MAOPhot 1.0.0

Welcome to MAOPhot 1.0.0, a PSF Photometry tool using Astropy 6.0.0 and photutils.psf 1.10.0

This program was derived from MetroPSF by Maxym Usatov.

MAOPhot calculates stellar magnitudes from Fit (*.fit, *.fits, *.fts) formatted digital photographs using PSF photometry. It produces an extended AAVSO (American Association of Variable Star Observers) report which can be submitted to the AAVSO using their online tool WebObs (http://www.aavso.org/webobs).

MAOPhot uses the PSF (point spread function) Photometry method exclusively.

PSF modeling is well suited for measuring stellar magnitudes in crowded fields, or the magnitude of a star that has a close companion, e.g., Z Tau.
(See https://www.aavso.org/lpv-double-trouble-campaign-0)

MAOPhot is written in Python using Astropy (a common core package for astronomy). MAOPhot also uses photutils.psf. See "PSF Photometry" (https://photutils.readthedocs.io/en/stable/psf.html) which describes many of the classes and methods used in MAOPhot.

MAOPhot has been redesigned for AAVSO reporting only and includes, but not limited to the following enhancements:

- uses Astropy 6.0.0 and photutils.psf 1.10.0 (all packages required have version specified in requirements.txt file)
- generation of Effective PSF model (EPSF model), and ability to create a 'rejection list' of stars that the user can select that will not be part of the EPSF model
- option to use an Integrated Gaussian PRF (Pixel Response Function) as model
- PSF Photometry using an iterative algorithm to perform point spread function photometry
- PSF Photometry using a non-iterative algorithm to perform point spread function
- PSF Photometry using an ensemble of comparison stars or a single comp star
- generation of Two-Color Photometry (B, V), (V, R) or (V, I), and Single Image Photometry reports in AAVSO extended format
- use of telescope Transformation Coefficients (needed for Two Color Photometry)
- user can specify check star and list of comp stars to use

- a Radio Button option to display all AAVSO comp stars as AAVSO label numbers and any found VSX objects in image field or only VSX and AAVSO comp stars specified in settings

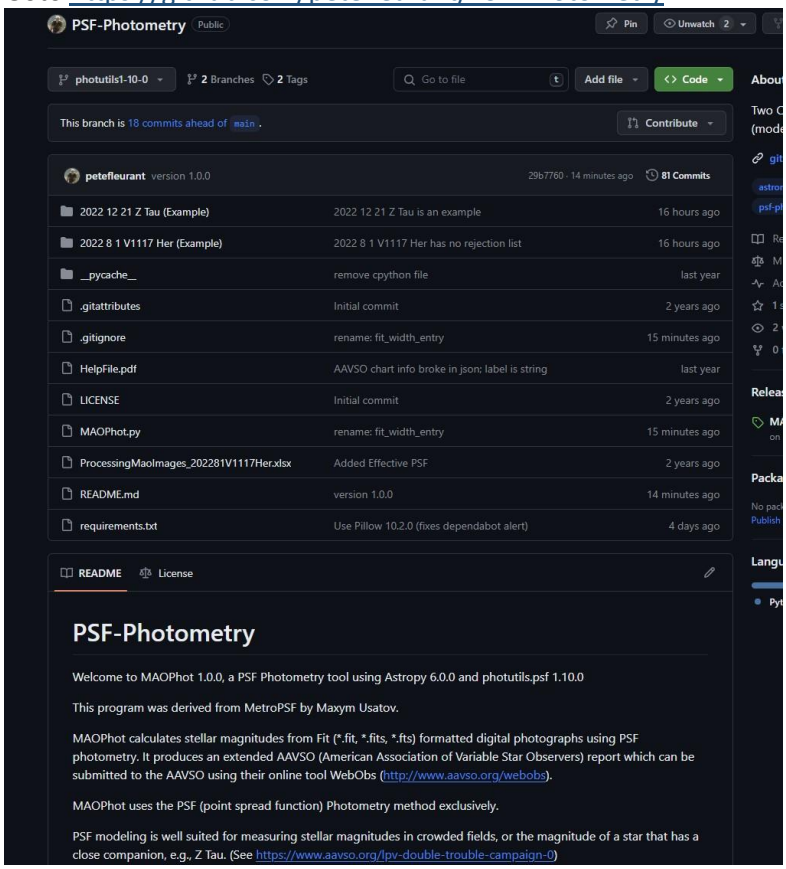
- intermediate results are saved as .csv files

