

**TFOP SG1**  
**Observation Guidelines**

**Revision 6.4**

**September 4, 2020**

**Dennis M. Conti**  
**email: dennis@astrodennis.com**

## **Introduction**

This document provides guidelines that are recommended for observers participating in the TESS Follow-up Observing Program Working Group (TFOP WG) Sub Group 1 (SG1). **Substantive changes since the last X.Y revision are denoted in red.** SG1 is focused on seeing-limited imaging and primarily provides time-series photometric follow-up of TESS Objects of Interest (TOIs). Targets from Kepler's follow-on mission, K2, are also available for follow-up when no TOIs are available for a specific time and observatory location. TESS targets are identified with a TIC number; K2 targets are identified with an EPIC number. TFOP SG1 observation planning, coordination, and data submission web tools are available and are described herein.

Observers will use the TESS Transit Finder (TTF) for determining observable targets at their location. Using their sign-in credentials, SG1 members can access the TTF via the following link:

[https://astro.swarthmore.edu/telescope/tess/find\\_tess\\_transits.cgi](https://astro.swarthmore.edu/telescope/tess/find_tess_transits.cgi). A description on use of the TTF can be found as the first entry by Karen Collins at the following Google Groups link:

<https://groups.google.com/forum/#!topic/tfop-sg1/u2liQYveVSg>.

All observers should record their intention to observe a target, prior to the observation, by completing an entry in the TESS Observations Coordinator (TOC). The TOC can be found at the bottom of the TTF target entries, or via the following link: <https://www.astro.louisville.edu/tessplanner>. Some of the fields in the TOC can easily be populated by selecting "Add to TOC" that appears in the left column of the TTF entry for the target to be observed. Observers should read the *Help* link at the top of the TOC for instructions on how to use the TOC.

Observers should always review the last couple of sentences in the TTF comments field when planning observations to understand what is needed next, whether it is a "deep" observation or a specific filter, or something else. Deep observations mean that increased exposure times are needed in order to determine if there are any events associated with faint stars that are close-in neighbors of the target, and if such events could potentially be the cause of a false positive detection. Deep exposures may mean that the target star itself becomes saturated, which may be warranted in order to increase the SNR of surrounding faint stars.

It should be noted that the predicted transit depths in the TTF are in parts-per-thousand (ppt) rather than milli-magnitude (mmag). This is because TESS depth units themselves are in parts-per-million (ppm), so the ppt values can be easily directly compared to the ppm values (namely, by just applying a factor of 1000). Furthermore, because 1 ppt = 1.0863 mmag, ppt and mmag are sometimes used interchangeably for shallow transit depths. Also be aware of the timing uncertainty in the TTF since a transit you are attempting to detect may fall outside of the TTF predicted Start/End times.

SG1 ground-based observations will help serve the following purposes:

1. Verification that the target star was the source of the TESS or K2 detected event.
2. Identification of situations that might be causing the TESS or K2 detected event to be a “False Positive.” Common sources of such False Positives and the nomenclature associated with their classification are:
  - **NEB** (Nearby Eclipsing Binary): Indicates that the TESS detection was caused by a nearby eclipsing binary contaminating the TESS aperture, as determined from follow-up photometry that resolved the nearby eclipsing binary.
  - **BEB** (Blended Eclipsing Binary): Indicates that an eclipsing binary blended in both the follow-up and TESS apertures caused the TESS detection. These systems are generally classified as BEB as a result of a chromatic transit depth in follow-up photometry.
  - **EB** (Eclipsing Binary): Indicates that the TESS detection is caused by an event on target, but the event is too deep to be caused by an orbiting planet.
3. Confirmation for TESS or K2 events, which are too shallow to be detected from the ground, that all stars bright enough and close enough to the target star to potentially be NEBs are not NEBs contaminating the TESS aperture. In this case, if all the target and nearby star light curves are flat, then the target may be passed on to other TFOP sub-groups to conduct spectroscopy, radial velocity measurements, or adaptive optics observations. For K2 targets, bright stars in the field-of-view (FOV) are checked to determine if they might be contaminating the K2 detector column that contains the target (i.e., the so-called “Kepler column anomaly”).
4. Since TESS will only be observing a large part of the sky for 28 days, further follow-up observations of confirmed planets will help refine their ephemerides.

In addition to helping to classify TESS events as one of the three False Positives (i.e., NEB, BEB or EB), follow-up observations will help classify TESS events into additional disposition classifications (see Appendix A). Appendix B is a flow chart that shows the typical progression from one disposition to another as more information is obtained.

Because some of the analysis and file upload steps are dependent upon the purpose and results of the observation, the following cases are defined and will be referred to in later sections:

**Case 1:** An event was detected with a high level of confidence in the target star’s aperture.

**Case 2:** A nearby star was identified as an NEB.

**Case 3:** No events were detected with either the target or with any nearby stars that were checked.

Although this guide is based on AstrolmageJ (AIJ), the concepts herein should be applicable to other data reduction tools and pipelines as well. **IMPORTANT:** Observers who are using AIJ should upgrade their version of AIJ to the latest daily build. This can be done as follows: from the main AIJ toolbar, select Help->Upgrade AstrolmageJ... and then in the “Upgrade to” box, scroll UP and select “daily build.”

References to “A Practical Guide to Exoplanet Observing” (hereinafter referred to as the “Practical Guide”) will be made in this document. The latest version of the Practical Guide can be found at: <http://astrodennis.com/Guide.pdf>.

A copy of this document can be found at [http://astrodennis.com/TFOP\\_SG1\\_Guidelines\\_Rev\\_6-4.pdf](http://astrodennis.com/TFOP_SG1_Guidelines_Rev_6-4.pdf). Since this document is subject to change as modifications are made to SG1 submission requirements, the reader is encouraged to check the following location periodically to obtain the latest updated version of this document: [http://astrodennis.com/TFOP\\_SG1\\_Guidelines\\_Latest.pdf](http://astrodennis.com/TFOP_SG1_Guidelines_Latest.pdf).

The author would like to thank Karen Collins for her valuable comments. Comments and suggestions to further improve this document can be forwarded to: [dennis@astrodennis.com](mailto:dennis@astrodennis.com).

As seen below, there are two distinct communications to be done by the observer after the analysis of each target: (1) an email describing the observation and (2) an upload of a set of data products to either ExoFOP-TESS or ExoFOP-K2.

Section 1 describes the various files that will need to be uploaded, as well as their naming conventions, since reference will be made to them in later sections. Section 2 provides guidance on the differential photometry, model fitting, and analysis part of the observation, as well as on the creation of most of the files that are to be uploaded. Section 3 describes how some additional files are created that also must be uploaded. Section 4 discusses the contents of the observation emails and reports. And Sections 5 and 6 describe the guidelines for making an entry in and uploading files to ExoFOP-TESS and ExoFOP-K2, respectively.

## 1. Files and File naming conventions

As a minimum, the first eight (8) of the files below will need to be uploaded to ExoFOP-TESS or ExoFOP-K2. Depending upon factors described in Section 3, the following files may or may not have to be uploaded: plot of the delta magnitude vs. RMS of stars within a 2.5' radius of the target (File 9), an NEB report table (File 10), a .zip file of “shallowest event” plots (File 11), and a Zoomed-in FOV file (File 12).

File 1: An AstrolImageJ Photometry Measurement Table, usually with an extension of .tbl, .csv, .txt, or .xls (Note: It is preferred that AIJ measurement tables be created with an extension of .tbl. This extension can be chosen as the default for AIJ's measurement tables by selecting Edit->Options->Input/Output... from the main AIJ toolbar, and then entering .tbl for “File extension for tables.”)

File 2: An AstrolImageJ Plot Configuration File, with an extension of .plotcfg.

File 3: An AstrolImageJ Photometry Aperture File, with an extension of .apertures.

File 4: Light Curve Plots, with an extension of .png. Note: when it is not possible to easily fit the light curves of the final set of comparison stars underneath the light curves associated with the target star, then a separate file associated only with such comparison star plots may be necessary.

File 5: A Field Image with Apertures, with an extension of .png showing the full field-of-view along with the final selection of target(s) and comparison stars shown.

File 6: A Plate Solved Image (i.e., containing WCS FITS keywords), with an \*.fit, or preferably a \*.fits, extension.

File 7: A Seeing Profile, with an extension of .png.

File 8: A Notes and Results Text file, with a .txt extension, is a plain text copy of the body of the email observation report (see Section 4 below).

File 9: A Delta Magnitude (Dmag) vs. RMS plot .png file depicting a plot of the delta magnitude vs. RMS of stars (see Section 2.1 below).

File 10: An NEB Table .txt file showing which stars within a user-specified radius of the target star are cleared, or likely cleared, as potential NEBs (see Section 2.1 and Case 3 of Section 2.2 below).

File 11: A .zip file of NEB Depth Plot files for all measured stars within a user-specified radius of the target, where the star's plot shows the shallowest event required for that star to mimic the TESS predicted transit depth.

File 12: A Zoomed-in FOV .png file showing the information described in Section 3 below.

Files 1-5 are automatically created when the results of an AIJ analysis are saved – see Section 2.1, item 12.b below. As described below, AIJ can also be used to generate files 6, 7, and 9-12. File 8 can be created by a text editor.

Each of the above files should have a file name of the form

***targetname-pp\_yyyymmdd\_observatory\_filter\_filetype.ext***, where:

- ***targetname-pp*** is the TIC ID or EPIC ID, including the planet number (pp),
- ***yyymmdd*** is the UT date/time of the beginning of the observation,
- ***observatory*** is the name of the observatory,
- ***filter*** is the filter used,
- ***filetype*** is an abbreviated description of the type of file (see the examples below), and
- ***ext*** is the appropriate extension for the type of file.

If the target has a decimal suffix for the planet number (e.g., “.01”), it is important to include this suffix as part of the ***targetname-pp*** by prefixing the planet number (pp) with a “-” instead of a “.” As an example, for TESS target TIC32090583.01, the target name used in each file name would be TIC32090583-01. This suffix is important because it will help distinguish this planet candidate from others in a multiple planetary system. Also, for ***observatory*** and ***filetype***, include dashes between words if the observatory name or file type is more than one word.

