The AstroImageJ Guide for LCO - TESS Observations

Processed through the OSS Pipeline

Boyce Research Initiatives and Education Foundation (BRIEF)

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The following are step-by-step instructions for using AstroImageJ (AIJ) to perform the reduction and analysis of a Las Cumbres Observatory (LCO) exoplanet observation processed through the OSS Pipeline. Many thanks to Grady Boyce of the Boyce Research Initiatives and Education Foundation (B.R.I.E.F – www.boyce-astro.org) for creating the predecessor to this Guide which is called the AIJ Cookbook and is available at www.astrodennis.com. Comments on and suggestions for improvements to the instructions below can be forwarded to info@boyce-astro.org. A link to the latest version of these instructions can be found at the Boyce-Astro website. http://boyce-astro.org/brief-exoplorer-program/exoplanet-observation-guides/.

These instructions supplement Section 7.0 of "A Practical Guide to Exoplanet Observing," a link to the latest version of which can be found at www.astrodennis.com and which will be referred to in the instructions below as "the Practical Guide." Note that the instructions below are not a substitute for the Practical Guide, but rather are a supplement to it. Reference will also be made below to "the Worksheet" – this is the worksheet depicted in Appendix A of the Practical Guide and which, when filled out per the instructions in the Practical Guide, will be useful in conducting the phases described below.

In addition to the Practical Guide, reference will sometimes be made to AstroImageJ's own guide, which can be found at www.astro.louisville.edu/software/astroimagej/ and which will be referred to here as "the AIJ Guide."

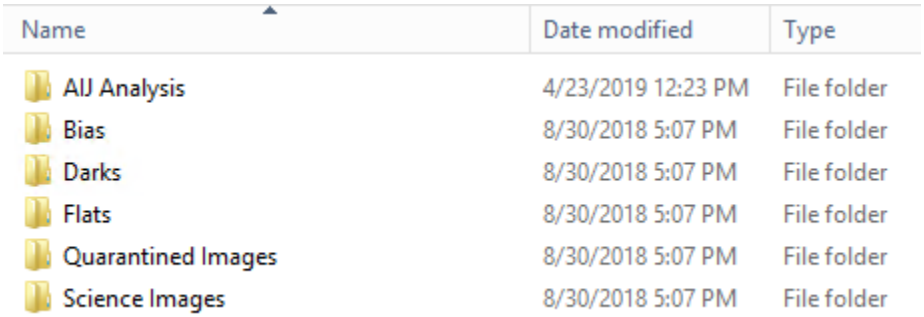
Some text in this guide will differentiated with red, underlined text[x] and a number in superscript. This indicates a file required for upload to ExoFOP-TESS or ExoFOP-K2. The number in superscript indicates which file this correlates to in the TFOP_SG1_Guidelines. Notes specific to Boyce-Astro Exoplorers are in red boxes located at the appropriate point in the procedures.

IMPORTANT: AIJ will remember settings from previous runs. It is important to follow this Guide by the letter as this will reset all settings to what you will need for each new run, thus avoiding confusion with settings from previous AIJ sessions.

Preparation Phase

1. Determine where on your computer you will store your captured images (referred to as "Science Images") and the files resulting from your AIJ analysis.

2. Create a directory tree containing the following directories in Figure 1:



Name	Date modified	Type
AIJ Analysis	4/23/2019 12:23 PM	File folder
Bias	8/30/2018 5:07 PM	File folder
Darks	8/30/2018 5:07 PM	File folder
Flats	8/30/2018 5:07 PM	File folder
Quarantined Images	8/30/2018 5:07 PM	File folder
Science Images	8/30/2018 5:07 PM	File folder

Figure 1 Recommended folders for any AIJ exoplanet analysis

Exoplorer Note: this set of folders are pre-made, are in the Latest Instructions Folder, and called New Analysis Template Folder – blank. Copy that folder into your Run Folder.

a. AIJ Analysis
   i. This is where AIJ process files will be kept
b. Bias
c. Darks
d. Flats
e. Quarantined Images
   i. These will contain images that are problematic
f. Science Images
   i. This is where your "light" images will go – that is, the original images of the target.
   ii. Calibrated images will later be kept in a subdirectory (e.g., pipeline out_) under this directory.

ExoFOP-TESS:

- It is recommended that you print and save a copy of the TESS Transit Finder (TTF, Figure 2) for reference during your AIJ analysis. You may need to separately save a copy of the Notes from the TTF to have a complete copy available for reference later.
- The information needed for the Exoplanet Worksheet (Figure 3) can be located at the ExoFOP website, observatory and camera websites, FITS header, and the Ohio State online calculator link on the worksheet. The ExoFOP data is provided when you click on the link provided under the "NAME" column in the "Info" section of the TTF page.
- Double check the RA/Dec between the FITS header and the TTF Website to ensure accuracy

Upcoming events for the next 4 days from 11-04-2018; start/end given in timezone UTC.

Night starts/ends at nautical twilight.

Results shown for LCO Cerro Tololo Interamerican, 0.4m latitude = -30.1674, longitude = -70.8048.

Colored text indicates a part of the transit that is during daylight, or a transit at elevation less than the user-specified limits, or that the Moon is relatively full and close to the target.

Click on column headers to sort the table by that column. Click again to reverse the sorting order. To sub-sort, first click one column (e.g. the left-hand one to sort by night), then *shift-click* another column to sort further within the first category. For example, to sort by priority within a given night (when multiple nights are displayed), first click the "Local evening date" header, then shift-click the "Priority" header. The highlighted column shows the current sorting.

The buttons can be used to toggle the visibility of columns, and the column order can be rearranged by clicking and dragging the column header.

Column visibility | Reset column order | Show all columns | Disable tooltips

Search: | Show if visible transit % + baseline % > 0 | V_{max}: | LCO Cerro Tololo Interamerican, 0.4m

Local evening date	Name	V mag	T mag	Start—Mid—End	Duration	BJD_{TDB} start-mid-end	Elev. at start, mid, end	% of transit (baseline) observable, Suggested obs. start, end	Az. at start, mid, end	HA at start, mid, end	RA & Dec (J2000)	Period (days)	Depth (ppt)	Priority	R_{planet} ($R_{\oplus}$)	Comments
Sun. 2018-11-04: Nautical twilight 2018-11-04 21:04 — 2018-11-05 05:49 local time / 2018-11-05 00:04 — 2018-11-05 08:49 UTC																
Sun. 2018-11-04 (local date) Nautical twilight 00:04–08:49 (UTC)	TIC 147203645.01 (TOI 166.01) Add to TOC Finding charts: Annotated, SkyMap; Info: ExoFOP, Simbad, Gaia, TIC, VSX, AIJ apertures, Vizier phot.; Airmass, ACP plan	11.328 Moon 8% @119°	10.696	01:51 02:18—02:55—03:33 04:00 ±0:27	1:14	8427.596 8427.622 8427.648	57° 52°, 46°, 39° 34°	100% (100%) 01:18—04:33	235° 236°, 236°, 236° 235°	+2.5 +3.0, +3.6, +4.2 +4.7	21:32:47.06 -44:01:04.1	5.06	6.9	3	12.8	target (r=5"). Chris Stockdale observed a nearly full transit (although with some clouded periods) on 20180925 in Ic

Showing 1 to 1 of 1 entries

Figure *2* TESS Transit Finder (TTF) results page for one transit

Exoplorer Note: The TTF copy will be provided in your Run Folder. Review the dip PPT and the notes to estimate whether the run will most likely be a Case 1, 2, or 3 in the Observation Guidelines. The calibrations have been completed for OSS Pipeline processed images so you will leave the Bias, Darks, and Flats folders in Figure 1 empty.

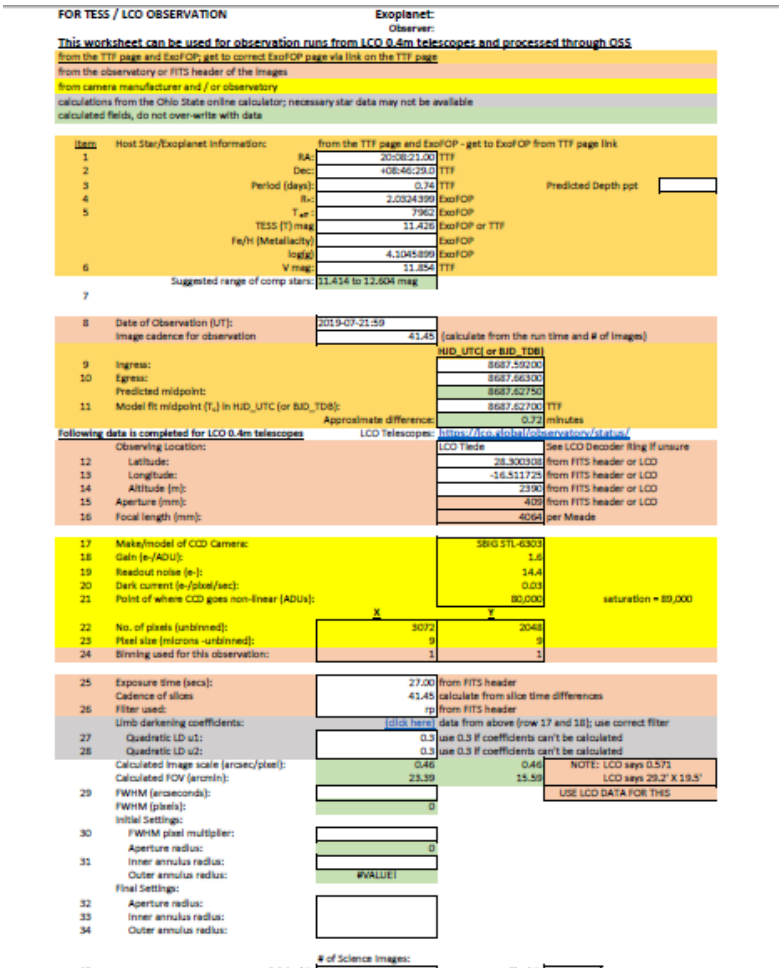
3. Ensure your bias, darks, flats, and science images from your imaging camera are loaded in the respective directories above. Note that, depending on the telescope providing your images the bias, dark and flat image calibration may have already been performed. In such cases these calibration images are not needed. **<u>This Guide assumes you have set up folders such as in this Figure 2 regardless of whether the Bias, Darks, and Flats are to be used.</u>**

4. Prepare the Exoplanet Worksheet (Figure 3).
   a. A general template can be located at: astrodennis.com
   b. The Worksheet contains data that will be used throughout your exoplanet project
   c. Fill in items 1-28 of the Worksheet. The other entries in the Worksheet can be filled in as you progress through the various phases.

