Exoplanet False Positive Detection with Sub-meter Telescopes

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Abstract

An initial step in confirming the existence of an exoplanet is the determination whether a light-curve produced by a photometric time-series analysis is caused by the transit of a planet or is blended light coming from other sources that might mimic an exoplanet transit. Such detection of false positives is especially needed when target stars are identified as possible exoplanet candidates by space-based telescopes that have large photometric apertures, such as TESS (Transiting Exoplanet Survey Satellite). With large-scale surveys such as TESS, the use of professional observatories to conduct such time-consuming times-series measurements becomes impractical. Fortunately, ground-based surveys such as KELT have established the value of using small (sub-meter diameter) telescopes to help detect exoplanet false positives.

This paper will describe the false positive detection scenarios commonly associated with all-sky surveys such as TESS, as well as methods used to detect them. Best practices, especially those associated with the differential photometry and transit modeling phases, will be discussed as they apply to false positive detection. This paper is intended to be especially useful for observers with sub-meter telescopes who wish to participate in large-scale exoplanet pro/am collaborations, such as the TESS follow-up program.

1. Introduction

The role that amateur astronomers have played in exoplanet research is well established (Conti et al. 2016). With small (i.e., sub-meter aperture diameter) telescopes, amateur astronomers have conducted time-series analysis of exoplanet transits with enough precision to help refine the ephemerides of known exoplanets. The Exoplanet Transit Database (ETD 2018), maintained by the Czech Astronomical Society (Poddany et al. 2010) represents several years of exoplanet observations by amateur astronomers. Such observations have been conducted in seeing-limited conditions – i.e., where the limitations on photometric precision have been governed more by the atmospheric conditions of the observing location than by the diffraction limitations of the telescope being used.

In addition to refining the ephemerides of known exoplanets, amateur astronomers have also participated in ground-based, large scale surveys such as KELT (Kilodegree Extremely Little Telescope) (Pepper et al. 2007) to help distinguish false positives from true exoplanet transits. Such follow-up observations by a network of observers with small telescopes have relieved the need for precious time at professional observatories. In the case of KELT, a global network of amateur and professional astronomers, in both the Northern and Southern hemispheres, have provided both the temporal and geographic coverage needed to provide follow-up observations of the KELT all-sky exoplanet survey. The success of the KELT Follow-up Network (KELT-FUN) is evidenced by the number of false positives detected by observers (Collins et al. 2018).

With the advent of TESS (Transiting Exoplanet Survey Satellite) (Ricker et al. 2014), the need for ground-based, seeing-limited, follow-up observations will especially be useful. In fact, such observations are the first step in the TESS pipeline leading to the confirmation of an exoplanet candidate. For TESS, such observations will help identify false positives, as well as help refine the ephemerides of confirmed exoplanet candidates.

This work will use the following definitions of "candidate exoplanet" and "confirmed exoplanet." as stated in the Glossary of the TESS Science Writers' Guide (NASA 2018a):

> **Candidate exoplanet:** A signal in the data that exhibits the characteristics of a transiting exoplanet but has not yet been confirmed.
>
> **Confirmed exoplanet:** A signal in the data that exhibits the characteristics of a transiting exoplanet and has been confirmed, typically with additional data from complementary surveys or statistical

analyses of existing data.

Section 2 provides a short overview of the TESS mission, since this will be used as the basis for discussion in subsequent sections. Section 3 describes the reason why false positives are of such high occurrence for all-sky surveys such as TESS. Section 4 discusses the photometric factors used to identify false positives. Section 5 presents various false positive scenarios and the false positive detection factors associated with each scenario. Section 6 includes an example of a false positive detection. Section 7 discusses some of the best practices associated with false positive detection.

2. TESS Overview

TESS is the next generation of space telescopes devoted to exoplanet science. Therefore, a review of the challenges that the TESS mission faces will be instructive in helping to understand the need for and the role of ground-based, follow-up observations in distinguishing false positives from true exoplanet transits.

TESS follows the very successful Kepler mission. Kepler concentrated on 150,000 stars in a small area of the constellation Cygnus (Figure 1) and has confirmed to-date over 2,300 exoplanets (NASA 2018b).

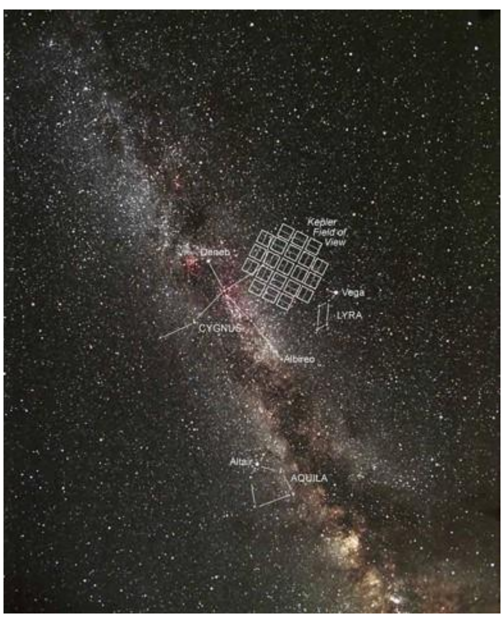

Figure 1: Kepler's Field-of-View (Courtesy NASA)

However, due to the loss of the second of its four reaction wheels, Kepler was then repurposed to conduct observations along the ecliptic plane (Figure 2).

