

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 <u>www.astrodennis.com</u> 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 AstroImageI's own guide, which can be found at <u>www.astro.louisville.edu/software/astroimagej/</u>and which will be referred to here as "the AIJ Guide."

Some text in this guide will differentiated with <u>red, underlined text</u>^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	Туре
🐌 AlJ Analysis	4/23/2019 12:23 PM	File folder
퉬 Bias	8/30/2018 5:07 PM	File folder
Jarks	8/30/2018 5:07 PM	File folder
퉬 Flats	8/30/2018 5:07 PM	File folder
퉬 Quarantined Images	8/30/2018 5:07 PM	File folder
퉬 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. AlJ 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 *zhift-click* another column to sort further within the first category. For example, to sort by priority within a given night (when nultiple nights are displayed), first click the "Local evening date" header, then shift-click the "Friority" 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 Show if visible transit % + baseline % > 0LCO Cerro Tololo Interamerican, 0.4m Search: Vmax: % of transit (baseline) observable Elev HA Az. at start, mid, end at start, mid, end RA & Dec (J2000) Local evening date BJDTDR v т Period (days) Depth (ppt) R_{plane} (R_⊕) Mid —End Duration Priority Comments Name mag start-mid-end mid, Suggested obs. start, end Sun. 2018-11-04: Nautical twilight 2018-11-04 21:04 - 2018-11-05 05:49 2018-11-05 00:04 - 2018-11-05 08:49 UTC local time Sun. 2018-11-04 (local date) 147203645.01 (TOI target (r=5"). Chris Stockdale observed a near full transit 166.01) Add to TOC Finding charts: 01-51 579 ு 235° +2.5 11.328 02:18-52°, 46°, 39° 236°, 236°, 236° +3.0, +3.6, +4.2 8427.596 02:55 ---03:33 21:32:47.06 -44:01:04.1 1:14 10.696 8427.622 8427.648 5.06 6.9 3 12.8 Nantical Info: ExoFOP, lthough with me clouded Moon 89 twilight 00:04 -LA J 04.00 100% (100%) 01:18—04:33 @119 +4.7 apertures, ±0:27 periods) on 20180925 in Ic 08:49 (UTC)

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</u> such as in this Figure 2 regardless of whether the Bias, Darks, and Flats are to be used.
- 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:

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



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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.

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- 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.



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.
- 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.

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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.]

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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.

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 8 General FITS Header Settings

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.

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26	REQNUM	'0001726655'		S	
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28	JD	2458525.5974724		R	
29	JD-MID	2458525.597774946		R	
30	BJD	2458525.594447706		R	
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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.]

-	TC-based	Time						
UTC: 201	8-12-04	21:20:03	Local: 2018-	12-04	01:20:03 PM	JD: 2458457	.388927	LST: 02:14:36
SIMBAD O	Object ID (d	or \$\$ Object) -	Time Zo	ne	Observat	ory ID		
			UTC offs	et -8	Custom I	Lon, Lat, and Alt	entry	,
Target Pr	oper Motic	on (mas/vr)		Geograph	ic Location of	Observatory -		
pmRA: 0		pmDec: 0		Lon: +00	:00:00	Lat +00:00:	00	Alt 0
tandard	Coordinate							1
tanuaru	coordinati	J2000	Equatorial			J20	00 Ecliptic	
IMBAD	RA: 00:0	0:00	Dec: +00:00	0:00	Lon: 0	0:00:00	Lat	00:00:00
		B1950	Equatorial				Galactic	
iky-Map	RA: 23:5	7:26.234	Dec: -00:16	:42.28	Lon: 9	6:20:14.17	Lat -	60:11:18.79
UTC-bas	ed Time	2000.01.01	12:00:00.1.07		10-56 AM	ID: 0454548	5 000000	I ST 10-41-50
Lock	Local	2000-01-01	04:00:00 AM		09:11 PM	HJD: 2451544	1.998974	dT: -00:01:29
Description	al Time							
1 mamic	OU Au	to 🗹 Leap-se	acs: 32.0	0	SU/internal 🗌	BJD: 2451544	999676	dT: -00:00:28
Update						Eclin	tic	
Update		- Equatorial				- only		0.00
Update	0:00:01.08	Equatorial Dec.	-00:00:07.08		Lon: 359:59:4	2.19	Lat: -00:0	00.00
Update	0:00:01.08	Equatorial 9 Dec. Horizontal	-00:00:07.08		Lon: 359:59:4	2.19 Hour Angle - Ze	Lat: -00:0	nce - Airmass
Update RA: -00 Alt: 10:	0:00:01.08 31:14.89	Equatorial 9 Dec: Horizontal Az	-00:00:07.08 90:00:07.2		Lon: 359:59:4 Direction - ir: E HA:	2.19 Hour Angle - Ze -05:18:09 ZD	Lat: -00:0 enith Dista 0: 79:28:45	nce - Airmass AM: 5.3007

