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1. Introduction

This master's project comprises the validation of *TESS Objects of Interest (TOIs)*, planetary candidates discovered by the *TESS (Transiting Exoplanet Survey Satellite)* mission, with small telescopes at the Kuffner Observatory in Vienna. For the case of successful transit detections, the focus lies on determining a rate of candidate validation for the given observability conditions (weather, light pollution, etc.), the telescopes and detectors within the limited time period of 6 months. This master's thesis campaign should provide quantitative information on how fast and accurate transit candidate validation can be performed once *ESA's PLATO (PLANetary Transits and Oscillation)* mission is operational from 2026 onwards.

The theoretical basis for the thesis is the transit detection method for exoplanets, where a photometric time series of a star is created for the purpose of measuring changes in stellar brightness. A sudden and recurring or periodic change in brightness can be attributed to a planetary transit, where the planet passes the apparent stellar disk and reduces the star's luminosity (see section 2).

Space telescopes are extremely precise and effective when measuring photometric time series. *TESS* is such a space probe, launched in 2018 by *NASA*, consisting of four cameras of 10 cm aperture each, scanning all directions of the sky for extrasolar planets (Ricker et al., 2014). Since its launch, it has discovered a large number of planet candidates - some of which are observable from Vienna.

By the time *TESS* measures its last light curve new missions will have been sent into space to take its place. One of the more ambitious projects will be *ESA's PLATO* mission. This telescope is expected to launch into space towards the end of 2026, with instruments operational a few months later (by 2027, Rauer (2021)). The probe will be located at the L_2 Lagrange point, as opposed to *TESS*, which is in Earth orbit. *PLATO* will wield 26 cameras with a diameter of 12 cm each (Nascimbeni et al. (2022), see section 3.1)).

As part of the *PLATO* mission, there will be an extensive ground-based campaign to validate candidates, sort out false positives and obtain planetary masses (Heras et al. (2020) and Rauer et al. (2021)). The study described here however, will contribute to the feasibility of another campaign - the *PLATO Citizen Contribution to Photometric Follow-Up*, a project in the Kuffner Observatory's responsibility for involving professional astronomers and citizen scientists with small telescopes to validate *PLATO* candidates. The *PLATO* mission will focus more on bright stars, making small, ground-based telescopes a viable option, also regarding costs for large telescope observations. Large telescopes are limited in number (worldwide), their coverage is confined by their concentrated positioning on the globe (i.e. Chile, Europe, USA) and the available observation time. Small telescopes or small observatories however, are numerous, can be set up anywhere on the globe to observe in any direction. This involves observing the different constellations of the North or the South from a given latitude, but also from any longitude, lifting the limit to single-night or single-session follow-ups and thereby reducing the inherent selection bias of ground-based observations for short-period planets. Short periods are inherently a bias of the transit method - the large ground-based observatories are often limited to single nights, which adds to that bias. A variety of observing stations along different longitudes would increase the likelihood of full transit coverage for planets with longer periods

(more on the transit method's bias in section 2.1).

Regarding the choice of the planetary candidate that should be observed, a handful of factors come into play. The geographical location of the observer limits the number of observable stars from the *TESS* dataset. The stellar position (coordinates and ephemeris), brightness, the instrumentation and the available dataset of ephemerides among other factors will further diminish the number of observable candidates (see section 5.1).

With the advent of high-performance technology introduced into daily usage and regular households, the interest and especially the capacity of the general public to participate in projects involving big data has risen drastically. More and more professional scientific projects try to engage "citizens" (or citizen scientists) to apply their own equipment, commonly in the shape of computers, cameras or even mobile phones to harness their gadget's power to support scientific progress. Today's personal computers and camera sensors have reached qualitative levels that were exclusively available to scientists in previous decades. Also, the affordability for sophisticated hardware is continuously rising, very likely making citizen science missions increasingly common in the future.

When it comes to citizen science missions, the *NASA* offers a wide array of options in different fields. The *NASA Citizen Science*¹ website lists projects such as *Backyard Worlds: Planet 9*, where people can help find the hypothesized ninth planet of the solar system in astronomical images, or *Cloudspotting on Mars*, where citizen scientists can support the mapping of clouds occurring in Mars's atmosphere; many more missions are available that even extend into other scientific fields. Similar citizen projects, e.g. also involving Mars images can be found at *ESA* as well². With respect to exoplanet missions, *NASA* also has a lot to offer³: participants can help find exoplanet transit signals in the data collected by the *TESS* space telescope (*Planet Hunters TESS*⁴). A project that is similar to the *PLATO* citizen follow-up mission is the *Exoplanet Watch*⁵ where one can apply one's own equipment to attempt follow-up observations for *TESS* candidates. Another similarity to the project described in this thesis can be found in the citizen science project *Planet Patrol*, which involves combing through *TESS* candidate images that are contaminated by instrumental or astrophysical artefacts. Clearly, the citizen contributions are already making big differences and will gain traction in the years to come.

The set-up for the here conducted experiment was arranged such that a realistic scenario of a citizen exoplanet observer could be recreated - minimal requirements regarding instrumentation, observation and data analysis were considered to be the premise. Starting from a basic standpoint, a bright enough star and a large enough aperture are the minimum standard for detecting slight differences in brightness. Regarding the instrumentation, the telescopes at the observatory - one from the 19th century in the dome and a modern one on a tripod - were considered to be the minimum. The telescopes are not only from two different historical

¹<https://science.nasa.gov/citizenscience>

²https://www.esa.int/Enabling_Support/Preparing_for_the_Future/Space_for_Earth/Citizen_science

³<https://exoplanets.nasa.gov/citizen-science/>

⁴<https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess>

⁵<https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/overview/>

eras but are very different builds altogether (see section 3.2). The brightness measurements were implemented with detectors, that were chosen to be conventional DSLR cameras, namely the *Canon EOS 5D Mark II* and the *Sony α 7 III* (see section 3.3). Also the data processing program was one common to the citizen science community, in order to conform to a citizen scientist's experimental setup. The applied method is differential photometry (see section 4.2).

The ephemerides were extracted from the *TESS*-Database ⁶, while information on other, mostly confirmed exoplanets and their ephemeris was provided by the *Exoplanet Transit Database (ETD)* ⁷. Two test observations of confirmed planets were undertaken, which is why the latter is relevant. The observable planetary candidates usually have a transit duration of about one hour in transit and two hours before and after transit - therefore, a total of 3 hours of observing each was to be expected. The next step composes of checking whether the predicted transit could be detected by the given instruments and detectors, within the framework of the night's limiting factors. Should that be the case, the question arises whether the measured transit is on target (and not on a nearby star or caused by another systematic signal) and whether there are any detectable differences to verified previous observations. The next step in the validation process is to attempt a differentiation for the origin of the dip in brightness being from a planetary orbit and therefore excluding false positives. A cause for such an incorrect signal could be a darker binary next to or behind the target, also known as a "background eclipsing binary" (BEB, see section 2.2). These objects also display dips in their photometric time series. The exclusion of such a false positive can also be achieved with smaller telescopes, as were applied in this project. The resolution of binaries unresolvable for space telescopes is possible due to the higher focal length and smaller pixel sizes (as compared to *TESS* or *PLATO*), while generally a better angular resolution could be possible due to the larger apertures (see section 3.1).

In the case of a successful transit detection, the depth, duration and timings of the target's light curve are then noted and compared to existing observations. The new observations of the *TESS* candidates would then be entered into *ETD*, where they can be rated according to precision and quality - and finally fitted for parameter analysis.

The time schedule consisted of a six month plan with one month of introductory studies, the first observations being conducted in February 2022, four months of observations during March, April, May and June and finalizing the written thesis from July and August onwards. Additionally, two test observations were conducted in August.

The expected results of this observation campaign comprise the number of *TOI* observations obtained over the course of the campaign, depending on weather, visibility, instrumentation and the planet candidates' ephemeris. The required time for observing *PLATO* candidates in the future with the aforementioned rate as well as a dependence of this rate on magnitude and transit depth will be estimated. The result should give a performance and precision estimation

⁶*TESS* Mission (NASA, MIT, CfA): Dataset from the *TOI* Catalog. <https://tev.mit.edu/data/collection/193/>, last access: 2022-09-29

⁷Czech Astronomical Society: *Exoplanet Transit Database (ETD)*. <http://var2.astro.cz/>, last access: 2022-08-09

for future *PLATO* transit candidate validation with small ground-based telescopes. As essential insights to the ground-based follow-up programme's feasibility, the dependence of the validation rate on stellar magnitude and transit depth would be estimated and the successful observations added to the *Exoplanet Transit Database* (ETD). Further essential observational attributes, such as airmass, homogeneity of the background, and the FWHM as an indicator for Seeing were investigated as possible limiting factors.

2. Detection Theory

2.1. The Transit Method

The theory behind the measurement of the exoplanet signal is the most fruitful detection method to date - the transit method. About 75% ⁸ of confirmed exoplanets (5271 as of 14/11/2022 ⁹) have been discovered with this method. Since its first successful application for the star *HD 209458* ¹⁰ in the year 2000 by David Charbonneau with a telescope of 10 cm aperture (Charbonneau et al. (2000), simultaneous radial velocity (RV) measurements by Henry et al. (2000)) it has been efficiently applied to many other objects. The root of this method's outstanding yield lies in the facile and rapid implementation and its low requirements; e.g. for space telescopes, due to its rather simple concept. Should the geometry of the planetary orbit around a distant star allow a configuration where the line of sight is close to the orbital plane, a transit, an occultation of the star by its satellite is detectable from Earth. Such a phenomenon can be observed within the confines of our own solar system as well; for example with the moon eclipsing the sun, or the inner planets transiting the sun. Venus or Mercury, visible in photographs as tiny black dots, moving across a bright "stellar disk" also undergo a transit. As the line of sight does not need to be exactly within the orbital plane, different configurations of the planet's orbit in relation to the star's center within a certain angle would still make the transit detectable. The decisive criterion in this case is the impact parameter b which gives insight to the apparent position of the planet on the stellar disk, which results in different shapes for a transit light curve (see blue and red light curve in Figure 1).

The impact parameter depends on the semi-major axis of the elliptical orbit a , the stellar radius $R_\star$ and the orbital inclination i . For the event of an orbit being edge-on with regard to the line of sight, the inclination equals 90 degrees ($i = 90^\circ$), when the orbit is "face-on" the inclination is equal to zero ($i = 0^\circ$). From the following equation one can infer what this means for the impact parameter b (Johnson (2015), Seager and Mallén-Ornelas (2003)):

$$b = \frac{a}{R_\star} \cos(i) \quad (1)$$

The parameter b is equal to zero, if the orbit is perfectly aligned with the line of sight; should the planet be positioned below the imagined central/equator line of the star the parameter is $b < 0$ and for the opposite case of a position above the center it will be positive ($b > 0$). A non-zero impact parameter will cause the transit light curve to appear increasingly V-shaped with a higher absolute value for b (Johnson, 2015).

In Figure 1 the parameters that describe the transit light curve are the transit duration T , the ingress/egress time τ and the transit depth ΔF . The process of ingress is the first phase of the transit, where the planet first "touches" the stellar disk and causes the initial reduction of stellar brightness (indicated with a yellow "1" in Figure 1); ingress ends once the planet is fully engulfed by the stellar surface (the yellow "2", "second touch"). The term "egress" is analogously defined - instead of the planet's entry, the egress can be seen as the planet exiting

⁸<https://exoplanets.nasa.gov/discovery/discoveries-dashboard/>

⁹<http://exoplanet.eu/catalog/>

¹⁰ $V = 7.65$ mag, $\Delta F = 0.0162$ mag (see footnote 7 for the source, and equation 4 for relevance)

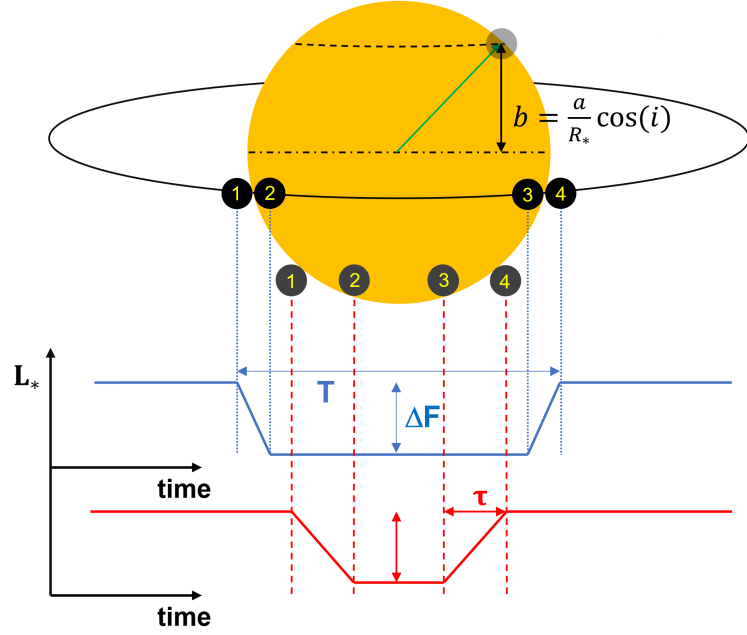


Figure 1: The Transit method and its differing light curves for a varying impact parameter b

the stellar disk (third to fourth touch or the yellow "3" to "4"). Figure 1 also shows how a non-zero impact parameter b causes a different transit shape, with shorter transit durations T and at the same time longer ingress/egress times τ . These two values of time depend on some parameters of the star-planet-system as given by the following equations (Johnson, 2015):

$$\tau = \frac{P \cdot R_p}{\pi \cdot a \cdot \sqrt{1 - b^2}} \quad (2)$$

$$T = \frac{P \cdot R_* \cdot \sqrt{1 - b^2}}{\pi \cdot a} \quad (3)$$

In the two equations, P represents the orbital period and R_p the planetary radius. Other factors that affect the shape of a transit light curve are for example the measured wavelength and the limb darkening of the star, an effect where the outer rim of the stellar disk is less bright, due to the difference in optical depth. Viewing the centre of a star implies observing deep into the star, while less optical depth is reached in the outer parts (Knutson et al. (2007), Johnson (2015)). A star with limb darkening therefore has centrally peaked brightness, which leads to a higher dimming during occultation and rounds the edges of the light curve - the trough gains in curvature and the transit looks more U-shaped. For fitting transit light curves, different approaches to adjust the limb darkening can be taken - linear, non-linear, quadratic, exponential and other functions. However, the non-linear approach appears to be the most representative of reality (Mandel and Agol, 2002).

The transit depth parameter ΔF yields essential information on the planet, namely the planetary

radius. The transit depth ΔF is directly dependent on the ratio of the apparent area of a star (as seen by the observer) to the area of the planet that occults the star (Deeg and Alonso, 2018). Therefore, the ratio of two circular areas leaves us with the ratio of two radii (Seager and Mallén-Ornelas, 2003):

$$\Delta F = \frac{F_{no\ transit} - F_{transit}}{F_{no\ transit}} = \left(\frac{R_p}{R_\star}\right)^2 \quad (4)$$

This means the larger the planetary area is in relation to the stellar area, the larger the transit depth ΔF will be.

Comparing familiar cases from our own solar system for the purpose of visualising the transit depth, the Jupiter-Sun orbit would result in a dip of about

$$\Delta F_{Jup} = \left(\frac{R_{Jup}}{R_\odot}\right)^2 = \left(\frac{1}{9.731}\right)^2 = 1.056\%,$$

while the Earth would change the solar brightness only by

$$\Delta F_\oplus = \left(\frac{R_\oplus}{R_\odot}\right)^2 = \left(\frac{1}{109.1}\right)^2 = 8.401 \cdot 10^{-5} = 0.008401\%$$

(Johnson, 2015).

Having defined three essential directly observable parameters of a transit light curve, namely transit depth and the time values T and τ , another aspect needs to be added, namely the transit timing. This is the time of occurrence of the observed event - precise measurements of that characteristic are important, since transit timing variations are used to postulate the existence of additional planets in the system. Apart from that, multiple precise transit measurements can be used to derive a relatively accurate period P of the orbit. Alternatively, often the RV method can be applied to the same planetary system and the planetary period will be constrained from the recurring radial velocity signal.

The period can be used to calculate the elliptical orbit's semi-major axis a from Kepler's third law,

$$P^2 = \frac{4\pi^2 a^3}{G \cdot M_\star} \quad (5)$$

in case the mass of the star $M_\star$ is known ($M_\star \approx M_\star + M_p$, the planetary mass is therefore negligible; G is the gravitational constant).

Should the mass not be at one's disposal, that would impair a calculation of the semi-major axis and therefore also the impact parameter b (see equation 1). However, using the equations 2 and 3, the parameter b can also be calculated with (Johnson, 2015):

$$b^2 = 1 - \sqrt{\Delta F} \frac{T}{\tau} \quad (6)$$

Similarly, the observable parameters of a transit light curve can be used to calculate the ratio of the semi-major axis and the stellar radius $a/R_\star$, also called the scaled semi-major axis (Johnson, 2015):

$$\frac{a}{R_{\star}} = \frac{P \cdot (\Delta F)^{1/4}}{2\pi} \left(\frac{4}{T\tau} \right)^{1/2} \quad (7)$$

The two previous equations represent a simpler breakdown of the problem, Seager and Mallén-Ornelas (2003) offer a more sophisticated approach.

Finally, the stellar radius $R_{\star}$ is another property that would have to be calculated externally. Many of the space telescopes that specialise in exoplanet search are also used for asteroseismology. This applies to the *Kepler* space telescope, but also to *TESS* and *PLATO*. The oscillations of stars and the respective models that asteroseismologists use to explain them also yield information on the stellar radius. Most models are based on "solar-like oscillations", which can be applied to solar-like stars and many red giant stars ¹¹.

Alternatively, the radius can be ascertained from the fact that stars are near perfect black body radiators, which makes their colour a clear indicator of their effective temperature T_{eff} . This fact can be exploited by solving the definition of the easily available luminosity $L_{\star}$, the Stefan-Boltzmann equation, for $R_{\star}$:

$$L_{\star} = 4\pi R_{\star}^2 \sigma T_{eff}^4$$

The greek letter σ represents the Stefan-Boltzmann constant (Johnson, 2015).

Another aspect of this detection method is the phenomenon of a secondary transit, that can be measured in some cases. The event occurs when the exoplanet passes behind the star, as opposed to the primary transit, where it crosses the star from the front. The fact that this effect can be measured at all is due to the geometry of the orbit; during the planet's movement around the star, the planet will exhibit changes of phase (similar to the moon), depending on its position relative to the star (see Figure 2). This means, that the reflected light will add to the stellar light, causing a total increase in flux until the reflected light is blocked out by the star. Once the planet emerges again, the reflection would recommence, until the reflection angle no longer allows the light to reach the observer.

Some important information that can be derived from this effect is the timing of the secondary eclipse, which carries information on the eccentricity of the orbit and the argument of periastron. The depth of the transit yields information on the reflected light and the thermal emission of the planet. In a general scenario, the observed eclipse depth will be a combination of the two mentioned components, which are difficult to distinguish - although thermal flux will be dominant in the near-infrared (NIR). Measuring the secondary eclipse in different wavelengths would help to distinguish the two contributions to the total emission; NIR measurements will mostly be thermal and the bluest visible colours will be dominated by reflected light (Alonso, 2018). According to Cowan and Agol (2011), the equilibrium temperature at the sub-stellar point of the planet is given as:

$$T_0 = T_{\star} \sqrt{R_{\star}/a} \quad (8)$$

¹¹<https://docs.lightcurve.org/tutorials/3-science-examples/asteroseismology-estimating-mass-and-radius.html>

¹²Astrobites: *A new discovery of a secondary eclipse* (2016). https://astrobites.org/wp-content/uploads/2016/12/phasecurve_flux.png, image credit: Josh Winn, last accessed: 2022-11-15

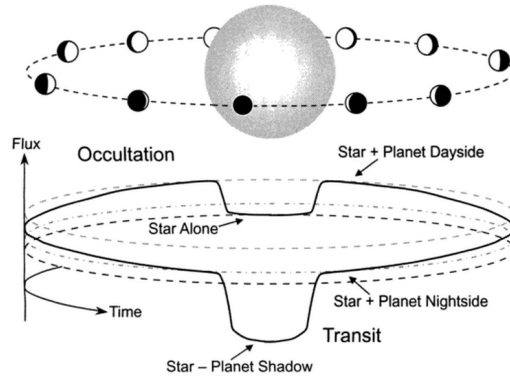


Figure 2: A schematic sketch of a secondary transit ¹²

which can be used to calculate the temperature at the dayside or the nightside, since planets which exhibit secondary transits are usually very close to the star and thus tidally locked. As mentioned before, the observation of the dayside emission at different wavelengths with narrow bands can be used to create a low-resolution spectrum. This would yield information with respect to features caused by molecular/elementary components of the planetary atmosphere (Alonso, 2018).

Short-period planets are more prone to secondary transits, due to multiple reasons. Firstly, the incident flux of the star is stronger and thus the reflected component will be all the larger, making a secondary transit depth more significant. Secondly, close-in planets are more likely to produce secondary eclipses, since there are more orbital inclinations at which the planet would pass behind the star as opposed to satellites that orbit further out. The transit duration of a short period-planet is in the order of a few hours and thus short enough to be observed within one night - at least for ground-based telescopes (Alonso, 2018). This means that so-called *Hot Jupiters*, planets with a large radius (mass) located very close to the host star are the most likely candidates to exhibit secondary transits.

However, this fact does not only apply to secondary eclipses, but holds true for the transit detection method in general. A geometric bias is responsible for more detections of short-period planets and a detection bias for larger planets (Kipping and Sandford (2016), Beatty and Gaudi (2008)). This means that short-period planets are easily validated with multiple sightings, while large radii cause more substantial or noticeable transit depths. The yield of currently detected exoplanets reflects that notion; transit exoplanets have shorter periods, but similar masses compared to planets detected by RV ¹³. Even though this method has skewed our knowledge of planets in our galaxy towards close-in gas giants, the method has been the most successful so far with a yield of $\sim 75\%$ of detected planets being discovered with it.

¹³see figure of NASA: *Exoplanet Discovery Dashboard*. <https://exoplanets.nasa.gov/discovery/discoveries-dashboard/>, last accessed: 2022-11-15

2.2. False Positives

However, there are some astrophysical phenomena that mimic transit signals. According to Brown (2003), these are mostly stellar systems that follow the following scheme - structured in a question format:

"(1) Is the primary of the eclipsing system a main-sequence star (M) or a giant (G)? (2) Is the secondary a main-sequence star (S) or a Jovian planet (P)? (3) Is the light from the binary undiluted by a third star (U) or diluted (D)? (4) If diluted, is the third star a foreground object (F), or is the system a bound triple (T)?"

(Brown (2003), p. L125)

Traditionally, the confirmation of a transit signal is implemented with a different detection method, namely by measuring its mass with high-precision radial velocity (RV). In cases where the signal is small enough to be of a terrestrial planet and therefore difficult to measure by RV, statistical techniques to find the probability of a planetary detection suffice to validate the planet (Deeg and Alonso, 2018). False-positive scenarios are very improbable when several transiting signals are detected on the same star (Lissauer et al., 2012) - and current validation procedures use this fact, which is why this project applies this concept of confirmation (Deeg and Alonso, 2018).

The main types of false signals are Eclipsing Binaries (EBs). These can be categorized as "undiluted" binaries, which are observed directly, and as "diluted" binaries, EBs whose light is diluted by a nearby third star. In most cases, in fact, the third star is the observed target. Typically, the latter is brighter, while the binary can be found as a faint background phenomenon (background eclipsing binary (BEB)) - the third star could be physically connected to the system (e.g. in a triple star system) or be unrelated. For planetary candidates with a low transit signal, one could even consider a stellar system with a giant planet that is in the background and diluted by a brighter star, thereby mimicking a small-planet transit. For the case of an undiluted binary, grazing EBs and the eclipses of two stellar components with large ratios in area or surface brightness might be responsible for planet-like eclipses (Almenara et al., 2009).

Figure 3 depicts some of the most common causes for exoplanet transit light curves: the top left pictures shows a grazing EB, where the orbit is seemingly located towards the edge of the primary. The top center image shows a diluted EB as discussed earlier, the one to the right an unresolved EB. Image 4 of the figure shows a very low mass star with a brown dwarf (VLMS/BD), the bottom center is a picture of close triple systems and lastly at the bottom right there is the actual planetary detection, which is a rare instance in general terms.

One of the goals of the here described project is to attempt to validate a planetary candidate signal by possibly excluding such a phenomenon as shown in Figure 3. Such an endeavour could be accomplished by the higher focal length and smaller pixel sizes as compared to TESS, which could lead to a better angular resolution enabling the detection of binaries unresolvable for space telescopes.

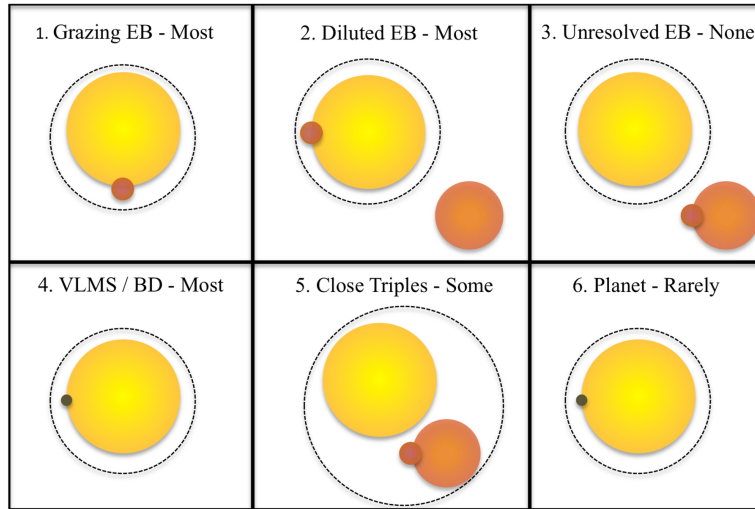


Figure 3: Different types of false positives that can occur in exoplanet transit data (Credit: STScI ¹⁴)

3. Instruments

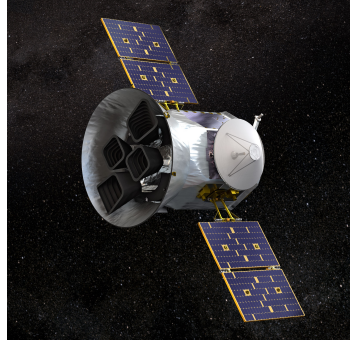
A wide range of instruments are relevant to this project's scientific context and to the experimental implementation. Some are directly relevant, such as the applied ground-based telescopes and cameras, and others are indirectly significant due to the usage of the instrument's data or future application. The latter case applies to the space telescopes *TESS*, of which ephemerides and planet candidate data were used and to *PLATO*, a project that will be launched in a few years, to which this project's results are of importance.

3.1. The Telescopes in Space - Present and Future

Both missions *TESS* and *PLATO* have set the goal to observe bright stars for their respective exoplanet searches. The reason for such endeavours is the fast and effective detection of a transit, simpler follow-up measurements with space and ground-based telescopes and for measuring planetary masses with RV and the atmospheres (e.g. with transmission spectroscopy, Ricker et al. (2014)).

The *Transit Exoplanet Survey Satellite (TESS)* (see Fig. 4a) is a *NASA* spacecraft launched in 2018 moving on an Earth orbit with a 13.7 day period. The space telescope has four identical lenses with 10.5 cm aperture and 14.7 cm focal length ($f/1.4$). The surfaces of the optical elements have a long-pass filter coating, which enforces a 600 nm cutoff. On the other end the sensor has a limit at 1000 nm, which is set by the quantum-efficiency curve of the CCDs (Ricker et al., 2014).

¹⁴Space Telescope Science Institute (STScI): *How Do I Use Kepler/K2 Data?* https://www.stsci.edu/~fleming/research/koi_fp.jpg, last access: 2022-07-29



(a) The *TESS* space telescope with its four cameras (Credit: NASA ¹⁵)



(b) The *PLATO* space telescope with its 24 cameras and 2 "fast" cameras (Credit: *platomission.com* ¹⁶)

Figure 4: The two space telescopes, *TESS* and *PLATO*

Each lens produces a $24^\circ \times 24^\circ$ image on a four-CCD mosaic, which are back-illuminated MIT/Lincoln Lab CCID-80 devices. Each consists of a 2048×2048 imaging array and a frame-store region of the same size with $15 \mu\text{m}$ square pixels. In total, the four CCDs create a 4096×4096 imaging array within a 62×62 mm square (Ricker et al., 2014).

The spacecraft concentrates on F5 to M5 stars on the main-sequence. Evolved and early type stars are too large for small planet detection; the latter type is known for rapid rotation, which leads to extensive spectral line broadening and thus to difficult RV follow-up measurements. The observation catalogue of *TESS* includes about 200,000 main sequence stars sufficiently bright and small for a possible detection of a transiting planet smaller than Neptune. Stars brighter than 12 mag for FGK- and brighter than 13 mag for M-stars (in the I_C -band) are being observed by the space telescope (Ricker et al., 2014).

The telescope surveys the northern and southern ecliptic hemisphere with 13 sectors each,

¹⁵NASA Scientific Visualization: *TESS in Space*. <https://svs.gsfc.nasa.gov/vis/a010000/a012700/a012727/TESSInSpaceRender1.jpg>, last access: 2022-07-30

¹⁶PLATO mission, ESA: *PLATO Fast Facts*. https://platomission.files.wordpress.com/2018/05/csm_plato-satellit_artist_s-impression__c__ohb-system-ag_cd2eb45818-e1551701363683.jpg?w=596, last access: 2022-07-30

which results in different total observation durations - with a big advantage for the ecliptic poles (see Fig. 5a and the differing colours for coverage). Each sector was observed for 27 days before changing to the next sector. Subsequently, the observation of one hemisphere takes one year with an observation area of about 30,000 square degrees per hemisphere.

The current status of the *TESS* mission is that during the first year (July 2018 - July 2019) the southern ecliptic hemisphere was observed, the northern hemisphere followed in the second year. Year 3 of the mission consisted of re-observing the southern ecliptic hemisphere, and currently (year 4, ending in September 2022) parts of the northern hemisphere are being re-observed, including a 240° swath of the ecliptic, which has not been observed so far. The following year includes the completion of the northern hemisphere and year 6 a new survey of the southern part ¹⁷.

The missions *TESS* and *PLANetary Transits and Oscillations of stars (PLATO)* have similar aims, but there are some significant differences. The *ESA* mission's current schedule is to launch towards the end of 2026 (Rauer, 2021). *PLATO*'s final design includes 24 cameras of 12 cm diameter each, four CCDs with 4510×4510 pixels per camera, a pixel size of $18\mu\text{m}$ and a read-out cadence of 25 seconds (Sacchetti et al., 2021). The 24 cameras are arranged in four groups of six with overlapping fields of view, which leads to an effective lens aperture of > 60 cm (see fig. 4b). Two additional "fast" cameras will observe bright stars with < 8 mag at a read-out cadence of 2.5 seconds. The observations will take place in the range between 500 - 1050 nm on a total field of view of $\sim 2232 \text{ deg}^2$ (approx. size of winter hexagon, Sacchetti et al. (2021)) ¹⁹. A list of data, giving a brief insight into the two aforementioned missions by comparing their specifics is given in Table 1.

While *TESS* is in an orbit between Earth and the Moon, *PLATO* will be placed at the L2 Lagrange point, which will expose it to less scattered light from the Moon or the Earth and will enable longer exposures of the star without being intercepted by the Earth to interrupt the measurement (longer temporal coverage, Rauer (2021)). Instead of observing many small sections of the whole sky for 27 days, *PLATO* will focus on one large area of the sky for two years or more. This permits the space telescope to detect long-period and small size planets around Sun-like stars, as compared to *TESS*'s yield of mostly planets around close-by M-stars ²¹.