- **Exoplorer Note**: A partially completed Worksheet for LCO-OSS processed images is contained in the Latest Instructions folder. The Worksheet is color coded for the sources of data. Copy this template into your Run folder and complete lines 1 through 28 before starting. The rest can be completed as you go. Cadence of your image run. (Calculate by dividing the total run duration by the number of images in the run. LCO 0.4m scopes with the SBIG CCD have a 14 second overhead. Use this and your exposure time to confirm your cadence calculation). Host Star Spectral Type, or the Effective Temperature (Teff), log (g), [Fe/H]. These may be obtained from GAIA or ExoFOP (see example in Figure 4). There is a link to it under the NAME column.

Data you will need to know for your run and the Worksheet include:

- RA/Dec, Date of observation
- Predicted Ingress/Egress (expressed as a fraction of the BJD-TDB day). You don't need first three characters
- Where observing from, except altitude
- Make/Model of camera
- CCD Parameters: Gain (e-/count), Readout Noise (e-), Dark Current per Sec (e-/pix/sec), Saturation point, Linearity point.
- Cadence of your image run
- Limb Darkening Coefficients: use data from ExoFOP for the star to enter into the web calculator at http://astroutils.astronomy.ohio-state.edu/exofast/limbdark.shtml
- Pixel Size
- Plate Scale/Image Scale
- Binning
- Exposure Time
- Filters
- FOV arcmins
- FWHM from AIJ Aperture Window (comes later)
- Host Star Radius (This may be obtained from GAIA as well as ExoFOP)
- Host Star Spectral Type, or the Effective Temperature (Teff), log(g), and [Fe/H]



FOR TESS / LCO OBSERVATION — Exoplanet: — Observer:

This worksheet can be used for observation runs from LCO 0.4m telescopes and processed through OSS

from the TTF page and ExoFOP; get to correct ExoFOP page via link on the TTF page
from the observatory or FITS header of the images
from camera manufacturer and / or observatory
calculations from the Ohio State online calculator; necessary star data may not be available
calculated fields, do not over-write with data

Item	Host Star/Exoplanet Information:	from the TTF page and ExoFOP - get to ExoFOP from TTF page link		
1	RA:	20:08:21.00	TTF	
2	Dec:	+08:46:29.0	TTF	
3	Period (days):	0.74	TTF	Predicted Depth ppt
4	R_*:	2.0324399	ExoFOP	
5	T_{eff}:	7962	ExoFOP	
	TESS (T) mag	11.426	ExoFOP or TTF	
	Fe/H (Metallacity)		ExoFOP	
	log(g)	4.1045899	ExoFOP	
6	V mag:	11.854	TTF	
	Suggested range of comp stars:	11.414 to 12.604 mag		
7				
8	Date of Observation (UT):	2019-07-21:59		
	Image cadence for observation	41.45	(calculate from the run time and # of Images)	
			HJD_UTC(or BJD_TDB)	
9	Ingress:		8687.59200	
10	Egress:		8687.66300	
	Predicted midpoint:		8687.62750	
11	Model fit midpoint (T_o) in HJD_UTC (or BJD_TDB):		8687.62700	TTF
	Approximate difference:		0.72	minutes
	Following data is completed for LCO 0.4m telescopes	LCO Telescopes:	https://lco.global/observatory/status/	
	Observing Location:		LCO Tiede	See LCO Decoder thing if unsure
12	Latitude:		28.300308	from FITS header or LCO
13	Longitude:		-16.511725	from FITS header or LCO
14	Altitude (m):		2390	from FITS header or LCO
15	Aperture (mm):		400	from FITS header or LCO
16	Focal length (mm):		4064	per Meade
17	Make/model of CCD Camera:		SBIG STL-6303	
18	Gain (e-/ADU):		1.6	
19	Readout noise (e-):		14.4	
20	Dark current (e-/pixel/sec):		0.03	
21	Point of where CCD goes non-linear (ADUs):		80,000	saturation = 89,000
		X	Y	
22	No. of pixels (unbinned):	3072	2048	
23	Pixel size (microns -unbinned):	9	9	
24	Binning used for this observation:	1	1	
25	Exposure time (secs):	27.00	from FITS header	
	Cadence of slices	41.45	calculate from slice time differences	
26	Filter used:	rp	from FITS header	
	Limb darkening coefficients:	[click here]	data from above (row 17 and 18); use correct filter	
27	Quadratic LD u1:	0.3	use 0.3 if coefficients can't be calculated	
28	Quadratic LD u2:	0.3	use 0.3 if coefficients can't be calculated	
	Calculated image scale (arcsec/pixel):	0.46	0.46	NOTE: LCO says 0.571
	Calculated FOV (arcmin):	23.39	15.59	LCO says 29.2' X 19.5'
29	FWHM (arcseconds):			USE LCO DATA FOR THIS
	FWHM (pixels):	0		
	Initial Settings:			
30	FWHM pixel multiplier:			
	Aperture radius:	0		
31	Inner annulus radius:			
	Outer annulus radius:	#VALUE!		
	Final Settings:			
32	Aperture radius:			
33	Inner annulus radius:			
34	Outer annulus radius:			
	# of Science Images:			

Figure 3 Exoplanet Worksheet

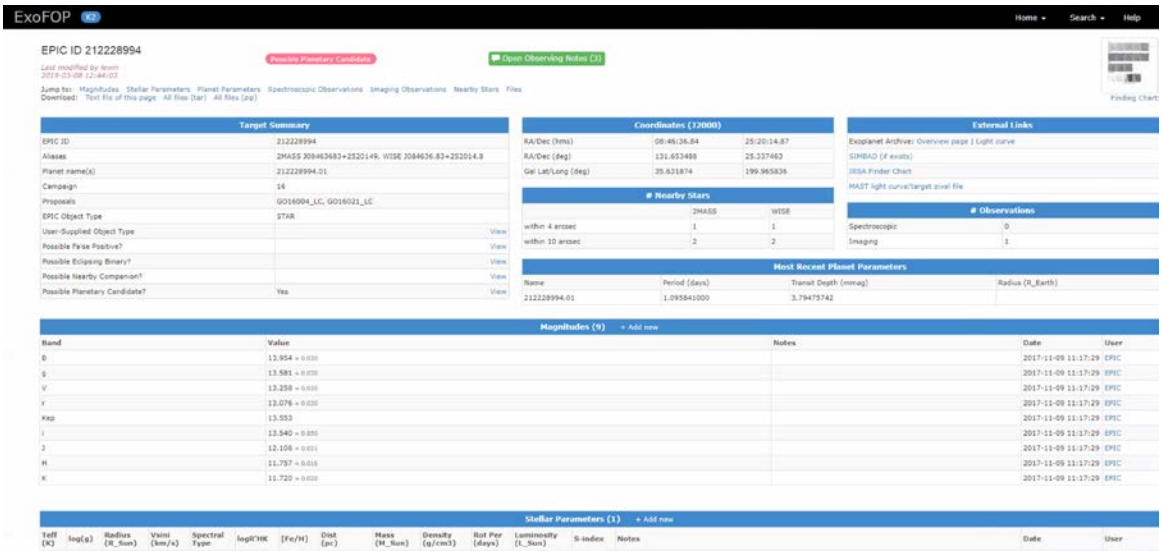


Figure 4. Example ExoFOP page for a TIC

5. Open AIJ
   a. Update AIJ to the Daily Build. Go to “Help” and “Update AstroImageJ”. In the box “Upgrade to:” slide the scroll bar to the top, click on “daily build” and click on OK.

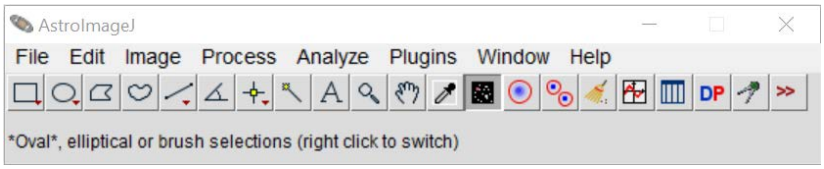


Figure 5 AIJ Main Toolbar

   b. Open all of the Science Images. Select from the main AIJ toolbar: File->Import->Image Sequence.
      - If running on a Windows machine, select the first file in the Science Images directory, hit Open, and AIJ will load all images in that directory.
      - If running on a Mac, select the subdirectory name.
   c. Hit OK.
   d. NOTE: If you receive an “Out Of Memory” message, you will also be given instructions for how to resolve this issue within the same message. You will need to check the box labeled “ Use virtual stack”. Follow those instructions before proceeding. You may have to restart AIJ for the new settings to take effect. If this happens, restart this section from the beginning before proceeding on.

6. Use the slider bar at the bottom of the Image Display to quickly review the quality of the images for any that are “bad” and should be excluded. “Bad” includes ones that are unreadable, have motion or focus problems, have satellite or meteor trails, etc. Move the bad images to the Quarantined directory.

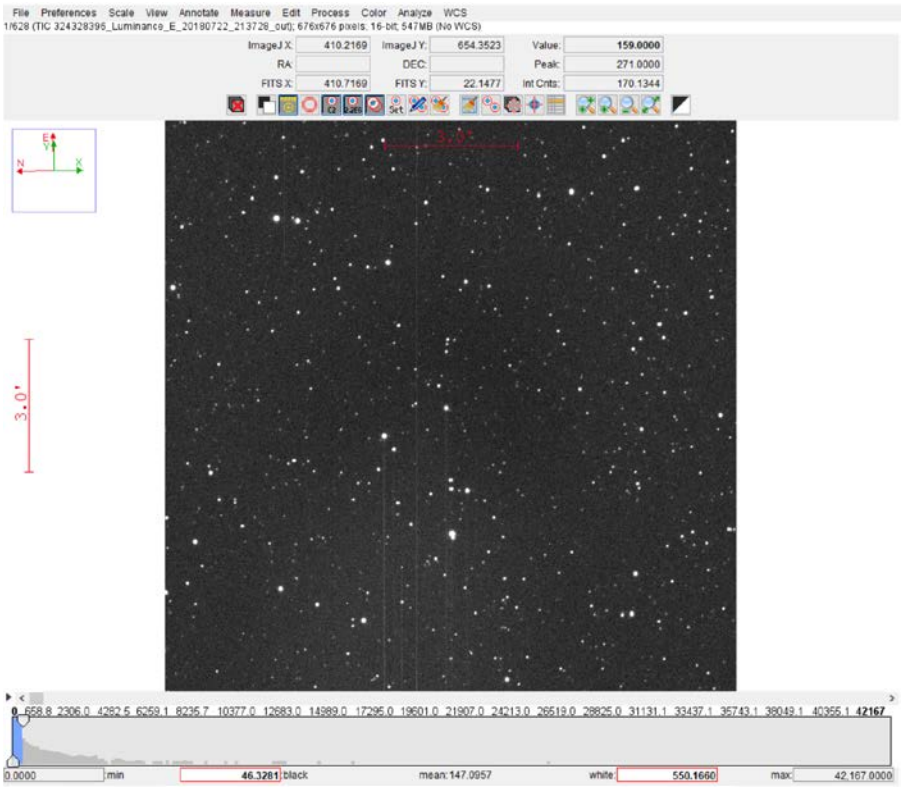


Figure 6 AIJ Image Display

7. If the Science Images are not closely aligned image-to-image, see the appropriate sections in the Practical Guide, Section 7.5.3 (astrodennis.com) for how to deal with misaligned images, as well as dealing with a meridian flip.