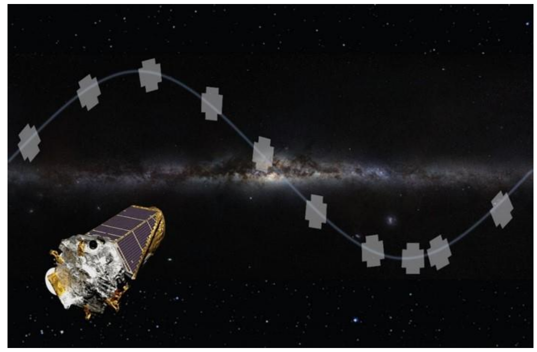

Figure 2: K2's Field-of-View (Courtesy NASA)

Named K2, this repurposed use of Kepler has to-date confirmed over 309 exoplanets (NASA 2018b).

Unlike its Kepler predecessors, TESS will conduct an all-sky survey of near-by, bright, cool stars. TESS was launched on April 18, 2018. The main science objective of TESS is to "measure the mass of 50 small (less than 4 Earth radii) transiting planets." A measurement of mass, along with radii measurements, will help exoplanet researchers determine the average density of the planet, and therefore whether or not the planet is rocky. This will then provide the James Webb Space Telescope (JWST) (NASA 2018c) with Earth and super-Earth size targets for which it can characterize their atmospheres. For this reason, TESS has been called a "finder scope" for JWST.

TESS operates in a unique elliptical orbit called P/2. The orbit is not aligned with the ecliptic plane, but rather is at an angle to it (see Figure 3).

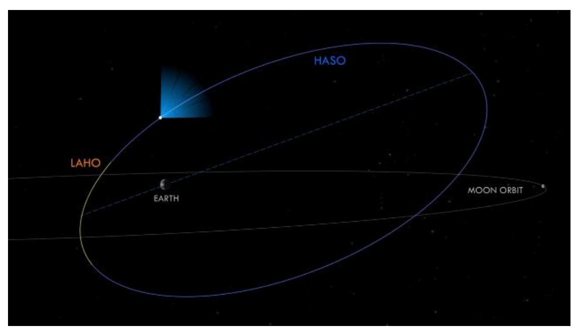

Figure 3: TESS Orbit (Courtesy Michael Richmond)

Also, TESS orbits the Earth in a 2:1 resonance with the Moon, so that for every orbit of the Moon around the Earth, TESS makes two orbits. Furthermore, at the LAHO (Low Altitude Housekeeping Operations) point in its orbit when it is closer to Earth, TESS will transmit to Earth the data it collected during the HASO (High Altitude Science Operations) portion of its orbit.

TESS consists of four 4" aperture cameras, each of which simultaneously looks at a different declination range of the ecliptic sphere (see Figure 4).

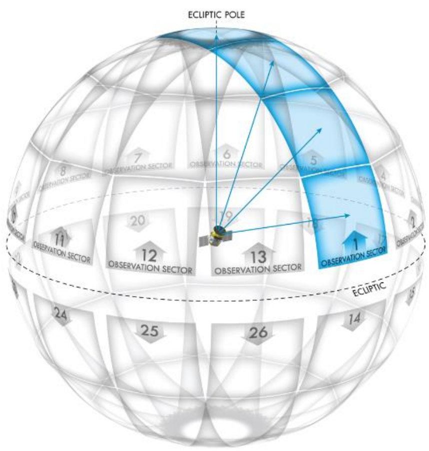

Figure 4: TESS Imaging per Sky Sector (Courtesy NASA)

Each camera has an f/1.4 lens and four (4) CCD detectors (see Figure 5).

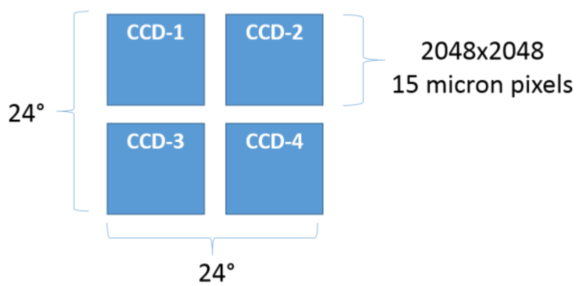

Figure 5: A Single TESS Camera

Each CCD detector consists of an array of 2048 x 2048 15 micron pixels. The combined focal length and pixel size result in an image scale of 21 arc-seconds (21”) per pixel.

Exposures are taken every two (2) seconds and are combined into two stacks (see Figure 6): sixty (60) images are stacked together to form a 2 minute combined exposure, and nine hundred (900) images are stacked together to form a 30 minute combined exposure.

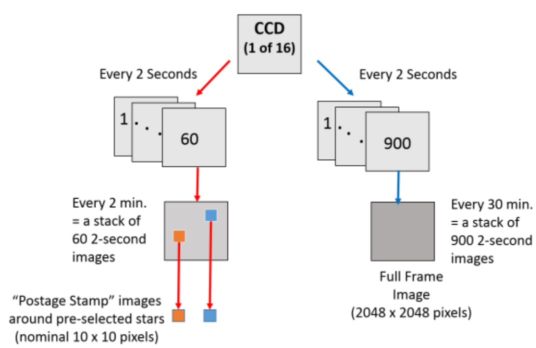

Figure 6: TESS Images

From the 2 minute combined exposure, “postage stamp” images of the pre-defined TESS targets are extracted, each nominally representing 10 x 10 pixels. From the 30 minute combined exposures, the “full-frame” images will be useful for other exoplanet and astrophysical research. As part of the TESS pipeline, a nominal 1 arc-minute (1’) photometric aperture is applied around each target.

