Welcome to MAOPhot 0.1, a PSF Photometry tool using Astropy and Photutils.psf

MAOPhot (MAOPhot.py) calculates stellar magnitudes from digital FIT formatted photographs. It produces an extended AAVSO (American Association of Variable Star Observers) report which can be submitted to the AAVSO using the online tool WebObs (http://www.aavso.org/webobs).

There are many photometry measuring programs available such as VPhot (http://www.aavso.org/vphot) and AstroImageJ (University of Louisville). VPhot uses the aperture photometry method.

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

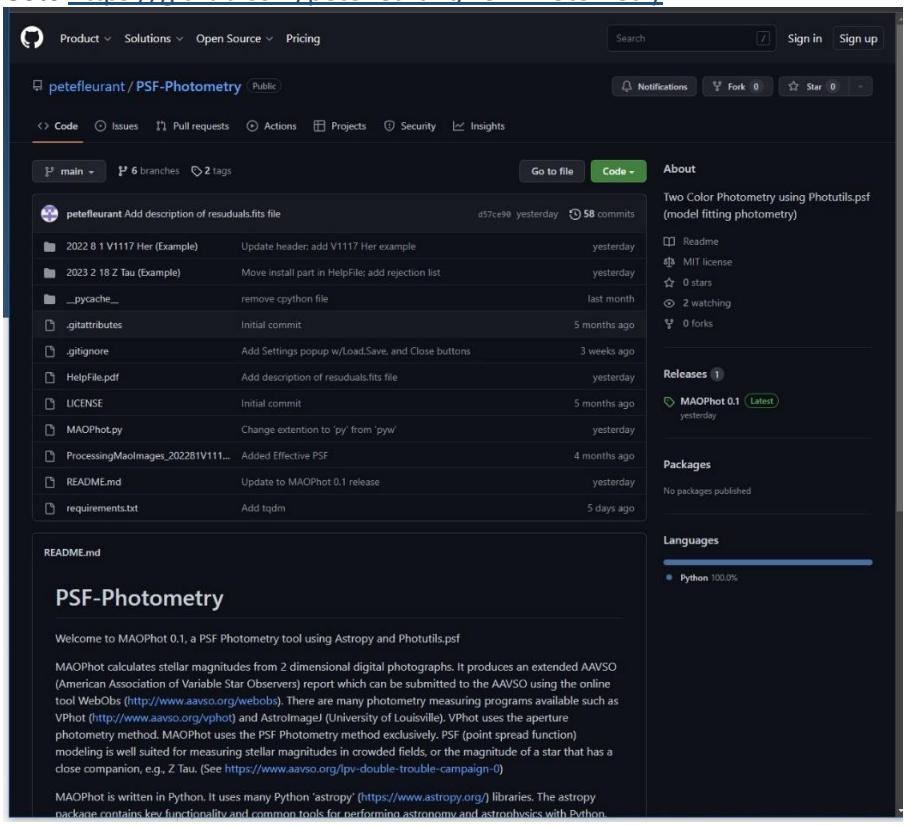
MAOPhot is written in Python. It uses many Python 'astropy' (https://www.astropy.org/) libraries. The astropy package contains key functionality and common tools for performing astronomy and astrophysics with Python. Included in the package is Photutils.psf. See "PSF Photometry" (https://photutils.readthedocs.io/en/stable/psf.html) which describes many of the classes and methods used in MAOPhot.

This program was derived from MetroPSF by Maxym Usatov.
It has been redesigned for AAVSO reporting only and includes, but not limited to the following enhancements:

- Generation of Effective PSF model, and ability to create a 'rejection list.'
- option to use an Integrated Gaussian PRF (Pixel Response Function) as model
- PSF Photometry using an iterative algorithm to perform point spread function photometry in crowded fields
- 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)
- Image display shows comp star AAVSO label number and name of any found VSX objects in image field
- Intermediate results are saved as .csv files
- User can optionally enter a AAVSO Chart ID when retrieving comparison star data
- User can specify check star and list of comp stars to use

