Imaging and Analyzation of TrES-2-b Light Curve

by: Ariana Hofelmann

This paper will outline the imaging and analysis process in early July of the exoplanet TrES-2 conducted in the Geissberger Observatory at St. Mary's College of California.

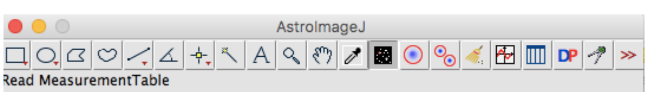
Subject: TrES-2-b
RA (J2000): 19:03:14.03
DEC (J2000): 49:18:59.0
Predicted Ingress: 9:58pm PDT
Predicted Egress: 11:28pm PDT
First Image taken: 9:41pm PDT
Last Image taken: 12:03am PDT

Image Specifications:
Using a ZWO ASI1600 Camera with a blue blocker filter. Exposure time was 15 seconds and 3x3 binning was used.[1] 541 images were captured.
60 darks were taken at the same exposure time (15sec) as well as 60 flats at 0.5 second exposure.
180 bias frames were taken the next day at 0.5 second exposure.
Camera field of view is ~20 arcmin by 14 arcmin. Mag limit of camera is 13 for star to be clear and imageable at 15 seconds.

NB: Mirror flop occurred at 10:04 PDT and at 10:50 PDT. As a result lots of manual focusing occurred throughout the data collection. Auto guiding was used the whole night with no fails.

Image Analysis:
Image Analysis was conducted in AstroImageJ, a program used by many amateur astronomers primarily to conduct differential photometry on a star field.

Image Calibration:
The first step of analyzing the images is to calibrate them, that is subtract the darks and bias frames and divide the flats. The "DP" tab on the AstroImageJ menubar will open two windows, one labeled "CCD Data Processor" and one labeled "DP Coordinate Converter."