An example of ***filetype*** for each of the above files can be seen in the following filename examples:

File 1: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_measurements.tbl

File 2: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_measurements.plotcfg

File 3: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_measurements.apertures

File 4: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_lightcurve.png

File 5: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_field.png

File 6: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_WCS.fit

File 7: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_seeing-profile.png

File 8: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_notes.txt

File 9: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_measurements\_dmagRMS-plot.png

File 10: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_measurements\_NEB-table.txt

File 11: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_measurements\_NEBcheck.zip

File 12: TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_field-zoom.png

As mentioned earlier for File 4, if a separate set of light curve plots are needed, then another file containing such plots would be labelled as:

TIC TIC32090583-01\_20181225\_LCO-CTIO-1m\_ip\_compstar-lightcurves.png

## 2. Analysis

This section is divided into two parts: those guidelines that are common to all three (3) observational cases identified earlier, and those guidelines that are case-specific.



### B.1. Case-Independent Guidelines

The following guidelines are to be followed for all cases:

1. The time system to be used in all observations and analyses should be BJD\_TDB (see Sections 7.2.2 and 7.6 of the Practical Guide how to include these values in an AIJ measurement table). Furthermore, when practical, it is best to keep a total cadence to no more than 2 minutes (including the time between exposures). However, if the transit duration is less than 30 minutes, then a cadence of 1 minute would be preferred, and if the duration of the overall observation is longer than 3-4 hours, then a cadence of 3 minutes would be acceptable.
2. Plate solve at least the first image in your ensemble of calibrated images. This will correctly set the North/East (N/E) arrows on AIJ's Image Display so that any subsequent images will also show the correct orientation. Copy this plate-solved image to a file and name the file using the naming conventions for File 6 as described in Section 1 above. This plate-solved image will later be uploaded to ExoFOP-TESS or ExoFOP-K2. It is desired that the image be oriented such that North is as close to pointing "up" in the vertical direction as possible, and East is as close to "left" as possible (see the example in Attachment C). In AIJ, this can be done using the View menu options on the Image Display.
3. Create a Seeing Profile plot, based on the target star, from the first calibrated (and plate-solved) image. If the target star is saturated, then a near-by bright star would be used as the basis for the Seeing Profile plot. Section 7.5.1 of the Practical Guide discusses how to create such a plot. Once created in AIJ, the plot may be saved to a .png file by clicking on the Save button on the lower left of the Seeing Profile plot screen. Name this file using the naming conventions for File 7 as described in Section 1 above. This file will also later be uploaded to ExoFOP-TESS or ExoFOP-K2.

4. If a TESS event has not previously been confirmed to occur in the target star from prior follow-up observations, it is best to define the stars within 2.5' of the original target as "target" stars. This can be done in AIJ by holding the shift key when placing apertures on them. Comp stars with brightness similar to the target should then be chosen outside the 2.5' radius. Although this approach is contrary to the common practice of choosing comp stars nearest the target, it is appropriate for doing a search of potential NEBs. However, if comp stars are in short supply, it is fine to choose bright stars within the 2.5' as comps, but they should then be individually checked for NEBs.


AIJ users should use the tools described in 9. below and in Appendix D to place apertures within 2.5' of the target.

5. A circle of 2.5' radius can be drawn around the target star (see Appendix C as an example), by performing the following steps:
  - a. Under Annotate at the top of the Image Display, 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.
  - f. Clicking OK will then put a circle of radius 2.5' around the target star.
6. To improve readability, especially when selecting many comparison stars and when creating the zoomed-in field (File 12), it is advisable to only display the photometry aperture and not the annulus. This can be done by deselecting (if it is gray) the  icon on AIJ's Image Display, as well as by turning off the display of the integrated counts using the icon .
7. All field-of-view images should be saved at very high contrast so that the faintest stars can be easily seen. This typically also means that the noise in the dark portion of the image can be seen. This allows reviewers to clearly see all faint stars in the images. Observers can do this by using a new feature that has recently been added to the AIJ daily build. To use it, display the first image in an image stack and then adjust the contrast sliders in the histogram below the image until all of the detail in the faint parts of the image can be seen. If more fine-grained control of the histogram is needed, enable Scale->"Use fixed min and max histogram values" and then enter a custom number, such as 3000, in the "max" box at the bottom-right of the histogram. Next, at the top of the Image Display, select Scale->"Grab auto brightness & contrast from histogram". Now when images are scrolled through in the stack, the same relative contrast and brightness will be maintained. When finished, use Scale->"Reset auto brightness & contrast to defaults" to return the histogram to its previous settings. Finally, the "Auto-grab auto brightness and contrast from histogram" option, which is enabled by default, automates the "Grab auto brightness and contrast from histogram" feature any time a histogram change occurs, without the user having to go back to the Scale menu and clicking "Grab auto brightness and contrast from histogram."




8. From the plot of each comparison star, note which ones have a lot of scatter. Using AIJ's Multi-plot Reference Star Settings screen, deselect such stars (this will cause each star's annotation to go from Cx to Tx).
9. Two new tools are now available that work together to assist AIJ users (and reviewers) in analyzing which stars might potentially be an NEB that is producing an event that could be the source of the TESS detection (i.e., is the cause of a "false positive" detection). Unless the user knows that an event has already been detected on target (i.e., has a classification of VPC or VPC+) or all of the potential NEBs have been cleared from the field (i.e., has a classification of CPC), using these tools will help determine which Case (1, 2, or 3) should be followed.

The first tool is implemented as a web-based application. This tool creates an AIJ \*.radec aperture file for all stars in the Gaia database that need to be checked as possible NEBs. Using this tool to define the apertures around the target will also help make the aperture numbers uniform from observer to observer. In addition to this web-based application, the TTF now includes a link that allows the user to directly download this aperture file. Appendix D contains instructions for using both of these methods for obtaining the \*.radec aperture file.

The second tool is implemented as an AIJ macro that takes as input the AIJ measurement table produced from the multi-aperture photometry based on the Gaia star apertures created from the first tool. It creates a number of products that help determine which stars, within a nominal 2.5' radius of the target, can be cleared as not being an NEB that could cause the TESS detected event. Appendix E includes instructions for using this NEB analysis tool.

10. If a particular star that you are trying to select as a comp or target star is too close to another star, you may find that, with "centroid apertures" turned on, AIJ will not put the aperture on the subject star, but rather will keep putting it on the nearby star. If this is the case, the following approach can be tried. On the Image Display, you will see the following icon when "centroid apertures" is selected: . When it is gray'ed out, then AIJ will attempt to place the aperture on the centroid of a star. However, for stars close to each other, AIJ may always place it on one and not the other. In such a case, to force AIJ to place the aperture on a particular star, select the above icon, which will un-gray it. Once you have manually placed the aperture on the center of the star, select the icon again where it will turn back to the state as shown above. For the remaining comp star selections, AIJ will then use the automatic "centroid aperture" mode. This allows you in one photometry run to use both the automatic and manual aperture selection modes on different stars, during which the uncentroided apertures will track the relative motions of the centroided apertures (note that T1 must be a centroided aperture to enable this feature).
11. Create a Light Curve image showing on it the following time series plots (Section 2.2 describes additional plots that should be included and that are case-specific):
  - a. In all cases, the predicted ingress/egress times obtained from the TTF should initially be entered in the Left and Right boxes under the Fit and Normalization Region Selection screen, as well as in the V.Marker fields. The V.Markers should then not be changed during the analysis, however, the left and right markers in the Fit and Normalization Region area can be adjusted to mark the apparent ingress and egress if either doesn't seem to happen

on time.

- b. In all cases, an unfitted plot of the light curve of the original target, with no detrending, should be the first plot. This is accomplished in AIJ by selecting the Fit Mode of “off.” In addition, the associated RMS should also be displayed. This is done as follows: on AIJ’s Multi-plot Main screen under the Legend section, click the “wrench” icon  and select “Append Std. Dev. to legend for all absolute curves.” Finally, this raw, unfitted undetrended light curve should always be plotted with Bin Size=1 and a Shift value of 0.0 on AIJ’s Multi-plot Y-data screen.
- c. The following two other Light Curve plots of the target should then be included for all cases, except when an NEB has been detected (i.e., Case 2). For both plots, start with an initial Bin Size that when multiplied by the exposure time, results in a value close to 3-5 minutes.
  - i. A plot of the target’s raw data with out-of-transit (OOT) data detrended. This is accomplished in AIJ by using the Fit Mode of  and a Norm/Mag Ref selection of , and making sure that the Right and Left values have been appropriately entered in the Fit and Normalize Region Selection area on AIJ’s Multi-plot Main screen.
  - ii. A transit model fitted plot of the target with appropriate detrending.

d. If a meridian flip occurred, this should be so indicated on the plot.

e. The Title at the top of the Light Curve should ideally be of the form:

**TIC NNNNNNNNN.pp UTyyyy.mm.dd**

where **NNNNNNNNN** is the TIC number, **pp** is the planet number, and **yyyy, mm, dd** are the year, month, and day of the beginning of the observation.

Also, the Subtitle underneath the Title should ideally be of the form:

**Observatory (f filter, nn exp, fap aa-bb-cc)** where,

**Observatory** is the name of the observatory, **f** is the type of filter used, **nn** is the exposure time in seconds, and **aa,bb,cc** are the aperture radius, inner annulus radius, and outer annulus radius respectively (note: “fap” stands for follow-up aperture).

The following is an example of such a Title and Subtitle:

TIC 32090583.01 UT2018.12.25  
LCO-CTIO-1m0 (ip filter, 120 exp, fap 12-27-41)

f. The bottom of the Light Curve image should contain the following additional plots:

- i. A plot of Width\_T1 – this is the mean of the X- and Y- direction FWHM of the target.



- ii. A plot of Sky/Pixel\_T1 – this will show changes in the background sky that is frequently associated with systematics.
- iii. A plot of (inverted) AIRMASS with tot\_C\_cnts overlaid on it - this will show what the transparency was like at the time of the observation.
- iv. Plots of X(FITS)\_T1 and Y(FITS)\_T1 – this will reflect the image shift during the observation.