The core sample of the *PLATO* observation campaign will consist of $\sim 15,000$ dwarf and sub-giant stars (F5 to K7) with < 11 mag, a statistical sample of $> 245,000$ dwarf and sub-giant stars with < 13 mag and > 5000 late type stars (M dwarfs). The core sample will have the advantage that radii and asteroseismology can be applied, while radii measurements will also be employed to the statistical sample, but asteroseismology and RV measurements are not

¹⁷TESS Mission, NASA, MIT, CfA: *TESS Observations*. <https://tess.mit.edu/observations/>, last access: 2022-08-15

¹⁸PLATO mission, ESA: *TESS and PLATO at a Glance*. <https://platomission.com/2018/07/03/tess-and-plato-at-a-glance/>, last access: 2022-08-24

¹⁹see footnote 18

²⁰*PLATO Survey Goals*. https://bmk10k.aip.de/wp-content/uploads/2018/06/grand_all_gal.png, last access: 2022-07-30

²¹see footnote 18

	PLATO	TESS
Launch	2026	2018
Telescope Aperture	12 cm	10.5 cm
Lenses	24+2	4
Telescope FoV	1037 deg ²	576 deg ² (24° × 24°)
Total FoV	2232 deg ²	2304 deg ² (24° × 96°)
Wavelength	500 - 1000 nm	600 - 1000 nm
Pixel size	18 μm	15 μm
Plate scale	15 "/px	21 "/px
CCD pixels/cam	4510 × 4510	4096 × 4096
Targets	F5 - K7 < 11 mag (main) < 13 mag (statistical), < 8 mag (fast)	F5 - M5 < 12 mag (FGK-stars) < 13 mag (M-stars)
Time per pointing	2+ years	27 days
Main objective	Earth-sized planets in HZ *	Nearby rocky planets (M-stars)
No. of stars	≥ 265,000	≥ 500,000
Noise	≤ 34 ppm in 1 hr (main sample) ≤ 800 ppm in 1 hr (M dwarfs)	≤ 220 ppm in 1 hr
Predicted yield	> 4000 planets 2-120 in HZs around solar-like stars	~ 1700 640-1340 around M-dwarfs 1-4 in HZ around M dwarfs
Primary mission	4 years	2 years
Location	L2	between Earth and Moon orbit

Table 1: Characteristics of the *TESS* and *PLATO* space telescopes; *: HZ = habitable Zone (Ricker et al. (2014), Sacchetti et al. (2021), Rauer (2021), ¹⁸)

possible. More than 4000 detected exoplanet systems are expected by the *ESA* (goal 7000), including > 100 high parameter precision planets with some habitable candidates. Both space telescope missions set the goal to find planets that are located within the confines of a habitable zone (HZ, see "main objective" and "predicted yield" in Table 1). This ring shaped area around

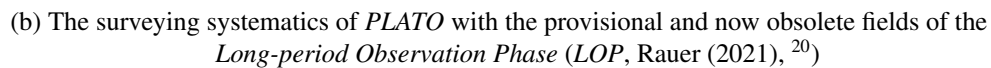
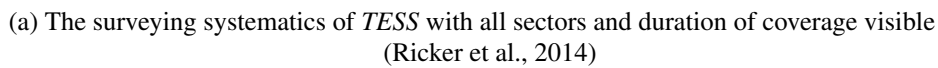


Figure 5: The two missions *TESS* and *PLATO* and their different pointings

a star is the zone where liquid water could exist on the surface of a terrestrial planet. The location and the size of that zone depends on a number of stellar factors, such as the spectral type, the mass and the age. The possibility of habitability on the planet however also depends on planetary factors such as the orbit (distance to the star), the mass, the composition and the atmosphere. There are a few habitability models that attempt to confine the definition of a HZ to concrete factors and equations, the most successful being described in Kasting et al. (1993) and Kopparapu et al. (2014).

As *TESS* has a short pointing of only 27 days, the period of a habitable planet would have to be short, indicating this would only be possible for an M-star. *PLATO* however, specialises on brighter FGK-stars and has a much longer pointing, which would make a long-period planet that could be located around a star of the specified spectral types feasible. This is another aspect why small telescope follow-ups are of importance, since long-period planets would have

longer transit times that are likelier to be covered by a "swarm" of observers on Earth. The exact field of view of *PLATO* has not yet been determined and will be fixed two years before launch - the observing strategy can be adapted during the mission (Rauer, 2021). Currently, the mission includes two fields, the *Long-duration Observation Phase (LOP)* fields, LOP1 and LOP2, which will likely be located in the northern and southern ecliptic hemisphere respectively ²². The expected observation duration will amount to 2 years, with a minimum observation duration of one year. The main pointings can be complemented by shorter pointings during the "*Step and stare*" *Observation Phase (SOP)* fields, which can expand the total areas surveyed to 40% of the sky - details for this part of the mission, including the exact pointing directions remain yet to be concluded (Nascimbeni et al., 2022). In Figure 5b one can see a no longer up-to-date version of an observation and pointing plan. The two blue areas with differing shades (degrees of coverage by the 26 cameras) represent the original and now obsolete *LOP* fields, the northern one including the *Kepler* field of view (magenta) and the lighter ones representing the *SOP* fields with parts of the *K2* mission (green) being included. *CoRoT*'s observation fields (red) are very close to the ecliptic equator and therefore would have not been included in this obsolete observation strategy.

As part of the *PLATO Ground-based Observation Programme* led by Stéphane Udry, the Kuffner Observatory and Dr. Günther Wuchterl in Vienna are responsible for the *PLATO Citizen Contribution to Photometric Follow-Up* ²³. This includes testing the possibilities of using small telescopes on the ground for measuring transit signals detected by *PLATO* from space. The background for this concept is the fact that most of the large telescopes on Earth are very high on demand and expensive to operate. Since all branches of astronomical research bid for observation time with the large instruments, the available time for follow-ups is limited. Small telescopes are easily accessible, numerous present all around the globe and therefore not limited to few locations on the globe (North America, Chile, Europe, Australia) but can be used from anywhere and by a much larger sample of people. This means that not only professional astronomers but also experienced citizen scientists/astronomers and observers can contribute to the mission by using their smaller observatories and amateur telescopes to confirm exoplanet candidates. Furthermore, the spread of observers around the globe would not only ensure a greater coverage of constellations (across latitudes, North-South), but also a greater temporal coverage that could make long-period planets measurable (across longitudes). This thesis is an attempt at testing this concept with two small telescopes at the Kuffner Observatory in the city of Vienna, Austria, where light pollution is prevalent, using commercially available detectors/cameras. The following chapters (section 3.2 and 3.3) will go into further detail on the specifics of the implemented instruments.

²²see footnote 18

²³University of Warwick: *Ground-based Observation Programme*. <https://warwick.ac.uk/fac/sci/physics/research/astro/plato-science/research/researchareas/followup/>, last access: 2022-08-10

3.2. The Telescopes at the Kuffner Observatory

The observational limits for ground-based telescopes differ from a space telescope's; they are much more restricted due to the Earth's atmosphere. As the research for this thesis will be implemented in Vienna, light pollution will be an additional factor for observability.

The telescopes applied for this research project are the equatorial "amateur" telescope, the *Meade LX50* mounted on a tripod and the Kuffner Observatory's own "*Large Refractor*", the largest lens telescope at the observatory. Constructed between 1884 and 1886, the refractor is still operational, positioned in one of the two domes of the observatory. The fact that it can still be implemented can be ascribed to continuous restorations - the last major one having been conducted in 1994-95. The objective lens which was originally installed in 1887 was refurbished 2017 ²⁴. The optical elements were planned and constructed by *Steinheil* in Munich, Germany and the mechanical elements by *Repsold & Söhne* in Hamburg, Germany. The telescope was manufactured with a German equatorial mount (see fig. 6a) and a semi-apochromatic objective lens ²⁵. With an aperture of 270 mm and a focal length of 3500 mm (Herz, 1889), the telescope has a focal ratio of $f/ = \frac{\text{focal length of primary mirror}}{\text{primary mirror diameter}} = 12.96$. The ratio is commonly noted as follows: $f/12.96 \approx f/13$ (Howell, 2006).



(a) The Kuffner Observatory's *Large Refractor* as seen from the side, with the hour angle scale visible (wheel in the centre of the mounting)



(b) The Kuffner Observatory's *Large Refractor* as seen from the bottom, from the eyepiece towards the closed dome slit

Figure 6: The Kuffner Observatory's *Large Refractor*

²⁴Kuffner Sternwarte Wien: *Die Instrumente der Sternwarte im Detail: Der Große Refraktor*. http://kuffner-sternwarte.at/sternwarte/vks_ksw_instr1.php, last access: 2022-08-10

²⁵see footnote 24

The German equatorial mount limits the complete freedom of movement of the instrument due to the fact that the counter weights of the telescope need to stay in equilibrium or be below the telescope's weight. Therefore, the telescope's orientation depends on the target's position - a target in the West requires the telescope to be located to the East of its pillar and vice versa. In Figure 6a the telescope is in its resting position in the West. Another restriction of movement is the fact that the telescope should never point below the horizon, since the optical elements could be dislocated.

The coordinate system used for this telescope is the variant of the equatorial system that relates to the observer's position. This means that the coordinate system's grid is fixed with respect to the observer and the star's positional value changes due to the Earth's rotation. The two coordinates used in this system are the declination δ and the hour angle, the latter of which is the value that changes over time. This is contrary to the moving equatorial coordinate system, where a star has a designated value for right ascension α and declination δ , due to a grid that is fixed to the sky.

The wheel in Figure 6a can be turned to adjust the hour angle, which is given in 24 hours due to the day's length. The zero point of the hour angle is at the local meridian, which is the connection between North and South. The declination δ is the angle from the celestial equator (the projection of the Earth's equator on the sky). Usually the celestial equator equals $\delta = 0^\circ$, the North Pole being $\delta = +90^\circ$ and the South Pole $\delta = -90^\circ$ (Weigert et al. (2010), ²⁶); but in the case of the *Large Refractor*, the declination angle goes up to 360° , where the North Pole equals 180° and the equator being either 90° or 270° , depending on the telescopes position and the target. The declination angle can be read through the right brass eyepiece in Figure 6b.

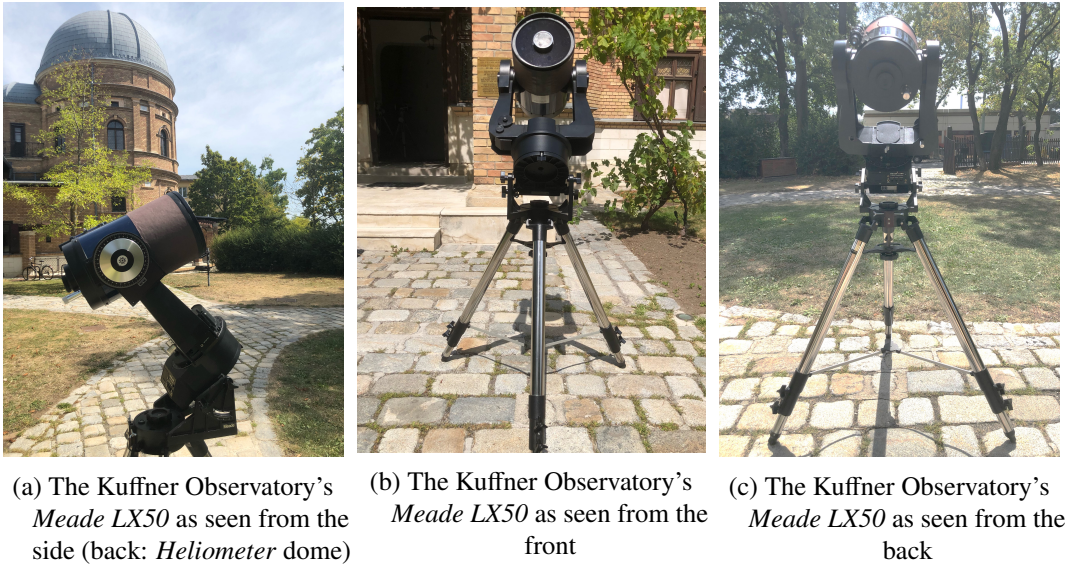


Figure 7: The Meade LX50 in the Kuffner Observatory's garden

²⁶Green Bank Observatory (GBO): *Equatorial Coordinate Sytem*. https://www.gb.nrao.edu/GBTopsdocs/primer/equatorial_coordinate_syste.htm, last access: 2022-09-30

The second telescope, which was used more frequently due to initial handling convenience and later due to the more accurate tracking motor, was the *Meade LX50*. With an aperture of 203.2 mm and a focal length of 2000 mm ($f/9.84 \approx f/10$), this telescope is fixed on an equatorial fork mount. This mounting is more convenient when it comes to quick pointing of the telescope and unlike the German mount does not have physical limitations. The *Meade's* fork mount is positioned on a tilted surface which can be adjusted according to polar altitude (see section 4.1.1). On this tilted surface sits the tracking motor, which needs to be connected to an electricity supply in order to run (see Fig. 7). The telescope is a Schmidt-Cassegrain (SC) build, which means it consists of a catadioptric system, combining one lens and two mirrors in its optics. The Cassegrain telescope has a spheric primary mirror and a convex secondary mirror²⁷ that reflects the light back through the central opening in the primary mirror and onto the detector. The typical errors that occur for this kind of optical system are caused by the primary mirror's shape, e.g. spherical aberration for light rays further away from the optical axis. Coma and astigmatism are common aberrations (for rays that enter at an inclination) in other systems but usually do not occur due to the SC's spherical mirror, which is one of its strengths. The SC telescope corrects for spherical aberration with a Schmidt corrector plate, which is a lens mounted at the telescope's opening. Since the SC is also essentially coma-free it can be called an aplanatic system (Roth et al., 1989). The corrector plate in the case of the *Meade LX50* is a thin lens with 2-sided aspheric correction²⁸. The plate itself can cause image errors of its own, but due to its very low refractive power, these effects are negligible (Roth et al. (1989); an example would be low level spherochromatism (Sacek, 2006a)). The secondary mirror is mounted in the center of the Schmidt corrector lens, from where light rays are reflected to pass through the primary mirror's central opening (Sacek (2006a), Roth et al. (1989)). The most substantial aberration for SC telescopes is the strong field curvature, where the image projection occurs on a curved surface. The radius of that curvature R_{fc} for Schmidt-telescopes in general is equal to (Roth et al., 1989):

$$R_{fc} = R_m/2 = f, \quad (9)$$

where R_m is the curvature radius of the primary mirror and f is the telescope's focal length. As seen in equation 9, the curvature radius is equal to the focal length, which equates to 2000 mm in the case of the *Meade LX50 8"* telescope. Compensation of the curvature would be possible with a curved detector surface or an SC telescope with a secondary mirror of the same curvature radius R_{fc} (Roth et al., 1989). But in most cases these are spherical without having that characteristic, which still causes curvature. In theory, an all-spherical SC has the advantage of low astigmatism and coma (Sacek, 2006a). The *Meade* telescope used here likely has a hyperbolic mirror (Murdock, 2007), but exact information on the mirror shape and curvature is difficult to find - without the secondary mirror's curvature the total field curvature of the image is hard to estimate, but it is substantial enough (see section 7).

The *Meade 8-inch-telescope* is a "middle-end" product in the amateur telescope category - devised to be used for simple observations with eyepieces but also for astrophotography. The greatest disadvantage for the *Meade's* usage is the exact polar alignment. Unlike the *Large*

²⁷Meade Instruments Corporation: *Instruction Manual 8" LX50 Schmidt-Cassegrain Telescope* (2000)

²⁸see footnote 27

Refractor, being mounted in the centre of a dome, on a pillar with a fixed polar position, the *Meade* telescope is mounted on a tripod that needs to be water-levelled to the ground before every observation and then aligned to the celestial North Pole by using a special technique. This procedure is called the *drift alignment method* which is described in more detail in section 4.1.1.

3.3. The Detectors

The two cameras applied in this project were the *Canon EOS 5D Mark II* and the *Sony $\alpha 7$ III* - two customary, consumer-level digital single-lens reflex (DSLR) cameras, more common for every-day usage and less for professional astronomy. However, they can be placed more on the high-end spectrum regarding costs. The two products both use CMOS sensors with three chromatic channels; red, green and blue (RGB). They were released at different times - the *Canon* camera was issued in 2008, while the *Sony* camera was introduced almost exactly 10 years later.

The *EOS 5D Mark II* has a sensor of 36×24 mm with 5616×3744 pixels and 14 bit per color channel (42 bit in total, ²⁹), the latter attribute being a characteristic it shares with the *Sony* camera. The *$\alpha 7$ III* has a sensor of 6000×4000 pixels with a size of 35.6×23.8 mm. The pixel size for the *Sony $\alpha 7$ III* is $5.93 \mu\text{m}$ ³⁰ and for the *Canon EOS 5D Mark II* is $6.41 \mu\text{m}$ ³¹. This results in differing plate scales according to detector and telescope configuration, which can be calculated with the help of equation 10 (Howell, 2006). The results are listed in Table 2. The plate scale P can be calculated with the camera's pixel size μ in μm and the focal length f in mm.

$$P = \frac{206.265 \cdot \mu}{f} \quad (10)$$

	Meade LX50	Large Refractor
Canon EOS 5D Mark II	0.6611 "/px	0.3778 "/px
Sony $\alpha 7$ III	0.6116 "/px	0.3495 "/px

Table 2: Plate scales for the applied detectors and telescopes

²⁹*Canon EOS 5D Mark II Datenblatt*. https://www.digitalkamera.de/Kamera/Canon/EOS_5D_Mark_II.aspx, last access: 2022-08-12

³⁰*Sony Alpha 7 III Specifications*. <https://www.the-digital-picture.com/Reviews/Camera-Specifications.aspx?Camera=1194>, last access: 2022-08-12

³¹*Canon EOS 5D Mark II Specifications*. <https://www.the-digital-picture.com/Reviews/Camera-Specifications.aspx?Camera=479>, last access: 2022-08-12

³²*Canon EOS 5D Mark II*. https://d1eh9yux7w8iql.cloudfront.net/product_images/None_0a96452c-fb19-4b9c-b057-63e2a80efa2d.jpg, last access: 2022-07-31

³³*Sony $\alpha 7$ III*. <https://www.sony.at/image/6888e27aa56d3635b8f306d2550d7574?fmt=pjpeg&bgcolor=FFFFFF&bgc=FFFFFF&wid=2515&hei=1320>, last access: 2022-07-31



(a) The *Canon EOS 5D Mark II* as seen from the front, with sensor exposed ³²



(b) The *Sony α7 III* as seen from the front, with sensor exposed ³³

Figure 8: The two cameras used for exoplanet candidate transit measurements

	Meade LX50	Large Refractor
Canon EOS 5D Mark II	$1^{\circ}1.877' \times 41.251'$	$35.358' \times 23.572'$
Sony α7 III	$1^{\circ}1.158' \times 40.772'$	$34.947' \times 23.298'$

Table 3: Field of view for the applied detectors and telescopes

Subsequently, using the four plate scales produced by the different telescope-detector configurations and the quantity of pixels of the cameras, four corresponding values of field of view (FoV) can be calculated. The result can be seen in Table 3 - the field of view for the *Meade* telescope is larger due to the smaller focal length f and therefore more stars can be seen in the image. This has an advantage for the differential photometry applied to the dataset, since more stars that can be used for reference generally means a higher accuracy for the photometric outcome.

Having presented the details of the two space telescopes, the small telescopes and the used detectors, one can briefly compare the values. Obviously, the two space telescopes have a much larger field of view, a smaller aperture (when it comes to the single telescope units), larger pixel sizes, larger plate scales and similar detector sizes compared to the ones used for this project (see Table 4).

The values for the field of view for the *Meade* and the *Large Refractor* telescope in Table 4 have been rounded, the accurate values can be found in Table 3. The detector size cannot be ascribed to a telescope, but since for the *Large Refractor* only the *Canon* camera was used, most of its characteristics were listed in that column. The *Sony* camera was only mounted on the *Meade* telescope, but in most cases also the *Canon* was applied. As can be seen in Table 4, the aforementioned smaller pixel size and the smaller plate scale than the space telescopes' are correct and the higher resolution of the star is theoretically given. However, in practice there is the earth's atmosphere that does complicate things a lot for ground-based telescopes, making

	TESS	PLATO	Meade LX50	Large Refractor
FoV	$24^\circ \times 96^\circ$	2232 deg^2	$1^\circ \times 40'$	$35' \times 24'$
Detector	$4096 \times 4096 \text{ px}$	$4510 \times 4510 \text{ px}$	$6000 \times 4000 \text{ px (Sony)}$	$5616 \times 3744 \text{ px (Canon)}$
Pixel size	$15 \mu\text{m}$	$18 \mu\text{m}$	$5.93 \mu\text{m (Sony)}$	$6.41 \mu\text{m (Canon)}$
Aperture	10.5 cm	12 cm	20.32 cm	27 cm
Plate Scale	$21 ''/\text{px}$	$15 ''/\text{px}$	$0.6611 \text{ or } 0.6116 ''/\text{px}$	$0.3778 ''/\text{px}$

Table 4: Comparing the space telescopes to the applied small telescopes

very precise measurements a lot more intricate.

The limitations in resolution of a space telescope compared to a ground-based telescope can be quantified with the following concept. In general, the angular resolution of a telescope is limited by diffraction, illustrated by the *Rayleigh criterion*, where the angle θ (in radians) describes the minimal angular separation at which two point sources can be resolved. The angle is restrained by the observed wavelength of light λ and the aperture or pupil diameter D (or the pupil radius r , (Léna et al., 2012, p. 224)):

$$\theta = 1.22 \frac{\lambda}{D} = 0.61 \frac{\lambda}{r} \quad (11)$$

This would be the critical restriction for a space telescope. However, the situation is different for a ground-based telescope, where atmospheric perturbations cause further reduction of the resolution. The term "seeing" is used in astronomy to quantify the deterioration of an image through atmospheric turbulence (scintillation, agitation, smearing, etc.) and the physical quantity is often given by the *Fried parameter* r_0 or the Full Width at Half Maximum (FWHM) of the Point Spread Function (PSF) indicating the angular size (in arcsec) of the perturbed stellar image on the detector.

Astronomical seeing would cause imaging of many little dots within a circular diameter instead of a single point-like stellar image. These little dots are called speckles and the diameter within which they occur is called the *seeing angle* (Léna et al., 2012, p. 234):

$$\Delta\theta = \frac{\lambda}{r_0} \quad (12)$$

where r_0 is the *Fried parameter*, which is given in units of length, just like the aperture D . Therefore, r_0 can be seen as the theoretical aperture at which the angular resolution (the diameter of speckle occurrences) of λ/r_0 (seeing angle) can be reached. If the parameter $r_0 \geq D$, there is no seeing taking place - this would apply to the 8.2 m VLT in the mid-infrared, where the generally highly chromatic r_0 is at 8.4 m for $\lambda = 20 \mu\text{m}$ (Léna et al., 2012, p. 234). Therefore, the single-unit-apertures of the space telescopes compared to the two telescopes applied in this work would suggest better resolution of stars (see Table 4), the seeing however does not allow that.

4. Methods

4.1. Observation Planning and Measurement Procedure

Towards the beginning of this project (End of January/ beginning of February 2022), practical training with the telescopes was required since the instruments and cameras were not yet familiar. The habituation and learning phase took about 2-3 weeks, including measurements of trial and error, starting with a bright building in the distance that was measured to understand the exposure times as well as other idiosyncrasies and settings of the instruments. The first successful measurement of a *TESS Object of Interest (TOI)* took place after less than a month's time - due to difficult weather conditions in February - resulting in new insights to the measurement procedure. As a comment on the procedure itself and the inherent learning process: every measurement, even the last ones of this project came with new understanding of the procedure regarding the instrument handling and the data analysis methods.

A significant part of the initial half of the observation campaign consisted of getting acquainted with the telescopes' and the cameras' handling. Every telescope has its own intricacies, which meant that every observation night had to be prepared accordingly (see section 4.1.1 and 4.1.2). The first telescope that was used was the *Meade LX50*, since it was easier to handle and less delicate as compared to the historical *Large Refractor* from the dome, which required proper training.

The general structure of a day with observation consists of planning the observation with the list of *TOIs* and a planetarium program. Such a virtual planetarium, for example like the application *Stellarium*³⁴, gives insights on the target star's location in the sky (coordinates, α or hour angle and δ) during the planned observation time. The height above the horizon, the constellation and the movement over the course of the night can all be simulated. A rough limitation of the *TOI* list is already given within the written *Python* programme, where the candidates are filtered according to the height of the mid-transit at $h > 40^\circ$, to a star with *TESS* magnitude (as given by the telescope) between 0 and 14 mag and to a solar height of $h_\odot < -12^\circ$. The rough limitations given in the provided list by Dr. Günther Wuchterl are then further specified for the given circumstances and the used telescopes (see section 4.1.1 and 4.1.2 for the telescope intricacies and section 5.1 for target selection).

The next step is to take flat-field images of the sky, without containing clouds unless it cannot be avoided. That would pose a disadvantage since the clouds would translate as features in the flat corrected image. Test flat-fields are taken in order to find the right exposure time for the given direction in the sky and the brightness/time of day, before a series of 300 images is initiated. The further procedure for observation depends on the two telescopes that were used.

4.1.1. Meade Handling

As part of the preparations for the *Meade* observations with *Stellarium*, the position of the star during the course of the night is evaluated. Since observations take place in the observatory's garden, the sky is partially obstructed by the building itself to the North and East and by trees to the South and West. Therefore, depending on the telescope's position in the garden, the lower

³⁴<https://stellarium.org/de/>

limit for a star's height from the horizon is somewhere between $h = 35^\circ - 45^\circ$. Since the limit in the aforementioned *TOI Python* program is set to 40° for mid-transit and the observations start an hour before ingress and end an hour after egress, the "garden limitations" can play an essential role in the observability of the planetary candidate. The minimal and maximal height of the star during the planned observation are read from the planetarium application and then tested with a provisional sextant from a feasible position in the garden.

Once the *Meade* 8-inch-telescope with its tripod are placed in a suitable position outdoors, two other positioning aspects in three-dimensional space need to be considered. The *Meade* is mounted on a tilted surface, which is set according to the geographic latitude/polar altitude, so that the telescope's axis can be parallel to the Earth's rotational axis. The first test measurement with the *Meade LX50* (taken with the *Canon* camera) resulted in data that exhibited a clear drift in the stars' position on the image. This was caused by the rough polar alignment of the session, which made accurate tracking of the target over an extended period of time impossible and caused the star to leave the field of view within less than an hour. This realization lead to the application of a method called the *drift alignment method* to achieve an accurate polar alignment - first of all by testing the axis position in the East-West direction and secondly by checking the polar altitude.

The telescope has two possibilities for fine adjustment, namely in the direction of the right ascension and in the declination direction. In this case the slight regulation of the telescope's orientation is done after a rough positioning, in case the telescope's axis is too far East or West of the celestial North Pole and if it is too far South or North of the pole. The calibration will have to be done every time, since the orientation is required to be quite exact. The adjustment screws of the *Meade* can be turned to fine-tune the rotational axis of the telescope, once the direction for corrections is known. As part of the drift alignment method, the telescope is roughly set along the polar axis by visual judgement. The tracking motor needs to be started, a $2\times$ Barlow lens fixed on the telescope and an illuminated reticle eye piece mounted onto it (see Figure 9).



(a) The $2 \times$ Barlow lens ³⁵

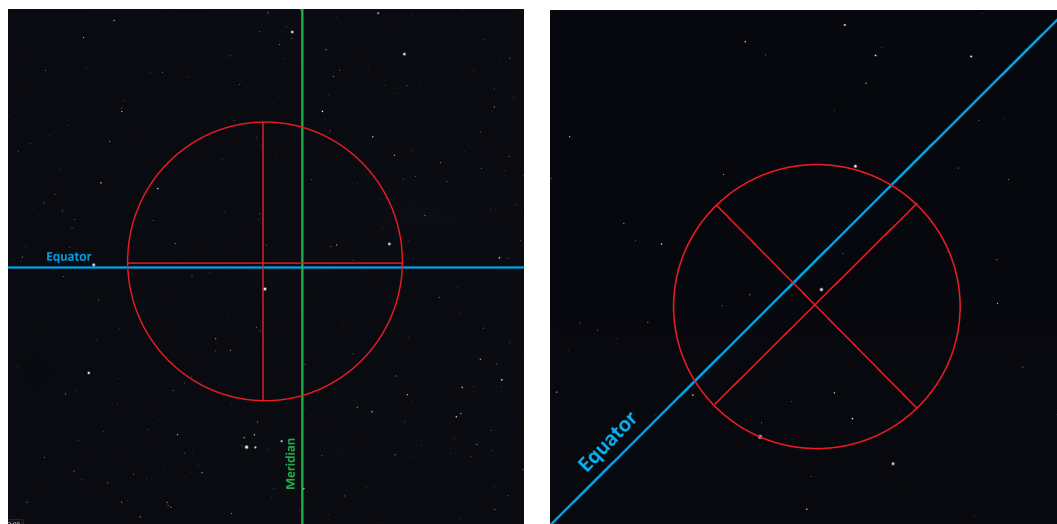


(b) The illuminated reticle eyepiece ³⁶

Figure 9: The two cameras used for exoplanet candidate transit measurements

The illuminated reticle eyepiece has the advantage that the silver cylinder on the side (see Fig. 9b) illuminates the eyepiece's field of view to create red light cross hairs for tracking exact movements ("drift") of the star over time. If the tracking and therefore the polar alignment are accurate, little to no drift should be visible. The Barlow lens helps to magnify the image, making the field of view very small. This facilitates the tracking of the stellar movement due to imprecise alignment over a short period of time, without having to wait too long.

The first step of the method is to observe towards the South, within $\alpha \pm 30'$ of the meridian and $\delta \pm 5^\circ$ of the celestial equator (see Fig. 10a) ³⁷. The stellar drift tells us where the telescope's axis currently is: if the star drifts towards the South (of the image, downwards from the equator and parallel to meridian) the axis is too far East of the South Pole and if it drifts towards the North, it is too far West. With the help of the fine adjustment screws of the *Meade*, the proper position can be found. One thing needs to be taken into consideration though; when looking through the eyepiece, the image is vertically and horizontally mirrored, which means that a drift to the bottom of the image is actually a drift towards the North.



(a) The drift alignment method towards the South with the meridian (green) and the celestial equator (blue) (Credit: Stellarium, Zotti et al. (2021))

(b) The drift alignment method towards the East with the celestial equator (blue) (Credit: Stellarium, Zotti et al. (2021))

Figure 10: The drift alignment method through the eyepiece

When trying to find the correct polar position in the declination axis (the polar altitude), the telescope should be pointing towards the East, about $20 - 30^\circ$ above the horizon, but still about

³⁵ *Optics Barlow Lens 2x*. https://nimax-img.de/Produktbilder/big/8700_1/TS-Optics-Barlow-Lens-2x-1-25-.jpg, last access: 2022-08-01

³⁶ *Illuminated Reticle Eyepiece*. https://www.firstlightoptics.com/user/products/large/ae_12.5mm_illum_ep_1.jpg, last access: 2022-08-01

³⁷ see footnote 27

$\delta = \pm 5^\circ$ along the celestial equator (see Fig. 10b) ³⁸. The stellar drift will still occur to the North or South of the equator - this time an upwards drift means the telescope axis is too far above/north of the pole and a drift downwards means the axis is below the pole. Again, there is a fine adjustment screw for this angle, this time to be turned with a hex-wrench. The screw regulates the tilt of the telescope mount.

The usual time for observing a single star's drift was about 5 minutes, usually enough time to detect unwanted movement; should the star remain stationary over that time period the alignment was considered accurate enough. The whole procedure itself took about one hour for a good alignment in declination δ and right ascension α .

Once the alignment process is completed, a bright star (easily found with the *Meade*) on the sky is selected for adjusting the focus to the camera, since eyepieces used for aligning the telescope require a different focal plane. With the focus zoom option of the camera the live image on its screen can be magnified. At the same time, the focus wheel of the telescope can be turned to find the most point-like image of the star. A focus control image of 30 seconds exposure is taken and inspected for the accuracy of the focussing. Thereafter, the actual target search begins, where minor focus adjustments can still be done.

