PRAIA Astrometry Task

Version 3.0.4

- User Guide -

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Contents

1 Introduction **4**

2 Astrometry with PRAIA **4**

3 Creating the Executable Code and Running the Task **4**

4 Configuring the Access to Gaia DR3 and 2MASS Catalogues **5**

5 Creating the User Catalogue **5**

6 Creating the Ephemeris Catalogue **6**

7 Creating the Target List **6**

8 Creating the Input File with FOV Information **7**

9 Configuring the PRAIA Astrometry Task **7**
9.1 Maximum allowed numbers . . . 8
9.2 Magnitude and key cutoffs for Gaia DR3 stars . . . 8
9.3 User Catalogue and Ephemeris Catalogue . . . 9
9.4 Astrometry mode . . . 9
9.5 FOV information and Target List . . . 9
9.6 Field Distortion Pattern Setup . . . 9
9.7 Masks of bad pixels . . . 10
9.8 Naming output PRAIA astrometry files . . . 11
9.9 Auxiliary information for output on MPC and NIMA target astrometry files . . . 11
9.10 Naming individual FOV output PRAIA astrometry files and ds9 regions . . . 11
9.11 Position and instant tolerances for target identification . . . 12
9.12 Pixel counts, Littleendian x Bigendian (byte-swap option), detector gain setups . . . 12
9.13 PAT (x,y) centring setup . . . 12
9.14 PAT (α, δ) reduction setup . . . 13
9.15 Setting the images to process . . . 14

10 PRAIA Astrometry Task Outputs **14**

11 Formats of All Output PRAIA Astrometry Files **14**
11.1 Photometric statistics output file format . . . 14
11.2 Astrometric reduction statistics output file format . . . 15
11.3 Target astrometry output PAT file format . . . 15
11.4 Target astrometry output MPC file format . . . 17
11.5 Target astrometry output NIMA file format . . . 17
11.6 Output individual FOV PAT xy file format . . . 18
11.7 Output individual FOV ds9 region file format . . . 19

12 Running PAT: an Example **21**

1 Introduction

This document presents the functionalities of the PRAIA astrometry task, release version 3.0.4. In any publication that made use of the PRAIA astrometry 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 astrometry 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 astrometric works, is the PRAIA astrometry task - hereafter PAT. PAT automatically performs fast, accurate and precise small FOV tangent plane astrometry on vast numbers of FITS images. It also does astrometry from lists of (x, y) or (α, δ) measurements. (α, δ)s, errors and other astrometric and photometric data are output. PAT is suited for the astrometry of point-like to moderately extended sources like stars, quasars, AGNs, NEAs, asteroids, Centaurs, TNOs, natural and irregular satellites, planets, dwarf-planets and comets.

2 Astrometry with PRAIA

Major astrometry upgrades/novelties were introduced in the last PAT version 3 (2019) from object detection to (x, y) measurements to (α, δ) reductions. Astrometric improvements came together with photometric ones, also implemented in version 3 of the PRAIA photometry task (Assafin, 2023b). Both tasks now share common and novel procedures. We tied fundamental photometry and astrometry concepts allowing for their mutual improvement. Now PAT accesses catalogues over the internet. Gaia DR3 (Gaia Collaboration, 2022) is the main task catalogue representing the ICRS in the optical domain. We can select the magnitude range of reference objects and eliminate Gaia stars lacking annual proper motions, parallax, radial velocity or having star duplicity flags. We extract infrared magnitudes from the 2MASS catalogue (Cutri et al., 2003). Using our original BOIA procedure (Browsing Objects: Identification and Analysis, Assafin 2023a) - also used in the latest (version 3) photometry and digital coronagraphy PRAIA tasks (Assafin 2023b,c) - we now automatically detect objects in the FOV without any sky background parameters. Widespreadly used in astrometric/photometric programs, sky background factors were completely abolished with BOIA. Procedures now eliminate false-positive detections like cosmic rays, diffraction-spike artifacts, etc. Masks for the elimination of bad pixels are now available for circular and rectangular regions, and ADU (Analogic Digital Unit) count ranges. Many PSF models are now available for the (x, y) centring: 2D circular and elliptical Gaussian and Lorentzian (extended Moffat) profiles, with elimination of pixel outliers in the PSF fittings. We also introduced a novel 2D modified moment centring algorithm named Photogravity Center Method (PGM) in analogy to the gravity centre of a distribution of particles. The (x, y) to (α, δ) reduction is made in apparent coordinates with full models (parallax, annual proper motions, radial velocities) for better tackling meteorological conditions, refraction and bandpass of observations. Reference star position weights from (x, y) errors are now available. Elimination of outliers is by sigma-clipping or by |O-C| cutoff in (α, δ) reductions. Solar System objects have output positions corrected by solar phase angle. Two (α, δ) reductions allow the identification of bad-measured/missing reference stars and targets, improving the astrometry of all objects. Richer ds9[1] region files are now output, improving visual experience.

3 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 codes consist of 2 files:

- PRAIA_astrometry_3_0_04.f: the FORTRAN source code
- PRAIA_astrometry_3_0_04.dat: the input data file

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

To create the executable task file `PRAIA_astrometry_3_0_04`, execute the following command in the prompt line:

gfortran -O3 `PRAIA_astrometry_3_0_04.f` -o `PRAIA_astrometry_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_astrometry_3_0_04 < PRAIA_astrometry_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_astrometry_3_0_04 < PRAIA_astrometry_3_0_04.dat > screen_output.txt`

The name of input data file ("`PRAIA_astrometry_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 `PAT`. We leave it to the creative/experienced user the building of such scripts.

4 Configuring the Access to Gaia DR3 and 2MASS Catalogues

Gaia DR3 (Gaia Collaboration, 2022) and 2MASS (Cutri et al., 2003) data are automatically accessed by the internet from the Vizier database at CDS (Ochsenbein, Bauer, & Marcout, 2000) using the `CDSCLIENT` tool[2]. The file `cdsclient_instalation.zip` contains the `README` file and a `tar/gzip` file for the installation of the `CDSCLIENT` tool in the computer:

- `cdsclient_instalation.zip` - furnished zip file
- `README` - readme file with simple instructions for the installation of the `CDSCLIENT` tool
- `cdsclient.tar.gz` - furnished `tar/gzip` file with files needed for installation

5 Creating the User Catalogue

The User Catalogue should contain ICRS positions with proper motions, parallaxes, radial velocities and magnitudes. They are set by the user for any type of object (stars, quasars, galaxies). Proper motions, parallax and radial velocities should be set to zero if not known. Positions and magnitudes must be furnished. For each catalogue object, the FORTRAN-like content and format of the User Catalogue file are:

- iah,iam,sa,isig,idg,idm,sd,ea,ed,codj,copma,copmd,erpma,erpmd,codmg,codmge,para,radve
- format(i2,1x,i2,1x,f7.4,2x,a1,i2,1x,i2,1x,f6.3,2x,2f7.3,2x,f16.8,1x,4(1x,f7.3),2(1x,f6.3),1x,f9.4,1x,f7.2)
- iah,iam,sa - right ascension (ICRS) at User Catalogue epoch (h, m, s)
- isig,idg,idm,sd - declination (ICRS) at User Catalogue epoch (^{o}, ', ") .:. (isig is the sign)
- ea,ed - (α, δ) errors (arcsec)
- codj - User Catalogue epoch (Julian Date)
- copma - α proper motion (multiplied by the cosδ factor) in arcsec/year
- copmd - δ proper motion in arcsec/year
- erpma,erpmd - (α, δ) proper motion errors in arcsec/year

[2]Vizier CDSCLIENT: http://cdsweb.u-strasbg.fr/doc/cdsclient.html

- codmg – magnitude
- codmge – magnitude error
- para – parallax (mas)
- radve – radial velocity (km/s)

6 Creating the Ephemeris Catalogue

The Ephemeris Catalogue is a special kind of `PAT` reference catalogue designed for a type of astrometry known as "similitude". The reference frame is given by natural satellite positions. Useful in the astrometry of the Saturn and Uranus systems, the catalogue has magnitudes and (α, δ) positions for the instants of the observations, among other data. For each catalogue object and observation instant, the FORTRAN-like content and format of the Ephemeris Catalogue file are:

