image
0381.0                                  |   01 target: y coordinate on the reference image
0178.0                                  |   01 ghost : x coordinate on the reference image (sky background nearby target)
0404.0                                  |   01 ghost : y coordinate on the reference image (sky background nearby target)
0                                       |   01 target: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 16: A sample of the Targets module for photometry mode 1 `PRAIA_photometry_3_0_04_targets_mode1.dat` furnished in the zip file of `PPT` for version 3.0.4.

The method to be used in mode 1 for all objects brute force or bisection method is setup in the Best Fixed Aperture Time Window and Flux Ratio module described in Section 7.22 (this module is only active in photometry mode 1).

Since the aperture radius and the radius and width of the sky background ring of ghosts are the same as those of their targets, the user must only set reference image (x, y) coordinates for ghosts.

7.21.3 Module: Targets and ghosts - photometry mode 2

The Targets module for photometry mode 2 is given by the input data file `PRAIA_photometry_3_0_04_targets_mode2.dat`. A typical example of this module input data file is shown in Fig. 17 for 1 target.

```
1                                       | Number of targets
-3.4                                    | * 01 target: equalize variable apertures (option 2 only): reference aperture radius r (pixels) (r<0 for free value)
+1                                      |   01 target: 1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       |   01 target: tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       |   01 target: tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     |   01 target: tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     |   01 target: tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
+3.5                                    |   01 target: maximum aperture radius (pixels) => input negative value for no radius limit
0.1                                     |   01 target: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
05.0                                    |   01 target: maximum sky background ring width (pixels) (suggestion = 5 pixels)
0190.0                                  |   01 target: x coordinate on the reference image
0381.0                                  |   01 target: y coordinate on the reference image
0178.0                                  |   01 ghost : x coordinate on the reference image (sky background nearby target)
0404.0                                  |   01 ghost : y coordinate on the reference image (sky background nearby target)
0                                       |   01 target: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gussian
```

Figure 17: A sample of the Targets module for photometry mode 2 `PRAIA_photometry_3_0_04_targets_mode2.dat` furnished in the zip file of `PPT` for version 3.0.4.

These are all the parameters that must be set by the user to setup the photometry and astrometry measurements of targets in photometry mode 2. Following the procedure that searches for the best aperture and sky background ring radius and width in terms of S/N described in Section 3.3, the best (x, y) centres of the targets are determined for the reference image as well as for all the other ones. The user can set a limit for the aperture radius of each target. This avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images. Put negative values for setting no radius limit.

Since the aperture radius and the radius and width of the sky background ring of ghosts are the same as those of their targets, the user must only set reference image (x, y) coordinates for ghosts.

7.21.4 Module: Targets and ghosts - photometry mode 3

The Targets module for photometry mode 3 is given by the input data file `PRAIA_photometry_3_0_04_targets_mode3.dat`. It is identical as the module of the calibrators for photometry mode 2. A typical example of this module input data file is shown in Fig. 18 for 1 target.

As explained in Section 3.6.4, in mode 3 all targets (and ghosts) are automatically found. The input (x, y) coordinates of the targets are automatically computed in the reference image and may or may not be updated for the reference image and for the other images, depending on the tracking option setup. Tracking and centring options are set once for all targets. The best aperture and sky background ring radius and width are found in terms of the best S/N. The user sets the pixel binning for the apertures of all targets (greater than 0 and up to 1; suggestion: 0.1 pixels) and the maximum width value allowed for testing the ring widths (suggestion: 5 pixels maximum width). Bins for searching the best sky background

```
1                                       | Targets: total number of targets (minimum number = 1)
+1                                      | Targets: +1 = tracking ;  0 = no tracking ;  -1 = fixed (except ref. image); -2 = fixed (all)
0                                       | Targets: tracking in X: nth-degree of polynomial in time T (N=0-21): X=a0+a1T+a2T^2+...
0                                       | Targets: tracking in Y: nth-degree of polynomial in time T (N=0-21): Y=b0+b1T+b2T^2+...
2.5                                     | Targets: tracking in X: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaX_fitting
2.5                                     | Targets: tracking in Y: Outliers, sigma FACTOR: exclude |O-C| > FACTOR*sigmaY_fitting
0.1                                     | Targets: aperture radius bin in best aperture radius determination (pixels): 0 < bin < 1
05.0                                    | Targets: maximum sky background ring width (pixels)
+3.5                                    |  Target 01: maximum aperture radius (pixels) => input negative value for no radius limit
0190.0                                  |  Target 01: x coordinate on the reference image (set NONE in x and y for automatic target search)
0381.0                                  |  Target 01: y coordinate on the reference image (set NONE in x and y for automatic target search)
0                                       | Targets: centering algorithm: 0 - mixed; 1 - PGM ;  2 - 2D Gaussian
```

Figure 18: A sample of the Targets module for photometry mode 3 `PRAIA_photometry_3_0_04_targets_mode3.dat` furnished in the zip file of `PPT` for version 3.0.4.

ring radius and width are internally set to 1. The user can also set a limit for the aperture radius – it is the same for all targets. This option avoids problems in the `BOIA` method due to crowded FOVs, nearby objects or features (like FOV borders) in the images. Put negative values for setting no radius limit.

Notice that in mode 3, the same centring method and tracking options are used for all targets. If the user needs to use different centring and/or tracking sets for different targets, mode 3 may not fit to the users needs. In this case, we recommend that the user chooses mode 2, where different sets for different targets can be setup.

Using tracking option "-2" in mode 3 will make `PPT` fix the relative distances (dx, dy) of targets with respect to the guide by taking as input the target (x, y) coordinates computed for the reference image in the preliminary step of automatic object identification and location (see Section 3.6.4). Using tracking option -1 will use updated (x, y) coordinates from the reference image as input.

For automatic identification of targets by `PPT`, set "NONE" in both x and y coordinate entries. If more than 1 target is set, there must be an equal number of x and y coordinate fields, even with the "NONE" (automatic) option. All targets must be set to be found automatically or be set to be explicitly indicated no mixing (NONE with numeric coordinates) is allowed in the current version of the task. In the example in Fig. 18 the target coordinates are explicitly furnished, so no attempting for automatic identification of targets will be carried out by `PPT` – only for calibrators.

The ghosts are completely defined automatically, independently of the way that the targets were defined (automatically or imposed by the user). Thus, there are no parameters in mode 3 to fill up regarding to ghosts, not even (x, y) coordinates. Using the reference image, after the definition of the aperture and sky background ring of each target, a search for the best corresponding ghost is conducted. Centered at 1 sky background ring radius distance from the target, circular areas with the same size of the target aperture are sampled 360 degrees around the target. The area with the least average pixel flux found with respect to the local sky background is set as the ghost for that target. After all ghosts are found, their coordinates relative to their targets are fixed, so that the ghosts can be measured in all images at the same relative distance to the targets, that is, always sampling the same local sky regions.

7.22 Module: Best fixed aperture time window and flux ratio setup (mode 1 only)

On line 37 the user furnishes the file name of the Best Fixed Aperture Time Window and Flux Ratio setup module.

The Best Fixed Aperture Time Window and Flux Ratio Setup module is given by the module input data file `PRAIA_photometry_3_0_04_best_fixed_aperture_tw.dat`. It is only active in photometry mode 1. This module serves to further setup the photometry mode 1.

A typical example is given in Fig. 19.

```
2                                       | Best fixed aperture/sky_background_ring: photometric parameters' search => (1) brute force; (2) bisection method
01                                      | Best fixed aperture/sky_background_ring: flux ratio flattening/normalization polynomial degree (N=0-21)
2.5                                     | Best fixed aperture/sky_background_ring: flattening/normalization sigma-clip factor elimination polyn. fit
1                                       | Best fixed aperture/sky_background_ring: number of sample time windows
+00780.0                                | Best fixed aperture/sky_background_ring: sample time window: t_min in user-time units
+00810.0                                | Best fixed aperture/sky_background_ring: sample time window: t_max in user-time units
```

Figure 19: A sample of the Best Fixed Aperture Time Window and Flux Ratio module for photometry mode 1 `PRAIA_photometry_3_0_04_best_fixed_aperture_tw.dat` furnished in the zip file of `PPT` for version 3.0.4.

First, the user sets up in this module the method of searching for the best aperture radius and sky background ring radius and width of all objects: brute force (option "1") or bisection method (option "2", recommended).

Second, it allows for the user to fix a number of time window sections (in user-defined time units). Using only images inside these time windows, PPT flats/normalizes provisional flux ratios (target/calibrator) in the search for the best set of values for the apertures and sky background rings of all objects. The entry is ignored for other photometry modes, 0, 2 or 3 (do not delete the line in any case).

In this module the user furnishes the polynomial degree and sigma-clip factor for the polynomial fit that flattens/normalizes the provisional flux ratio. Up to 20 time window sections are allowed. They must be selected so that no flux variation is expected for any of the targets within them. The size of the time windows should be large enough to contain a sufficient number of images to grant good statistics, but at the same time small enough to avoid excessive computer time consumption. We recommend that the reference image be contained in one of the time window sections.

7.23 Target in low count regime; Module: Time windows for target events

On line 38 the user sets the option for PPT to automatically detect ("1") or not ("2")) if the targets are in low ADU counts regime.

On line 39 the user furnishes the file name of the Time Windows for Target Events module. The module file PRAIA_photometry_3_0_04_events_time_windows_Ph.dat is furnished in the zip file of PPT.

The optimization of measurements of all objects in all the photometry modes (0 to 3) depends upon the search for the best obtainable S/N. However, in the case of transient events such as mutual phenomena or stellar occultations, and (to a much lesser extent) also in rotational light curves, there will be images in which the target is expected to present very low counts. On those images, the photometry procedures aimed for higher S/N ratios are meaningless and may even result in the loss of the target location in the FOV.

In such cases, for images with a target in low count regime, PPT conservatively stops applying the "S/N"-based procedures for the target only. In all photometry modes the tracking (if set) is turned off, and in modes 2 and 3 the photometry of the target is done using the last used aperture radius and sky background ring radius and width.

PPT offers 2 ways to set a target in low count regime. One way is to set PPT to search for it automatically. The other is simply to furnish to PPT time window sections, directly indicating the images that have a target in low count regime. One way automatically cancels the other and vice-versa.

The automatic search procedure is as follows. Image by image, the task performs the photometry as usual in the targets. After the measurement, a Student-t test is applied to compare the pixel counts of the aperture with those of the sky background ring. If the mean of both distributions are not significantly different, then we have a low count situation. No (x, y) centre update/storing is performed nor proper motions are updated. The photometry of the target in modes 2 and 3 is made as explained with the photometric parameters of the last image. The task then goes on to the next image and the photometry proceeds normally.

The direct way makes use of the Time Windows for Target Events module, which can be setup for any of the photometry modes 0, 1, 2 or 3, and which is given by the module input data file PRAIA_photometry_3_0_04_events_time_windows_Ph.dat. Indeed, in practice the same module is also used in mode 4 when we build the LC, since it parameterises the same event (stellar occultation, mutual event, etc). A typical example of the input data file is shown in Fig. 20.

```
1                                          | Number of time windows for time events (0 to 20):
+01097.0                                   |   01 time window: t_min in user-time units
+01266.0                                   |   01 time window: t_max in user-time units
```

Figure 20: A sample of the Time Windows for Target Events module (photometry modes 0–3) PRAIA_photometry_3_0_04_events_time_windows_Ph.dat furnished in the zip file of PPT for version 3.0.4.

The user must furnish the number of time window sections and, for each one, 2 lines indicating the beginning and ending of the time window in User Time units. If the automatic search for targets low count regime is turned off, the photometry of targets for images inside the time windows furnished in this module is made with the setup for target low count regime.