3. Occurrence of False Positives

In order to efficiently conduct an all-sky survey of exoplanets in a reasonable amount of time, a large field-of-view (FOV) is needed for each captured image. This is true for both space-based and ground-based all-sky surveys.

For example, whereas a typical amateur astronomer performing deep sky imaging, might capture an image with a FOV of, say, 23’ x 18’, an image in all-sky survey such as TESS would be on the order of 6° x 6°. Even with such a large FOV, it will take TESS two (2) years to complete its survey of both ecliptic hemispheres.

Furthermore, for an all-sky survey such as TESS, its relatively large photometric aperture and pixel scale means that the light from multiple stars will be blended together. For example, a TESS photometric aperture will nominally have a radius of 1’, whereas a ground-based photometric aperture might have a much smaller photometric aperture of, say, 7”.

Figure 7 depicts a ground-based image showing a TESS aperture and pixel overlaid on it. As can be seen, several stars would be blended into the TESS aperture and two stars that are resolvable from the ground would even be blended together in the same TESS pixel. In fact, as we shall see in the example in Section 6, the star in the upper left of the TESS pixel in Figure 7 is actually a near-by eclipsing binary (NEB) that, when blended with the light of the (target) star in the lower right, mimics an exoplanet transit.

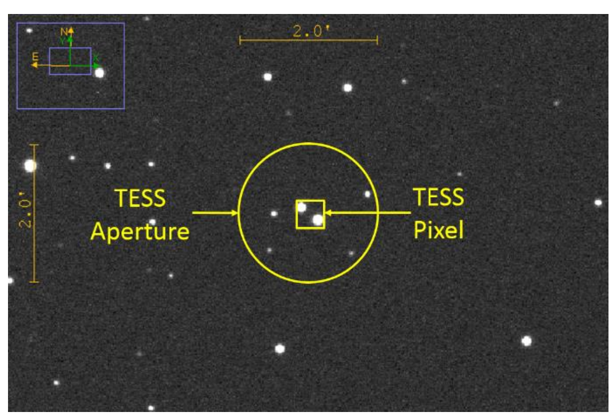

Figure 7: TESS Aperture and Pixel

With such a large photometric aperture, the light from a number of stars are blended together with the target star and the light from a near-by eclipsing source could “contaminate” the aperture such that the target star mimics an exoplanet transit. As a result of this blending, except for a few cases (Santerne et al. 2013), data from the all-sky survey itself may not be sufficient to resolve the source of a periodic dip in light.

The following example, derived from Santerne et al. (2013), demonstrates how the light of an eclipsing binary (EB), blended with a brighter nearby star, can mimic a transiting exoplanet.

Assume that the flux of a target star is blended with that of a neighboring EB and that the blended system is 10 magnitudes greater than the light of the EB alone. Furthermore, assume that the EB contains two stars of equal mass and radius. Each eclipse of the binary system would then result in a 50% reduction in the combined flux of the EB. Now, let:

δ_{eb} = the transit depth of the EB system itself,

m_{eb} = the magnitude of the EB system,

δ_t = the transit depth of the blended target and EB,

m_t = the magnitude of the blended target and EB.

Since

$m_{eb} - m_t$ is approximated by $2.5 * \log10(\delta_{eb} / \delta_t)$ and

$\delta_{eb} = 0.5$ and $m_{eb} - m_t = 10$

then:

$\delta_t = 0.00005$.

Namely, the blended system could mimic a transiting exoplanet with a transit depth of 0.005%.

Ground-based observations, even in seeing-limited conditions, have proven to be a valuable asset in resolving the source of light curve dips and therefore identifying false positives. Coupled with other techniques such as precise radial velocity measurements, a true exoplanet transit can then be distinguished from a false positive.

4. Photometric Factors Used to Detect False Positives

There are a number of photometric indicators used to help identify exoplanet false positives. This section discusses the more common ones. Section 5 will discuss how these indicators are used in various false positive scenarios.

4.1 Shape of the Light Curve

The shape (“morphology”) of the light curve itself can provide a clue as to whether a dip in the light curve is caused by an exoplanet transit or by an eclipsing binary. For example, a bucket-shaped light curve is more indicative of a small body transiting a star than a V-shaped light curve (see Figure 8 below).

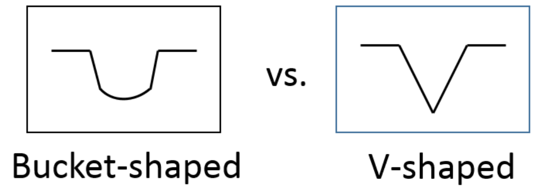

Figure 8. Bucket-shaped curve (indicative of a transiting exoplanet) vs. a V-shaped curve (indicative of an eclipsing binary)

This is due to the fact that an eclipsing body with a much smaller radius than the star it is eclipsing will have a fairly quick drop in light, followed by a constant reduction in light of the host star, and followed again by a fairly quick return to the nominal out-of-transit value. Hence, a bucket-shaped curve results.