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.

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. <u>Optional</u>: 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: <u>http://astrodennis.com/TFOP_SG1_Guidelines_Latest.pdf</u>

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.

First sli	ice <	E	>	1	
Last sli	ice <		>	628	
Radius of object apert	ure <	6	>	3	
Inner radius of background annu	lus <	101	>	40	
Outer radius of background annu	llus <		>	60	
Use previous 0 apertures (1-click to set first a	perture loc	ation)			
Use RA/Dec to locate aperture positions					
Use single step mode (1-click to set first aper	ture locatio	n in each ir	mage)		
Allow aperture changes between slices in sin	gle step m	ode (right c	lick to	advance	image)
Centroid apertures (initial setting)	Halt proce	ssing on W	CS or	centroid	error
Remove stars from background		ackaround		200	
It is not background i	Assume b	ackground	is a pl	ane	
Vary aperture radius based on FWHM	Assume o	ackground	is a pl	aire	
Vary aperture radius based on FWHM FWHM factor (set to 0.00 for radial profile mod	Assume o de): <		is a pl	1.40	
Vary aperture radius based on FWHM FWHM factor (set to 0.00 for radial profile moc Radial profile mode normalized flux cut	de): < toff: 0.01	0 (0 < ci	s a pl: > uffoff <	1.40 1 ; defau	lt = 0.010
Vary aperture radius based on FWHM FWHM factor (set to 0.00 for radial profile mod Radial profile mode normalized flux cut Prompt to enter ref star apparent magnitude (r	de): < toff: 0.01	0 (0 < ci	is a pl , iffoff < ippare	1.40 1 ; defaul	It = 0.010 desired
Vary aperture radius based on FWHM FWHM factor (set to 0.00 for radial profile mod Radial profile mode normalized flux cut Prompt to enter ref star apparent magnitude (Update table and plot while running	de): < toff: 0.01 required if 1 7 Show he	0 (0 < ci arget star a Ip panel du	is a pl > uffoff < ippare ring ap	1.40 1 ; defaul nt mag is perture se	lt = 0.010 desired
Vary aperture radius based on FWHM FWHM factor (set to 0.00 for radial profile mod Radial profile mode normalized flux cut Prompt to enter ref star apparent magnitude (i Update table and plot while running CLICK PLACE APERTURES' AND SELECT APE THEN RIGHT CLICK or «ENTER> TO BEGINPE (to abort aperture selection or processing, press	de): < toff: 0.011 required if 1 7 Show he ERTURE LI ROCESSIN s <esc>)</esc>	0 (0 < ci arget star a lp panel du OCATIONS G.	IS a pli s uffoff < ippare ring ap WITH	1.40 1 ; defau nt mag is berture se LEFT CLI	lt = 0.010 desired lection CKS.

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.