Exoplorer Note: LCO 0.4m scopes are not guided so misalignment occurs. The OSS Pipeline images are all plate solved and the misalignment can be overcome in the Differential Photometry phase procedure.

8. Open one of the science images by selecting File->Open from the AIJ Main Toolbar and navigating to your Science Images directory, or use one of the images already open when the Image Sequence was opened:
    a. Select an image
    b. Hit OK
    c. In the window containing the single image, open the FITS header to attempt to locate a few essential items. Select Edit->Edit FITS Header. You will not actually be editing the header, but you just want to verify the information contained.
    d. Locate and note the keywords for your site's latitude and longitude (e.g., something like SITELAT and SITELONG).
        1) Verify if those are the exact coordinates of where your Observatory is located images were obtained.
        2) If South latitude or West longitude contains a + symbol, when it really should include a - symbol, make a note of this. We will address this shortly.

e. Locate and note the keywords for the image's RA and DEC (e.g., something like RA_OBJ and DEC_OBJ, or OBJCTRA and OBJCTDEC).
   1) Verify these coordinates against the spreadsheet.
f. Locate and note the keywords for Airmass, if included, and the date/time of the observation. IMPORTANT: For non LCO images, you may need to convert the date/time to UT if the CCD FITS Header does not already provide this information.
g. Hit CANCEL.

9. The Preparation Phase is now complete. [Good place for a BREAK.]

B. The Calibration Phase

1. Open AIJ, if not already open, to see the AIJ Main Toolbar.

2. Press the DP button on the AIJ Main Toolbar, Figure 5, to start "Data Processing." Two windows will appear: the CCD Data Processor, Figure 7, window and the DP Coordinate Converter window, Figure 11. Unless otherwise noted, the following steps apply to the CCD Data Processor window or the windows opened from it.

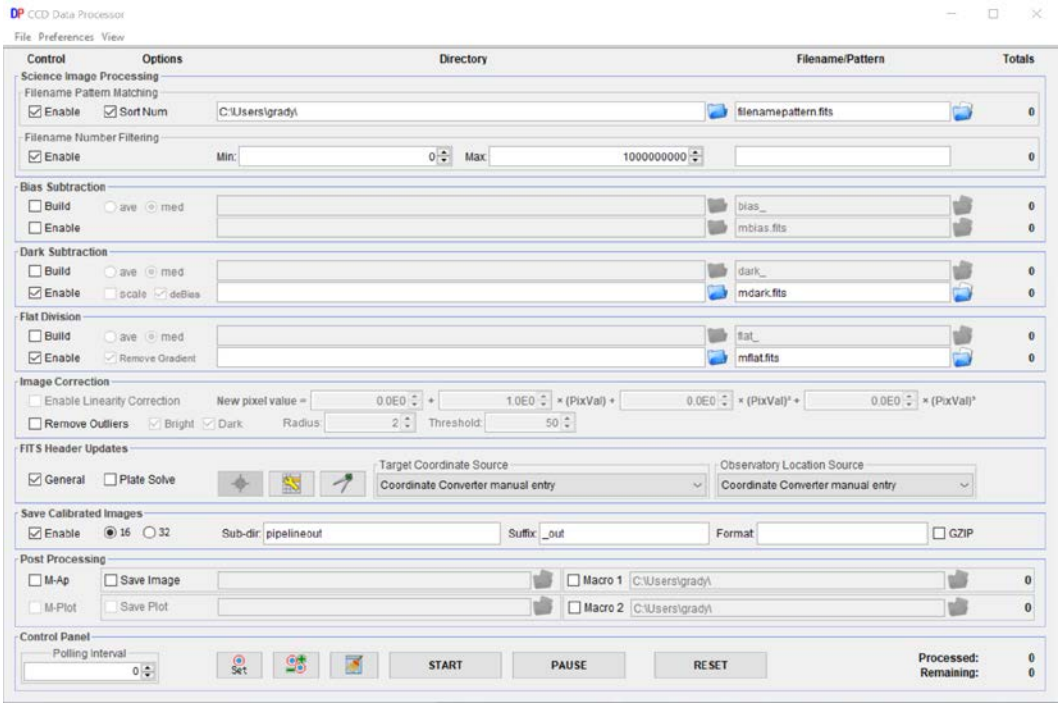


Figure 7. CCD Data Processor Window

Exoplorer Note: The OSS Pipeline has performed the calibrations and plate solving described in this Phase. The FITS Headers will need to be modified to conform to AIJ's needs. The old steps 3 through 7 and 9, 10, and 11, are replaced with instructions below.

2. a. Make your CCD Data Processor window follow the highlights here and these specific notes:

A – Point to your Science Image folder

B – Look at an image file and be sure to that the extension matches – OSS should be *.fit

C – You will not have your A and B entries correct until the correct number of images is displays here.

D– Click on the wrench and see step 2.b. You will need to correct the labels that AIJ looks for in the FITS header for the LCO / OSS processed images

E – You will return to this window to click START <u>only AFTER</u> you have completed the settings on the following pages (through Step 3).

[**Note:** For LCO images, check the 32 bit, not 16 bit, box in the "Save Calibrated Images" section.]

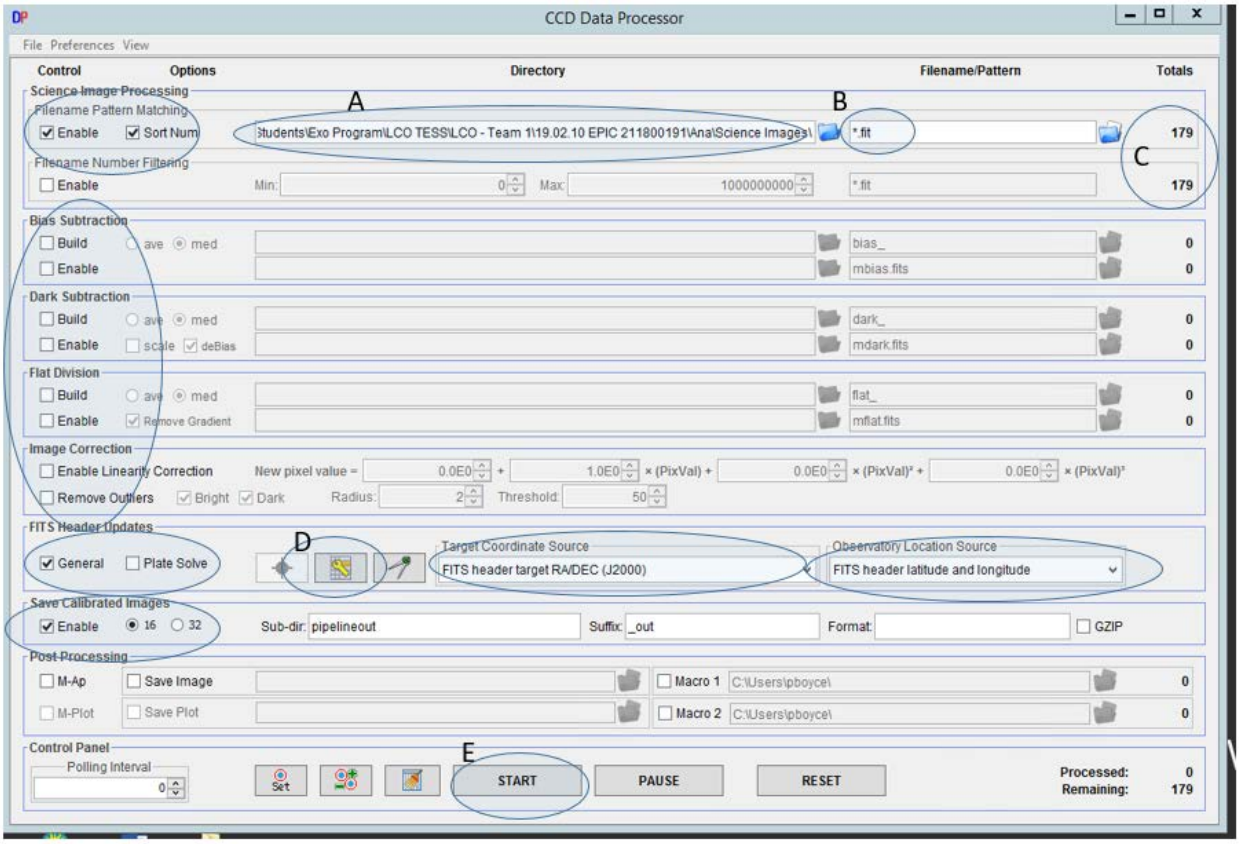


Figure 7A. CCD Data Processor Window for OSS processed images

2. b. When you click on the wrench icon, the General FITS Header Settings window (Figure 8) will appear. For LCO / OSS files, you should change the default General FITS Header Settings that first appear to these. If you are unsure of any of these settings, see 2.c. for how to read your FITS Header.

Change the FITS Header Input Settings to match these that should match the labels in your FITS Header files from OSS.

Be sure to check the Degrees box.

If your observatory is west of the prime meridian and east of the international dateline, then its longitude should be negative. If your FITS header displays West longitude as a positive number, then you should check the "negate" box to indicate to AIJ that the number found in the FITS header should really have a negative sign associated with it. This should be the case for LCO / OSS images, but you should check this to confirm.