The *Meade* telescope has the option of using setting circles for applying the δ and α coordinates of the target - but since these circles are moveable or adjustable, the exact pointing of the telescope on a target is difficult to achieve with that method. Out of experience there is a more effective method, namely preparing the observation beforehand with *Stellarium* by getting acquainted with the target's stellar neighbourhood and the constellation. Specifically stars visible with the naked eye are of interest, since those can easily be pinpointed with the help of the finderscope, assuming the finder and telescope pointing have been aligned before usage. The bright star can then be used to apply a method called "star hopping", where the live picture on the camera and the telescope handset with the fast motor movement function make finding the actual target possible. By knowing how many seconds it takes for the fast motor setting to move the mentioned orientation-star from one end of the live image to the other, the required lengths of the field of view that need to be traversed to reach the target can be roughly estimated using *Stellarium*. In some cases the target star is located in a constellation which is barely visible with the naked eye, especially in the city of Vienna, which requires the help of binoculars to roughly locate the brighter star on the sky and then again use the telescope's finder to position the aperture in that direction. This method of target location relies heavily on field of view comparison with the planetarium application, which makes stellar constellation and image recognition of a certain position much easier. A control image of 30 second exposure is taken for precise localisation, which is necessary due to the fact that the live feed of the camera only shows the brighter stars of most constellations. The whole process of target finding can take from 20 minutes up to one hour in the most difficult cases, since the target also needs to be precisely positioned in the center of the field of view.

In most cases a 30 second exposure series of the star was taken, starting at one hour pre-ingress and ending one hour post-egress, with an average of 3.42 hours of total observation time. The latest observations included brighter stars that required shorter exposures - for more see section 4.2.

³⁸see footnote 27

4.1.2. Large Refractor Handling

Operating the Kuffner Observatory's *Large Refractor* is in many aspects easier - as mentioned before, the telescope's equatorial mount is fixed in space and therefore need not be aligned to the celestial pole. Other idiosyncrasies of the telescope are the before mentioned coordinates (declination and hour angle) and the German equatorial mount that can cause the necessity of positioning the instrument on the opposite side of the pillar due to the danger of falling below the counter weight. This means that the target's movement throughout the night needs to be tested before the observation in *Stellarium*. In case of a necessary "flip" of the telescope, either two different types of flat field images have to be taken during the day (before the observation), or the flat-field images would need to be turned upside down digitally. This is necessary because the change of sides will cause a 180° flip of the image as well, which means that systematic effects on the flat-field are suddenly on the opposite side. But since this issue never occurred during the *Large Refractor* observations, the image flip never had to be processed.

The mounting of the camera on the 136-year-old instrument is done with a specifically fabricated adapter, that reduces the opening of the telescope on the eyepiece end to two inches, where the camera's adapter can be fixed with special screws.

Having completed the preparations at this point, the next step is to find a bright star for focussing - a step necessary for both telescopes. The live image of the camera can be used yet again and the black double knob focus handle on the *Large Refractor* can be used to adjust the focus point (see Figure 6b, at the center of the image, above the main black eyepiece).

The final step is to find the target with the hour angle and declination given by *Stellarium* at the time of observation and adjust the telescope by reading the value of the declination from its scale first. This is done by looking through the small auxiliary telescope, next to which a button will turn on a light to illuminate the declination scale and its value can be read through the eyepiece. The declination telescope can be seen on Figure 6a as a long brass tube and in Figure 6b as the eyepiece to the very right. For fixing the telescope's position in the declination angle, there is a wooden knob mounted on a metal rod that will tighten screws in the telescope's mount to stop it from moving. After having positioned the telescope at the right δ position, this fastener knob is tightened. A similar procedure for the hour angle is required as well - the scale here is around the wheel seen directly above the pillar in Figure 6a, which is used to adjust the angle. Once the target has been found, a 30 second control image can be taken, before finally starting the camera's intervalometer for a time series of the transiting planet.

4.2. Data Analysis - Photometry

The time series data collected with the *Canon* and *Sony* detectors need to be read, photometrically analyzed and understood. For the purpose of approaching a scenario for citizen scientists implementing data processing on their own measurements, an easily applicable program with a facile interface was used for photometry - *Siril*. The interface is clearly structured with sections for data conversion, sequences, pre-processing, image registration, stacking, a command line, a console for output and for plotting.

The first part of using this analysis program is to structure one's data in directories and to create a working directory where all converted and processed files can be saved without mixing

with the raw files. The *Canon* and *Sony* camera have different raw file data formats, namely *.CR2* and *.ARW* respectively. The files are stored in a directory for bias frames, one for darks, another one for flats and lastly one for the science/light frames.

In theory, biases are zero-second-exposures for determining the intrinsic noise properties of the detector/the pixels while collecting photons at any given exposure. Since there is effectively no such thing as a zero-second exposure, the shortest possible exposure is chosen, which is 1/8000 seconds for both cameras.

The dark frames are a measure for the dark current - an effect of temperature, which causes thermal noise. Due to the temperature, electrons will be freed from the valence band in the semi-conductive material of the detector, collected in the pixel's potential well. When the pixel is read out, these additional electrons become part of a measured signal and change the outcome of an exposure (Howell, 2006).

The purpose of a flat-field image is to even out the light frame's illumination and to remove the influence of dust particles and other impurities in the optical system of the detector and the telescope. A telescope aperture has the property that more light will enter in the center, close to the optical axis, while less will be able to reach the detector from the periphery. Each pixel has a slightly different gain or quantum efficiency value when compared with its neighbours. The flat-field flattens the relative response for each pixel to the incoming radiation (Howell, 2006). The exposure time of a flat-image is chosen such that it is evenly exposed (not saturated).

Once the pictures are uploaded to a computer, *Siril* comes into play. The first step is to convert the raw data format into a *FITS*-file - the program uses the ending *.fit* in this case, which is equivalent. Starting with the bias frames, which were usually about 300, the stacking process could be implemented straight away by using a median type stacking without normalization. The same can be done with the (usually 100) dark frames, which have the same exposure time as the science images. After each of the images have been stacked, the output is a masterbias and a masterdark image, which is saved as a single file. The procedure for a flat-field image is somewhat different (usually 300), since it needs to be edited in the "pre-processing" tab of *Siril* by entering the masterbias's path into the "offset" section and running the process. The flat-pictures are bias-corrected during that process and can then be stacked with a median algorithm. This is done with multiplicative scaling to create a masterflat. This whole pre-processing procedure works according to the following concept (eqn. 13) ³⁹:

$$\frac{\text{image} - (\text{dark} - \text{bias}) - \text{bias}}{\text{flat} - \text{bias}} = \frac{\text{image} - \text{dark}}{\text{flat} - \text{bias}} \quad (13)$$

This means that the pre-processing of the science frames only requires subtracting the masterdark (since it already contains the bias) and to divide it by the (bias-subtracted) masterflat. Therefore, the bias section for light frame reduction in *Siril* is left free. Finally, before pre-processing the images, the "debayer" button is activated for demosaicing the three pixel colors and thereby separating the three chromatic channels.

The process of debayering is necessary in this case, since the pixels of the sensor are arranged in a Bayer-matrix, where differently coloured pixels are located next to each other. The red, green and blue pixels have differing values, often varying significantly. If the images were left

³⁹<https://siril.org/tutorials/tuto-manual/>

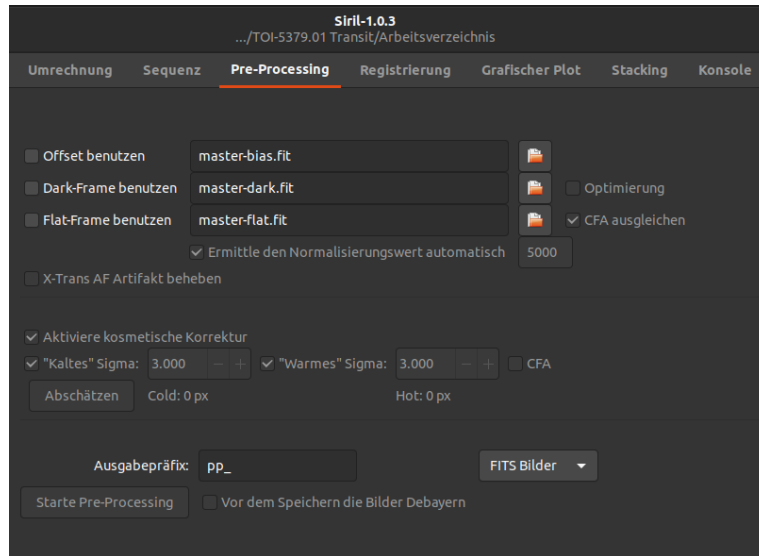


Figure 11: *Siril*'s interface for pre-processing and the other existing tabs (Credit: Hourdin et al. (2022))

the same way they were taken, the applied photometry would have to deal with high systematic errors that come with the colour filters. On the other hand, each debayering process is an act of interpolation, where the "missing" pixels in each of the channels are "replaced" by interpolated pixels to fit the channel's read-out systematics. The issue with this process of debayering is the accuracy of the individual interpolated pixel values and the method that is being applied. The process itself can introduce errors by misrepresenting the "missing" pixel. The different methods include using information from the neighbouring pixel to create one of a different colour in its stead, sometimes different coloured pixels are left out altogether (Furtner, 2001). This process is the reason why using the green channel is the most accurate approach, since there are as many green pixels as red and blue ones together. Using green would therefore involve less interpolation.

When considering the pre-processing of the images and applying demosaicing to the bias, dark and especially the flat-field, the excess of interpolating creates a trend which would multiply extensively - accuracy would be very questionable. Therefore, the demosaicing process takes place after image correction and only affects the science frame. The last tick box in Figure 11 next to the "Start pre-processing" button will initiate debayering. In the case of the two cameras applied here, the Bayer-pattern is RGGB, which means that the pixels are arranged in pairs of four, where the first two pixels are red and green and the second two (in the next array below) are green and blue (Milgrom et al., 2010). Apart from the before mentioned interpolation and the number of green pixels, *Siril* also strongly recommends to use the green channel for data analysis, since the red channel is mostly contaminated and noised with light pollution and the blue channel with atmospheric refraction⁴⁰.

⁴⁰The Free-Astro Development Team: *User Guide Siril 0.9.9, Version 1.53* (2018). <https://free-astro.org/>

Once that process is done, the image needs to be registered, since the field of view changed during the course of the observation night due to the imperfect tracking motor or an incomplete polar alignment (or both). Measuring with the *Large Refractor*, one is confronted more with the former issue, while with the *Meade* telescope more of the latter. Even in the best cases, with long and precise polar alignment images had to be registered, since no alignment is perfect. However, this poses a challenge, since the star will be located at different pixel positions and make photometry difficult for the program if it cannot locate the star in the same region for all images. Two different methods offered by *Siril* were applied in the case of the data here, one being the one-star-registration, where the selection tool is applied to the central variable star and an algorithm searches for the star in the other images. The other method is the global star alignment, where as many stars as possible are detected on the field by *Siril* and the resulting pattern is then compared to the other image files in the sequence. The different locations of the star on the detector can also cause difficulties with the flat-field applied to the total image, due to vignetting and coma effects towards the periphery. This effect is prevalent in the *Large Refractor* measurements, while the *Meade* telescope is exposed to effects of field curvature due to the Schmidt-Cassegrain system (see section 3.2, and more in section 7) in addition to minor vignetting and slight coma. This means that due to the primary mirror's spherical and the secondary mirror's convex or hyperbolic shape (Murdock (2007), ⁴¹), the stars lose their focus, the further away from the optical axis they are located on the image. The last step is to select the star with the planetary candidate by using the square selection tool to limit the region within which the star is located and choosing the "PSF for the sequence" option. This will produce three concentric circles, where the innermost represents the aperture, the space between the first and the second is left empty and the annulus between second and third circle is used for background measurement (see Figure 12).

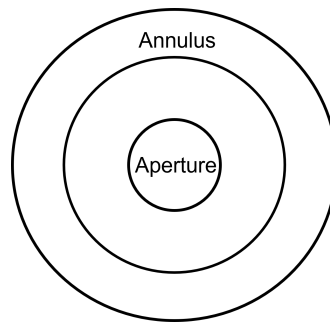


Figure 12: Schematic representation of aperture and annulus used for photometry in *Siril*

The measurement of the magnitude consists of measuring the flux of an object and of the background. The reason for the space between the aperture and the annulus is to prevent contamination of the sampled background pixels with the object itself. The aperture should be placed close to the star so as to not involve another object or too much background in the target

[download/siril-doc-0.9.11-en.pdf](#), last access: 2022-10-03

⁴¹see footnote 27

object.

During this procedure, the program calculates the PSF (Point Spread Function) of the star according to a 2D-Gaussian formula ⁴²,

$$G(x, y) = B + A \cdot \exp\left(-\left(\frac{(x - x_0)^2}{2\sigma_x^2} + \frac{(y - y_0)^2}{2\sigma_y^2}\right)\right) \quad (14)$$

where B is the average local background component (average of the pixels), A is the function's amplitude or maximal intensity, x_0 and y_0 being the centres of the function for the respective coordinates and σ_x and σ_y being their respective spreads.

After having selected the target/variable star, the process continues by choosing comparison stars in the field, required for differential photometry. The maximum amount of stars that can be selected for photometry is one variable and six comparison/reference stars. Before selecting any star in the field, the *AAVSO Variable Star Plotter* ⁴³ is used to examine the "stellar neighbourhood" of the target for other variable stars that could contaminate the transit if added to the ensemble of comparison stars. An example for that can be found in Figure 13, where the target is marked by the black cross hairs and the variable stars are designated by a number. In this case, the target itself has a number, since the *AAVSO* files it as variable. The stars with a number were avoided in the photometric process, since they might cause their own variations to be visible in the resulting light curve.

The algorithm applied by *Siril* to the reference stars is not exactly known, since the documentation does not specify. Nonetheless, it is likely to be such that the reference stars are used to form a single comparison star C (e.g. by averaging), which is then subtracted from the variable star V to create $V - C$ data points (in relative magnitudes) plotted against time to form a light curve. The photometric procedure is theorised to be this way, since the program appears to have some similarities with existing photometry methods, such as ensemble and artificial star photometry. Some photometry programs like *Muniwin* use one reference and multiple check stars, which are supposed to act as a reference for the reference star, since it could be a variable star itself and therefore falsify the light curve of the target star. An ensemble in differential photometry however, involves multiple reference stars and no check stars, where all are compared to the variable star, resulting in a multitude of $V - C$ datasets. On the other hand, the artificial star method is not actually differential photometry, since the star is generated by the program and used as reference for the observed variable star (Gary, 2010).

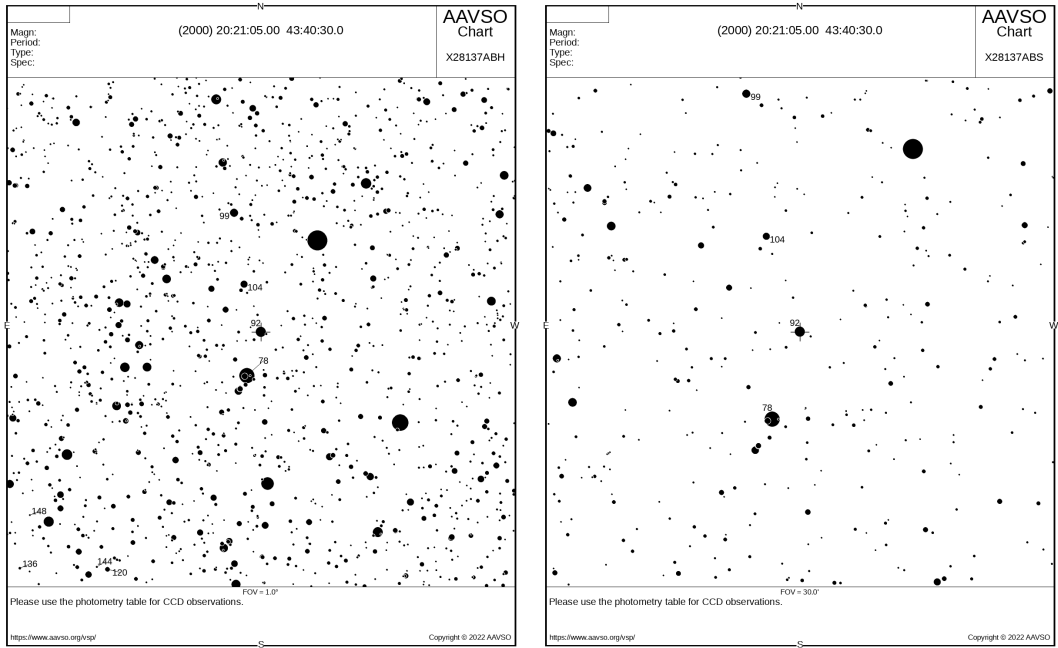
For *Siril*, there is only one $V - C$ output, which is independent of the order of reference star selection, thereby excluding the theory that the program uses check stars or an ensemble of reference stars, but rather creates a single reference star C out of the selected stars and consequently subtracts artefacts and common trends from the variable. The exact procedure of constructing the star out of the references is unknown, but is suspected to be a form of averaging.

As seen in Figure 14, for every "PSF for the sequence" command given for a reference star,

⁴²see footnote 40: User Guide *Siril* 0.9.9 p. 183

⁴³<https://app.aavso.org/vsp/>

⁴⁴American Association of Variable Star Observers (AAVSO): *AAVSO Variable Star Plotter*. <https://app.aavso.org/vsp/>, last access: 2022-10-18



(a) The result of the AAVSO Variable Star Plotter for the field of TOI-4496/BD+43 3573 at 1° (b) The result of the AAVSO Variable Star Plotter for the field of TOI-4496/BD+43 3573 at 30''

Figure 13: The result of the AAVSO Variable Star Plotter for the field of TOI-4496/BD+43 3573 ⁴⁴

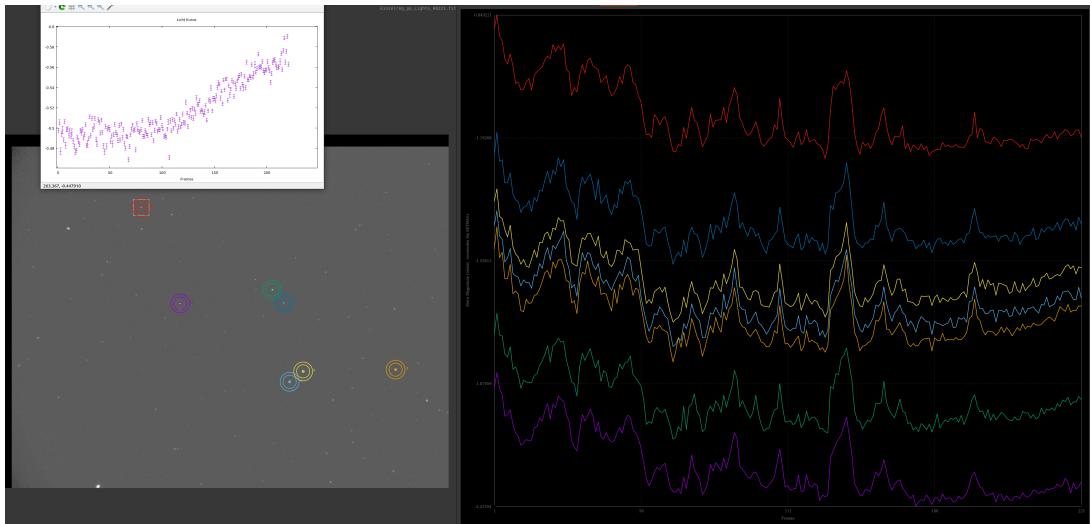


Figure 14: The Siril interface when applying photometry and PSF functions to a variable (violet) and reference stars (other colours); right: the graphical interface with magnitudes, (Hourdin et al., 2022)

Siril plots another star as a colourful line on the right side, given in relative magnitudes. The selection process takes place according to the brightness, location and shape of the star's light curve in the graph section of *Siril*. The star should be close to the variable star, so as to prevent other effects coming from the reduction with the flat-field or optical issues such as defocusing by field curvature are reduced. The reference star's brightness should be similar as well, since the S/N ratio, the FWHM and other factors such as roundness are comparable and can make for a much more precise measurement of the transit. In case the star's light curve looks suspicious due to specific factors, such as saturation, smeared features, defocussing and others, the star may have to be deselected for the purpose of preventing a contamination of the resulting data points of the variable star's light curve.

Once the reference star selection is done, there is a button below the "Magnitude" graph as seen on the right in Figure 14, which is called "Light Curve". Its output is a *.dat*-data-file, visualised with a *GNUplot*-graph seen as the plot with white background in the same figure, with an x-axis of Julian Date and a y-axis of $V - C$. The light curve plot also displays error bars that are calculated from the rectangular selection of pixels used to create a PSF of the star. The selection is needed to calculate the S/N ratio, which depends on the background and the stellar amplitude. From the change in these factors over the course of the observation the error bars are determined.

Further parameters that can be viewed for all selected stars in the application are the amplitude (the A parameter of the 2D Gaussian), the background (the B parameter of the same equation), the FWHM of the PSF, the roundness (ratio of the FWHM of the star in two directions, namely x and y), the S/N ratio, and finally the change of X- and Y-position over the course of the observation. All these parameters, including the magnitude of all selected stars can be exported as *.csv*-files and analysed further.

5. Observations

5.1. Target Selection Process

Over a timespan of 6 months (from mid February to mid August 2022) 26 observations of exoplanets and candidates were undertaken - out of which one was qualitatively insufficient for analysing and another crossed the boundaries of the here expected workload, using an experimental camera. This means 24 observations which yielded final results, 22 out of which were *TESS Objects of Interest (TOIs)* and two were confirmed planets, which are extreme cases, observed as transit detection attempts.

But according to which parameters were the planetary candidates chosen? There are multiple layers to the answer of that question. The first filter was applied, as mentioned before, in the *Python* program that sorted out the observable stars for the day. The transits candidates and their ephemerides were provided by Dr. Günther Wuchterl using the *TESS-Database*⁴⁵ with a self-written *Python* program to extract the data. Two other targets for observational tests were selected from the *Exoplanet Transit Database (ETD)*⁴⁶ according to highest possible brightness, transit depth and observability during the time (July/August 2022).

As mentioned before, for the *TESS*-candidates the limitations in the *Python*-script were set to a mid-transit minimal height of $h > 40^\circ$, a solar height of $h_\odot < -12^\circ$ and a *TESS* magnitude (as given by the telescope, T_{mag}) between 0 and 14 mag. Further restrictions in height above the horizon were implemented due to airmass and the positioning of the *Meade* (as mentioned in section 4.1.1, also discussed later in this section).

Wuchterl (2022) states the minimal requirements for the observation campaign to be given by a telescope of > 7 cm diameter and > 50 cm focal length, an equatorial mount, a cooled CCD camera (or equivalent), target stars brighter than 10 mag_V as well as image series photometry software. These points were abided by roughly, except for a cooled CCD and the 10 mag brightness limit.

Generally, the available stars with greater brightness and higher transit depth were chosen. The lower limits for these factors were preferably $< 11 \text{ } T_{mag}$ or in the *V*-band (see Table 5 and 7 respectively) and a depth of $d > 0.2\%$ (see Table 7). Within the observation plan, these predispositions did not always result in observable candidates. Often on days with good observing conditions none of the candidates adhered to the requirements, or vice versa, but on some days the necessary conditions were fulfilled - by the weather and the targets. In some rare cases the prerequisites of brightness and transit depth were not abided by fully and a few exceptions were made.

The reason for the choice of stellar brightness were numerous. Firstly, the *PLATO* mission will focus more on bright stars, which are brighter than 11 mag (see Table 1, about 1 mag brighter than *TESS*), therefore the *TOI* sample was chosen in order to be representative for *PLATO* follow-ups. Secondly, the increased number of available candidates above 10 mag in the *TOI*-dataset (see section 7), thereby making use of more nights with good observability conditions. The last factor is the estimated accuracy for the here applied instruments, where faint stars and shallow transit depths will succumb to the noise. This aspect also depends on

⁴⁵see footnote 6

⁴⁶see footnote 7

the background component, which highly influences the photometric accuracy (see Figure 15).

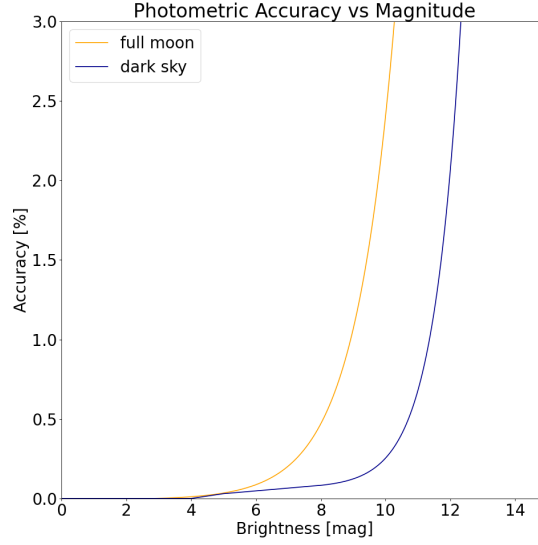


Figure 15: Achievable photometric accuracy in percent for a star of given magnitude, observed with a telescope of $D = 20\text{cm}$ at 15s exposure; yellow = full moon, dark-blue = dark sky (Roth et al., 1989, p. 382)

This figure displays what maximal photometric accuracy for a 20 cm telescope aperture (comparable to the *Meade*) with a 15s exposure time can be achieved during full moon and for a dark sky. For all *TOI* measurements a 30s integration time was applied, while the test observations were stacked to a 50s exposure.

Thus, the photometric accuracy for a 30s and 50s exposure would be a little better. Since the signal-to-noise ratio increases by $S/N \propto \sqrt{t_{exp}}$ (Howell (2006), more on the S/N ratio later in this section), one could say that the photometric accuracy for a 30s exposure would increase by a factor of $\frac{1}{\sqrt{2}}$ and for a 50s exposure by a factor of $\frac{1}{\sqrt{3.333}}$, without considering an increase in noise for the background due to the moon. The brighter background, specifically in the full moon phase, makes accurate measurements of the stellar brightness difficult - especially in the less luminous range of stars. This estimate describes the general increase in background noise due to the moon, without considering the location of the star relative to the moon. Thus, the lunar phase is an essential factor to the quality of the data. Here, the moon phase was not considered for the choice of observation - the effect of it was considered within the data analysis and pre-emptively a star further away from the moon was chosen in most cases.

Another aspect was the disposition given in the *TESS* data - there are two dispositions, namely the *TESS Follow-Up Observing Program Working Group (TFOPWG)* ⁴⁷ and the *Exoplanet Follow-up Observing Program (ExoFOP)* ⁴⁸ dispositions. These are two separate evaluations of a candidate's status within the database. The most common indicator is *PC* which stands for "planetary candidate"; often to be encountered is the *APC*, which stands for "ambiguous

⁴⁷<https://tess.mit.edu/followup/>

⁴⁸<https://exofop.ipac.caltech.edu/tess/>

planetary candidate". A "confirmed planet" is designated with the abbreviation *CP* and a "false positive" with *FP* ⁴⁹. In Table 5 the disposition of the observed objects is listed - this is information given at the time of observation - the current indicator could be different.

Planet/TOI ID	TOI Disp	EXOFOP Disp	T_{mag} [mag]
TOI-1425.01	PC	APC	9.258
TOI-627.01	PC	FP	9.945
TOI-1789.01	CP	CP	9.182
TOI-4620.01	PC	PC	9.570
TOI-1784.01	PC	APC	9.614
TOI-5379.01	PC	PC	9.598
TOI-1273.01	PC	PC	10.418
TOI-1179.01	PC	APC	10.131
TOI-1186.01	PC	APC	9.924
TOI-1820.01	PC	PC	10.572
TOI-1194.01	PC	PC	10.478
TOI-1181.01	PC	PC	10.079
TOI-1012.01	PC	PC	8.127
TOI-1717.01	PC	PC	9.523
TOI-1831.01	PC	PC	7.432
TOI-4496.01	PC	PC	9.159
TOI-1371.01	PC	APC	9.948

Table 5: *TOI* and *EXOFOP* Dispositions and *TESS Magnitude* (T_{mag}) for all observed *TOIs* ⁵⁰

As can be seen in Table 5, the targets were mostly chosen to be *PCs*, some are also *APCs*, which were considered interesting since the validation or the source of the planetary signal could be attempted to be resolved. In the table, one case of a confirmed planet and one false positive are also present. These two dispositions are correspondent to observations that were chosen before the implementation of the disposition selection process - all other targets were chosen if they either corresponded to *PC* or *APC*. The candidate *TOI-4620.01* in the list was observed with an *Axiom* camera and will not be discussed further.

⁴⁹Caltech: *TESS Objects of Interest Table Data Columns*. https://exoplanetarchive.ipac.caltech.edu/docs/API_TOI_columns.html#tessID, last update: 2021-09-09; accessed: 2022-09-28

⁵⁰see footnote 6

Other aspects for target selection were the height of the star an hour before ingress and an hour after egress - together with the timing of the mentioned events. If the transit was too low, due to considerations of airmass (not too close to the horizon, specifically for the *Large Refractor*) or if the limitations for the *Meade*-telescope due to the minimal observation height caused by the surrounding trees and buildings were not met (see section 4.1.1), the observation was reconsidered to a certain degree.

Generally, most transits will consist of one hour before, one in-transit and one after transit, resulting in a total expected observation duration of three hours. This further constrains the choices of observable stars, although in the case of this project, an observable ingress or egress sufficed for its purposes. Therefore, depending on the minimum observability of at least either ingress or egress the star was either observed at a later time or sorted out altogether. Notably, most of the 26 observations did not include complete transits.

If the transit was too early - the time needed for the alignment and set up (1.5 - 2 hours for *Meade*, ~20 min for the *Large Refractor*) had to be considered as well.

The spectral type has also been a factor for target selection - early type stars have typically been avoided due to line-broadening, which poses a challenge for radial velocity follow-ups (see section 3.1). This rule was however not always implemented for reasons of convenience (see spectral types in Table 9).

Finally, the last aspect was the transit uncertainty given by the *TESS* data, which was kept below 1 hour, since a higher value would indicate more serious issues and probably a false positive. The dataset here contains one star with 1.4 hour uncertainty (TOI-627), which also turned out to be an "FP" designated star.

Table 6 contains all 24 successfully analysed observations with their respective dates of observation, the Ingress, Egress and mid-transit times, the uncertainty, the transit duration T_{Dur} , their coordinates in *RA* (α) and *Dec* (δ) and the constellation.

5.2. Overview and First Results

All information in Table 6 is the pre-observation status of the targets. Most of the data has been collected from the *TESS* database ⁵³, except for the transit duration T_{Dur} , which has been calculated from the given transit ingress and egress times without considering the uncertainty of the transit event listed in said table. Two planets in the list are from the *ETD*, namely *WASP-33 b* and *HD 189733 b*, where a transit uncertainty is not given, apart from the fact that the two planets are considered confirmed ⁵⁴.