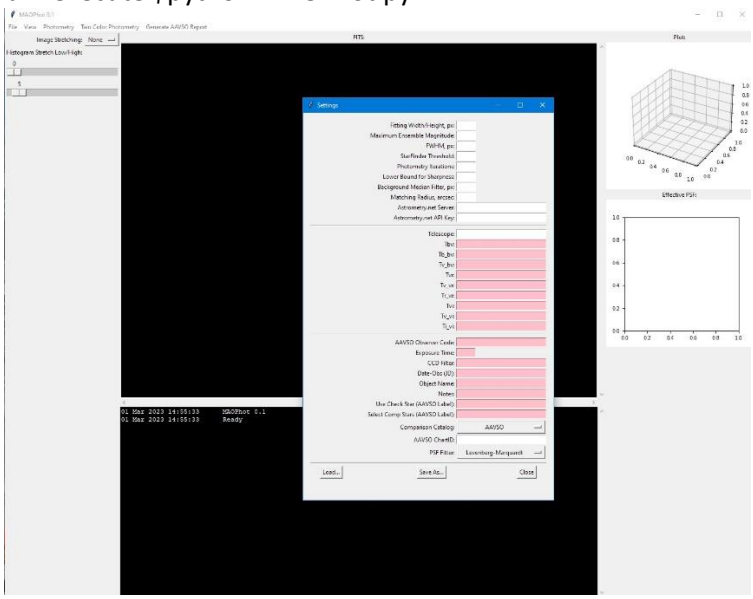
Installation

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 the PSF-Photometry, open a shell, cmd window, or console window in the said PSF-Photometry directory
4. Execute the following in the PSF-Photometry directory
    a. $pip install -r ./requirements.txt.
    b. There is a common error: ‘ERROR: Failed building wheel for pyerfa’
    c. Solution: install latest pip and install Microsoft Visual C++ 14.0 or greater
        i. If you got this error, then goto https://visualstudio.microsoft.com/visual-cpp-build-tools
        ii. Click on “Download Build Tools”, this uploads “vs_BuildTools.exe” to your download area
        iii. Execute vs_BuildTools.exe
        iv. Install the MSVC v143 – VC 2022 C++ (version 14.0 or greater)
        v. execute ‘pip install -r ./requirements.txt’

5. Test by executing MAOPhot
    a. open a shell, 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

The following packages were of the following versions for this release (0.1):

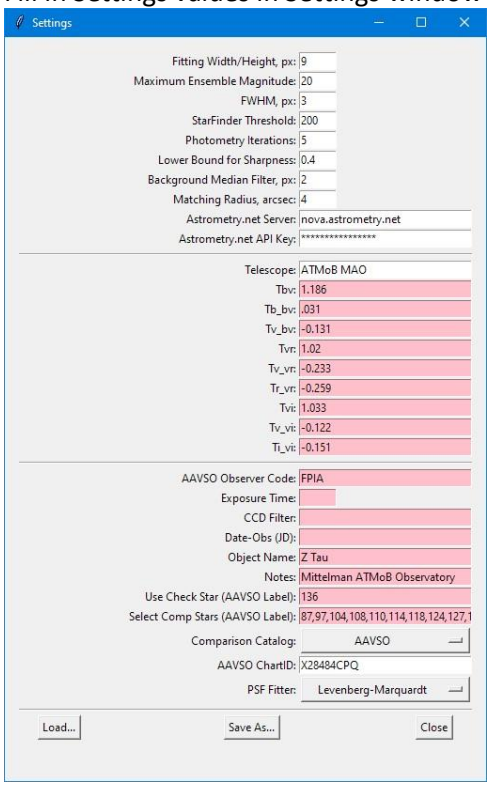
pkg	version
numpy	1.24.2
pandas	1.5.3
scipy	1.10.1
astropy	5.2.1
pillow	9.4.0
astroquery	0.4.6
matplotlib	3.7.0
photutils	1.6.0
tqdm	0.4.6

Single Image Photometry Workflow
General Workflow for Single Image Photometry and AAVSO report generation

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
2) Launch MAOPhot by running the following command in the working directory