On the other hand, a transit caused by an object such as a grazing planet or a star, either of whose disk is never completely inside the disk of the host star and will reach the opposing limb of the host star rather quickly, will result in very little, if any, of a flat bottom. Hence, a V-shape curve results.

4.2 Alternating Depths

If alternating (“odd-even”) eclipses of a target exhibit different, deep V-shaped depths, then this is usually indicative of two transiting stars (Figure 9).

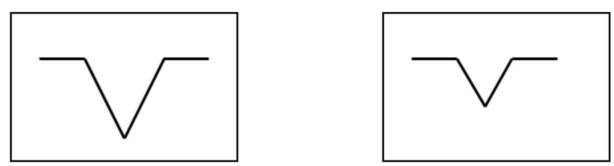

Figure 9: Alternating V-shaped curves indicative of an eclipsing binary system

Furthermore, if such odd-even eclipses are not evenly spaced, this is usually indicative of two eclipsing stars in an elliptical orbit.

4.3 Depth Variations in Different Passbands

If the eclipse of a target exhibits depth differences of a few mmag or greater when imaging is done in two passbands, say with a Johnson-Cousins’ B filter and I filter, then this is usually indicative of two eclipsing stars. This is especially true of two stars of different stellar types (Figure 10).

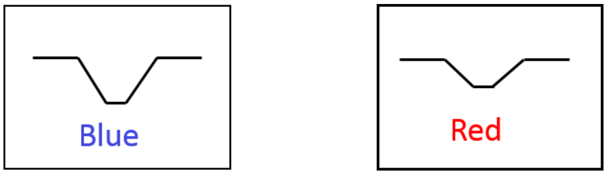

Figure 10: Color differences indicative of eclipsing stars

4.4 Depths Indicating a Non-planetary Body

The depth of the light curve itself, combined with the knowledge of the approximate radius of the star, can help determine if an eclipse is possibly being caused by a non-grazing planet. For example, the depth of the light curve = $(R_p/R_*)^2$, where R_p=the radius of the putative planet and R_* = the radius of the host star. Thus, given R_* and the light-curve depth, one can estimate R_p. If R_p is > 2.5 times the radius of Jupiter, then the eclipsing object is likely to be of a non-planetary nature. For a grazing planet, the depth represents a lower limit of the planet's radius.

5. False Positive Scenarios

This section includes various false positive scenarios and how the factors described in the previous section are used to identify them. These identification techniques can be used by observers even in seeing conditions of 3.5"- 4.0" or less.

The terms EB and NEB below refer to an eclipsing binary star system and to a "near-by" eclipsing binary system, respectively. An NEB is an EB that is near the target being observed. Here, the EB and the NEB are themselves assumed to be eclipsing stars that are so tightly bound that their primary and secondary stars are not resolvable by the ground-based observation.

5.1 Target Star Has a Distinguishable NEB

In this scenario, the target star and a NEB are blended together in the survey's photometric aperture such that there are periodic dips in the survey's light curve. However, ground-based observations are able to resolve the target star from the NEB (see Figure 11). Furthermore, the NEB itself generally shows depth changes on alternating observations and each light curve usually shows a deep, V-shaped curve.

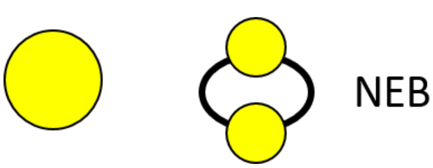

Figure 11: Target Star and a NEB

In addition, if the V-shaped curves are not evenly spaced in time, this could be indicative of a NEB that is in an elliptical orbit. Note that this scenario can also occur if the target and NEB appear in the sky as close companions due to a chance alignment.

5.2 Target Star and a NEB are not Distinguishable

In this case the target and the NEB are blended together in the survey's photometric aperture, however, they are also indistinguishable even in ground-based observations (see Figure 12).

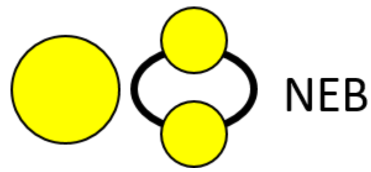

Figure 12: Target Star Blended with a NEB

In this case, if a periodic eclipsing event taken in two different passbands– ideally, one in the blue end of the spectrum and the other at the red end – shows a difference in depths of a few mmag or more, then it is likely that this represents a blend of the target star and a NEB. Here the same or different observers would use filters in each passband either on the same night or on successive occurrences of the periodic eclipsing event to capture any such light curve differences. Section 7.7 discusses some of the techniques for capturing such observations in different passbands. Note that this scenario can also happen if the target and NEB are not gravitationally bound, but rather represent a chance alignment.

5.3 Target Star and a NEB are a Hierarchical Triple

In this situation, the target star and the NEB are orbiting each other – i.e., they represent a so-called hierarchical triple (Figure 13).

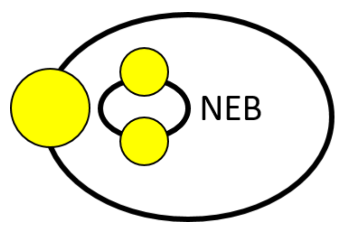

Figure 13: A Hierarchical Triple

The same detection method is used for this scenario as the one used to identify the above scenario, namely a periodic eclipsing event showing a few mmag or more depth difference in two different passbands.