- iahas,iamas,asas,isigas,idgas,idmas,dsas,datalv, iobalv,iahap,iamap,asap,isigap,idgap,idmap,dsap, dist,apmag,fase,radius,wl
- format(1x,2(i2.2,1x),f9.6,1x,a1,i2.2,1x,i2.2,1x,f8.5,1x,f16.8,1x,a20,1x,2(i2.2,1x),f9.6,1x,a1,i2.2,1x, i2.2,1x,f8.5,1x,e23.16,1x,f5.2,1x,f8.4,1x,f11.3,1x,f7.4)
- iahas,iamas,asas – right ascension (ICRS, topocentric, astrometric) at observation instant (h, m, s)
- isigas,idgas,idmas,dsas – declination (ICRS, topocentric, astrometric) at observation instant (^{o}, ', ") .:. (isigas is the sign)
- datalv – observation instant (Julian Date)
- iobalv – object nickname
- iahap,iamap,asap – right ascension (ICRS, topocentric, apparent) at observation instant (h, m, s)
- isigap,idgap,idmap,dsap – declination (ICRS, topocentric, apparent) at observation instant (^{o}, ', ") .:. (isigap is the sign)
- dist – object distance to observer at observation instant (km)
- apmag – object apparent magnitude
- fase – object solar phase angle at observation instant (degrees)
- radius – object radius (km)
- wl – wavelength of observation (μm)

The apparent coordinates must not be affected by refraction or solar phase angle. The ephemeris information can be retrieved from the Jet Propulsion Laboratory (JPL) Horizons System web service[3]. Also, the `PRAIA` ephemeris task can be used to produce Ephemeris Catalogues in the required internal `PRAIA` format, from JPL or other ephemeris database.

7 Creating the Target List

`PAT` targets may have fixed or varying coordinates. Objects with fixed coordinates may be stars, quasars, galaxies, etc. Their coordinates are set by the user and are valid for any observation date. No proper motions, parallax, etc are given – they are absorbed in the input position. Objects with varying coordinates are interpreted as Solar System ones. Their individual positions are only valid for each FOV with an specific mid-instant of observation. Other information like estimated magnitude, solar phase angle and wavelength of each observation are also necessary. Fixed targets are searched for all FOVs by their (α, δ) only, while for moving targets the instant of measured positions must also match.

For each (fixed or moving) target entry, the format of the Target list file is exactly the same as that described for the Ephemeris Catalogue (see Section 6). In the case of fixed targets, insert a negative

[3]JPL Horizons System: https://ssd.jpl.nasa.gov/horizons/app.html#/

Julian Date observation instant, otherwise it will be treated as a moving target. For fixed targets like stars, galaxies or quasars, the distance, radius and solar phase angle must be set to zero. Topocentric astrometric and apparent positions, apparent magnitudes and solar phase angle are mandatory in all cases.

The `PRAIA` ephemeris task can be used to produce Target lists for Solar System objects in the required internal `PRAIA` format.

8 Creating the Input File with FOV Information

In the astrometry of FITS images, it is necessary to create an input file with the necessary FOV information for each observation. This information is usually available in the FITS header of the images. For each FITS image, the FORTRAN-like content and format of the input file with FOV information are:

- iah,iam,sa,isig,idg,idm,ds,iuth,iutm,sut,iutano, iutmes,iutdia,djm,dj,iexps,ichfil,infits,ichobj,nx,ny
- format(1x,i2.2,1x,i2.2,1x,f7.4,1x,a1,i2.2,1x,i2.2,1x,f6.3,2x,i2.2, 1x,i2.2,1x,f5.2,1x,i4.4,1x,i2.2,1x,i2.2, f16.8,1x,f16.8,2x,i4.4,2x, a20,2x,a50,1x,a20,2(1x,i5.5))
- iah,iam,sa - FOV right ascension (ICRS, topocentric, astrometric) at observation instant (h, m, s)
- isig,idg,idm,ds - FOV declination (ICRS, topocentric, astrometric) at observation instant (^{o}, ', ") .:. (isig is the sign)
- iuth,iutm,sut - (h, m, s) of observation instant (UTC) at observation date
- iutano,iutmes,iutdia - (year, month, day) date of observation
- djm,dj - Modified Julian Date and Julian Date of observation
- iexps - exposure (seconds)
- ichfil - filter
- infits - FITS file name
- ichobj - target nickname
- nx,ny - (x, y) FOV dimensions (pixels)

If an information is not available, leave it blank. However, FOV central coordinates, instant of observation and FOV sizes are mandatory.

The `PRAIA` FITS header extraction task can be used to produce input files with FOV information in the required internal `PRAIA` format.

In the astrometry of input lists of (x, y) measurements or (α, δ) positions previously reduced by `PAT`, all necessary FOV information is extracted from these respective input lists.