- user can optionally enter a AAVSO Chart ID when retrieving comparison star data

- if intermediate results include found comp stars or VSX objects associated with an image being loaded, then these objects are displayed

Installation

1. Install Python.
    a. Goto https://www.python.org/downloads/
    b. Download the latest version for your OS
2. Clone PSF-Photometry
    a. Goto https://github.com/petefleurant/PSF-Photometry

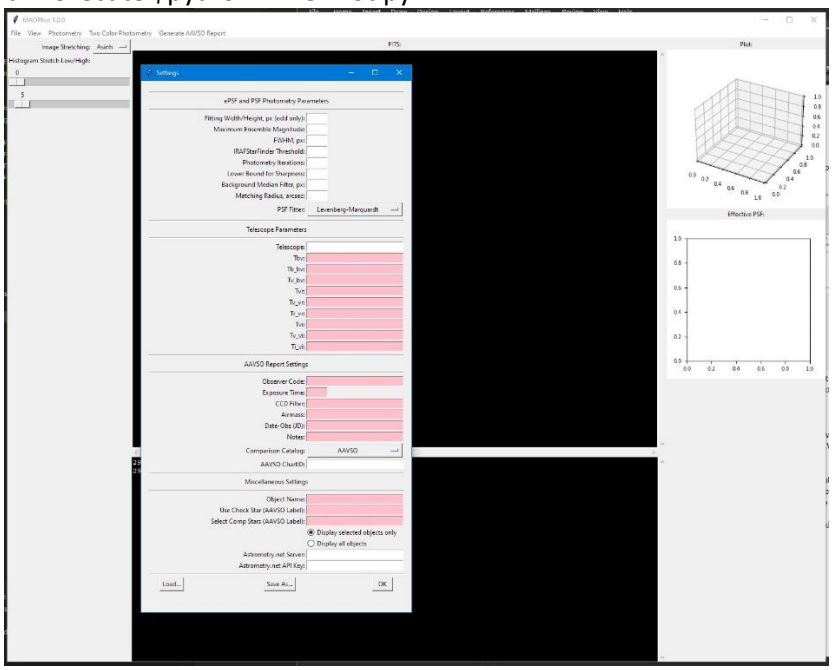


    b. Click on “<>Code” button
    c. Select your preferred method or just select “Download ZIP”
        i. Unzip package in your preferred subdirectory
3. After unzipping or cloning, open a shell, cmd window, or console window in your chosen PSF-Photometry directory

4. Create a virtual environment. It is strongly encouraged that you create a virtual environment for running MAOPhot.py.
    a. To create the virtual environment, execute the following (Here we use myMAOvenv as a name for the to be created virtual environment:
        i. >>cd PSF-Photometry\
        ii. >>python -m venv <myMAOvenv> # here using example name: myMAOvenv
        iii. >><myMAOvenv>\Scripts\activate.bat # activate it

5. With <myMAOvenv> activated, execute the following in the PSF-Photometry directory
    a. $pip install -r ./requirements.txt.
        i. Requirements used in MAOPhot 1.0.0 listed here for reference:
            1. astropy==6.0.0
            2. astroquery==0.4.6
            3. matplotlib==3.8.2
            4. numpy==1.26.2
            5. pandas==2.1.4
            6. photutils==1.10.0
            7. Pillow==10.2.0
            8. scipy==1.11.4
            9. tqdm==4.66.1