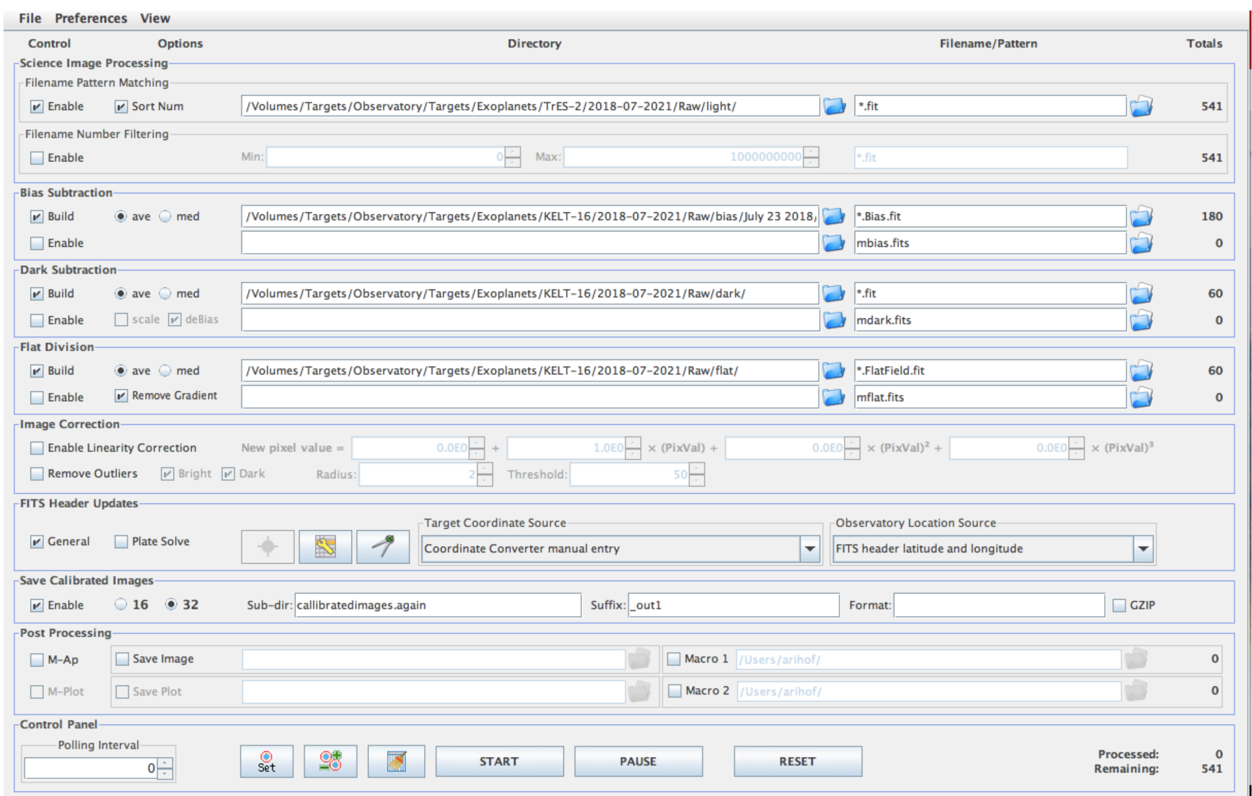


[1] Binning essentially combines the light from multiple pixels and reads that value out as if it came from one pixel. 3x3 binning combines the light from 9 pixels (a 3x3 square) and reads it out as if it was one pixel.

On the “CCD Data Processor” window, locate the “Science Image Processing,” “Bias Subtraction,” “Dark Subtraction,” and “Flat Division” boxes. The first box, “Science Image Processing” will be where all the raw lights are loaded (the TrES-2-b transit had 541 images). Make sure the boxes “Enable,” and “Sort Num” are checked. In the middle of the box is a blue folder. Click on the folder and then locate the directory holding the raw light images. The file path should show up in the white box. In the adjacent white box should be a sample file name, with an asterisk used to allow the program to identify all the files. Make sure the number to the very right of the box is the same number of images to be processed.

Ignore the “FileNumberFiltering” box. This is used to remove images from a selection of files, but it is only effective for removing chunks of images, not a single few. If images must be removed, make a copy of the lights under a new directory and delete them there before uploading them to be calibrated. Always keep a copy of the original set of lights, just in case.

Check both “Build” and “ave” in the Bias, Dark, and Flat boxes. This allows AstroImageJ to calibrate the selected images using uploaded bias, dark, and flat frames. The “ave” box means that the program will take the average of the frames and then apply that to the lights. Another option is using the median instead. As before, upload the desired bias, dark, and flat frames from their respective directories and make sure the number to the far right matches the number of images uploaded. The following picture is this window prepared to calibrate the TrES-2 images.

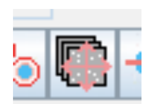


The window “FITS Header Updates,” controls how the information assigned to each picture changes[2]. If “plate solve” is selected, then AstroImageJ will attempt to identify each star in the picture and match it to a known database of star fields. This is not necessary for differential photometry and usually more effort than it is worth.

Always ensure that “Enable” is checked under “Save Calibrated Images.” They will save as a subdirectory under where the lights currently are saved. The calibrated images will have the suffix “_out” unless otherwise specified. Hit “Start” to begin calibration.

The “DP Coordinate Converter” window is only really necessary for plate solving. The way AstroImageJ performs differential photometry is the user places apertures on the stars, more specifically on certain pixels. Then the program measures how many electrons ended up in each well of the camera which corresponds to each pixel in the picture and chosen by the aperture radius. If the “star” moves to a different pixel, the aperture will not move with it. Therefore, the primary concern in differential photometry is making sure that the stars never move from different pixels.

Alignment of the Images:
Once all the images are calibrated find them in the subdirectory and load them in AstroImageJ[3] as a virtual stack[4]. Next choose the align stack option (see image). A window will pop up asking for the target and comparison stars to be selected. Choose the desired stars and then hit enter. The best comparison stars are not at the edge of the image, close in brightness to the target star (to avoid saturation), and isolated, so other stars are not caught in its background aperture.