9 Configuring the PRAIA Astrometry Task

The input data file (say, `PRAIA_astrometry_3_0_04.dat`) is a simple ASCII text file. It consists of blocks separated by consecutive "****" symbols. Each block is interpreted as a distinct set of input FOVs and parameters that are treated independently from each other. The FOVs are usually FITS images, but they can also be lists of (x, y) measurements or (α, δ) positions. Thus, if wished, one can treat several independent sets of observations at once in one task run. It is up to the user to create and edit the input data file. Usually, the user will edit a previously existing file, or make a copy and edit the new input data file. As typical in many other `PRAIA` tasks, the input data file content has some formatting. The entries are followed by comments, separated by a "|" character which delimits the valid fields for the input values. Usually the valid space of the entry fields consists of 50 column spaces or characters, but there are exceptions. The order of each entry in the input data file must not be changed. The layout (position) of the separating "|" character, for each entry, must also not be changed. Otherwise, unpredictable execution errors or wrong output results may occur. In Fig. 1 we display a typical filled in block of an input data file for task version 3.0.4.

```
300000                                          | Maximum number of FOV objects
3000000                                         | Maximum number of FOV-extracted Gaia DR3 catalogue stars
1000000                                         | Maximum number of FOV-extracted 2MASS catalogue stars
4097                                            | Maximum FOV size in x (pixels)
4097                                            | Maximum FOV size in y (pixels)
00.0                                            | Magnitude cutoffs: minimum magnitude defining Gaia_DR3 catalogue solution
30.0                                            | Magnitude cutoffs: maximum magnitude defining Gaia_DR3 catalogue solution
0                                               | Key to cut Gaia DR3 stars without proper motions  : (0) do not cut; (1) cut
0                                               | Key to cut Gaia DR3 stars without parallax        : (0) do not cut; (1) cut
0                                               | Key to cut Gaia DR3 stars with dupliticy          : (0) do not cut; (1) cut
GAIA2_User_Catalogue.cat                        | User reference catalogue (PRAIA format)
Ephemcat.cat                                    | Ephemeris reference catalogue (PRAIA format)
1                                               | (RA,Dec) reduction with User reference catalogue: (1) Do it; (2) Do not do it
2                                               | (RA,Dec) reduction with Ephemeris reference catalogue: (1) Do it; (2) Do not do it
0                                               | (0) Astrometry of fits images .:. Remake astrometry from PRAIA's previous: (1) measured (x,y)s ; (2) measured (RA,DEC)s (tangent plane technique)
FOV_Triton                                      | Astrometry option = 0: file with extracted header data from fits images .:. option = 1,2: list of PRAIA xy files for remaking astrometry
Targets_Triton                                  | Targets input file: (RA,Dec), JD, target name
1                                               | FDP file type: (1) d(x,y)s (pixels) or d(RA,Dec)s (") mask; (2) (x,y)/(RA,Dec) 3rd degree distortion polynomial; (3) = polynomial FITS keywords; (4) DES
fdp_DES.dat                                     | FDP (Field Distortion Pattern) file (images/remaking astrometry) with polinomial coeffs. or mask for d(x,y)s or d(RA,Dec)s (tangent plane technique)
4                                               | n nearest points for FDP mask interpolation (FDP file type 1 only)
1                                               | Output (x,y)s: (1) without FDP correction (keeps original xys in all astrometry modes); (2) with FDP correction (tangent plane xys in astrometry mode 2)
bad_boxes.pix                                   | Mask of bad pixels: rectangular regions (xmin, xmax, ymin, ymax, key) (only applies for astrometry mode 0) .:. cut inside  regions => key > 0
bad_circles.pix                                 | Mask of bad pixels: circular regions (xc, xc, radius, key)          (only applies for astrometry mode 0)  .:. cut outside regions => key < 0
bad_fluxes.pix                                  | Mask of bad pixels: ADU counting range (count_min, count_max, key) of bad pixels to exclude (only applies for astrometry mode 0) .:. cut inside/outside
astrometry_photometry_Gaia_DR3                  | Photometric statistics of each field                                                                                                                range: key > or < 0
astrometry_reduction_Ephemcat                   | Reduction statistics of each field with the Ephemeris catalogue
astrometry_reduction_Gaia_DR3                   | Reduction statistics of each field with the Gaia DR3 catalogue
astrometry_reduction_CUSER                      | Reduction statistics of each field with the User catalogue
astrometry_target_PRAIA_Ephemcat                | Target file PRAIA format for Ephemeris catalogue solution
astrometry_target_PRAIA_Gaia_DR3                | Target file PRAIA format for Gaia DR3 solution
astrometry_target_PRAIA_CUSER                   | Target file PRAIA format for User reference catalogue solution
astrometry_target_MPC_Ephemcat                  | Target file MPC format for Ephemeris catalogue solution
astrometry_target_MPC_Gaia_DR3                  | Target file MPC format for Gaia DR3 solution
astrometry_target_MPC_CUSER                     | Target file MPC format for User reference catalogue solution
astrometry_target_NIMA_Ephemcat                 | Target file NIMA format for Ephemeris catalogue solution
astrometry_target_NIMA_Gaia_DR3                 | Target file NIMA format for Gaia DR3 solution
astrometry_target_NIMA_CUSER                    | Target file NIMA format for User reference catalogue solution
C|-----------------------------------------------| MPC designation for observation type (Note 2 in https://www.minorplanetcenter.net/iau/info/OpticalObs.html)
I|-----------------------------------------------| Magnitude bandpass for target MPC output format only
874|---------------------------------------------| IAU code of observation site or user-based site designation for target NIMA/MPC output formats only
W|-----------------------------------------------| User Catalogue MPC code for target NIMA/MPC output formats only
ephemcat.red.xy                                 | Extension of "xy" output file, Ephemeris catalogue reduction
gaia_DR3.red.xy                                 | Extension of "xy" output file, Gaia DR3 reduction
cuser.red.xy                                    | Extension of "xy" output file, User Catalogue reduction
ephemcat.reg                                    | Extension of "ds9" output file, Ephemeris catalogue reduction
gaia_DR3.reg                                    | Extension of "ds9" output file, Gaia DR3 reduction
cuser.reg                                       | Extension of "ds9" output file, User reference catalog reduction
1.0                                             | Time instant tolerance for target identification (seconds)
2.0                                             | Position error radius for target identification (arcsec)
1                                               | Pixel physical counts: 0 = from image header or 1 = from user (here)
1.0                                             | Pixel physical counts: bscale;  Pixel = bscale * matrix + bzero
0.0                                             | Pixel physical counts: bzero ;  Pixel = bscale * matrix + bzero
-99                                             | Bitpix: -99 reads from image header; otherwise use 8, 16, 32, 64, -32, -64 following FITS conventions
0                                               | Litteendian x bigendian: byte-swap (0 = automatic; 1 = don't swap ; 2 = swap bytes)
1                                               | Sample a pixel to check for image reading configurations? (1) yes; (2) no
04.0                                            | Detector gain (dfault 1.0 if not known)
2                                               | (x,y) centering PSF round-shaped objects: (1) Photogravity Center; (2) Circular or (3) Elliptical Gaussian; (4) Circular or (5) Elliptical Lorentzian
0.9                                             | Object shape classification: eccentricity cutoff for identification of rounded/elongated objects (suggestion: e = 0.5 in normal conditions)
10                                              | FOV RA  area for Gaia DR3 stars extraction and automatic identication (arcmin) .:. (negative values ===> default 2dg)
10                                              | FOV Dec area for Gaia DR3 stars extraction and automatic identication (arcmin) .:. (negative values ===> default 2dg)
2.0                                             | Error radius (arcsec) for cross-identification between brightest Gaia DR3 catalogue/measured objects
2                                               | Weight polynomial fit ? (1) yes; (2) no (weight=1 to all points)
0.120                                           | (O-C) cutoff for outliers in (RA,DEC) reductions with Ephem catalogue           .:. negative values => sigma-clip factor for elimination of outliers
0.060                                           | (O-C) cutoff for outliers in (RA,DEC) reductions with Gaia DR3 catalogue       .:. negative values => sigma-clip factor for elimination of outliers
0.120                                           | (O-C) cutoff for outliers in (RA,DEC) reductions with User's reference catalogue .:. negative values => sigma-clip factor for elimination of outliers
1                                               | Polynomial model index for (x,y) <===> (X,Y) (RA,DEC) reductions: (see note below about model options)
001                                             | first field (image, xy PRAIA file) to proccess  .:. zero for first and last fields -> proccess all fields
001                                             | last  field (image, xy PRAIA file) to proccess  .:. zero for first and last fields -> proccess all fields
************************************************************************************************************************************************************************************************************************
```

Figure 1: A sample of the input data file of PAT for version 3.0.4.

After the blocks, as in all PRAIA tasks, there can be notes from PRAIA and/or any annotations made by the user. In the case of PAT, after the blocks with input data, we furnish notes regarding to the available tangent plane polynomial models by the task, and Minor Planet Center (MPC) catalogue codes.

In the following sub-sections, we give the meaning of each entry displayed in Fig. 1 regarding to the input data file of PAT version 3.0.4.

9.1 Maximum allowed numbers

The user can set number limits to certain quantities in order to avoid computer memory overflow during PAT execution. They are:

- Line 1 – Maximum number of FOV objects to be identified or to be input
- Line 2 – Maximum number of FOV-extracted Gaia DR3 catalogue stars
- Line 3 – Maximum number of FOV-extracted 2MASS catalogue stars
- Line 4 – Maximum FOV size in x (pixels)
- Line 5 – Maximum FOV size in y (pixels)

9.2 Magnitude and key cutoffs for Gaia DR3 stars

On lines 6 to 10 of the input data file, we set the minimum/maximum G magnitude cutoffs of Gaia DR3 stars. Key cutoffs are also set for proper motions, parallax and duplicity flags. Gaia stars within magnitude cutoffs are excluded. Key cutoffs are in the sense "do not cut Gaia star" (value = 0) or "cut Gaia star" (value = 1). Key cutoff "1" for proper motions will cut a Gaia star that does not present proper motion values in the catalogue. Key cutoff "1" for parallax will cut a Gaia star that does not present a parallax value in the catalogue. Key cutoff "1" for duplicity flag will cut a Gaia star that indicates duplicity in the respective flag in the catalogue.

9.3 User Catalogue and Ephemeris Catalogue

On lines 11 and 12, we furnish respectively the User Catalogue and Ephemeris Catalogue file names. On lines 13 and 14, we inform `PAT` if we do wish (value = 1) or not (value = 2) to make reductions with the User Catalogue and Ephemeris Catalogue respectively.

If no reduction is attempted with these catalogues (value = 2), they are simply ignored regardless of the file names left in the input data file.

9.4 Astrometry mode

On line 15 of the input data file, we indicate what kind of astrometry `PAT` will do. There are 3 modes (options) available:

- Mode 0 - Astrometry of FITS images
- Mode 1 - Remake astrometry from `PAT`'s previously measured (x, y)s
- Mode 2 - Remake astrometry from `PAT`'s previously obtained (α, δ) positions

9.5 FOV information and Target List

On line 16 of the input data file, we furnish the file name containing FOV information.

In Astrometry mode 0 (Section 9.4), this is the file with extracted header data from all FITS images to be reduced, as explained in Section 8.

In Astrometry modes 1 and 2, this file contains the names of the input `PAT xy` files from which we will remake the astrometry. These `xy` files may be the output of previous `PAT` runs (versions 3.0.X) over FITS images or older `PAT xy` files, or they may have been generated by other software and converted to `PAT xy` internal format (versions 3.0.X) - see `PAT xy` file internal format details in Section 11.6.

On line 17 of the input data file, we give the file name with the Target List as explained in Section 7.

9.6 Field Distortion Pattern Setup

On lines 18 to 21 we setup the correction for Field Distortion Pattern (FDP) available by `PAT`. If a FDP is available for the FOV, input measurements - (x, y) measured from images (astrometry mode 0), or (x, y) and (α, δ) positions from input `PAT xy` files (astrometry modes 1 or 2) - are corrected by the FDP maps previously to the (α, δ) reductions. The setup of FDP is as follows:

- Line 18 - FDP file type (values = 1 - 4)
- Line 19 - FDP file name with the FDP mask (map)
- Line 20 - Number n of nearest points for FDP mask (map) interpolation (FDP file type 1 only)
- Line 21 - Output type on output `PAT xy` files

If m is the original measurement - (x, y)s or (α, δ)s - and M is the measurement corrected by FDP, then `PAT` works with a dm FDP mask (map) such that $M = m$ - dm. There are 4 types of FDP masks (maps).