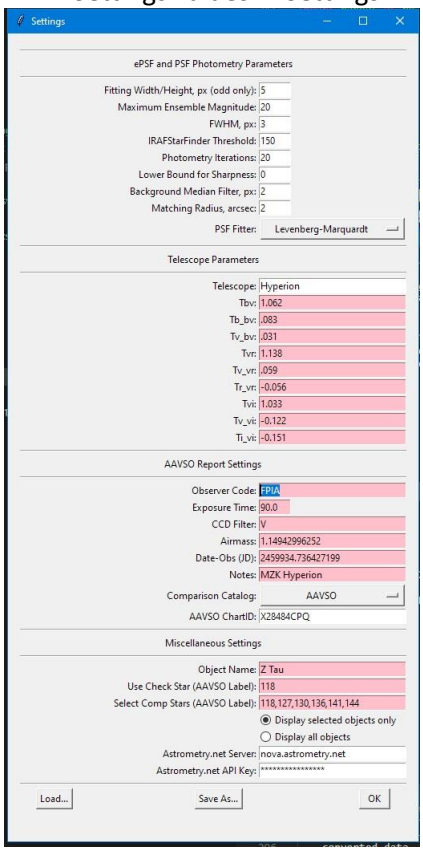
6. Test by executing MAOPhot
    a. open a cmd window, or console window in the PSF-Photometry directory
    b. execute $python MAOPhot.py



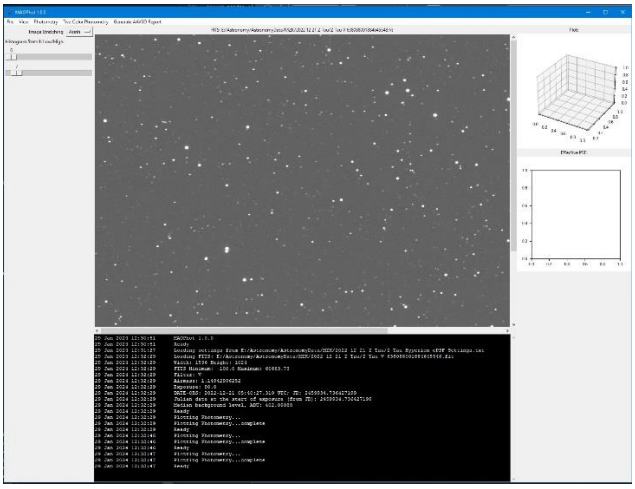
    c. DO NOT execute ‘pythonw’ since the console output is necessary! A progress bar is displayed in that console window for certain operations.

Single Image Photometry Workflow
General Workflow for Single Image Photometry and AAVSO report generation
Using example ”2022 12 21 Z Tau (Example)”

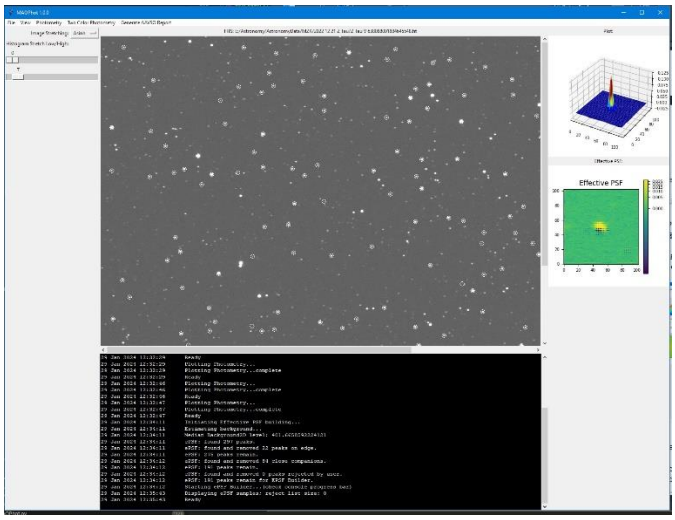
1) Prepare master images.
   a) The master should be calibrated in proper FIT format. It should be cropped such that no 'black' or zero value ADU exists at the edges. The image need not be plate solved but RA and DEC values should exist for proper plate solving in MAOPhot. (see below for Astronometry.net server settings)
2) Launch MAOPhot by running the following command in the working directory
   a) ‘python MAOPhot.py
3) Fill in Settings values in Settings window by hand or use “Load…”