If your FITS header has AIRMASS data, you should uncheck this box so that AIJ does not overwrite that data. LCO / OSS images should have AIRMASS data.

.

Be sure time keyword is BJD_TDB so AIJ creates the correct FITS header data.

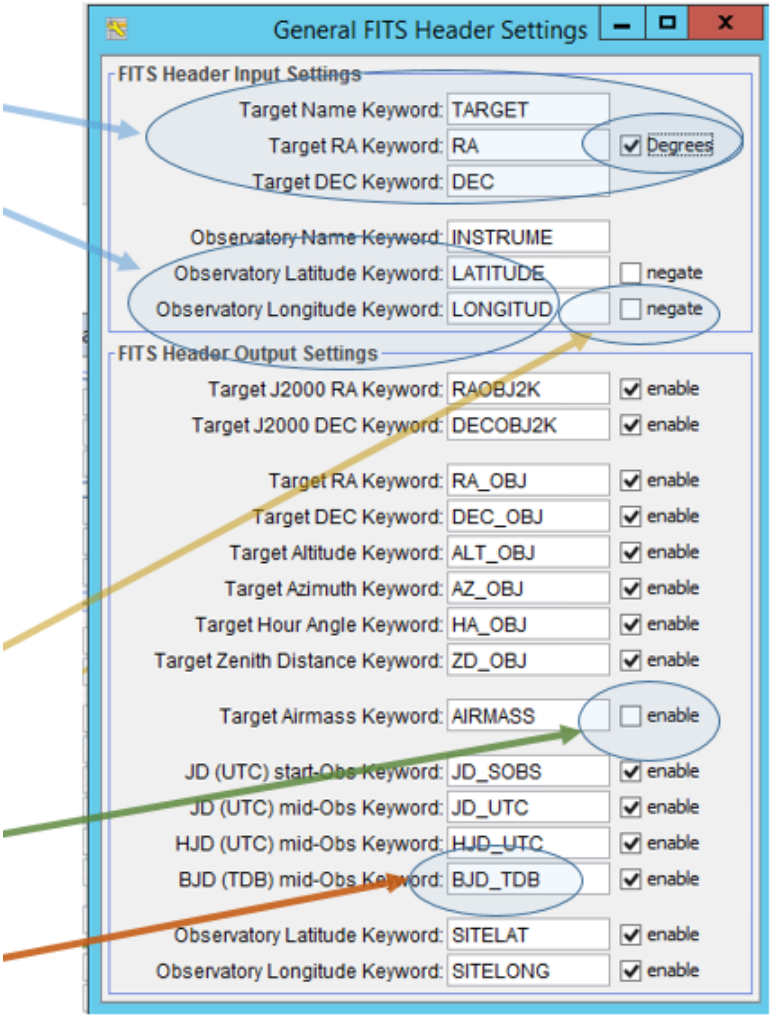


Figure 8 General FITS Header Settings

2. c. To see your FITS header, open a science image, click on Edit, and select Edit FITS header

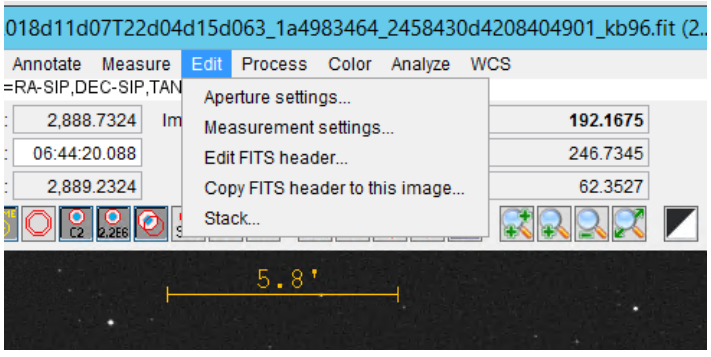
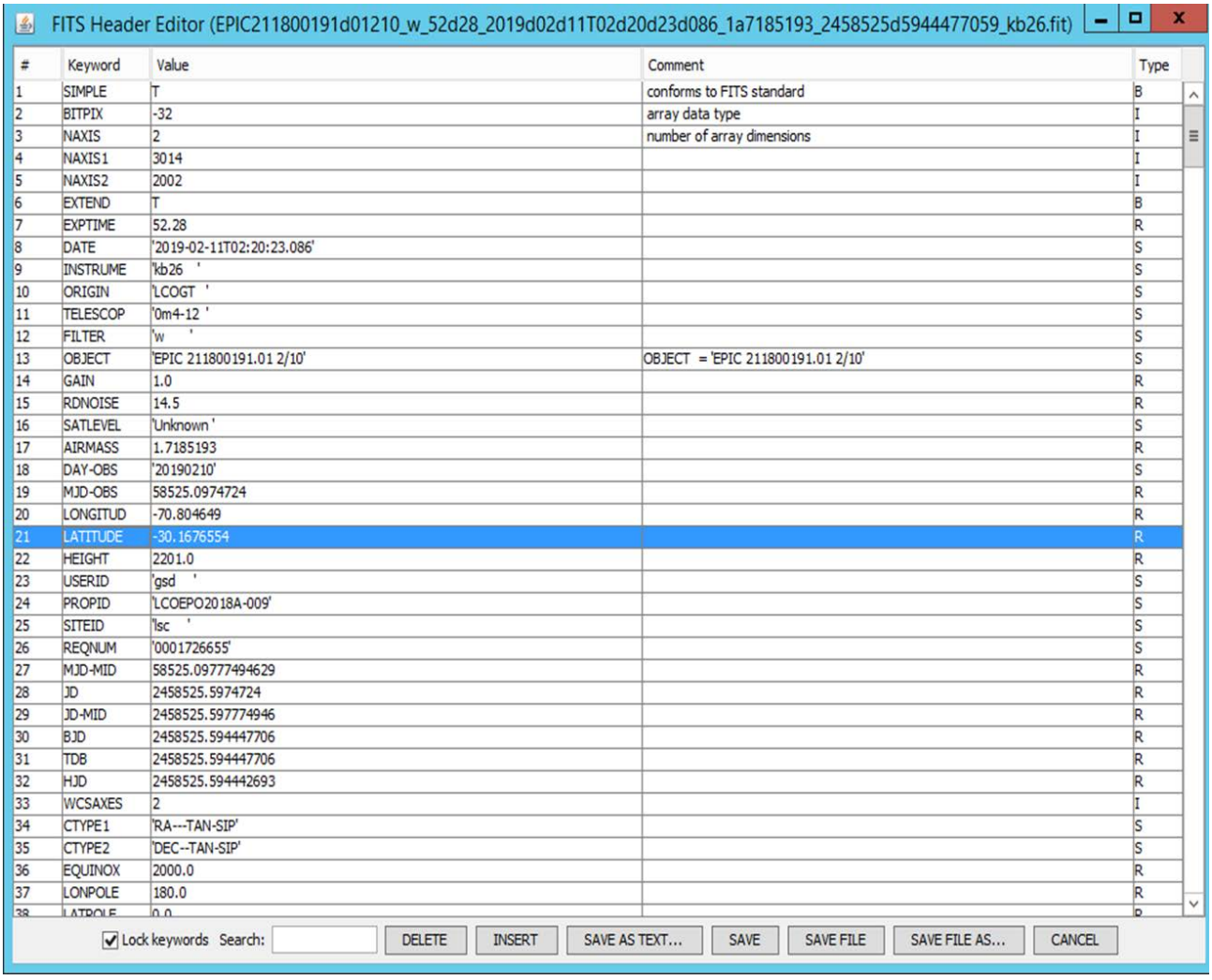


Figure 9 Top of Image Display Window

Figure 10: Note the LONGITUD field is correctly negative for a west of the prime meridian location. The location for LCO images is defined by the INSTRUME field that in this case is kb26 – the camera located at Cerro Tololo in Chile. To find other fields such as RA and Dec, you may need to scroll down the page a good degree. After you have done the calibration, it is good practice to do a sanity check of the added keywords. They will be at the bottom of the FITS Header.



#	Keyword	Value	Comment	Type
1	SIMPLE	T	conforms to FITS standard	B
2	BITPIX	-32	array data type	I
3	NAXIS	2	number of array dimensions	I
4	NAXIS1	3014		I
5	NAXIS2	2002		I
6	EXTEND	T		B
7	EXPTIME	52.28		R
8	DATE	'2019-02-11T02:20:23.086'		S
9	INSTRUME	'kb26 '		S
10	ORIGIN	'LCOGT '		S
11	TELESCOP	'0m4-12 '		S
12	FILTER	'w '		S
13	OBJECT	'EPIC 211800191.01 2/10'	OBJECT = 'EPIC 211800191.01 2/10'	S
14	GAIN	1.0		R
15	RDNOISE	14.5		R
16	SATLEVEL	'Unknown '		S
17	AIRMASS	1.7185193		R
18	DAY-OBS	'20190210'		S
19	MJD-OBS	58525.0974724		R
20	LONGITUD	-70.804649		R
21	LATITUDE	-30.1676554		R
22	HEIGHT	2201.0		R
23	USERID	'gsd '		S
24	PROPID	'LCOEPO2018A-009'		S
25	SITEID	'lsc '		S
26	REQNUM	'0001726655'		S
27	MJD-MID	58525.09777494629		R
28	JD	2458525.5974724		R
29	JD-MID	2458525.597774946		R
30	BJD	2458525.594447706		R
31	TDB	2458525.594447706		R
32	HJD	2458525.594442693		R
33	WCSAXES	2		I
34	CTYPE1	'RA---TAN-SIP'		S
35	CTYPE2	'DEC--TAN-SIP'		S
36	EQUINOX	2000.0		R
37	LONPOLE	180.0		R
38	LATPOLE	0.0		R

Figure 10 Example LCO-OSS FITS header page 1

3. On the **DP Coordinate Converter window**, Figure 11, make sure that the appropriate settings are made so that AIJ can correctly compute BJD_TDB:
    a. Locate the Dynamical Time section.
    b. Check the Auto checkbox.
    c. Check the Update button. Hit OK. This can take a few seconds. If there is an error message, click on Network at the top and be sure that "Use proxy server for internet access" is checked. Try again.
    [NOTE: the USNO website may not be accessible while it is undergoing major updates from November, 2019 through April, 2020. If unable to reach USNO, use 32.0 in the Leap-secs box.]