In FDP file type "1", the FDP mask is (da, db, a, b), where the first two values give (da, db) distortion values for the (a, b) coordinates in the same units. Each line in the FDP file thus contains (da, db, a, b) values, ideally covering all the (a, b) space contained by the FOV. In astrometry modes 0 and 1, the FDP mask reads (dx, dy, x, y) in pixel units, and in mode 2 $(d\alpha, d\delta, \alpha, \delta)$ in arcsecond units. Distortion interpolation to (a, b) coordinates other than those furnished by the FDP mask are performed using the n nearest points setup for FDP mask.

In FDP file type "2", the FDP mask (da, db) is described by a third degree bi-variate polynomial P in (a, b) so that $(da, db) = P(a, b)$. P is formally identical as the polynomial used to transform (x, y) measurements to (X, Y) standard coordinates in the tangent plane in astrometric reductions. The FDP file then must contain 10 lines with the polynomial coefficients for a and b. Each line i is thus described as (A_i, B_i), where A and B are the polynomial coefficients associated to the (a, b) coordinates. For astrometry modes 0 and 1, the units of the coefficients must be compatible with (da, db) and (a, b) expressed in pixels, and for astrometry mode 2 in arcseconds.

In FDP file type "3", the FDP mask (dx, dy) (only applied in astrometry mode 0) is described by third degree bi-variate polynomials px and py in (x, y) that follow the Word Coordinate System (WCS) convention of FITS format given by Greisen & Calabretta (2002), which is different in y of the tangent plane transformation convention. We have $dx = px(x, y) = a_{00} + a_{10}\ x + a_{01}\ y + a_{20}\ x^2 + a_{11}\ xy + a_{02}\ y^2 + a_{30}\ x^3 + a_{21}\ x^2y + a_{12}\ xy^2 + a_{03}\ x^3$ and $dy = py(x, y) = b_{00} + b_{10}\ y + b_{01}\ x + b_{20}\ y^2 + b_{11}\ yx + b_{02}\ x^2 + b_{30}\ y^3 + b_{21}\ y^2x + b_{12}\ yx^2 + b_{03}\ x^3$. Each of the 10 lines of the FDP file thus contains the respective (a, b) polynomial coefficients so that line 1 has (a_{00}, b_{00}), line 2 (a_{10}, b_{10}), ..., and line 10 (a_{03}, b_{03}). These polynomial coefficients are usually listed as `PV`-type WCS keys in the headers of FITS images.

FDP file type "4" is dedicated for Dark Energy Survey (DES) FITS images (Flaugher, 2005). The FDP mask (dx, dy) (only applied in astrometry mode 0) is described by third degree bi-variate polynomials px and py in (x, y) that follow the Word Coordinate System (WCS) convention of FITS format given by Greisen & Calabretta (2002), as for FDP file type "3". Extra coefficients are also furnished for characterizing the coordinates of the central pixel and scale and rotation of axes, prior for applying the distortion polynomial corrections. Following WCS convention, they are `CRPIX1` and `CRPIX2` key values (anti-penultimate line), `CD1_1` and `CD2_1` key values (penultimate line), and `CD1_2` and `CD2_2` key values (last line). A FDP file sample is furnished with `PAT` in this case. Details about the astrometry of DES images with `PAT` can be found in Banda-Huarca et al. (2019).

In all modes, output type "1" preserves the original (x, y) measurements while output type "2" updates them according to the used FDP in the output of `PAT xy` files.

9.7 Masks of bad pixels

Bad pixels are not processed in the astrometry (mode 0). The user can setup 3 types of bad pixel masks: rectangular regions, circular regions and ADU ranges. Rectangle and circular regions mask bad pixels inside (or outside) of rectangular and circular areas. ADU ranges mask pixels inside (or outside) of ADU count limits. In the input data file, the 3 bad pixel mask file names are furnished as follows:

- Line 22 - Rectangular (box) region mask
- Line 23 - Circular region mask
- Line 24 - ADU range mask

The user can setup masks of bad pixels that apply for individual images only. The user must furnish individual mask files at the same directory of the images. The individual bad pixel mask file names must be the same as the FITS file names, omitting the ".fits" or ".FITS" extensions (if present) and using the following extension rules:

- `image_root_name.bfpx` - ADU range mask
- `image_root_name.bbpx` - Rectangular (box) region mask
- `image_root_name.bcpx` - Circular region mask

The mask files may contain any number of regions or ADU ranges, one per line. A key indicates if the user wants to mask pixels inside or outside of the given regions or ADU ranges. For each mask type, the entries (one per line) are as follows:

- ADU range mask: C1, C2, key (C2 $\geq$ C1)
- Rectangular region mask: Xmin, Xmax, Ymin, Ymax, key (Xmax $\geq$ Xmin, Ymax $\geq$ Ymin)
- Circular region mask: X_{CENTER}, Y_{CENTER}, Radius, key

Positive keys (+1, +2, ...) mean mask "inside" pixels, and negative ones (-1, -2, ...) mean mask "outside" pixels. For instance, C1 = 10.45 and C2 = 20.32 masks (excludes) pixels with counts 10.45 $<$ pixel $<$ 20.32 for Key = +1, and for key = -1 keeps all pixels with counts 10.45 $<$ pixel $<$ 20.32 and masks (excludes) the rest. Using positive keys masks (excludes) pixels inside rectangular or circular regions, while negative keys masks (excludes) pixels outside these regions keeping only the pixels inside the regions.

9.8 Naming output PRAIA astrometry files

From lines 25 to 37, we set the names of output `PAT` files that furnish overall astrometric and photometric information for all processed FOVs:

- Line 25 – Photometric statistics of each FOV
- Line 26 – Statistics of each FOV for reductions with the Ephemeris Catalogue
- Line 27 – Statistics of each FOV for reductions with the Gaia DR3 catalogue
- Line 28 – Statistics of each FOV for reductions with the User catalogue
- Line 29 – Target astrometry for reductions with the Ephemeris Catalogue: `PAT` format
- Line 30 – Target astrometry for reductions with the Gaia DR3 catalogue: `PAT` format
- Line 31 – Target astrometry for reductions with the User catalogue: `PAT` format
- Line 32 – Target astrometry for reductions with the Ephemeris Catalogue: MPC format
- Line 33 – Target astrometry for reductions with the Gaia DR3 catalogue: MPC format
- Line 34 – Target astrometry for reductions with the User catalogue: MPC format
- Line 35 – Target astrometry for reductions with the Ephemeris Catalogue: NIMA format
- Line 36 – Target astrometry for reductions with the Gaia DR3 catalogue: NIMA format
- Line 37 – Target astrometry for reductions with the User catalogue: NIMA format

MPC refers to the "Minor Planet Center"[4] and NIMA to "Numerical Integration of the Motion of an Asteroid" (Desmars et al. 2015 and references therein). The internal formats of the above files are described in detail in Section 11.

9.9 Auxiliary information for output on MPC and NIMA target astrometry files

From lines 38 to 41, we setup auxiliary information for output on MPC and NIMA target astrometry files:

- Line 38 – MPC designation for observation type (see Section 11.4)
- Line 39 – Magnitude bandpass of target observations
- Line 40 – IAU code of observation site
- Line 41 – MPC reference catalogue code

9.10 Naming individual FOV output PRAIA astrometry files and ds9 regions

From lines 42 to 47, we setup extensions for naming output `PAT` individual FOV files that furnish astrometric, photometric and visual information for each processed FOV individually:

- Line 42 – Extension of output `PAT xy` file, Ephemeris Catalogue reduction
- Line 43 – Extension of output `PAT xy` file, Gaia DR3 catalogue reduction
- Line 44 – Extension of output `PAT xy` file, User Catalogue reduction
- Line 45 – Extension of output `ds9` FOV region file, Ephemeris Catalogue reduction
- Line 46 – Extension of output `ds9` FOV region file, Gaia DR3 catalogue reduction
- Line 47 – Extension of output `ds9` FOV region file, User Catalogue reduction

[4] MPC: https://www.minorplanetcenter.net/

9.11 Position and instant tolerances for target identification

The (α, δ) and observation mid-instant tolerances for target identification are set as follows:

- Line 48 – Mid-instant time difference tolerance for target identification (seconds)
- Line 49 – Position radius tolerance for target identification (arcseconds)

The time tolerance usually depends on the cycle time between exposures. A position radius tolerance of 1 arcsecond usually suffices.

When targets are fixed objects in the input Target List (Section 7), only the position radius tolerance is used – no mid-instant time matching is attempted.

9.12 Pixel counts, Littleendian x Bigendian (byte-swap option), detector gain setups

The setup related to certain FITS header keys must be correctly done in order to properly retrieve the pixel counts of images in the FITS files.