   a) Use ‘Load…’ to load an existing set of settings (E.g., 2022 12 21 Z Tau (Example)\Z Tau Hyperion Settings.txt)
   b) adjust the ‘Fitting Width/Height so that it contains stellar images of target magnitude
   c) adjust FWHM to the average FWHM in image
   d) Close the Settings Window by pressing OK
4) 'File->Open...' (E.g., 2022 12 21 Z Tau (Example)\Z Tau V.fit)
   a) Image Stretching uses Asinh by default. Adjust stretch if necessary. (This is only a screen stretch.)



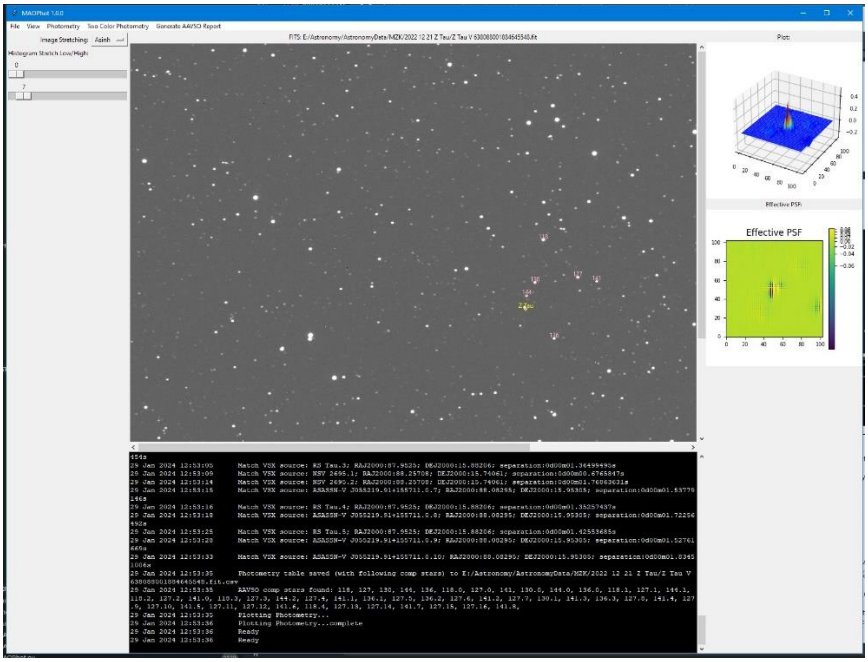
5) [Optional] 'Photometry->Create Effective PSF'
   a) Watch progress bar in output console; (same console where you executed ‘python MAOPhot.py’)
   b) [Optional] Select stars to be rejected (by mouse clicking) (This causes the circle about the star to turn red.), or see step 6
      i) select stars NOT well isolated from their neighbors (most are done automatically)
      ii) select stars with poor SNR levels, or saturated stars
      iii) [optional] save rejection list (Photometry-> Save rejection list)
      iv) then select 'Photometry->Create Effective PSF' again and repeat if necessary
      v) inspect “Effective PSF Plot” for a “reasonable” looking PSF