Table 7 lists the name of the star as given by the *SIMBAD* database ⁵⁵, the respective V-magnitudes from *TESS* ⁵⁶ (in some cases from *SIMBAD*), the used telescope and camera, the start and end of the observation given in UTC, the duration of the observation T_{Obs} , and finally

⁵¹see footnote 6

⁵²see footnote 7

⁵³see footnote 6

⁵⁴see footnote 7

⁵⁵Université de Strasbourg/CNRS: *SIMBAD Astronomical Database - CDS (Strasbourg)*. <http://simbad.u-strasbg.fr/simbad/>, accessed: 2022-09-15

⁵⁶see footnote 6

Planet/TOI ID	Date	Ingress [UTC]	Mid [UTC]	Egress [UTC]	T_{dur}	$\pm$	RA [hh:mm:ss]	Dec [hh:mm:ss]	Const
TOI-1425.01	13/02/2022	21:49	22:42	23:34	01:45	0.00	21:56:22	68:59:54	Cep
TOI-627.01	23/02/2022	18:19	19:24	20:28	02:09	1.40	05:27:42	07:55:06	Ori
TOI-1789.01	01/03/2022	23:54	00:53	01:52	01:57	0.00	09:30:58	26:32:24	Leo
TOI-1784.01	09/03/2022	21:50	22:15	22:41	00:51	0.80	10:14:12	29:05:06	LMi
TOI-5379.01	10/03/2022	21:24	23:15	01:06	03:42	0.10	07:29:42	50:41:00	Lyn
TOI-1273.01	13/03/2022	22:56	23:42	00:27	01:31	0.20	14:16:29	58:23:24	UMa
TOI-1179.01	19/03/2022	00:58	01:31	02:05	01:07	0.00	12:28:13	67:14:24	Dra
TOI-1186.01	20/03/2022	21:49	01:41	05:32	07:43	0.00	16:46:32	65:42:54	Dra
TOI-1820.01	22/03/2022	18:39	20:01	21:22	02:43	1.30	12:30:45	27:27:06	Com
TOI-1425.01	22/03/2022	01:19	02:12	03:04	01:45	0.00	21:56:22	68:59:54	Cep
TOI-1194.01	23/03/2022	19:01	19:49	20:37	01:36	0.10	11:11:17	69:57:54	UMa
TOI-1273.01	27/03/2022	20:23	21:09	21:54	01:31	0.20	14:16:29	58:23:24	UMa
TOI-1181.01	27/03/2022	00:18	02:20	04:23	04:05	0.00	19:48:52	64:21:18	Dra
TOI-1012.01	11/04/2022	19:17	20:06	20:55	01:38	0.00	07:48:23	06:47:06	CMi
TOI-1717.01	12/04/2022	20:04	21:21	22:39	02:35	0.10	06:58:31	67:40:36	Cam
TOI-1831.01	13/04/2022	19:09	19:35	20:00	00:51	0.70	13:21:49	17:45:54	Com
TOI-4496.01	11/06/2022	21:45	22:38	23:32	01:47	0.00	20:21:05	43:40:30	Cyg
TOI-1371.01	12/06/2022	22:29	23:54	01:19	02:50	0.40	22:04:28	31:01:06	Peg
TOI-1181.01	15/06/2022	22:25	00:28	02:30	04:05	0.00	19:48:52	64:21:18	Dra
TOI-4496.01	18/06/2022	00:33	01:26	02:20	01:47	0.00	20:21:05	43:40:30	Cyg
TOI-1425.01	23/06/2022	22:05	22:57	23:50	01:45	0.00	21:56:22	68:59:54	Cep
TOI-1425.01	26/06/2022	00:22	01:15	02:07	01:45	0.00	22:56:22	69:59:54	Cep
WASP-33 b	04/08/2022	00:17	01:39	03:00	02:43	-	02:26:51	37:33:02	And
HD189733 b	09/08/2022	22:15	23:10	00:04	01:49	-	20:00:44	22:42:39	Vul

Table 6: Information on the stars before the observations ⁵¹, ⁵²

the transit depth ΔF in percent and magnitudes (originally provided in ppm). The conversion from percent to magnitudes can be done with the definition of the magnitude (equation 15, Voigt et al. (2012)). This is necessary, since the magnitude is per definition logarithmic and small numerical values represent a high physical value. The conversion was done by defining the transit flux percentile as a radiant flux (Φ) difference of the star out of transit $\Phi_2 = 1$ and the flux of the star during transit $\Phi_1 = 1 - \Delta F$ (with ΔF given as an absolute value).

$$\Delta m = m_1 - m_2 = -2.5 \cdot \log_{10} \left(\frac{\Phi_1}{\Phi_2} \right) \quad (15)$$

As can be seen in Table 7, V can drastically differ from T_{mag} in Table 5, since *TESS* observes in the red to infrared range (600 - 1000 nm, see Table 1). In most cases T_{mag} will be lower (brighter) than the visible V (yellow at 550 nm (Léna et al., 2012, p. 106)), since infrared light is included in *TESS* measurements. From the observation time T_{Obs} in Table 7, one can calculate the average observation time, which was 3.42 hours.

The collected data from the listed observation nights was analysed with *Siril*, as mentioned in detail in the previous section (section 4.2). The output of the analysis is given in the shape of light curve files (.dat) and .csv-files. The latter contains information on the variable and the reference stars, from the former light curve plots were generated. A few of these plots will be presented in the next chapter (section 6), while others are just added to the end of the thesis - in the appendix (A).

The data from the .csv-files presented here was reduced to information on only the variable star, of which the parameters are listed as their respective median and standard deviation values (over the course of the whole observation) in Table 8. This table contains the parameters mentioned at the end of the previous chapter, namely amplitude of the Gaussian function (A), the FWHM, the roundness of the light source, the background (parameter B of equation 14) and the S/N ratio (SNR). The relative magnitude was not included, since it is of little relevance to our purposes here.

The FWHM is an attribute of the Gaussian PSF-fit, where the width of the Gauss function at half maximum is often used as a qualitative attribute of an observation night, due to its relation to astronomical seeing. The roundness of a point source in *Siril* is defined as a value between 0 and 1, since it is the ratio between the FWHM of the shorter axis to the longer axis - assuming an elliptical shape of the source⁵⁷. The value "1" would therefore be a circularly shaped stellar image.

For the calculation of the S/N ratio (SNR) in *Siril*, no information could be found - but the procedure is rather likely to resemble the following concept (equation 16)⁶¹:

⁵⁷see footnote 40

⁵⁸see footnote 6

⁵⁹see footnote 7

⁶⁰see footnote 55

⁶¹Space Telescope Science Institute (STScI): *Wide Field and Planetary Camera 2 Instrument Handbook for Cycle 14; 6.5 Signal-to-Noise Ratio Estimation; 6.5.2 Point Sources – Aperture Photometry* (2004). https://www.stsci.edu/instruments/wfpc2/Wfpc2_hand_current/ch6_exposuretime6.html, last access: 2022-10-04

Planet/TOI ID	Star	V [mag]	ΔF [%]	ΔF [mag]	Telescope	Camera	Start [UTC]	End [UTC]	T_{obs}
TOI-1425.01	BD+68 1260	9.875	0.586	0.00638	Meade	EOS 5D Mark II	21:29:55	00:55:00	03:25:05
TOI-627.01	HD 35804	10.219	0.537	0.00584	Meade	EOS 5D Mark II	18:47:33	22:04:17	03:16:44
TOI-1789.01	HD 82139	9.721	0.222	0.00241	Meade	EOS 5D Mark II	22:14:00	03:27:00	05:13:00
TOI-1784.01	BD+29 2016	10.016	0.125	0.00136	Meade	EOS 5D Mark II	20:16:30	00:31:14	04:14:44
TOI-5379.01	HD 233395	10.060	1.079	0.01178	Meade	EOS 5D Mark II	21:24:00	01:50:00	04:26:00
TOI-1273.01	TYC 3865-379-1	10.980	0.486	0.00529	Meade	EOS 5D Mark II	21:59:00	01:38:00	03:39:00
TOI-1179.01	TYC 4161-688-1	10.879	0.261	0.00284	Meade	EOS 5D Mark II	01:05:00	03:05:00	02:00:00
TOI-1186.01	BD+65 1145	10.605	0.899	0.00980	Meade	EOS 5D Mark II	21:10:00	04:00:00	06:50:00
TOI-1820.01	CI* Melotte 111 AV 1961	10.899	0.614	0.00669	Meade	EOS 5D Mark II	20:46:00	23:42:00	02:56:00
TOI-1425.01	BD+68 1260	9.875	0.586	0.00638	Meade	EOS 5D Mark II	00:46:00	04:03:00	03:17:00
TOI-1194.01	TYC 4385-509-1	11.302	0.703	0.00766	Refractor	EOS 5D Mark II	18:49:00	21:43:00	02:54:00
TOI-1273.01	TYC 3865-379-1	10.980	0.486	0.00529	Meade	EOS 5D Mark II	20:45:00	23:06:00	02:21:00
TOI-1181.01	TYC 4239-1136-1	10.582	0.710	0.00774	Meade	EOS 5D Mark II	23:38:00	03:51:42	04:13:42
TOI-1012.01	HD 63283	8.180	0.189	0.00205	Refractor	EOS 5D Mark II	18:37:00	22:17:58	03:40:58
TOI-1717.01	TYC 4359-220-1	9.875	0.904	0.00986	Meade	EOS 5D Mark II	20:06:55	23:45:57	03:39:02
TOI-1831.01	HD 116206	7.820	0.035	0.00038	Refractor	EOS 5D Mark II	19:41:30	21:45:40	02:04:10
TOI-4496.01	BD+43 3573	9.259	0.261	0.00284	Meade	EOS 5D Mark II	21:40:05	00:32:52	02:52:47
TOI-1371.01	BD+30 4602	10.357	1.428	0.01562	Meade	Sony $\alpha 7$ III	22:28:50	02:00:00	03:31:10
TOI-1181.01	TYC 4239-1136-1	10.582	0.710	0.00774	Meade	Sony $\alpha 7$ III	22:17:40	01:40:40	03:23:00
TOI-4496.01	BD+43 3573	9.259	0.261	0.00284	Meade	Sony $\alpha 7$ III	23:13:54	01:45:08	02:31:14
TOI-1425.01	BD+68 1260	9.875	0.586	0.00638	Meade	Sony $\alpha 7$ III	22:15:13	01:01:26	02:46:13
TOI-1425.01	BD+68 1260	9.875	0.586	0.00638	Meade	Sony $\alpha 7$ III	23:15:30	01:45:30	02:30:00
WASP-33 b	HD 15082	8.300	1.381	0.01510	Meade	Sony $\alpha 7$ III	23:31:58	02:00:00	02:28:02
HD189733 b	HIP 98505	7.670	2.564	0.02820	Meade	Sony $\alpha 7$ III	21:35:05	01:28:31	03:53:26

Table 7: All observations that yielded results and their timings and the instruments used ⁵⁸, ⁵⁹, ⁶⁰

$$SNR = \frac{S \cdot f(r)}{\sqrt{B \cdot \pi r^2}} \quad (16)$$

Generally speaking, the S/N ratio depends on the Poisson noise of the object and noise of the background, with the latter consisting of CCD (or in this case CMOS) read-out-noise N_{read} , Poisson noise of the dark current P_{dark} , the sky background P_{sky} and the diffuse background light from astrophysical sources, $P_{background}$ ⁶². In equation 16, the specific case of the S/N ratio for aperture photometry is considered; it should be noted that other methods, e.g. more specific ones to PSF-fitting could have been used (see reference of footnote 61). The first variable in the equation is the number of detected photons $S = R_{object} \cdot t_{exp}$, consisting of the photon counts for the object R_{object} multiplied by the integration time. The term $f(r)$ is the fraction of the total counts encircled by the aperture radius, with r being that said radius - B are the effective background counts per pixel, defined by the noise components mentioned just before⁶³:

$$B = N_{read}^2 + P_{dark} \cdot (t_{exp} + 46) + P_{sky} \cdot t_{exp} + P_{background} \cdot t_{exp} \quad (17)$$

Alternatively, a more general equation for the S/N ratio can be considered (Mortara and Fowler, 1981):

$$SNR = \frac{N_*}{\sqrt{N_* + n_{pix} (N_S + N_D + N_R^2)}} \quad (18)$$

In this equation, the integration time t_{exp} , used in previous equations 16 and 17 is implicit: N_* is the total number of photons collected from the target, be it from a stellar profile or a rectangular area of X by Y pixels (Howell, 2006). The latter option is likelier in the case of *Siril*, since the calculation of the SNR was only possible, if the square/rectangle selection tool encompassed enough pixels. The noise terms in equation 18 are very similar to the ones mentioned earlier - N_S is the total number of photons per pixel from the background/sky, N_D is the number of dark current electrons per pixel, N_R is the e^-/px of the read-out-noise and n_{pix} the number of pixels under consideration for the calculation (Howell, 2006).

Further parameters of the observation nights were gathered for an estimation of error sources, i.e. the airmass, the moon phase, the ratio of the amplitude and the background component A/B , the FWHM of the .csv-file converted from pixels to arcseconds to estimate a kind of "seeing" and a spectral type. These values can be found in Table 9. The seeing can not actually be considered as such, since the FWHM values are too high due to specific effects: the imperfect alignment, focus, coma or effects of field curvature can falsify the PSF-fitting and can therefore not accurately represent the seeing at the moment of measurement. As can be seen in Table 9, many values for the FWHM in arcseconds are rather high - values between $2'' - 5''$ are feasible for qualitative indication. However, further analysis of the FWHM will be done in pixels. The conversion of pixels to arcseconds is done with the plate scales of the respective cameras

⁶²see footnote 61

⁶³see footnote 61

Planet/TOI ID	Amplitude		FWHM [px]		Roundness		Background		SNR [dB]	
	$\tilde{x}$	σ	$\tilde{x}$	σ	$\tilde{x}$	σ	$\tilde{x}$	σ	$\tilde{x}$	σ
TOI-1425.01	0.041126	0.017664	10.558	2.006	0.873	0.081	0.003199	0.000187	28.521	1.071
TOI-627.01	0.083020	0.024070	10.302	3.462	0.602	0.178	0.002225	0.000331	28.415	0.211
TOI-1789.01	7561.860	1802.882	17.299	2.270	0.900	0.083	378.484	27.687	27.228	1.190
TOI-1784.01	0.153339	0.028892	9.836	2.780	0.653	0.171	0.004014	0.000836	24.749	1.645
TOI-5379.01	6938.885	1759.561	10.817	2.641	0.645	0.137	241.000	23.138	28.223	0.133
TOI-1273.01	0.035830	0.011683	12.445	2.565	0.830	0.094	0.003756	0.000613	23.860	0.772
TOI-1179.01	0.069584	0.013241	8.894	1.826	0.802	0.111	0.005580	0.000136	23.957	0.828
TOI-1186.01	0.123058	0.031300	7.719	1.467	0.879	0.073	0.005727	0.001178	27.317	0.923
TOI-1820.01	0.065613	0.017115	9.968	3.681	0.684	0.165	0.003521	0.000699	24.330	1.347
TOI-1425.01	6144.740	1141.602	8.888	1.294	0.614	0.084	140.469	80.751	25.804	0.848
TOI-1194.01	8417.640	1147.154	7.684	1.442	0.557	0.071	120.988	20.079	25.035	0.660
TOI-1273.01	9050.355	2076.223	6.985	2.609	0.662	0.185	247.894	32.656	25.903	1.193
TOI-1181.01	0.110490	0.025225	6.633	1.899	0.793	0.147	0.002007	0.002586	26.297	0.516
TOI-1012.01	11756.900	3182.350	13.848	2.532	0.829	0.128	101.955	13.403	31.609	0.845
TOI-1717.01	0.124854	0.025895	7.383	1.458	0.827	0.110	0.002486	0.000240	28.197	0.550
TOI-1831.01	16083.400	628.407	21.735	4.640	0.612	0.128	317.013	39.762	34.599	0.241
TOI-4496.01	7585.680	1913.248	8.888	3.672	0.612	0.197	84.489	19.873	27.316	1.247
TOI-1371.01	0.020590	0.007975	18.516	3.302	0.825	0.110	0.004240	0.008126	24.906	1.402
TOI-1181.01	0.172957	0.035832	6.227	1.879	0.670	0.146	0.002436	0.001103	28.821	0.570
TOI-4496.01	9368.280	1846.247	9.857	2.830	0.500	0.116	63.374	22.690	29.108	0.800
TOI-1425.01	10945.300	2158.545	8.346	1.725	0.820	0.112	105.978	6.139	30.369	0.260
TOI-1425.01	0.120422	0.020530	6.755	1.395	0.689	0.127	0.000634	0.000576	28.653	0.509
WASP-33 b	0.305276	0.018462	6.804	0.273	0.922	0.022	0.000917	0.000089	31.999	0.084
HD 189733 b	0.700712	0.157534	6.841	1.181	0.866	0.042	0.001365	0.000273	33.543	0.031

Table 8: All observations and their *Siril* output

(see Table 10). The airmass is calculated with the help of the height h (or the zenith angle $\zeta = 90^\circ - h$) of the star over the course of the observation time (eqn. 19, (Léna et al., 2012, p. 109), (Roth et al., 1989, p. 398)):

$$X = \sec(\zeta) = \csc(h) \quad (19)$$

The values of the height of the star were collected from the *Stellarium* program, both of the beginning and end of the observation and the minimal and maximal values (Zotti et al., 2021). The minimal and maximal airmass can differ from the start end end values, if the start of the observation took place before and ended after passing the meridian.

The information on the lunar phase was gathered in the form of the new moon dates ⁶⁴ and then converted to percentage of the lunar cycle. This value tells us how far from returning to a new moon the phase was on that specific day; the first quarter would logically be at 25%, the full moon at 50% and so on. The stellar spectral type was collected from *SIMBAD*, which was not always possible. The unavailable spectral types of stars were calculated with $B - V$, which were both gathered from *Simbad* as well ⁶⁵. The $B - V$ values were then compared to common Hertzsprung-Russell-diagrams with $B - V$ vs. absolute magnitude and spectral type as a second y-axis (e.g. (Weigert et al., 2010, p. 159)). Thereafter, the approximate spectral type was inferred from the graph (see Table 9, values with †). One spectral type was acquired from a paper, since the *Simbad* entry was ambiguous - the classification of *WASP-33* (marked by *) is given as A5m by Collier Cameron et al. (2010).

The final set of values that was generated are the median and standard deviation values of all light curves (of all observations) before ingress (designated with a subscripted "i", $\tilde{x}_i$ and σ_i), at mid-transit ($\tilde{x}_m$ and σ_m) and after egress ($\tilde{x}_e$ and σ_e). Table 10 lists the calculated values and at the same time indirectly indicates whether the ingress, mid-transit and egress were observed by the presence of the value in the respective column for $\tilde{x}$ and σ . An exception to that is *TOI-1371.01*, where the ingress was calculated from values within the uncertainty of the ephemeris - the "official" ingress could not be observed that day.

Due to a range of factors, including a misinterpretation of the first observation results, which were far away from saturation, many of the observations following thereafter, were interpreted to require as much exposure as possible. The issue with this was that factors of weather and a lack of training with focus finding in the first observations led to that notion. The more recent observations were mostly better regarding focus and thereby resulted in overly saturated stars. Unfortunately, this issue was recognized late and therefore only had a relatively small impact on the last observations. Due to these circumstances, the saturation of the images was analysed by checking which pixels out of the three channels were close to the maximal value of a 14 bit camera (applies to both *Canon* and *Sony*), which equals $N = 2^{14} = 16384$ values - but since the lowest value is 0, the maximum value is equivalent to $2^{14} - 1 = 16383$ (Howell, 2006). The pixels could easily be evaluated with the *RGGB Bayer matrix*, which means that the first

⁶⁴What is the Moon Phase Today? *Lunar Phases 2022*. <https://www.space.com/18880-moon-phases.html#section-moon-phase-calendar-for-2022>, last access: 2022-09-03

⁶⁵see footnote 55

⁶⁶see footnote 64

⁶⁷see footnote 55

Planet/TOI ID	X_{min}	X_{max}	Moon [%]	A/B	FWHM ["]	Spectral Type
TOI-1425.01	2.063	2.178	40.637	12.856	6.980	G0
TOI-627.01	1.327	2.252	74.501	37.321	6.811	A2
TOI-1789.01	1.081	2.595	94.819	19.979	11.436	K0
TOI-1784.01	1.059	1.218	23.705	38.197	6.502	G0
TOI-5379.01	1.074	1.977	27.091	28.792	7.151	F8
TOI-1273.01	1.016	1.210	37.250	9.540	8.227	F-G [†]
TOI-1179.01	1.080	1.186	57.569	12.469	5.880	G at RGB [†]
TOI-1186.01	1.048	1.576	60.955	21.488	5.103	G
TOI-1820.01	1.070	1.255	67.728	18.635	6.590	G [†]
TOI-1425.01	1.300	1.740	67.728	43.744	5.876	G0
TOI-1194.01	1.077	1.173	71.114	69.574	2.903	late F [†]
TOI-1273.01	1.054	1.247	84.660	36.509	4.617	F-G [†]
TOI-1181.01	1.168	1.619	84.660	55.061	4.385	late F [†]
TOI-1012.01	1.396	3.588	33.864	115.315	5.231	B8
TOI-1717.01	1.191	1.640	37.250	50.232	4.881	F [†]
TOI-1831.01	1.195	1.518	40.637	50.734	8.211	F0
TOI-4496.01	1.035	1.376	40.637	89.783	5.876	A2
TOI-1371.01	1.116	1.932	44.023	4.857	11.324	F0
TOI-1181.01	1.041	1.130	54.182	71.000	3.808	late F [†]
TOI-4496.01	1.003	1.091	64.341	147.825	6.028	A2
TOI-1425.01	1.097	1.267	81.273	103.279	5.104	G0
TOI-1425.01	1.076	1.173	91.432	189.958	4.131	G0
WASP-33 b	1.148	1.693	23.705	333.086	4.161	A5m [*]
HD189733 b	1.204	1.593	40.637	513.338	4.184	K2V

Table 9: Information on observing conditions and other star characteristics; [†]: estimation from $B - V$ and a HRD; RGB here: Red Giant Branch; ^{*}: from Collier Cameron et al. (2010) (Zotti et al. (2021), ⁶⁶, ⁶⁷)

pixel of the matrix (0,0) is red (R), the second of the first row (0,1) and the first of the second row are green (G) and the second of the second row (1,1) is blue (B) (Milgrom et al., 2010). This pattern repeats throughout the detector’s area, making the numerical coordinate values indicators for the channel and therefore identifiable regarding saturation of the target star (the *RGGB* pattern is used by both cameras).

The strategy applied to the data analysis therefore was to use the saturated image sequences to analyse their respective on-target accuracy by using the channels that were not over-exposed. These channels can be found in the *RGB*-column in Table 10, although the strategy also applies to the *.csv*-files (since they were generated together with the light curves) and is therefore also relevant to the data in Table 8.

At the same time, a second strategy was chosen, namely to apply photometry to another star in the field of view as well. This star would not be saturated in the green (G) channel (the main channel, since it has more pixels and therefore higher signal) to review the theoretical accuracy

Planet/TOI ID	RGB	$\tilde{x}_i$	$\tilde{x}_m$	$\tilde{x}_e$	σ_i	σ_m	σ_e	ΔF [mag]
TOI-1425.01	G	-0.830642	-0.657358	-0.845524	0.006319	0.061953	0.012270	0.00638
TOI-627.01	G		0.0705665	0.083569		0.015351	0.062452	0.00584
TOI-1789.01	G	-0.198267	-0.239974	-0.200017	0.010336	0.01923	0.009650	0.00241
TOI-1784.01	R	-1.159328	-1.152393	-1.188404	0.028013	0.026017	0.030049	0.00136
TOI-5379.01	G		-0.046212	-0.177039		0.012566	0.014180	0.01178
TOI-1273.01	G	-0.096246	-0.084812	-0.085440	0.011921	0.013191	0.015597	0.00529
TOI-1179.01	G		-0.492103	-0.516294		0.018968	0.013379	0.00284
TOI-1186.01	G	-0.466235	-0.464853		0.018284	0.011026		0.00980
TOI-1820.01	G		0.328305	0.331064		0.016848	0.011852	0.00669
TOI-1425.01	R	-0.446505	-0.453362	-0.461505	0.023725	0.018925	0.016136	0.00638
TOI-1194.01	R	-1.212166	-1.178106	-1.146896	0.028603	0.023088	0.027881	0.00766
TOI-1273.01	G		0.052829	0.022717		0.014186	0.012357	0.00529
TOI-1181.01	B	-0.035300	-0.034258		0.019261	0.023004		0.00774
TOI-1012.01	R	-2.244680	-2.284995	-2.292867	0.036746	0.024545	0.012938	0.00205
TOI-1717.01	G		-0.496237	-0.550041		0.008933	0.009234	0.00986
TOI-1831.01	G		-1.689902	-1.876173		0.044629	0.084755	0.00038
TOI-4496.01	R	-0.123188	-0.137833	-0.132905	0.022683	0.019233	0.01788	0.00284
TOI-1371.01	G	-0.063686	-0.061093	-0.061708	0.014221	0.008655	0.010851	0.01562
TOI-1181.01	G	-0.057227	-0.021469		0.005601	0.012856		0.00774
TOI-4496.01	R	-0.255908	-0.251729		0.022916	0.021816		0.00284
TOI-1425.01	G		-0.619134	-0.642608		0.018954	0.009351	0.00638
TOI-1425.01	R	-0.519852	-0.517537		0.033226	0.062361		0.00638
WASP-33 b	G	-1.260847	-1.283391		0.006913	0.009669		0.01510
HD189733 b	G	-1.352574	-1.328442	-1.390224	0.006248	0.006069	0.007101	0.02820

Table 10: Median $\tilde{x}$ and standard deviation σ of all light curves at ingress, mid transit and egress compared to transit depth

that could have been possible on that day of observation without excessive exposure. The calculated values for another star on the image of the green channel can be found in Table 11. The penultimate row of that table includes an observation of *TOI-1425.01* which is designated with a "G" in Table 10, since it was on the verge of being considered saturated. Up to the ~ 100 th frame of the sequence, the star was often very close to saturation, therefore it was decided to create another light curve and sequence of values (*.csv*-files) in the same green channel. Another star with the main analysis in the "G" channel and an additional accuracy check within the same channel is *TOI-1831.01*, which had to be done, since the target was over-exposed in the *R* and *G* channel. The logical consequence would be to use the blue channel (B), but that was not possible due to optical effects of the *Large Refractor*, which displays effects of chromatic aberration, since it is a semi-apochromat⁶⁸. An apochromat corrects the spherical aberration with the help of multiple layered lenses that cancel out the effect. Semi-apochromats however, are less sumptuous and therefore correct only a part of the spectrum (Sacek, 2006b). For the *Large Refractor* the blue wavelengths are not corrected by the lens, causing the image of the B-channel to be smeared and out of focus.

When matching the values of the stars listed in Table 11 to the corresponding ones in Table 10, one can see that the dispersion σ of the light curve data points have improved significantly

⁶⁸see footnote 24

Planet/TOI ID	$\tilde{x}_i$	$\tilde{x}_m$	$\tilde{x}_e$	σ_i	σ_m	σ_e	ΔF [mag]
TOI-1784.01	-0.316436	-0.329947	-0.343406	0.023817	0.018733	0.017437	0.00136
TOI-1425.01	0.041776	0.052906	0.066087	0.009942	0.011476	0.007636	0.00638
TOI-1194.01	-0.389200	-0.365942	-0.383029	0.050024	0.049686	0.026462	0.00766
TOI-1181.01	-0.411683	-0.442873		0.017243	0.015671		0.00774
TOI-1012.01	-0.321503	-0.326353	-0.309709	0.009206	0.013513	0.014603	0.00205
TOI-1831.01		-0.687461	-0.683352		0.007315	0.009594	0.00038
TOI-4496.01	-0.405003	-0.400395	-0.400821	0.006933	0.006421	0.004444	0.00284
TOI-4496.01	-0.448326	-0.444146		0.004845	0.003846		0.00284
TOI-1425.01		0.240758	0.218318		0.009419	0.008025	0.00638
TOI-1425.01	-0.426712	-0.413482		0.007871	0.013244		0.00638

Table 11: Median $\tilde{x}$ and standard deviation σ of alternative variable star in field of saturated observations - at ingress, mid transit and egress compared to transit depth

in the green channel (Table 11) for all measurements except for *TOI-1194.01*. The reason for this anomaly is that the other stars in the field are significantly less bright than the target and therefore more noise is added into the off-target photometry. In all other cases the accuracy is higher, even though the selection of a different star without saturation in the same field of view means a choice of a star with less magnitude. The overall improved result can however be traced back to two facts; the lack of saturation and the more accurate green channel that was used for the stars in Table 11.

The improvement of σ with this new star choice could still not bring about enough change to be less in value than their respective transit depths, although the three listed measurements of *TOI-1425.01* and the two observations of *TOI-4496.01* came very close to the ΔF value. It is not unlikely that the variable star with the planetary candidate could have reached enough accuracy if a smaller exposure time had been chosen, therefore preventing the excessive saturation.

The lowest measured dispersion over the course of 6 months of observation was reached with *HD 189733 b*, which was a test to see if a star with high brightness and strong transit signal would be observable with the given instrumentation. If we compare *HD 189733 b*'s dispersion σ_m during mid-transit, we can see that the value of approximately 0.0061 mag is a lot smaller (factor of ~ 4) than its transit depth of 0.0282 mag.

Compared to the rest of the transit depths, starting with the first observation of *TOI-1425.01*, the transit depth of 0.0064 mag is just a slight bit higher and might have very narrowly been observable if no other systematics came into play. The initial σ_i in that case would have also been lower than *TOI-1425.01*'s ΔF and had the accuracy been kept, the transit might have just been detectable. But if we look at *TOI-1425.01*'s first observation and the resulting light curve (Figure 47), there actually seems to be a transit taking place. But comparing the data points with the red line of the expected transit, one can see that expectation would suggest a much lower transit depth. The phenomenon of the star darkening significantly over the course of the night was suspected to be the result of clouds. But after assessing the height h above the horizon over roughly 3.5 hours of observation time (using *Stellarium*), the likelier scenario would be an obstruction by the observatory building. The star was rather low, being in the

Cepheus constellation close to the North Pole (see airmass X in Table 9). The *Meade* telescope was being used in the observatory's garden and the star was rather close to the building's roof - a miscalculation of the star losing height before the meridian and rising after the meridian to the North is the likely cause.

Even the lowest measured dispersion of all measurements by *HD 189733 b* would not have been enough for the next three transit measurements - here the depths of approximately $\Delta F = 0.006$, 0.002 and 0.001 would have been very difficult or near impossible to measure. Comparing the lowest dispersion to all other transit depths, only a handful would have been possible - starting with the already mentioned *TOI-1425.01*, which was observed for a total of five times. The second observation is not in the analysed dataset, being the overall second observation of the campaign - it had to be dropped due to a lack of stellar tracking accuracy, stemming from imperfect polar alignment. The next planetary candidate with a "manageable" ΔF would be *TOI-5379.01* with $\Delta F = 0.0118$, *TOI-1186.01* with $\Delta F = 0.0098$ mag, then *TOI-1820.01* with $\Delta F = 0.0067$, *TOI-1194.01*, *TOI-1181.01* (observed twice), *TOI-1717.01*, *TOI-1371.01* and finally the test observations of *WASP-33 b* and *HD 189733 b*. This comparison between the lowest measured dispersion and the observed stars' transit depth is only of limited relevance, since the other stars were observed at different weather conditions, airmass, focus, alignments, backgrounds, etc., but most importantly at different magnitudes. This also means the S/N ratio was quite different - the lowest dispersion was achieved with a star of $V = 7.67$ mag, which is about 2.5 orders of magnitude brighter than the average *TOI* observation of about $V_{\mu} = 10$ mag!

Therefore, it makes more sense to compare the transit depth with the dispersion of the same observation, which leaves the previously mentioned list of best observations reduced to *TOI-5379.01*, *TOI-1186.01*, *TOI-1717.01*, *TOI-1371.01* and the two last observations of *WASP-33 b* and *HD 189733 b*. These are the best observations of the 24 listed measurements and since not all of them can be discussed here in detail, these will be discussed in the next sections (section 6.1 to 6.5). The discussion will be conducted as a comparative case study of the six observations, where the most important parameters will be qualitatively evaluated in order to reach a conclusion on the reason for the achieved accuracies.

6. Results

6.1. TOI-5379.01

The measurements of *TOI-5379.01*, located in the Lynx constellation were taken with the *Meade* Schmidt-Cassegrain telescope and the *Canon* camera on 10th March 2022. The planetary candidate's ephemerides have an uncertainty of 0.1 hours (6 minutes, see Table 6), a transit depth of 0.01178 mag (1.079 %) and a stellar brightness of $V = 10.06$ mag (see Table 7). The value for ΔF is on the higher end of the here listed observations, while the brightness is very close to the average of 10.04 mag. Table 12 lists all important parameters of the planetary candidate for a quick overview.

