

## INTRODUCTION

The TESS Follow-up Observation Program (TFOP) has been an integral part of the TESS mission. Follow-up observations of candidate exoplanets help distinguish between transiting exoplanets orbiting TESS objects of interests (TOIs), or nearby/blended eclipsing binary stars (NEBs). The TESS mission pixel size is 22 arc-seconds on the sky, and light from multiple stars can be blended into one pixel. We present our work analyzing data from 200+ nights of TFOP SG1 photometric data using the 0.8m George Mason Observatory. The findings from this research have and continue to contribute to TOI detections and confirmation of TESS mission candidates.

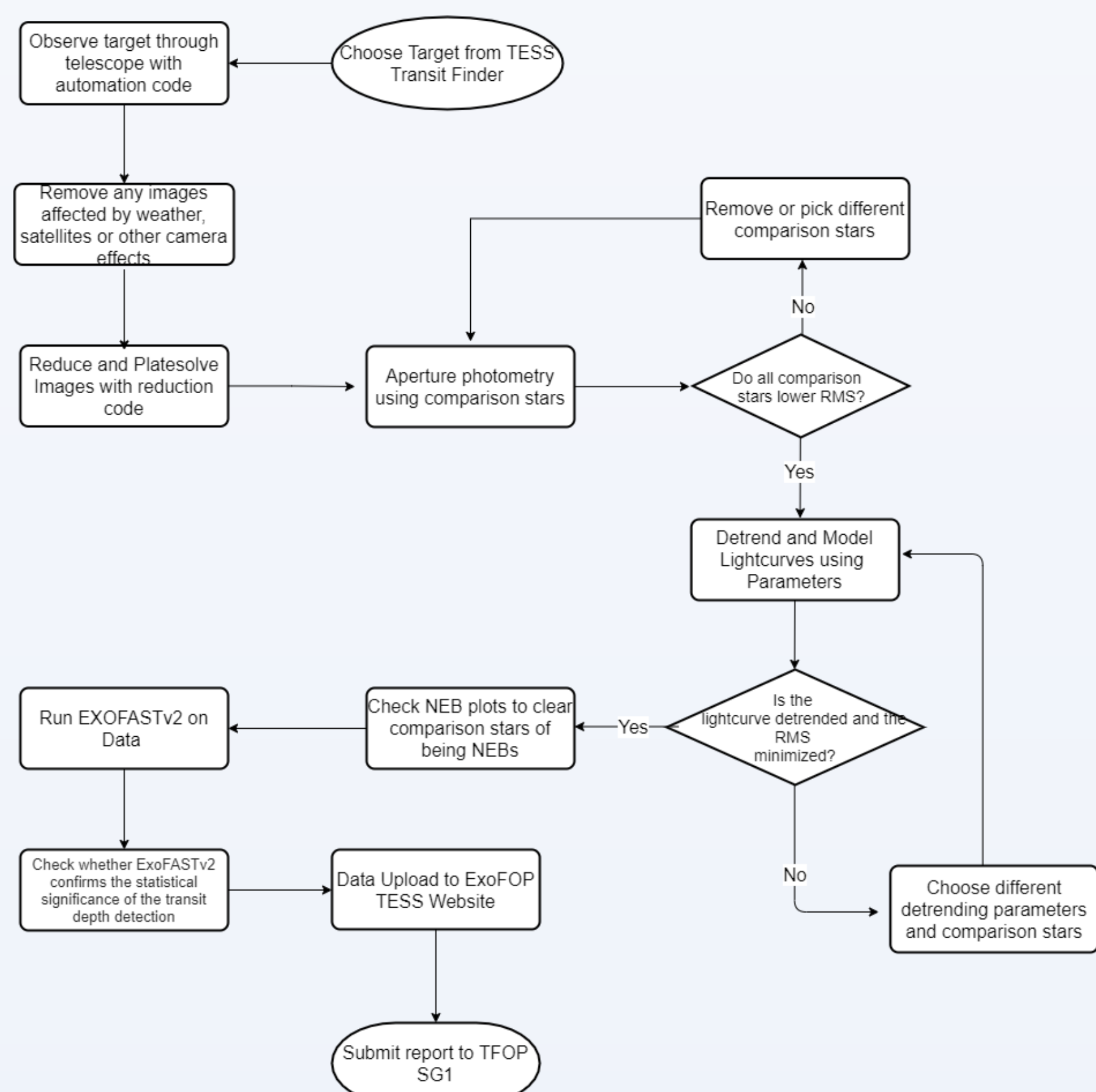


Figure 1: Block diagram describing the data analysis process

## TARGET SELECTIONS AND OBSERVATIONS

Targets are selected through the TESS Transit Finder and selected for brightness, transit depth, priority and visibility. Targets are observed every clear, dry night with a 0.8 m Ritchey-Chretien telescope fitted with a SBIG 16803 CCD camera. Observation is completely automated through a Python script (see Michael Reefe's poster), which automatically focuses the camera, as well as locates and tracks the target through the night, while taking science, darks and flats images. To date, approximately 150 TOIs have been observed by the telescope over the course of two and a half years. The data presented herein is an example observation from a transit of TOI 1710.01, a confirmed exoplanet detection which was observed on February 29<sup>th</sup> 2020.

## REDUCTION/PLATESOLVING

Science images taken on observing nights must be reduced to remove electronic noise and instrument systematics, and plate solved to determine the location of the stars in the sky. These steps are implemented in a Python script, *alnitak* which reduces images by subtracting dark images and dividing by flats. Plate solving is performed with the package *astroquery*, which accesses *nova.astrometry.net*, a website that returns known astronomical objects from an image, among other features. The code is accessible at this link: <https://github.com/oalfaro2/alnitak>.