6) [Optional] Photometry->Load Rejection List… (E.g., 2022 12 21 Z Tau (Example)\Z Tau-rejectionV.csv)
   a) After loading select 'Photometry->Create Effective PSF' again
7) Photometry->Iteratively PSF Photometry
   a) Watch progress bar in output console; (same console where you executed ‘python MAOPhot.py’)
8) [optional] Photometry->Solve Image (example Z Tau V.fit and Z Tau R.fit files already have WCS data)
   a) 'Photometry->Solve Image' to plate solve if FITS file does not contain WCS Header data

b) [optional] After solving, 'File->Save' or 'File->Save As…' to save WCS data in FITs file
Note: if your input file image already has WCS Header data, there is no need to "Solve Image"

9) Photometry->Get Comparison Stars [WCS Header data required]



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10) 'Generate AAVSO Report->Single Image Photometry'
    a) Select the <fits filename>.csv file that was generated by step 8 (E.g., 2022 12 21 Z Tau (Example)\Z Tau V.fit.csv)
    b) this generates the AAVSO report in a subdirectory (E.g., aavso_reports/AAVSO Z Tau V Z Tau_single.txt)

Example AAVSO report:

#TYPE=Extended
#OBSCODE=FPIA
#SOFTWARE=Self-developed; MAOPhot 1.0.0 ; using Photutils
#DELIM=,
#DATE=JD
#OBSTYPE=CCD
#NAME,DATE,MAG,MERR,FILT,TRANS,MTYPE,CNAME,CMAG,KNAME,KMAG,AMASS,GROUP,CHART,NOTES
Z Tau,2459934.73643,14.853,0.06,V,NO,STD,118,-7.777,118,-7.777,1.14942996252,na,X28484CPQ,MZK Hyperion|CMAGINS=-7.777|CREFERR=0.004|CREFMAG=11.81|KMAG=11.81|KMAGINS=-7.777|KREFERR=0.004|KREFMAG=11.81|VMAGINS=-4.735

More about Single Image Photometry

Single Image Photometry does not utilize the Transformation coefficients. Simple differential photometry is used. Only a single comp star is used (which must be the case if the AAVSO VPhot tool, 'Transform Applier' is to be used).

Two Color Photometry Workflow

General Workflow for Two Color Photometry and AAVSO report generation with V and R filters.

Execute steps 1 through 9 above for the V master and then the R master images.

Then continue with step 10:

10) 'Generate AAVSO Report->Two Color Photometry->(V-R)'
    a) Select the 2 csv files that were generated in step 9 (1 for V and 1 for R; e.g., Z Tau V 638088001884645548.fit.csv' and 'Z Tau R 638088001885055673.fit.csv')
    b) If any outliers (comparison stars) noted, delete from 'Select Comp Stars (AAVSO Label)' list
    c) then select 'Generate AAVSO Report->Two Color Photometry->(V-R)'again

Typical Output after running 'Generate AAVSO Report->Two Color Photometry->(V-R)':

```
29 Jan 2024 20:01:46      Check Star Estimates using check star: 118 (V: 11.810) (R: 11.666)
    type name  comp       IMV       IMR       V       R  delta_v_minus_r  delta_V_minus_R   delta_v   delta_r  comp_v_minus_r     V_star     R_star     outlier
0  check  118   127 -7.118447 -6.111712  12.673  12.335         0.465321         0.529535 -0.658959 -1.124281       -1.006735  12.045283  11.181065
1  check  118   130 -6.741278 -6.057307  12.992  12.567         0.142557         0.162230 -1.036129 -1.178686       -0.683970  11.965443  11.379229
2  check  118   136 -5.789824 -7.141185  13.585  13.143        -1.892775        -2.153978 -1.987583 -0.094808        1.351362  11.470332  13.168815  <--OUTLIER
3  check  118   141 -5.708323 -4.728656  14.077  13.704         0.438253         0.498732 -2.069084 -2.507337       -0.979667  12.037341  11.168734
                                                                                                                  V* Ave: 11.880  R* Ave: 11.724
                                                                                                                  V* Std:  0.275  R* Std:  0.968
29 Jan 2024 20:01:46                                                                                              Check Star IQR limit for V*: 11.545;12.336
29 Jan 2024 20:01:46                                                                                              Check Star IQR limit for R*: 10.205;12.800
29 Jan 2024 20:01:46

29 Jan 2024 20:01:46      Variable Star Estimates of Var: Z Tau
  type   name  comp       IMV       IMR       V       R  delta_v_minus_r  delta_V_minus_R   delta_v   delta_r  comp_v_minus_r     V_star     R_star
0  var  Z Tau   127 -7.118447 -6.111712  12.673  12.335         4.462802         5.078669  2.383627 -2.079175       -1.006735  15.356268   9.971419
1  var  Z Tau   130 -6.741278 -6.057307  12.992  12.567         4.140038         4.711363  2.006457 -2.133581       -0.683970  15.276428  10.169583
2  var  Z Tau   136 -5.789824 -7.141185  13.585  13.143         2.104706         2.395155  1.055003 -1.049702        1.351362  14.781317  11.959169
3  var  Z Tau   141 -5.708323 -4.728656  14.077  13.704         4.435734         5.047866  0.973502 -3.462232       -0.979667  15.348326   9.959087
                                                                                                                  V* Ave: 15.191  R* Ave: 10.515
                                                                                                                  V* Std:  0.275  R* Std:  0.968
```