PPT will read as much lines in this input data file as it should, given the number of time windows. If there are more lines than necessary, they will be ignored. If there are fewer, than an error will occur. Time instants are furnished in User-Time units.

A way of turning off either the automatic and the direct setup of target low count regime is turning off the automatic detection and at the same time setting the number N of time windows equal to zero, or making for instance N=1, then furnishing a "fantasy" time window with time instants outside the observed range of images. In any way, both lines - the one with the automatic option and that with the module file name - must be present in the photometry block of the main input data file `PRAIA_photometry_3_0_04.dat`

The line 40 marks the end of the photometry block of the main input data file `PRAIA_photometry_3_0_04.dat`. Notice the mandatory "**********" string at this end line, signaling the end of the photometry block.

8 Configuring the Task for Building a LC from Photometry Measurements

We strongly recommend the user to read Section 4 and Assafin (2023a) before proceeding. Here, we describe the contents of the LC building block - the most commonly used light curve block by `PPT`, where a LC is obtained as the outcome of photometry measurements. Only one LC building block mode is available: mode 4. Another type of LC block much less utilized serves to eliminate the intruding flux in a LC - the contents of that LC block are described in Section 9.

A LC is the result of the calibration of the clean flux of a target by the use of the unified clean flux from calibrators. We calibrate the target flux by dividing it by the calibration flux derived from calibrators. We refer to the calibrated flux of a target as the flux ratio. Often (but not necessarily), we flat and normalize the flux ratio, using large portions of the LC that we want to set as unity. In essence, a LC produced with `PPT` presents (target/calibration) flux ratios as a function of time. It is important to state that `PPT` works only with 1 target at a time in the confection of a LC.

A special kind of object is the ghost. A target always has (or should have) a ghost associated to it. In what concerns the building of LCs by `PPT`, every procedure applied to the target is also applied to its ghost. For simplicity, "flux ratio" will always refer to the flux ratio of the target throughout the text. The flux ratio of the ghost will always be explicitly stated as so, whenever it be the case.

`PPT` produces LCs from previous photometry measurements made with the task itself. But `PPT` also accepts aperture or PSF photometry measurements not made by the task, in the context of differential photometry or not. If the photometry measurements were made with `PPT`, the obtained LC consists of flux ratios in the context of differential aperture photometry. Depending on the inputs available from the photometry measurements, many more output information is furnished in the LCs. The amount of this output information is complete when the photometry measurements come from the use of `PPT`.

A typical content of the LC building block mode 4 of `PPT` is shown in Fig. 21. The value in the first line of the LC building block mode 4 must be "4", indicating the unique mode currently available for this block by `PPT`. The second entry must be "1" or "2", indicating respectively if the user wants or not to effectively run the block/mode.

All the entries in mode 4 are commented in the following sub-sections. The sub-sections are presented following (in general) the order of the entries in the LC building block mode 4. This order is more or less the same of the LC processing. As with the photometry block, there are modules specific to LC building block mode 4, as well as modules shared with the other blocks/modes.

8.1 Output file names: PPT LCs, User-defined LC module

There are 3 light curve output files generated by `PPT` in the LC building block mode 4, including a User-defined LC which is actually a LC building block mode 4 `PPT` module. Their content and format are described in Section 11. The output file names must be furnished as follows:

- Line 3 - Main `PPT` output LC with complete LC information
- Line 4 - Short version `PPT` output LC with main LC information
- Line 43 - User-defined output LC with User-defined content .:. Module: User-defined output LC file format PRAIA_photometry_3_0_04_LC_user.dat

```
4                                                | Light Curve (LC) production, mode (4)
1                                                | Generate light curve? (1) yes; (2) no
curve72.dat                                      | Output name of LC (read notes below)
curve_short72.dat                                | Output name of LC, short version (read notes below)
+0000000000|-------------------------------------| FWHM cutoff for target: MLF key (read User Guide and notes below)
999.00                                           | FWHM cutoff for target: if FWHM > cutoff, update MLF key of outliers
+0000000000|-------------------------------------| FWHM cutoff for calibrators: MLF key (read User Guide and notes below)
999.00                                           | FWHM cutoff for calibrators: if FWHM > cutoff, update MLF key of outliers
+2222022222|-------------------------------------| Calibration flux error FACTOR sigma-clip elimination: MLF key (read User Guide and notes below)
2.5                                              | Calibration flux error FACTOR sigma-clip elimination: e_i-e_mean>FACTOR*sigma, update MLF key of outliers
+0000002000|-------------------------------------| LC flux ratio error cutoff in magnitudes: MLF key (read User Guide and notes below)
999                                              | LC flux ratio error cutoff in magnitudes: error > cutoff, update MLF key of outliers
+0000022222|-------------------------------------| LC flux ratio error FACTOR sigma-clip elimination: MLF key (read User Guide and notes below)
2.5                                              | LC flux ratio error FACTOR sigma-clip elimination: e_i-e_mean>FACTOR*sigma, update MLF key of outliers
PRAIA_photometry_3_0_04_user_time.dat            | Module: User-time reference instant (aperture photometry and LC, all modes, mode0=mode1=...=mode4)
PRAIA_photometry_3_0_04_select_calibrators.dat   | Module: Selection of best calibrators (LC, mode4)
PRAIA_photometry_3_0_04_smooth_calibration.dat   | Module: Smoothing calibration flux (LC, mode4)
2                                                | Smooth the LC flux points with moving time window? (1) Yes; (2) No
3.5                                              | Time window dt for LC flux smoothing (seconds); each point T is the average of points within [T-dt/2, T+dt/2]
2                                                | Bin the LC flux points with a moving time window? (1) Yes; (2) No
032                                              | Time window dt for LC flux binning (seconds); each point t is the average of points within [t-dt/2, t+dt/2]
00.000000                                        | Target flux contamination correction (0-100%): final_target_flux = original_target_flux * (1 - CORR/100)
0                                                | Calibration and target fluxes: (0) Do nothing; (1) Flatten fluxes only; (2) Flatten and normalize fluxes
2                                                | LC flux ratio  : (0) Do nothing; (1) Flatten flux ratio only; (2) Flatten and normalize flux ratio
0                                                | Calibration flux: degree of flattening/normalization           polynomial (N=0-21; typically N=0 to N=2)
0                                                | Target flux     : degree of flattening/normalization/flux_corr polynomial (N=0-21; typically N=0 to N=2)
1                                                | LC flux ratio   : degree of flattening/normalization           polynomial (N=0-21; typically N=0 to N=2)
+0222022222|-------------------------------------| Calibration flux flattening/normalization      : MLF key for outliers (read User Guide and notes below)
2.5                                              | Calibration flux flattening/normalization      : sigma factor for sigma-clip elimination in polynomial fit
+0000222222|-------------------------------------| Target flux flattening/normalization/flux_corr : MLF key for outliers (read User Guide and notes below)
2.5                                              | Target flux flattening/normalization/flux_corr : sigma factor for sigma-clip elimination in polynomial fit
+0000022222|-------------------------------------| LC flux ratio flattening/normalization         : MLF key for outliers (read User Guide and notes below)
2.5                                              | LC flux ratio flattening/normalization         : sigma factor for sigma-clip elimination in polynomial fit
PRAIA_photometry_3_0_04_events_time_windows_LC.dat| Module: Time windows for Target flux and flux ratio flattening/normalization (mode0=mode1=...=mode4)
2                                                | Offset the output LC flux ratio for plotting purposes: 1 = magnitude offset; 2 = flux ratio ADU/ADU units
0.d0                                             | Flux ratio offset: 1: Dmag_final=Dmag_original+VALUE; 2: final_flux_ratio=original_flux_ratio+VALUE
-1.0d0                                           | Target flux offset VALUE (plotting)      : final_flux = original_flux + VALUE (not in magnitude units)
-2.d0                                            | Calibration flux offset VALUE (plotting) : final_flux = original_flux + VALUE (not in magnitude units)
-0.0d0                                           | Ghost target flux ratio offset VALUE     : final_flux = original_flux + VALUE (not in magnitude units)
photometry72.dat                                 | Input photometry file
PRAIA_photometry_3_0_04_input_time_photometry.dat | Module: Time instants of input photometry file (LC, mode 4)
PRAIA_photometry_3_0_04_format_photometry.dat    | Module: Input photometry file format (LC, mode 4)
PRAIA_photometry_3_0_04_LC_user.dat              | Module: User-defined output LC file format (LC, mode 4); (NONE = do not generate user-defined output LC)
*************************************************************************************************************************************************************************
```

Figure 21: A sample of the LC building block mode 4 in the main input data file `PRAIA_photometry_3_0_04.dat` furnished in the zip file of `PPT` for version 3.0.4.

8.2 MLF keys and cutoff values and factors for FWHM and flux ratio errors

From lines 5 to 14 the user fills up MLF keys, cuttoff values and cutoff factors regarding to the FWHM of calibrators and targets, and (provisional, raw) flux ratio errors in magnitudes and in dimensionless "ADU/ADU" units.

The first procedure in the LC production is to check the FWHM (seeing) of targets and calibrators, and provisional raw flux ratio errors in magnitude units.

The FWHM, read in arcsecond units, is the very first quality control parameter checked by `PPT`, if it is indeed furnished in the photometry measurements. Its checking is straightforward. The utility of this parameter is to segregate bad from good sky condition observations, which sometimes can improve a lot the final LC.

The user must take some precautions. First, one must be sure that reliable estimates for the FWHM are indeed available. One must also be sure that the FWHM is indeed furnished in arcsecond units (not in pixel units, for instance) from the input photometry measurements.

If the FWHM of the target is above the threshold set by the user, the MLF of the point is updated according to that furnished on line 5 of the LC building block mode 4. If more than one calibrator exists, it takes only one above the FWHM threshold to update the MLF of that point on line 7. If the MLF setup in the input data file has - in position 1, then the LC points with FWHM outliers according to the cutoff values in lines 6 (target) and 8 (calibrators) are readily eliminated from the LC.

Another quality control parameter that is early checked by `PPT` is the flux ratio error in magnitude units. Thus, prior to any subsequent LC procedures set up by the user, the LC points are first checked for anomalous LC points. The use of magnitudes at this stage is convenient for two reasons. First, it results in the same error value in magnitudes, regardless of normalization or not of the flux ratio. Second, magnitudes are always an intuitive brightness scale to the user. Since, in fact, no flux ratio normalization has yet been done at this stage, it would be much more difficult to figure out a reasonable threshold value for the flux ratio error. If the MLF setup on line 11 of the LC building block mode 4 has - in position 1, then the LC points with flux error outliers in magnitudes according to the cutoff value in line 12 are readily eliminated from the LC.

At a given point in the middle of the LC processing, a sigma-clip procedure is conducted for marking outliers in calibration flux ***errors*** (setup on lines 9 and 10) and in the flattened/normalized flux ratio ***errors*** (setup on lines 13 and 14). When outliers are detected their MLFs are updated. It is up to the user to decide, using the MLF, if these new outliers are to be excluded from the rest of the LC processing, or even dropped from the LC.

8.3 Module: User time

On line 15 of the LC building block mode 4 the user furnishes the input file name of the User-time module. The description of this module content was already given in Section 7.12.

The user sets a time scale that is more convenient for plotting and analysis purposes, instead of being restricted to the usual Julian Date. Indeed, the User time is the time scale utilized to define forbidden LC time window sections in some smoothing and flattening/normalizing operations. The user-time is a time counting from a reference instant. The reference instant can be furnished in Gregorian date, Julian Date or Modified Julian Date format. The User time is counted from this instant on, in some scale defined by the user (seconds, minutes, hours, fraction of a day, etc). The user time must always be setup.