On line 50 of the input data file, the "Pixel physical counts" option indicates how to retrieve the "raw" counts of pixels written in the FITS image files. Use "0" to extract this information directly from the FITS header, or "1" to explicitly input the scale and zero level of the counts (lines 51 and 52) in the input data file. Before choosing "0", the user must be sure that the FITS header of the images do contain the `BSCALE` and `BZERO` FITS header 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.

On line 51, explicitly input the scale of the "raw" FITS counts.

On line 52, explicitly input the zero level of the "raw" FITS counts.

Notice that lines 51 and 52 must always be present in the input data file, even with the "Pixel physical counts" option "0" – in this case, the values in these two next lines are simply ignored.

On line 53 of the input data file, 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 `PAT` use the value directly furnished in the FITS header. Otherwise, insert the correct value. Valid values are "8", "16", "-32", "+32", "-64", "+64".

On line 54 of the input data file, use option "0" to let `PAT` automatically detect the correct number representation (or byte-swap option) of FITS images, or insert the option explicitly: "1" (don't byte-swap the numbers in the FITS file) or "2" (byte-swap numbers). Depending on the architecture of the machine/system from which the FITS file was first created, the numbers (pixel raw counts) may (or may not) be written with bytes swapped with respect to the architecture of the user's computer. This regards to the number representation in machines (Littleendian or Bigendian structure).

On line 55, set the option to display ("1") or not ("2") the true image count of the central pixel in the FOV. If the display is turned on, the task outputs on the screen and on the report log file the count value for the central pixel of the image. Thus, the user can check if this value is correct by comparing it with the output of another program or image software, such as the FITS image display program `ds9`. If the value is not the same as that displayed by `ds9`, odds are that the BITPIX value or the byte-swap option ("0", "1" or "2") or both are wrong. These entries must thus be changed until the correct count value is extracted by the task. Only then, one can be sure that the correct pixel counts are being used by `PAT`, otherwise unpredictable outputs may result.

On line 56 of the input data file, set the detector gain. Usually the gain is furnished in the FITS header of images under header key "GAIN". If not known, set gain = 1. Furnish the correct detector gain whenever possible, so that `PAT` can compute correct absolute values for the signal-to-noise ratio (S/N) of objects during `BOIA` procedures. Correct position error estimates for the PGM centring method depend on correct S/N values.

9.13 PAT (x,y) centring setup

On line 57, we set the `PAT` centring method by choosing one of the following 1-5 options:

- 1 – Photogravity Center Method (PGM)
- 2 – Circular bi-variate (x, y) Gaussian PSF
- 3 – Elliptical bi-variate (x, y) Gaussian PSF

Table 1: `PAT` polynomial models that relate tangent plane (X, Y) coordinates with (x, y) measurements.

Model	X	Y
Four Constants	$a_{00} + a_{10}\ x + a_{01}\ y$	$b_{00} - a_{01}\ x + a_{10}\ y$
First Degree (1rst)	$a_{00} + a_{10}\ x + a_{01}\ y$	$b_{00} + b_{10}\ x + b_{01}\ y$
Second Degree (2nd)	1rst (X) $+a_{20}\ x^2 + a_{11}\ xy + a_{02}\ y^2$	1rst (Y) $+b_{20}\ x^2 + b_{11}\ xy + b_{02}\ y^2$
2nd+Rad.Dist. 3rd (23rd)	2nd(X) $+a_3\ x(x^2 + y^2)$	2nd(Y) $+b_3\ y(x^2 + y^2)$
2nd+Rad.Dist. 35rd (235rd)	23rd(X) $+a_5\ x(x^2 + y^2)^2$	23rd(Y) $+b_5\ y(x^2 + y^2)^2$
Third Degree (3rd)	2nd (X) $+a_{30}\ x^3 + a_{21}\ x^2y + a_{12}\ xy^2 + a_{03}\ x^3$	2nd (Y) $+b_{30}\ x^3 + b_{21}\ x^2y + b_{12}\ xy^2 + b_{03}\ x^3$
3rd+Rad.Dist. 5rd (35rd)	3rd(X) $+a_5\ x(x^2 + y^2)^2$	3rd(Y) $+b_5\ y(x^2 + y^2)^2$
Fifth Degree	3rd(X) $+a_{40}\ x^4 + a_{31}\ x^3y + a_{22}\ x^2y^2 + a_{13}\ xy^3 + a_{04}\ y^4 +$ $a_{50}\ x^5 + a_{41}\ x^4y + a_{32}\ x^3y^2 + a_{23}\ x^2y^3 + a_{14}\ xy^4 + a_{05}y^5$	3rd(Y) $+b_{40}\ x^4 + b_{31}\ x^3y + b_{22}\ x^2y^2 + b_{13}\ xy^3 + b_{04}\ y^4 +$ $b_{50}\ x^5 + b_{41}\ x^4y + b_{32}\ x^3y^2 + b_{23}\ x^2y^3 + b_{14}\ xy^4 + b_{05}y^5$

Note: Models are presented in hierarchical order with respect to the automatic identification of reference catalogue objects (see Assafin 2023a).

- 4 – Circular bi-variate (x, y) Lorentzian PSF with free (α, β) coefficients
- 5 – Elliptical bi-variate (x, y) Lorentzian PSF with free (α, β) coefficients

On line 58, we let the user indicate an eccentricity cutoff for the identification of round-shaped objects and elimination of more elongated ones during `BOIA` procedures. For well exposed images, an eccentricity cutoff $e = 0.5$ suffices.

The following internal setup serves for all PSF model options. In the PSF fittings, the ADU pixel elimination threshold factor is set to 4 sigmas. The PSF sigma convergence limit is set to 1%. The PSF centroid convergence threshold in pixels is set to 0.005 pixels. The limiting number of Least-Squares iterations in the PSF fitting is set for a maximum of 30 iterations. All these are optimized internal values adequate for a vast range of object types and sky sampling conditions. See Assafin (2023a) for details.

9.14 PAT (α, δ) reduction setup

On lines 59-66, we setup the `PAT` (α, δ) reductions.

On lines 59-60, we furnish the (α, δ) FOV sizes for the Gaia DR3 stars extraction and automatic identication (arcmin). Negative values on any or either fields make `PAT` automatically extract a default FOV of 2^o x 2^o.

On line 61, we furnish the tolerance radius (arcseconds) for cross-identification between brightest Gaia DR3 catalogue and measured objects. A tolerance of 2 arcseconds usually suffices.

On line 62, we can set `PAT` to weight (option "1") or not ("2") the polynomial fittings in the tangent plane during (α, δ) reductions. Weighting is done according to the (x, y) measuring errors.

On lines 63-65, we set |(O-C)| cutoffs (arcseconds) for the elimination of outliers in the (α, δ) reductions with the Ephemeris Catalogue (line 63), Gaia DR3 (line 64) and User Catalogue (line 65) respectively.

On line 66, we set the index of the polynomial model to be used in the tangent plane fittings relating the (x, y) and (X, Y) standard coordinates. The polynomial model indexing is as follows (see also Table 1):

- index 0 – Four Constants model
- index 1 – Complete First Degree model
- index 2 – Complete Second Degree model
- index 3 – Complete Third Degree model
- index 4 – Complete Second degree model plus radial distortion term of third degree
- index 5 – Complete Fifth Degree model
- index 6 – Complete Second degree model plus radial distortion terms of third and fifth degrees
- index 7 – Complete Third Degree model plus radial distortion term of fifth degree

9.15 Setting the images to process

On lines 67-68 we set which FOVs (FITS images, `PAT xy` files) we want to do astrometry:

- Line 67 - First FOV ("0" starts from first FOV in input FOV list)
- Line 68 - Last FOV ("0" ends on last FOV in input FOV list)

10 PRAIA Astrometry Task Outputs

All output positions are ICRS astrometric topocentric coordinates, including reference catalogue object (O-C)s, Target List and ephemeris position offsets. For Solar System bodies, positions are corrected by solar phase angle (Lindegren, 1977), stellar aberration, precession and nutation, gravitational deflection of light by the Sun, Jupiter and Saturn, and light time delay, following JPL's definitions.

Output magnitudes m are given by m=k-2.5log$_{10}(F)$. The zero point k is computed with the magnitude of reference catalogue objects – G band for Gaia DR3 stars – and with the total flux F from PSF fittings or `BOIA` aperture photometry. Outliers are eliminated by sigma-clipping. Mean errors come from the standard deviation of the magnitude (O-C)s of measured and catalogue objects.