MAOPhot checks for values outside the IQR (interquartile range) to detect outliers.

If there is an outlier (<--OUTLIER) then remove the associated comp star from the 'Select Comp Stars (AAVSO Label)' list [optional], then repeat 'Two Color Photometry->(V-R)'

Result after removing 136:

```
29 Jan 2024 20:02:31      Check Star Estimates using check star: 118 (V: 11.810) (R: 11.666)
    type name  comp       IMV       IMR       V       R  delta_v_minus_r  delta_V_minus_R   delta_v   delta_r  comp_v_minus_r     V_star     R_star outlier
0  check  118   127 -7.118447 -6.111712  12.673  12.335         0.465321         0.529535 -0.658959 -1.124281       -1.006735  12.045283  11.181065
1  check  118   130 -6.741278 -6.057307  12.992  12.567         0.142557         0.162230 -1.036129 -1.178686       -0.683970  11.965443  11.379229
2  check  118   141 -5.708323 -4.728656  14.077  13.704         0.438253         0.498732 -2.069084 -2.507337       -0.979667  12.037341  11.168734
                                                                                                                  V* Ave: 12.016  R* Ave: 11.243
                                                                                                                  V* Std:  0.044  R* Std:  0.118
29 Jan 2024 20:02:31                                                                                              Check Star IQR limit for V*: 11.942;12.101
29 Jan 2024 20:02:31                                                                                              Check Star IQR limit for R*: 11.017;11.438
29 Jan 2024 20:02:31

29 Jan 2024 20:02:31      Variable Star Estimates of Var: Z Tau
  type   name  comp       IMV       IMR       V       R  delta_v_minus_r  delta_V_minus_R   delta_v   delta_r  comp_v_minus_r     V_star     R_star
0  var  Z Tau   127 -7.118447 -6.111712  12.673  12.335         4.462802         5.078669  2.383627 -2.079175       -1.006735  15.356268   9.971419
1  var  Z Tau   130 -6.741278 -6.057307  12.992  12.567         4.140038         4.711363  2.006457 -2.133581       -0.683970  15.276428  10.169583
2  var  Z Tau   141 -5.708323 -4.728656  14.077  13.704         4.435734         5.047866  0.973502 -3.462232       -0.979667  15.348326   9.959087
                                                                                                                  V* Ave: 15.327  R* Ave: 10.033
                                                                                                                  V* Std:  0.044  R* Std:  0.118
29 Jan 2024 20:02:31      Master Report saved to E:\Astronomy\AstronomyData\MZK\2022 12 21 Z Tau\Z Tau-V-R-Master-Report.csv
```

11) 'Generate AAVSO Report->Two Color Photometry->(V-I)'
    a) this generates the AAVSO report in a subdirectory aavso_reports/