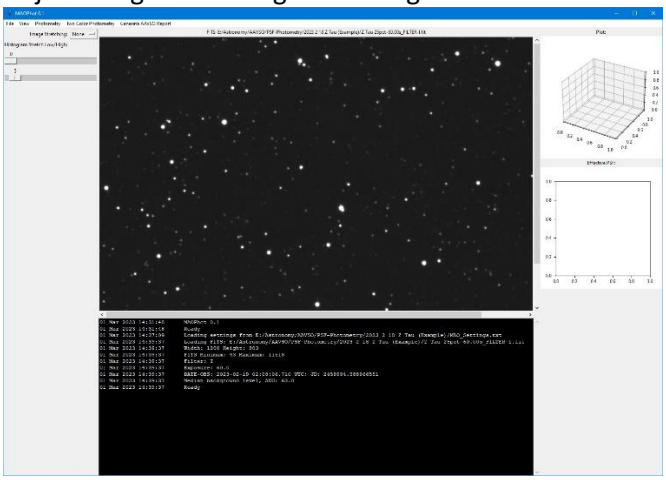
a) ‘python MAOPhot.py

3) Fill in Settings values in Settings window



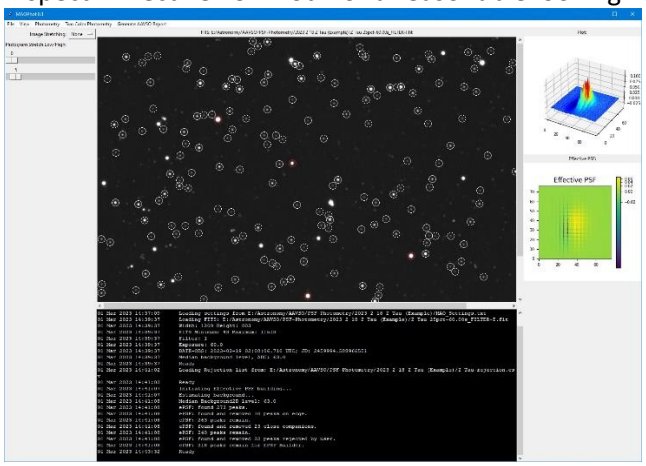
a) Use ‘Load…’ to load an existing set of settings (E.g., ‘2023 01 09 Z Tau\MAO_Settings.txt’)
b) adjust the ‘Fitting Width/Height so that it contains stellar images of target magnitude
c) adjust FWHM to the average FWHM in image
d) Close the Settings Window

4) 'File->Open...' (E.g., ‘2023 2 18 Z Tau (Example)\Z Tau 25pct-60.00s_FILTER-I.fit')
a) Adjust Image Stretching and Histogram Stretch if necessary. (This is only a screen stretch.)