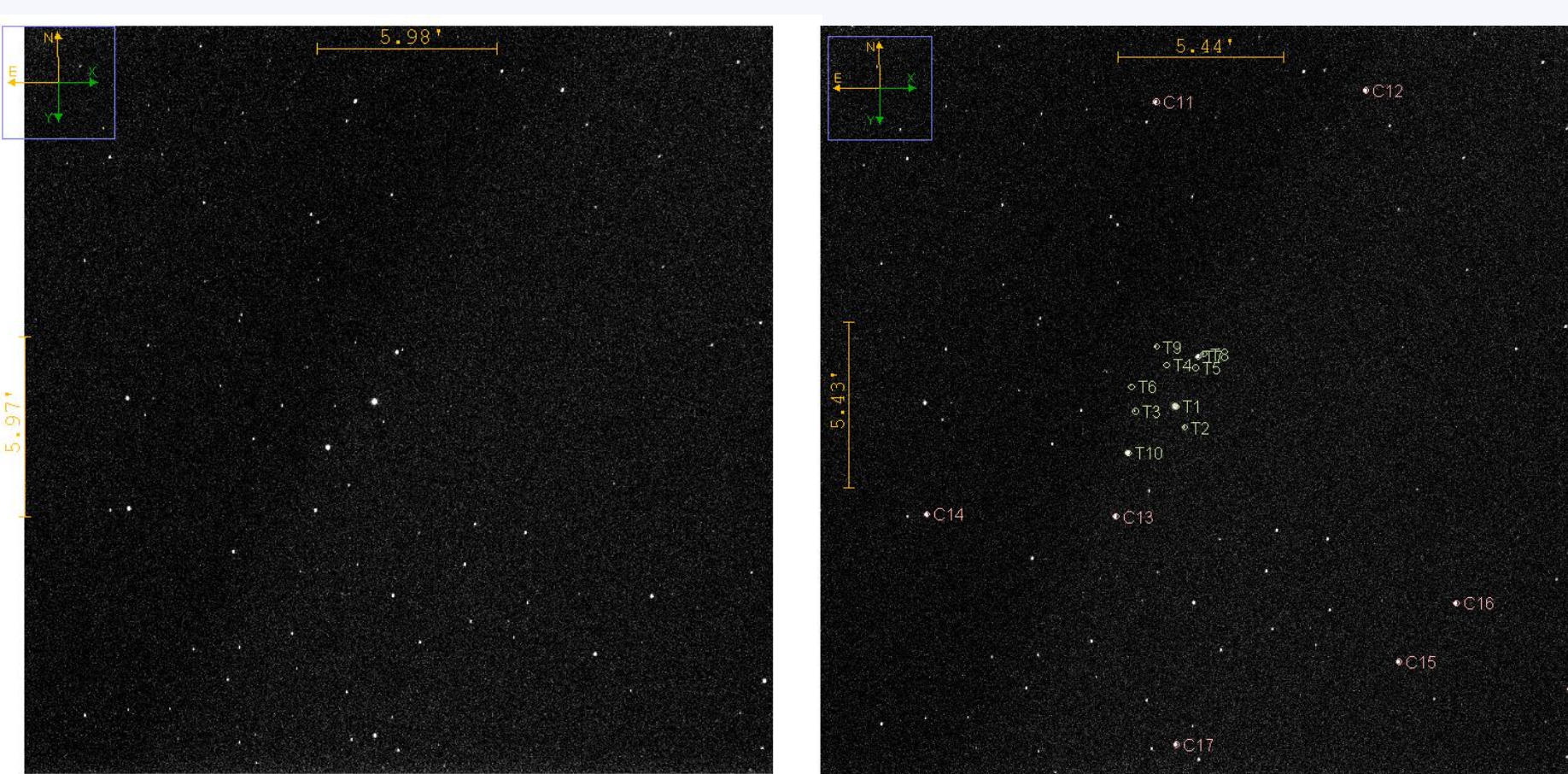


Figure 2: Reduced science image of TOI 1710.01 (left), Reduced science image with apertures (right)

## APERTURE PHOTOMETRY AND LIGHTCURVE DETRENDING

Both aperture photometry and light curve detrending are conducted using tools in the open-source software *AstrolmageJ* (Collins, 2016). Apertures are chosen for their relative brightness to the target; stars with similar brightness are preferred. Another factor in aperture selection is a comparison star's distance from the target. Usually, around 8-10 apertures are selected. Figure 2 shows an example of an image with apertures and GAIA stars.