HINT: Due to the wide range of values for items i-iv, it is advisable to select Page Rel on AIJ's Multi-plot Y data screen for these items. When Page Rel is selected, Scale is interpreted as the % of the plot's Y-range that the data should be scaled, and Shift is interpreted as the % of the plot's Y-range that the data should be shifted. To invert a data item, such as AIRMASS, the value for Scale should be negative. Suggested Scale and Shift values for items i-iv, as well as colors, are:

	<u>Scale</u>	<u>Shift</u>	<u>Color</u>
Width_T1	15	-42	light gray
Sky/Pixel_T1	15	-42	yellow
AIRMASS	-15	-42	teal
tot_C_cnts	15	-42	brown
X(FITS)_T1	15	-42	pink
Y(FITS)_T1	15	-42	light blue


12. After completing the differential photometry and model fitting:
  - a. Create and append to the currently open measurement table the relative, normalized flux values, and their associated errors, for the target star – see Section 7.12 of the Practical Guide how to do this.
  - b. Finally, save all relevant files by selecting File->Save all... in the upper left on the Multi-plot Main screen. When the “Save all” dialogue screen appears, enter in the “File name” section the file name and extension of the measurement table. If the file naming convention described in Section 1 above is followed for the measurement table, then this same file name will also be used for Files 2-5 that AIJ will also automatically create at this time.

## 2.2. Case-Dependent Guidelines

The following guidelines dealing with the analysis phase are case-specific:

### Case 1 –An event was detected with a high level of confidence in the target star’s aperture

In cases where there is a clear detection of an event on the target, and no False Positive was found, then

include in the Light Curve image the fitted light curve of the target. This is done by selecting the  icon as the Fit Mode on AIJ's Multi-plot Y data screen. Also make sure that the Scale entry on the Multi-plot Y-

Data screen for this row is set to 1.0. If there is no detection of an event on-target, then a second run should be run to try to clear the field of possible NEBs (see Case 3).

If attempting to detect sub 3-4ppt transits, include in-transit model residuals, which should be much smaller than the transit depth being measured, so that a reasonable shallow detection can be claimed.

To optimize a full transit model fit, move the Left and Right Fit and Normalize values to what visually appears to be the ingress and egress respectively. The Left and Right markers should generally be separated by the same distance as between the predicted ingress and egress markers (i.e., the V.Markers). Then, initially select AIRMASS as the only detrend parameter, sequentially deselect/select comparison stars to achieve the lowest RMS, and then try detrending again with other parameters until the lowest BIC (Bayesian Information Criterion) is achieved (note: this value appears on AIJ's Data Set Fit Settings screen). If adding the best detrend parameter reduces BIC by more than 2.0, then keep the detrend parameter. Otherwise, do not detrend the light curve. A second detrend parameter can be considered if it reduces the BIC by more than 2 below the single detrend parameter's BIC. Use at most two (2) detrend parameters. Following the selection of any new detrend parameters, complete another round of sequentially deselecting/selecting comparison stars to see which ones achieve the lowest RMS.


For partial transits, detrending may produce undesirable results since out-of-transit (i.e., "baseline") data are not available to constrain the fit on both ends. If there is an obvious curvature in the out-of-transit data of the partial transit, then AIRMASS detrending may be warranted. If a straight line trend is obvious in the baseline, then time (e.g., BJD\_TDB) detrending may be warranted as a detrend parameter. If a meridian flip (MF) occurred, then only the MF should be used as a detrend parameter, UNLESS there is a strong trend in the light curve affected when either AIRMASS or time is also selected as a detrend parameter. In any case, for a partial transit, if the transit shape changes dramatically, detrending may not be giving a valid result.

The light curves of 5-6 comparison stars, each of which are detrended only with Airmass, should be included. Since for this case there is a detection of an event on target, there is no need to search for events in nearby, faint stars.

For this case, observers should first determine the photometric aperture that results in the smallest scatter (i.e., RMS) of the fitted light curve. This is the light curve that should be included in the Light Curve image described in Section 2.1, item 11. However, smaller apertures should be tested to determine the smallest aperture that will result in a light curve shape and depth that is similar to the light curve produced by an aperture with the smallest scatter. This second aperture size should also be reported in the observation email and report (see Section 4.2, Case 1 below).


## Case 2 – A nearby star was identified as an NEB

If a comparison or nearby "target" star shows an event, it could be an NEB or a Nearby Planet Candidate (NPC) – see Appendix A for a complete definition of an NPC. If observational data exists for the full predicted transit duration, along with sufficient pre-ingress and post-egress out-of-transit data, then the Fit

Mode using the icon  should be used with no detrending, unless a meridian flip occurred. To select meridian flip as a "trend", perform the following for the NEB's entries on AIJ's Multi-plot Y data screen:

1. Click on a box under Trend Select to turn it green.

2. If the circle in the box is selected, then the detrend parameter associated with that box appears under the Trend Dataset column for that row.
3. Select meridian flip as the appropriate detrend parameter in the Trend Dataset dropdown menu.

In addition, a fitted version of the NEB light curve can be included by selecting the  icon as the Fit Mode, as described for on-target events in Case 1. This is optional depending on observer preferences and plotting space available.

Just as in Case 1 above, make sure that the Scale entry on AIJ's Multi-plot Y-data screen is set to 1.0 for the NEB plot. Otherwise, the visual representation of the NEB's depth will be scaled to whatever value you have in the Scale entry.

If an NEB is detected, there is no need to include the light curves of other comparison stars, or to upload Files 9, 10, and 11.

When the NEB is deselected as a comparison star and therefore becomes a "target," you may also see that this dramatically affects the light curve of the original target, as well as the other comparison stars, since its deep depth as a comparison star was disproportionately affecting the target star, as well as the other comparison stars.

**Case 3 – No clear detection of an event associated with the target or any nearby stars**

This is likely to be the case where the transit is too shallow to be detected from the ground. In this case, we are generally trying to exclude as NEBs all of the stars that are within a 2.5' radius of the target. The fainter a nearby star is, the deeper the event for that star has to be in order to produce the predicted target depth. However, the fainter the star, the greater is the light curve scatter (i.e., its RMS).

The differential photometry run in this case generally is done with a smaller aperture and fainter comparison stars than in Case 1.


In order to know which stars within the 2.5' radius are "cleared" as not being a potential NEB, an "NEB Table" should be created, as described below. First, however, consider Table 1 that shows, for a given predicted depth, the delta magnitude ( $\Delta\text{mag}$ ) down to which nearby stars should be checked.

**Table 1.**

Predicted Depth (ppt)	$\Delta\text{mag}$ (mag)
0.1	10.0
0.2	9.2
0.3	8.8
0.4	8.5
0.5	8.3
1.0	7.5
2.0	6.7
3.0	6.3

4.0	6.0
5.0	5.8
10	5.0
20	4.2
30	3.8
40	3.5
50	3.3
100	2.5

Thus, given the predicted depth of the original target, stars that are within 2.5' of the original target star and are brighter than the  $\Delta\text{mag}$  associated with this predicted depth, should be included in the NEB Table. For each star that meets this criterion, the NEB Table should include the following information:

1. The distance (d) in m'ss" (arc-minutes and arc-seconds) from the original target to the star.
2. The delta magnitude ( $\Delta\text{mag}$ ) of the star relative to the original target.
3. The position angle (PA) in degrees of the star.
4. The star's RMS in ppt. The Fit Mode for the star's light curve should be "off" or the straight line, all green icon . In the case of the all green icon, no detrend parameters should be enabled, except meridian flip, if one occurred. The RMS value used should be after the data is binned to approximate three-minute equivalent exposures.
5. The depth of an NEB ("NEBdepth") that would be needed to produce the predicted target depth (PredTargetDepth). This is calculated for each star by the following formula:

$$\text{Let } X = 10^{(-\Delta\text{mag}/2.5)}$$

$$\text{NEBdepth} = \text{PredTargetDepth}/X.$$

In order to compensate for the difference between the TESS band and the filters typically used in the follow-up observations, a -0.5 mag correction is made to  $\Delta\text{mag}$  in the above calculation.

6. The value NEBdepth/RMS is calculated for each star.
7. And finally one of the following dispositions should be noted for the star, based on the accompanying criteria:
  - Cleared-too faint - the star is too faint to have caused the TESS event detection
  - Cleared - NEBdepth /RMS  $\geq 5$
  - Likely cleared - NEBdepth/RMS is between 3 and 5
  - Not cleared-flux too low - there is not enough flux in the aperture to measure a reasonable  $\Delta\text{mag}$
  - Not cleared - if none of the above apply.

In the case of the star being "Likely cleared," its undetrended light curve should still be checked to see if an NEB event occurred. The quantitative criteria used for the "Not cleared-flux too low" disposition is if the (weighted) average of the star's Source-Sky counts per aperture pixel is less than 10. The quantitative criteria used for "Cleared-too faint" is if NEBdepth is  $\geq 1000$  ppt. Finally, if a star is not cleared by simple RMS analysis, inspect the star's light curve for obvious eclipse events.

Consider the example in Appendix C for a sample target T1. Assume that the predicted depth of the target is 50 ppt. Table 1 then suggests that nearby stars that have a delta  $\Delta\text{mag}$  of 3.3 mag or less than the target star should be included in the NEB Table. From the example in Appendix C, at least two stars, T4 and T10

with  $\Delta\text{mag}$ 's of 2.91 and 1.06 respectively, should thus be considered.

Assuming that the RMS values (in ppt) for stars T4 and T10 are 3.01 and 4.02, respectively, then the NEB Table rows for the two stars in this example would be:

<u>Star</u>	<u>Separation from target (")</u>	<u>PA (deg.)</u>	<u><math>\Delta\text{mag}</math></u>	<u>RMS (ppt)</u>	<u>NEBdepth (ppt)</u>	<u>NEBdepth/RMS</u>
T4	00'49"	298	2.91	3.01	729.4	242.3
T10	01'59"	165	1.06	4.02	132.7	33.0

Because  $\text{NEBdepth/RMS} > 5$  for both stars, they would be cleared as not being a source of a False Positive.