The desired aperture sizes depend on the stars, sometimes it is useful or necessary to run multiple alignments if the stars move around from image to image. The program will “search” within the aperture radius for the star. Sometimes the largest radius is necessary to ensure the program can find the star if there is a big jump[5].

The aligned images will save in another subdirectory called aligned.

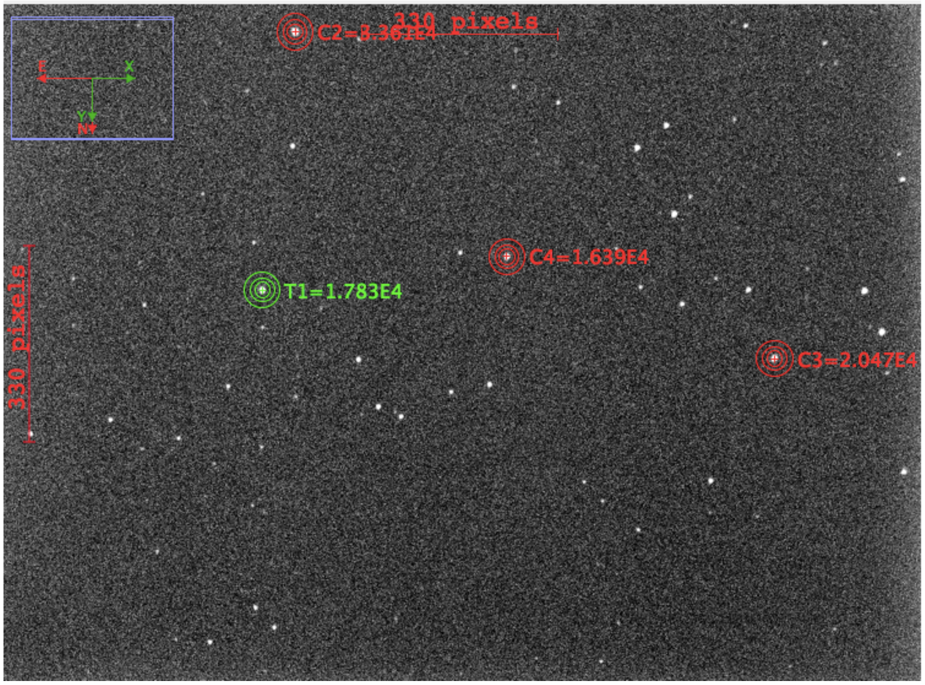
Differential Photometry:
Open the pictures from the aligned subdirectory. Click on the multi-aperture photometry icon (see image. Set the first slice to be 1 and the last slice at 541 (because that is the number of pictures taken for TrES-2). Set the appropriate aperture size. For this run it was 13, 20, and 30. Select the Target star, and three or four comparison stars. Then hit enter.

[2] The FITS Header is a set of data that each picture has. It includes the binning, the filter, the camera type, the location of the picture, and the location/name of the stars in the frame.

[3] To do this go to File->Import->Image Sequence, then choose the directory in which the calibrated files were saved.

[4] Always load image stacks as virtual stacks to prevent the stack from taking all the AstroImageJ memory on the computer.

[5] Using the slider to choose aperture radius will max out at 100, but it is possible to manually type in a much larger number (there seems to be no limit). But realistically more than 100 is rarely necessary, because the apertures of multiple stars start to overlap.



Above is a sample picture, with the target star and three comparison stars selected (these were the same stars used to gather the following data).