5. 5. 55.			
Radius of object aperture	<	>	
Inner radius of background annulus	۰ 🔳	> 7	
Outer radius of background annulus	۰ 🔳	> 11	
Use variable aperture (Multi-Aperture only)			
FWHM factor (set to 0.00 for radial profile mode)	۲ 📄	> 1.40	
Radial profile mode normalized flux cutoff	0.010 (0	0 < cutfoff < 1 ; default = 0.010)	
Centroid apertures 🔽 Use Howell ce	ntroid method	1 □ Fit background to plane	
Use exact partial pixel accounting in source aper	tures (if dese	elected, only pixels having centers inside the aperture radius are counted)	
Prompt to enter ref star absolute mag (required i	f target star a	bsolute mag is desired)	
List the following FITS keyword decimal values in	n measureme	ents table:	
Keywords (comma separated):	JD_SOBS,J	JD_UTC,HJD_UTC,BJD_TDB,AIRNASS,ALT_OBJ,CCD-TEMP,EXPTIME,RAOBJ2K,DECOBJ2K	
CCD gain	1.000000	[e-/count]	
CCD readout noise	0.000000	[e-]	
CCD dark current per sec	0.000000	[e-/pix/sec]	
FITS keyword for dark current per exposure [e-/pix]			
	der in Ref Sta	r Panel)	
Saturation warning ('Saturated' in table) (red bor			
Saturation warning (Saturated' in table) (red bor for levels higher than	55000		
Saturation warning (Saturated' in table) (red bor for levels higher than Linearity warning (yellow border in Ref Star Pane	55000 H)		

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.