Astrometric data are output for all measured objects: (α, δ) positions, standard errors (E_α, E_δ), measurement errors (e_α, e_δ), mean errors $(\sigma_\alpha, \sigma_\delta)$, (O-C)s of reference catalogue objects (including flags for outliers), FWHMs, catalogue and measured magnitudes and errors (including infrared 2MASS magnitudes), instants. No total error for the (α, δ) positions is furnished – this is a controversial topic – but all kinds of error estimates and related values are available, so that one can compute total errors in accord to one's own judgment.

For targets, "measured minus reference" (α, δ) offsets are given, and separate files output in `PAT`, `MPC` and `NIMA` (Numerical Integration of the Motion of an Asteroid, Desmars et al. 2015) formats.

For visual inspection analysis, `PAT` outputs files in `ds9` region format (Section 11.7).

During `PAT` running, messages are output on screen displaying the current FOV being processed and the current astrometry step. During reference catalogue object identification, information is displayed regarding to the number of extracted and provisionally identified stars, fitted tangent plane polynomial coefficients, etc. After the astrometry of each FOV, `PAT` displays on screen final values for the pixel scale, error, FOV sizes and orientation angle of x with respect to the right ascension direction. For each FOV, `PAT` also displays on screen a summary of the (α, δ) reduction with information on the targets found - target position offsets (ephemeris offsets in the case of Solar System objects), mean error of (α, δ) reduction, number of used reference catalogue objects, object position and computed magnitude, exposure time and UTC instant of observation.

`PAT` outputs all the astrometric and photometric results, and visualisation information in the files defined in Sections 9.8 and 9.10. The file contents are described next in Section Sec:OUTPUTformats.

11 Formats of All Output PRAIA Astrometry Files

Here, we present the internal formats for the output `PAT` files presented in Sections 9.8 and 9.10.

11.1 Photometric statistics output file format

The FORTRAN-like content and format of the this output file (Section 9.8) are:

- fwhm,sigfwh,fundo,fundo2,fpmag,fpmags,rps2mg,g1fmg,g1fmgs,g1smg,fsmag,fsmags, rss2mg,nest,iexps,ichfil,infits,ichobj,nx,ny
- format(2(1x,f5.3),2(1x,f7.1),9(1x,f6.3),1x,i5,2x,i4,2x,a20,2x,a50,2x,a20,2(1x,i5))
- fwhm,sigfwh - Average seeing and sigma about this average (arcseconds)
- fundo,fundo2 - Average and sigma of sky background in ADUs
- fpmag,fpmags,rps2mg - Average and sigma magnitude of sky background and sigma of instrumental x catalogue magnitude fitting based on the Ephemeris catalogue magnitude system
- g1fmg,g1fmgs,g1smg - Average and sigma magnitude of sky background and sigma of instrumental x catalogue magnitude fitting based on the Gaia DR3 G magnitude system

- fsmag,fsmags,rss2mg – Average and sigma magnitude of sky background and sigma of instrumental x catalogue magnitude fitting based on the User Catalogue magnitude system

11.2 Astrometric reduction statistics output file format

The FORTRAN-like content and format of the this output file (Section 9.8) are:

- alfsg1,delsg1,nstag1,nfing1,percg1,avamg1,dvamg1,dj,iah,iam,sa,isig,idg,idm,ds,iexps, ichfil,infits,mchobj,nx,ny,(g1cofx(i),i=1,icofsp),(g1cofy(i),i=1,icofsp),(g1ecfx(i),i=1,icofsp), (g1ecfy(i),i=1,icofsp)
- format(2(1x,f6.3),2(1x,i4),1x,f6.2,2(1x,f6.3),1x,f16.8,1x,i2.2,1x,i2.2,1x,f7.4,1x,a1,i2.2,1x,i2.2,1x,f6.3, 2x,i4,2x,a20,2x,a50,1x,a20,2(1x,i5),1x,4(21(1x,es24.16e3)))
- icofsp – Maximum allowed number of tangent plane polynomial coefficients, currently set on icofsp = 21
- alfsg1,delsg1 – Sigma (mean error) of (α, δ) FOV reduction (arcseconds)
- nstag1,nfing1,percg1 – Initial/final number of reference objects, and elimination percentage from (α, δ) FOV reduction
- avamg1,dvamg1 – FOV average standard errors in (α, δ) (arcseconds; see Eichhorn & Williams (1963); Assafin (2023a)
- dj – Julian Date
- iah,iam,sa,isig,idg,idm,ds – Central (α, δ) of FOV (h, m, s, ^{o}, ', ")
- iexps – Exposure time (seconds)
- ichfil – Filter
- infits – File name (FITS image or input `PAT` xy file) of reduced FOV
- mchobj – Main target nickname of the FOVs
- nx,ny – (x, y) FOV dimension sizes (pixels)
- g1cofx, g1cofy – tangent plane polynomial coefficients in (x, y) (astrometry mode 0 or 1) or in (X, Y) tangent plane standard coordinates (astrometry mode 2)
- g1ecfx, g1ecfy – errors of the respective polynomial coefficients

The tangent plane polynomial coefficients are such that the corresponding (X, Y) standard coordinates are always in radians. In astrometry modes 0 and 1 the linear coefficient in x reads in radian/pixel units, the x^2 one in radian/pixel^2 units and so on. For astrometry mode 2, the same coefficients read respectively in radian/radian units, radian/radian^2 units and so on.

11.3 Target astrometry output PAT file format

These are very important outputs by `PAT`. They carry complete astrometric results for the targets from the reductions of each used reference catalogue. The outputs from each reference catalogue share the same format. The FORTRAN-like content and format of the these output files (Section 9.8) are:

- dx,dy,xob,yob,seng,altu,fgcc,xfdp,yfdp,xmgu,cudmg,cudmg2,xmgj,xmgh,xmgk,fumag,fumag2, ermgj,ermgh,ermgk,pma,pmd,epma,epmd,ex,ey,erau,edeu,alfsiu,delsiu,nstaru,nfinau,alsiu,desiu, ktirau,ra,de,iuth,iutm,sut,iutano,iutmes,iutdia,dj,iexps,ichfil,infits,iobalv,nx,ny,kind,obtype
- format(2(1x,f7.3),2(1x,f7.2),1x,f5.2,2f10.2,2f7.3,11(1x,f6.3),4(1x,f7.3),6(1x,f6.3),2(1x,i4),2(1x,f6.3), 1x,i4,2(1x,f13.9),1x,i2.2,1x,i2.2,1x,f5.2,1x,i4,1x,i2.2,1x,i2.2,1x,f16.8,2x,i4,2x,a20,2x,a50,1x,a20, 2(1x,i5),1x,a5,1x,a1)
- dx,dy – Offsets in (α, δ) in the sense "`PAT` minus target position" (arcseconds); if target is also a reference catalogue object, the target catalogue position is used instead of the listed target position for computing the offsets, and (dx,dy) = (alsiu,desiu)

- xob,yob – (x, y) measured coordinates (pixels)
- seng – FWHM (arcsec)
- altu – PSF central peak (ADU units)
- fgcc – local sky background derived from the `BOIA` aperture and used in the PSF fitting (ADU units)
- xfdp,yfdp – Used FDP for (x, y) (pixels, astrometry mode 0 and 1) or (α, δ) (arcseconds, astrometry mode 2)
- xmgu – Magnitude given in the target list
- cudmg – Target PSF magnitude based on the reference catalogue magnitude system
- cudmg2 – PSF magnitude error
- xmgj,xmgh,xmgk – J, H, K 2MASS magnitudes (if it is a 2MASS star)
- fumag – Sky background magnitude based on the reference catalogue magnitude system
- fumag2 – Sky background magnitude dispersion based on the PSF fitting of the local sky background of the objects
- ermgj,ermgh,ermgk – J, H, K 2MASS magnitude errors (if it is a 2MASS star)
- pma,pmd – (α, δ) reference catalogue proper motions (arcseconds/year; α proper motion without the cosδ factor)
- epma,epmd – (α, δ) reference catalogue proper motion errors (arcseconds/year; α proper motion error without the cosδ factor)
- ex,ey – (α, δ) errors from (x, y) measurements (Assafin (2023a)) (arcseconds)
- erau,edeu – (X, Y) standard errors rigorously computed from variance-covariance matrix of (x, y) to (X, Y) Least Squares reduction with tangent plane polynomials (Eichhorn & Williams (1963); Assafin (2023a)) (arcseconds)
- alfsiu,delsiu – (α, δ) mean errors from (α, δ) reduction (i.e. standard-deviation from the (O-C) residuals for the reference catalogue objects) (arcseconds)
- nstaru,nfinau – Initial/final number of reference catalogue objects in final (α, δ) reduction
- alsiu,desiu – (O-C) residuals in the sense "`PAT` minus reference catalogue position" (arcseconds)
- ktirau – "7" if target is also a reference catalogue object; "8" if target is not a reference catalogue object;
- ra,de – (α, δ) ICRS topocentric astrometric coordinates corrected by solar phase angle if it is a Solar System object (units in hour and decimals, and degrees and decimals respectively)
- iuth,iutm,sut – UTC instant of observation (h, m, s)
- iutano,iutmes,iutdia – Date of observation (year, month, day)
- dj – Julian Date of observation
- iexps – Exposure time (seconds)
- ichfil – Used filter
- infits – Image FITS file or `PAT` xy file name
- iobalv – Target nickname
- nx,ny – (x, y) FOV dimension sizes (pixels)