Notice that this module is the same as that introduced in the photometry block and used with any of the modes 0 to 3. In practice, the User time setup of this module is exactly the same, numerically speaking, in all modes 0 to 4, for the photometry of a given set of images. That is, the same module input data file can and should be used throughout modes 0 to 4. This also holds true for the usage of this module in the LC intruding flux block mode 5 (Section 9).

8.4 Module: Selection of best calibrators

On line 16 of the LC building block mode 4 the user furnishes the input file name of the Best Calibrators module. We setup the selection of the best calibrators with this module. The content of this module input data file is given in Fig. 22.

```
2                                          | Automatic selection of best calibrators? (1) Yes; (2) No .:. if Yes, fill up lines below (*)
01                                         | * Input photometry flux ratio: degree of flattening/normalization polynomial (N=0-21; typically N = 0 - 2)
2.5                                        | * Input photometry flux ratio flattening/normalization: sigma factor for sigma-clip cutoff in polyn. fit
PRAIA_photometry_3_0_04_events_time_windows_LC.dat| * Module: Time windows setup for target events (aperture photometry and LC, all modes, mode0=mode1=...=mode4)
```

Figure 22: A sample of the Selection of Best Calibrators module file `PRAIA_photometry_3_0_04_select_calibrators.dat` furnished in the zip file of `PPT` for version 3.0.4.

In the example, the user setup `PPT` not to perform the selection. This means that all calibrators available (one or more) in the input photometry file will be used. All other lines in the input data file are ignored.

However, when more than 1 calibrator is available, frequently the user wants to select the best set of them to construct the LC. `PPT` can automatically select the best calibrators among those available. In this case, put "1" as the option in the first line of the module input data file.

In this case, the task automatically searches for the best combination of calibrators. All calibrator combinations are tested. For each combination, a provisional LC with flux ratios is constructed, and the flux ratio dispersion computed. The provisional LC with the least flux ratio variation with time gives the best combination of calibrators.

The user sets up some parameters in order to control basic procedures for the production of the provisional LCs which are used to probe the calibrators. `PPT` computes provisional flux ratios and forcibly flattens and normalizes them. The user must setup the degree N of the polynomial used in these operations, as well as the sigma-clip factor for the elimination of outliers.

In particular, the user must furnish here the file name of the `PPT` module Time windows for target events, say `PRAIA_photometry_3_0_04_events_time_windows_LC.dat`. For obvious reasons, flat/normalization operations are prohibited inside the window time sections indicated by this module, which was already described in Section 7.23. Notice that by purpose we used different extension names there ("Ph" for Photometry) and here ("LC" for Light Curve). This is to indicate that although both modules (and the internal formats) are the same, the setup of window time sections may be different for photometry and LC building. For instance, to avoid time consumption when the LC is quite large with a great number of points, one can setup here larger time windows or more time sections to drop the number of points to be used in the flat/normalization fittings. Except for such cases with extremely large numbers of LC points, we do recommend here the use of the same photometry setup (same Time windows for target events module file).

After the selection of the best group of calibrators, the other ones are discarded and the final calibration flux and errors are computed and stored. Due to machine limitations in computing all possible combinations of calibrators, there is a limit of 20 in the input number of calibrators. Exceeding this limit makes the task stop.

8.5 Module: Smoothing calibration flux

On line 17 of the LC building block mode 4 the user furnishes the input file name of the Smoothing calibration flux module. This module sets up PPT for smoothing calibration flux along the entire LC. The content of this module input data file is given in Fig. 23.

```
10                                                | Smooth calibration flux? 0=automatic (* fill up lines below); 1=no; 2=+1 neighbor; 3=+2 neighbors, 4=+3 ...
02                                                | * Provisional flux ratio. Degree of flattening/normalization polynomial (N=0-21; typically N = 0 - 2)
2.5                                               | * Provisional flux ratio. Flattening/normalization: sigma factor for sigma-clip cutoff in polyn. fit
PRAIA_photometry_3_0_04_events_time_windows_LC.dat| * Module: Time windows setup for target events (aperture photometry and LC, all modes, mode0=mode1=...=mode4)
```

Figure 23: A sample of the Smoothing calibration flux module file `PRAIA_photometry_3_0_04_smooth_calibration.dat` furnished in the zip file of PPT for version 3.0.4.

Prior to computing LC flux ratios, the calibration fluxes may be smoothed by using neighbor calibration fluxes. This can be done automatically or manually. Setting "1" in the first line of the module input data file means no smoothing. Setting "10" as in the example averages the calibration flux of the current point with that of the nearest 9 neighbors in time. Putting "3" averages the current point with the two nearest neighbors in time, and so on.

Choosing "0" makes PPT automatically find the best number of neighbors for smoothing. In option "0", PPT can even come to the conclusion that no smoothing (0 neighbors, equivalent to option "1") may be the best solution this possibility is also verified by the task. In the automatic mode, all neighbor number combinations are tested. For each combination, a provisional LC with flux ratios is constructed, and the flux ratio dispersion computed. The provisional LC with the least flux ratio variation with time gives the best number of neighbors (if any) to use in the calibration flux smoothing.

The user sets up some parameters in order to control basic procedures for the production of the provisional LCs. PPT computes provisional flux ratios and forcibly flattens and normalizes them. The user must setup the degree N of the polynomial used in these operations, as well as the sigma-clip factor for the elimination of outliers.

In particular, the user must also furnish here (as in the case of the selection of best calibrators – see Section 8.4) the file name of the PPT module Time windows for target events, say `PRAIA_photometry_3_0_04_events_time_windows_LC.dat`. For obvious reasons, flat/normalization operations are prohibited inside the window time sections indicated by this module, which was already described in Section 7.23. Notice that by purpose we used different extension names there ("Ph" for Photometry) and here ("LC" for Light Curve). This is to indicate that although both modules (and the internal formats) are the same, the setup of window time sections may be different for photometry and LC building. For instance, to avoid time consumption when the LC is quite large with a great number of points, one can setup here larger time windows or more time sections to drop the number of points to be used in the flat/normalization fittings. Except for such cases with extremely large numbers of LC points, we do recommend here the use of the same photometry setup (same Time windows for target events module file).

8.6 LC smoothing and binning

On lines 18-21 of the LC building block mode 4 the user furnishes the options for LC smoothing and binning.

The LC flux ratios may also be smoothed. For that, a time window that "moves" with the LC points must be set. The flux ratio of each LC point is represented by the unweighted average of the flux ratios of all LC points within the time window centred at the current LC point. If the MLF of the current point prohibits, it is not smoothed. If the MLF of some of the points within the time window prohibits, they are discarded from the averaging. The same operation is carried out for the flux ratio of the ghost. All flux quantities are also smoothed. The S/N and errors are also updated. The original instant of time of each LC point may change as a result of the points used in the smoothing. The original number o LC points is preserved.

The LC flux ratios may also be binned. For that, the time window bin must be set. The flux ratio of each LC point is represented by the unweighted average of the flux ratios of all LC points within each time bin. If the MLF of a LC point prohibits, it is not used in the LC binning. The same operation is carried out for the flux ratio of the ghost. All flux quantities are also averaged. The S/N and errors are also updated. The instants of time of each generated LC point after the binning are the unweighted average of the time instants of each contributing point within each time bin. The final number of LC points is smaller than the original number of points.

8.7 Target flux contamination correction

On line 22 of the LC building block mode 4 the user furnishes the target flux contamination correction.

It is often the case when a steady, intruding flux from another nearby object a bright nearby source or a close companion star is mixed with the flux of the main target itself.

In stellar occultation observations for instance, during the flux drop, the flux of the occultation body remains. In the particular case of a body with an atmosphere, star flux is also present. In this case, the determination of the amount of residual star flux, separated from that of the intruding body (mostly if the body is not faint), is essential for the correct interpretation of the LC, and for its use in the fitting of pressure and temperature atmospheric models.

`PPT` allows for the user to remove such contaminating flux from the intruding body by setting it up as a percentage of the total measured flux of the target. Note that no updates are made regarding to the S/N and error of the target flux.

The flux contamination correction $CORR$ must be given as a percentage of the total flux of the target, so that equation **??**olds:

$$(final\ target\ flux) = (original\ target\ flux) * \left(1 - \frac{CORR}{100}\right) \tag{5}$$

A background about how to compute the percentage of intruding flux is given in Section 4.2. This computation is carried out by `PPT` with the LC intruding flux block mode 5, which content is given in Section 9.

8.8 Flattening and normalization of calibration, target and flux ratios

On lines 23 to 33 of the LC building block mode 4 the user parameterises the flattening and normalization of calibration flux, target flux and flux ratios. These operations are of utmost importance in the production of the LC. We strongly recommend the reading of Section 4.1. These procedures are described in detail in Assafin (2023a).

Flattening and normalization are commonly utilized - they are mandatory in stellar occultation and mutual phenomena work. In some occasions it may also be useful in rotation light curve work, although in those cases it is more delicate to define the forbidden LC time window sections for the flattening and normalization computations.

In principle, we only need to flat and normalize the (target/calibration) flux ratios. But sometimes there are also advantages in flattening and normalizing calibration and target fluxes prior to flattening and normalizing flux ratios. For instance, by doing so, it becomes more evident the detection of LC outliers by the normalized calibration flux errors. Not to mention the possibility of eliminating systematic errors with time, separately for the calibration and for target fluxes. Another utility in the flattening and normalization resides in enabling the analysis of the behavior of calibration and target fluxes with time in a completely comparable scale, which is otherwise very difficult due to the usually very distinct levels of the fluxes involved.

The same polynomials fitted and used in the flattening and normalization of target fluxes and target flux ratios are applied for ghost fluxes. Therefore, by construction, flatted/normalized ghost fluxes and ghost flux ratios are not set to unity as calibration and target fluxes are.

The filling up of this part of the LC building block mode 4 input data file is straightforward. The user defines if she/he wants that calibration fluxes, target fluxes and flux ratios be flattened and normalized. For making sense, flattening and normalization applied to calibration fluxes must also be applied for target fluxes. Therefore, there is only one single option for both.

The degree N of the polynomials used in the flattening and normalization can be freely set for each type of flux separately: calibration, target and flux ratio. Usually polynomials with degree N=1 or N=2 suffice to cope with sky extinction and other smooth flux variations with time in the observations. We notice that first, calibration and target fluxes are flattened and normalized separately (if that was set by the user, of course). Only after that, flux ratios are flattened and normalized. This means that the calibration and target fluxes that are used in the flattening and normalization of flux ratios may themselves already be flattened/normalized.

The flattening and normalization applied to target fluxes and flux ratios are also applied to ghost fluxes and flux ratios of the ghost.

There is one MLF key set up by the user for each of the flattening/normalization operations on calibration fluxes, target fluxes and flux ratios. The MLF defines what to do with the LC outliers found

in the sigma-clip procedure in the polynomial fittings. Usually, the user does not want to eliminate the points in the flattening/normalization of calibration and target fluxes, so the first MLF position will be "+". If in the operations with the flux ratio, the user wants to eliminate discrepant points, then a "-" must be set in the first position on the appropriate MLF. For each kind of flux, there is a position in the MLF regarding to flattening/normalization operations (see Table 1 in Section 4.1.1). Specifically, the positions 3, 6 and 7 in the MLF refer respectively for the flattening/normalization of calibration flux, target flux and flux ratios. Using "1" on each of the respective positions enables all points to be used, even if they are found as outliers in the sigma-clip procedures. By setting "2" on each of the respective positions will make the found outliers not be used in the respective flattening/normalization operations, but the outliers will not be eliminated from the LC (unless the "-" be set in the first position of the MLF).

It is up to the user to correctly set up the flattening/normalization of calibration and target fluxes, and of flux ratios, the respective degrees N of the polynomials, the sigma-clip factors, and the forbidden LC time window sections (see next Section 8.9), so that the procedures actually make sense and that the best LC be produced.