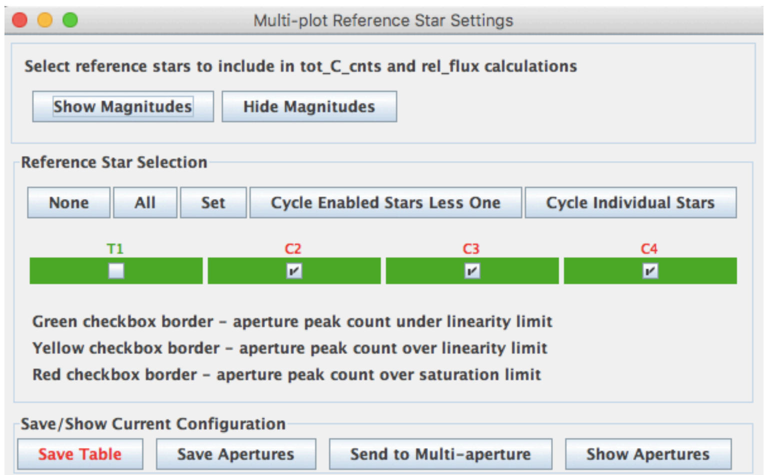
Once the differential photometry is finished, a table will appear, as will a plot and a few different windows controlling the plot: “Multi-plot Y-data,” Multi-plot Reference Star Settings,” “Multi-plot Main,” “Plot of Measurements,” and “Measurements.”

The “Measurements” window is the table of all the values gathered in the photometry. It has the name of the picture, the saturation level, five different times, the airmass, aperture settings, relative flux of the target star (T1) and the three comparison stars (C2, C3, and C4). It also has a calculated error for each star. This window is the most important to save as soon as good data is collected. The graphs can always be reproduced if the table is saved.