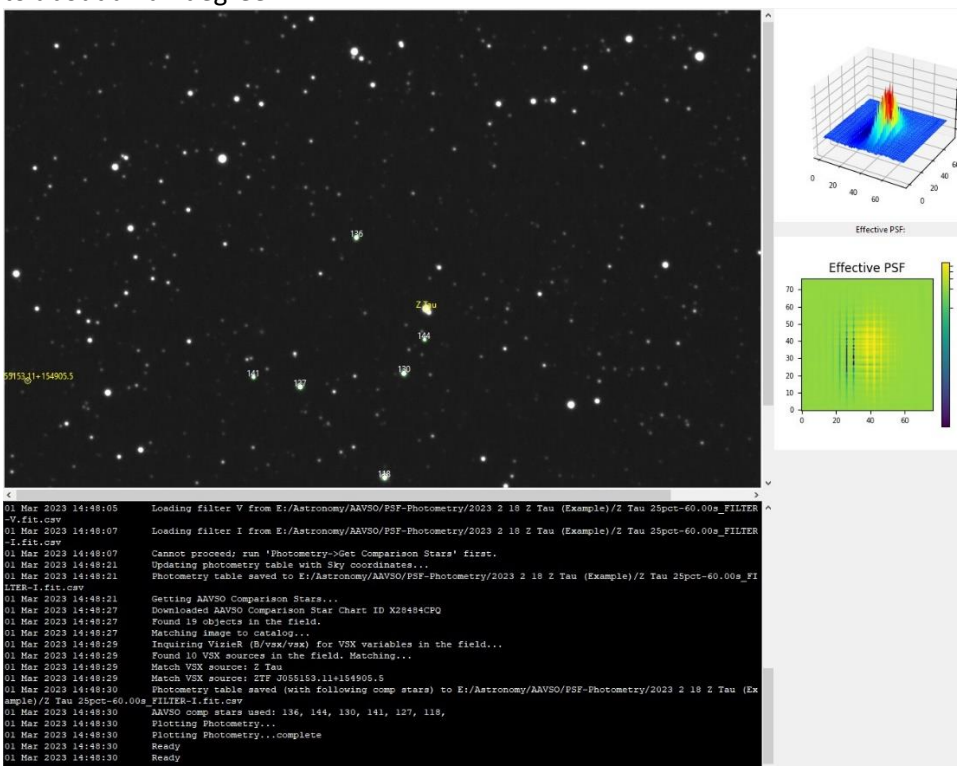


5) [Optional] 'Photometry->Create Effective PSF'
a) Watch progress in output console; (same console where you executed ‘python MAOPhot.py’)
b) [Optional] Select stars to be rejected (by mouse clicking) (This causes the circle about the star to turn red.)
i) select stars NOT well isolated from their neighbors (most are done automatically)

ii) select stars with poor SNR levels, or saturated stars
iii) then select 'Photometry->Create Effective PSF' again and repeat if necessary
iv) [optional] save rejection list
v) inspect “Effective PSF Plot” for a reasonable looking PSF



6) Photometry->Iteratively Subtracted PSF Photometry
   a) Unfortunately, the ‘progress_bar=True’ using tqdm does not work
   b) Inspect <image_file_name>-residules.fits to see if ‘subtraction’ is sufficient; if not adjust settings and repeat (https://photutils.readthedocs.io/en/stable/psf.html#performing-psf-photometry)
7) [optional] Photometry->Solve Image (see below for Astronometry.net server settings)
   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 keep WCS data in FITs file
8) Photometry->Get Comparison Stars [WCS Header data required]
   a) If this times out it may be due to a large number of VSX objects in the field; try cropping the FOV to about a half degree



9) 'Generate AAVSO Report->Single Image Photometry'
   a) Select the <fits filename>.csv file that was generated by step 8 (E.g., '2023 2 18 Z Tau (Example)\Z Tau 25pct-60.00s_FILTER-I.fit.csv')
   b) this generates the AAVSO report in a subdirectory aavso_reports/

Example AAVSO report:

```
#TYPE=Extended
#OBSCODE=FPIA
#SOFTWARE=Self-developed using photutils.psf; DAOPHOT
#DELIM=,
#DATE=JD
#OBSTYPE=CCD
#NAME,DATE,MAG,MERR,FILT,TRANS,MTYPE,CNAME,CMAG,KNAME,KMAG,AMASS,GROUP,CHART,NOTES
Z Tau,2459994.57866,16.688,0.091,V,NO,STD,144,-7.097,136,-7.869,na,na,X28484CPQ,Mittelman ATMoB Observatory|CMAGINS=-
7.097|CREFERR=0.012|CREFMAG=14.434|KMAG=13.662|KMAGINS=-7.869|KREFERR=0.006|KREFMAG=13.585|VMAGINS=-4.843
```

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 I filters.

Execute steps 1 through 8 above for the V master and then the I master images.

Then continue with step 8:

8) 'Generate AAVSO Report->Two Color Photometry->(V-I)'
   a) Select the 2 csv files that were generated in step 7 (1 for V and 1 for I; e.g., Z Tau 25pct-60.00s_FILTER-V.fit.csv' and 'Z Tau 25pct-60.00s_FILTER-I.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-I)'again

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

```
---------------------------------------------------------------------------------------------------------------------------------------------------------
28 Oct 2022 15:52:45    Check Star Estimates using check star: 144 (B: 14.933) (V: 14.404)
   star label     IMB       IMV       B      V  delta_b_minus_v  delta_B_minus_V   delta_b   delta_v  comp_b_minus_v    B_star    V_star    outlier
0  check  113 -9.625943 -10.379204  12.144  11.277       -0.267405       -0.317142  2.794538  3.061943        0.753261  14.928707  14.380488
1  check  132 -7.841239  -8.512675  13.963  13.178       -0.185579       -0.220097  1.009835  1.195414        0.671436  14.966012  14.402247
2  check  138 -7.219232  -7.874955  14.560  13.811       -0.169865       -0.201460  0.387828  0.557693        0.655722  14.941583  14.395085
3  check  139 -7.089318  -7.820401  14.709  13.873       -0.245227       -0.290839  0.257913  0.503140        0.731083  14.957897  14.414240
4  check  141 -6.871317  -7.597812  14.902  14.092       -0.240638       -0.285397  0.039912  0.280550        0.726495  14.933065  14.409937
5  check  142 -6.881629  -7.476356  14.892  14.227       -0.108870       -0.129119  0.050224  0.159094        0.594727  14.938222  14.403009
6  check  150 -5.915583  -6.694471  15.853  15.024       -0.293032       -0.347536 -0.915822 -0.622790        0.778889  14.926404  14.446737  <--OUTLIER
                                                                    B* Ave: 14.942  V* Ave: 14.407
                                                                    B* Std:  0.015  V* Std:  0.021
28 Oct 2022 15:52:45                                                        Check Star IQR limit for B*: 14.903;14.978
```