5.4 Target is Actually an EB with Blending from a Neighbor

Here the target star and a near-by star are spatially resolvable by ground-based observations, but the target is actually an EB (Figure 14).

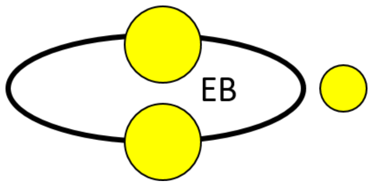

Figure 14: Target is an EB with Neighbor

This is indicated by its light curve usually showing a deep, V-shaped pattern.

5.5 Target is an EB and the Secondary Star Mimics a Planet Transit

In this case the target is an EB and the secondary star is small enough relative to the size of the primary star that it results in a bucket-shaped light curve (Figure 15).

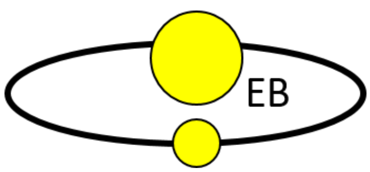

Figure 15: Small Secondary Star in an EB

However, if the radius of the transiting object is estimated to be greater than 2.5 times the radius of Jupiter, then the object is more likely of a non-planetary nature (see Section 4.4).

5.6 Target is an EB and the Secondary Star Grazes the Primary Star

As in the previous scenario, the target is actually an EB, however the secondary star "grazes" the primary star (Figure 16). This would typically result in a V-shaped vs. a bucket-shaped light curve, thereby identifying this as a potentially non-planetary transit. However, a radial velocity study would be needed to confirm this.

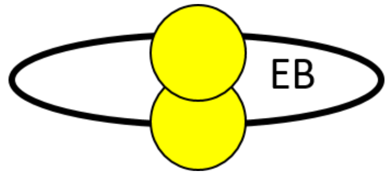

Figure 16. A Grazing Secondary Star

6. Example: False Positive Detection

This section contains an example of the detection of a false positive of the form described in Section 5.1. As will be seen, factors described in Sections 4.1, 4.2, and 4.4 were used to confirm this detection. That is, a combination of the shape of the light curve, alternating depths, and the non-planetary size of the eclipsing object helped confirm that there is a NEB contaminating the photometric aperture of the target star.

In this example, the target (identified by T1 in Figure 17) was a 11.28 V-magnitude star in the TESS input catalogue.

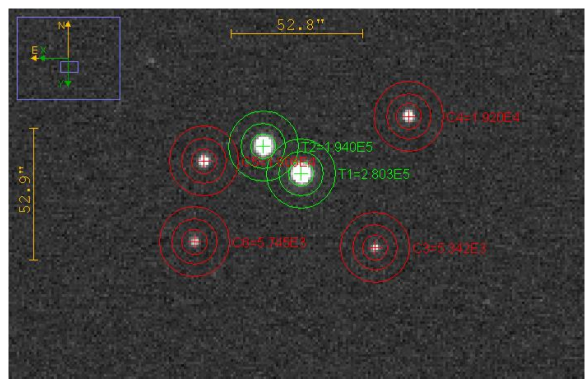

Figure 17: Original target T1 and detected NEB T2

This target was also previously a target identified by the KELT project as having periodic eclipses every 0.63 days.

As described below, two observations confirmed that there was a NEB (identified by T2 in Figure 17) causing the KELT pipeline to initially identify the target as an exoplanet candidate.

One observation was conducted by Rick Schwarz and Harvey Patashnick using the Patashnick Voorheesville Observatory (PVO) with a V-filter (Figure 18).

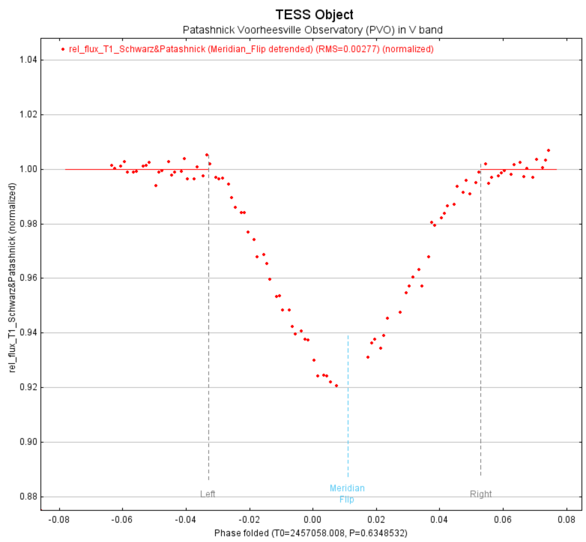

Figure 18: Observation of NEB by Patashnick Voorheesville Observatory

This was followed 11 eclipses later by the author's observation of the NEB using a V filter (Figure 19).