- kind (see Assafin (2023a):
  - `BOIA1`: primarily detected `BOIA` object with final (x, y) measurements from primary detection
  - `BOIA2`: primarily detected `BOIA` object with final (x, y) measurements from post-detection
  - `BOIA3`: post-detected `BOIA` object with final (x, y) measurements from post-detection
- obtype – Round object = "r"; elongated (trace-shaped) object = "t"

11.4 Target astrometry output MPC file format

These are very important outputs by `PAT`. They carry the astrometric results for the targets from the reductions of each used reference catalogue in MPC standard format. The outputs from each reference catalogue share the same format. The FORTRAN-like content and format of these output files (Section 9.8) are:

- iobalv,obtipo,iutano,iutmes,dia,iah,iam,sa,isig,idg,idm,ds,cudmg,band,iau,icat
- format(a14,a1,i4.4,1x,i2.2,1x,f8.5,1x,i2.2,1x,i2.2,1x,f6.3,a1,i2.2,1x,i2.2,1x,f5.2,9x,f5.2,a1,6x,a3, 1x,a1)
- iobalv – Target name or nickname
- obtipo – MPC designation for observation type[5]
- iutano,iutmes,dia – UTC date of observation (year, month, day and fraction of day)
- iah,iam,sa,isig,idg,idm,ds – Target (α, δ) ICRS topocentric astrometric coordinates (h, m, s, ^{o}, ', ")
- cudmg – Target PSF magnitude based on the reference catalogue magnitude system
- band – Magnitude bandpass of observation
- iau – IAU code of observation site
- icat – MPC reference catalogue code[6]

Rules for MPC astrometry report format can be found at: https://www.minorplanetcenter.net/iau/info/OpticalObs.html.

11.5 Target astrometry output NIMA file format

These are very important outputs by `PAT`. They carry the astrometric results for the targets from the reductions of each used reference catalogue in NIMA internal format. The outputs from each reference catalogue share the same format.The FORTRAN-like content and format of these output files (Section 9.8) are:

- iah,iam,sa,isig,idg,idm,ds,cudmg,dj,iau,icat,iobalv
- format(i2.2,1x,i2.2,1x,f7.4,2x,a1,i2.2,1x,i2.2,1x,f6.3,3x,f6.3,2x,f16.8,2x,a3,2x,a1,3x,a20)
- iah,iam,sa,isig,idg,idm,ds – Target (α, δ) ICRS topocentric astrometric coordinates (h, m, s, ^{o}, ', ")
- cudmg – Target PSF magnitude based on the reference catalogue magnitude system
- dj – Julian Date of observation
- iau – IAU code of observation site
- icat – MPC reference catalogue code
- iobalv – Target name or nickname

[5]MPC designation for observation type, see Note 2 in https://www.minorplanetcenter.net/iau/info/OpticalObs.html
[6]MPC catalogue codes: https://minorplanetcenter.net//iau/info/CatalogueCodes.html

11.6 Output individual FOV PAT xy file format

These are very important outputs by `PAT`. They carry complete astrometric results for the individual FOV reductions with each of the used reference catalogues. The outputs from each reference catalogue reduction share the same format. The FORTRAN-like content and format of these individual FOV `PAT xy` files (Section 9.10) are:

- xob,yob,seng,altu,fgcc,xfdp,yfdp,xmgu,cudmg,cudmg2,xmgj,xmgh,xmgk,fumag,fumag2, ermgj,ermgh,ermgk,pma,pmd,epma,epmd,ex,ey,erau,edeu,alfsiu,delsiu,nstaru,nfinau,alsiu,desiu, ktirau,ra,de,iuth,iutm,sut,iutano,iutmes,iutdia,dj,iexps,ichfil,infits,iobalv,nx,ny,kind,obtype
- format(2(1x,f7.2),1x,f5.2,2f10.2,2f7.3,11(1x,f6.3),4(1x,f7.3),6(1x,f6.3),2(1x,i4),2(1x,f6.3), 1x,i4,2(1x,f13.9),1x,i2.2,1x,i2.2,1x,f5.2,1x,i4,1x,i2.2,1x,i2.2,1x,f16.8,2x,i4,2x,a20,2x,a50,1x,a20, 2(1x,i5),1x,a5,1x,a1)
- xob,yob – (x, y) measured coordinates (pixels)
- seng – FWHM (arcsec)
- altu – PSF central peak (ADU units)
- fgcc – local sky background derived from the `BOIA` aperture and used in the PSF fitting (ADU units)
- xfdp,yfdp – Used FDP for (x, y) (pixels, astrometry mode 0 and 1) or (α, δ) (arcseconds, astrometry mode 2)
- xmgu – Magnitude given by the reference catalogue (99 if not a catalogue object)
- cudmg – Object PSF magnitude based on the reference catalogue magnitude system
- cudmg2 – PSF magnitude error
- xmgj,xmgh,xmgk – J, H, K 2MASS magnitudes (if it is a 2MASS star)
- fumag – Sky background magnitude based on the reference catalogue magnitude system
- fumag2 – Sky background magnitude dispersion based on the PSF fitting of the local sky background of the objects
- ermgj,ermgh,ermgk – J, H, K 2MASS magnitude errors (if it is a 2MASS star)
- pma,pmd – (α, δ) reference catalogue proper motions (99 if not a catalogue object) (arcseconds/year; α proper motion without the cosδ factor)
- epma,epmd – (α, δ) reference catalogue proper motion errors (99 if not a catalogue object) (arcseconds/year; α proper motion error without the cosδ factor)
- ex,ey – (α, δ) errors from (x, y) measurements (Assafin (2023a)) (arcseconds)
- erau,edeu – (X, Y) standard errors rigorously computed from variance-covariance matrix of (x, y) to (X, Y) Least Squares reduction with tangent plane polynomials (Eichhorn & Williams (1963); Assafin (2023a)) (arcseconds)
- alfsiu,delsiu – (α, δ) mean errors from (α, δ) reduction (i.e. standard-deviation from the (O-C) residuals for the reference catalogue objects) (arcseconds)
- nstaru,nfinau – Initial/final number of reference catalogue objects in final (α, δ) reduction
- alsiu,desiu – (O-C) residuals in the sense "`PAT` minus reference catalogue position" (99 if not a catalogue object) (arcseconds)
- ktirau – "0" if it is a reference catalogue object maintained in the (α, δ) reduction; "1" if it is a reference catalogue object eliminated in the (α, δ) reduction; "7" if it is a target and a reference catalogue object; "8" if it is a target but not a reference catalogue object; "99" if it is an unidentified field object (not a listed target nor a catalogue object)

- ra,de – (α, δ) ICRS topocentric astrometric coordinates corrected by solar phase angle if it is a Solar System object (units in hour and decimals, and degrees and decimals respectively)
- iuth,iutm,sut – UTC instant of observation (h, m, s)
- iutano,iutmes,iutdia – Date of observation (year, month, day)
- dj – Julian Date of observation
- iexps – Exposure time (seconds)
- ichfil – Used filter
- infits – Image FITS file or `PAT` xy file name
- iobalv – Object nickname
- nx,ny – (x, y) FOV dimension sizes (pixels)
- kind (see Assafin (2023a):
  - `BOIA1`: primarily detected `BOIA` object with final (x, y) measurements from primary detection
  - `BOIA2`: primarily detected `BOIA` object with final (x, y) measurements from post-detection
  - `BOIA3`: post-detected `BOIA` object with final (x, y) measurements from post-detection
- obtype – Round object = "r"; elongated (trace-shaped) object = "t"

11.7 Output individual FOV ds9 region file format

These are very useful outputs by `PAT`. They furnish individual FOV `ds9` region files that can be used for visualisation of the astrometry. Individual FOV `ds9` region files follow the "image-type" format rules of `ds9`. The FORTRAN-like content and format of individual FOV `ds9` region files (Section 9.10) are:

- xob,yob,radius
- format('image; circle(',2(f16.8,','),f16.8,') color=xxxxx ')
- xob,yob – (x, y) measured coordinates (pixels)
- radius – `BOIA` aperture radius
- color – "xxxxx" can be any of the following colors: green, yellow, red, blue, orange or black

The meaning of colors in individual FOV `ds9` region files are:

- red – Target in the FOV
- green – Reference catalogue object used in (α, δ) reduction
- yellow – Reference catalogue object eliminated in (α, δ) reduction
- orange – Reference catalogue object cut off (not used) prior to the (α, δ) reduction (magnitude range, proper motion, parallax or duplicity cutoff)
- black – Reference catalogue object not identified in the FOV
- blue – Not identified object (not a reference catalogue object or listed target)

One, two or three drawn circles are related to the object kind (see Section 11.6). They have the following meaning:

- 1 circle – `BOIA1` kind: primarily detected `BOIA` object with final (x, y) measurements from primary detection
- 2 circles – `BOIA2` kind: primarily detected `BOIA` object with final (x, y) measurements from post-detection

- 3 circles – `BOIA3` kind: post-detected `BOIA` object with final (x, y) measurements from post-detection

Orange and black circles have 4-digit codes written in the `ds9` region files. The meaning of these codes are:

- 0000 – Not a cutoff reference catalogue object
- 0003 – Reference catalogue object: trigonometric parallax cutoff
- 0030 – Reference catalogue object: proper motion cutoff
- 0300 – Reference catalogue object: duplicity flag cutoff
- 3000 – Reference catalogue object: magnitude range cutoff

For visualisation inspection with `ds9`, run the following command in the prompt:

```
ds9  image_root_name.fits  -region  image_root_name.ds9_region_extension
```

where:

- image_root_name – Root name of image
- ds9_region_extension – `ds9` extension of `ds9` region file name (see Section 9.10)
- `image_root_name.fits` – Image FITS file name
- `image_root_name.ds9_region_extension` – `ds9` region file name

As example of visualisation with `ds9` is given in Fig. 2.

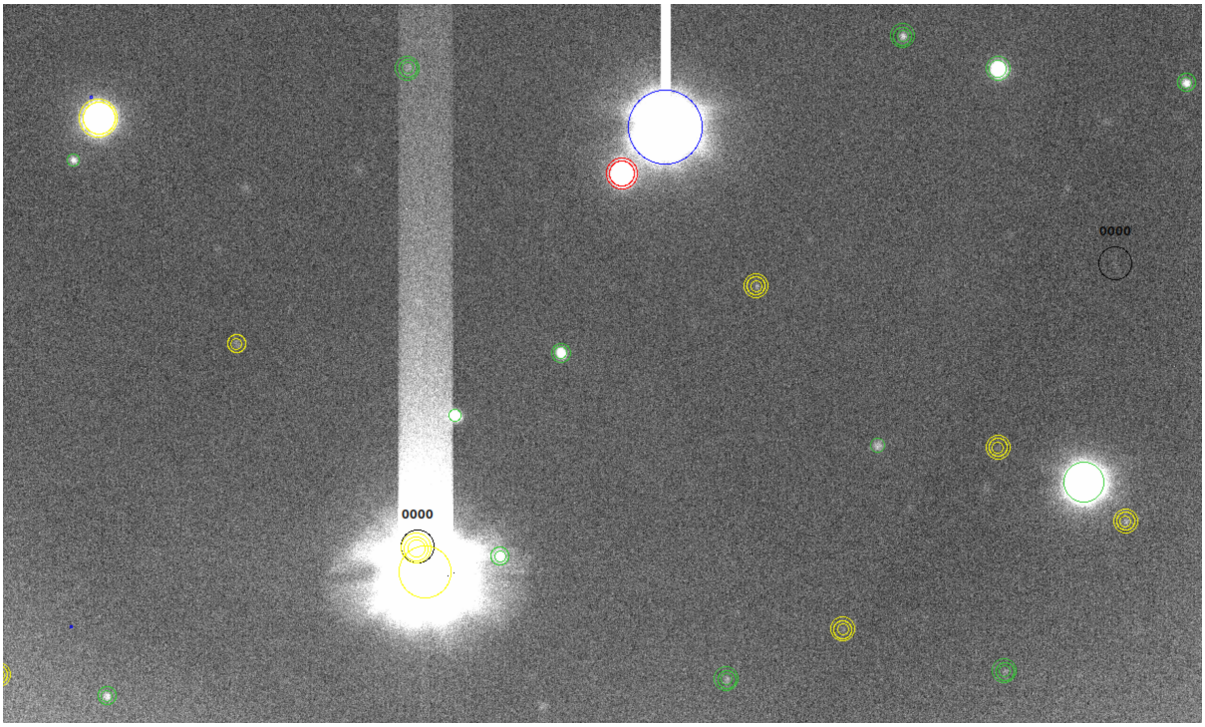


Figure 2: FOV with Triton, Neptune's main satellite . Circles are centred at the measured (x, y)s with aperture sizes as determined by `BOIA` procedures. Targets (Triton here) are indicated by red circles. Green and yellow colors respectively indicate used and discarded (high |O-C|s) Gaia reference stars. Blue circles (e.g. Neptune) regard to measurements that are neither targets nor reference catalogue objects. Gaia stars not successfully identified/measured are indicated by black circles with numeric codes. Single, double and triple circles regard to the (x, y) origin of the `BOIA` measurement, as explained in the text.

12 Running PAT: an Example

In the `Example_input_files_astrometry.zip` file that comes with `PAT` distribution, one has:

- `PRAIA_astrometry_3_0_04.dat` - `PAT` input data file
- `TritaoELseq10_05.01.29_0001.fits` - Sample FITS image file
- `FOV_Triton` - FOV input data file
- `GAIA2_User_Catalogue.cat` - Sample User Catalogue (Gaia DR2 positions of the FOV)
- `Targets_Triton` - Target List input file

The sample FOV is a 60s exposure of 6'x6' sizes taken in 2017 far from the meridian with the OPD/LNA 1.6m telescope (IAU code 874) with objects ranging from 10.5 to 21 G magnitudes. It has few stars, some very faint, some very bright with CCD leaking features. The observation was made during a campaign to observe Neptune and Triton, visible in the field (see Assafin 2023a). The Target List input file has DE440/nep097 JPL ephemeris for Triton taken at the instants of observations. The sampled FITS image corresponds to the first entry in the FOV input data file, which contains FOV information extracted from the FITS headers of the original images.

After running `PAT` with the command line:

`PRAIA_astrometry_3_0_04 < PRAIA_astrometry_3_0_04.dat > log.PAT`

one should generate the same output files and output screen log file furnished in the `Example_output_files_astrometry.zip` that also comes with `PAT` distribution:

- `astrometry_photometry_Gaia_DR3` - photometry report of FOVs
- `astrometry_reduction_CUSER` - astrometry report of FOVs from User Catalogue reductions
- `astrometry_reduction_Gaia_DR3` - astrometry report of FOVs from Gaia DR3 catalogue reductions
- `astrometry_target_MPC_CUSER` - astrometry report of targets in MPC format from User Catalogue reductions
- `astrometry_target_MPC_Gaia_DR3` - astrometry report of targets in MPC format from Gaia DR3 catalogue reductions
- `astrometry_target_NIMA_CUSER` - astrometry report of targets in NIMA format from User Catalogue reductions
- `astrometry_target_NIMA_Gaia_DR3` - astrometry report of targets in NIMA format from Gaia DR3 catalogue reductions
- `astrometry_target_PRAIA_CUSER` - astrometry report of targets in `PAT` format from User Catalogue reductions
- `astrometry_target_PRAIA_Gaia_DR3` - astrometry report of targets in `PAT` format from Gaia DR3 catalogue reductions
- log.PAT - Output screen log file from `PAT` run
- `TritaoELseq10_05.01.29_0001.cuser.red.xy` - astrometry report of individual FOV (`PAT xy` file) from User Catalogue reductions
- `TritaoELseq10_05.01.29_0001.cuser.reg` - `ds9` region file of FOV from User Catalogue reductions
- `TritaoELseq10_05.01.29_0001.gaia_DR3.red.xy` - astrometry report of individual FOV (`PAT xy` file) from Gaia DR3 catalogue reductions
- `TritaoELseq10_05.01.29_0001.gaia_DR3.reg` - `ds9` region file of FOV from Gaia DR3 catalogue reductions

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