8.9 Module: Time windows for target events

On line 34 of the LC building block mode 4 the user furnishes the input file name of the Time windows for target events module, say `PRAIA_photometry_3_0_04_events_time_windows_LC.dat`.

This is the same module already described in Section 7.23. The user must furnish the number of, and the respective time windows of forbidden LC sections (in User-time) which will be excluded from the final flattening/normalization operations for targets and flux ratios. However, regardless of this module, the whole LC is used in the flattening/normalization of calibration fluxes (only).

As pointed out in the selection of best calibrators (Section 8.4) and calibration flux smoothing (Section 8.5), by purpose we used different extension names there ("Ph" for Photometry) and here ("LC" for Light Curve). This is to indicate that although both modules (and the internal formats) are the same, the setup of window time sections may be different for photometry and LC building. In fact, the setup of this module can be different for the photometry, the selection of best calibrators, the smoothing of calibration flux and for the final flattening/normalization operations for targets and flux ratios. However, we recommend for the final flattening/normalization operations the use of the same photometry setup if possible (same Time windows for target events module file). Since the module is used here for the last time for final flattening/normalization operations, the use of most or all points available for such procedures is recommended.

8.10 Flux offsets for plotting/analysis purposes

From lines 35 to 39 of the LC building block mode 4 the user sets up `PPT` to apply (or not) offsets for the output LC calibration and target fluxes, and for the target and ghost flux ratios. These offsets serve mostly for plotting and analysis purposes, but eventually they are used for other justified causes.

The user can offset calibration fluxes, target fluxes, flux ratios of the target and flux ratios of the ghost. In the case of (target, ghost) flux ratios, the user is offered with 2 options: set the offset in magnitude units or in dimensionless ("ADU/ADU") units. For individual calibration and target fluxes, offsets in magnitudes are not allowed.

When all the fluxes are normalized to unity, a better visualization in the same plot can be reached by successively offsetting the output fluxes by 1, except (in principle) for the ghost flux ratio which is expected to be around zero, thus already far from the usual values of the other objects (nevertheless, the user can freely setup an offset for the ghost too).

8.11 Input photometry measurements

From lines 40 to 42 of the LC building block mode 4 the user furnishes the file names of the input photometry data file with photometry measurements from which `PPT` will derive the LC, the Time instants of input photometry file module file and the Input photometry file format module file.

`PPT` accepts photometry made with other packages. However, all the photometry measurements must be contained in only one input file. And this input photometry file must contain at least the most basic photometry data: time instants, calibrator and target fluxes. If more data are present, like ghost fluxes, FWHM, etc, the better.

It is also possible to use as input a photometry file obtained with older `PPT` versions. But it is only by using the current `PPT` version (3.0.04) of the task, from the use of photometry modes 0, 1, 2 or 3, that the

input photometry file will have the necessary complete set of photometry information needed for making the best LC possible with PPT.

The content of the input photometry data file thus depends on its origin. The setup to correctly retrieve the photometry measurements and metadata is carried out with two modules, described in the following sub-sections.

8.11.1 Module: Time instants of input photometry file

Regardless of the origin of the input photometry data file, the time instants of the measurements are setup with this module. The content of the Time Instants of input photometry file module is shown in Fig. 24.

```
7                                       | Input photometry file time units (tu): 1=ss 2=mm 3=hh 4=dd 5=mo 6=yr 7=JD; 8=MJD (1-6, fill up lines below *)
19                                      | * Input photometry file reference instant: hours   (converts time units 1-6 to JD; not used if tu=7 or tu=8)
37                                      | * Input photometry file reference instant: minutes (converts time units 1-6 to JD; not used if tu=7 or tu=8)
06.851                                  | * Input photometry file reference instant: seconds (converts time units 1-6 to JD; not used if tu=7 or tu=8)
02                                      | * Input photometry file reference instant: day     (converts time units 1-6 to JD; not used if tu=7 or tu=8)
04                                      | * Input photometry file reference instant: month   (converts time units 1-6 to JD; not used if tu=7 or tu=8)
2018                                    | * Input photometry file reference instant: year    (converts time units 1-6 to JD; not used if tu=7 or tu=8)
```

Figure 24: A sample of the Time Instants of input photometry file module file `PRAIA_photometry_3_0_04_input_time_photometry.dat` furnished in the zip file of PPT for version 3.0.4.

By default, the time instants of photometric measurements made with PPT are given in Julian Date (JD is coded "7"). Older task versions also use this time scale. The Modified Julian Date (MJD) is coded "8". PPT can automatically read the time contents of old and current PPT-generated photometry files.

If JD or MJD were not used, odds are that this is not a PPT-generated photometry file. And this means that the time is furnished in some time unit (seconds, minutes, , days, coded as "1" to "6") with respect to some reference instant. In this case, the user must indicate the time unit (codes "1" to "6") and fill up the lines marked "*" in the module input data file to set the reference instant, as shown in the example. The reference instant must be furnished in Gregorian format. PPT assumes that the time is UTC.

If the time unit is JD or MJD, the remaining lines in the module are ignored.

This module is also the same - with the exact quantitative content (if it is the case) as that used in LC intruding flux block mode 5 (see Section 9).

8.11.2 Module: Input photometry file format

Regardless of the origin of the input photometry file, the user sets up with this module how to retrieve information from the input photometry data file about the time instants, calibrator, target and ghost fluxes and errors, FWHM, etc. An example of the Input photometry file format module is shown in Fig. 25.

```
1                                       | Input photometry file format: (1) PRAIA_photometry_3_XX ; (2) PRAIA_photometry_2 ... (old formats); (3) user-defined
04                                      | Input photometry file nth-column = instant of time                                  (user format only)
05                                      | Input photometry file nth-column = air mass (zero if not available)                 (user format only)
06                                      | Input photometry file nth-column = target flux                                      (user format only)
07                                      | Input photometry file nth-column = target S/N ratio                                 (user format only)
08                                      | Input photometry file nth-column = target fwhm (put zero if not available)         (user format only)
09                                      | Input photometry file nth-column = target sky bkg sig. factor (0 if not available) (user format only)
55                                      | Input photometry file nth-column = ghost flux (sky backg. nearby target)           (user format only)
63                                      | Input photometry file nth-column = FITS image file name                             (user format only)
3                                       | Number of calibrators                                                               (user format only)
18                                      | Input photometry file nth-column   = 001-calibrator flux                            (user format only)
19                                      |   Input photometry file nth-column = 001-calibrator object S/N ratio                (user format only)
20                                      |   Input photometry file nth-column = 001-calibrator fwhm (zero if not available)    (user format only)
30                                      | Input photometry file nth-column   = 002-calibrator flux                            (user format only)
31                                      |   Input photometry file nth-column = 002-calibrator object S/N ratio                (user format only)
32                                      |   Input photometry file nth-column = 002-calibrator fwhm (zero if not available)    (user format only)
42                                      | Input photometry file nth-column   = 003-calibrator flux                            (user format only)
43                                      |   Input photometry file nth-column = 003-calibrator object S/N ratio                (user format only)
44                                      |   Input photometry file nth-column = 003-calibrator fwhm (zero if not available)    (user format only)
```

Figure 25: A sample of the Input photometry file format module file `PRAIA_photometry_3_0_04_format_photometry.dat` furnished in the zip file of PPT for version 3.0.4.

PPT can automatically read all the needed photometry data, not only from input photometry files generated with the current task version (option "1" in the first line of the module), but also the contents from PPT files generated with older versions 2 (option "2" in the first line of the module). In that case, all the other lines of the module are ignored.

In the case that the input photometry file was not generated with PPT, the user must explicitly indicate (by the user-defined option "3" in the first line of the module input data file) the columns of the input photometry file that correspond to key photometry data, as shown in the example in Fig. 25.

The example is actually based on an input photometry file generated by the current PPT version. That is, for each requested quantity in all module file lines, the informed columns are exactly the ones where PPT outputs values on the output photometry data file in the current version (using photometry modes 0-3). There must be information for the time instants, the target and calibrator fluxes. In particular, the user must indicate the number of calibrators present in the input photometry file. If a specific information is not available, put "0". The task stops if no time is furnished, or if flux is not available for the target or for any one of the calibrators. If all the requested photometry information above is available in the input photometry file, than it is all what is needed for obtaining the best possible LC by the current version of PPT.

Finally, after the field for inputting the User-defined output LC file name (line 43 already commented in Section 8.1), notice the mandatory ********** string in line 44 signaling the end of the LC building block mode 4.

9 Configuring the Task for Eliminating the Intruding Flux in a LC

We strongly recommend the user to read the entire Section 4.2 and Assafin (2023a) prior to proceeding to this section.

The LC intruding flux block has only one mode – mode 5. It is used to determine the intruding flux ϕ_o in a LC, i.e. the flux of an object that was measured together with the true target in a LC. The assumption is that, besides the contaminated LC, there are another LCs (PPT-made or not) available with the intrude object and true target measured separately. Once ϕ_o is found, PPT can produce a new LC without contamination by a new run with LC building block mode 4, after setting the intruding flux correction to the target flux (see Section 8.7).

The need for finding intruding flux in LCs is relatively rare. It is sometimes found in stellar occultation work. We use stellar occultation terminology here in order to make it easier for the reader to understand the meaning of certain parameters and output results. In general, "occultation star" reads "true target", and "body" means "intruding flux object".

A typical example of the LC intruding flux block mode 5 is shown in Fig. 26.

The value in the first line of the LC intruding flux block mode 5 must be "5", indicating the only mode (mode 5) currently available for this block. The second entry must be "1" or "2", indicating respectively if the user wants or not to effectively run the block/mode (in the example, the option is "2" = "do not run the block"). Some lines presenting "———" symbols are there to facilitate input data visualization.

The results are output in 6 files, one being a report file and the other 5 being "compact" LCs.

The report file contains complete results using all 3 methods available by PPT to compute ϕ_o, including alternative results from weighted mean values from the ϕ_o solutions (with weighted sigma and uncertainties) from Method 1 with Method 2 and 3. It lists and compares many quantities (with errors) besides the ϕ_o solutions (F_0, F_C, S_C, B_C, etc).