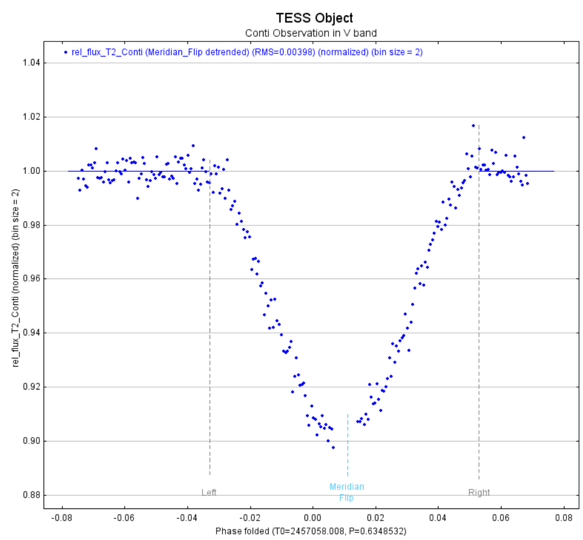

Figure 19: Observation of NEB by Conti Private Observatory

Both observations showed no variability in the target star, however, as seen in Figures 18 and 19, both showed a deep, V-shaped light curve for a star 19" away.

When the two observations of this nearby star are overlaid on each other, a depth difference of approximately 3% percent is seen (see Figure 20).

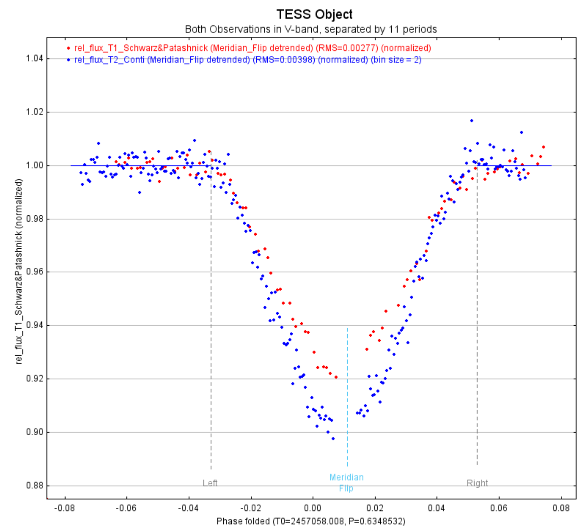

Figure 20: Both NEB observations

This depth difference of "odd-even" eclipses, along with the V-shape of both light curves and the amount of transit depth, confirmed this NEB as the reason that the target was originally and correctly identified in the KELT pipeline as a potential candidate.

7. Best Practices for Detecting Exoplanet False Positives

Best practices associated with exoplanet observing have been well-documented elsewhere (Conti 2017a and Gary 2014). Also, "A Practical Guide to Exoplanet Observing" by the author (http://astrodennis.com) provides a step-by-step approach to exoplanet observing using AstroImageJ (AIJ). AIJ (Collins et al. 2016) is an all-in-one software package for image reduction and exoplanet transit analysis. In addition, online courses sponsored by the American Association of Variable Star Observers (AAVSO) provide training material for conducting high, precision exoplanet observing. To-date, however, such documentation and training have been primarily oriented toward the observation of confirmed exoplanets.

This rest of this paper will concentrate on those best practices and observational methods related to the detection of false positives associated with candidate exoplanets.

For large-scale surveys such as TESS, false positive detection is an important part of the overall exoplanet confirmation process. For example, Figure 21 depicts the pipeline associated with the confirmation of exoplanets for the TESS survey.

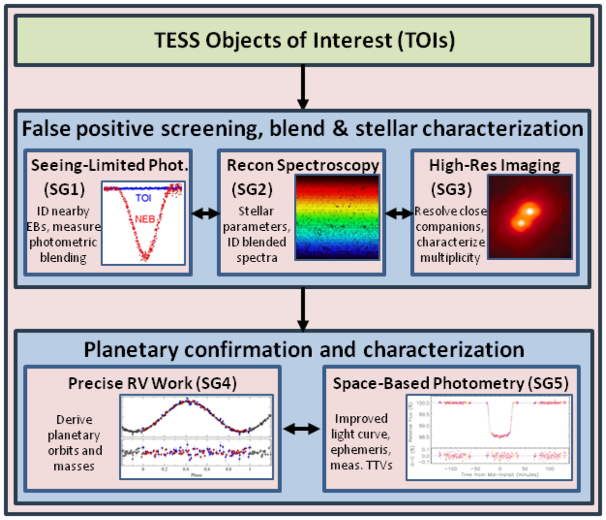

Figure 21: The TESS Planet Confirmation Pipeline

As can be seen, the first step in the pipeline, is "Seeing-Limited Photometry." This step consists of ground-based observations of TESS Objects of Interest that are first classified by automated and human means as potential exoplanet candidates.

The observational challenges facing the detection of false positives includes: resolving NEBs from the original target, characterizing the depth of such NEBs, and observing color dependent depths of the target. This section will address the best practices associated with these challenges.

7.1 Objective of the Observation

First, the purpose of the observation should be understood. For example, is the purpose:

1. To detect if any EB's exist in the vicinity of the target star?
2. To determine the transit depth in a particular passband?
3. To determine if the transit depth at an odd period is different from the depth at an even period?
4. To refine the midpoint of when an eclipse occurs?

For professionally conducted surveys such as TESS, observers will often be given guidance as to the purpose of an upcoming observation for a particular target.

If the objective is to detect any NEBs, guidance will typically be given as to the distance from the target star that neighboring stars should be checked for a detectable transit. A program such as AIJ easily allows for such checks to be done. With AIJ, stars around the target are initially designated as comparison stars during the differential photometry process. One by one, each can then be treated as target stars themselves to see if they exhibit the characteristic deep, V-shaped light curve of an EB.