TOI ID	V [mag]	ΔF [mag]	σ_i	σ_m	σ_e	A	FWHM [px]	R
TOI-5379.01	10.060	0.01178	-	0.012566	0.014180	6938.885	10.817	0.645
TOI ID	B	SNR [dB]	X_{min}	X_{max}	Moon	A/B	Spec. Type	
TOI-5379.01	241.000	28.223	1.074	1.977	27.091	28.792	F8 E	

Table 12: Most relevant values of the *TOI-5379.01* observation

The observation is one of the most defocussed, suggesting a higher roundness (R), which is however rather low with a median value of 0.645. The so-called FWHM value that is displayed in the tables here is to be taken with a grain of salt - the fitted PSF has to adjust to too many other issues apart from seeing or scintillation to adapt - movement in the telescope tracking, imperfect alignment and therefore tracking errors and of course the defocussed image that is relevant in this case.

With a median S/N ratio of around 28 dB, the observation is in the upper range of measurements, possible due to the 30s exposure and the defocussing which prevented saturation. The ratio between amplitude and background A/B - which can also be understood as an indicator of quality for the dataset however, is comparatively low with a value of 28.8. The reason for that lies in the high background and high amplitude value; a trait that a few observations showcase in the sample - a connection of the high background value to the moon phase is not given, since some observations with more lunar influence can have smaller values of B than others. The moon phase is just above the first quarter, meaning it is somewhere close to being a half moon - not ideal, but also certainly not a significant issue for photometric measurements for a star of 10 mag (see Figure 15). The photometric accuracy during that presence of the moon should be in the range of 0.75% for a 15s exposure. As mentioned earlier, the photometric accuracy for a 30s exposure would increase by a factor of $\frac{1}{\sqrt{2}}$, which would be an accuracy of about 0.53%. Since the background noise increases with a longer exposure, the true value would be somewhere in between. Both values - for 15 and for 30 seconds are below the ΔF of *TOI-5379.01* (which is 1.079 %) and would therefore be theoretically measurable, solely going by lunar phase.

If we look at the produced light curve for this exoplanetary candidate (Figure 16), we can see a certain resemblance of the dataset with the red line of the expected transit. The first data points seem to indicate an ingress and there would seem to be a linear trend towards the second half of the dataset that could indicate an egress, but the strong slope makes a certain

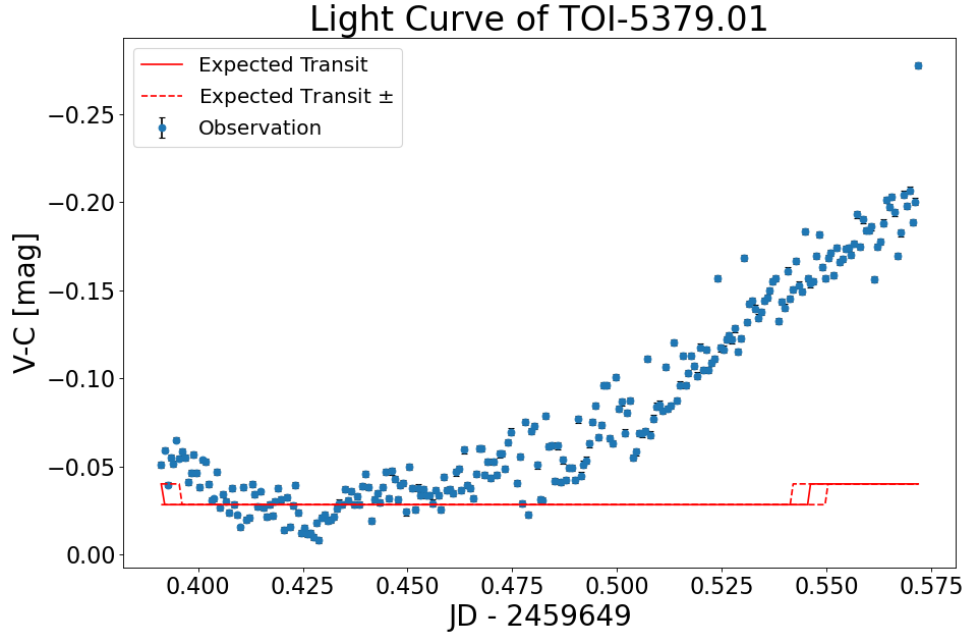
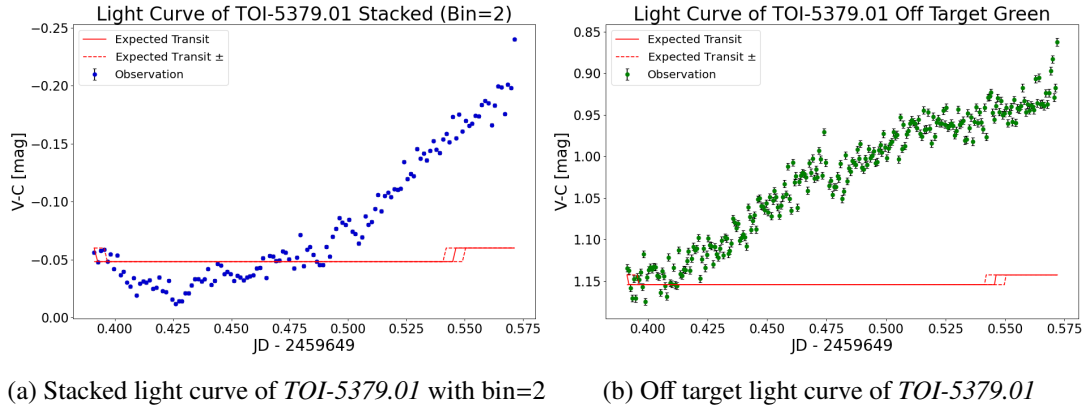


Figure 16: Generated light curve of TOI-5379.01



(a) Stacked light curve of *TOI-5379.01* with bin=2 (b) Off target light curve of *TOI-5379.01*

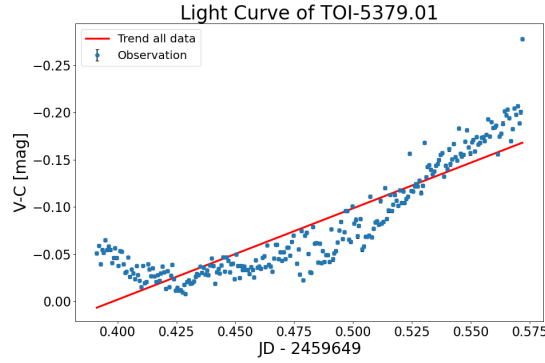
Figure 17: Stacked light curve of *TOI-5379.01* and an off-target light curve

deciphering impossible.

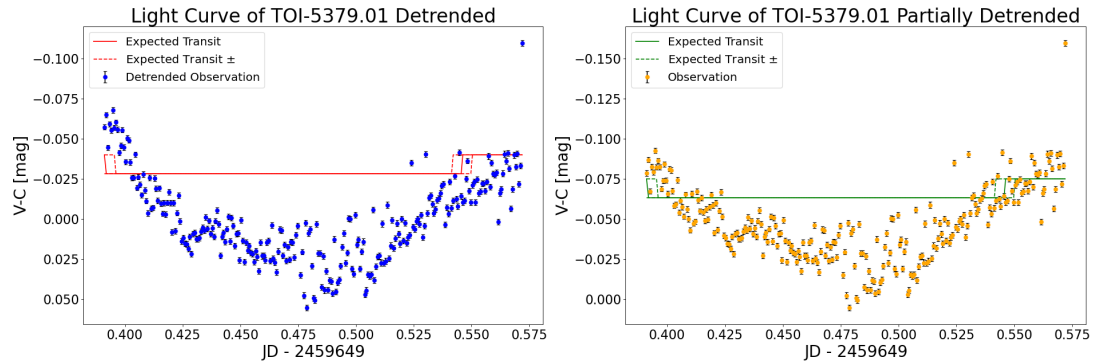
Two attempts at solving this issue were made: one in form of stacking the image to double the integration time (from 30 to 60 seconds) and the second being a linear de-trending of the data. Another step to be taken before analysing in detail is excluding a systematic origin of the light curve shape, a state in which all stars would be affected by the same cause, manifesting itself in the shape of a transit-like trend. In order to exclude this scenario, a light curve of only the reference stars that were used for the regular light curve photometry was generated (see Figure 17b). Should the off-target light curve exhibit similar features as the "regular" one, the

correlation of systematics is present. In the case here, one can see a similar attribute - the original and the off-target light curve have an increasing linear trend. However, the transit-like feature with indications of an ingress and an egress cannot be found in the off-target graph, which would suggest that this feature could be specific to the *TOI* target. Still, this assumption can neither be confirmed or denied, since the transit shape could still be of systematic origin.

The stacked light curve of *TOI-5379.01* can be found in Figure 17a, showing what difference the process of stacking with *Python* made. The difference is marginal though - the shape of the light curve did not change dramatically, the underlying systematics of the original light curve however are more clearly visible since the data point dispersion has reduced. The theoretical egress that might be visible in the data can now be placed somewhere close to the value of 0.525 on the x-axis, which is clearly outside the uncertainty of the egress timings of the expected transit. Even the ingress does not correspond to the expected timings, which makes a definite cause of the light curve shape very hard to determine. The systematics and oscillations in brightness clearly visible in the stacked image are all larger than the expected transit depth - another issue with a definite identification of the cause.



(a) Linear trend/fit used to de-trend *TOI-5379.01*'s light curve



(b) De-trended light curve of *TOI-5379.01* with the whole data trend (c) Partially de-trended light curve of *TOI-5379.01* with the two small trends

Figure 18: Linear trends in *TOI-5379.01*'s light curve, totally and partially de-trended

The attempts at de-trending can be seen in Figure 18a. We are dealing with an upwards trend for the stellar brightness. This tendency was subtracted in two different manners, namely by de-trending the linear function over the whole dataset (see Figure 18b) or by using the same trend to be partially removed from the most affected part of the light curve (Figure 18c). The difference between total and partial de-trending of the data is marginal - the light curve at least resembles that of a transit more than before, with a depth of about 0.05 mag. This is a value that is about five times higher than the expected transit depth. The difficulty of analysing the outcome is to allocate a certain cause out of the many to the shape of the light curve - the fact that a linear trend was subtracted from the dataset to form this light curve makes a definite statement difficult. The value of ΔF is certainly too high and even in the case of a detection it is likely still contaminated with a trend or systematics. Therefore, there is no guarantee that the actual trend occurring in the data is actually linear and the de-trending produced the expected exoplanetary signal. Additionally, the dispersion of the data points can be quite high ($> \Delta F$) which obviously does not change after de-trending - the cause of the transit-like shape cannot be clearly pin-pointed and could be a coincidence.

The maximal airmass value is equivalent to the value at the end of the observation in this case, which could be an explanation for the linear trend in the data. The increase in X also contributes to a lesser accuracy in photometry. However, the more likely scenario in this case is the imperfect polar alignment and the movement of the star across the image over the observation duration. This causes the star to enter different areas of illumination and mainly of focus, which induces a change of relative brightness. Different areas of influence of the flat-field image could theoretically also make a difference, but unlikely such a significant one. With the shift of the pointing, the reference stars can move to a region where the focus is significantly worse due to field curvature (or astigmatism). There they would appear less bright and thus make the target brighter in relation, thereby creating the linear trend (see more in section 7). The pointing variation during the observation night was highly significant - to an extent that the telescope had to be realigned to the target, since the star had moved too far. After realigning, the movement of the star across the image changed, causing the star to be exposed to additional areas of the field that are influenced by the curvature (or flat-field) to a different degree. Therefore, the major contributor to this trend seems to be the field curvature of the Schmidt-Cassegrain optics system (as discussed earlier). The flat-field image clearly shows a loss of light and focus towards the outer areas of the image (see section 7).

The final test regarding the possibility of a transit in the data was to upload it to the *Exoplanet Transit Database*, as intended for measured transits. However, the algorithm could not detect a transit in the light curve - an evaluation that is considered to be the final verdict for this question. Considering the set-up of this experiment and the intentions of feasibility for citizen science implementation, no further direct analysis than the *ETD* upload will be undertaken. This is the case, although theoretically with additional means of operating, this light curve might have turned out to be a transit.

6.2. TOI-1186.01

TOI-1186.01 is located within the Draco constellation and was observed on the 20th of March 2022 with the *Meade* telescope. The transit duration according to its ephemeris is the longest

TOI ID	V [mag]	ΔF [mag]	σ_i	σ_m	σ_e	A	FWHM [px]	R
TOI-1186.01	10.605	0.00980	0.018284	0.011026	-	0.123058	7.720	0.879
TOI ID	B	SNR [dB]	X_{min}	X_{max}	Moon	A/B	Spec. Type	
TOI-1186.01	0.005727	27.317	1.048	1.576	60.955	21.488	G D	

Table 13: Most relevant values of the *TOI-1186.01* observation

of all candidates observed during this campaign with 7:43 hours, which extended well into the morning hours after sunrise. Therefore, the transit event took too long for an observation of the egress. The target attribute of $V = 10.605$ mag is on the smaller end of the spectrum within the observations, while the transit depth of $\Delta F = 0.0098$ mag is on the higher end. Table 13 lists the most important values of the observation.

Compared to the previously discussed candidate, *TOI-5379.01*, the Amplitude A and background B values are small, corresponding to the majority of results in Table 8. The focus of the image series for this candidate is on the more precise end of the spectrum, with an FWHM of 7.72 and a higher median roundness of 0.879, which is also one of the better values in the list of observations. The S/N ratio SNR and the quality indicator A/B are however below average - which could be due to the rather prominent moon, which is just a few days after a full moon having undergone about 61% of the lunar cycle. This would suggest a maximal photometric accuracy of close to or more than 3% (see Figure 15, about 2.12% for 30s), which implies low quality for the time series and therefore could be an explanation for the low SNR and A/B . Another factor for less accuracy were the weather conditions, which included the presence of some small and occasional streaks of clouds. One such brief cloud coverage can be seen in the central part of the observation in Figure 19, where some data points suddenly exhibit larger error bars. The cloud coverage causes a drop in S/N ratio and therefore the error bars grow in size (see the end of section 4.2, second to last paragraph).

The σ values in Table 13 could therefore be lacking the accuracy needed to detect the transit depth, due to the lunar phase and weather conditions, albeit a very slim difference between the dispersion and ΔF values. The transit light curve however, seems to resemble the previous one in its linear trend with a rising brightness towards the end of the observation. This is again an indicator for the movement of the target across the field of view and the location at a different point within the telescope's aperture. A similar phenomenon seems to be taking place towards the beginning of the observation, where the opposite effect, namely a brightness reduction takes place. This is very likely the opposite effect, where the reference stars and the target moved from an outer part to the center, just to move back into an outer part where the stellar brightness in the light curve increases again. This means the reference stars become brighter in the beginning by moving towards the image centre and then decrease again by crossing the centre and reaching the outer part on the other side (from defocussed/low incidence of light to higher, then again low). There is also an interruption of the observation, due to a mistake in realigning the telescope to the target, which caused the visible gap.

When the images are stacked with *Python*, the result (Figure 20) resembles the ingress of an exoplanet more - though the linear trends actually still remain. A partial de-trending of the stacked dataset would result in an ingress of about 0.03 mag which is more than three times

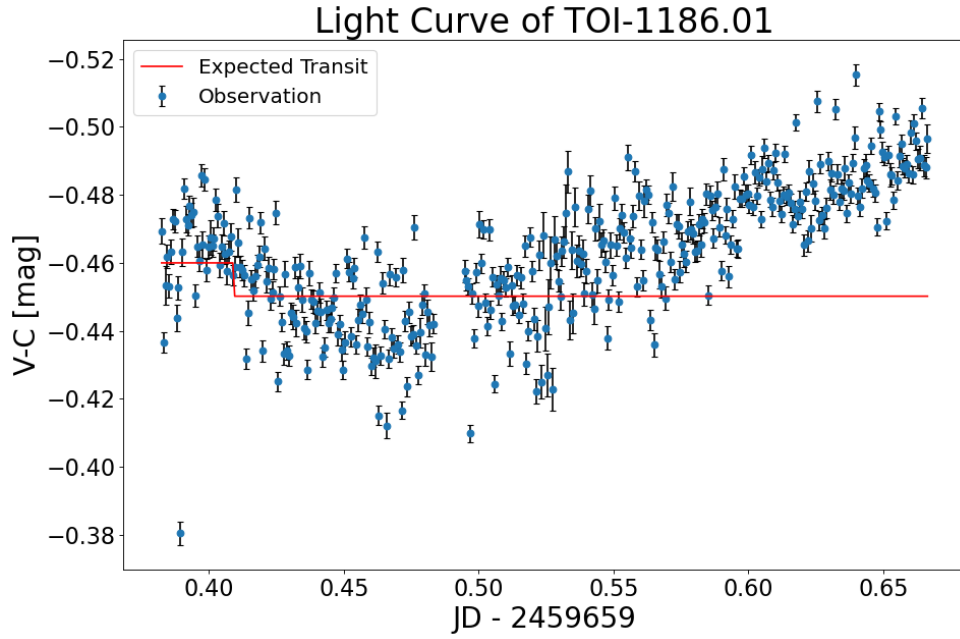


Figure 19: Generated light curve of TOI-1186.01

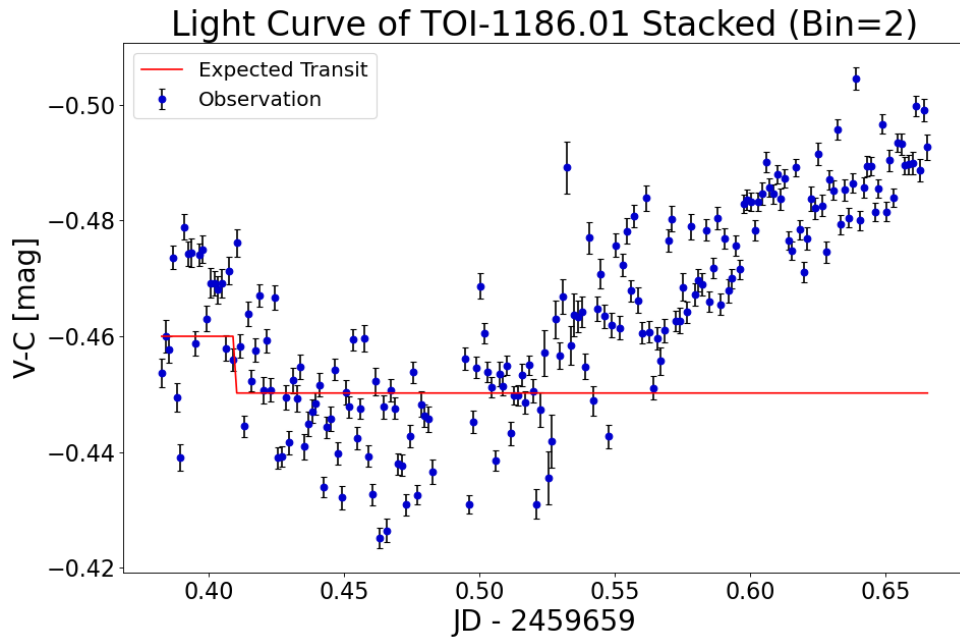


Figure 20: Stacked light curve of *TOI-1186.01* with bin=2

the depth of the expected transit. Nevertheless, the data point dispersion would still be larger

TOI ID	V [mag]	ΔF [mag]	σ_i	σ_m	σ_e	A	FWHM [px]	R
TOI-1717.01	9.875	0.00986	-	0.008933	0.009234	0.124854	7.383	0.827
TOI ID	B	SNR [dB]	X_{min}	X_{max}	Moon	A/B	Spec. Type	
TOI-1717.01	0.002486	28.197	1.191	1.640	37.250	50.232	F [†]	

Table 14: Most relevant values of the *TOI-1717.01* observation

than the expected transit and would therefore make a definite statement on a successful transit measurement difficult - without considering the sources of error on that evening, including clouds and bright moon. An estimation of a transit depth for the original data seems unnatural due to the shape of the light curve, that seems to be dominated by systematics. The upload of the data to *ETD* was unsuccessful, with the algorithm evaluating the dataset to be unrecognisable.

6.3. TOI-1717.01

Of the *TESS Objects of Interest* that have been observed during this campaign, the data dispersion of *TOI-1717.01* is the lowest relative to its transit depth. The σ values of mid-transit and egress are both smaller than the ΔF value of 0.00986 mag, which is the case only for two *TOI* measurements, the other being *TOI-1371.01*. The ingress of this planetary candidate could not be measured - only mid-transit and egress. With a magnitude of 9.875 mag, the host star is one of the brighter ones in this dataset, while the transit depth can also be classified as one of the larger ones. Table 14 once again lists the most important values for the observation night and stellar/planetary attributes.

The values for the amplitude and background are within the range of being between 0 and 1 (which is more common), the FWHM is rather low (relatively speaking), which can be seen in the images from that observation night: well focussed, not too much movement or too many alignment inaccuracies. This fact is also represented in the median roundness value of 0.827, which is high. The S/N ratio of more than 28 dB is also a higher value, which explains the good accuracy in the photometry. Another factor for photometric accuracy is the moon phase, which has exceeded the first quarter and is almost exactly halfway between a half and a full moon, with a lunar cycle percentage of 37.25%. The accuracy for photometry should be around 1% (0.71% for 30s without background noise adjustment), at least when it comes to an estimation according to Figure 15. The value is plausible when looking at the light curve's dispersion. However, looking at Figure 21, the actual dispersion of the data points does not seem to be sufficiently represented by the σ values, since the points are a little more evenly distributed than in other light curves, where there seems to be a clearer line with outliers above and below it. The data points here therefore do not represent a normal distribution and the dispersion is about double of the calculated σ values.

The qualitative indicator of *A/B* is one of the higher values that the analysis with *Siril* has provided. All indicators in this case exhibit some of the highest quality in the analysed dataset. The light curve also mostly reflects that fact - with one caveat in the form of a linear trend towards the second half of the curve (see Figure 21). Again, this is possibly caused by the image curvature and movement of the star across the image, where even small movements can suffice to cause this linear trend. Attempts at de-trending have provided some insights into the

light curve's feasibility.

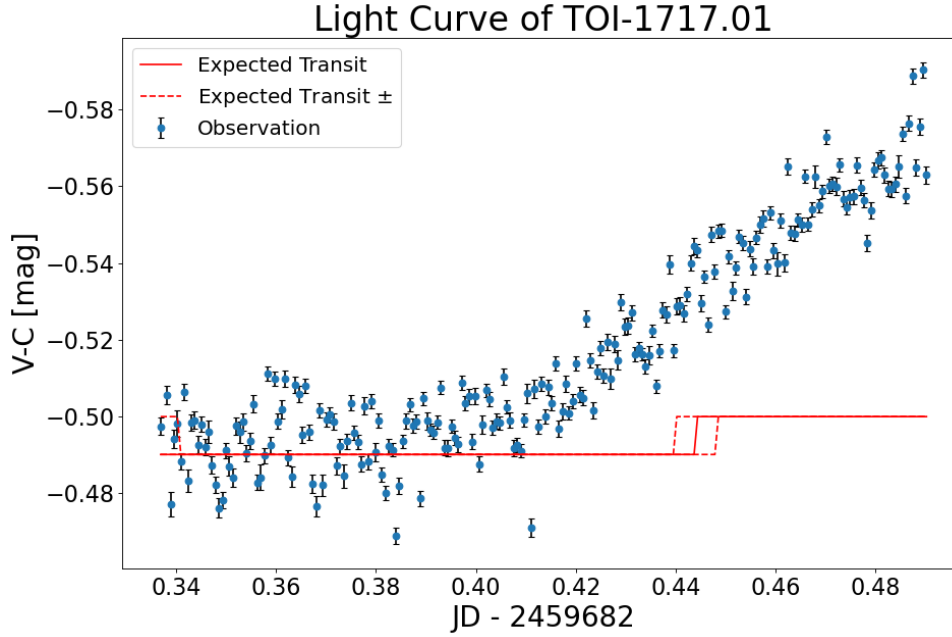


Figure 21: Generated light curve of *TOI-1717.01*

Once again, we are confronted with a problem of transit identification that is founded in the lack of accuracy, plus a higher dispersion than reflected in the data. The fact that we are dealing with a very accurate measurement from the sample of observation nights could give a boost in plausibility, but that cannot be founded on more than intuition as opposed to scientific evidence. Again, the systematics of the observation are not necessarily of a linear nature and could therefore be more complicated than the correction that was applied here. If one is to grant the partially de-trended light curve in Figure 23c some more feasibility, the measured transit depth would be somewhere around 0.02 mag, which is about double the expected value. This would either imply a higher planetary radius or further systematics left in the dataset, which is rather difficult to pinpoint, especially if a partial de-trending was undertaken.

The question of an off-target signal that could possibly resemble the measured transit light curve of the target needs to be answered as well. From the reference stars used to generate the target curve, another light curve for the purpose of comparing the systematics has been created. Figure 24b shows the result for that calculation, which resembles the original light curve to a certain extent. The linear trend towards the end of Figure 21 is not present in the off-target graph, which is probably due to the fact that most of the reference stars are relatively close together (see Fig. 22). Four of the reference stars are almost vertically aligned and therefore likely exposed to similar systematics, since those increase radially from the centre outwards. That means that for the off-target graph the differences in brightness for the reference stars stayed roughly the same (as opposed to the target light curve), except for the little jump at the end of Figure 24b. That shape resembles the egress that is supposed to be visible for the actual

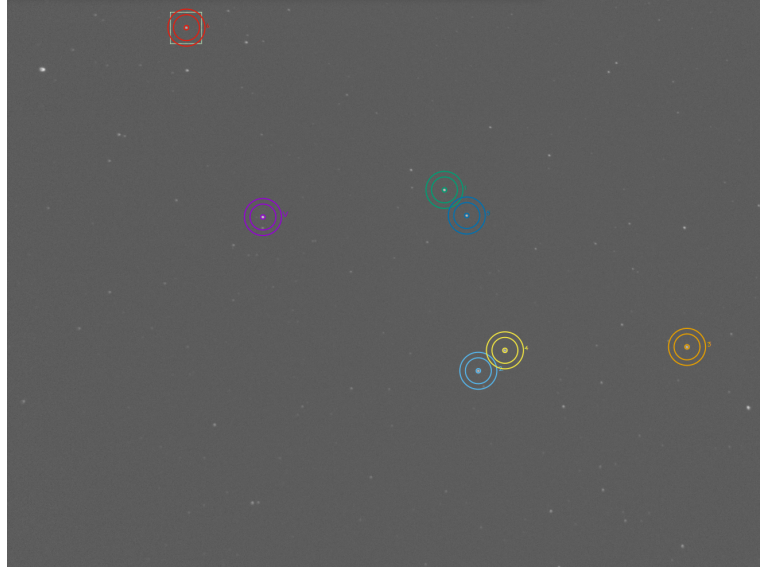


Figure 22: The applied aperture photometry on *TOI-1717.01* (violet) with the reference stars

target - even the depth of that "egress" looks very similar to the one in Figure 23c. The issue here is that there is an egress visible where there should be none, taking away legitimacy from the original curve, since it was believed to have a similar feature after de-trending. The notion that the off-target feature also exists in the original data is now difficult to ignore and highly likely.

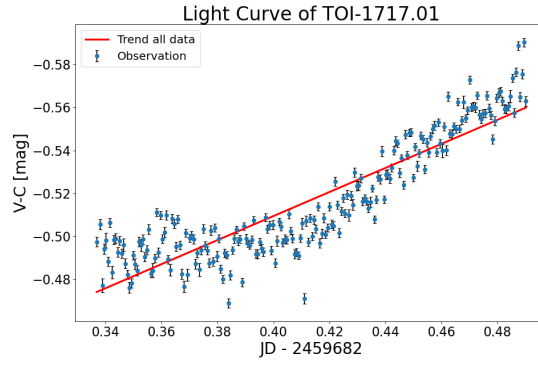
The dataset here was also stacked with a binning of 2, which doubled the effective integration time from 30s to 60s, as can be seen in Figure 24a. The stacking of images however, did not result in essential differences regarding the light curve shape and therefore would still result in a similar theoretical ΔF value.

The values for the airmass are low and relatively close to 1 ($X = 1$ at $h = 90^\circ$) and therefore probably do not affect the quality of the data dramatically. The upload to the *ETD* was however not successful in this case either.

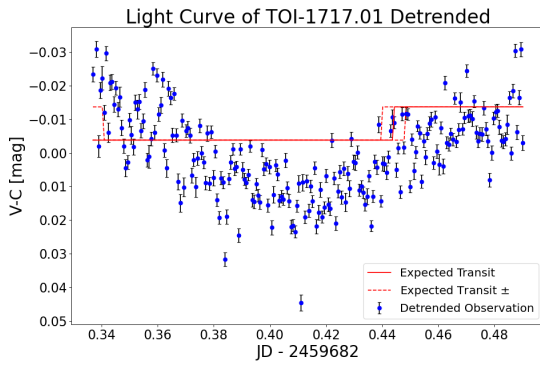
The last three observations described here have one thing in common, namely the linear trend that is ingrained in the second half of the light curve. There are more observations with this phenomenon, namely the second observation of *TOI-1273.01* (see appendix A.1) and the test observation of *HD 189733 b*. The latter will be discussed in section 6.5.

6.4. TOI-1371.01

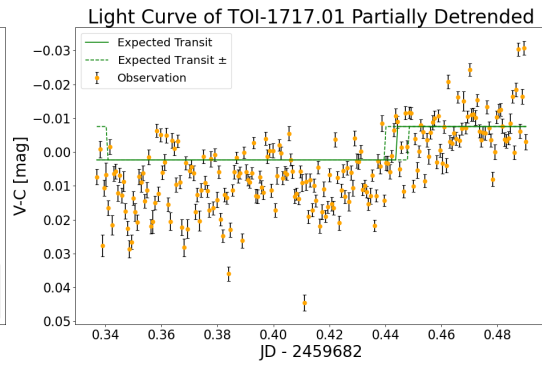
Another observation with good σ values relative to the target's transit depth is *TOI-1371.01*. This is the first observation discussed in further detail that was observed with the *Sony $\alpha 7 III$* camera. The observation night was on the 12th June 2022 - a night with cloud streaks and other disturbances, such as strong moon light (see Table 15) and an observation start far in the East, located within the city of Vienna's dome of light pollution. These are quite difficult conditions to work with, especially considering the background noise caused by them.



(a) Linear trend/fit used to de-trend *TOI-1717.01*'s light curve

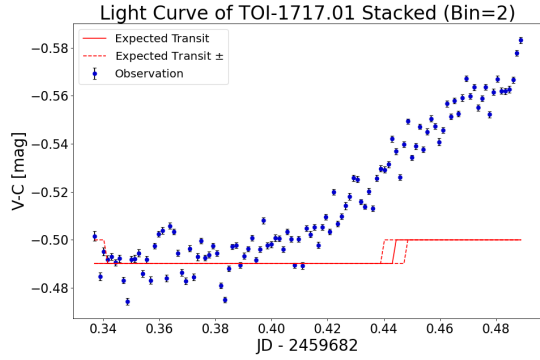


(b) De-trended light curve of *TOI-1717.01* with the whole data trend

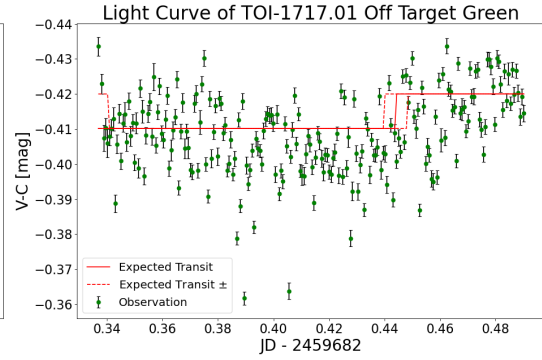


(c) Partially de-trended light curve of *TOI-1717.01* with the two small trends

Figure 23: Linear trends in *TOI-1717.01*'s light curve, totally and partially de-trended



(a) Stacked light curve of *TOI-1717.01* with bin=2



(b) Off target light curve of *TOI-1717.01*

Figure 24: Stacked light curve of *TOI-1717.01* and an off-target light curve

In analysis sessions after the observation, the advantage of this night was the new detector (camera) that was used for the first time and therefore the focus settings were not executed as

TOI ID	V [mag]	ΔF [mag]	σ_i	σ_m	σ_e	A	FWHM [px]	R
TOI-1371.01	10.357	0.01562	0.014221	0.008655	0.010851	0.020590	18.516	0.825
TOI ID	B	SNR [dB]	X_{min}	X_{max}	Moon	A/B	Spec. Type	
TOI-1371.01	0.004240	24.906	1.116	1.932	44.023	4.857	F0 D	

Table 15: Most relevant values of the *TOI-1371.01* observation

precisely as they could have been. This can be considered a positive development in a way, since some of the henceforth following observations turned out to be over-exposed due to better focus.