For AIJ users, an AIJ aperture file can be automatically created from Gaia data that essentially uses the equivalent calculations of Table 1 to find those stars that need to be checked as possible NEBs causing the TESS detection. This is done using one of two methods (see Appendix D) that extracts all of the Gaia stars that need to be checked for NEBs and produces an AIJ \*.radec aperture file that the user can use during the multi-aperture photometry process. The aperture file can then be dragged and dropped onto the first image of an AIJ stack prior to conducting the multi-aperture photometry. Conducting the multi-aperture photometry with the star locations in the aperture file thus covers all stars that need to be checked for NEBs.

Furthermore, using a new AIJ NEB analysis tool (see Appendix E), the NEB Table can be automatically created from an AIJ measurement file, ideally from one resulting from the multi-aperture photometry that employed the above tool. A .txt file is automatically generated by this tool and can directly be used as File 10 above (see Appendix E, Figure E-2). The NEB table feature of this tool will also provide the user with statistics on the average aperture radius and the amount of image shift in X and Y during the observation, both of which will be helpful in filling out other information required for the observation report. Appendix E provides detailed instructions on the use of this NEB analysis tool.

As a companion to the NEB Table, the above-mentioned AIJ NEB analysis feature can also produce a plot for each star within a user-specified radius, showing the star's data points and an overlay depicting the "shallowest event" that could produce the TESS detection (see Appendix E, Figure E-3). The user can then visually judge if the marginal "Likely cleared" stars are truly cleared. A subfolder containing a .png file for each such plot is generated. Files in the subfolder can then be zipped by the user and submitted as File 11 above.

Finally, this NEB analysis feature also allows for a plot of  $\text{d}\text{mag}$  vs. RMS to be produced for all measured stars within a user-defined radius (see Appendix E, Figure E-4). Such plots are typically of an exponential nature and will help indicate which comparison or target star might be an EB or NEB. Such stars typically are "off the curve" shown for the other stars. A .png file is automatically generated for this product and can directly be used as File 9 above. The user can optionally select that the plot be generated as  $\text{D}\text{mag}$  vs.  $\log_{10}(\text{RMS})$ , which typically produces a straight line vs. an exponential plot.

If this new AIJ NEB analysis feature is not used, then AIJ users can manually gather the above NEB Table information as follows:

1. Items 1-3 above can be found by performing the following steps on a plate-solved image (note: make sure that you have the latest AIJ daily build): (1) place the cursor on the original target star, (2) hold the center or right mouse button down, or hold alt and use the left mouse button (or for

Mac users, control-command-click drag), (3) move to the nearby star, and release the mouse button.

2. The RMS for a star's fit is available from AIJ's light curve legend for that star. RMS in ppt is obtained by multiplying this value by 1,000. Binning of the data to achieve RMS values for the equivalent of a three minute cadence (for exposures shorter than 1 minute) can be done by knowing the exposure time and employing the corresponding "Bin Size" control on the Multi-plot Y-data panel to get this three-minute equivalent.

The NEB Table should be included in the observation email and report, as well as uploaded to ExoFOP (see Section 4.2, Case 3).

### 3. Create Additional Upload Files

After the above steps in Section 2 are completed, Files 1-7 should have been created. In addition, a plain text file should be created by the observer that contains the body of the observation email described in Section 4 below. The file name of this file should conform to that of File 8 in Section 1 above.

If there was no event detected on target (i.e., Case 3), then an NEB Table as described above should have been created

Finally, an optional file, a Zoomed-in FOV (File 12), should be created under the following circumstances:

1. If an event is detected with the target and its photometry aperture overlaps with a nearby star.
2. If an event is not detected with the target. The Zoomed-in FOV image should then show the stars within 2-3 arcminutes of the target. Ideally, this would be a 6'x6' view around the target star. It is also best for this view to turn off the background annulus rings in order to provide less clutter in the view.
3. If an event is detected with a star near the target. The Zoomed-in FOV image should then show the  $\Delta$ mag and distance vector to the star relative to the target. This can be done in AIJ by Ctrl, right mouse click and drag, or click on mouse scroll wheel and drag.
4. If there is no detection of an event in the target or in a nearby star. The Zoomed-in FOV should then show the  $\Delta$ mag and distance vector to the faintest star checked by the observer that is cleared by the NEBdepth/RMS.

The contrast for the Zoomed-in FOV should be increased so that the faintest stars can be seen in the image. The feature described in Section 2.1, item 7 describes how this can be accomplished.

### 4. Observation Email

Emails describing the observation should be sent to [tfopsg1@gmail.com](mailto:tfopsg1@gmail.com) and should contain the following information. Just as with the Light Curve plot, there is some information independent of the observation case that should be included in the body of the observation email, as well as information that is case-dependent.

#### 4.1. Case-Independent Information

The following guidelines apply to all observation emails:

1. The subject line of the email should be of the form as shown in the following example:  
TIC 32090583.01 (TOI-218.01) on UT2018.12.25 from LCO-CTIO-1m in ip.  
That is, the target name, the associated TOI number, the UT date of the beginning of the observation, the name of the observatory, and the filter used in the observation. Make sure that there is a space between “TIC” and the TIC number.
2. A short statement describing the goals of the submitted run.
3. A short statement describing your interpretation of the results.
4. The radius of the photometry aperture in arc-seconds.
5. The predicted transit center time from the TTF.
6. An indication of any Gaia stars that are contaminating the aperture and FWHM of the target star.
7. A statement indicating if the appropriate files have yet been uploaded to ExoFOP-TESS or ExoFOP-K2.
8. Other observation notes such as if a meridian flip occurred, maximum and standard deviation of image shift in pixels and arc-seconds, seeing conditions, other local conditions (e.g., light wind), any detrend parameters used.
9. If other observations have been done of this target, then a copy of the notes in the TESS Transit Finder (TTF) entry for this target
10. For all cases, attachments to the email should include Files 1, 2, 4, 5, and 7.

#### **4.2. Case-dependent Information**

The following guidelines apply to case-specific information that should be included in the observation email.

##### **Case 1 – An event was detected with a high level of confidence in the target star’s aperture**

The size in pixels and arc-seconds of the smallest aperture that produces a light curve shape and depth comparable to the light curve reported for the aperture that produced the light curve with the smallest scatter (see Section 2.2, Case 1).

Differences between predicted vs. observed mid-point transit times, as well as any differences between predicted vs. observed transit durations.

The approximate depth of the event in the target star.

Include as an attachment File 12, a Zoomed-in FOV if one was created (see Section 3).

### **Case 2 – A nearby star was identified as an NEB**

If an NEB is discovered, then the depth of the NEB's event as estimated from its light curve, and distance and between the target and the NEB, as well as the direction of the NEB relative to the original target (e.g., South-Southwest "SSW").

### **Case 3 – No clear detection of an event associated with the target or any nearby stars**

If the predicted depth is too shallow to be detected by the observer and there are no events in nearby stars, then the NEB Table described in Section 2.2, Case 3 should be reported.

Include as attachments File 10 (the NEB table) and File 12 (a Zoomed-in FOV) - see Section 3.

## **5. Uploads to ExoFOP-TESS**

The following is the procedure for uploading the appropriate files to ExoFOP-TESS (<https://exofop.ipac.caltech.edu/tess/>). Note, this presumes that the observer already has login credentials to ExoFOP-TESS; if not they can be applied for by clicking on "Request an account."

To upload a TESS (i.e., TIC) observation to ExoFOP-TESS:

1. Login to ExoFOP-TESS and enter into the search box the TIC ID (that is the TIC number WITHOUT the "TIC") **or using the TOI number**.
2. Under the Time Series Observation section for this TIC, click "Add new."
3. Enter the appropriate information in the pop-window:
  - a. For "Estimated PSF" enter the FWHM in arc-seconds of the target star at the beginning of the observation. The FWHM in arc-seconds can be found at the top of the Seeing Profile image of a plate-solved image. For Faintest Neighbor  $\Delta$  Magnitude, if an NEB is found, enter the magnitude difference between the target and the NEB, otherwise enter the magnitude difference between the target and the faintest star in the field for which you checked for an NEB and the NEBdepth/RMS>5 test passed.
  - b. When entering a "Tag," see the notes on the bottom of the pop-window Data Tagging. A suggested template for each new tag is: YYYYMMDD\_username\_timeseriesplot\_0001, where only the date might change. However, if more than one observation is uploaded per night, then 0001 would change to 0002, etc. Note that the four text substrings must be separated by three underscores.
  - c. For the Notes item, enter any relevant information such as weather conditions, whether a meridian flip occurred, etc. If you don't care that the public will be able to see your assessment of the nature of your observation (e.g., if an NEB was found), then you may also include this information in the Notes section as well. However, do not include any



information in the Notes section that you want to keep protected within the TFOP team and covered by the TFOP Publication Policy.

- d. When you have completed your entry, click “Add Time Series.”
4. The file uploads should then take place as follows. Under the Files section, click “Add new.” Select “Light\_Curve” as the Type for ALL files. File names should be of the format described in Section 1 above. Furthermore, the Description fields for the various file types should be as follows:

- File 1: AstrolImageJ Photometry Measurement Table
- File 2: AstrolImageJ Plot Configuration File
- File 3: AstrolImageJ Photometry Aperture File
- File 4: Light Curve Plot
- File 5: Field Image with Apertures
- File 6: Plate Solved Image
- File 7: Seeing Profile
- File 8: Notes and Results Text
- File 9: Dmag vs. RMS plot
- File 10: NEB Table
- File 11: NEB Depth Plots
- File 12: Zoomed-in FOV

If there is a separate file for comparisons star plots, upload it as well with a description field of “Compstar Light Curve Plots.”