7.2 Resolving an EB from the Target Star

In the case of a close-in EB, the ability to conduct differential photometry on it will be a function of whether it can be resolved sufficiently enough from the target star to be able to conduct differential photometry on it. The ability to resolve the EB from the target will be determined by a number of factors. Although the aperture of the telescope itself defines the theoretical resolution limit, the following are the factors in practice that limit the observer's resolving power:

1. The atmospheric seeing and transparency conditions at the time of the observation.
2. The focus precision.
3. The amount of image shift caused by polar misalignment and/or inadequate auto-guiding.
4. The exposure time of each image capture.

The observer can control all but the first factor. However, setting the appropriate exposure time does have its challenges, as discussed below.

7.3 Setting the Appropriate Exposure Time

If the target will be ascending at the beginning of the observation, then the exposure time should be set such that its brightness does not reach the saturation or non-linearity points of the imaging camera before it reaches the local meridian.

If a faint neighbor is close to the target, then setting the exposure time is more problematic, as described below.

7.4 Dealing with a Bright Target and Faint Neighbors

If one or more neighboring stars are much fainter than the target and they are to be tested along with the target star to see if there are signs of any detectable transits, then a second observation run would normally have to be done with an exposure time large enough to achieve sufficient SNR on the fainter stars, at the expense of saturating the target star.

An alternative approach, however, would be as follows. If the observer's image capture software allows for it, alternating series of images can be taken with different exposure times. For example, the exposure time for Series 1 would be set to provide high SNR for the target, while the exposure time for Series 2 would be set to provide a higher SNR for the faint star(s), at the expense of saturating the target star. Images would be captured alternating between each series. Two separate differential photometry runs could then take place on the two separate sets of images: the first would be used to detect a transit associated with the target star, and the second to detect any transits of the fainter star(s).

Although this approach will result in the reduction in cadence of both exposure series, if the objective is to detect a NEB and a short exposure time is all that is needed for the bright star, then the cadence may not be that critical.

For front-illuminated CCD detectors, however, one should first conduct a test to see if the CCD detector exhibits any RBI (residual bulk image) effects due to the target star being saturated. If present, RBI could affect the photometric precision of the target, even at the reduced exposure times on a subsequent image. An explanation of RBI can be found at NASA (2009).

7.5 Establishing an Out-of-Transit Baseline

In establishing an accurate measure of the transit depth either of the target star or of a NEB, an adequate out-of-transit baseline should be established. Ideally, this would include 30 minutes of pre-ingress and 30 minutes of post-egress imaging. Even if only a partial observation is possible, a sufficient amount of pre-ingress or post-egress baseline is necessary.

7.6 Conducting a Meridian Flip

In the case of a German equatorial mount, a meridian flip (MF) may be necessary due to the target passing from East to West across the local meridian. Ideally, the MF should be timed as close as possible to the mid-point of the transit. Furthermore, the time lost in conducting the MF and getting back on target should be minimized.

A program such as AIJ can later be used to correct for ("detrend") any artificial increase or decrease in flux measurements as the star field is flipped across the diagonal of the detector.

The extent of the correction needed is also related to the ability of flat-field correction to compensate for differences in the responsiveness of photosites and the effects of dust donuts on the detector. It should be noted that flat-field correction is also helpful in increasing overall photometric precision in the presence of image shift.

7.7 Determining Chromatic Differences

As described in Section 4.3, one of the factors in determining whether an eclipse is a true exoplanet transit or an EB, is to determine any detected transit depths in different passbands. This could be accomplished by observing the target at the predicted transit times in two different filters. Often the survey that the observer is participating in will give guidance as to which filter(s) to use. As described below, two techniques can be used to image the target in two different filters during a single observing session.

One approach is to alternate between two filters installed in the observer's filter wheel. This can be done using popular capture software or automated control software. The disadvantages of this approach include: the reduction in cadence in each of the passbands, the possible need to image with different exposure times and to refocus when each filter is used, and possible systematics introduced in moving between filters in the filter wheel.

An alternative approach is to image simultaneously in two passbands, specifically in both the near-infrared (NIR) and any of the standard filters available in the visible spectrum. This has been demonstrated (Conti 2017b) using two imaging cameras along with the commercially available On-Axis Guider (ONAG) – see Figure 22.

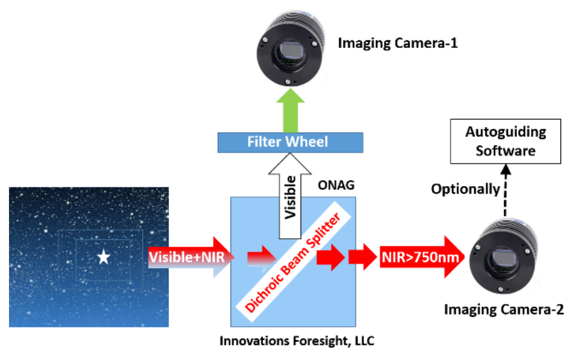

Figure 22: Use of an ONAG to simultaneously image in two different passbands

This approach overcomes all of the disadvantages of the above filter wheel approach. However, it does require an additional imaging camera and the ONAG, although the imaging camera on the ONAG's guide port can also be used to conduct high-precision autoguiding.