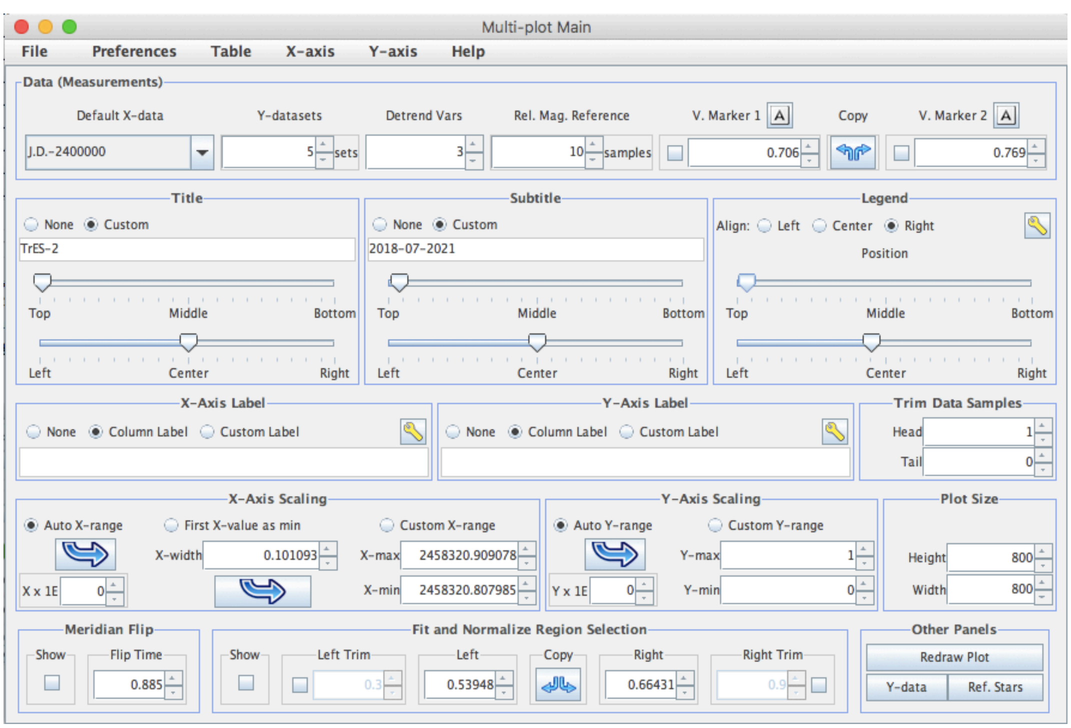
Measurements

	Label	slice	Saturated	J.D.-2400000	JD_UTC
1	aligned_00004484.GSC 3549_2811_out1.fit	1.000000	0.000000	58320.695255	2458320.695
2	aligned_00004486.GSC 3549_2811_out1.fit	2.000000	0.000000	58320.695862	2458320.695
3	aligned_00004487.GSC 3549_2811_out1.fit	3.000000	0.000000	58320.696043	2458320.696
4	aligned_00004488.GSC 3549_2811_out1.fit	4.000000	0.000000	58320.696224	2458320.696
5	aligned_00004489.GSC 3549_2811_out1.fit	5.000000	0.000000	58320.696405	2458320.696
6	aligned_00004490.GSC 3549_2811_out1.fit	6.000000	0.000000	58320.696586	2458320.696
7	aligned_00004491.GSC 3549_2811_out1.fit	7.000000	0.000000	58320.696767	2458320.696
8	aligned_00004492.GSC 3549_2811_out1.fit	8.000000	0.000000	58320.696950	2458320.696
9	aligned_00004493.GSC 3549_2811_out1.fit	9.000000	0.000000	58320.697131	2458320.697
10	aligned_00004494.GSC 3549_2811_out1.fit	10.000000	0.000000	58320.697312	2458320.697
11	aligned_00004495.GSC 3549_2811_out1.fit	11.000000	0.000000	58320.697494	2458320.697
12	aligned_00004496.GSC 3549_2811_out1.fit	12.000000	0.000000	58320.697675	2458320.697
13	aligned_00004497.GSC 3549_2811_out1.fit	13.000000	0.000000	58320.697856	2458320.697
14	aligned_00004498.GSC 3549_2811_out1.fit	14.000000	0.000000	58320.698038	2458320.698
15	aligned_00004499.GSC 3549_2811_out1.fit	15.000000	0.000000	58320.698219	2458320.698
16	aligned_00004500.GSC 3549_2811_out1.fit	16.000000	0.000000	58320.698401	2458320.698
17	aligned_00004501.GSC 3549_2811_out1.fit	17.000000	0.000000	58320.698582	2458320.698
18	aligned_00004502.GSC 3549_2811_out1.fit	18.000000	0.000000	58320.698763	2458320.698
19	aligned_00004503.GSC 3549_2811_out1.fit	19.000000	0.000000	58320.698945	2458320.698
20	aligned_00004504.GSC 3549_2811_out1.fit	20.000000	0.000000	58320.699126	2458320.699
21	aligned_00004505.GSC 3549_2811_out1.fit	21.000000	0.000000	58320.699307	2458320.699
22	aligned_00004506.GSC 3549_2811_out1.fit	22.000000	0.000000	58320.699489	2458320.699
23	aligned_00004507.GSC 3549_2811_out1.fit	23.000000	0.000000	58320.699670	2458320.699
24	aligned_00004508.GSC 3549_2811_out1.fit	24.000000	0.000000	58320.699851	2458320.699

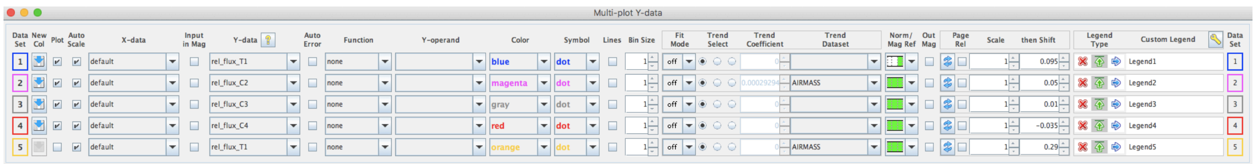
The “Multi-plot Reference Star Settings” gives an idea of how reliable AstroImageJ thinks the data from each star is. Green means good. Yellow means that the star is over the linearity limit (meaning that its values do not fit a linear trend) and red means that the star is saturated at some values of t, so that its actual flux at that value cannot be determined. Run the photometry with different comparison stars until their graphs are relatively flat, and they are all in the green on this window.