The stellar magnitude of $V = 10.357$ is dimmer than the average brightness of targets, which is another additional challenge to the measurement accuracy. The crucial factor for giving this candidate gravity within the sample is the largest transit depth of the measured *TOIs*. This fact is also the reason why the accuracy of its measurement can appear quite high - when in reality the σ values are slightly below average, but are quite good when related to the planetary candidate's ΔF value.

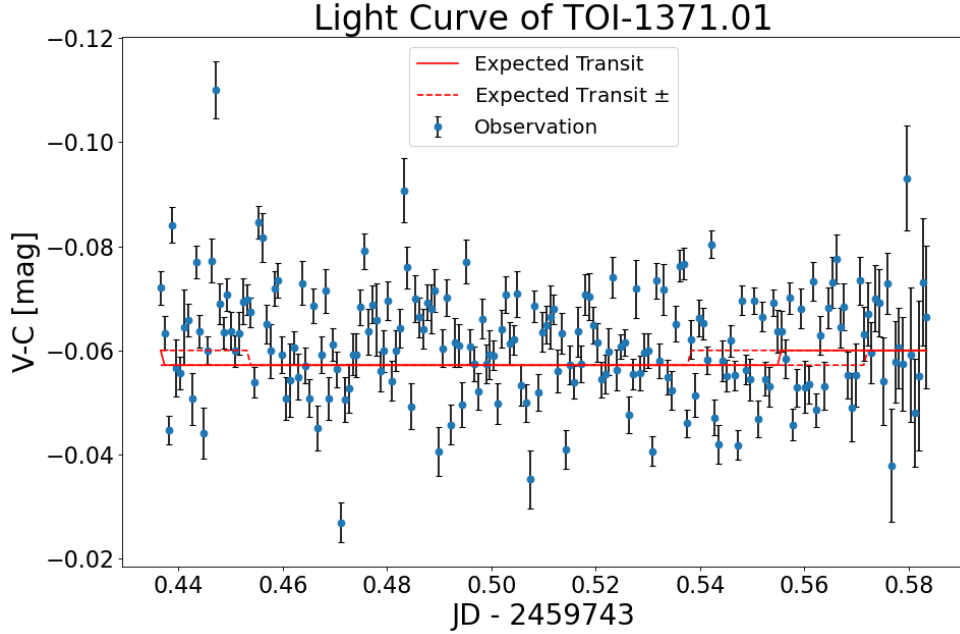
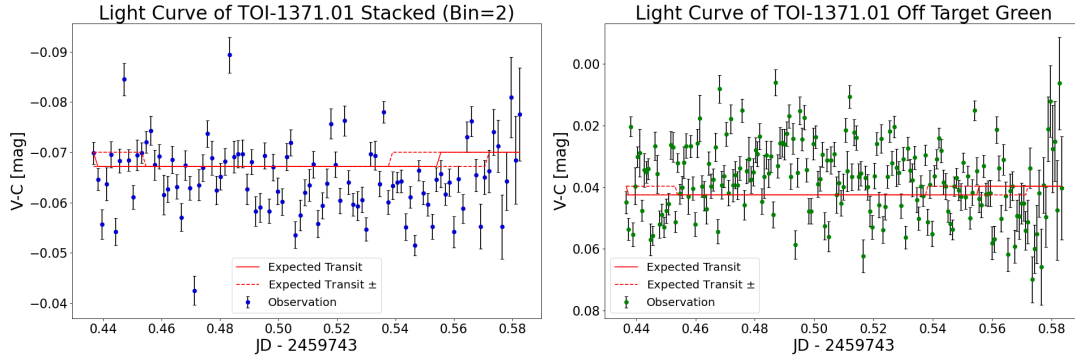


Figure 25: Generated light curve of TOI-1371.01

Regarding the observation times, measurements took place during the expected mid-transit and egress - the values for the median and standard deviation of the ingress are calculated with data points within the ephemerides' uncertainty, since the observation starts exactly at the time of the expected ingress.

As can be seen in Figure 25, the distribution of values is a lot higher than the transit depth. All three σ values are actually smaller than ΔF , but when inspecting the graph, one can see that

the data points are highly distributed, which makes the standard deviation values unreliable indicators of the actual dispersion. If one were to search for a transit shape in this light curve one would have a hard time finding it due to the dispersion - it is practically impossible. The reasons for that seem to be diverse - the median FWHM of this observation is by far the highest of the observations discussed so far - which can be traced back to the defocussed image on the one hand but possibly also due to the weather conditions and likely unfavourable seeing conditions of the night. The focus of this observation is not "worse" or more defocussed than *TOI-5279.01* and therefore the weather conditions are very likely playing a meaningful role. The roundness R of the observation is on the higher end of observations, which is probably also due to the focus condition.



(a) Stacked light curve of *TOI-1371.01* with bin=2

(b) Off target light curve of *TOI-1371.01*

Figure 26: Stacked light curve of *TOI-1371.01* and an off-target light curve

Another indicator for a deficient observation night is the S/N ratio of 24.906 which is one of the lower values of all measurements and definitely the lowest of the ones discussed in detail. The airmass of the observation starts off rather high, since the time series was initiated at a low height (high zenith distance) in the East at $X = 1.932$, which is another problematic factor for photometry. The distance to the zenith reduced over the course of the night and reached the lowest point at the end, which resulted in an airmass of 1.116. The moon's influence however, was rather strong since its phase was close to a full moon. All these factors, strong moon, start of observation in the East with most light pollution exposure, initial low height (high airmass) cause a high background value B - which leads us to the last variable, namely A/B . This indicator is actually the lowest of all observations (see Table 9) which shows that the B here is actually the highest relative to the PSF function's amplitude A in the whole dataset. One can relatively safely conclude that the background noise in this data sample is likely too high and thereby make accurate transit measurements difficult, even though we are dealing with a relatively "comfortable" ΔF .

In Figure 26b another off-target image from photometric measurements with the reference stars of *TOI-1371.01*'s light curve has been generated. This kind of measurement would be essential in the case of a light curve measurement that resembles a transit. The data points of the target light curve here are distributed in a way that an ingress or egress are impossible to discern, which makes the off-target light curve obsolete. The data in Figure 25 is evenly

Planet	V [mag]	ΔF [mag]	σ_i	σ_m	σ_e	A	FWHM [px]	R
WASP-33 b	8.300	0.01510	0.006913	0.009669	-	0.305276	6.804	0.922
Planet	B	SNR [dB]	X_{min}	X_{max}	Moon	A/B	Spec. Type	
WASP-33 b	0.000917	31.999	1.148	1.693	23.705	333.086	A5m	

Table 16: Most relevant values of the *WASP-33 b* observation (from the stacked images)

scattered around a certain y-value but does not exhibit any significant change in brightness. Similarly, not much is happening in the off-target curve, which looks rather similar, with larger error bars at the end of the observation due to sunrise setting in. The only anomaly here is a small bump/peak around the time where the target exoplanetary candidate would experience mid-transit - a feature that is non-existent in the actual *TOI* light curve. Thus, one has to conclude that the light curves discussed for this candidate are nondescript regarding a transit. Finally, a last attempt at detecting something can be made by stacking the images with a binning of 2 and see if that changes anything in the outcome. As Figure 26a shows, the high scattering of data has reduced, but that can still not compensate for the lack of a visible transit. The high distribution of data points is most probably caused by *B*. Looking at Figure 15 alone, the magnitude of about 10.4 mag and the closeness to a full moon (50%) imply a photometric accuracy of likely more than 3% (2.12% for 30s exposure, without increase in background noise), which is far too little when confronted with a transit depth of 1.428%.

An investigation into a transit in the data with the tools of the *ETD* remained futile.

6.5. WASP-33 b and HD 189733 b

The final two observations were undertaken in order to test the capabilities of the optical system with the *Meade* telescope and the *Sony* camera regarding stars with higher brightness and transit depth. Both stars, *WASP-33* and *HD 189733*, are much brighter than the average *TOI* in our data sample - with 8.3 and 7.67 mag (*V*), respectively.

As can be seen in Table 16, the transit depth ΔF is very similar to the one of *TOI-1371.01*, in fact it is slightly lower. The brightness however, is significantly (~ 2 mag) higher and was therefore believed to possibly make the difference when it comes to a transit detection. The observation took place on the 4th August 2022, on a day with very clear weather conditions - and therefore an auspicious night for detecting a transit. The factor of weather and the stellar magnitude make the requirement of test observations before the actual time-series all the more important. Five different integration times were tested with three frames each for checking the saturation levels. After having set up the *Meade* telescope, these exposures were shot and the resulting test-frames checked in *Siril* - with the result that the exposures with the shortest tested time were the only ones without excessive saturation. These were taken at 5s and thus, 10 exposures per minute (5s exposure + 1s interval) were taken over the length of the planned observation. That night, the moon phase was at 23.7% (see Table 16), which means that a half waxing moon was illuminating the night sky. Considering *WASP-33*'s magnitude and the lunar phase, we can estimate the resulting photometric accuracy to being close to 0.2% (see Figure 15, 0.14% for 30s), which would be enough to measure the transit.

An advantage given by the short exposure images that were taken in this case is the influence

of dark current, which is higher the longer the exposure (Howell (2006), Gary (2010)). The disadvantages of such short exposures can be found in higher scintillation noise. Regarding the data handling, short exposures result in large bulks of data which can be tedious. The solution for that issue was to stack the images with a written *Python* script up to an integration time of 50s, which is equivalent to a binning of 10 images. The summation of images comes with the advantage that the S/N ratio is increased by $S/N \propto \sqrt{t_{exp}}$ (Howell, 2006) and therefore the image quality, photometric accuracy and the likelihood of detecting a transit increases, especially with a binning of 10.

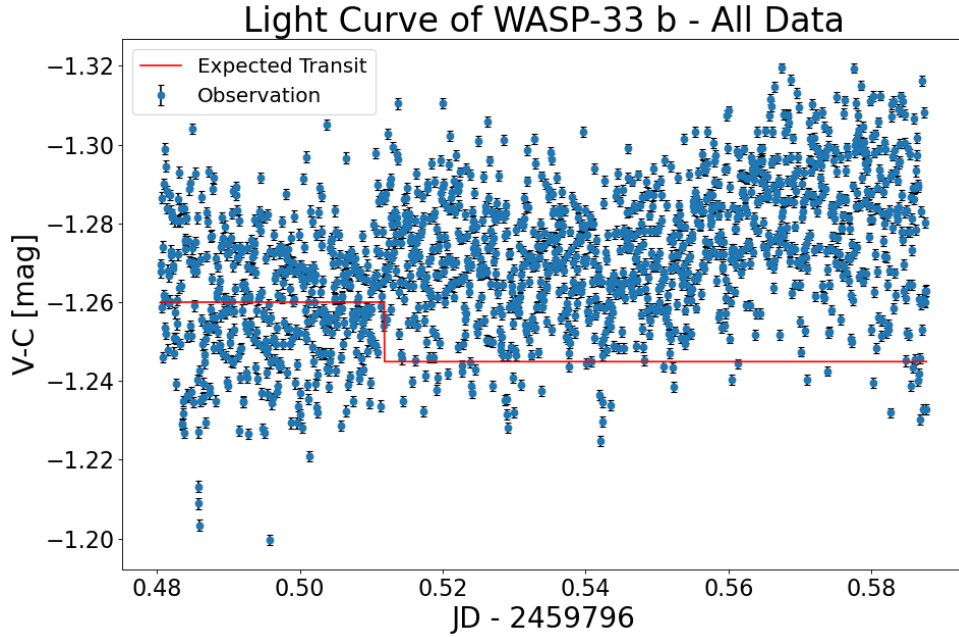


Figure 27: Generated light curve of WASP-33b with 5s exposure

The FWHM and roundness values for this observation session are some of the best of all here attempted planetary measurements - the roundness is in fact the best at a median of 0.922. These values speak for the good observing conditions that day, for the polar alignment and therefore the good stellar tracking. The listed data in Table 16 was extracted from the analysed stacked images, which also increased the value of roundness (original value: 0.885). The good roundness values are not an indicator for defocussing this time, since the focussing procedure was familiar - the FWHM value is also low, which could affirm the supposition of a good focus. Further indicators of quality are the S/N ratio and the A/B values which are clearly much higher than any other observation up to this point (see Table 8 and 9), with $SNR \approx 32$ and $A/B \approx 333$. These attributes can be traced back to the magnitude of the star and the stacking of the frames to a 50s exposure - which adds to the overall signal.

The airmass at the beginning of the observation was relatively high and at its maximum with $X_{max} = 1.693$, which is equivalent to a height of $h = 36.2^\circ$. Incidentally, this was relatively far in the East, which is yet again a position that is highly influenced by the city lights and therefore

influences the photometric accuracy. Towards the end of the measurement the airmass reached a minimal level of $X_{min} = 1.148$, which means that the target moved upwards (regarding height) and towards the South, thereby removing itself from strong light pollution but also from too much atmospheric influence.

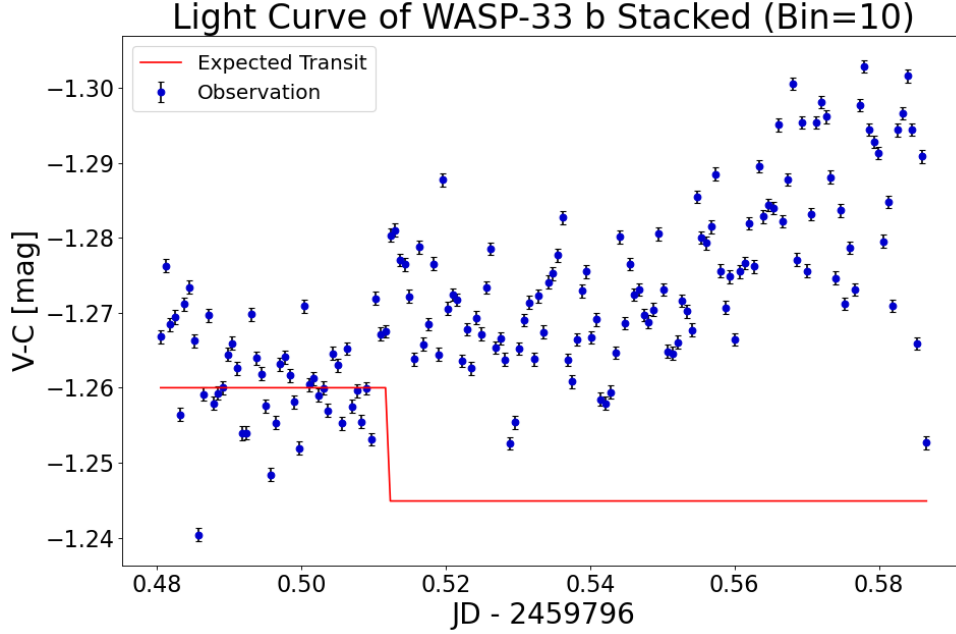


Figure 28: Stacked light curve of *WASP-33 b* with bin=10

When comparing the σ values of the light curve to the anticipated transit depth, the standard deviations clearly represent a value that is about half of ΔF . These are however the values calculated for the stacked light curve with a binning of 10; the original 5s exposure gives us a value of $\sigma_i = 0.021115$ for the ingress and $\sigma_m = 0.015885$ for mid-transit. This difference in dispersion can be seen distinctly when comparing the two light curves (Figure 27 and 28). The root of this effect in data point distribution can be found in the integration time, which is too small at 5s to overcome atmospheric turbulence, seeing, scintillation and other systematics (see more in the discussion in chapter 7, Beck et al. (2019), Gary (2010)).

Figure 28 shows how compact a 50s exposure time makes the light curve, at least compared to the original measurements. When it comes to the expectations for this observation, the distribution of data in the graph was hoped to be less and a semblance of a transit shape were thought to appear. However, the latter was not the case - the dispersion of the light curve would have been enough to make a $\Delta F = 1.38\%$ transit depth noticeable, but instead we are left with some systematic and seemingly periodic signal that appears to induce an increase in brightness in two steps. The previously mentioned photometric accuracy of $0.14 - 0.2\%$ seems to be in the right order of magnitude, when looking at the light curve. This shape of light curve can already be recognized in the original data in Figure 27, which means that the signal that causes this shape is likely not due to scintillation or seeing. The moon as a source of disturbance seems

unlikely as well, since the lunar signal would likely manifest itself with a smoother feature and not with rather abrupt steps. A feasible theory would be light pollution - but not any, since the characteristics of a constant light dome over the Eastern part of the sky from the Kuffner Observatory would be similar to the moon. Possibly an event or source with a fluctuating signal could have influenced the background of the star, thereby being the cause of this phenomenon.

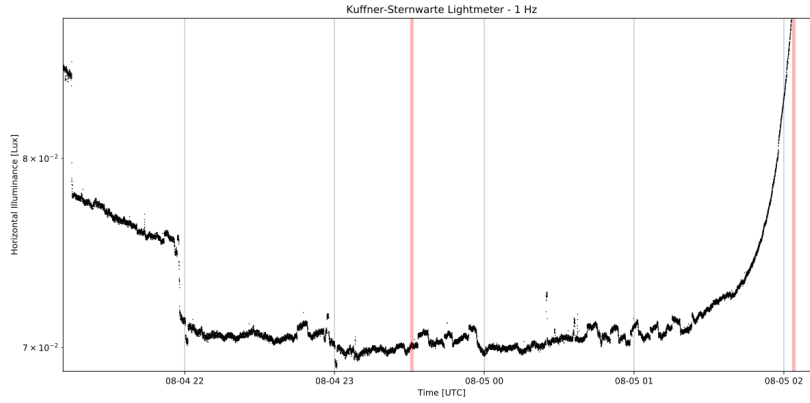


Figure 29: Sky background/illumination measurements on 04/08/2022 using a lightmeter on the Kuffner Observatory's roof (Credit: Günther Wuchterl)

Measurements of a lightmeter situated on the Kuffner Observatory's roof could confirm some recurring, unidentified signal in the sky (see Figure 29). The red vertical lines in that graph illustrate the beginning and end for the here described measurements of *WASP-33 b*. However, the periodically occurring fluctuations of the sky are at a different time scale than the systematics in Figure 28. Another explanation could be - yet again - the movement of the star across the detector, that could cause the differently illuminated parts of the telescope aperture to result in different "relative magnitudes" as mentioned earlier. However, the pointing drift of this observation session is not as strong as during the other nights, which raises doubts about that theory.

An attempt at de-trending the outcome of the stacked images was undertaken, since the possibility of a "hidden" transit in the data points was suspected (see Figure 30). However, this linear trend that was subtracted from the dataset resulted in an inconclusive light curve (Figure 30b), where a reduction in brightness within the range of the transit depth is visible. This reduction takes place at a later point than expected (red line) and also rises back to the previous level before the end of the observation and can therefore not be allocated to a transit.

Another aspect that is interesting about the star *WASP-33* is its variability. It belongs to the δ Scuti variable stars, that generally exhibit a varying amplitude and period - in this case however, the frequency of variability is in the range of ~ 20 -30 cycles per day (about once every hour) and an amplitude of about 1 mmag (von Essen et al., 2014). The period of the brightness fluctuations would actually affect the time scale of measurements applied here. Nevertheless,

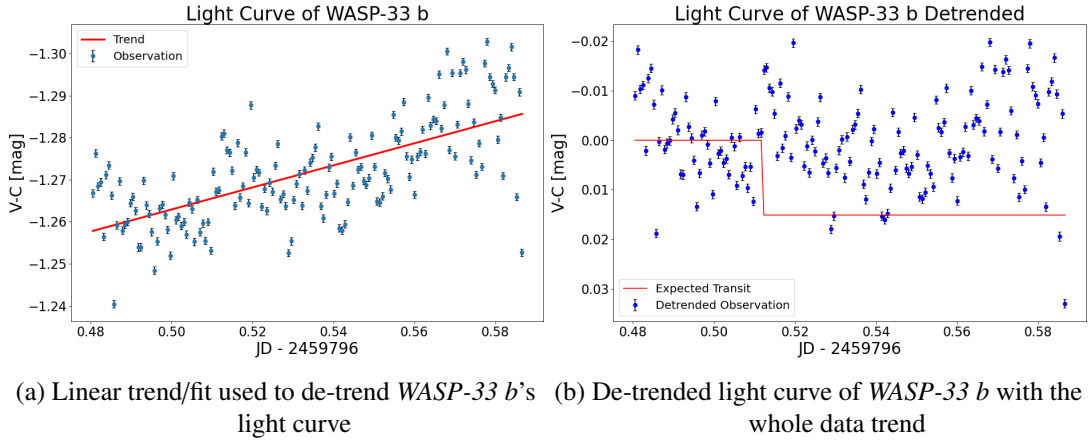


Figure 30: Linear trend and de-trended light curve of WASP-33 b

the brightness variations themselves should not be too impactful, since 1 mmag is small enough not to change the ΔF of ~ 15 mmag substantially. The variability amplitude could however influence shape of the transit and could induce some additional systematics.

The second observation for the purpose of testing took place on the 9th August 2022, where a star in the Vulpecula constellation, *HD 189733*, was observed. This is a K-type star, the latest spectral type that was investigated during this campaign. Its transit possesses attributes that are even more "extreme" than the ones of WASP-33. The star is very bright with 7.67 mag, which is not yet visible with the naked eye, at least under Viennese observing conditions, but yet again almost 1 mag brighter than the last target. On the other hand, the transit depth is also by far the highest with 0.0282 mag (2.564 %), which is almost double the value of WASP-33 b. The stellar magnitude made halving the exposure time of the science frames a logical conclusion, a notion that was confirmed with the test images that were taken before the time-series. The chosen integration time of 2s per image resulted in a total number of 4661 pictures during a course of almost 4 hours of observation time (see number of data points in Figure 31). The weather conditions during that summer night were not as favourable as the previous one - a slight haziness was noticeable, while some strong gusts of wind blew over the observatory on occasion. Wind can cause movements and vibrations of the telescope during the observation and thereby reduce the essential image quality (especially FWHM and roundness). The moon was positioned very low - close to the horizon and to the South, while the observation started in the South-West. The lunar phase was a waxing crescent, close to a half illuminated moon and set at approximately 00:00 UTC, which was 1.5 hours before the observation ended. Therefore, the moon's influence can only be considered for the first ~ 2.5 hours, but due to its low positioning it was likely less than usual. In that time, the photometric accuracy could be at worst around 0.15% (0.11% for 30s), considering the fact that *HD 189733* is very bright (7.67 mag) and therefore compensating for the disrupting influence of the moon (see Fig. 15).

As practised before, the most important parameters of the observation night are listed in a small table - in this case Table 17. It should be noted, that the σ values apply to the green

Planet	V [mag]	ΔF [mag]	σ_i	σ_m	σ_e	A	FWHM [px]	R
HD 189733 b	7.670	0.02820	0.006248	0.006069	0.007101	0.700712	6.841	0.866
Planet	B	SNR [dB]	X_{min}	X_{max}	Moon	A/B	Spec. Type	
HD 189733 b	0.001365	33.543	1.204	1.593	40.637	513.338	K2V C	

Table 17: Most relevant values of the *HD 189733 b* observation (from the stacked images)

channel measurements, which was the case for all other observations discussed in detail as well - but is important to note at this point, since the other channels were also analysed in this case. The values listed here are determined from a binned dataset, where every 25 images were stacked to create 187 total frames with an integration time of 50s each. The resulting qualitative indicators of the S/N ratio and the ratio of amplitude and background (A/B) are the highest of all observations during this campaign with 33.543 dB and 513.338 respectively. The FWHM and roundness of the observation are likewise one of the best values, though very similar and yet slightly lower than the one of the previous observation. The reason could be in the comparable method of stacking the images for data analysis, where short exposures could be less susceptible to vibrations caused by the telescope surroundings or tracking motor imperfections. At the same time, the stacking of images causes the erroneous or smeared stellar images to be mixed with good ones, which generally gives the final star image an overall round shape.

During the process of stacking, the maximal possible value for photometry implemented in *Siril* is $2^{16} - 1 = 65535$, since the photometry tool has been programmed for 16 bit images. This had to be taken into consideration when the maximal values of the star were added up to reach a $\sim 25\times$ higher value than the 2s exposure. Since the value would have overshoot the limit, the stacking process had to be scaled to reach maximal values below the 16-bit maximum.

The values for the airmass increased over the course of the observation, as the height from the horizon decreased from $\sim 36^\circ$ to $\sim 39^\circ$. Starting from about 1.2 as the initial airmass and reaching a maximum of almost 1.6, the influence on the dataset could be a factor towards the end of the observation.

The photometric accuracy of 0.1 – 0.15% due to the lunar phase (as mentioned earlier) seems plausible when looking at the dispersion of the data. When comparing the standard deviations of the light curves at the three points (ingress, mid-transit, egress), all three of them are clearly below ΔF . In fact, at mid-transit the dispersion reaches a level of $\Delta F \approx 4.65 \cdot \sigma_m$ and at egress the dispersion is about 3.97 times smaller than the transit depth. These values imply very favourable circumstances for actually being able to recognize a transit, which is clearly the case looking at Figure 31 and the figures 32, 33a and 33b.

An exciting side-note to the detection of the transit is that the 2s exposures were already enough to actually measure a difference in brightness of the star - which shows how strong the signal - both of star and transit - actually is. The scintillation, the lunar and light pollution influence and other aspects of the night sky from a ground-based perspective were smaller in magnitude at this integration time than the transit depth of *HD 189733 b*! Since the images had to undergo demosaicing, the transit would have to be visible in all three channels of the image (RGB) - which is clearly the case when looking at the respective light curves (Figure 32, 33a and 33b). All three graphs exhibit a similar transit shape, depth and a common feature towards

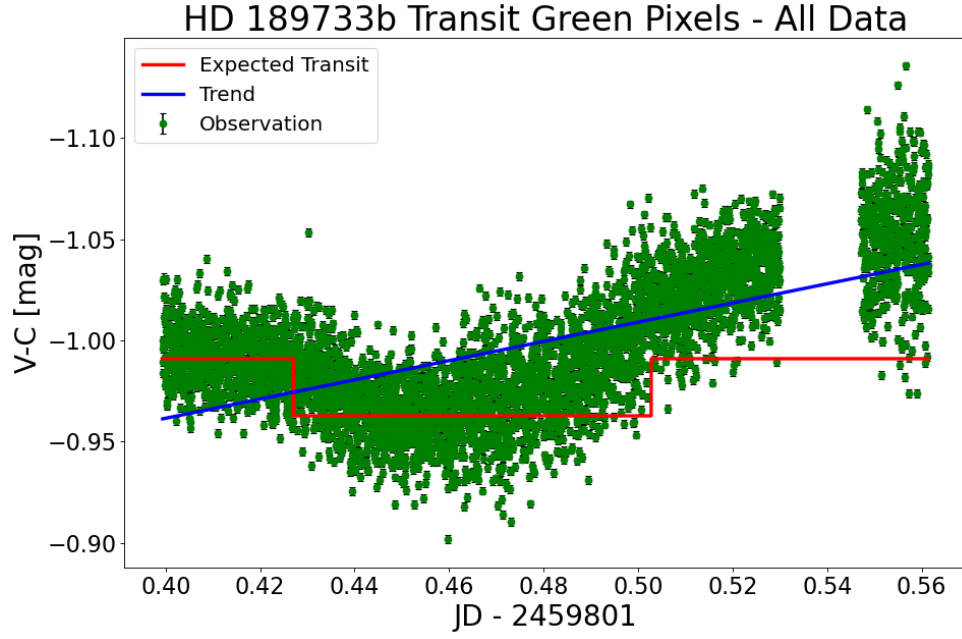


Figure 31: Generated light curve of HD 189733b with 2s exposure

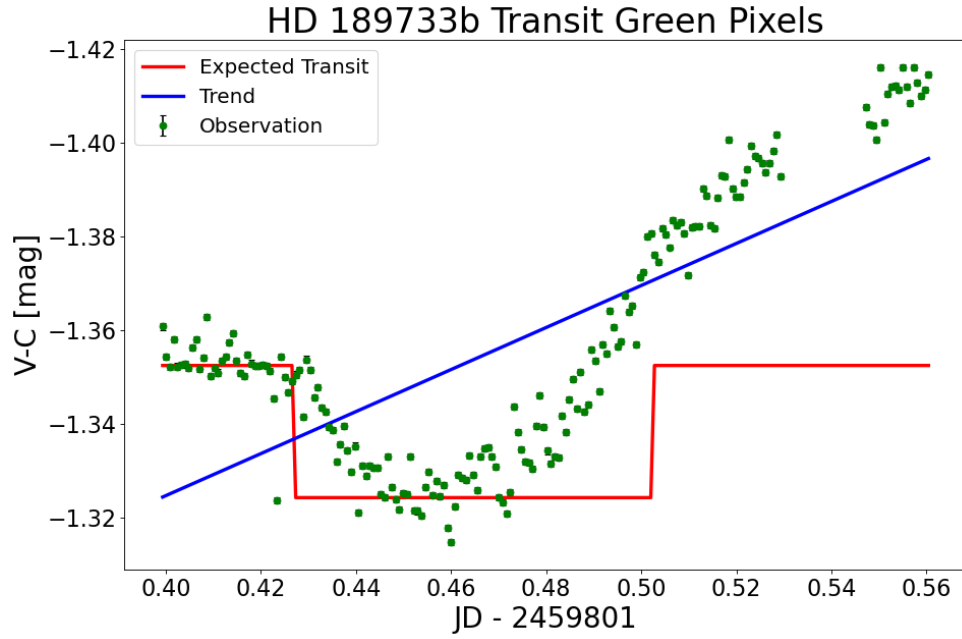


Figure 32: Stacked light curve of *HD 189733 b* with 50s exposure, green pixels

the end of the observation. This feature established itself in the form of a linear increase in

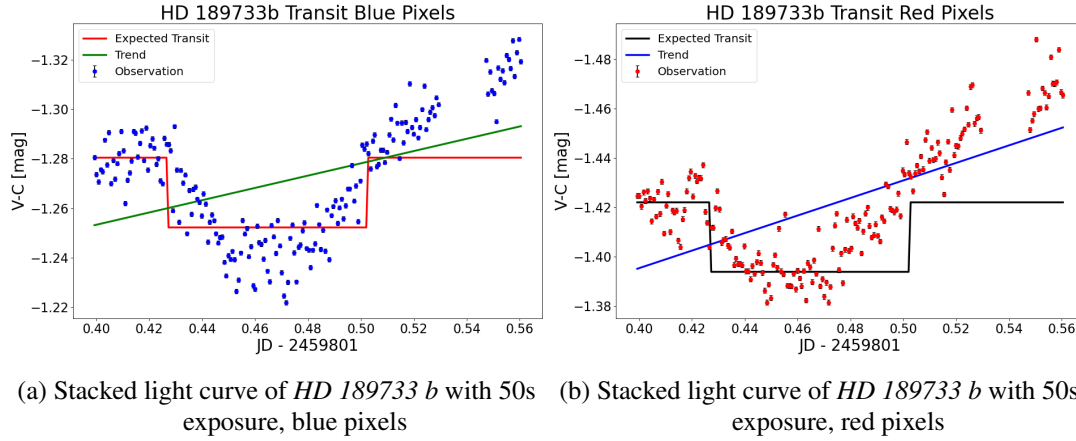


Figure 33: Stacked light curve of *HD 189733 b* with 50s exposure, red and blue pixels

brightness within the egress. The overall linear trend of the respective light curves has been plotted as a blue or green line in the figures. The strongest feature is visible in the green curve. The origin of this trend could - to a very small degree - be due to the increasing airmass, but is more likely due to the star's movement across the image, since the polar alignment did not go according to plan. When looking at the science frames a clear movement of the star from the image center towards the bottom right can be seen, which not only exposes the star and its reference stars to different elements or sections of the flat-field image but also to the image curvature, as mentioned in other cases as well. At the same time, this observation also exhibits a strong field rotation, which has a similar effect on the target as the axial pointing variation. The reason for that lies in an imperfect alignment of the polar height, causing an effect more common to alt-azimuth mountings.