% 1	feasurements																					
File	Edit Font Options																					
	Later	slice	Saturated	J.D2400000	JD_UTC	JD_SOBS	HUD_UTC	BUC_TOB	ARMASS	ALT_OBJ	CCD-TEMP	EXPTIME	RAOBJ2K	DECOBJ2K	EWEM_Mean	Source_Radius	Sky_Rad(min)	Sky_Rac(max)	ret_flux_T1	rel_flux_C2	rel_flux_C3	ret_flux_ ~
1	TIC 324326396_Luminance_E_20180722_219728_out.fts	1.000000	0.000000	58822.692824	2458322.692824	2458322.692778	2458322 694312	2458322.695114	-1.0000000	-3.628364	-14.352030	8.000000	21.990000	51.176667	2.568324	4.000000	7.000000	11.000000	0.222505	0.417243	0.043163	D.17956
2	TIC 324328396_Luminance_E_20180722_219757_out.fts	2.000000	0.000000	58822.693137	2458322.693137	2458322.693090	2458322 694624	2458822.695427	-1.0000000	-8.851977	-14.380369	8.000000	21.990000	\$1.176667	2.845861	4.000000	7.000000	11.000000	0.219695	0.434070	0.042220	0.17798
3	TIC 324326396_Luminance_E_23180722_213824_out.fts	3.033000	0.003000	58322.653438	2458322.693438	2458322.693391	2458322.694925	2458322.695728	-1.000000	-3.674615	-14.396035	8.000000	21.990000	51.176667	2.803745	4.300000	7.030003	11.000000	0.222943	3,428619	0.041992	0.17619
8	TIC 324328396_Luminance_E_20180722_21S901_out.fts	4.000000	0.0000000	58322.693866	2458322.653866	2458322.693819	2458322.695353	2458322.696156	-1.0000000	-3.706658	-14.440090	8.000000	21.990000	\$1.176667	2.866848	4.000000	7.000000	11.000000	0.222142	0.429868	0.040837	0.17865
5	TIC 324320396_Luminance_E_23180722_213927_out.fts	5.000000	0.000000	53322.694178	2458322.684178	2458322.094132	2450322.095066	2458322.696468	-1.000000	-3.729914	-14/465237	8.000000	21.990000	51.176667	2.914797	4.000000	7.030003	11.000000	0.213454	3.423326	0.042353	0.17901
6	TIC 324326396_Luminance_E_20180722_213954_out.fts	6.000000	0.000000	53322.694479	2458322.694479	2458322.694433	2458322.695967	2458322.696769	-1.0000000	-3.752207	-14.487239	8.000000	21.990000	51.176667	2.815218	4.000000	7.000000	11.000000	0.217715	0.424602	0.041644	0.17976
7	TIC 324320396_Luminance_E_20180722_214020_out.fts	7.000000	0.000000	53322.094700	2458322.094780	2458322.094734	2450322.696268	2450322.697070	-1.0000000	-3.774400	-14.521015	0.000000	21.990000	51.176667	2.762663	4.000000	7.000000	11.000000	0.221261	0.400005	0.042214	0.17509
0	TIC 024020396_Luminance_E_20100722_214047_out.fts	0.000000	0.000000	50022.615010	2450322.655093	2450322.695046	2450322.696500	2450322.097303	-1.000000	-3.797341	-14.520102	0.000000	21.990000	\$1.176667	2.025677	4.300000	7.000000	11.000000	0.210222	0.421104	0.043641	0.17945
9	TIC 324326396_Luminance_E_20100722_214113_out.fts	9.000000	0.0000000	53322.615394	2450322.075394	2450322.095347	2450322.696601	2458322.697684	-1.000000	-3.819330	-14.552534	0.000000	21.990000	51.176667	2.798672	4.300000	7.000000	11.000000	0.217025	0.434607	0.041059	0.17734
10	TIC 324328396_Luminance_E_20180722_214140_out.fts	10.000000	0.000000	58322.615706	2458322.695706	2458322.695660	2458322.607104	2458322.607095	-1.000000	-3.842060	-14.590956	8.000000	21.990000	\$1.176667	2.787705	4.300000	7.000000	11.000000	0.218058	0,423681	0.040943	0.18026
11	TIC 324326396_Luminance_E_20180722_214206_out.fts	11.000000	0.000000	58322.696007	2458322.656007	2458322.695961	2458322.697495	2458322.698297	-1.000000	-3.863846	-14.503826	8.000000	21.990000	51.176667	2.875255	4.000000	7.000000	11.000000	0.220055	0.427442	0.042335	0.17711
12	TIC 324326396_Luminance_E_23180722_214233_out.fts	12.000000	0.000000	58322.656319	2458322.656319	2458322.696273	2458322.697807	2458322.698610	-1.000000	-3.886363	-14.519256	8.000000	21.990000	\$1.176667	2.816047	4.300000	7.000000	11.000000	0.220799	0,428493	0.041147	0.18195
13	TIC 324326396_Luminance_E_20180722_214259_ouLfts	13.000000	0.000000	59322.696632	2458322.696632	2458322.696586	2458322.698120	2458322.698922	-1.000000	-3.906773	-14.534972	8.000000	21.990000	51.176667	2.827009	4.000000	7.000000	11.000000	0.216363	0.424762	0.042562	0.18027
14	TIC 324326396_Luminance_E_20180722_214326_out.fts	14.000000	0.000000	53322.616933	2458322.696933	2458322.696887	2458322.698421	2458322.699223	-1.000000	-3.930250	-14.550638	8.000000	21.990000	\$1.176667	2.875347	4.000000	7.000000	11.000000	0.218509	0.425319	0.042724	0.17984