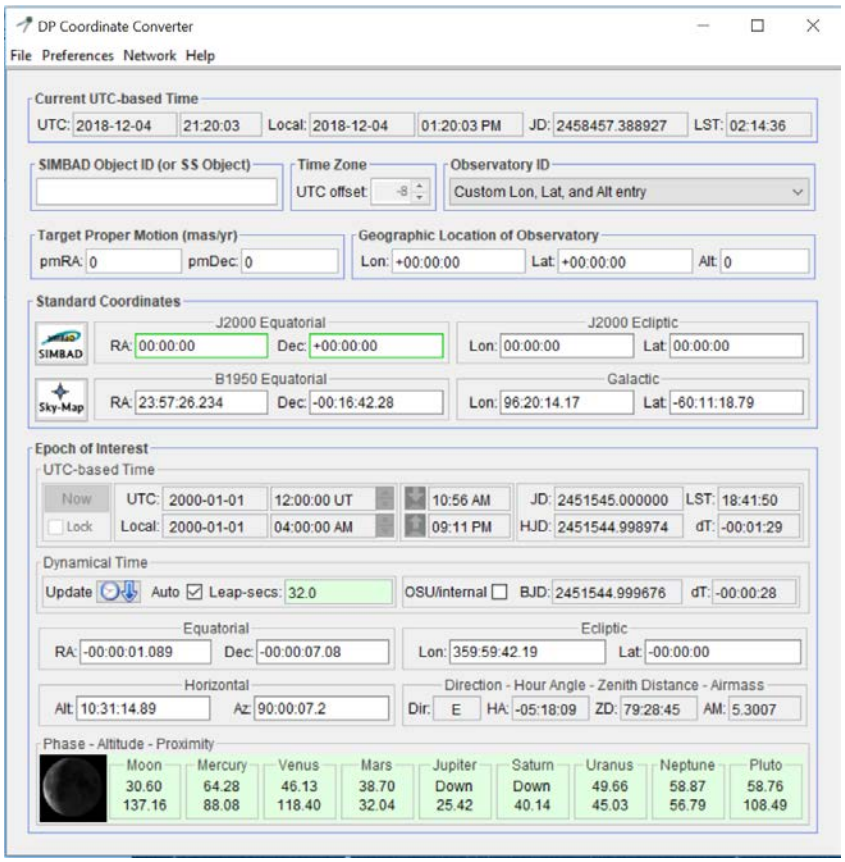


Figure 11. DP Coordinate Converter

4. On the CCD Data Processor window, click START when ready.
    d. You should see a Log File appear, as well as the calibrated science images scrolling by. The Log File will show the steps involved in the creation of the masters, as well as the calibration of each science image, and the adjustments made to the FITS header (e.g., for BJD time, Airmass, etc.).

5. When complete, ensure you save the Log File in to your AIJ Analysis directory.

ExoFOP-TESS:

You should have each image orientated with North up, and East left. To do this….

- Select the first frame in your Pipelineout file and open it.
- In the image window, select the VIEW menu.
- Select Invert X, Invert Y, or Invert X and Y as necessary

ExoFOP-TESS:

For TESS observations, at least one image must be plate solved with WCS to enable the some of the ExoFOP reports but not all images need to be plate solved. See Section 7.4 of A Practical Guide for how to do this in AI. OSS processed images are plate solved so this step can be ignored.

Exoplorer Note: The OSS Pipeline has performed the plate solving on all images so doing an AIJ plate solve is unnecessary.

6. The Calibration Phase is now complete. You can take a break safely at this point.

Differential Photometry Phase

1. Optional: If you are a member of the AAVSO, you may first want to access the AAVSO Variable Star Plotter program at https://www.aavso.org/apps/vsp/ to obtain the magnitude and stellar types of possible comparison stars to be used during the differential photometry process.

a. Input the RA and DEC of your observation from the FITS header.
b. Set the Chart Scale to desired.
c. Set Chart Orientation to CCD.
d. Set Plot a Finder Chart to Photometry.
e. Hit PLOT CHART

Exoplorer Note: You do not need to do this step. The OSS Pipeline files will include recommended comp stars based on a thorough analysis of the stars in your image run FOV.

i. This chart can be used to identify known magnitudes of potential comp stars and whether any stars in the field are variable. Use this in Step 9 below.
ii. It is possible that the RA/DEC coordinates may not have any comparison stars in the vicinity that are known to the AAVSO.

TESS observations have macros that can be installed in AIJ to facilitate in identifying Nearby Eclipsing Binaries (NEBs) that could create a false positive. These will become additional Target stars in the analysis. The macro automates the selection process by querying the Gaia database in the region of interest (2.5') to create a set of apertures for those stars called a *.radec aperture file. See Appendix C in the TFOP SG1 Guidelines located here for further explanation: http://astrodennis.com/TFOP_SG1_Guidelines_Latest.pdf

Check to be sure these macros have been installed by opening File for an image. The option "Create NEB search reports and plots…" will be listed. If not, update AIJ per Preparation Phase, Step 5.

The two methods for creating the *.radec aperture file are: use of a link in the TTF entry for a target, or use of a web-based tool. Method 1 is easier when you have the TTF page with its links. Refer to the Guidelines if you need to use the other method.

2. Use Method 1: use the TTF link: The TTF (Figure 1) now includes a link labelled "AIJ apertures" in the Name column for each TTF entry. Clicking on this link will cause the aforementioned *.radec aperture file to be generated for the target represented by the entry. Save this file to the AIJ Analysis folder.

3. Open the range of calibrated images from the calibration subdirectory (e.g., pipelineout) by selecting from the AIJ Main Toolbar: File->Import->Image Sequence

a. If running on a Windows machine, select the first file in the calibration subdirectory, hit Open, and AIJ will load all images in that subdirectory. Be sure to check "Use virtual stack".
b. If running on a Mac, select the subdirectory name.
c. The Sequence Options window will appear. Confirm that AIJ is recognizing all the images in your folder.
d. Check "Sort names numerically" and "Use virtual stack"
e. Click on OK

4. Target Location

a. The target star can be found in a number of ways:
   i. The easiest way since the image has been plate solved by OSS is to locate the RA/Dec of the target from your target source information (Ex. KEPLER, GAIA, TESS, etc.). Move the cursor over the WCS solved image until the RA/Dec of the target star is matched in the RA and Dec windows in the AIJ Image Window.
   ii. Software planetarium programs can also be useful through looking for patterns of stars around the target star.

5. .Left click on the target star in the image. You will not see any activity, until you then:

a. Select Analyze->Plot Seeing Profile. Alternatively, you can place your cursor on the target star and then hit Alt/Left Click. The Seeing Profile Window will appear, Figure 12.
b. Record the following values: Radius, Back>, and Back<
   i. These will be used to define the (initial) annulus and aperture.
c. Save in the AIJ Analysis folder. [*Note this is an ExoFOP required file.]*
d. Close the Seeing Profile window.

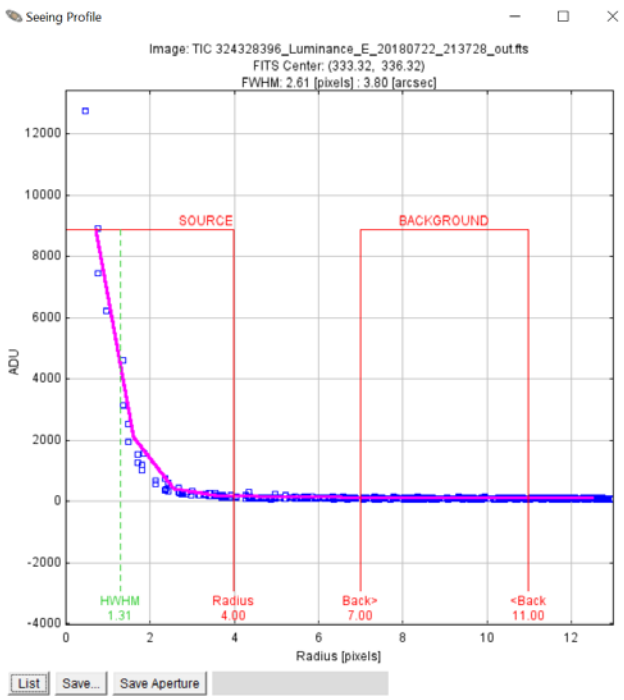


Figure 12. Seeing Profile Window

6. Load the NEB Apertures**.** The NEB aperture file can be loaded from the Image Display by selecting File->Import apertures from RA/Dec list. Apertures are automatically created over those stars that needed to be checked as potential NEBs causing the TESS detection. They will be annotated as T's with T1 being your target and the other T's as possible causes for a false positive observation for T1.

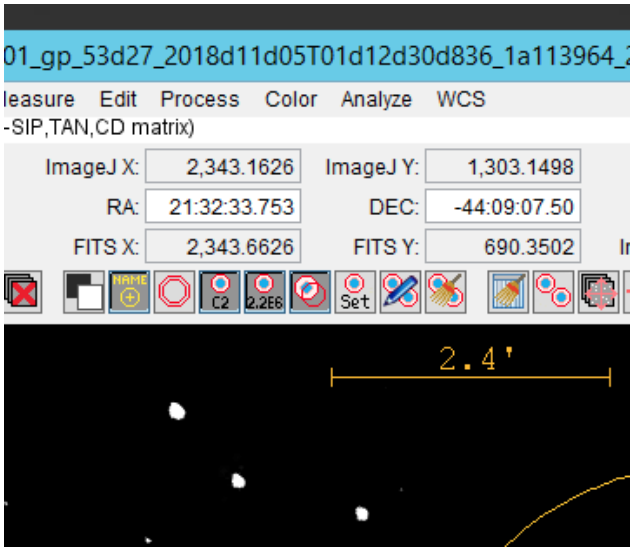


Figure 13 portion of AIJ Image Window 1

Be sure the 3 boxes above the image starting with the one labeled C2 have been clicked and are gray (see Figure 13).

7. Annotate an image for the region of interest**.** A circle of 2.5’ radius can be drawn around the target star (see Guidelines Appendix B as an example), by performing the following steps:

a. Under Annotate at the top of the Image Display Window, make sure that the “Right click in image opens annotation dialogue” option is selected.
b. Right click on the target star and a dialogue box opens up.
c. For “Custom Text,” enter Radius=2.5’
d. Check only the Show Circle option
e. Enter the number of pixels that equates to 2.5’ (i.e., 150 arc-seconds). For example, if the pixel scale is 1.5 arc-seconds per pixel, then 100 should be entered for the number of pixels. This information is available in your Worksheet. For LCO 0.4m telescopes with the SBIG camera (creates 0.57” pixel images), use 263.
f. Clicking OK will then put a circle of radius 2.5’ around the target star.