5. The Tag for each file would be the short-hand, integer version that was created for the associated Time Series Observation entry. This short-hand version is the integer value to the far right of the associated Time Series Observation entry.
6. For files that you upload to ExoFOP-TESS, there is a dialog option to select a 0 or 12 month proprietary period (note: ExoFOP-K2 has no such proprietary period). You should choose the 12 month proprietary period and the Group designation should be “tfopwg.”
7. Click Upload when ready to upload a file.
8. Repeat steps 4-7 for each file to be uploaded.

Note: Work is ongoing with NExSci to provide an alternative to the upload method described above that will simplify the upload process.

## 6. Uploads to ExoFOP-K2

The following is the procedure for uploading the appropriate data products to ExoFOP-K2 (<https://exofop.ipac.caltech.edu/k2/>) for K2 targets. The same credentials for ExoFOP-TESS can also be used for ExoFOP-K2.

To upload a K2 (i.e., EPIC) observation to ExoFOP-K2:

1. Login to ExoFOP-K2 and enter into the target name search box the EPIC ID (that is the EPIC number WITHOUT the “EPIC” and WITHOUT any decimal numbers).
2. Under the Imaging Observations section, click “Add new.”
3. Enter the appropriate information in the pop-window. Note, for “Estimated PSF” enter the FWHM in arc-seconds of the target star at the beginning of the observation, since it may change throughout. The FWHM in arc-seconds can be found at the top of the Seeing Profile image of a plate-solved image. For Estimated Contrast, if an NEB is found, enter the magnitude difference between the target and the NEB, otherwise enter the magnitude difference between the target and the faintest star in the field for which you checked for an NEB. Also, enter here the separation (in arc-seconds) between the target star and either the NEB or the faintest star checked. For the Notes item, enter information as described above for ExoFOP-TESS entries. When you have completed your entry, click “Add Imaging.”
4. The file uploads should then take place as follows. Under the Files section, click “Add new.” Select “Photometry” as the Type for ALL files (NOTE: this is different than the Light\_Curve type entered above for ExoFOP-TESS entries). File names should be of the format described in Section 1 above. Furthermore, the Description fields for the various file types should be as described above for ExoFOP-TESS file uploads.
5. Click Upload when ready to upload a file.
6. Repeat steps 4-5 for each file to be uploaded.

## Appendix A: Additional Classifications

**VPC (Verified Planet Candidate):** Indicates that the event has been verified by SG1 follow-up to occur on target and that there are no other obvious or Gaia DR2 stars contaminating the follow-up aperture. These planet candidates will generally be retired from the TTF, but may sometimes be left active if there is a need to collect light curves in other filter bands for the purposes of publication (or to potentially reclassify the target as a False Positive if chromaticity is found).

**VPC+:** This is a VPC with no obvious depth chromaticity.

**VPC-:** This is a VPC, but the follow-up aperture is contaminated.

**CPC (Cleared Planet Candidate):** Indicates that the TESS detected event is too shallow to be detected with ground-based photometry, but that follow-up observations have ruled out all obvious and Gaia DR2 stars as potential causes of the TESS detection. In other words, no NEBs have been found in stars that are close enough and bright enough to have caused the TESS detection. These planet candidates will generally be retired from the TTF.

**PPC (Promising Planet Candidate):** Indicates that all nearby stars have not been rigorously ruled out as being the potential cause of the TESS detection, but that follow-up observations have found no NEBs in obvious nearby sources. These planet candidates will be left active on the TTF in hopes of eventually ruling out all potential sources of NEBs and promoting the candidates to CPC status. TOIs with a transit deep enough to firmly detect from the ground will also be classified as PPC if the transit event has possibly been detected in follow-up observations at low significance, or if a transit is detected with high significance, but the follow-up aperture is contaminated with a nearby star that is bright enough to have produced the TESS detection. SG2 (and other Subgroups) will be notified that the planet candidate has been promoted to PPC status, which may provide more incentive for SG2 observers to collect recon spectroscopy simultaneous to the continued SG1 observations.

**PC (Planet Candidate):** Indicates a new planet candidate with no follow-up observations, or with follow-up observations that are so far inconclusive.

**NPC (Nearby Planet Candidate):** Indicates that the TESS event is caused by an event on a nearby star, but the event is still consistent with a potential planet around the nearby star. The nearby star will be assigned a new TOI number, and will have an initial disposition of PC. When the new TOI is assigned, the NPC TOI will be retired as a False Positive.

**PNEB (Possible NEB):** A possible NEB was detected in a single epoch.

**P (Confirmed Planet):** Indicates a confirmed planet with a mass measurement.

**STPC (Single Transit PC):** Indicates that there was a single transit detected in the TESS data.

**VP (Validated Planet):** Indicates a statistically validated planet that does not have a mass measurement.

**KP (Known Planet):** Indicates an already known and confirmed planet.

**SB1 (Spectroscopic Binary - Single-lined):** Indicates that the RV measurements from SG2 are too large to be

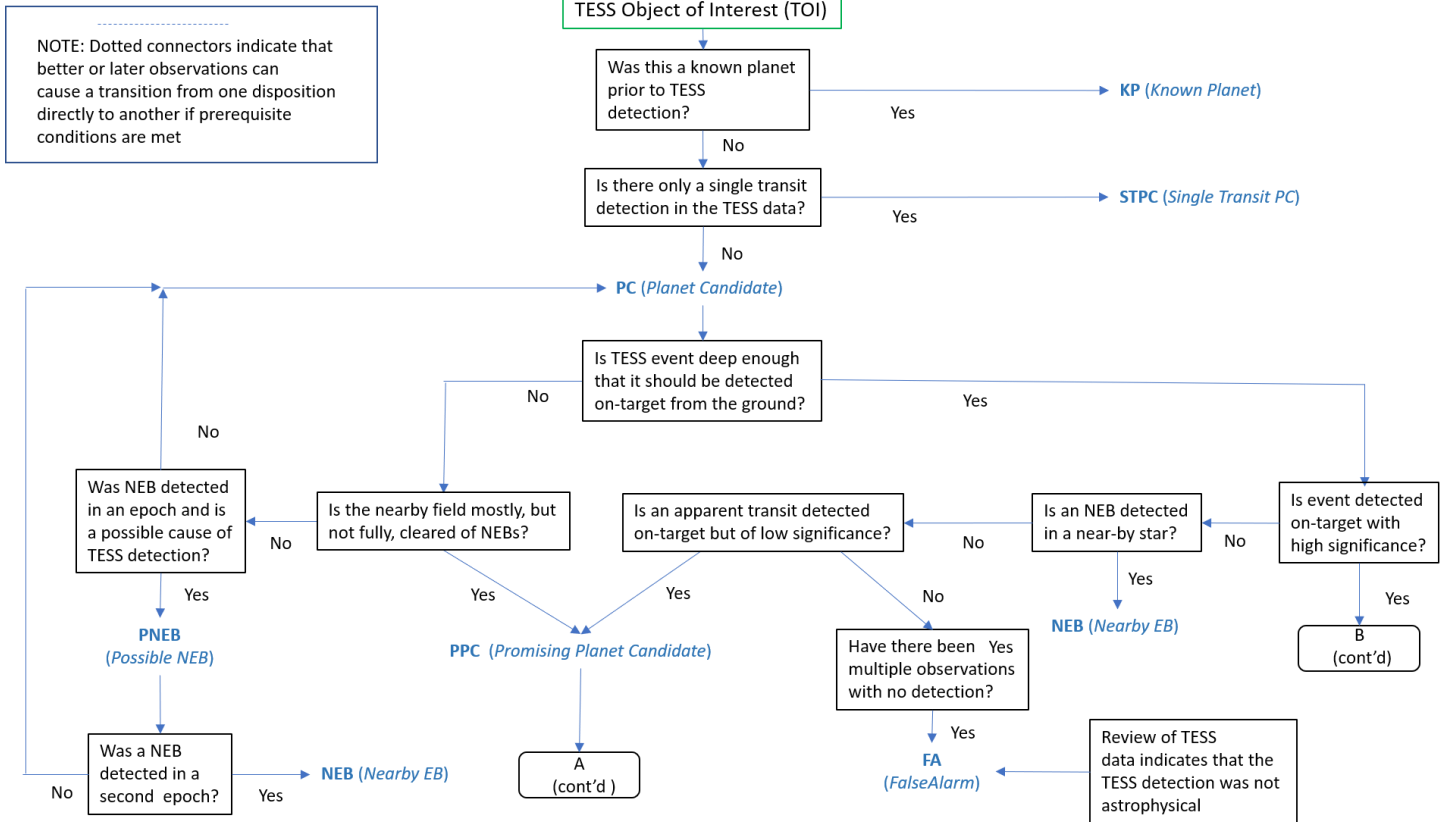
caused by an orbiting planet.

**SB2 (Spectroscopic Binary - Multi-lined):** Indicates that the target star(s) spectrum is multi-lined which suggests that the TESS event is caused by a blended or hierarchical eclipsing system. These are not necessarily false positives, but usually prove to be false positives, so additional spectroscopy is often not pursued.