The 5 output "compact" LCs serve for plotting and sanity (consistency) checking visual analysis purposes. They are:

- "Body flux / (Occ_Star + Body flux)" LC .:. The so called FLC (Fraction or Flatted Intruding Light Curve), obtained from calibration images
- "Occ_Star + Body flux" LC .:. LC short version of the occultation LC itself (contaminated with the intruding body flux)
- "Occ_Star" LC .:. LC obtained from calibration images
- "Body" LC .:. LC obtained from calibration images
- "Occ_Star + Body flux" LC .:. LC obtained from calibration images

  Note: all LCs are target fluxes (Occ_Star, Body, Occ_Star + Body fluxes) with respect to the fluxes of the same photometric calibration star(s), i.e. all LCs are target/calibration flux ratios, except FLC; all LCs are flatted, but not normalized.

```
5                                                  | Intruding body flux from occultation and calibration LCs, mode (5)
2                                                  | Compute intruding body flux? (1) yes; (2) no
Liverpool - Occ Triton 05 October 2017  Cal 301    | Label for report of results
curve64.dat                                        | Input: Occultation LC with Occ_Star + Body flux
curve56.dat                                        | Input: Calibration LC with Occ_Star flux
curve58.dat                                        | Input: Calibration LC with Body flux
---------------------------------------------------|
PRAIA_photometry_3_0_04_user_time.dat              | Input: module: User-time reference instant at occultation (aperture photometry, LCs, all modes, mode0=...5)
PRAIA_photometry_3_0_04_events_time_windows_LC.dat| Input: module: Event's time windows for Target/flux ratio flattening/normalization (mode0=...=mode5)
---------------------------------------------------|
23                                                 | Input: Occultation mid-instant t0: hours
49                                                 | Input: Occultation mid-instant t0: minutes
37.000                                             | Input: Occultation mid-instant t0: seconds
05                                                 | Input: Occultation mid-instant t0: day
10                                                 | Input: Occultation mid-instant t0: month
2017                                               | Input: Occultation mid-instant t0: year
---------------------------------------------------|
22                                                 | Input: Calibration reference instant tc (same occ air mass): hours
28                                                 | Input: Calibration reference instant tc (same occ air mass): minutes
30.000                                             | Input: Calibration reference instant tc (same occ air mass): seconds
04                                                 | Input: Calibration reference instant tc (same occ air mass): day
10                                                 | Input: Calibration reference instant tc (same occ air mass): month
2017                                               | Input: Calibration reference instant tc (same occ air mass): year
---------------------------------------------------|
-1                                                 | Input: Calibration air mass increases/decreases as in occultation? +1/-1 Yes/No
---------------------------------------------------|
14                                                 | Input: Occultation LC (Body + occultation star): target flux column
15                                                 | Input: Occultation LC (Body + occultation star): calibrator flux column
04                                                 | Input: Occultation LC (Body + occultation star): time column
PRAIA_photometry_3_0_04_input_time_photometry.dat  | Input: Occultation LC (Body + occultation star): module: time instants of LC photometry file (LC, modes 4,5)
---------------------------------------------------|
14                                                 | Input: Calibration LC Occ_Star: target flux column
15                                                 | Input: Calibration LC Occ_Star: calibrator flux column
04                                                 | Input: Calibration LC Occ_Star: time column
PRAIA_photometry_3_0_04_input_time_photometry.dat  | Input: Calibration LC Occ_Star: module: time instants of LC photometry file (LC, modes 4,5)
---------------------------------------------------|
14                                                 | Input: Calibration LC Body: target flux column
15                                                 | Input: Calibration LC Body: calibrator flux column
04                                                 | Input: Calibration LC Body: time column
PRAIA_photometry_3_0_04_input_time_photometry.dat  | Input: Calibration LC Body: module: time instants of LC photometry file (LC, modes 4,5)
---------------------------------------------------|
1                                                  | Input: LC flux polynomial fittings: degree of flattening (N=0-21; typically N=0 to N=2)
7.5                                                | Input: LC flux polynomial fittings: sigma factor for sigma-clip elimination
---------------------------------------------------|
report_Liverpool_301.dat                           | Output: report with intruding body flux values, errors, complementary information
curve61f1.dat                                      | Output: Flatted intruding  FLC with Body/(Occ_Star + Body) flux ratio
curve64f1.dat                                      | Output: Flatted occultation LC with Occ_Star + Body flux
curve56f1.dat                                      | Output: Flatted calibration LC with Occ_Star flux shifted by DT=t0-t1
curve58f1.dat                                      | Output: Flatted calibration LC with Body flux shifted by DT=t0-t1
curve62f1.dat                                      | Output: Flatted calibration LC with Occ_Star + Body flux
***************************************************************************************************************************************************************
```

Figure 26: A sample of the LC intruding flux block mode 5 in the main input data file `PRAIA_photometry_3_0_04.dat` furnished in the zip file of `PPT` for version 3.0.4.

The content format of the output report and from all these 5 output LCs are given in Section 12.

All the entries in LC intruding flux block mode 5 are commented in the following sub-sections. The sub-sections are presented following in general the order of the entries in the main input data file of `PPT`. There are no new specific modules for LC intruding flux block mode 5 – all needed modules were already introduced in the previous photometry/LC blocks/modes.

9.1 Label, input/output LCs, report file names

On line 3 of the LC intruding flux block mode 5, the user furnishes a label for registering the ϕ_o solutions in the output report file.

Also in the beginning of the block, there are 3 input LC files that the user must furnish:

- Line 4 – The occultation LC with "Occ_Star + Body" mixed fluxes + photometric calibration flux
- Line 5 – The calibration LC with Occ_Star fluxes + photometric calibration flux
- Line 6 – The calibration LC with Body fluxes + photometric calibration flux

The input LCs can be `PPT`-made or not. They must contain the clean flux of the target (isolated Occ_Star, isolated Body, or mixed Occ_Star + Body fluxes), and the clean flux of the photometric calibration (same calibrators for all sets). The clean fluxes are needed for flux flattening at t_0 and t_c (no normalization to unity is made). The LCs may or may not have been obtained with `PPT`. The only needed content in the LCs are individual (not normalized or flatted) target and photometric calibration fluxes (using the same photometric calibrators in all sets), and respective time instants.

The file names for the 5 types of output "compact" LCs plus the output report are furnished at the end of the block with entries easily recognizable for each file type:

- Line 45 – Report with intruding body flux values, errors, complementary information
- Line 46 – "Body flux / (Occ_Star + Body flux)" LC `.:.` The so called `FLC` (Fraction or Flatted Intruding Light Curve), obtained from calibration images

- Line 47 – "Occ_Star + Body flux" flatted LC `.:.` LC short version of the occultation LC itself (contaminated with the intruding body flux)
- Line 48 – "Occ_Star" LC `.:.` LC obtained from calibration images
- Line 49 – "Body" LC `.:.` LC obtained from calibration images
- Line 50 – "Occ_Star + Body flux" LC `.:.` LC obtained from calibration images

  Note: all LCs are target fluxes (Occ_Star, Body, Occ_Star + Body fluxes) with respect to the fluxes of the same photometric calibration star(s), i.e. all LCs are target/calibration flux ratios, except `FLC`; all LCs are flatted, but not normalized.

9.2 Input times, time modules and fluxes in the input LCs; polynomial fittings

The user must furnish the occultation mid-instant t_0 and the corresponding calibration reference instant t_c (see Section 4.2 for time definitions).

The user must also indicate if the air mass in the calibration LCs increase/decrease around t_c in the same manner ("+1") or contrary ("-1") as that at the occultation instant t_0. This information is used to "convert" calibration User Times into occultation User Times, allowing to plot the output calibration and occultation LCs in a coherent way with regard to increasing/decreasing air masses, using occultation User Times around the occultation mid-instant t_0.

For each input occultation and calibration LC file, the user furnishes the corresponding columns regarding to the clean target and photometric calibration fluxes, and their time instants. In the example of Fig. 26, the columns regard to a typical `PPT` output main LC file produced with LC building block mode 4.

The user must also furnish the User Time (Sections 7.12 and 8.3), Event Time Windows (Sections 7.23 and 8.9) and Input Time Photometry (Section 8.11.1) module files. If the occultation and calibration LCs were obtained with `PPT`, the Input Time Photometry module is exactly the same as that used to get the LCs, and the User Time and Event Time Windows modules are exactly the same as those used for obtaining the occultation LC.

`PPT` flattens LCs taking the proper time instants as reference, but does not normalize the LCs in order to allow for visual sanity (consistency) checkings (see examples in Assafin 2023a). The user sets the parameters for the flattening with polynomial fittings.

Filling up all the above input information in the corresponding lines of the LC intruding flux block mode 5 is done as follows:

- Line 8 – User Time module with reference instant at occultation
- Line 9 – Event Time Windows module used for the occultation
- —
- Lines 11-16 – Occultation mid-instant at t_0
- —
- Lines 18-23 – Calibration reference instant at t_c (same occultation air mass)
- —
- Line 25 – Calibration air mass around t_c: increases/decreases as in occultation? Yes ("+1"); No ("-1")
- —
- Line 27 – Occultation LC (Body + occultation star): target flux column
- Line 28 – Occultation LC (Body + occultation star): calibration flux column
- Line 29 – Occultation LC (Body + occultation star): time column
- Line 30 – Occultation LC (Body + occultation star): Input Time Photometry module of this LC

- —
- Line 32 - Calibration LC Occ_Star: target flux column
- Line 33 - Calibration LC Occ_Star: calibration flux column
- Line 34 - Calibration LC Occ_Star: time column
- Line 35 - Calibration LC Occ_Star: Input Time Photometry module of this LC
- —
- Line 37 - Calibration LC Body: target flux column
- Line 38 - Calibration LC Body: calibration flux column
- Line 39 - Calibration LC Body: time column
- Line 40 - Calibration LC Body: Input Time Photometry module of this LC
- —
- Line 42 - LC flux polynomial fittings: degree of flattening (N=0-21; typically N=0 to N=2)
- Line 43 - LC flux polynomial fittings: sigma factor for sigma-clip elimination

Notice the mandatory "**********" string at line 51 signaling the end of the LC intruding flux block mode 5.

10 Output PPT photometry file formats

10.1 Output PPT photometry file format

The output `PPT` photometry file is the main output of the photometry block. It contains all data related to the photometry measurements in one file. The file format is the same regardless of the photometry mode used (0, 1, 2, 3).

The format of the file is not exactly rigid. The content structure of the file depends on the number NT of targets and NC of calibrators used. However, the data is easy to access once the number of targets and calibrators is extracted in the first lines of the file.

The `PPT` photometry file format is as follows:

- Column 01 - *n-th* processed image ordered in chronological order by the time instant
- Column 02 - number of targets (NT targets); same number of ghosts
- Column 03 - number of calibrators (NC calibrators)
- Column 04 - Julian Date
- Column 05 - air mass

  ... and now comes NT blocks with 13 columns each, regarding to each block of data of target i, $i = 1, ..., NT$, that are read as:

- Column 06 + (i-1)*13 - target i flux in ADUs corrected from sky background
- Column 07 + (i-1)*13 - target i S/N
- Column 08 + (i-1)*13 - target i seeing in arcseconds (if pixel scale was furnished)
- Column 09 + (i-1)*13 - target i observed photometry factor about the sky background for the brightest pixel around the aperture center: factor=(pixel-sky)/sigma_sky

- Column 10 + (i-1)*13 - target i astrometric aperture radius (pixels)
- Column 11 + (i-1)*13 - target i photometric aperture radius (pixels)
- Column 12 + (i-1)*13 - target i sky background ring radius (pixels)
- Column 13 + (i-1)*13 - target i sky background ring width (pixels)
- Column 14 + (i-1)*13 - x centre of target i (pixels)
- Column 15 + (i-1)*13 - y centre of target i (pixels)
- Column 16 + (i-1)*13 - x centre error of target i in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 17 + (i-1)*13 - y centre error of target i in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 18 + (i-1)*13 - astrometric flag of (x, y) target i centre; "0" means "ok", "1" means that the (x, y) was not computed/updated (a previous initial input value was used to locate the object)

  ... and now comes more NC blocks with 12 columns each, regarding to each block of data of calibrator j, $j = 1, ..., NC$, that are read as:

- Column 06 + NT*13 + (j-1)*12 - calibrator j flux in ADUs corrected from sky background
- Column 07 + NT*13 + (j-1)*12 - calibrator j S/N
- Column 08 + NT*13 + (j-1)*12 - calibrator j seeing in arcseconds (if pixel scale was furnished)
- Column 09 + NT*13 + (j-1)*12 - calibrator j astrometric aperture radius (pixels)
- Column 10 + NT*13 + (j-1)*12 - calibrator j photometric aperture radius (pixels)
- Column 11 + NT*13 + (j-1)*12 - calibrator j sky background ring radius (pixels)
- Column 12 + NT*13 + (j-1)*12 - calibrator j sky background ring width (pixels)
- Column 13 + NT*13 + (j-1)*12 - x centre of calibrator j (pixels)
- Column 14 + NT*13 + (j-1)*12 - y centre of calibrator j (pixels)
- Column 15 + NT*13 + (j-1)*12 - x centre error of calibrator j in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 16 + NT*13 + (j-1)*12 - y centre error of calibrator j in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 17 + NT*13 + (j-1)*12 - astrometric flag of (x, y) calibrator j centre; "0" means "ok", "1" means that the (x, y) was not computed/updated (a previous initial input value was used to locate the object)

  ... and now comes NT blocks with 3 columns each, regarding to each block of data of ghost k, $k = 1, ..., NT$, that are read as:

- Column 06 + NT*13 + NC*12 + (k-1)*3 - ghost flux in ADUs corrected from sky background
- Column 07 + NT*13 + NC*12 + (k-1)*3 - x centre of ghost k (pixels)
- Column 08 + NT*13 + NC*12 + (k-1)*3 - y centre of ghost k (pixels)

  ... and now finally comes the 7 last columns of the file that are read as:

- Column 06 + NT*13 + NC*12 + NT*3 - x centre of guide (pixels)

- Column 07 + NT*13 + NC*12 + NT*3 - y centre of guide (pixels)
- Column 08 + NT*13 + NC*12 + NT*3 - x centre error of guide in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 09 + NT*13 + NC*12 + NT*3 - y centre error of guide in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 10 + NT*13 + NC*12 + NT*3 - guide astrometric aperture radius (pixels)
- Column 11 + NT*13 + NC*12 + NT*3 - FITS image file name
- Column 12 + NT*13 + NC*12 + NT*3 - User time with respect to the reference instant set by the user; the time is in user-defined units

10.2 Output PPT (x,y) astrometry file format

The output `PPT` (x, y) astrometry file contains solely astrometry data, i.e. information on the (x, y) measurements of the target, calibrators and guide made for all images. It is generated together with the `PPT` photometry file with the photometry block. Its file format is the same regardless of the photometry mode used (0, 1, 2, 3).