8. In the Image Display Window, Figure 13, select the multi-aperture photometry settings icon (the icon with two circles on it). The Multi-Aperture Measurements Window will appear, Figure 14.

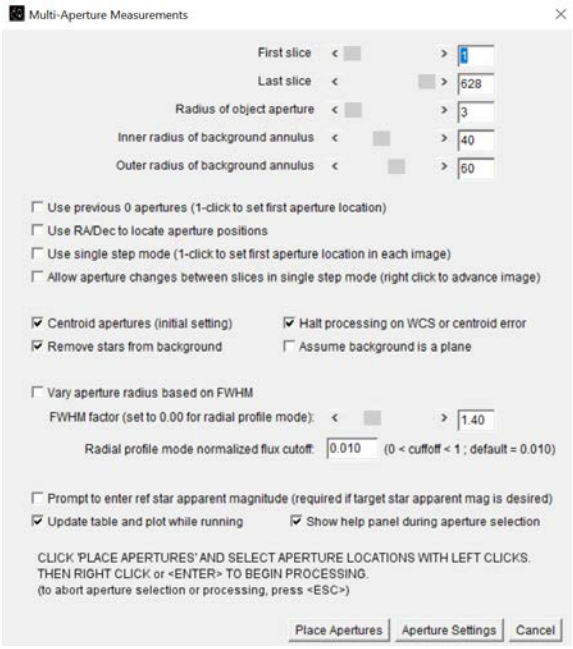


Figure 14. Multi-Aperture Measurements Window

a. On the Multi-Aperture Measurements window, ensure that the First Slice and Last Slice represent the total number of images (the first image through the last image) in your calibration subdirectory (e.g., pipelineout_).
b. Ensure that Radius of object aperture, the Inner radius of background annulus, and the Outer radius of background annulus entries are set with the Radius, Back> (Inner Radius of background annulus), and Back< (Outer radius of background annulus) values, respectively per the Seeing Profile in the step above.

c. Ensure that these boxes checked are: Centroid apertures (initial setting) and Remove stars from Background. **Since NEB aperture targets have been created from the Gaia macros, be sure to check the box labeled "Use previous nn apertures". For LCO images which are unguided but processed through the OSS Pipeline, check "Use RA/Dec to locate aperture positions".** You can also check "Update table and plot while running" to track your progress during the run and click "Show help panel…" if you wish.

d. Click on the Aperture Settings button at the bottom. The Aperture Photometry Settings screen will appear, Figure 15.

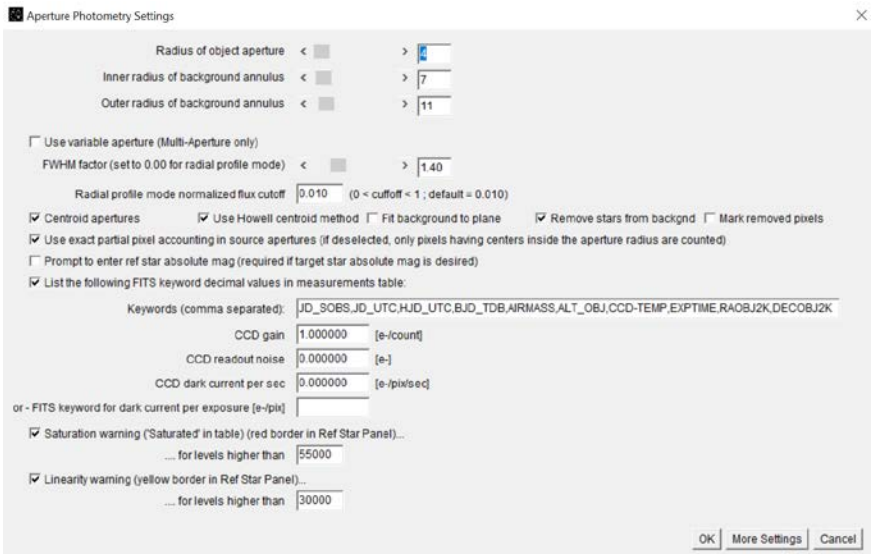


Figure 15. Aperture Photometry Settings Window

e. Ensure that the only boxes checked are: Centroid apertures, Use Howell centroid method, Remove stars from background, Use exact partial pixel…, List the following FITS keyword…, Saturation warning and Linearity warning.

f. Next, input settings relative to your CCD camera that were used to acquire the Science Images

i. Ensure that the following are set for your CCD Camera:

1. CCD gain
2. CCD readout noise
3. CCD dark current per sec

(Note: if you had binned your CCD camera to something other than 1x1, then enter the adjusted values for the binning you have selected.)

ii. For Saturation warning, ensure that a value is entered for the saturation point of the CCD camera being used.

iii. For Linearity warning, enter the ADU value where your CCD camera becomes non-linear.

g. Hit OK, which will return you to the Multi-Aperture Measurements screen.

IMPORTANT NOTE: Typically, the circle annotation will be lost during this Step 8. If so, cancel out of the Multi-Aperture Measurements screens after you made all the right settings on those two screens but <u>BEFORE</u> you click on "Place Apertures". Return to Step 7 and set the circle annotation again. When that is completed return to this Step 8. Your last Multi-Aperture Measurement settings will have been saved by AIJ. You should not repeat Step 8. Go to Step 8.h. and click on "Place Apertures". This procedure will enable making the screen grab in Step 8 with all the features required.

h. Hit Place Apertures. You will see all the T stars from the NEB aperture file appear in yellow.

9. Select the comp stars by left clicking on your desired comp star. These will be labeled with a C# (The # will change with each comp star you select. Example: C23, C24, C25, etc.). [Note: If you have placed the Gaia NEB apertures already, your Comp stars will continue numbering following the last T number, e.g. T8, T9, C10, C11…] A suggestion for good comp stars are those that are of similar apparent magnitude and color and are non-variable. You may need to refer to Gaia or Simbad to identify those of similar color. You may need to choose 6 to 10 comp stars; some of these may prove to be too variable to be used in your modeling. Having more will assure that you will have at least 3 to use in your modeling.

10. Save a screen grab of your image with the NEBS and Comps as a PNG file. [*Note this is an ExoFOP required file.*

11. Hit Enter key on your keyboard, or right click, to start the differential photometry process.

12. A Measurement Table will be created, Figure 16, that will, once the processing is complete, contain:
    a. A top header row and then a row for each image. The Source-Sky and Rel_flux columns are described below. The meaning of the other columns are described in: https://arxiv.org/abs/1601.02622.
    b. Source-Sky_XX. ADU counts in the aperture, with the ADU counts for the background sky in the annulus subtracted out. Hence the Source - Sky name.
    c. Rel_flux_XX If XX=T1, this refers to the relative flux of T1, which equals Source-Sky_T1 divided by the Source - Sky counts for all of the comp stars. If XX=Cn, this refers to the relative flux of Cn (the n'th comp star), which equals Source-Sky_Cn divided by Source – Sky counts for all the other comp stars. Note that the target star's Source - Sky counts are not included in the denominator for the relative flux numbers for the comp stars.
    d. Save the Measurement Table in the AIJ Analysis folder.

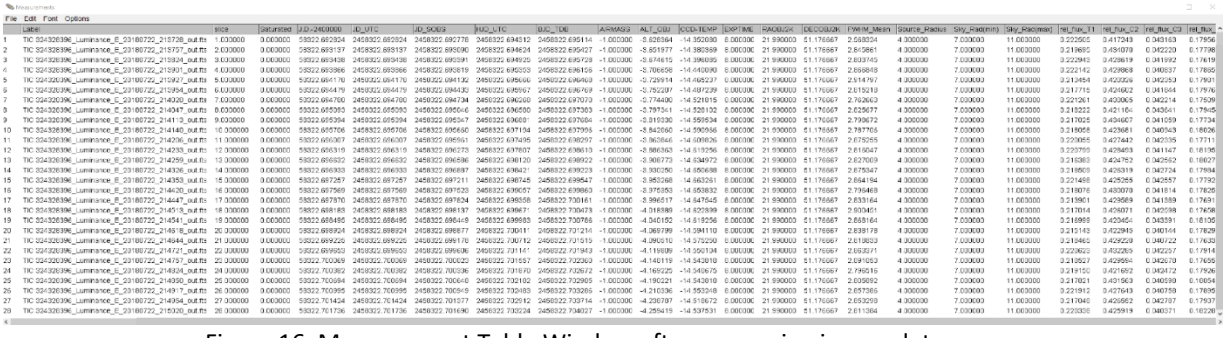


Figure 16. Measurement Table Window after processing is complete.

For OSS processed Measurement Tables created before November 2019, the order of the slices will not be sequential with BJD_TDB. The Measurement Table needs to be resorted. See the last 2 pages of Attachment A for the procedure.

This completes the Differential Photometry Phase. **Take a BREATHER!**

Transit Modeling Phase

1. Load and unzip the following AIJ plot configuration file from http://astrodennis.com: Measurements_Template.plotcfg (NOTE: This might be listed as a ZIP file). Store it in the AIJ Analysis subdirectory, and NOT in the C:/Programs directory. Unzip to this directory if needed.

2. Open the Measurements file from the Differential Photometry Phase. From the main AIJ toolbar, Figure 1, select File->Open and then the Measurements file that was saved above. Or you can click on the icon that looks like a spreadsheet to the left of the DP icon. Minimize the window when it opens.

3. Select the MultiPlot icon on the main AIJ toolbar (looks like a graph with a sine wave)
   a. When you select this, a series of 4 windows will appear: Plot of Measurements (Figure 17, Multi-plot Y-data (Figure 18), Multi-plot Reference Star Settings (Figure 19), and Multi-plot Main window (Figure 20

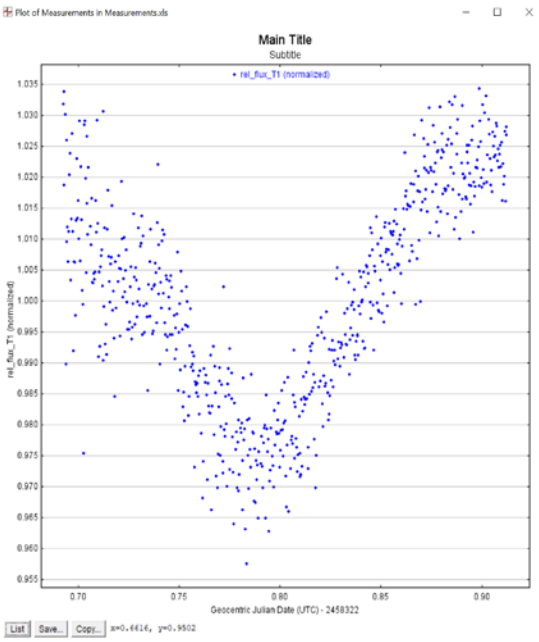


Figure 17. Plot of Measurements.