Example AAVSO report:

#TYPE=Extended
#OBSCODE=FPIA
#SOFTWARE=Self-developed; MAOPhot 1.0.0 ; using Photutils
#DELIM=,
#DATE=JD
#OBSTYPE=CCD
#NAME,DATE,MAG,MERR,FILT,TRANS,MTYPE,CNAME,CMAG,KNAME,KMAG,AMASS,GROUP,CHART,NOTES
Z Tau,2459934.73695,15.327,0.044,V,YES,STD,ENSEMBLE,na,118,12.016,1.149,na,X28484CPQ,MZK Hyperion|KMAGINS=-7.777|KMAGSTD=12.016|KREFMAG=11.81|Tvr=1.138|VMAGINS=-4.735
Z Tau,2459934.73613,10.033,0.118,R,YES,STD,ENSEMBLE,na,118,11.243,1.149,na,X28484CPQ,MZK Hyperion|KMAGINS=-7.236|KMAGSTD=11.243|KREFMAG=11.666|Tr_vr=-0.056|VMAGINS=-8.191

More about Two Color Photometry

MAOPhot mimics VPhot's "Two Color Photometry" (for this discussion we use B and V).
See spreadsheet: ProcessingMaoImages_202281V1117Her.xlsx It includes formulas to generate "two color photometry".

Error Estimation

MAOPhot mimics VPhot when calculating error estimation.
From VPhot documentation:

> In an ensemble solution with more than two comp stars,
> the magnitude is estimated as the average of the individual
> comp stars estimate [of the check star], and the error is taken as
> the standard deviation of this sample.
>
> If one or two comp stars are used, the error estimate is
> based on the SNR of each measurement (the target measurement
> and the comp stars measurements). The standard error of a
> measurement is defined as 2.5 * np.log10(1 + 1 / SNR)
> [The errors are added in quadrature.]

Menu Functionality

Menu functions:

File->Open	load a FITs file into MAOPhot for analysis
File->Save	save loaded FITS file
File->Save As…	save loaded FITS file to a file
File-> Edit Settings…	this brings up the 'Settings' window
File->Exit	this exits the application
View->Zoom In	zoom in in +.5 scale increments
View->Zoom Out	zoom out in -.5 scale increments
View->100% Zoom	zoom to normal scale
View->Refresh	Usually used if settings: "Display selected objects only has changed"

Photometry->Create Effective PSF

Analyzes image and generates an ePSF model following the prescription of Anderson and King (2000; PASP 112, 1360)
(Max number of iterations is hardcoded at 50)
Any two peaks within an aperture width/height are rejected.
If a rejection list has been loaded, then peaks in list are also rejected

Photometry->Load Rejection List…

Loads a previously saved rejection list

Photometry->Save Rejection List…

After running "Create Effective PSF", user can select peaks to be rejected by mouse clicking on the FIT image.
When user clicks on a star, then a red circle appears. This is to be rejected. These can be saved.

Photometry->Clear ePSF Data

clears all ePSF data, ePSF and rejection list.

Photometry->Non-Iterative PSF Photometry

Executes algorithm to perform PSF photometry on the image.

Photometry->Iterative PSF Photometry

Executes iterative algorithm to perform PSF photometry on the image with max number of iteration set in “Photometry Iterations” setting

Photometry->Solve Image

Use Astronometry.net server to add WCS Header information.

Photometry->Get Comparison Stars

Queries AAVSO for comparison stars in the field.

Two Color Photometry->(B,V) Executes two color photometry for B and V

Two Color Photometry->(V,R) Executes two color photometry for V and R

Two Color Photometry->(V,I) Executes two color photometry for V and I

Generate AAVSO Report->Single Image Photometry

This generates an AAVSO report in extended format of a single Filter. The data is not transformed.

Generate AAVSO Report->Two Color Photometry->(B,V)

This generates an AAVSO report in extended format for 2 filters, (B,V). The data is transformed.