The “Mulit-plot Main” window controls the X-data, the title of the graph, the legend position, the scaling and range of both axes and the lines that mark the predicted ingress and egress of the exoplanet (this will be addressed later). Usually it is necessary to have the x and y axes on auto range. If something happens and the graph gets skewed, it is always possible hit “Redraw Plot” in the lower right corner. If all else fails, under the “Preferences” tab in the window there is an option “Reset Preferences to Default Settings.” It will require restarting AstroImageJ but will usually help.

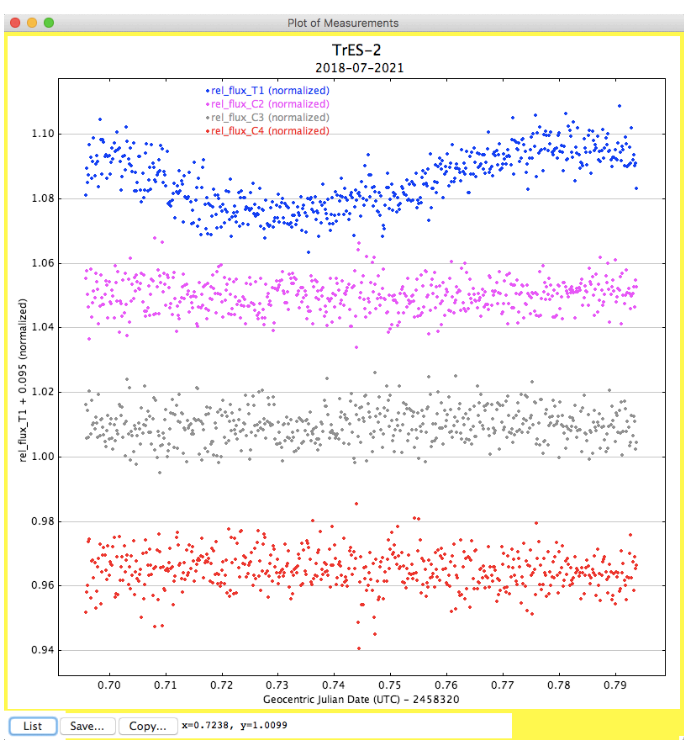


The “Multi-plot Y-data” window controls the Y data graphed. Each variable can be selected to be plotted or not. Error bars can also be shown using “Auto Error.” The color and shape/line used for each variable can be customized. The”Bin Size” determines how many data points are combined; this is meant to reduce error. Next to these settings are the fit settings and the Trend settings. Then the “Norm/Mag Ref” determines which part of the curve is used for normalization. The last column determines the scale and shift of each graphed variable. Usually the scale is left at 1, and the shift is changed so no two variables intersect with each other.



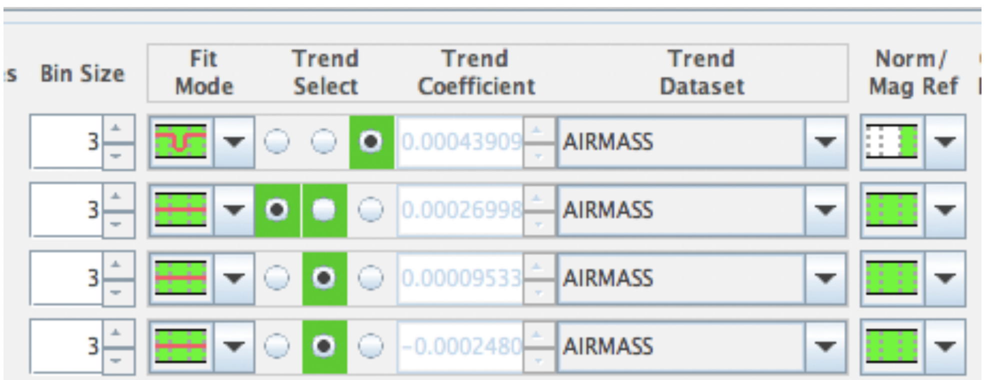
It may seem strange, but it does not matter *where* on the graph each curve is placed. Differential photometry is only concerned with the change within a curve. Notice that what is being graphed is the relative flux, not the actual flux. Is is calculated by finding a weighted mean using each value from each comparison star from each picture. Then the measured flux value for each comparison star in every picture is divided by this weighted mean. If there was no shift than each comparison star should be close to a straight line at a constant, usually 1. The target star values are also divided by this weighted mean. However, the mean is not calculated using the target star, so the resulting values should create some sort of curve. Therefore, the target star curve shows how the brightness of the target star changes in relation to the comparison stars, not in absolute magnitude.