28 Oct 2022 15:52:45 Check Star IQR limit for V*: 14.379;14.432
28 Oct 2022 15:52:45

28 Oct 2022 15:52:45 Variable Star Estimates of Var: W Her

	star	label	IMB	IMV	B	V	delta_b_minus_v	delta_B_minus_V	delta_b	delta_v	comp_b_minus_v	B_star	V_star
0	var	113	-9.625943	-10.379204	12.144	11.277	0.470010	0.557432	2.470806	2.000796	0.753261	14.632086	13.204772
1	var	132	-7.841239	-8.512675	13.963	13.178	0.551835	0.654477	0.686102	0.134267	0.671436	14.669391	13.226530
2	var	138	-7.219232	-7.874955	14.560	13.811	0.567549	0.673113	0.064095	-0.503454	0.655722	14.644962	13.219368
3	var	139	-7.089318	-7.820401	14.709	13.873	0.492188	0.583735	-0.065819	-0.558007	0.731083	14.661276	13.238523
4	var	141	-6.871317	-7.597812	14.902	14.092	0.496776	0.589177	-0.283820	-0.780597	0.726495	14.636444	13.234221
5	var	142	-6.881629	-7.476356	14.892	14.227	0.628545	0.745454	-0.273508	-0.902053	0.594727	14.641601	13.227293
6	var	150	-5.915583	-6.694471	15.853	15.024	0.444383	0.527038	-1.239554	-1.683937	0.778889	14.629784	13.271021

B* Ave: 14.645 V* Ave: 13.232
B* Std: 0.015 V* Std: 0.021

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-I)'

Note, in the example above, that comp star 150 is an outlier in V

9) '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 using photoutils.psf; DAOPHOT
#DELIM=,
#DATE=JD
#OBSTYPE=CCD
#NAME,DATE,MAG,MERR,FILT,TRANS,MTYPE,CNAME,CMAG,KNAME,KMAG,AMASS,GROUP,CHART,NOTES
Z Tau,2459994.57866,15.823,0.019,V,YES,STD,ENSEMBLE,na,136,13.617,na,na,X28484CPQ,MZK Hyperion|KMAG=13.617|KMAGINS=-7.843|KREFMAG=13.585|T_vi=1.033|VMAGINS=-5.071
Z Tau,2459994.58897,10.319,0.078,I,YES,STD,ENSEMBLE,na,136,12.739,na,na,X28484CPQ,MZK Hyperion|KMAG=12.739|KMAGINS=-7.081|KREFMAG=12.731|Ti_vi=-0.151|VMAGINS=-8.8
```

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

Photometry->Create Effective PSF

> Analyzes image and generates an ePSF model following the prescription of Anderson and King (2000; PASP 112, 1360)
> (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…

> 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->Iteratively Subtracted PSF Photometry

Executes iterative algorithm to perform PSF photometry on the image.

Photometry->Solve Image

Use Astronometry.net server to add WCS Header information.

Photometry->Get Comparison Stars

Queries AAVSO for comparison stars in the field.
Queries VizieR (B/vsx/vsx) for VSX variables 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
This is very similar to how VPhot executes
Two Color Transform.

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	
StarFinder 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	arc secs	
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	
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
Date-Obs	Entered into report; usually found in FITs header	JD	yes
ObjectName	variable star name to be measured	string	yes
Notes	Entered into report under notes	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
Comparison Catalog	Only AAVSO catalog supported at this time	list selection	
AAVSO ChartID	specific chartID to be used; (e.g., X28484CPQ) (optional)	string	
PSF Fitter	Type of fitter used in Interatively SubtractedPSFPhotometry	list selection	

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

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