15	TIC 324326396_Luminance_E_20180722_214353_ouLfts	15 000000	0.000000	58322.697257	2458322.697257	2458322.697211	2458322.698745	2458322.699547	-1.000000	-3.953268	-14.663261	8.000000	21.990000	51.176667	2.864194	4.000000	7.000000	11.000000	0.221498	0,425265	0.042557	0.17792
16	TIC 324328396_Luminance_E_20180722_214420_out.fts	16.000000	0.000000	58322.697569	2458322.697569	2458322.697523	2458322.699057	2458322.699860	-1.000000	-3.976353	-14.553832	8.000000	21.990000	\$1.176667	2.795468	4.000000	7.030003	11.000000	0.218076	0.430070	0.041814	0.17825
17	TIC 324328396_Luminance_E_20180722_214447_out.fts	17.000000	0.000000	58322.697870	2458322.697870	2458322.697824	2458322 699358	2458822.700161	-1.000000	-3.996517	-14.847545	8.000000	21.990000	\$1.178667	2.833164	4.000000	7.000000	11.000000	0.213901	0.429589	0.041389	0.17691
18	TIC 324328396_Luminance_E_20180722_214513_out.fts	18.000000	0.000000	58322.698183	2458322.698183	2458322.698137	2458322 699671	2458822.700473	-1.000000	-4.018389	-14.522899	8.000000	21.990000	\$1.178867	2.900461	4.000000	7.000000	11.000000	0.217014	0.428071	0.042598	0.17658
19	TIC 324326396_Luminance_E_20180722_214541_out.fts	19.000000	0.000000	55322.698495	2458322.698495	2458322.698449	2458322.699983	2458322.700786	-1.000000	-4.040152	-14.619256	8.000000	21.990000	\$1.176667	2.668164	4.000000	7.000000	11.000000	0.216999	0.420464	0.043391	0.18105
20	TIC 324328396_Luminance_E_20180722_214518_out.fts	20.000000	0.0000000	58322.698924	2458322.698924	2458322.698877	2458322.700411	2468322.701214	-1.0000000	-4.069799	-14.594110	8.000000	21.990000	\$1.176667	2.838178	4.300000	7.000000	11.000000	0.215143	0.422945	0.040144	0.17829
21	TIC 324326396_Luminance_E_23188722_214644_out.fts	21.000000	0.000000	55322.699225	2458322.699225	2458322.699178	2458322.700712	2458322.701515	-1.000000	-4.090510	-14.575250	8.000000	21.990000	\$1.176667	2.618633	4.000000	7.000000	11.000000	0.218465	0.429220	0.040722	0.17633
22	TIC 324326396_Luminance_E_20180722_214721_out.fts	22.000000	0.000000	53322.699553	2458322.659663	2458322.699606	2458322.701141	2468322.701943	-1.0000000	-4.119609	-14.550104	8.000000	21.990000	\$1.176667	2.863371	4.000000	7.000000	11.000000	0.220623	0.432265	0.042257	0.17914
23	TIC 324326396_Luminance_E_23188722_214757_out.fts	23.000000	0.000000	53322.700369	2458322.700069	2458322.700023	2458322.701657	2458322.702363	-1.0000000	-4.148119	-14.543818	8.000000	21.990000	51.176667	2.091053	4.300000	7.030003	11.000000	0.210527	0.429594	0.042678	0.17655
24	TIC 324326396_Luminance_E_20180722_214324_out.fts	24 000000	0.000000	58322.700382	2458322.700382	2458322.700336	2458322.701870	2458322.702672	-1.000000	-4.169225	-14.540675	8.000000	21.990000	\$1.176667	2.796516	4.000000	7.000000	11.000000	0.219150	0.421692	0.042472	0.17926
25	TIC 324326396_Luminance_E_20180722_214050_out.fts	25 000000	0.000000	53322.700594	2458322.700594	2458322.700648	2458322.702182	2458322.702985	-1.0000000	-4.190221	-14.543010	8.000000	21.990000	\$1.176667	2.005092	4.000000	7.000000	11.000000	0.217021	0.431563	0.040590	0.10054
26	TIC 324326396_Luminance_E_20180722_214917_out.fts	26.000000	0.000000	53322.700995	2458322.700995	2458322.700949	2458322 702483	2458322.703285	-1.000000	-4.210336	-14.553248	8.000000	21.990000	\$1.176667	2.657386	4.000000	7.000000	11.000000	0.221912	0.427643	0.040758	0.17895
27	TIC 324326396_Luminance_E_20180722_214954_out.fts	27 000000	0.000000	53322.701424	2458322.701424	2458322.701377	2458322.702912	2458322.703714	-1.000000	-4.236787	-14.518672	8.000000	21.990000	51.176667	2.653298	4.000000	7.000000	11.000000	0.217048	0.425552	0.042787	0.17937
28	TIC 324326396_Luminance_E_20180722_215020_out.fts	26.000000	0.000000	53322.701736	2458322.701736	2458322.701690	2458322.703224	2458322.704027	-1.000000	-4.259419	-14.537531	8.000000	21.990000	51.176667	2.611364	4.000000	7.030003	11.000000	0.220338	0,425919	0.040371	0.18228