7.8 Image Reduction and Analysis

Consider the following three phases involved in analyzing the observation of a confirmed exoplanet:

1. The image calibration phase, where bias, dark current, and flat-field corrections are applied to the raw science images.

2. The differential photometry phase, where the flux of a target star is computed relative to the total flux of an ensemble of suitable comparison stars. Here a photometric aperture is selected whose radius is at least two (2) times the number of pixels of the target star's full-width-at-half-maximum (FWHM). An appropriate

size annulus is also selected that typically contains four (4) times the number of pixels in the aperture.

3. The transit modeling phase where an attempt is made to fit an exoplanet transit to the relative flux of the target star. This phase also includes steps to optimize the fit using some limited number of "detrend" parameters, of which airmass is the most typical, as well as deselecting some comparison stars and perhaps even redoing the differential photometry phase with a different size aperture.

The same best practice techniques dealing with image calibration of confirmed exoplanet observations (Conti et al. 2017a) apply to false positive detections as well. However, for observations where false positive detection is the principal focus, then slightly different approaches to the differential photometry and transit modeling may be needed. Furthermore, these approaches may vary depending upon the particular objective of the observation (see Section 7.1). This section provides some examples.

7.8.1. Detecting an EB or NEB

If the objective is to determine whether the target or a near-by star is an EB, the observer will typically be given guidance as to the area around the target star to be tested. First, differential photometry in the normal way is performed on the target star and all surrounding stars, the latter all being considered initially as "comparison stars." Next, one by one, each comparison star is designated as a "target" star to detect any transits it might exhibit. For AIJ, this is easily done by alternately deselecting each comparison star using AIJs Multi-plot Reference Settings window. AIJ then treats this (former) comparison star as a new target.

If the resulting light curve for either the original target star or one of the comparison stars shows a deep, V-shaped transit, then there is less a need for an accurate transit fit, except to determine approximate transit depth.

7.8.2. Determining the transit depth in a particular passband

If the objective is to determine any chromaticity differences associated with a transit, then three observation scenarios are possible, as described in Section 7.7: (1) the observation is done with only one bandpass filter and later compared with observations done using another filter by other observations at the same time or subsequent times; (2) an observation is conducted with two alternating filters by a single observer; or (3) a single observation uses two imaging cameras to record a transit simultaneously in two different wavelengths. In each of these scenarios, differential photometry is conducted separately for each bandpass run. The transit depths in each bandpass are then compared to see if they meet the "few mmag or greater" difference criteria specified in Section 4.3.

7.8.3. Refining the Midpoint of a predicted transit

If the objective of the observation is to refine the midpoint of a predicted transit, then the differential photometry and transit modeling phase would be performed in the normal way for confirmed exoplanets, as outlined in Conti (2017).

8. Summary

An overview of the TESS mission is presented as an example of an all-sky survey and the challenges it presents with detecting true exoplanet transits. In particular, the blending of light from multiple sources can, in a number of different ways, mimic the transit of an exoplanet transit. The various scenarios and methods for detecting such false positives are presented. To demonstrate the application of several of these methods to a single observation, the actual detection of an EB is presented.

Best practices with exoplanet false positive detection are presented, specifically as they apply to the differential photometry and transit modeling phases.

This paper is intended to be useful to observers with sub-meter telescopes who wish to participate in all-sky exoplanet surveys such as TESS.

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10. References

Collins, K., et al., "*The KELT Follow-Up Network and Transit False Positive Catalog: Pre-vetted False Positives for TESS*," (2018), arXiv:1803:01869.

Collins, K., et al., "*AstroImageJ: Image Processing and Photometric Extraction for Ultra-Precise Astronomical Light Curves*," (2016), arXiv:1601.02622.

Conti, D., "*The Role of Amateur Astronomers in Exoplanet Research*" (2016), Proceedings of the 2016 Meeting of the Society for Astronomical Sciences.

Conti, D., & Gleeson, J., "*Exoplanet Observing: From Art to Science*" (2017a), Proceedings of the 2017 Meeting of the Society for Astronomical Sciences.

Conti, D., "*Achieving High Precision Transit Observations with Sub-meter Telescopes*" (2017b), Proceedings of the Know Thy Star - Know thy Planet Conference.

ETD: http://var2.astro.cz/ETD/predictions.php (2018)

Gary, B., Exoplanet Observing for Amateurs, Second Edition (Plus), (2014), Reductionist Publications.

NASA: "*Taming Residual Bulk Image in CCDs*" (2009) NASA Tech Briefs, Vo. 33, No. 4).

NASA: TESS Science Writer's Guide (2018a).

NASA:https://exoplanetarchive.ipac.caltech.edu/docs/counts_detail.html (2018b).

NASA: https://jwst.nasa.gov/index.html (2018c).

Pepper, J., et al., "*The Kilodegree Extremely Little Telescope (KELT): A Small Robotic Telescope for Large-Area Synoptic Surveys*," (2007), arXiv: 0704.0460v2.

Poddany, S., et al., "*Exoplanet Transit Database. Reduction and processing of the photometric data of exoplanet transits*," (2010) *New Astronomy*. 15: 297-301.

Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9143, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 20.

Santerne, A. et al., "*Astrophysical False Positives in Exoplanet Transit Surveys: Why Do We Need Bright Stars?*" (2013), arXiv:1310.2133v1.