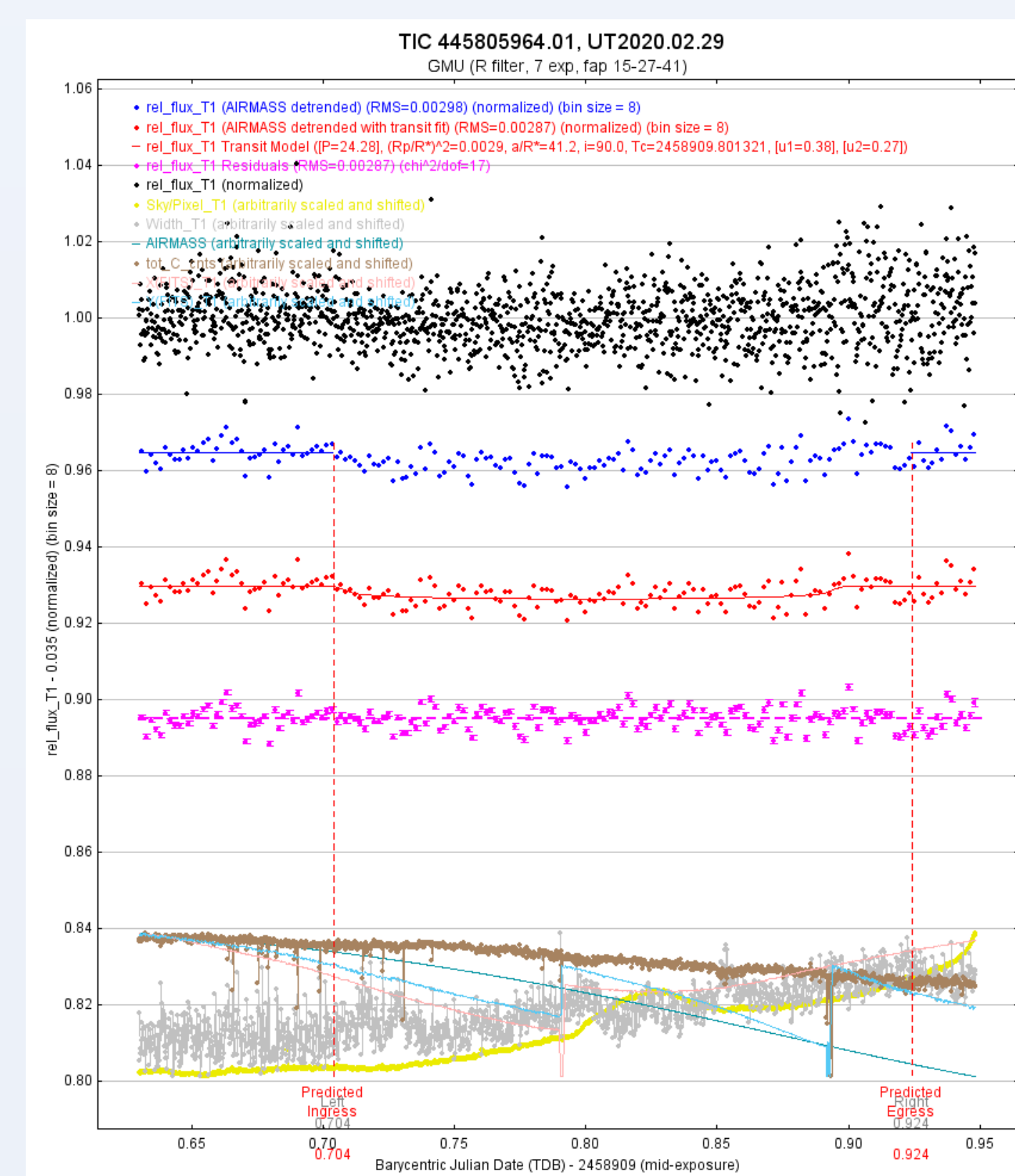


Figure 3: Photometric and ancillary time-series for TOI 1710.01 generated with *AstrolmageJ* aperture photometry

AIJ will automatically generate lightcurves from the apertures once the photometry run is finished. Apertures/comparison stars must be checked to ensure that they help in detrending the light curve through decreasing its RMS. Stars that increase the RMS are removed, and in the case where there are not enough comparison stars after the removal phase, the data will be sent back for another aperture photometry run.

Lightcurves are then detrended with observing parameters such as airmass, or the width and the x and y positions of the target star, the T1 aperture. Like comparison star selection, the goal is to minimize RMS by mixing and matching parameters. Figure 3 shows the detrended light curve of TOI 1710.01, using the airmass parameter.