Generate AAVSO Report->Two Color Photometry->(V,R)

This generates an AAVSO report in extended format for 2 filters, (V,R). The data is transformed.

Generate AAVSO Report->Two Color Photometry->(V,I)

This generates an AAVSO report in extended format for 2 filters, (V,I). The data is transformed.

List of parameters in Setting Window

Parameter	Description	Units	Req*
Fitting Width/Height	Rectangular shape around the center of a star that will be used to define the PSF-fitting region (must be an odd number)	pixels	
Maximum Ensemble Magnitude	Stars fainter than this magnitude will not be fetched	magnitude	
FWHM	IRAFStarFinder searches for peaks with similar FWHM	pixels	

IRAFStarFinder Threshold	The absolute image value above which to select sources	float	
Photometry Iterations	Number of iterations to perform in Iteratively Subtracted PSF Photometry	integer	
Lower Bound for Sharpness	The lower bound on sharpness for object detection.	float	
Background Median Filter	used in Background2D; the window size of the 2D median filter to apply to the low-resolution background map	integer	
Matching Radius	Tolerance between image coordinate and catalog, if within tolerance than a match is made	arcsecs	
PSF Fitter	Type of fitter used in Interactive PSF Photometry	list selection	
Telescope	Name of telescope; for reference only (OPTIONAL not used)	string	
Tbv	Transformation Coefficients	float	yes
Tb_bv		float	yes
Tv_bv		float	yes
Tvr		float	yes
Tv_vr		float	yes
Tr_vr		float	yes
Tvi		float	yes
Tv_vi		float	yes
Ti_vi		float	yes
AAVSO Observer Code	Entered into the report under #OBSCODE	string	yes
Exposure Time	exposure usually found in FITS header; used to calculate instrumental magnitude	float	yes
CCD Filter	filter used for image; usually found in FITs header	string	yes

Airmass	Found in FITs header	float	
Date-Obs	Entered into report; usually found in FITs header	JD	yes
Notes	Entered into report under notes	string	yes
AAVSO ChartID	specific chartID to be used; (e.g., X28484CPQ) (optional)	string	
ObjectName	variable star name to be measured	string	yes
Use Check Star	KNAME	AAVSO label	yes
Select Comp Stars	comma delimited list of AAVSO labels specifying comp stars to be used in measurement; if more than 1, then "ENSEMBLE" keyword is entered into report	AAVSO labels	yes
Display selected objects only	Display only objects listed in Comp Stars, Check Star, and Object Name	Radio Button	
Display all objects	Display all objects found by Astronomy.net (redundant have .0, .1, …etc. appended to name)	Radio Button	
Astronometry.net Server	URL of astronomy.net server (e.g., nova.astrometry.net or a local one)	string	
Astronometry.net API Key	To use astroquery.astrometry.net you will need to set up an account at astrometry.net and get your API key. The API key is available under your profile at astrometry.net when you are logged in. Copy the key and insert into this field.	string	

*Req: these settings are directly inserted into the AAVSO Report; most are automatically filled in from the FIT header (Only some TCs are inserted into AAVSO Report)

Definitions

IRAF	IRAF is a general Image Reduction and Analysis Facility providing a wide range of image processing tools for the user. IRAF is a product of the National Optical Astronomy Observatories and was developed for the astronomical community although researchers in other scientific fields have found IRAF to be useful for general image processing. (see https://iraf-community.github.io/)

Contact:
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Miscellaneous

Helpful commands for venv:

>>cd PSF-Photometry
>>python -m venv .myMAOvenv # create a virtual environment called .myMAOvenv
>>. myMAOvenv \Scripts\activate.bat # activate it
>>pip install -r ./requirements.txt #these will only get installed in the .venv_0_0_2 environment
>>. myMAOvenv \Scripts\deactivate.bat

GitHub notes:

- Don't check in the .myMAOvenv folder, ignore it
-