Before one can analyse the produced light curves in more detail, a confirmation of the apparent transit signal would be required. One way of achieving that goal is to use the same reference stars of the photometric calculation to create an "off-target" light curve. Since the transit signal is measurable in all three colour channels (RGB), the off-target-check will have to be executed analogously. In Figure 34 all three channels exhibit a similar scatter plot image, which is the result of differential photometry applied to the first comparison star with the same reference stars as used before. That means the first reference star of *HD 189733* is now considered to be the variable star and the remaining stars still as reference stars. The similarity of the light curves in all three channels is a very good sign - but the even more important information extracted from these plots is the lack of a transit feature. This implies that the dip in brightness is exclusive to the target object.

Following the successful production of light curves, they were subsequently subjected to two de-trending processes: One within the confines of a *Python*-script and another by fitting the data in the plotting/fitting tool of the *Exoplanet Transit Database (ETD)*.

The linear trends identified in the figures 32, 33a and 33b were subtracted in *Python* either from the whole dataset or just partially. Since the trend in the data that specifically causes the egress to slope upwards seems to start somewhere around mid-transit, the partial de-trending

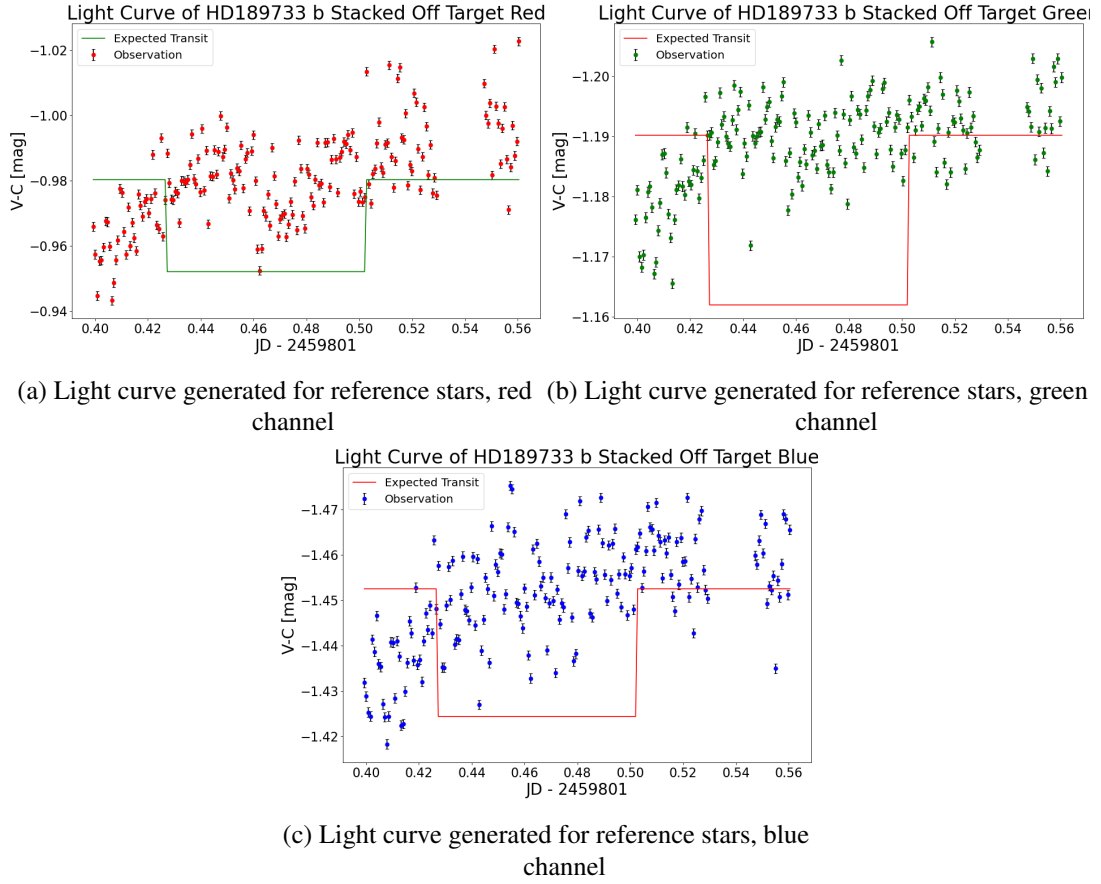
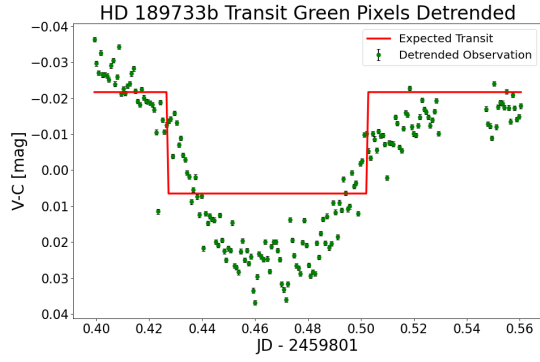


Figure 34: Light curve generated for *HD 189733*'s reference stars (off target), for RGB

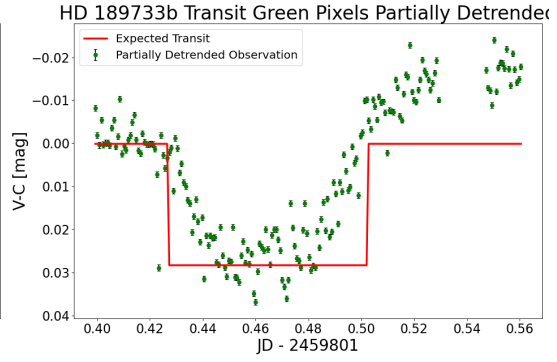
applied the same trend only to the second half of the data points. In Figure 35, all three colour channels are either fully or partially de-trended, with different outcomes each. Estimates of what the transit depths could be for the different colour channels can be found in Table 18.

As can be seen in that table, the values for ΔF tend towards larger values than the expected 0.0282. For the fully de-trended data, the depth is much higher than the partially corrected data set. The reason for that is that the first half of the observation is still exposed to "normal" circumstances with weaker image curvature, which causes a stronger distortion that cannot fully be removed by the here applied fit. A reason why the trend in the green channel is more sloped than the other two colours could be due to the amount of green pixels, which is the same as red and blue pixels together. That might cause the slope in G to be steeper, since the deviation of the de-focussing effect of image curvature from centre to periphery could be stronger. The most accurate values in Table 18, when comparing the expected transit depth to the data can be found in the partial de-trending of the red and green channel.

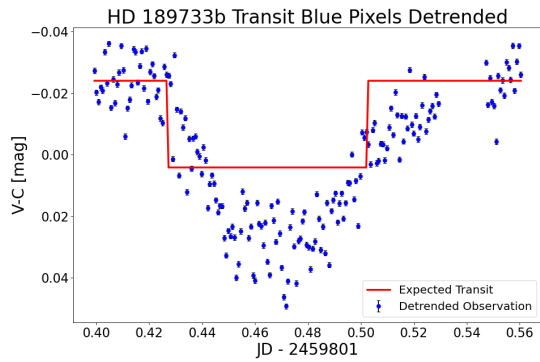
The second method involved uploading the transit data acquired from *Siril* as a .csv-file to *ETD* and fitting the light curve. This was done yet again with all three colour channels.



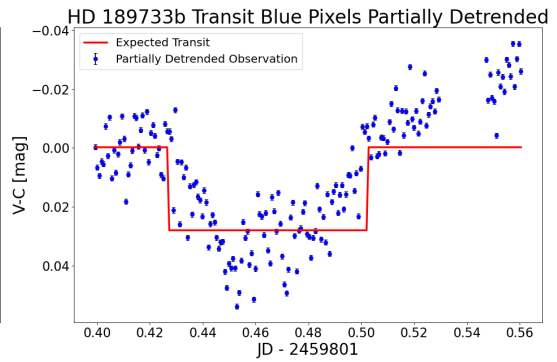
(a) Whole light curve of *HD189733 b* de-trended, green pixels



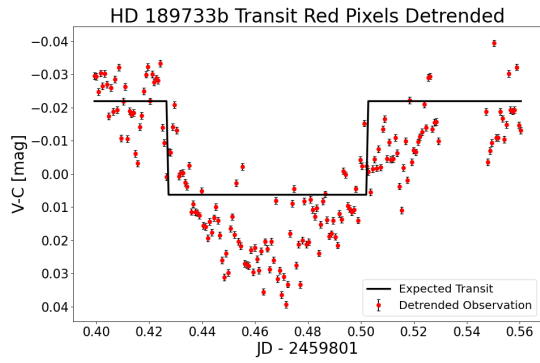
(b) Second half of light curve of *HD189733 b* de-trended, green pixels



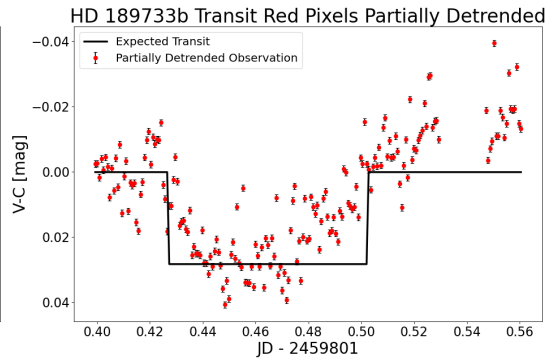
(c) Whole light curve of *HD189733 b* de-trended, blue pixels



(d) Second half of light curve of *HD189733 b* de-trended, blue pixels



(e) Whole light curve of *HD189733 b* de-trended, red pixels



(f) Second half of light curve of *HD189733 b* de-trended, red pixels

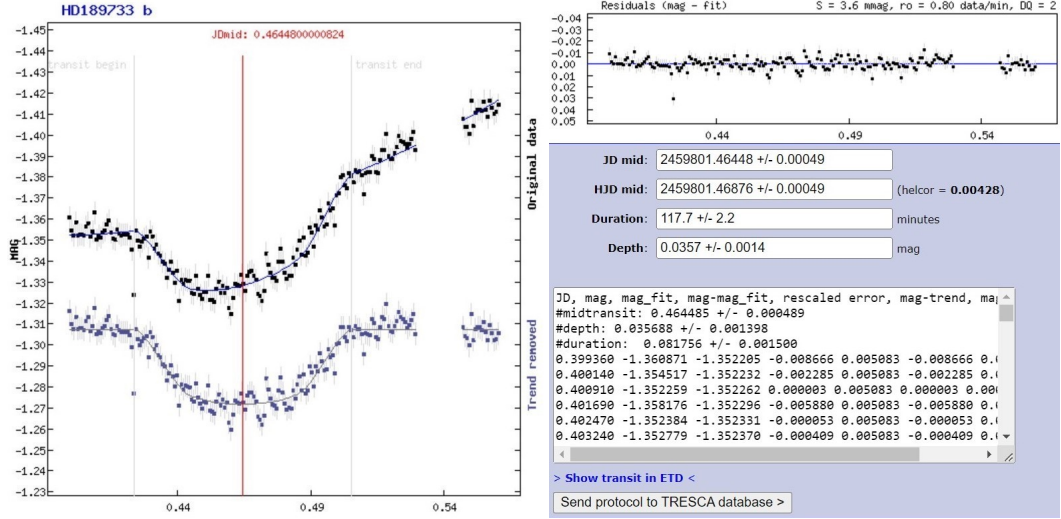
Figure 35: Whole and second half of light curve of *HD189733 b* de-trended; green, blue and red pixels

Before uploading the data file, one has to select the star's name on the *ETD* interface. Then,

⁶⁹see footnote 7

De-trended	ΔF_R [mag]	ΔF_G [mag]	ΔF_B [mag]
Fully	0.030 - 0.040	0.037 - 0.045	0.045 - 0.052
Partially	0.028 - 0.038	0.027 - 0.042	0.030 - 0.040

Table 18: The estimated transit depths for the fully and partially de-trended light curves of *HD 189733 b* in all three channels (RGB, de-trending with *Python*)



(a) Light curve of *HD 189733 b* in the ETD, green pixels, bottom: de-trended (b) Residuals of the fit and the resulting transit duration and depth, green pixels

Figure 36: The fitting process for *HD 189733 b* in the *Exoplanet Transit Database (ETD)* with results, green channel ⁶⁹

as one implements the data fit in the next step, some stellar and planetary parameters are assumed as an initial condition by the fitting tool. These are predicted parameters of the mid-transit (2459801.461 HJD, which is 2459801.46528 JD or 09/08/2022 23:10 UTC, see Table 6), the transit duration of 109.6 minutes, the planet radius of $0.148 R_{\star}$, the impact parameter b of 0.680 and a limb darkening factor of 0.5.

The *ETD* can apply up to three algorithms to remove systematic errors, out of which all three were applied for the de-trending here. These are: "zero power", a vertical fit to the observed data, "linear function", a correction of linear trends in the data and "square power", a parabolic fit to remove other systematics ⁷⁰. The exact procedure of the model-fitting of the data is described by Poddaný et al. (2010), where the correction function is elaborated in detail. The function includes the impact parameter b , as well as three variables A , B and C , that describe the zero-point shift, the linear and quadratic systematic errors as mentioned before (Poddaný

⁷⁰see footnote 7

et al., 2010). Limb darkening is included by a linear law, the relative flux function is employed according to Mandel and Agol (2002). The *ETD* data fit function also implements a Levenberg-Marquardt non-linear least squares fitting algorithm from Press et al. (1992) (Poddaný et al., 2010).

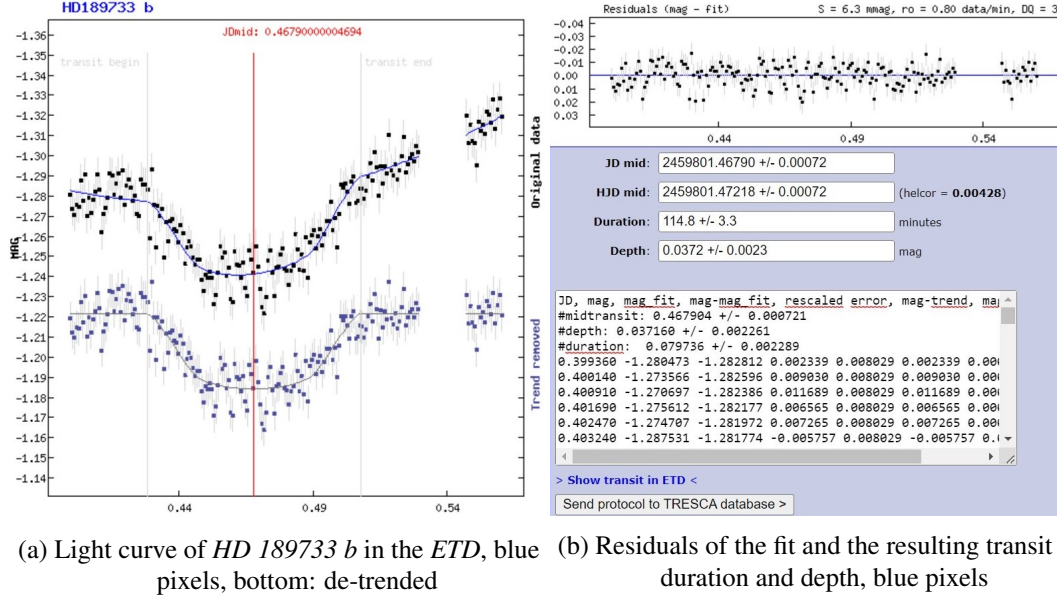


Figure 37: The fitting process for *HD 189733 b* in the *Exoplanet Transit Database (ETD)* with results, blue channel ⁷¹

As can be seen in the Figures 36 - 38, the implemented algorithm of the *ETD* de-trends the light curve to an extent, where the slope is no longer visible. This was not achieved before in the light curves in Figure 35, where the fitting process was insufficient to do so. The fit output, as seen in Figures 36 - 38 includes the calculated mid-transit, the transit duration and the transit depth. These parameters have been listed for all three color channels with the expected values as comparison in Table 19. The graphs in the Figures 36a, 37a and 38a include both light curves, original and de-trended with the mid-transit marked with a red vertical line and the transit beginning and end indicated by two light gray vertical lines.

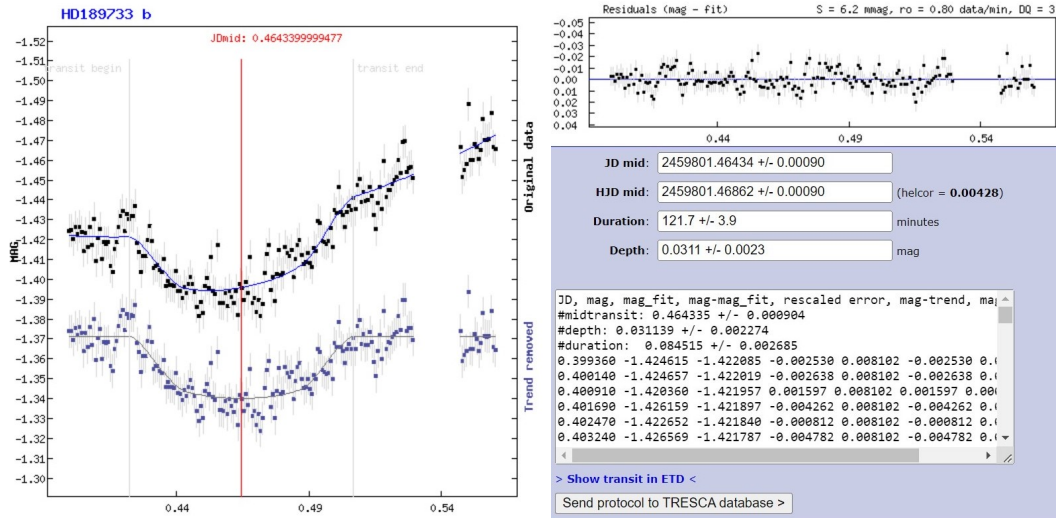
Comparing the output values for the three colour channels in Table 19, one can see that the results do differ to a certain degree. Many of the calculated parameters in one colour do not resemble the other colour within their respective margins of error. But having said that, the differences amongst the RGB channels are still not excessive. The reason for the differences of the values amongst the three channels could possibly be ascribed to the debayering-interpolation that has a stronger component in R and B or the fact that the red channel is mostly contaminated by light pollution and the blue channel with atmospheric refraction (as mentioned in section 4.2).

The calculated transit depths and transit durations are interestingly both larger than expected.

⁷¹see footnote 7

These are likely caused by systematics that are unaccounted for in the *ETD* data fit and de-trending. The reason could be found in the applied methods to de-trend, that might have left out a specific factor - or more likely it could be due to the increase in airmass or image curvature. The latter seems a little more likely since Poddaný et al. (2010) state that airmass systematics are mostly compensated by linear trends.

The mid-transit uncertainties are in the range of 1.3 minutes (0.0009 JD) and 42 seconds (0.00049 JD), which is not much, yet not enough to encompass the expected mid-transit time for any of the three results. The red channel's upper limit of uncertainty barely misses the expected mid-transit timing. The red channel's result misses the expected value by 81s, the green channel is off by about 70s and the blue channel by 226s (3.77 min). When it comes to the transit duration, the blue channel is however the closest one with 5.8 min off, then green (8.7 min) and finally red (12.7 min). For the transit depth the red and blue channel have an uncertainty of 2.3 mmag, while the green only has a value of 1.4 mmag. The red channel however, is closest when it comes to similarity to the expected value, followed by green and blue. Generally speaking, the green channel has the smallest margins of error for all three parameters, likely because the accuracy is the highest and the dispersion the lowest for the light curve. When it comes to the accuracy within the measurement itself, the green channel is the best, but when it comes to similarity to the expectation, both the red and the green channel give the best results.



(a) Light curve of *HD 189733 b* in the *ETD*, red pixels, bottom: de-trended (b) Residuals of the fit and the resulting transit duration and depth, red pixels

Figure 38: The fitting process for *HD 189733 b* in the *Exoplanet Transit Database (ETD)* with results, red channel⁷²

The outcome of the two approaches of fitting the data are relatively similar - comparing Table 18 with 19, one can see a higher similarity between the transit depth values of the

⁷²see footnote 7

partial de-trending and the expected value as opposed to the global de-trending, which actually resembles the *ETD* results. The transit depth calculated by the website are almost exactly in between the two values in the "Partially de-trended" row of Table 18. That fact is applicable to all three colour channels!

Since this observation session can now be considered a success, in the sense of an exoplanetary transit signal detection, the next step, as was intended for the successful measurement of a *TOI*, is to fully upload it to the *ETD* website. The green channel result with the highest accuracy within the RGB channels and therefore the highest light curve quality (less dispersion) was uploaded and added to the *ETD* dataset of observations. The database *TRESCA* specifically was chosen for the upload. The acceptance procedure is a matter of a few days to weeks and the full observation can now be accessed on an own web-page ⁷³. The data was classified as data quality type 2 out of 5, with 1 being the best quality.

The *ETD* fitting and plotting tool also creates *O – C* (observed minus calculated) diagrams of the uploaded observations and compares the freshly uploaded result to the ones of previous uploaders. The graphs show what was mentioned earlier (Table 19) as well: blue is furthest from the average in transit depth and mid-transit but closest in transit duration; green is best in epoch (mid-transit) and red is closest to the expected depth.

R_p :	1.138 +/- 0.027 R_{Jup}	1.383 $_{-0.027}^{+0.026}$ R_{Jup}
R_* :	0.788 +/- 0.051 R_{Sun}	<i>fixed, errors included in i</i>
A :	0.03099 +/- 0.00063 AU	<i>fixed, errors included in i</i>
Per :	2.2185733 days	<i>fixed</i>
i :	85.76 +/- 0.29 °	85.48 $_{-0.22}^{+0.23}$ $_{1.20}^{+1.47}$ °

Figure 39: The planetary radius R_p and the orbital inclination i as calculated by the stellar and orbital parameters in the *ETD*, green channel ⁷⁴

Now that some transit depths have been calculated, some planetary and orbital parameters can be derived from that. Recalling the geometric relation between transit depth and stellar and planetary radii (equation 4), the planetary radius can be quickly calculated. In fact, the *ETD* does the calculation for you after successfully uploading your observation. The results for the green channel upload can be found in Figure 39, where the applied stellar radius R_* , the semi-major axis A , the Period Per are given as fixed parameters and the expected planetary radius R_p and the orbital inclination i are listed with the expected and the calculated value. The planetary radius is about 0.245 R_{Jup} larger than expected, while the inclination roughly corresponds to the expectation, although the margins of error do not include it.

When applying equation 4 to the ΔF values to the values in Table 19, then the planetary radius for the green channel follows as $R_p = 1.523 R_{Jup}$, for red as $R_p = 1.420 R_{Jup}$ and for the blue channel $R_p = 1.556 R_{Jup}$. These values are even higher than the expected one mentioned earlier. The green value is also not the same as the one calculated by *ETD*, which implies a different approach to calculating the planetary radius. The values for red and blue cannot be compared

⁷³<http://var2.astro.cz/EN/tresca/transit-detail.php?id=1663772335>

⁷⁴see footnote 7

since the data was not uploaded to the *Exoplanet Transit Database*.

	Red	Green	Blue	Expected
ΔF [mag]	0.0311 ± 0.0023	0.0357 ± 0.0014	0.0372 ± 0.0023	0.0282
T_{Dur} [min]	121.7 ± 3.9	117.7 ± 2.2	114.8 ± 3.3	109.0
Mid [JD*]	0.46434 ± 0.00090	0.46448 ± 0.00049	0.46790 ± 0.00072	0.46528

Table 19: The calculated transit depths, durations and mid-transit for all three channels with the *Exoplanet Transit Database (ETD)*; *JD–2459801

7. Discussion

7.1. Correlations

As an unambiguous analysis or a definite statement on the decisive factors regarding accuracy in the light curves is difficult to achieve, another tool to try to solve the issue is implemented: correlation diagrams. The previously listed parameters, such as V magnitude, FWHM, roundness, S/N ratio, A/B , airmass X and moon phase were plotted against the dispersion of the light curve in Figure 40. Looking at the overall situation of the trend lines/linear fits that were applied to the datasets, one can see that most of the time the lines are almost horizontal, which does not really speak for a correlation.

A measure for the correlation of the two plotted parameters is R^2 , the coefficient of determination, which is the square of the correlation coefficient R . Its value is between 0 and 1, indicating a correlation the closer the value is to 1 (Glantz et al., 2016, p. 77/78).

The first diagram in Figure 40a was created to find a possible seasonal factor when it comes to accurate measurements. A clear answer to that question is difficult, since the warm summer months include less data points (observations), but it seems like the observations tend to be slightly less dispersed towards the end of the observation campaign. From a point of view of noise and its dark current contribution, the colder weather would speak for a higher accuracy, since higher temperature causes more electrons to be released from the sensor. Two factors could be responsible for the better light curve quality towards the end of the campaign, namely on the one hand the observer's learning curve and the routine in handling instruments and software, and on the other the use of the more sensitive *Sony* as opposed to the *Canon* camera in the later stages of the campaign.

The V magnitude vs σ diagram in 40b would intuitively display better dispersion values at higher brightness, but looking at the linear trend, the result seems to be skewed towards the lower brightness. A reason for this would be the much higher number of low-brightness candidates in the range between 9.5 and 11 mag, with only four observations below 9 mag, creating an under-representation. Two observations in the higher magnitude section clearly have the lowest σ value and therefore would indicate that with greater brightness comes less dispersion. However there are also two other observations that counter that theory - which is an indicator that magnitude might not play the main role here. Still, this is a difficult diagram for deriving any decisive conclusions.

On the other hand, the graphs in Figures 40c and 40d are the closest to resembling a correlation of all the plots represented here - even though they exhibit R^2 values of 15% and 20% respectively. This cannot be called a definite correlation, but as one inspects the two graphs, one can see a trend in higher light curve quality with lower FWHM and higher roundness. These are both facts, that clearly make sense and are easily understood. The two parameters are closely related to image quality and can be regarded as indicators for weather conditions, optical aberrations and tracking errors.

A correlation between the S/N ratio and the A/B ratio to the standard deviation however cannot be concluded from Figure 40e and 40f. The two values represent a relatively similar concept of data quality and therefore give similar results when compared to σ . The trend of the linear approximation, in both cases, go in the wrong direction. The standard deviation should

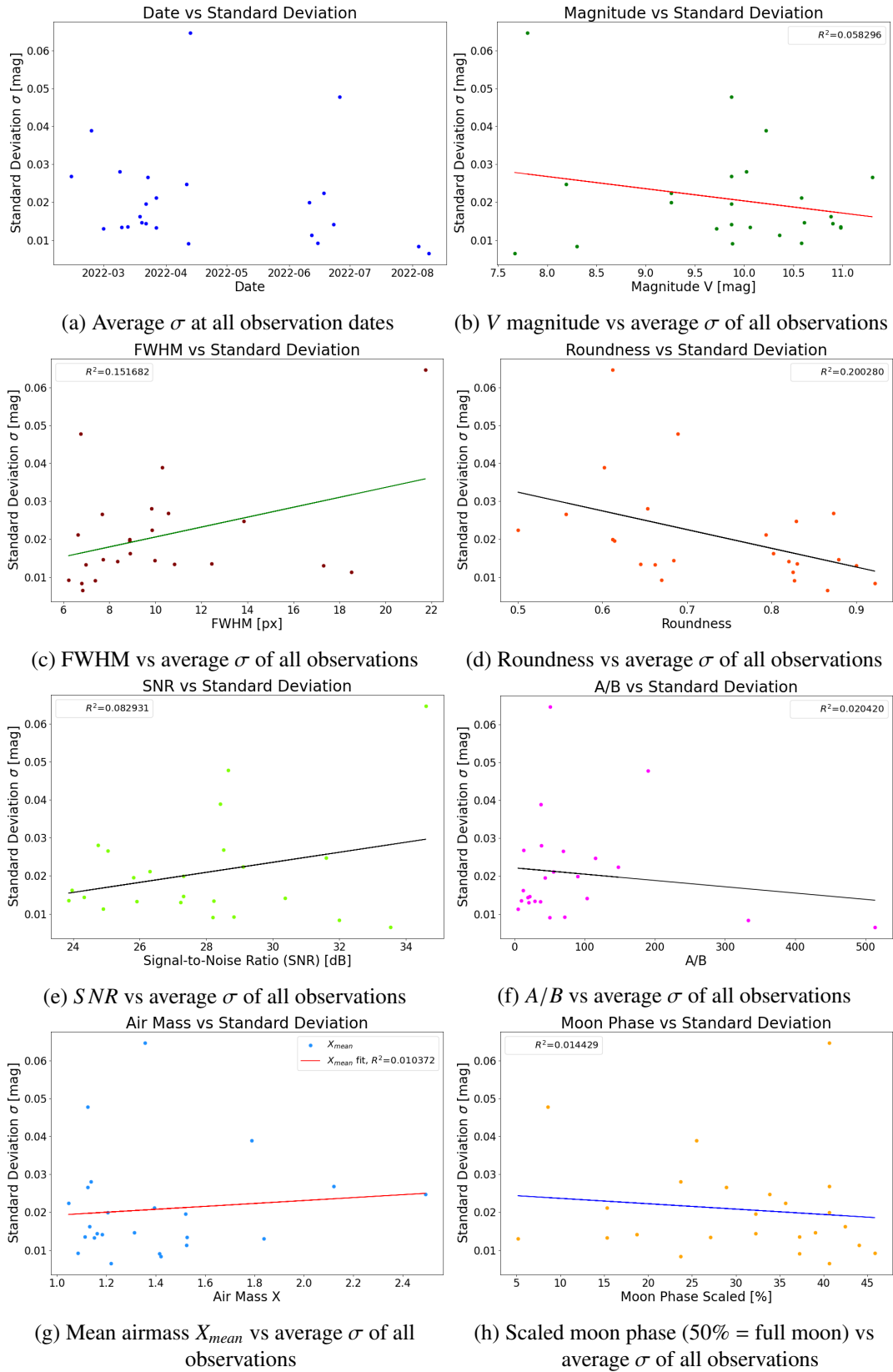


Figure 40: Correlation plots for the significant parameters regarding data quality

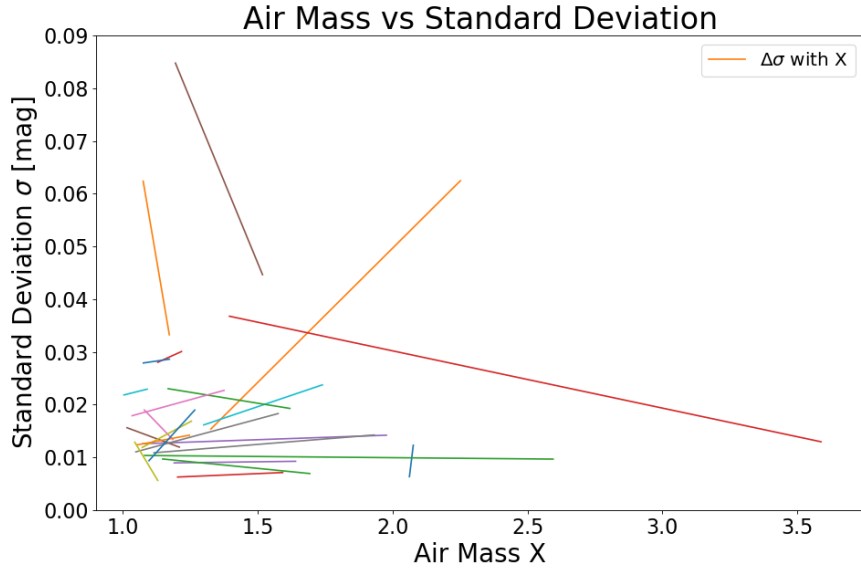


Figure 41: The change of σ from Airmasses X_{start} to X_{end} over the course of the observations

decrease with higher S/N and A/B , however seemingly the opposite is the case. The reason for that can however be concluded from the lack of samples in the upper range of S/N and A/B values, which is why the linear fit in the datasets does not represent the reality. Additionally, there are significantly more factors that play a role in the σ , one of them being the reference stars, specifically regarding their number or their quality - crucial factors when it comes to data quality in differential photometry.