Fitting to the Exoplanet Transit and Detrending:
A raw graph should look something like this:



The transit curve is obvious and the comparison stars are relatively flat. Now detrend parameters can be applied, binning performed, and AstroImageJ can prove a fit curve for the transit.

Locate the “Fit Mode” column. For the target star select the exoplanet dip curve. Select a straight line for the three comparison stars. In the “Trend Select” column, select Airmass. The in the “Norm/Mag Ref” column, select the far right of the data set for the target star, and all of the data set for the comparison stars[6]. Binning all the data sets at 2 or 3 helps reduce the error, and allows for a better curve fit. Binning more than this is possible but not really necessary.



This image assumes that the order of the variables is T1, C2, C3, C4.

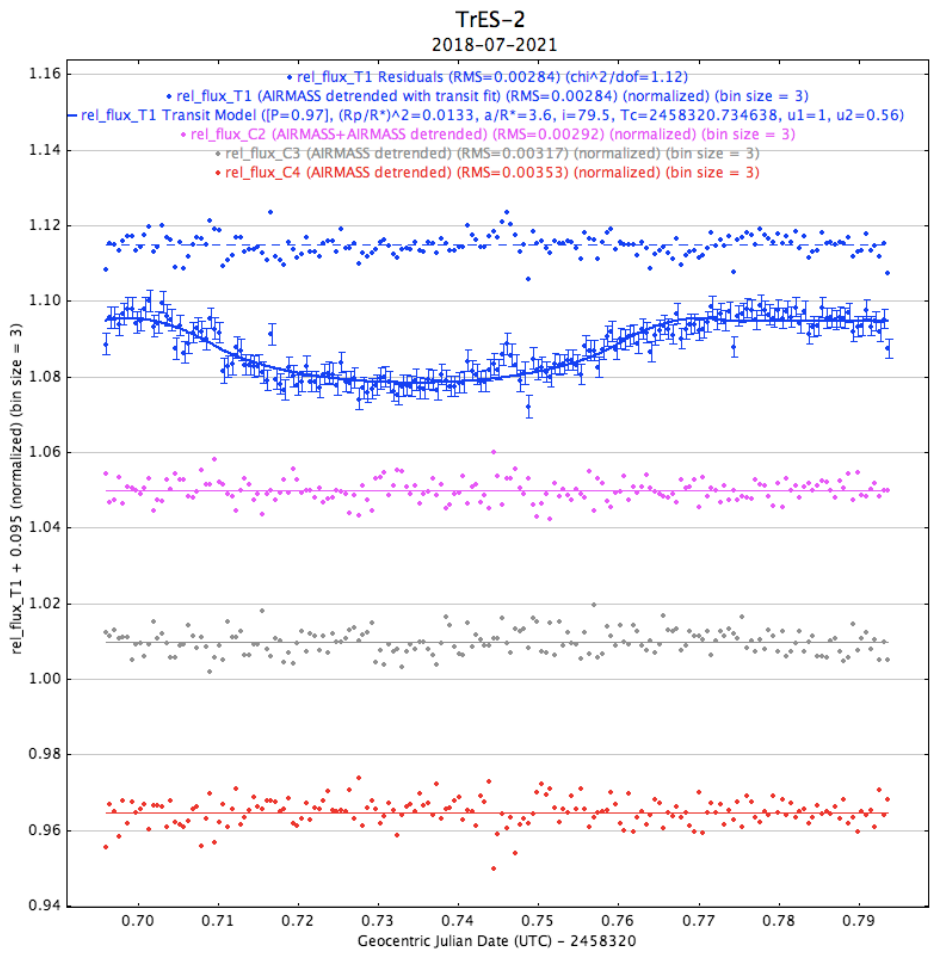
Once the exoplanet fit is selected for the target star, a new window will pop up called “Data Set 1 Fit Settings.” Towards the bottom is a place to select detrend parameters. Select “Airmass.” At the bottom is a place to select “Show Residuals” and shift the line up. This will show a dotted line with points scattered around it. Each point shows how much error exists between the fit line and a data point for the target star. The rest of the window shows the values calculated from the curve fit, such as the midpoint of the curve and the ratio of the star size to planet size.