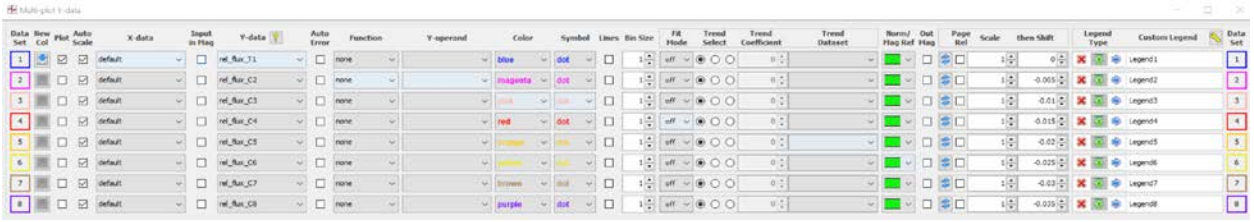


Figure 18. Multi-plot Y-data window.

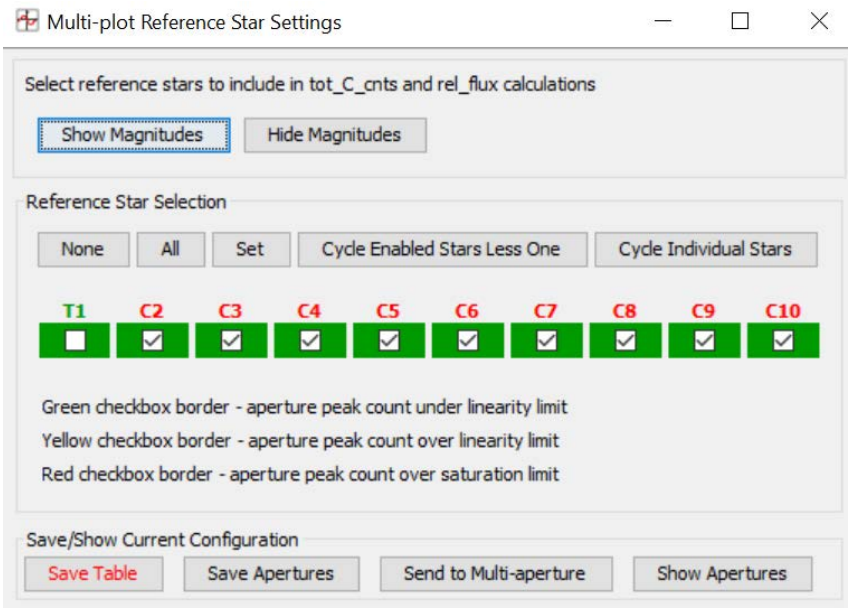


Figure 19. Multi-plot Reference Star Settings window.

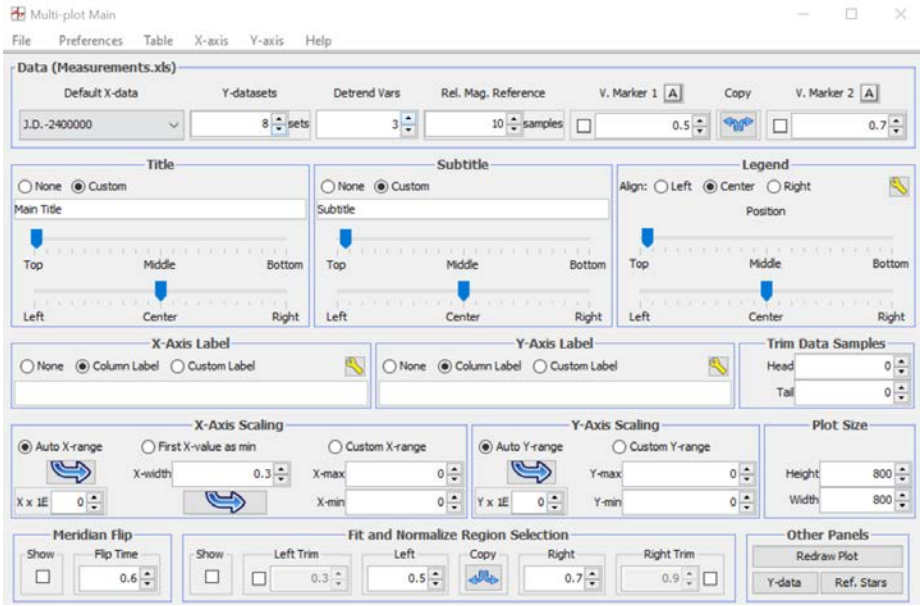


Figure 20. Multi-plot Main window.

4. From the "Multi-plot Main" window, Figure 20:
    a. Select File->Open Plot Configuration from file…
    b. Select the Measurements Template.plotcfg file from the AIJ Analysis directory mentioned above.
    c. The open windows will refresh, and another window will open, Data Set 2 Fit Settings, Figure 21.

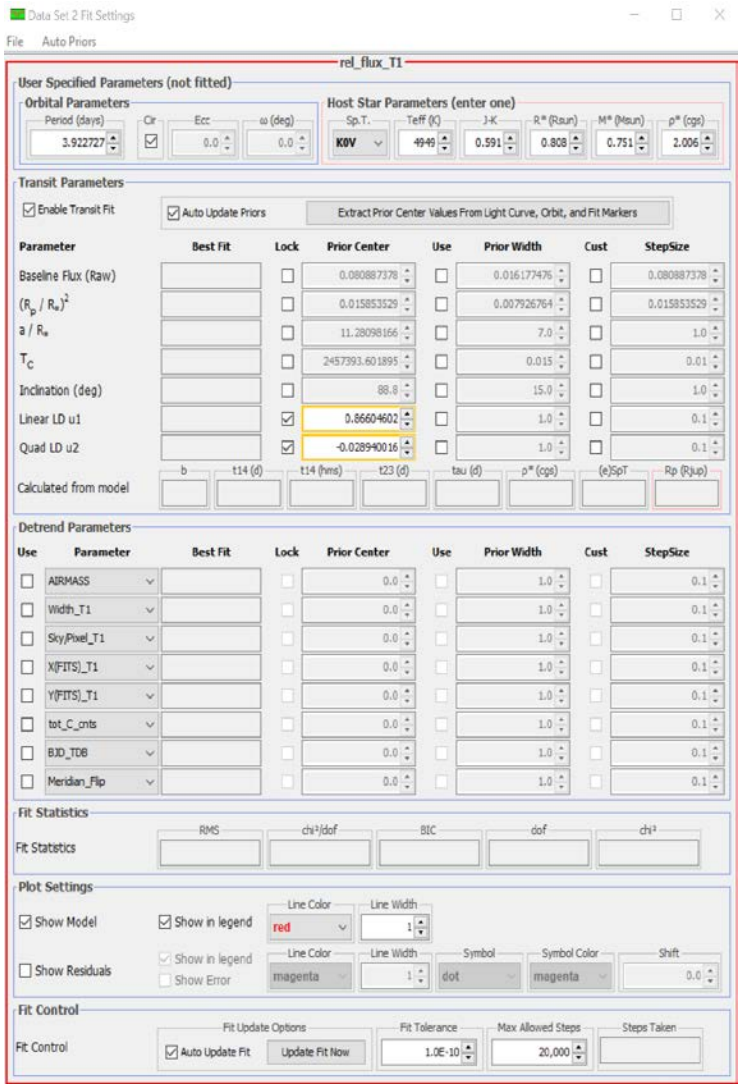


Figure 21. Data Set 2 Fit Settings window.

    d. If changes are later made to the Measurements_Template.plotcfg file, you can save this revised .plotcfg by selecting File->Save plot configuration…, name the file and save it.
    e. In the Multi-plot Main window, Figure 20 locate the Data section at the top of the screen and fill in the following fields:
        i. Default X-data: Set to BJD_TDB.
        ii. Y-datasets: Set to 37.

iii. Set V.Marker 1 and V.Marker 2 to the predicted ingress and egress times, respectively. These values can be found on your Worksheet. This will establish markers on the graph showing where the expected beginning and end of the light curve dip shall should occur. Only enter the fraction of the day, i.e. the digits following the decimal point. If the transit crosses into a new day, make the egress add 1 to the egress day fraction (if the egress day fraction is.123456, then set the egress to be 1.123456).

iv. At the bottom, locate the section called Fit and Normalize Region Selection. This establishes a pre-ingress and post-egress baseline for the model fit and should be initially set to the predicted ingress and egress times. Click on Copy (looks like two arrows moving left and right). This will pull in the V. Marker 1 & 2 values from above. Click twice to get both fields copied from the V. Marker boxes at the top of the screen.

v. Now locate the Multi-plot Y-Data screen. Ensure that the Plot box for the first row of the Multi-plot Y-Data screen, Figure 18, is checked.

vi. Back on the Multi-plot Main screen, Figure 20, go to X-Axis Scaling and select Auto X-Range, then click on the blue arrow pointing to the right. This will automatically find the minimum and maximum X axis values that are in the Measurements table and/or the V.Marker and baseline regions. So, for example, if your observation started after the predicted ingress time, this will pick up the minimum X value from the left entry of the Fit and Normalize region. If desired, these minimum and maximum values can be overridden by selecting Custom X-range and manually entering them.

f. Locate the Title section
   i. Ensure that Custom is selected.
   ii. Name the model according to what you are studying. For example, WASP-12b on UT2016-01-06.

ExoFOP-TESS:
This name should be the same name as the name provided on the TTF. The Title should be the TTF Target name followed by the UT for the observation.

g. Locate the Subtitle section
   i. Ensure that Custom, from above, is selected.
   ii. Enter your name, filter, and science image exposure time.

h. Locate the Meridian Flip section. Use this if there was a meridian flip, or there was a discontinuity in imaging where the target star ended up on a different portion of the detector. If it is used, ensure that Show is checked and the decimal part of the time of the occurrence is entered.