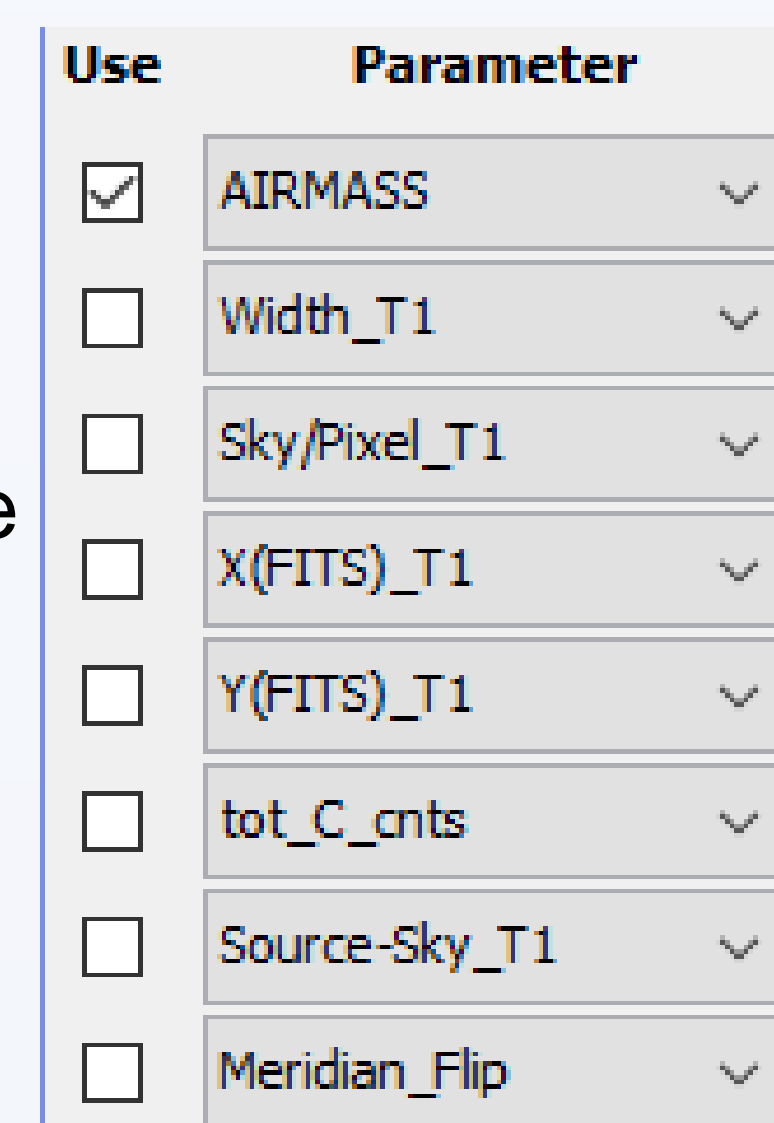


Figure 4: AIJ parameters in lightcurve detrending

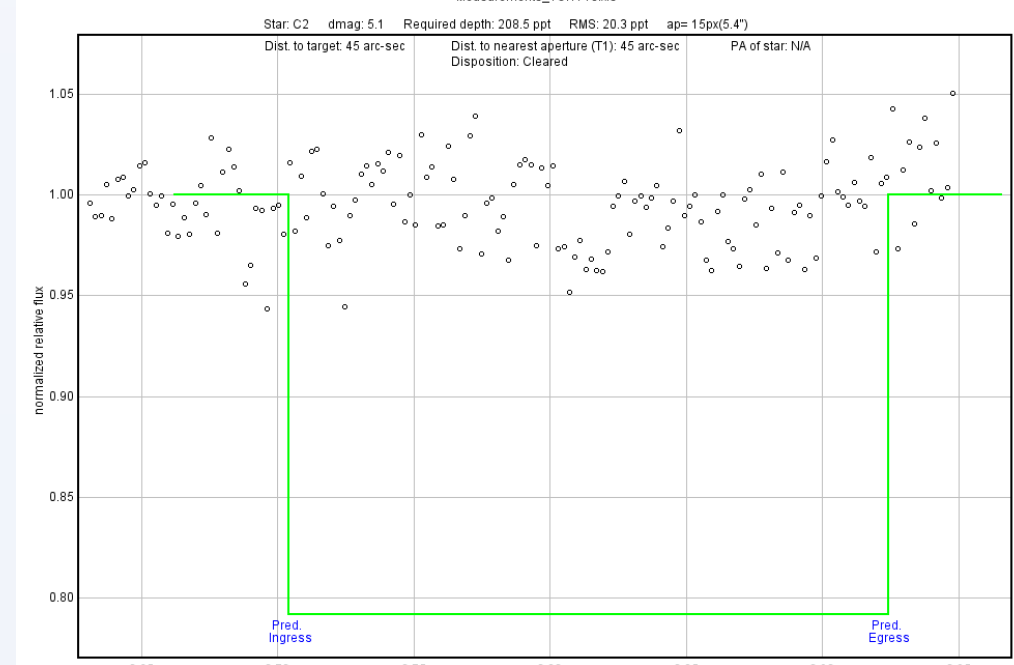


Figure 5: Lightcurve of a cleared comparison star

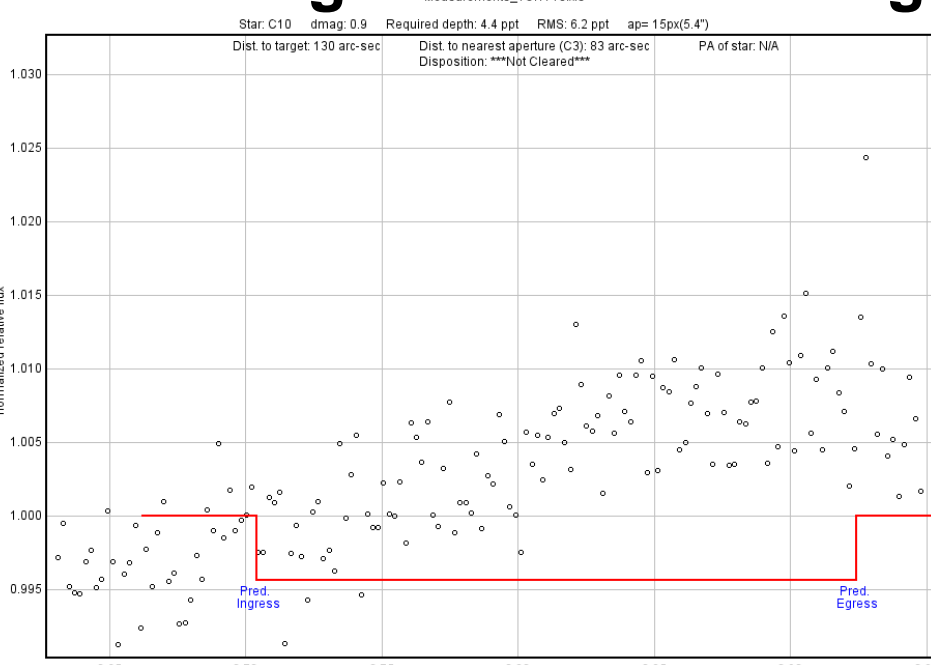


Figure 6: Lightcurve of a comparison star that is not cleared of a NEB

Once the lightcurve is detrended, NEB plots can be generated for each of the comparison stars, as well as a NEB table that lists the information and dispositions of comparison stars. An example of a cleared comparison star's lightcurve is Figure 5, where the necessary change in brightness to produce an NEB is ruled out because the light curve is not that variable, whereas in Figure 6, we present a light curve of a comparison star that is not cleared of being a NEB, as we can not rule out a change in brightness for this comparison star that would be consistent with an NEB.

## EXOFASTv2 RESULTS

The exoplanet transits are fitted and modeled using the software package *ExoFASTv2* (Eastman, 2019). The program generates many useful models and posteriors. Three useful analyses are the covariance, posterior probability distribution function for depth (pdf) and transit plots. The covariance plots are used as diagnostic plots and depict correlations between model parameters.

Round (scatter) covariance plots indicate the model parameters are uncorrelated, and the data is well described by the model. The transit is modeled using Markov Chain Monte Carlo (MCMC) methods, and the transit plot provides a depiction of the median exoplanet transit. Figure 8 shows the plot, with a clear drop in the flux. Posterior PDFs are generated for each parameter, and we use the depth posterior distribution as a detection metric diagnostic. If the function is peaking toward zero, it is likely a non-detection. As the distribution peaks near a non-zero value, we can confidently report a detection with a sufficiently uninformed prior.