As in the case of the photometry file, the format of the `PPT` (x, y) astrometry file is not exactly rigid. The content structure of the file depends on the number NT of targets and NC of calibrators used. However, the data is easy to access once the number of targets and calibrators are known.

The `PPT` (x, y) astrometry file format is as follows:

- First comes NT blocks with 2 columns each, regarding to each block of data of target i, $i = 1, ..., NT$, that are read as:

  Column 01 + (i-1)*2 - x centre of target i (pixels)
  Column 02 + (i-1)*2 - y centre of target i (pixels)

  ... then comes 1 column:

- Column 01 + NT*2 - Julian date

  ... then comes more NT blocks with 2 columns each, regarding to each block of data of target j, $j = 1, ..., NT$, that are read as:

- Column 02 + NT*2 + (j-1)*2 - x centre error of target j in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 03 + NT*2 + (j-1)*2 - y centre error of target j in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)

  ... then comes more NT blocks with 2 columns each, regarding to each block of data of target k, $k = 1, ..., NT$, that are read as:

- Column 02 + NT*2 + NT*2 + (k-1)*2 - astrometric flag of (x, y) target k centre; "0" means "ok", "1" means that the (x, y) was not computed/updated (a previous initial input value was used to locate the object)
- Column 03 + NT*2 + NT*2 + (k-1)*2 - target k observed photometry factor about the sky background for the brightest pixel around the aperture center: factor=(pixel-sky)/sigma_sky

  ... then comes NC blocks with 2 columns each, regarding to each block of data of calibrator ii, $ii = 1, ..., NC$, that are read as:

- Column 02 + NT*2 + NT*2 + NT*2 + (ii-1)*2 - x centre of calibrator ii (pixels)
- Column 03 + NT*2 + NT*2 + NT*2 + (ii-1)*2 - y centre of calibrator ii (pixels)

... then comes NC blocks with 2 columns each, regarding to each block of data of calibrator jj, $jj = 1, ..., NC$, that are read as:

- Column 02 + NT*2 + NT*2 + NT*2 + NC*2 + (jj-1)*2 - x centre error of calibrator jj in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 03 + NT*2 + NT*2 + NT*2 + NC*2 + (jj-1)*2 - y centre error of calibrator jj in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)

... then comes more NC columns regarding to the kk calibrator, that are read as:

- Column 02 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + (kk-1) - astrometric flag of (x, y) calibrator kk centre; "0" means "ok", "1" means that the (x, y) was not computed/updated (a previous initial input value was used to locate the object)

... then comes more 4 columns regarding to the guide, that are read as:

- Column 02 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + NC - x centre of guide (pixels)
- Column 03 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + NC - y centre of guide (pixels)
- Column 04 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + NC - x centre error of guide in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)
- Column 05 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + NC - y centre error of guide in milliarcseconds (milli-pixels if pixel scale not furnished; -1.0 if not computed/available)

... then comes 1 more column indicating the n-th image number:

- Column 06 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + NC - image number order in the file

... and at the end comes 1 last column with the image file name:

- Column 07 + NT*2 + NT*2 + NT*2 + NC*2 + NC*2 + NC - FITS image name

11 Output PPT light curve building file formats

11.1 Output PPT main light curve file format

The main `PPT` main light curve file format reads as follows:

- Column 01 - ith LC point
- Column 02 - MLF key string indicating the filters that the LC point passed or not
- Column 03 - air mass
- Column 04 - Julian Date
- Column 05 - User time with respect to the reference instant set by the user; the time is in user-defined units
- Column 06 - FWHM of target (arcseconds or pixels depending on user setup)
- Column 07 - average FWHM of used calibrators (arcseconds or pixels depending on user setup)

- Column 08 – LC flux ratio target/calibration flux in magnitudes
- Column 09 – LC flux ratio error in magnitudes
- Column 10 – LC flux ratio in dimensionless "ADU/ADU" ratio units
- Column 11 – LC flux ratio error in dimensionless "ADU/ADU" ratio units
- Column 12 – flux ratio ghost/calibration in dimensionless "ADU/ADU" ratio units
- Column 13 – target photometry aperture radius (pixels)
- Column 14 – target clean flux (corrected from sky background)
- Column 15 – calibration clean flux (corrected from sky background)
- Column 16 – ghost clean flux (corrected from sky background)
- Column 17 – target flux error
- Column 18 – calibration flux error
- Column 19 – target S/N
- Column 20 – calibration S/N
- Column 21 – target observed photometry factor about the sky background for the brightest pixel around the aperture center: factor=(pixel-sky)/sigma_sky
- Column 22 – average flux ratio at LC flattened/normalized time window sections (zero if no flattening/normalization was done)
- Column 23 – sigma (dispersion) about the above LC flux ratio average (zero if no flattening/normalization was done)
- Column 24 – initial FWHM of target (arcseconds or pixels depending on user setup)
- Column 25 – initial average FWHM of calibrators (arcseconds or pixels depending on user setup)
- Column 26 – initial LC flux ratio target/calibration in magnitudes
- Column 27 – initial flux ratio error in magnitudes
- Column 28 – initial flux ratio in dimensionless "ADU/ADU" ratio units
- Column 29 – initial flux ratio error in dimensionless "ADU/ADU" ratio units
- Column 30 – initial target clean flux (corrected from sky background)
- Column 31 – initial calibration clean flux (corrected from sky background)
- Column 32 – initial ghost clean flux (corrected from sky background)
- Column 33 – initial target flux error
- Column 34 – initial calibration flux error
- Column 35 – initial target S/N
- Column 36 – initial calibration S/N
- Column 37 – initial target observed photometry factor about the sky background for the brightest pixel around the aperture center: factor=(pixel-sky)/sigma_sky
- Column 38 – FITS image name

11.2 Output PPT quick look light curve file format

The PPT quick look light curve file is a short version of the main PPT main light curve file. Its contents and format read as follows:

- Column 01 – ith LC point
- Column 02 – Julian Date
- Column 03 – User time with respect to the reference instant set by the user; the time is in user-defined units
- Column 04 – LC flux ratio target/calibration flux in magnitudes
- Column 05 – LC flux ratio error in magnitudes
- Column 06 – LC flux ratio in dimensionless "ADU/ADU" ratio units
- Column 07 – LC flux ratio error in dimensionless "ADU/ADU" ratio units
- Column 08 – flux ratio ghost/calibration in dimensionless "ADU/ADU" ratio units
- Column 09 – target photometry aperture radius (pixels)
- Column 10 – average flux ratio at LC flattened/normalized time window sections (zero if no flattening/normalization was done)
- Column 11 – sigma (dispersion) about the above LC flux ratio average (zero if no flattening/normalization was done)

11.3 Output PPT User-defined light curve file format - Module User-defined output LC file

The output PPT User-defined light curve file contents are defined by the user through the setup of the User-Defined Output LC File module. The module file name is given at the end of the LC building block mode 4. A sample of this module is shown in Fig. 27.

```
curve72_user.dat                              | Output LC with user-defined output data .:. Use NONE for no output, or fill up values below:
-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
00| 01 - ith LC point                                                                                                                                - "0" excludes the value;
00| 02 - MLF key string indicating the filters that the LC point passed or not                                                                       - "1 to 38" idicates the
00| 03 - air mass                                                                                                                                      nth column where the
01| 04 - Julian Date                                                                                                                                   value will appear in
02| 05 - time with respect to the reference instant set by the user; the time is in user-defined units                                                 the output file (the
00| 06 - FWHM of target                                                                                                                                (indicated numbers show
00| 07 - average FWHM of used calibrators                                                                                                              where the value appears
00| 08 - LC flux ratio target/calibration flux in magnitudes                                                                                           in the main output LC
00| 09 - LC flux ratio error in magnitudes                                                                                                             file)
03| 10 - LC flux ratio in ADU/ADU ratio units
04| 11 - LC flux ratio error in ADU/ADU ratio units
00| 12 - flux ratio ghost/calibration in ADU/ADU ratio units (ghost = sky background nearby target)
05| 13 - target photometry aperture radius (pixels)
00| 14 - target clean flux (corrected from sky background)
00| 15 - calibration clean flux (corrected from sky background)
00| 16 - ghost clean flux (corrected from sky background) (ghost = sky background nearby target)
00| 17 - target flux error
00| 18 - calibration flux error
00| 19 - target S/N ratio
00| 20 - calibration S/N ratio
00| 21 - target observed photometry factor about the sky background for the brightest pixel around the aperture center: factor=(pixel-sky)/sigma_sky
06| 22 - average flux ratio at LC flattened/normalized outside time-window sections (zero if no flattening/normalization was done)
07| 23 - sigma (dispersion) about the above LC flux ratio average (zero if no flattening/normalization was done)
00| 24 - inittial FWHM of target
00| 25 - initial average FWHM of calibrators
00| 26 - initial LC flux ratio target/calibration in magnitudes
00| 27 - initial flux ratio error in magnitudes
00| 28 - initial flux ratio in ADU/ADU ratio units
00| 29 - initial flux ratio error in ADU/ADU ratio units
00| 30 - initial target clean flux (corrected from sky background)
00| 31 - initial calibration clean flux (corrected from sky background)
00| 32 - initial ghost clean flux (corrected from sky background) (ghost = sky background nearby target)
00| 33 - initial target flux error
00| 34 - initial calibration flux error
00| 35 - initial target S/N ratio
00| 36 - initial calibration S/N ratio
00| 37 - initial target observed photometry factor about the sky background for the brightest pixel around the aperture center: factor=(pixel-sky)/sigma_sky
08| 38 - FITS image name
```

Figure 27: A sample of the User-Defined Output LC File module PRAIA_photometry_3_0_04 LC_user.dat (used in the LC building block mode 4), furnished in the zip file of PPT for version 3.0.4.