ExoFOP-TESS:
The Subtitle should be your name followed by the filter used and exposure time.

i.

5. On the Multi-plot Y Data window, Figure 18, the following should be done to properly control what is being plotted:
    a. In the third column from the left labelled "Plot," place a check mark for each of the values titled in the Y-Data column that you want plotted. Y-data is the 7th column from the left side. Typically you will start with checking each Comp Star.
    b. Be sure that all the Y-data dropdown boxes specify relative flux of the target or comp star (rel_flux_T# or C#).
    c. Set the color and symbol for each plot to your taste.
    d. For Fit Mode:
        i. These selections tell AIJ what type of model fit, if any it should apply to the dataset you have selected in the Y-data column.
        ii. For the first row, ensure that the relative flux of the target star (may appear as rel_flux_T1) is titled under the Y-Data column (column 7). Then set the Fit Mode to "Off" for this first row. This will cause AIJ to graph the data without doing a fit.
        iii. For the second row, again ensure that the relative flux of the target star is selected under the Y-Data Column, but now set the Fit Mode to what looks like an exoplanet dip icon.

ExoFOP-TESS:
You will also have T (target) stars listed under T1 for each of the stars identified by Gaia as having potential for causing a false positive measurement of T1. You should not check Plot for these "Targets" but set everything else as if they are Comp Stars.

        iv. For every comp star data set located in the Y-data column (column 7), set the Fit Mode to a straight line.
    d. Go to the Norm/Mag Ref column:
        i. For both rows for the target star (ex. rel_flux_T1 and rel_flux-T1), select the icon with green bars on the left and right, with a white bar in the middle. This establishes the left and right regions specified in the Fit and Normalize Region Selections values entered on the Multi-plot Main screen that will be used normalize the plot in the middle.
        ii. For the comp stars, select the icon that is all green.
    e. The meaning of other columns, such as Scale and Shift, can be seen by hovering your mouse over the column name.

6. Go to the Data Set 2 Fit Settings window, Figure 21. This is where you will enter values that AIJ will use to do its exoplanet transit model fit, as well as if and how residuals are displayed.
    a. If this window does not appear, go back to the Multi-plot Y-data, Figure 18, screen and make sure that the transit model icon is selected from the Fit Mode column.
    b. Under Orbital Parameters, enter the Period per the data from your Worksheet.

ExoFOP-TESS:
This data can be found in the TTF information provided for the star that you are plotting or from your Worksheet.

c. Under Host Star Parameters, enter for R*(Rsun) the radius of the target star from your Worksheet. If the radius is not known, enter the spectral type (Sp.T.) of the host star. NOTE: If you have the Teff of the Host Star, it will auto fill the Spectral Type.
d. In the Transit Parameters section:
    i. Ensure Enable Transit Fit is checked.
    ii. Ensure Auto Updates Prior is checked.
    iii. Enter the limb darkening coefficients, Linear LD u1 and Quad LD u2 in the Prior Center column second from the left if you were able to compute them. Ensure that the LOCK boxes for these items are selected and that the numbers appear in the boxed in the Best Fit column (1st from left). If not available, use 0.3 for both fields.
    iv. In the Detrend Parameters section select click on the Use box in the first line and select Airmass from the dropdown list to its right in the Parameter Column.

7. Return to the Multi-plot Main window, Figure 20:
    a. In the Y-axis Scaling section, you can adjust the Y-max and Y-min values to adjust the plots on the Plots display.
    b. In the X-axis Scaling section, it is best to leave Auto X-range selected.

8. Locate the Multi-plot Reference Star Settings window, Figure 19. This is used to deselect or select which comp stars will be included in the model fit. For example, if a comp star does not fit a linear path, it may be a variable star and thus would need to be excluded.

ExoFOP-TESS:
To make your model and the light curve plot it is useful to shrink the Multi-plot Y Data window, Figure 18 to half screen. Then place the Plot of Measurements, Figure 17 also at half page size next to it. This screen layout allows you to make the plotting changes described below and elsewhere in the Multi-plot Y Data window and see the effect in the Plot of Measurements. You wil also want to have the Multi-plot Reference Star window, Figure 19 available.

- Now review the plots for each Comp star you have designated. You will want to deselect those that fluctuate significantly. They may be plotted on top of each other and you will need to move each one up or down in to get a clear view. You do this moving the plot using the up or down arrows in the Shift Column in the right side of the Multi-plot Y-data screen. You can also blink them on and off with the Plot check box.
- You will want to deselect those comp stars that visibly fluctuate significantly. In making these decisions you can reference the RMS value at the top of the plot to determine if a good fit was made for that star. Higher RMS values indicate poorer fit.
- In the second line of the labels, you will see the data for the quality of the fit for T1. You will want to select and deselect Comp Stars per step 8 to get the best fit (i.e. lowest RMS). The RMS value is also shown in the Data Set 2 Settings window, Figure 21. Ideally, you will end up retaining three or more of the comp stars in your model.
- Next, be sure that you have unchecked Plot for all the comp stars that were deselected. Also, adjust the colors of the selected stars for best visibility and distinction. Be sure the same scaling factor is used for all plots.
- When satisfied, be sure the plot and legends are legible with Target, selected Comp Stars and the four standard plots at the bottom (Airmass, total counts, X(FITS) and Y(FITS)). Use the Shift Column function to spread out the curves. You can also zoom in and out on the plot and drag it with your mouse.

9. Review Section 7.11 of the Practical Guide (www.astrodennis.com) to choose the appropriate Detrend parameters and to further optimize your model fit. Generally you will always use Airmass as a

ExoFOP-TESS: Go to the Multi-plot Main window and click on File. In the dropdown list, click on Create NEB search reports and plots… A new window will open and you will need to complete as in this example Figure here.

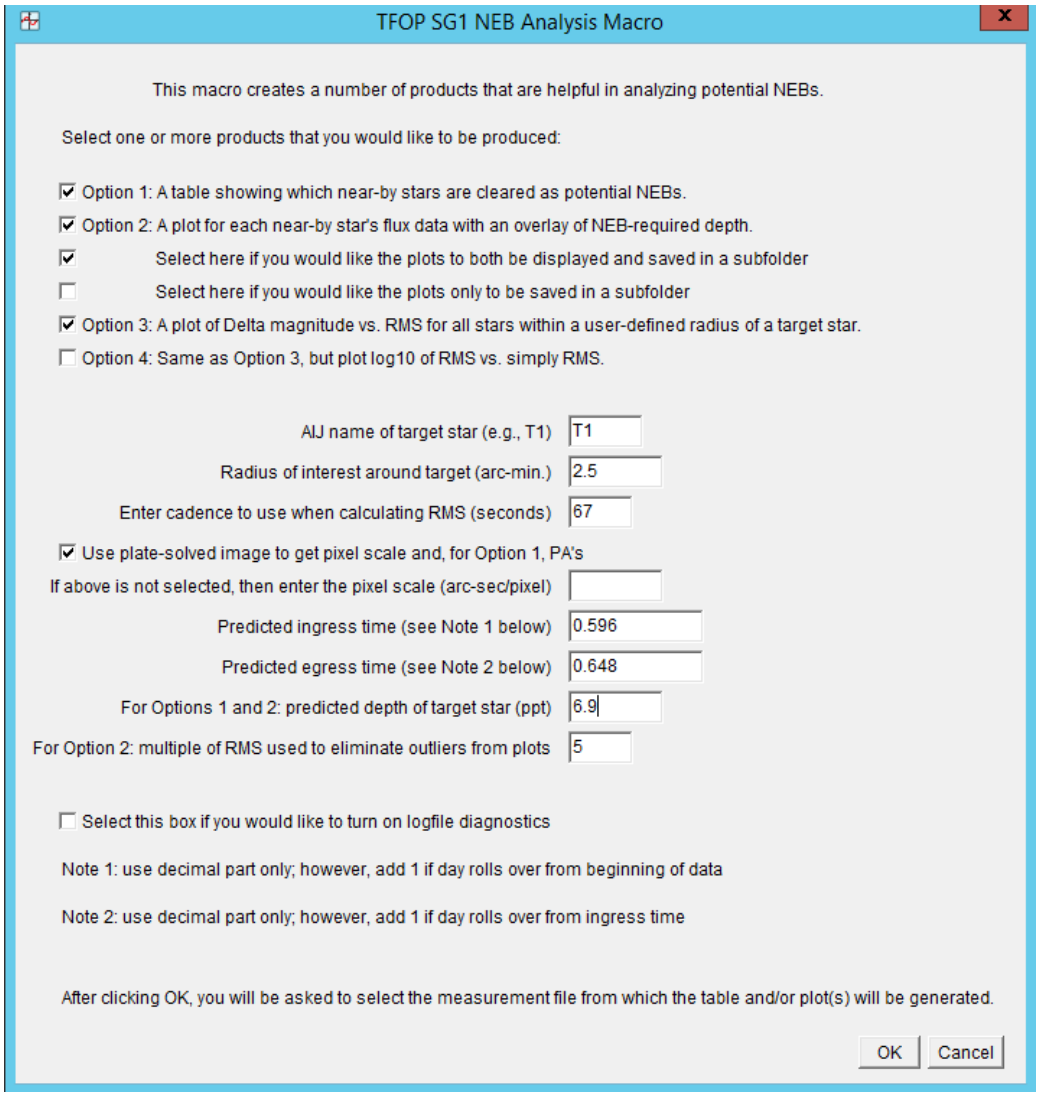


Figure 22 TFOP SG1 NEB Analysis Macro

The cadence is the time between successive images. You can calculate this by adding the exposure time and the CCD overhead cycle time (time used to download the image data from one frame). Or you can take the difference in BJD_TDB between successive frames and calculate the seconds elapsed. It may be wise to do both to confirm your cadence entry. Leave the last box, multiple of RMS, set at 5. The other data can come from your Worksheet.

When you click on OK it will ask you to select the measurement file that was used for the plots you have generated. Use the pipeline out file that you have used. When done, all the reports generated by the NEB analysis will be generated.

detrend parameter which should have been automatically chosen by AIJ.

10. On the Multi-plot Main screen, Figure 10, select File->Save all... to save your work to the AIJ Analysis directory.

■ Go OUT FOR A CELEBRATION – You've done!

Come back later and compile your ExoFOP data files – see our separate instructions for that.