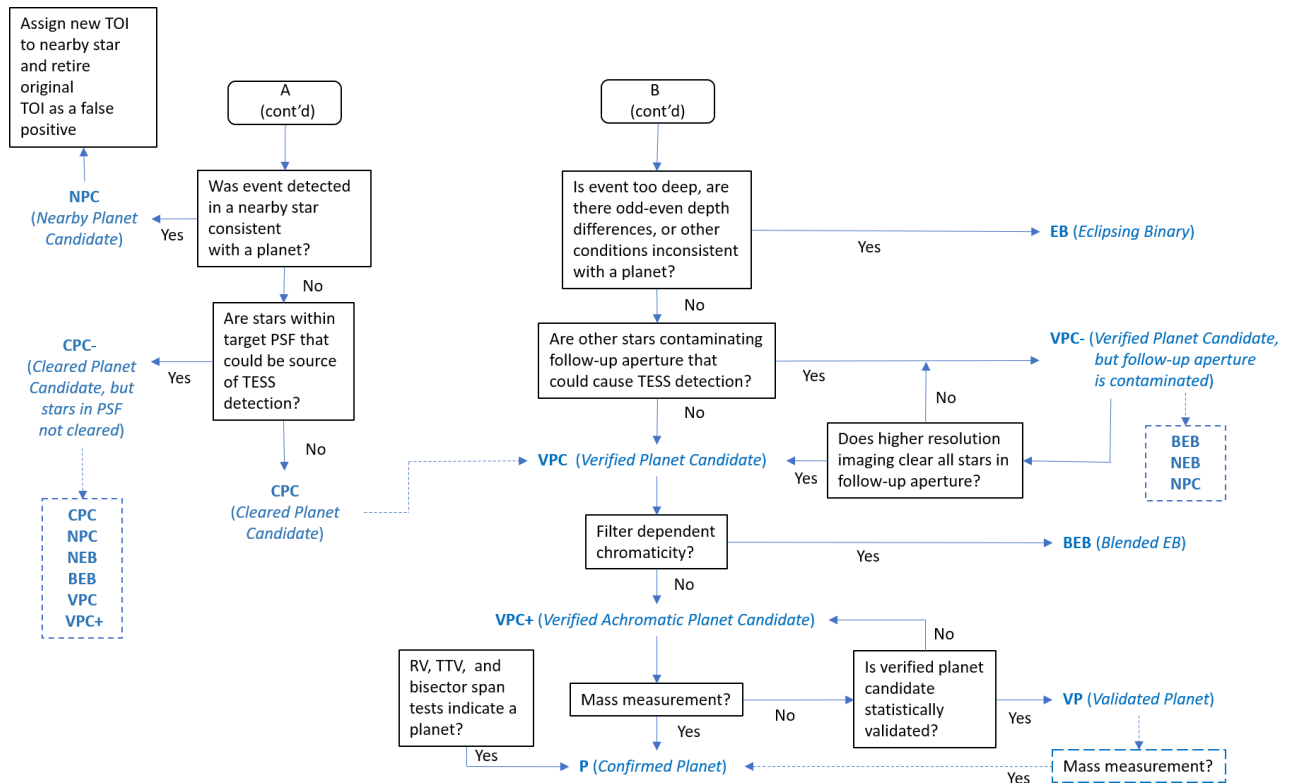
**FA (False Alarm):** Indicates that the TESS detection was deemed to be a false alarm.

## Appendix B:

### Flow Chart of Disposition Categories

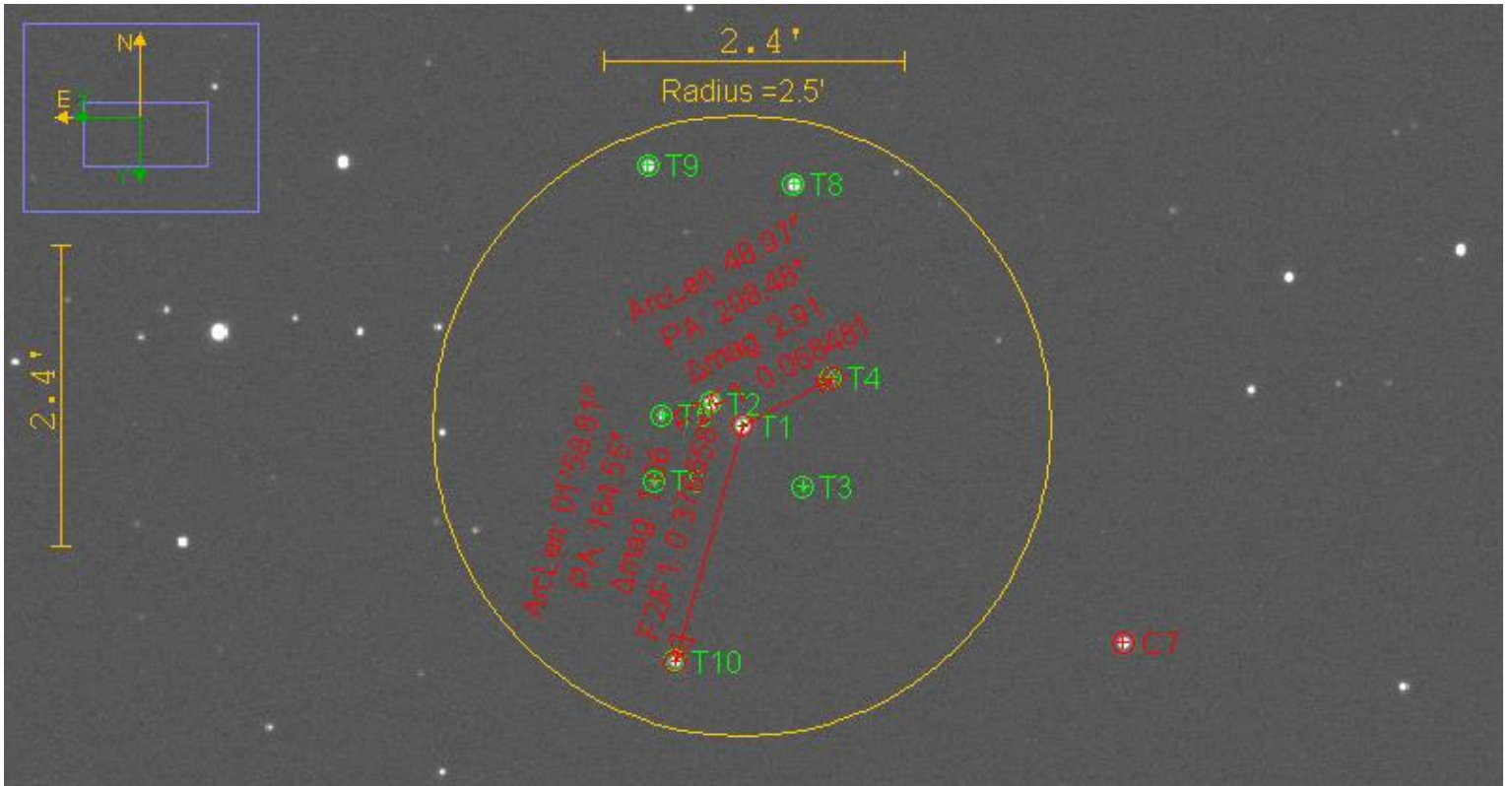


## Flow Chart of Disposition Categories (cont'd)



### Appendix C:

Sample plate-solved image with 2.5' radius circle and distance,  $\Delta\text{mag}$ , and PA measurements



## Appendix D:

### Instructions for Using the Gaia Aperture Generating Features

The following describes two methods for generating an AIJ \*.radec aperture file from Gaia data. The aperture locations in this file will be for those stars that need to be checked as NEBs which could be the source of the TESS detection. As described below, this use of such apertures work hand-in-hand with the new AIJ NEB analysis feature described in Appendix E.

Just as Table 1 is used in Section 2.2, Case 3 to determine stars visible in the user's images that need to be checked for a given predicted depth, generating apertures using one of the two methods below is much more comprehensive in that Gaia data will be queried for all stars that need to be checked. In fact, it may likely be the case that apertures will be returned of faint stars that are not even visible in the user's images. Thus, when AIJ's multi-aperture photometry is run, the apertures of these very faint stars may register very small, if not in some cases negative, integrated counts. This is the intended result since the new NEB analysis feature (see Appendix E) will then flag these Gaia stars a **\*\*\*Not Cleared-flux too low\*\*\***, which indicates that the complete field had not been cleared of NEBs.

It should be noted that a large number of Gaia stars included in AIJ's multi-aperture photometry may result in the need to increase AIJ's working memory. This can be done from the main AIJ toolbar by selecting Edit->Options->Memory&Threads... and then increasing the maximum memory amount.

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. Use of a TTF link**

The TTF 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. The user can then save this file for later use during the multi-aperture photometry run, as described in the "Loading Aperture File" section below.

#### **Method 2. Use of a Web-based Tool**

To use the web-based tool for generating the \*.radec file, the user would navigate via a browser to: [https://www.astro.louisville.edu/gaia\\_to\\_aij/](https://www.astro.louisville.edu/gaia_to_aij/). A web form as depicted in Figure D-1 would then be displayed.



**Find Gaia Stars in TESS Fields**

[\*Help\*](#)

Observation UTC <input type="text" value="2019-01-10"/>	Right Ascension <input type="text" value="hh:mm:ss.s"/>	Declination <input type="text" value="dd:mm:ss.s"/>
Magnitude <input type="text" value="TESS"/>	Transit Depth <input type="text" value="PPT"/>	Query Gaia <input type="button" value="Submit"/>

**Query Gaia database for stars within 2.5 arcminutes.**

**Figure D-1. Web-based Tool**

The user would first select the correct UTC date of the observation. Next, the user enters the RA and Dec of the target star, as well as its TESS magnitude (not V magnitude or any other magnitude) and predicted depth (the latter in ppt). The TESS magnitude can be found in the “T mag” column of the TTF entry for the target, and the predicted depth can be found in the “Depth” column. Figure D-2 is an example showing sample user inputs:

**Find Gaia Stars in TESS Fields**

[\*Help\*](#)

Observation UTC <input type="text" value="2018-12-16"/>	Right Ascension <input type="text" value="23:32:58.3"/>	Declination <input type="text" value="-29:24:54.4"/>
Magnitude <input type="text" value="13.458"/>	Transit Depth <input type="text" value="6.5"/>	Query Gaia <input type="button" value="Submit"/>

**Query Gaia database for stars within 2.5 arcminutes.**

**Figure D-2. Example of User Inputs to Web-based Tool**

Upon clicking on Submit, a message will appear indicating that the Query is finished and will include a link from where the AIJ \*.radec aperture file can be downloaded.

**Loading the Aperture File**

Prior to loading the aperture file, the user should first create a 2.5’ circle around the target star. See Section 2.1, item 5, how to do this. The aperture file created from either the TTF or the web-based tool can then be drag and dropped on the first image in a stack of images for which the user wishes to conduct multi-aperture photometry. (Note: this first image should be a plate-solved image.) Instead of drag and dropping it, the aperture file can also be loaded from the Image Display by selecting File->Import apertures from

RA/Dec list ... . Whether the file is drag and dropped or selected with the Import or Open menu items, apertures are automatically created over those stars that needed to be checked as potential NEBs causing the TESS detection. **Next, the user should select AIJ's multi-aperture photometry feature, select "Use previous nn apertures," turn on "Use RA/Dec to locate aperture positions," and then click on Place Apertures.** All of the Gaia apertures will then be placed on their respective locations. The user can now click other stars as additional comparison stars before the photometry run is initiated.