The user has total control over what data is to be output, and in what order. In the example, the output content of the User-defined light curve file will have 8 columns, in the following output order:

- Column 01 – Julian Date
- Column 02 – User time with respect to the reference instant set by the user; the time is in user-defined units
- Column 03 – LC flux ratio in dimensionless "ADU/ADU" ratio units
- Column 04 – LC flux ratio error in dimensionless "ADU/ADU" ratio units
- Column 05 – target photometry aperture radius (pixels)
- Column 06 – average flux ratio at LC flattened/normalized time window sections (zero if no flattening/normalization was done)
- Column 07 – sigma (dispersion) about the above LC flux ratio average (zero if no flattening/normalization was done)
- Column 08 – FITS image name

12 Output PPT light curve intruding flux file formats

12.1 Output report with intruding flux ϕ_o solutions

A typical output report content using the LC intruding flux block mode 5 for an analysis labelled "Elvas - Occ Triton 05 October 2017 CAL 0506" (see labelling in Section 9.1) is given. It is based in the analysis of LCs from the Triton's stellar occultation in 5 October 2017 (Credits: B. Sicardy; see also Marques Oliveira et al. 2022). In the example, the intruding flux ϕ_o (around 0.36 or 36%) in the Elvas LC comes from Triton.

Elvas - Occ Triton 05 October 2017 CAL 0506

Method 1.

Intruding Body flux = 0.374769
Intruding Body flux (%) = 37.476853

Sigma Intrud. Body flux = 0.000428
Relative sigma Intrud. Body flux (%) = 0.114245

Uncertainty Intruding Body flux = 0.001095
Relative uncer. Intrud. Body flux (%) = 0.292215

Initial number of LC points (B+S)/C = 2000
Final number after sigma-clip elim. = 1352

Initial number of LC points (S/C) = 341
Final number after sigma-clip elim. = 341

Method 2.

Intruding Body flux = 0.361451
Intruding Body flux (%) = 36.145068

Sigma Intrud. Body flux = 0.022786
Relative sigma Intrud. Body flux (%) = 6.304154

Uncertainty Intruding Body flux = 0.001286
Relative uncer. Intrud. Body flux (%) = 0.355764

Method 3.

Intruding Body flux = 0.368469
Intruding Body flux (%) = 36.846925

Sigma Intrud. Body flux = 0.013214
Relative sigma Intrud. Body flux (%) = 3.586299

Uncertainty Intruding Body flux = 0.000736
Relative uncer. Intrud. Body flux (%) = 0.199811

Summary:

Intruding Body flux Method 1 (M1) = 0.374769
Intruding Body flux Method 2 (M2) = 0.361451
Intruding Body flux Method 3 (M3) = 0.368469
Intruding Body flux: M1 - M2 = 0.013318
Intruding Body flux: M1 - M3 = 0.006299
Intruding Body flux: sigma Method 1 = 0.000428
Intruding Body flux: sigma Method 2 = 0.022786
Intruding Body flux: sigma Method 3 = 0.013214
Intruding Body flux: Uncer. Method 1 = 0.001095
Intruding Body flux: Uncer. Method 2 = 0.001286
Intruding Body flux: Uncer. Method 3 = 0.000736

Intruding Body flux: weighted mean % M1 + M2 = 37.476383
Intruding Body flux: weighted mean M1 + M2 = 0.374764
Intruding Body flux: weighted sigma M1 + M2 = 0.000605
Intruding Body flux: weighted uncer. M1 + M2 = 0.001095

Intruding Body flux: weighted mean % M1 + M3 = 37.476192
Intruding Body flux: weighted mean M1 + M3 = 0.374762
Intruding Body flux: weighted sigma M1 + M3 = 0.000605
Intruding Body flux: weighted uncer. M1 + M3 = 0.001095

(Body+Star)/Calibrator at occultation full flux = 0.069773
(Body+Star)/Calibrator at occultation sigma = 0.004630
(Body+Star)/Calibrator at occultation uncertainty = 0.000126
Initial number of LC points = 2000
Used number of LC points after sigma-clip elimination = 1352

Star/Calibrator from calibration (same air mass) flux = 0.043624
Star/Calibrator from calibration (same air mass) sigma = 0.002865
Star/Calibrator from calibration (same air mass) uncertainty = 0.000155
Initial number of LC points = 341
Used number of LC points after sigma-clip elimination = 341

Body/Calibrator from calibration (same air mass) flux = 0.025453
Body/Calibrator from calibration (same air mass) sigma = 0.002257
Body/Calibrator from calibration (same air mass) uncertainty = 0.000124
Initial number of LC points = 330
Used number of LC points after sigma-clip elimination = 330

(Body+Star)/Calibrator at occultation full flux = 0.069773
Body/Cal + Occ_star/Cal flux from calibration = 0.069077

(B+S)/C at occ minus (S/C + B/C) from calib. (flux) = 0.000696
(B+S)/C at occ minus (S/C + B/C) from calib. (sigma) = 0.005893
(B+S)/C at occ minus (S/C + B/C) from calib. (uncertainty) = 0.000235
Initial number of LC points = 319
Used number of LC points after sigma-clip elimination = 314

12.2 Output "compact" sanity-check LCs

The data format of the 5 "compact" sanity-check output LCs of the LC intruding flux block mode 5 are the same:

- Column 1 – ith point in the LC
- Column 2 – Julian Date
- Column 3 – User time; see user time definitions for each type of output LC (occultation of calibration) in Section 9
- Column 4 – original flux ratio
- Column 5 – flatted flux ratio

13 Running the Task - Examples

We give examples for running each of the `PPT` blocks: photometry block, LC building block and LC intruding flux block.

13.1 Example 1: running PPT photometry block

In the `PPT_example_input_files_photometry.zip` file that comes with the `PPT` distribution, one has:

- `occ_images.zip` – 870 MB zip file with 3000 FITS images (≈ 1 GB of uncompressed images)
- PRAIA_photometry_3_0_04.dat – `PPT` main input data file
- `list` – input file with the file names of the 3000 FITS images
- `bad_fluxes.pix` – sample file for bad pixel ADU counts
- PRAIA_photometry_3_0_04_FITS_header_keys.dat – Module of FITS header keys
- PRAIA_photometry_3_0_04_input_time.dat – Module of time instants
- PRAIA_photometry_3_0_04_user_time.dat – Module of User time
- PRAIA_photometry_3_0_04_guide_mode2.dat – Module of guide (photometry mode 2)
- PRAIA_photometry_3_0_04_calibrators_mode2.dat – Module of calibrators (photometry mode 2)
- PRAIA_photometry_3_0_04_targets_mode2.dat – Module of targets (photometry mode 2)
- PRAIA_photometry_3_0_04_events_time_windows_Ph.dat – Module of time windows for target events

All furnished `PPT` input files are already properly filled up for the photometry of the images in the zip file. Notice that only strictly necessary `PPT` modules are furnished in the zip.

The images regard to the 5 October 2017 stellar occultation by Triton (Marques Oliveira et al., 2022). The FOV of the images is shown in Fig. 28. The target is the occultation star already mixed with Triton in the images. Neptune was used as photometric calibrator in this example.

After running `PPT` with the command line:

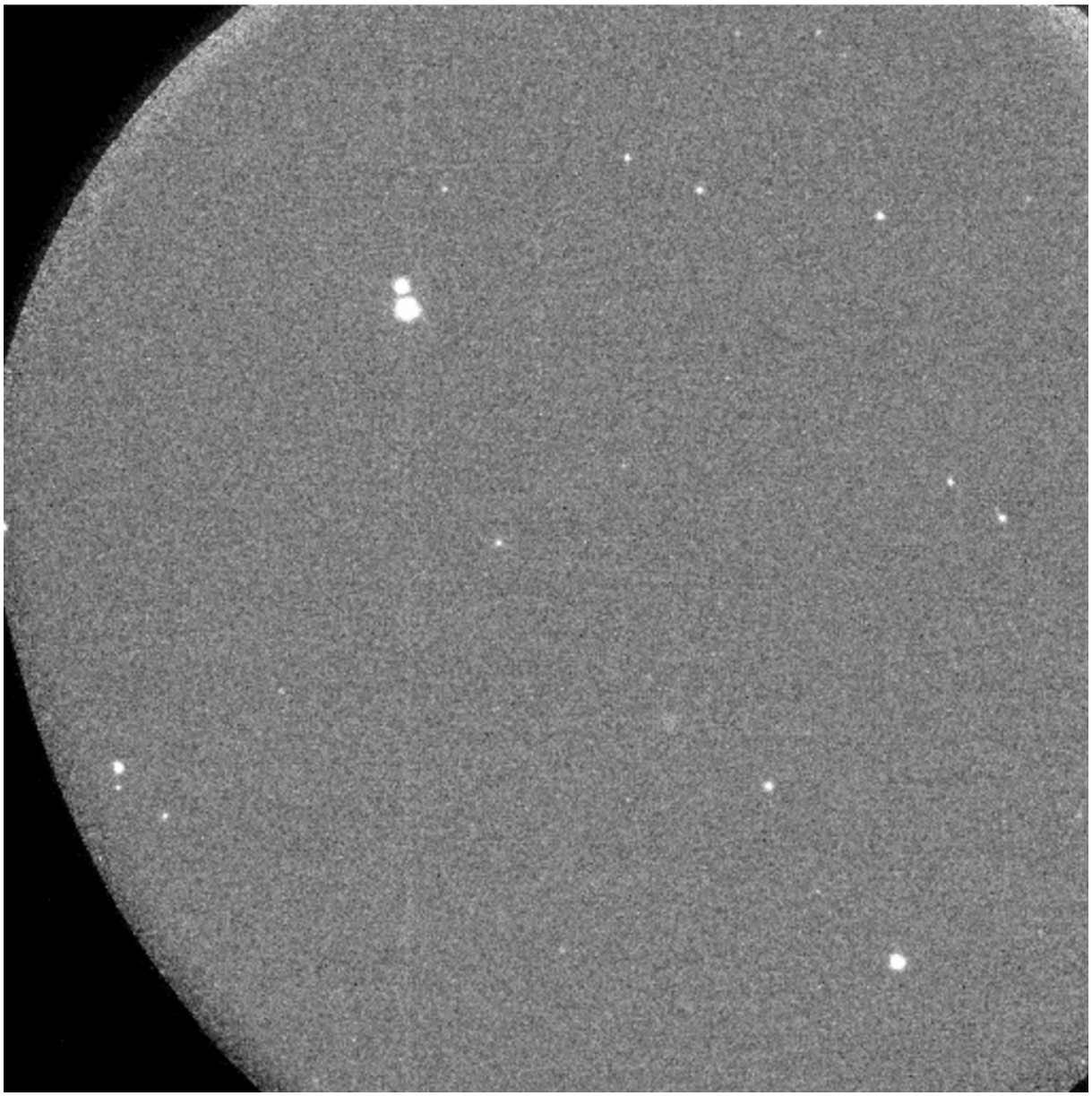


Figure 28: FOV of the images furnished in the input zip file. The two brightest objects a little above and to the left of the centre are Neptune and Triton. The satellite is already mixed with the occultation star - together they form the target in the photometry. Neptune or the bright star to the right-low corner of the FOV may be used as calibrators. Images were taken with the 2 m Liverpool telescope (IAU code J13) in Canary Island, La Palma, Spain. Credits: J. L. Ortiz.

```
PRAIA_photometry_3_0_04 < PRAIA_photometry_3_0_04.dat
```

one should generate the same output files furnished in the `PPT_example_output_files_photometry.zip` that also comes with the `PPT` distribution, which has:

- `photometry72.dat` - `PPT` photometry output file
- `xy72.dat` - `PPT` astrometry output file
- `regions72.ds9` - `ds9` batch movie file for the 3000 images
- `ds9_regions.zip` - zip file containing individual `ds9` region files for each of the 3000 images

In the example, playing the `ds9` batch movie may take some time due to the large number of files to be loaded. The command line for that is:

source `regions72.ds9`

or

./`regions72.ds9`

The photometry output and some of the modules used in the photometry block in this example are used to build a light curve, as shown in the next example in Section 13.2.