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

- Load and unzip the following AIJ plot configuration file from <u>http://astrodennis.com</u>: 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 AlJ 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.

Data Set	Res Col	-	Auto	£	X-data	3	nput. Mag	Y-data 🦞		Auto treor	Function		Y-operand		Color		Syn	ibol	Lines	Bin Size	Fit Hod		Trend Select	Trend Coefficient	Trend Dataset		Norm/ Hog Ref	Out	Page Rel	Scale 6	hen Shift	Legen	d. :	Custom Legend	-
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Figure 18. Multi-plot Y-data window.

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Figure 19. Multi-plot Reference Star Settings window.

Data (Measurements.xls) Default X-data	Y-datasets	Detrend Vars	Rel. M	lag. Refere	ince	٧.	Marker 1 🛕	Сору	V. Ma	rker 2 🔺
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Left Center	Right	Left	Cent	er		Right	Left	0	enter	Right
X-Axis	Label		~	Y	Axis La	abel			Trim Data	Samples
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X x 1E 0	9	X-min	0 🗧	Y x 1E	0 0	Y-m	n	0 0	Width	800
Meridian Elin		Fit and Norn	nalize R	egion Se	lection	6		1.1	Other	Panels
a star extension a star		Copy Right		Right Trim		Redraw Plot				
Show Flip Time	ShowLeft Trir	n Left	1	Copy	Righ	t	Right Trim		Redra	w Plot

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.

					rel_flux_T1 -						
User :	Specified Param	eters	(not fitted)	_							
Orbi	tal Parameters -	~	Fee	(dec)	Host Star Parameters (enter one)						
3.922727		0.0 1 0.0 1		KOV 4949 0.591 0.808			0.751 2.006				
Trans	it Parameters -	_									
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Paran	neter	er Best Fit Lo		Lock	Prior Center	Use	Prior Width	Cust	StepSize		
Baseli	ne Flux (Raw)	1		1 0 [0.080887378		0.016177476		0.080887378		
(R_/	R_) ²			1 0 1	0.015853529 🔅		0.007926764 +		0.015853529		
a / R.				1 0 1	11.28098166		7.0 🐥		1.0		
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Inclina	ation (deg)			1 0	88.8	Í	15.0		1.0		
Linear	LD u1				0.86604602		1.0		0.1		
Quad	LD u2				-0.028940016		1.0 🛟		0.1		
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Calcula	ated from model										
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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. <u>Only enter the fraction of the day</u>, 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.

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.

- 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.

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 <u>in the Prior</u> <u>Center</u> 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.

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 (<u>www.astrodennis.com</u>) 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.
TFOP SG1 NEB Analysis Macro
This macro creates a number of products that are helpful in analyzing potential NEBs. Select one or more products that you would like to be produced:
✓ Option 1: A table showing which near-by stars are cleared as potential NEBs.
I ✓ Option 2: A plot for each near-by star's flux data with an overlay of NEB-required depth.
Select here if you would like the plots to both be displayed and saved in a subfolder
✓ Ontion 3: A plot of Delta magnitude vs. RMS for all stars within a user-defined radius of a target star
Option 4: Same as Option 3, but plot log10 of RMS vs. simply RMS.
AIJ name of target star (e.g., T1) T1
Radius of interest around target (arc-min.) 2.5
Enter cadence to use when calculating RMS (seconds) 67
✓ Use plate-solved image to get pixel scale and, for Option 1, PA's
If above is not selected, then enter the pixel scale (arc-sec/pixel)
Predicted ingress time (see Note 1 below) 0.596
Predicted egress time (see Note 2 below) 0.648
For Options 1 and 2: predicted depth of target star (ppt) 6.9
For Option 2: multiple of RMS used to eliminate outliers from plots 5
Select this box if you would like to turn on logfile diagnostics
Note 1: use decimal part only; however, add 1 if day rolls over from beginning of data
Note 2: use decimal part only; however, add 1 if day rolls over from ingress time
After clicking OK, you will be asked to select the measurement file from which the table and/or plot(s) will be generated.
OK Cancel
Figure 22 TFOP SG1 NEB Analysis Macro
The cadence is the time between successive images. You can calculate this by adding the experime

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.