The final curve should looks something like this:

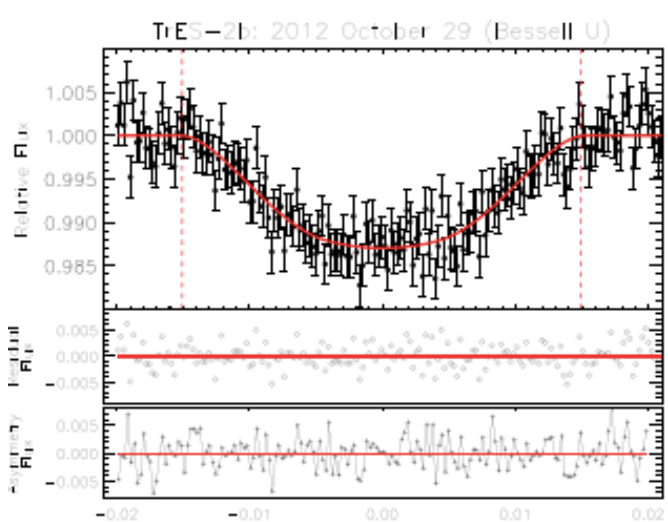
The error bars have been turned on for the target star. The binning has been set to 3. Airmass detrending as been selected for all four stars. The top line is the residuals of the fit. The three comparison stars have been fitted with a line.

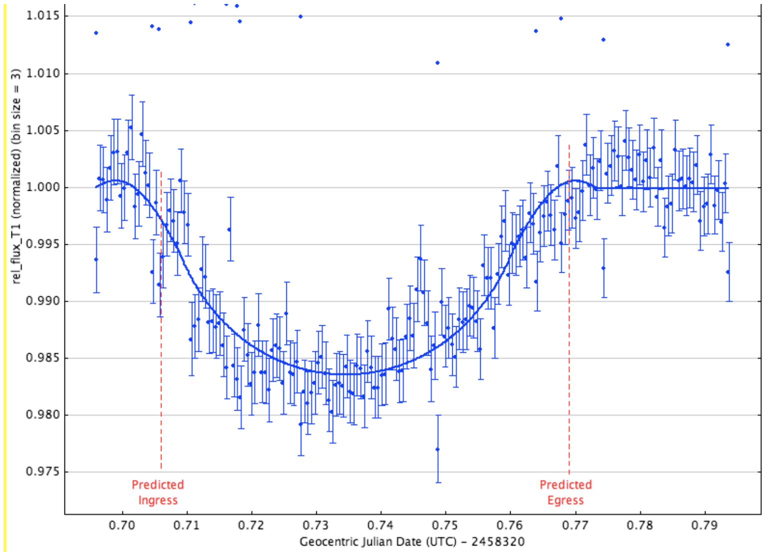
---

[6] There is an option for the target star using the beginning and the end of the data for normalization i.e. not the transit part. However, this data does not have a significant enough amount of data before ingress, so using only the portion after egress is best.



Comparatively, here is data collected in October of 2012 of TrES-2. The data was caollected and analyzed in the paper "Ground-based near-UV observations of 15 transiting exoplanets: constraints on their atmospheres and no evidence for asymmetrical transits” by Tuner at al. Published by the Monthly Notes of the Royal Astronomical Society in 2016.





For comparison, here is the exoplanet curve blown up, at starting at the same value (1) to be directly compared to Turner's graph.