13.2 Example 2: running PPT LC building block

In the `PPT_example_input_files_light_curve_building.zip` file that comes with the `PPT` distribution, one has:

- PRAIA_photometry_3_0_04.dat - `PPT` main input data file
- `photometry72.dat` - `PPT`-made input photometry file (output of photometry block in the example shown in Section 13.1)
- PRAIA_photometry_3_0_04_user_time.dat - Module of User time
- PRAIA_photometry_3_0_04_select_calibrators.dat - Module for selection of best calibrators
- PRAIA_photometry_3_0_04_smooth_calibration.dat - Module for smoothing calibration flux
- PRAIA_photometry_3_0_04_events_time_windows_LC.dat - Module of time windows for target events, and for target flux and flux ratio flattening/normalization
- PRAIA_photometry_3_0_04_input_time_photometry.dat - Module for definition of input time instants of input photometry file
- PRAIA_photometry_3_0_04_format_photometry.dat - Module with input photometry file format
- PRAIA_photometry_3_0_04_LC_user.dat - Module with User-defined output LC file format

All furnished `PPT` input files are already properly filled up for building the LC. Notice that only strictly necessary `PPT` modules are furnished in the zip.

After running `PPT` with the command line:

`PRAIA_photometry_3_0_04 < PRAIA_photometry_3_0_04.dat`

one should generate the same output files furnished in the `PPT_example_output_files_light_curve_building.zip` that also comes with the `PPT` distribution, which has:

- `curve72.dat` - `PPT` main output LC file
- `curve_short72.dat` - `PPT` Quick look short version output LC file
- `curve72_user.dat` - `PPT` User-defined output LC file

From the `PPT` main output LC file `curve72.dat` we can plot the LC as in Fig. 29.

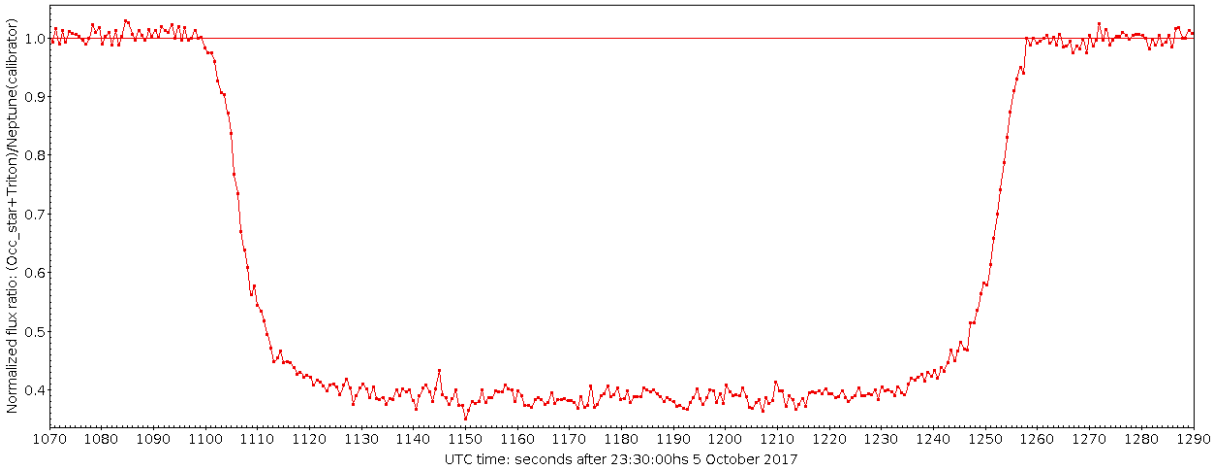


Figure 29: Triton's 2017 occultation LC obtained by `PPT` from the output file `curve72.dat`, originated from the photometry measurements in the `photometry72.dat` file. The target was Triton mixed with the occultation star, and Neptune was used as calibrator. The LC dispersion at the wings out of the occultation window was 0.0116 (1.16%).

13.3 Example 3: running PPT LC intruding flux block

In the `PPT_example_input_files_light_curve_intruding_flux.zip` file that comes with the `PPT` distribution, one has:

- PRAIA_photometry_3_0_04.dat - `PPT` main input data file
- `curve64.dat` - The occultation LC with "Occ_Star + Body" mixed fluxes + photometric calibration flux
- `curve56.dat` - The calibration LC with "Occ_Star" fluxes + photometric calibration flux
- `curve58.dat` - The calibration LC with "Body" fluxes + photometric calibration flux
- PRAIA_photometry_3_0_04_user_time.dat - Module of User time with same setup for occultation
- PRAIA_photometry_3_0_04_events_time_windows_LC.dat - Module of time windows for target events
- PRAIA_photometry_3_0_04_input_time_photometry.dat - Module for definition of input time instants of input photometry file

All furnished `PPT` input files are already properly filled up for computing the LC intruding flux. Notice that only strictly necessary `PPT` modules are furnished in the zip.

The example is based on occultation and calibration observations made at approximately the same air mass with the Liverpool telescope for the Triton 2017 event. Fig. 30 display the FOV of calibration images coded "301". The occultation LC in `curve64.dat` was obtained using a star as calibrator instead of Neptune. The calibration LCs with separate "Occ_Star" (`curve56.dat`) and "Body" (`curve58.dat`) as targets were photometrically calibrated with the same calibration star.

For Liverpool (IAU code J13), the Triton occultation of 5 October 2017 occurs around t_0 = 23:49:37hs at a height of 51.9 degrees (west of the meridian). The calibration images were all taken east of the meridian in the night before (4 October), for which this same height is achieved at t_c = 22:28:30h. Therefore the calibration and occultation images evolve in time with air masses evolving in opposite directions, around the reference air mass at height = 51.9 degrees (this fact is taken into account in the user time stored in the compact LCs).

After running `PPT` with the command line:

```
PRAIA_photometry_3_0_04 < PRAIA_photometry_3_0_04.dat
```

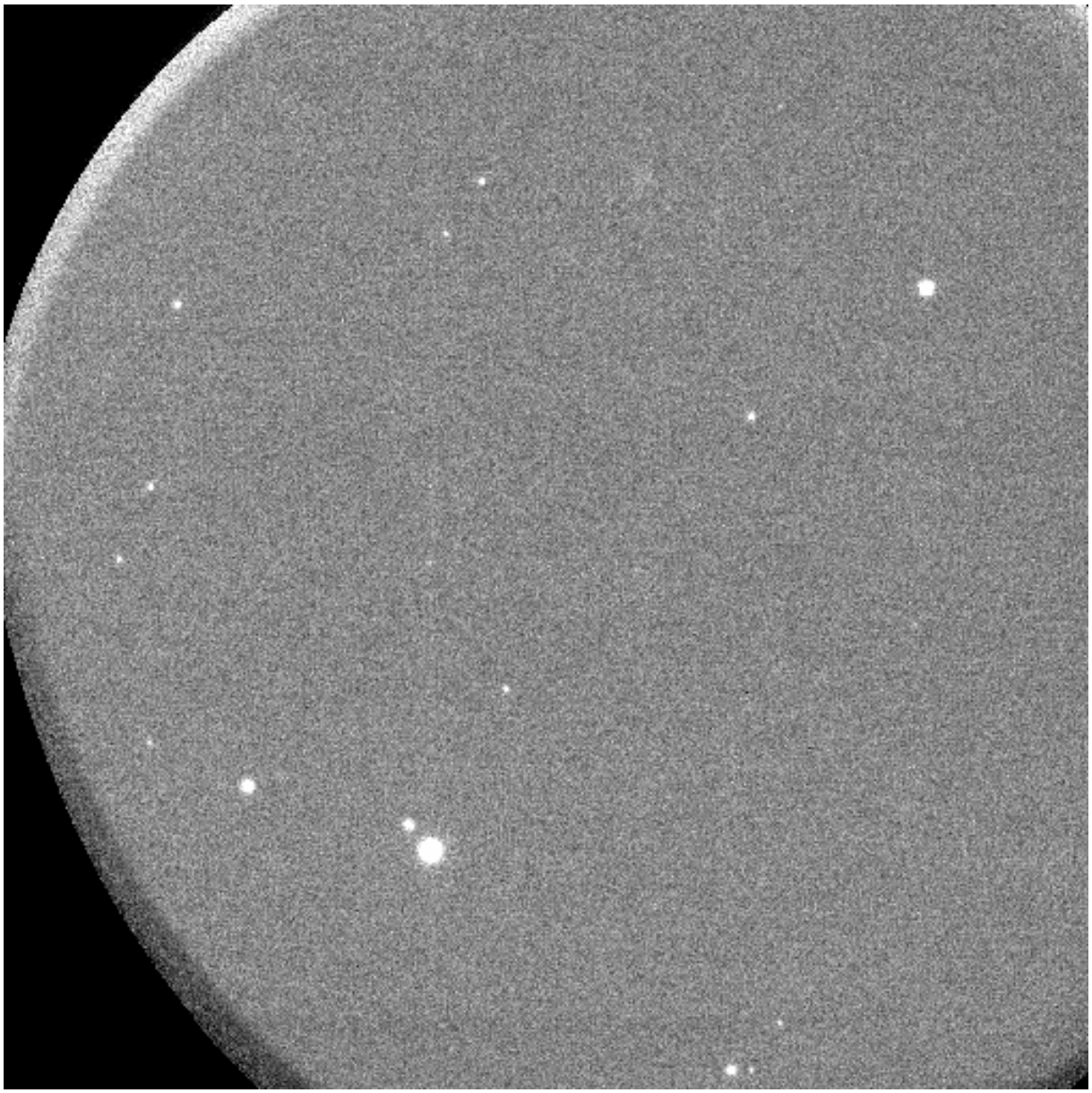


Figure 30: FOV of calibration images coded "301" taken with the 2 m Liverpool telescope for the Triton 2017 occultation campaign (Credits: J. L. Ortiz). The occultation star is the object at left of Neptune (the brightest object in the FOV, with Triton close-by) and the calibrator star is the brightest object far in the opposite corner.

one should generate the same output files furnished in the `PPT_example_output_files_light_curve_intruding_flux.zip` that also comes with the `PPT` distribution, which has:

- `report_Liverpool_301.dat` - complete report with intruding body flux values, errors, complementary information
- `curve61f1.dat` - "Body flux / (Occ_Star + Body flux)" LC `.:.` The so called `FLC` (Fraction or Flatted Intruding Light Curve)
- `curve64f1.dat` - "Occ_Star + Body flux" LC `.:.` LC short version of the occultation LC itself, flatted (not normalized) (contaminated with the intruding body flux)
- `curve56f1.dat` - "Occ_Star" LC `.:.` Calibration LC flatted (not normalized)
- `curve58f1.dat` - "Body" LC `.:.` Calibration LC flatted (not normalized)

- `curve62f1.dat` – "Occ_Star + Body flux" LC `.:.` Calibration LC (separate "Occ_Star" and "Body" flux ratios added), flatted (not normalized)

References

Assafin M., 2023a, Differential aperture photometry with PRAIA, Planetary and Space Science (submitted)

Assafin M., 2023b, Digital coronagraphy with PRAIA, Planetary and Space Science (submitted)

Bickerton, S. J., Lupton, R. H., 2013, MNRAS, 431, 1275

Gendler D., Eisele C., Seiffer D. et al., 2018, arXiv, arXiv:1812.10515

Marques Oliveira J., Sicardy B. et al., 2022, A&A, 659, A136

Press, W. H., Teukolsky, S. A., Vetterling, W. T., Flannery, B. P., 1982, Numerical Recipes in FORTRAN. The Art of Scientific Computing, Second Edition, Cambridge University Press

Wells, D. C., Greisen, E. W., Harten, R. H., 1981, A&AS, 44, 363