The AIJ measurements file created can then be used as input to the AIJ NEB analysis featured described in Appendix E.

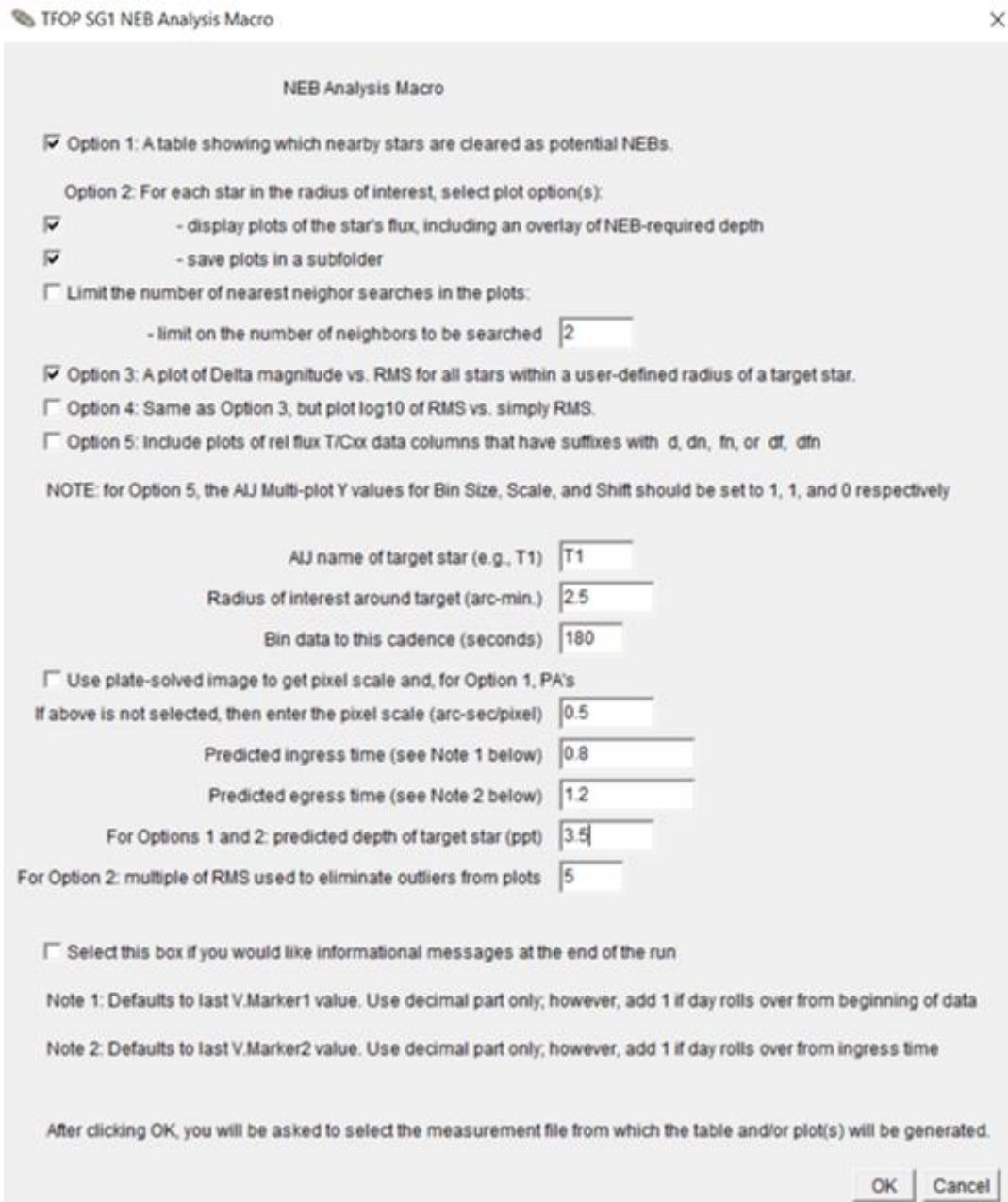
Please refer all comments and questions regarding this feature to John Kielkopf at [jkielkopf@gmail.com](mailto:jkielkopf@gmail.com)

## Appendix E:

### Instructions for Using the AIJ NEB Analysis Feature

The purpose of this AIJ feature is to assist the user in analyzing measured stars in the vicinity of a target star so as to determine whether they are potential sources of “false positives.” That is, whether stars that are in close proximity to the target star, when blended in TESS’ aperture, have an event that mimics a TESS detection. This feature can be accessed from either an AIJ Image Display screen or from the Multi-plot Main screen, by selecting File-> Create NEB search reports and plots... The feature is implemented as an ImageJ macro. (Note: make sure that AIJ is updated to the latest “daily build”.)

An AIJ measurement table, and optionally a plate-solved image, are used as input to the macro. As can be seen in the user dialogue depicted in Figure E-1, the user can select one or more output products. The entries for the predicted ingress time, egress time and depth default to the last values entered in AIJ’s Multi-plot Main V.Marker fields. They should therefore represent the predicted ingress and egress times for this observation. Also, as seen in the example in Figure E-1, if the “day” “rolls over from the predicted ingress time, then the predicted egress will have a “1” in front of the decimal part and should be entered as such. **NOTE:** it may also be the case that the user data starts a “day” before the predicted ingress time, in which case BOTH the predicted ingress and egress times should have a “1” in front of the decimal part. For example, if the data starts on 2458504.95 and the predicted ingress and egress times are 2458505.033 and 2458505.410 respectively, then the entries for ingress and egress should be 1.033 and 1.410.



**Figure E-1. User Dialogue Screen**

If Option 1 is chosen, an NEB Table will be generated as a .txt file and will have a file name of XXXX\_NEB\_table.txt, where XXXX is the file name of the measurement table, excluding its extension, that was used as input to the macro. Figure E-2 shows an example of such an NEB Table. The top portion contains relevant information entered by the user, as well as other useful information such as the binning used, the average aperture size used during the observation, and the -0.5 mag correction to the delta-magnitude when computing the NEB predicted depth in order to compensate for the difference between the TESS band and the filters typically used in the follow-up observations. A detailed description of the contents of the NEB Table and the meaning of each disposition can be found in Section 2.2, Case 3 of these guidelines. Note: stars with a disposition of **\*\*\*Not Cleared-flux too low\*\*\*** will show N/A for both NEBdepth and NEBdepth/RMS.

```

TIC271581073-01_20200723_LCO-SAAO-0m4_ip_4px_measurements_NEb-table - Notepad
File Edit Format View Help
TFOP NEB Search Table for:
TIC271581073-01_20200723_LCO-SAAO-0m4_ip_4px_measurements.tbl

Created by AIJ macro Revision 2.23
on 2020-07-23

-----
Pixel Scale (arc-seconds/pixel): 0.57
Predicted ingress time: .429
Predicted egress time: .493
Target predicted depth: 2.64
Target Star: T1
Search Radius: 2.5
Duration of Observation (min.): 335.1
Number of Images: 311
Average Exposure Plus Delay Time (sec.): 64.7
Cadence Requested When Calculating RMS (sec.): 180.0
Binning Used When Calculating RMS: 2
Average Aperture Radius: 4.0 (pixels); 2.3 (arc-seconds)
Dmag correction factor to account for difference with TESS band:-0.5

Separation from target PA (deg.) Uncorr. RMS(ppt) NEBdepth(ppt) NEBdepth/RMS Disposition
Star T2 0'04" NA 1.823 74.17 8.9 0.1 ***Not Cleared***
T3 0'31" NA 6.081 73.76 451.0 6.1 Cleared
T4 0'45" NA 5.938 65.89 395.0 6.0 Cleared
T5 0'53" NA 7.423 213.45 1551.3 7.3 Cleared-too faint
T6 0'54" NA 6.129 76.72 471.4 6.1 Cleared
T7 1'00" NA 6.526 110.77 679.1 6.1 Cleared
T8 1'06" NA 7.881 289.94 2366.5 8.2 Cleared-too faint
T9 1'07" NA 6.784 127.99 861.3 6.7 Cleared
T10 1'11" NA 5.950 66.88 399.6 6.0 Cleared
T11 1'15" NA 3.796 17.40 55.0 3.2 Likely cleared
T12 1'26" NA 4.584 26.08 113.5 4.4 Likely cleared
T13 1'35" NA 4.671 25.44 123.1 4.8 Likely cleared
T14 1'35" NA 5.117 29.81 185.6 6.2 Cleared
T15 1'35" NA 6.360 91.78 583.0 6.4 Cleared
T16 1'41" NA 7.255 215.38 1329.7 6.2 Cleared-too faint
T17 1'46" NA 6.487 101.82 655.0 6.4 Cleared
T18 1'56" NA 6.273 80.74 538.1 6.7 Cleared
T19 1'57" NA 5.104 36.94 183.4 5.0 Likely cleared
T20 2'13" NA 6.427 98.85 620.1 6.3 Cleared
T21 2'14" NA 5.848 61.85 363.6 5.9 Cleared
T22 2'20" NA 7.153 170.54 1210.1 7.1 Cleared-too faint
T23 2'23" NA 5.758 58.77 334.9 5.7 Cleared
T24 2'25" NA 2.969 14.14 25.7 1.8 ***Not Cleared***

Possible dispositions of the star being the source of the target predicted depth:
Likely cleared (NEBdepth/RMS is between 3 and 5)
Cleared (NEBdepth/RMS is >= 5)
Cleared-too faint (NEBdepth >= 1000ppt)
***Not Cleared-flux too low*** (weighted average of Source-Sky counts per aperture pixel < 2)
***Not Cleared*** (none of the above conditions are met)

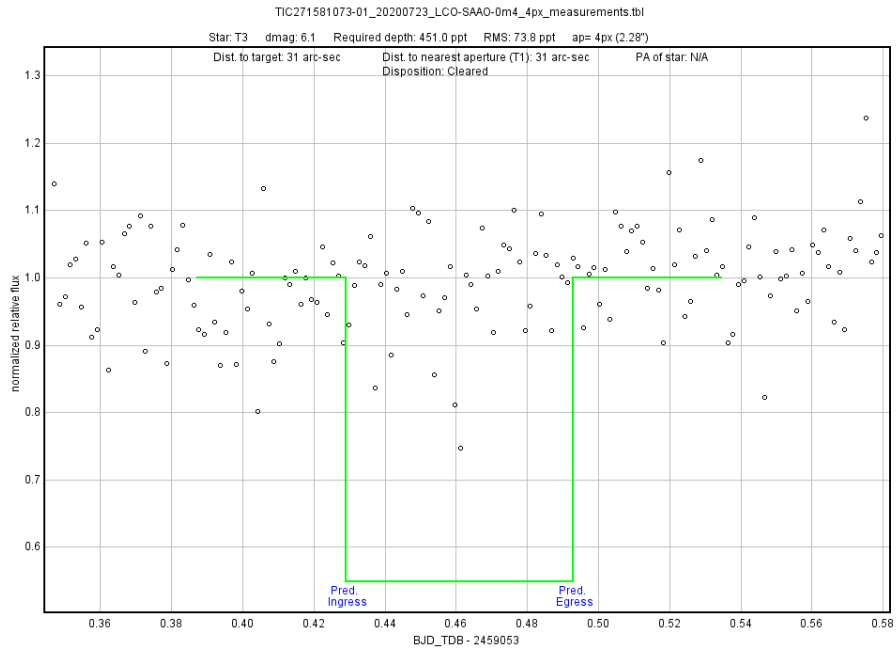
Image shift statistics:
stdev.(arc-seconds): 0.1966 in X and 0.2172 in Y
max. deviation (pixels): 2.0193 in X and 3.3347 in Y