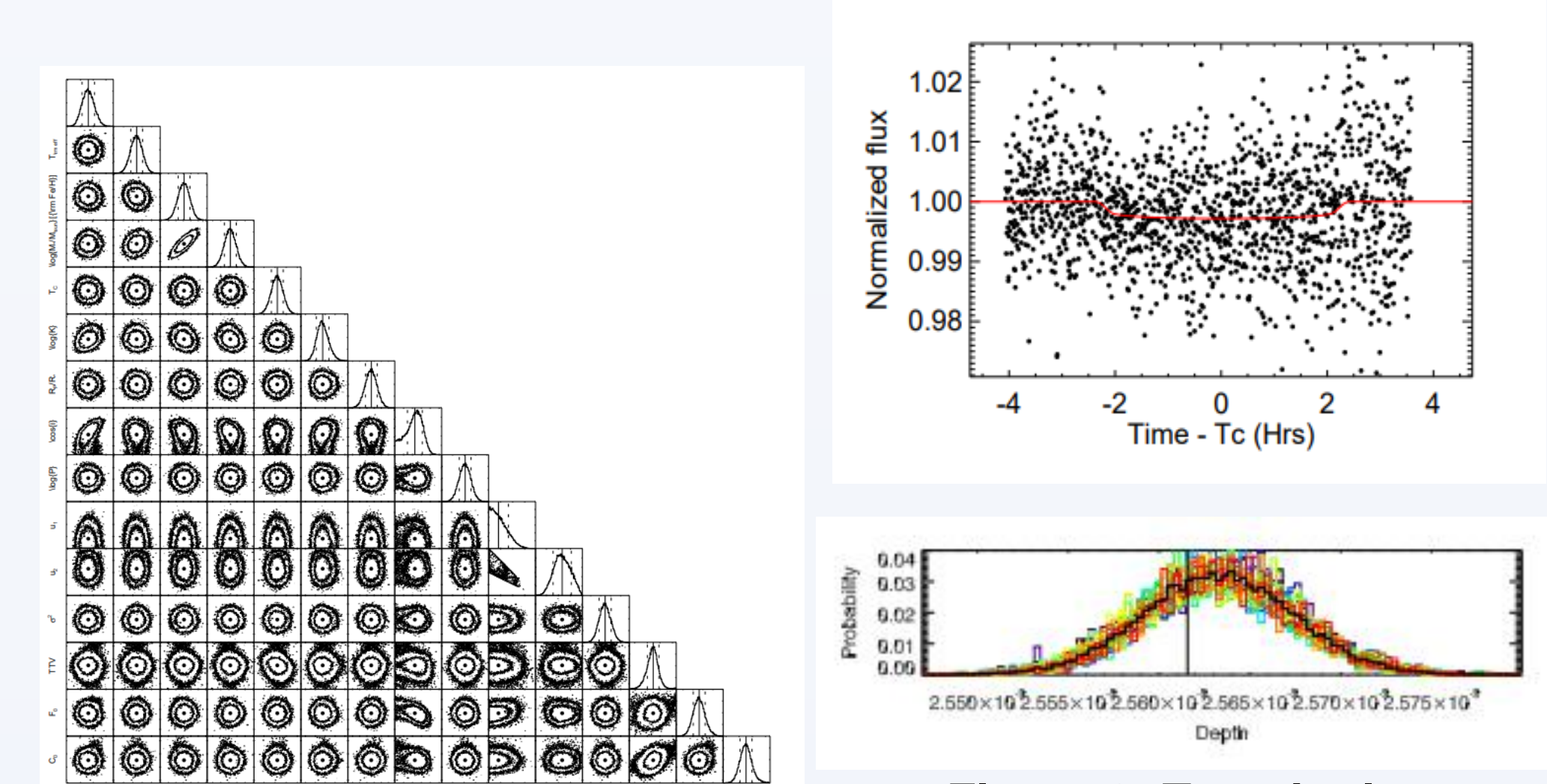


Figure 7: Covariance plot of EXOFASTv2 parameters

Figure 8: Transit plot modeled with MCMC (top), Depth pdf (bottom)

## CONCLUSIONS

We present methods for analyzing data and follow up to TESS observations, using photometry and lightcurves to identify candidate exoplanet transits and rule out false positives such as NEBs. Our confirmed exoplanet detections have contributed to the discovery and characterization of exoplanet systems, such as TOIs 442, 1333, 1468, 1601, 1710 and more to be reported in the future (Orell-Miquel et al. submitted, Rodriguez et al. 2021, Dreizler et al. 2020). Some improvements can still be made to the process, such as refining the data reduction code or automating the aperture photometry process.

## REFERENCES

Collins et al.(2016). Collins, K. A., Kielkopf, J. F., Stassun, K. G., et al. 2016, arXiv:1601.02622  
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