```

**Figure E-2. Sample NEB Table**

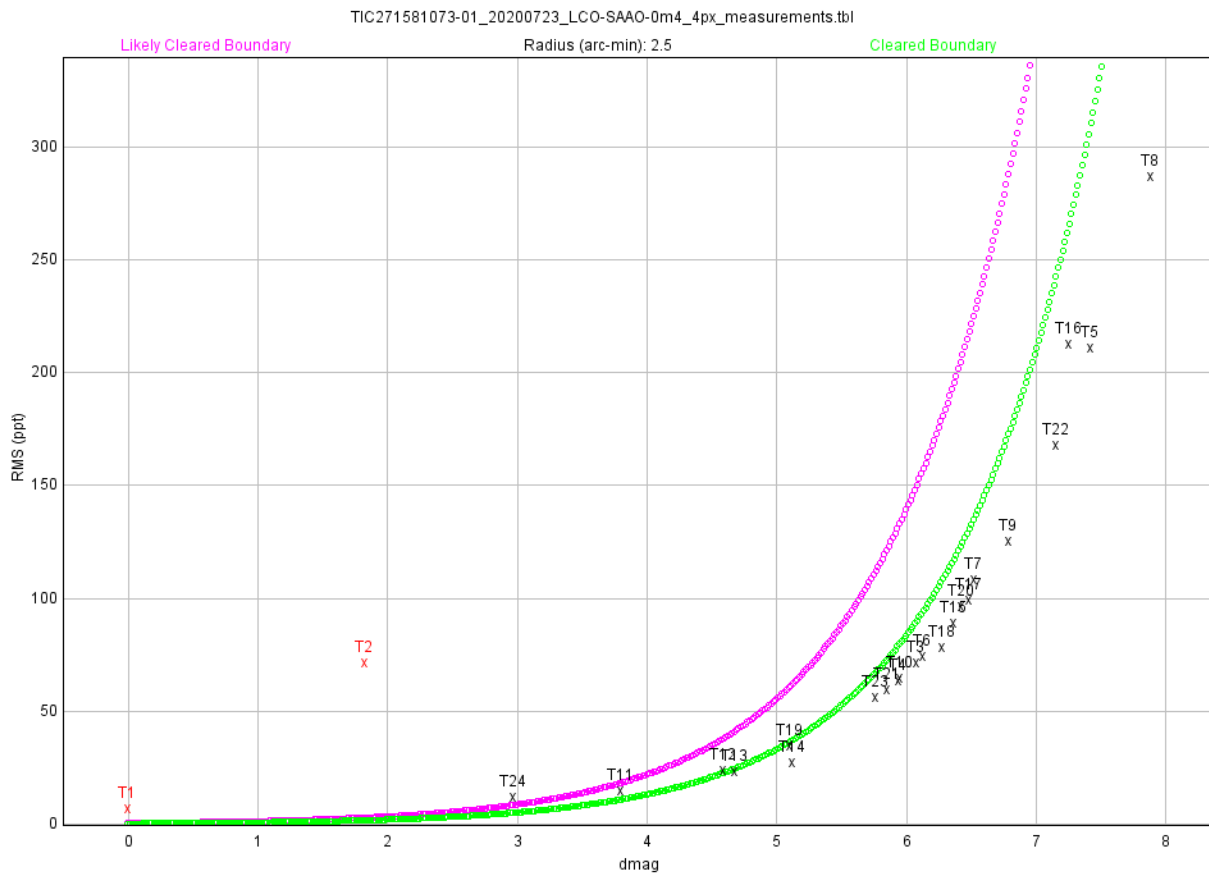
For Option 2, for each star within the user-specified radius, a plot will be generated showing measured data points for that star overlaid with the shallowest transit that could produce the TESS detected event (see Figure E-3). The latter is the same depth displayed in the NEB Table under the heading NEBdepth. Optionally, each plot can be saved to a .png file, where the file name is XXXX\_NN\_NEBdepth\_plot.png, where XXXX is the file name of the measurement table used by the macro, and NN is the name of the star. If selected as an option, all such saved plots will be stored in a subfolder called XXXX\_NEBcheck that will be created under the folder containing the measurement table. Note: stars with a disposition of \*\*\*Not Cleared-flux too low\*\*\* will show a straight red line for the transit depth.

Each star plot will also show the distance of the star to the nearest aperture. The user may optionally place a limit on the number of neighbors to be searched. This may be used to limit the processing time needed to generate the plots, especially in the case of a dense star field.



**Figure E-3. Sample "shallowest event" plot**

For Option 3, a plot of delta magnitude vs. RMS will be generated for each star within the user-specified radius (see Figure E-4).



**Figure E-4. Sample Dmag vs. RMS plot**

Such a plot will typically be of an exponential nature, where the fainter a star is, the greater its RMS. This plot is useful in identifying potential NEBs and EBs, since such stars are typically outliers that are “off the curve.” Two boundary lines are also generated for this plot in order to give the user a visual idea of the disposition of stars in the field. Stars to the right of the green boundary line indicate stars that are “cleared,” and stars in between the magenta and green boundary lines indicate stars that are “likely cleared.” Stars not cleared are to the left of the magenta line.

A related option, Option 4, allows the user to plot delta magnitude vs. log base 10 of RMS. This will typically produce a straight line vs. an exponential curve and may be more useful for identifying NEBs or EBs. Note: stars with a disposition of \*\*\*Not Cleared-flux too low\*\*\* will not be included in the Dmag vs. RMS plots.

Option 5 allows plots to be generated of detrended data if the AIJ measurement table includes such data. Note that when these columns are generated by AIJ, the Bin Size, Scale, and Shift values on the AIJ Multi-plot Y panel should be set to 1, 1, and 0 respectively.

User data inputs include the AIJ name of the target star (default is T1), the radius of stars around the target that will be included in the analysis (default is 2.5'), and the cadence desired when calculating RMS (default is 180 seconds). The macro will calculate the number of binned images such that the total of their exposure (plus delay) times comes closest to the Cadence entered and will use this binning to compute a star's RMS. Additional user inputs include the predicted ingress time, egress time, and the transit depth. As mentioned earlier, the ingress and egress times default to the last values entered in AIJ's Multi-plot Main V.Marker fields. Of course, these values, as well as the transit depth, should be the same values as those that are in the TESS Transit Finder associated with this observation. Note that for the ingress and egress time, only the decimal parts are included. Finally, a multiple of RMS (default is 5) is used when deciding which stars to exclude as outliers from the Option 2 plots.

There are also two additional optional selections. One option allows the user to select a plate-solved image as the source for the pixel scale and for use in generating the Position Angles (PA's) that are included in the NEB Table. Another option allows the user to generate informational messages at the end of the run.

The user will be asked to select the AIJ measurement file associated with this observation. The macro also has the option of using a plate-solved \*.fit or \*.fits file to automatically compute the pixel scale for the observation, as well as the Position Angles (PA's) of each star. The checkbox should be selected for this option. If the user wishes to manually enter the pixel scale without using a plate-solved image, then the checkbox should remain unchecked and the pixel scale should be manually entered. In this case, however, no PA's will be calculated.

Once the above information is entered and the user selects OK, the user will then be prompted to select the AIJ measurement file associated with the observation. If the selection was made to use a plate-solved image to derive the pixel scale and the PA's for the NEB Table, then the user will also be asked to choose a plate-solved \*.fit or \*.fits associated with the observation.

After execution, the macro will: (1) create the NEB Table file, if Option 1 was selected; (2) display the “shallowest event” plots if Option 2 was selected, as well as optionally save each plot to the NEBcheck subfolder; and (3) will display and save to a file the dmag vs. RMS plot if either Option 3 or 4 was selected.

If the user runs into operational problems, it is recommended that a run be made with the log file option selected so that detailed diagnostics can be generated. The log file and a description of the problem can then be forwarded to the email address below for further help.

Please refer all comments and questions regarding the NEB analysis feature to Dennis Conti at [dennis@astrodennis.com](mailto:dennis@astrodennis.com). If the user experiences any unexplained errors, it is requested that Dennis be notified at this email address and that a log file be attached.