Figure 40g shows the relation between airmass and the standard deviation. Even in this case the dependency of data quality on airmass is definite - but the data points and their correlation do not really exemplify that notion. The reason for that is likely due to other observational factors that are responsible for the individual standard deviations.

If one were to study the change of the σ values over the course of the observation night and the inherent change of airmass, one could see that in some cases the dispersion would increase with lower airmass (Fig. 41). But in most cases there is an increase of light curve quality with smaller airmass. In Figure 41 each line represents an observation night, over the course of which the value for the dispersion and the airmass changes. Since most of the lines slope downwards with increasing X , there could be an airmass contribution to the light curve dispersion, but it cannot explicitly be confirmed (Fig. 40g).

A relation between airmass and S/N ratio cannot really be found in Figure 42c either - the linear function's slope in the graph is rather counter-intuitive, but the reason for that lies in the varying quality of image from observation to observation. But mostly the S/N ratio depends on the target star's brightness that obviously contributes to the signal, therefore this graph cannot be conclusive. Looking at Figure 42e's graph and linear fit, one can see that the 76% of correlation of V magnitude and SNR can be considered quite significant.

The relation between the dispersion and the lunar phase with its concomitant effective back-

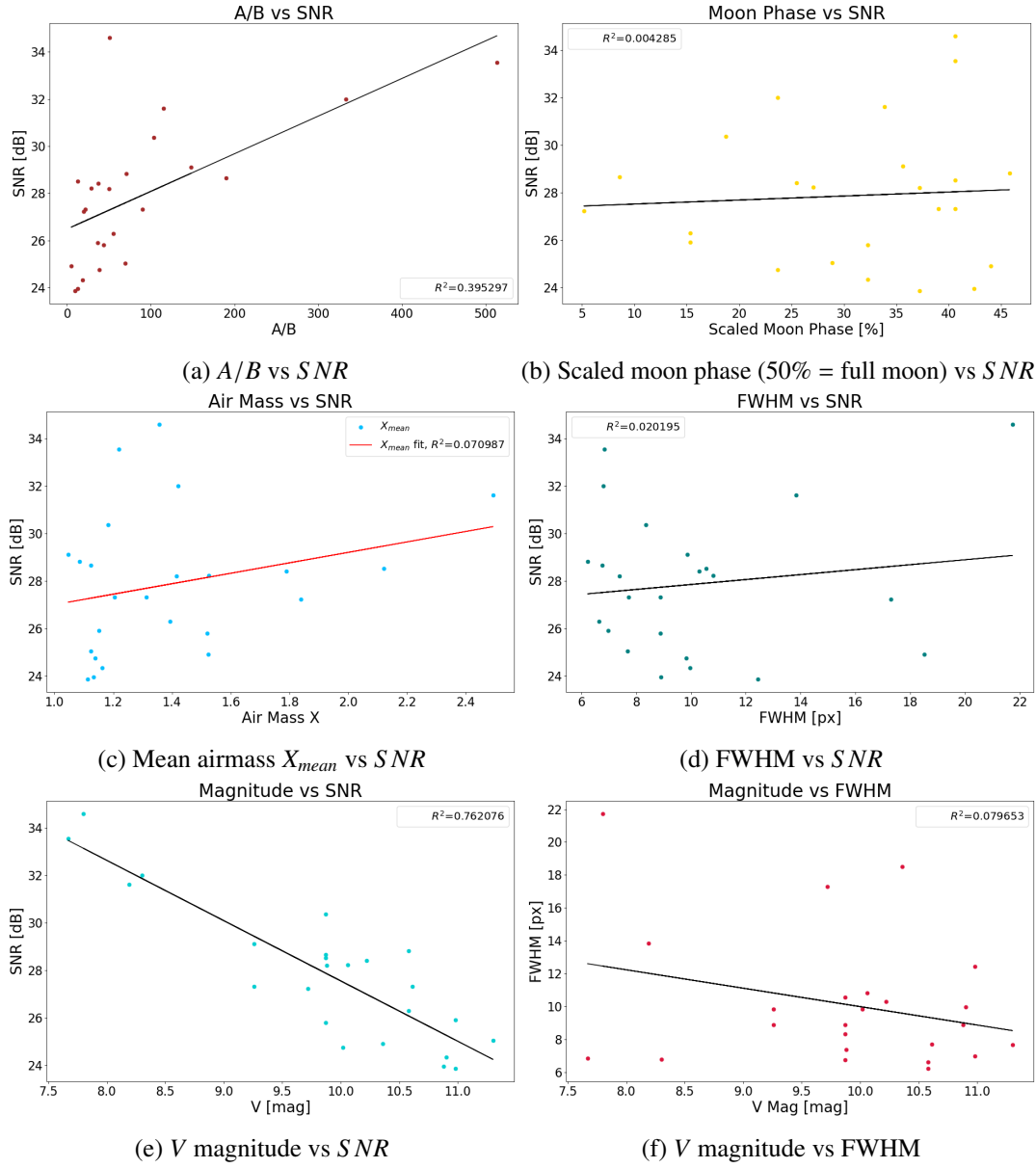


Figure 42: Correlation plots for the significant parameters regarding data quality

ground increase is another case, where a correlation cannot be found. The reason for that could be the lack of data points/observations around the time of new moon. Another aspect to be considered when it comes to the influence of the moon on the measurements is the distance of the target to the moon on the night sky. Since that dependency is not included in the graph in Figure 40h, the dispersion of data points corresponding to observation events, are rather dispersed. Additionally, more factors than only the moon are responsible for σ , just as the other parameters mentioned before. The moon phase in this diagram has been scaled according to lunar brightness, where the recorded lunar phases above 50% (full moon) were scaled down or in other words redefined from a waning to a waxing moon. The dependency of lunar phase and the maximal photometric accuracy exists, as mentioned earlier (see Figure 15 and (Roth et al., 1989, p. 382)), the higher background levels reduce the S/N ratio and therefore cause the accuracy to drop. The relation between the measured S/N ratio and the same lunar phase values can be seen in Figure 42b, where there is no visible correlation yet again - a fact that does speak for a less significant relevance than expected, regarding the lunar phase in this data sample.

As mentioned earlier, the A/B and S/N ratios can be considered similar concepts; when looking at the relation between A/B and SNR in Figure 42a this point of view can at least be called founded to a certain degree. A correlation of 40% can be regarded as noticeable - especially considering the low correlation values for most of the diagrams so far.

The two final figures, Figure 42d and 42f both show no correlation within their respective datasets. The reason for that lies in the fact that the FWHM depends more on atmospheric factors, the instrumental implications and optical effects than on the signal or the noise itself. The signal is yet again dependant on the magnitude and therefore on V as mentioned before, which is again an issue when it comes to a correlation between FWHM and the magnitude. Intuitively though, there could be a relation between FWHM and the S/N ratio, since the FWHM depends on the telescope's focus and a defocussed image would lead to a lower signal. The connection between these two concepts is not really measurable due to the varying contributions of other factors in both parameters and the small number of actually defocussed images. Therefore, the lack of correlation should not come as a huge surprise.

Summarizing the outcome of this correlation study, only two parameters seem to have a slight correlation with the light curve standard deviation, namely the FWHM and the roundness. The latter parameter is actually dependant on the FWHM, since it is a ratio of the FWHM of two perpendicular axes of the PSF. This means that the FWHM can be used as a rough indicator for the data quality.

The other graphs in Figure 40 were expected to show some relation, but either the contamination of other factors or the lack of data points to deliver a meaningful conclusion caused this outcome. The same can be said about the diagrams in Figure 42, where the only correlations can be found in obvious cases, which cannot be used as indicators of quality.

Using the FWHM and roundness as an additional factor for assessing the most and least qualitatively relevant measurements in this dataset, the following can be concluded from Table 8. The observations with the highest roundness were in descending order: *WASP-33 b*, *TOI-1789.01*, *TOI-1186.01*, *TOI-1425.01* (No. 1), *HD 189733 b*. The ones with the lowest roundness

in ascending order: *TOI-4496.01* (No. 2), *TOI-1194.01*, *TOI-627.01*, *TOI-1831.01* and *TOI-4496.01* (No.1). The best FWHM values can be found with (descending): *TOI-1181.01* (No.2), *TOI-1181.01* (No. 1), *TOI-1425.01* (No. 5), *WASP-33 b* and *HD189733 b*, while the worst are (ascending): *TOI-1831.01*, *TOI-1371.01*, *TOI-1789.01*, *TOI-1012.01* and *TOI-1273.01* (No. 1). The two observations that can be found in the both categories as some of the best are *WASP-33 b* and *HD 189733 b*, while *TOI-1831.01* can be considered the worst in both categories. *TOI-1789.01* interestingly has one of the highest FWHM values and at the same time a high roundness - this can be ascribed to a defocussed observation with a strong pointing variation (drift) where the target had to be realigned in the middle of the observation night (see Figure 49 in the appendix). This means that polar alignment was insufficient, additionally causing elongation or smearing of the star images due to the incorrect tracking and thereby forcibly enlarging the fitted PSF function.

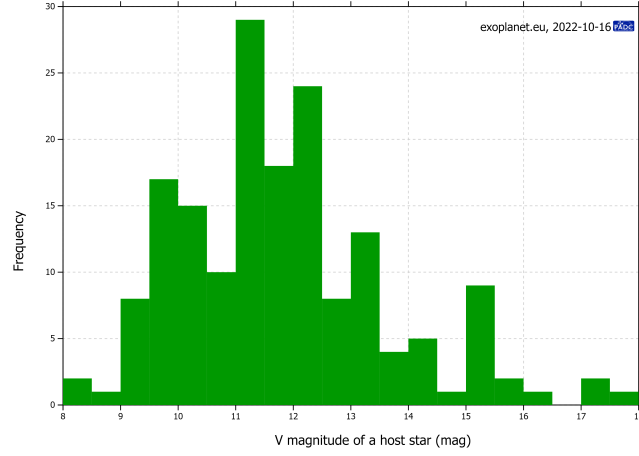
The observations that were discussed in detail in the previous sections were selected according to their performance in light curve dispersion in relation to the respective transit depth. A classification according to SNR or A/B would yield yet another list.

7.2. Direct Takeaways and Comparative Discussion

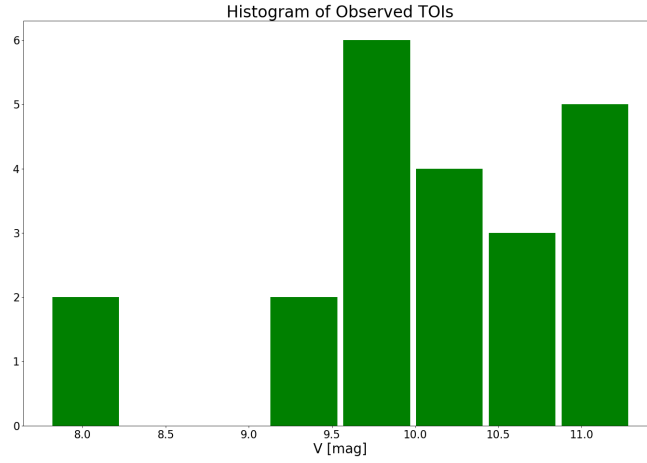
Having presented a filtered portion of the observation campaign results, the most important takeaways from the analysis will have to be reiterated.

Looking back at Table 10, containing the list of all dispersions and transit depths, one can conclude that the approach to measuring a transit of the average *TOI* with the given instrumentation and general implementation of hardware and software would have to be slightly different. The average V -magnitude of the observed *TESS Objects of Interest* is (as mentioned before) $V_\mu = 10.045$ mag, while the average transit depth was $\Delta F_\mu = 0.546\%$ (or 0.005946 mag). The σ values in Table 10 suggest however, that the applied configuration of instruments does not suffice for V_μ or ΔF_μ , especially not the combination of the two. Even for the test observations with *WASP-33 b* and *HD 189733 b* a transit depth of 0.005946 mag would have been difficult to observe, in the best case just barely measurable. Considering the average measured *TOIs* had magnitudes of about 1.7/2.4 orders of magnitude lower than the two test targets, the lack of accuracy in the light curves does not come as a surprise.

The immediate solution to this issue would be to keep maintaining the current strategy and to observe brighter stars (in the range 7-8 mag) with transit depths $> 1\%$ (ideally larger than 2%). But had these kind of exoplanet candidates been available, they would have been observed within the course of this campaign. The availability of *TOIs* to a small telescope observer can be traced back to two factors. On the one hand, the currently available candidates that have not been confirmed as yet (four years after the *TESS* launch in 2018) are out of necessity candidates that are not easy to validate. The difficulty in confirmation can lie in various factors, such as binary stars that can produce similar signals or false positives (see section 2.2), or in errors of ephemerides and other systematics. The second factor for availability is the sample of discovered *TESS* candidates itself, which depends on the mission's goals and instruments, making observations of small transit depths and low brightnesses more challenging. The up to this point unconfirmed planets, but also the *TESS* sample in general will have to fall into the category of less bright and small depth. This can be confirmed by the histograms in Figure 43.



(a) The frequency of *TESS* detections (confirmed planets) according to their V magnitude ⁷⁵



(b) Histogram of *TOIs* observed for this work with V-magnitudes ^{76, 77}

Figure 43: Histograms of confirmed and here observed *TOIs* with V-magnitudes

The histogram in Figure 43a shows that the confirmed *TOIs* are in fact even less bright than the sample that was observed. Only a small representation in the < 10 mag range can be seen in that graph, in fact most of them are > 11 mag, with the average being somewhere between 11 and 12 mag. This fact also roughly corresponds to the *TESS* mission's goals as listed in Table 1, where the objective of a (12-13 mag) lower limit for target magnitudes was listed. The

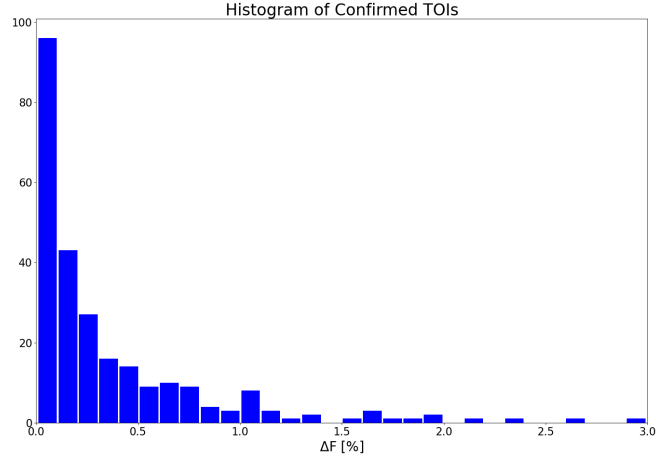
⁷⁵Histogram plot confirmed *TOIs*: V mag vs frequency. <http://exoplanet.eu/diagrams/?t=h>, last accessed: 2022-10-16

⁷⁶TESS Mission (NASA, MIT, CfA): Dataset from the *TOI Catalog*. <https://tev.mit.edu/data/collection/193/>, last access: 2022-10-16

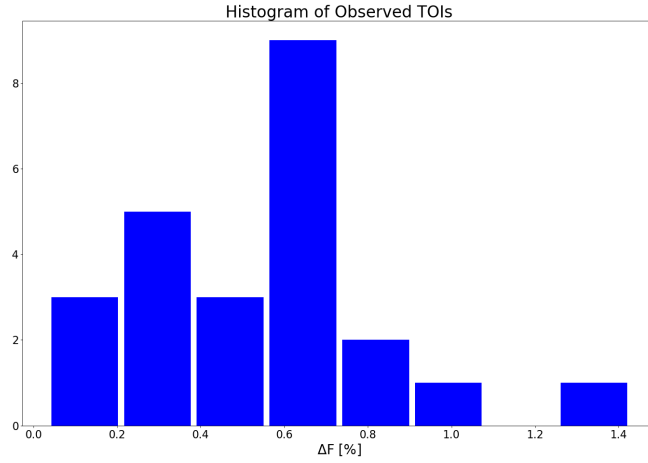
⁷⁷see footnote 55

PLATO mission aims for a comparable sample of targets, tending towards stars that are about 1 mag brighter than *TESS*'s.

When looking at the histogram of Figure 43b, the previously mentioned average *V*-magnitude can clearly be seen represented. The most stars are located between 9.5 and 10 mag, but a lot of them were above 10 mag, causing the average to rise to the value of 10.045 mag. This makes sense, because the choice of brighter *TOIs* pre-observation left us with this sample. However, the current instrumental configuration would require an on average brighter sample for a definite transit detection.



(a) The frequency of confirmed *TOIs* according to their transit depth ΔF



(b) Histogram of *TOIs* observed for this work with transit depths ΔF

Figure 44: Histograms of confirmed and observed *TOIs* (for this work) with transit depths ΔF

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⁷⁸see footnote 76

Similarly, the choice of transit depths was attempted to be kept close to 1%, but since the data sample only very rarely allowed for such a planetary candidate, the choice was to go with what was available. Looking at the observed ΔF values in the histogram of Figure 44b, we can clearly see the previously mentioned average of $\sim 0.5\%$, where the largest column can be found around 0.6% with a larger sample in the range below 0.6% than above. In fact, out of the observed *TOIs* there are only two candidates with or around 1% depth. Looking at the data sample of *TESS* detections up to this point, one can see that most of the transit depths are below 0.25% and only very few around 1%. This means that the data sample only contains few candidates in that range, but in turn mostly have very small transit depths that are far beneath the achievable framework with the observational configuration applied in this project. Revisiting the specific cases that were discussed in the previous section (section 6), Table 20 lists the important parameters according to their quality. A green tick symbolizes good quality, while a red cross stands for insufficient quality. The orange tilde represents mid-range (mediocre) values and combinations of the three symbols indicate a classification between the mentioned ones.

When looking at the column of *TOI-5379.01*, we find a slightly better than average FWHM - still a little high due to a lack of focus, a low roundness (contradictory to the low focus) due to tracking errors, a good *SNR*, a relatively high X_{max} and a low A/B . The moon's influence would cause a minimal photometric accuracy of 0.75% (likely higher accuracy), which would be sufficient for that case if the other systematics are minimal. However, the target was relatively close to the moon, but it set about two hours before the end of the observation. This planetary candidate's light curve resembles that of a transit to a certain degree after undergoing linear de-trending. But since there are some factors such as roundness, A/B , the maximal airmass, significant pointing variation (listed as "Low Drift" in Table 20), possibly the moon and an inconclusive off-target diagram with similarities to the target light curve, the dip in brightness cannot be excluded to be of systematic origin.

For *TOI-1186.01* the crucial factors for the lack in accuracy are founded in the mid-range *SNR* and the low A/B , the lunar phase, the weather and the pointing variation. As can be seen in the column for this target, the moon phase itself would reduce the photometric accuracy to a level above 3%. During the course of the night the moon rose in the South-East, while the observation took place in the North-East, therefore a certain proximity is given. Another important factor during this observation could have been the direction in which the target was being captured by the detector - the observation started in the North-East and moved up towards the North. This means that the light pollution dome would have had a significant influence by increasing the background signal. Additionally, there were cloud streaks present even within the images - all factors that explain the high background signal (see A/B value).

The observation night of *TOI-1717.01* for the most part seems to be average to above average. The *SNR* value seems to be good, while the A/B is close to average - the observation itself took place during a night with a waxing moon phase between half and full in the North-West direction, which is not strongly influenced by the city's light pollution. However, the row labelled as "Low Drift" in Table 20 suggests that the target pointing changed due to imperfect polar alignment, very likely being responsible for the linear trend in the second half of the

	TOI-5379.01	TOI-1186.01	TOI-1717.01	TOI-1371.01	WASP-33 b	HD 189733 b
FWHM	~	✓	✓	✗	✓	✓
Roundness	✗	✓	✓	✓	✓	✓
SNR	✓	~	~ ✓	✗	✓	✓
A/B	~ ✗	✗	~	✗	✓	✓
X_{min}	✓	✓	✓	✓	✓	✓
X_{max}	✗	~ ✓	~	✗	~	~ ✓
Moon	~	~ ✗	~	✗	✓	~
Off-Target	~	—	✗	?	—	✓
Focus	✗	~	✓	✗	✓	✓
Moon Acc.	~ 0.53 – 0.75%	~ 2.12 – 3%	~ 0.71 – 1%	~ 2.12 – 3%	0.14 – 0.2%	0.11 – 0.15%
Weather	~ ✓	✗	✓	~ ✓	✓	~ ✓
Low Drift	✗	~ ✗	~ ✗	~	~ ✓	✗
Ref. Stars	✓	~ ✓	✓	~ ✓	~	~ ✓
Direction	NW	NE → N	NW	E → SE	NE → E	S → W

Table 20: Summarized qualitative assessment of the essential observational parameters (discussed sample, good quality = ✓, medium = ~, insufficient = ✗)

observation. This phenomenon could also be responsible for a similar effect occurring in the off-transit light curve produced from the used reference stars, which contains a similar feature. The maximal photometric accuracy achievable with the given lunar phase is close to 0.5%, which could theoretically add to the overall dispersion of the data. The choice and the options for the reference stars (or comparison stars, marked as "Ref. Stars" in Table 20) was sufficient - in fact similar enough to the target variable in brightness and systematics to be called a good sample.

The situation is rather grim for *TOI-1371.01*, which possesses a prevalence in negative characteristics when it comes to the significant qualitative parameters. The FWHM and focus can be classified as insufficient, the former being a symptom of the latter - inadequate focussing enlarges the PSF and in turn the roundness is good. The S/N and amplitude-to-background ratios however are some of the lowest of the whole sample. The maximal airmass of $X_{max} > 1.9$ and the lunar phase close to full moon are also unfavourable. The direction of observation is difficult as well, having started in the East and ending to the South-East, the star is fully encompassed by Vienna's light pollution dome. Therefore, the high airmass, the moon's phase (resulting max. accuracy > 3%) and the light pollution, as well as the focus are the main causes for an insufficient *SNR* and *A/B*, creating insufficient data quality and thus no indication of a transit in the light curve.

The first test observation, being conducted with *WASP-33 b*, has some mysterious elements to it. Most of the values are above average and would be believed to suffice for a transit detection. Nevertheless, the transit could not be detected, most likely due to two reasons: the light pollution and the comparison stars. The maximal airmass is at 1.693, which is not too high but large enough to possibly have an impact on the measurement quality. The moon was close to being a half-moon, but it set before the observation, around 20:00 UTC and therefore cannot have a negative impact on the observation. The images display a certain amount of drift, however not to an excessive degree. The only other explanations left in the list of factors

considered in this project are the direction of observation, which started in the North-East and proceeded to the East - both directions that would be influenced strongly by light pollution. There seems to have been a strange background signal that night (see Figure 29), displaying a dip in brightness around 00:00 UTC, which is possibly also visible in the data at the same time (~ 2459796.51 JD). A dip in background brightness could mean an increase in the target's brightness, which is why the feature in the light curve looks like an increase in brightness.

The other lightmeter background features are not really visible, which could mean that this signal was not responsible for the lack in accuracy - but maybe it was the light pollution in general that interfered with the photometry. The A/B and SNR values in this case are quite high in relation to the *TOI* observations. But even considering that *WASP-33 b*'s and *HD 189733 b*'s values are calculated from a stacked 50s integration time image, as opposed to the *TOIs* at 30s, the background values do not seem to be affected. Therefore, the S/N ratio would be slightly lower for a 30s exposure, while the A/B ratio would remain a similar value, since amplitude and background are just added up in the stack. This means, that even though the observation was exposed to direct light pollution, the background value as compared to the *TOI*-observations does not seem to be particularly high. This is likely the case because of the stacking process, that created a different background component than it would have in the case of an instrumental 30s exposure. At the same time though, the lunar influence is not there with *WASP-33 b*.

Another error source that might be responsible for a lack of a transit measurement could be the available reference stars. The target has a magnitude of $V = 8.3$ mag, while all the stars used for comparison are at least 1 mag less bright. These stars have added some noise factor into the equation, where the 5s original exposure could be too little for that noise to be compensated. Specifically the scintillation noise is an issue that needs to be taken into account (see more later with equation 20).

The last observation of all was the second test measurement, where *HD 189733 b* was being inspected. Here, similarly to *WASP-33*, most parameters are of the highest quality within the dataset and speak for the possibility of a transit detection. The SNR and A/B values are some of the highest, the moon was not too influential, the weather was inconspicuous, and the maximal airmass is not ideal but not catastrophic either ($X_{max} \approx 1.6$). The most issues with this observation can be found in the pointing variation and field rotation, since the star drifts from the center of the image towards the bottom right, which most likely caused the linear trend in the egress. In this case the direction of observation was good as well - starting in the South and moving towards the West, meaning that the light pollution exposure is not too extreme. The success of this observation certainly lies in the strong signal (low magnitude and high transit depth), which causes a substantial signal-to-noise ratio. Apart from that, not too high levels of airmass, a low standing moon, good weather and a direction that is further away from the city lights certainly helped - however the pointing variation and field rotation is strong enough to ruin the observation for most other stars. The fact that this trait of the observation night can still be overcome, speaks yet again for the strong signals.

As a conclusion to the detailed discussion of the exoplanet observations, one has to acknowledge that just the last observation was successful - the others were close, but too many error factors contaminated the data, making a clear and certain conclusion on the source of the

transit-like feature impossible. This applies specifically to *TOI-5379.01* and *TOI-1717.01*, the other two discussed measurements are even less accurate and more contaminated.

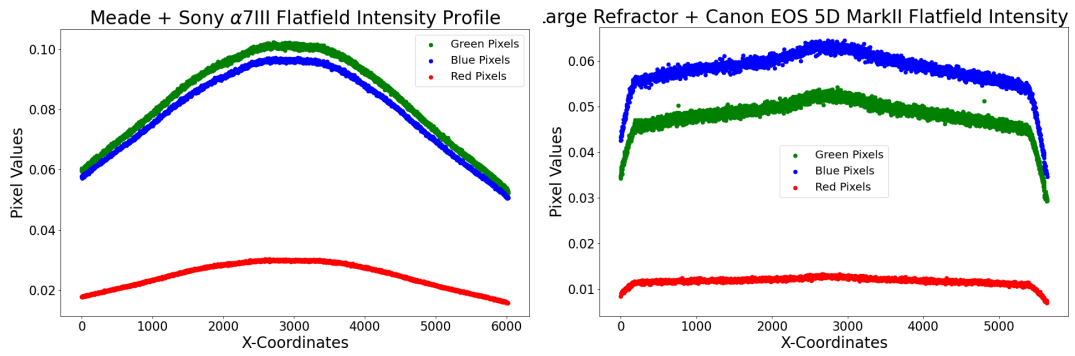
7.3. Sources of Error in Detail

The repeatedly mentioned issue of pointing and the movement across the detector over the course of the observation is founded on two separate problems. Firstly, the positioning of the target and its reference stars on different pixels can result in different circumstances for the measurement of the stellar brightness, since pixels can react differently to exposure to light. Secondly, parts of the image that are off the optical axis - are by definition exposed to less light, which causes the objects to have a lower light intensity. This has an effect on the exposure itself and can be corrected - to a certain degree - by the flat-field image. However, if the star moves across the image and its reference stars with it, the flat-field of differing radii of intensity will correct the target and other stars differently at different times across the image. This can result in a variance of the brightness caused alone by the flat-field correction.

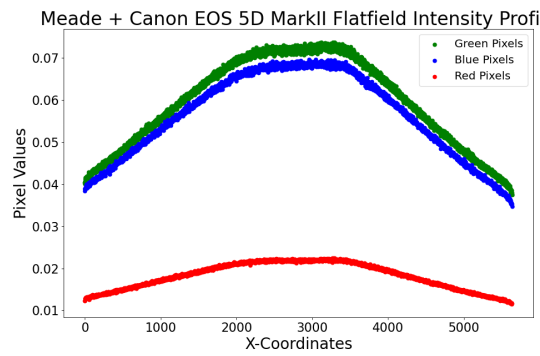
As most time-series have been recorded with either a *Canon* or *Sony* camera using the *Meade LX50* telescope, one can see what the intensity profile of the flat-field looks like for the *Meade* telescope in Figure 45a and 45c. From the edge to the centre, the light loss is at around 40% for the *Meade* telescope. When comparing that image to the one of the *Large Refractor* in Figure 45b, one can clearly see that the intensity is evenly distributed with a loss only significant very far on the edge of the detector. That loss can be quantified at around 30%, but since it happens only very close to the edge it is comparatively insignificant to the other two graphs in Figure 45. The *Meade* telescope however, almost exhibits something similar to a Gaussian bell curve (without the exponential characteristics) - indicating a high loss of light already at a relatively small radius from the optical axis. This would indicate a strong effect on the stellar brightness in the differential photometric detection method of transit, since the regions of differing focus combined with the pointing drift would falsify the relative magnitudes (reference vs target star). The noise of the flat-field and its imperfections will also have different effects on the reference and target stars, especially in a scenario of pointing variation over time.

The higher intensity of blue pixels in Figure 45b can be ascribed to the semi-apochromat lenses of the *Large Refractor* (Sacek, 2006b). These issues of the *Meade* telescope are to be ascribed to the field curvature of the Schmidt-Cassegrain system. Additionally, there are also effects of vignetting that naturally occur due to geometry of the optical system, where some structural element, such as the tube of the telescope or the adapter for the camera will block/reduce influx of light on the detector at the periphery. This effect will however be less strong in the case of the observations conducted here.

As was described for three of the discussed observations, the light curves exhibited a linear upwards trend towards the end of the observation (*TOI-5379.01*, *TOI-1717.01* and *HD 189733 b*). This effect can be traced back to two effects with a similar symptom. The direct cause of the apparent brightening of the variable star is related to the defocussing of the reference stars over the course of the observation, making them less bright in relation to the target. The effect of defocussing is stronger in the "outer regions", further away from the optical axis, resembling the symptoms of a coma aberration (comet-like appearance). The reason for the defocussing can originate from a focus drift, where elements of the telescope change their



- (a) The intensity profile of the flat-field image of the *Meade* telescope with the *Sony* camera in R, G and B
- (b) The intensity profile of the flat-field image of the *Large Refractor* telescope with the *Canon* camera in R, G and B



- (c) The intensity profile of the flat-field image of the *Meade* telescope with the *Canon* camera in R, G and B

Figure 45: The intensity profile of the flat-field images of both telescopes with two different cameras in R, G and B

position, e.g. due to temperature changes or mechanical issues (Gary, 2010). The other cause for defocussing would be produced by the imperfect polar alignment and the concomitant pointing drift, inducing a stellar movement across different pixels in the series of images. Since the *Meade* telescope exhibits field curvature, the stars in the periphery of the image are less focussed. Pairing this effect with the reference stars moving from a central position to a marginal one, thereby being exposed to regions of higher curvature, which means less focus and therefore also less brightness over time, will make the target star appear brighter compared to the reference stars.

An essential aspect of successful photometry is the quality of reference stars - without them systematics and specific characteristics of the observation cannot be eliminated. For that to work there need to be enough stars to compare the individual light curves with and they also need to have similar properties, such as similar brightness and a position not too far from the star since different regions of the image have other influences from the flat-field or are not as well exposed to the detector as the central target star. Another attribute of the star is the colour, which depends on the spectral type but also on the atmospheric extinction, as was mentioned earlier. Since these two states both affect the apparent colour, the comparison of a blue and a red star will cause an airmass induced curvature (Gary, 2010). This aspect of photometry was not considered in detail, since a comprehensive study of the comparison stars would have had to be done. The sample of stars inspected here were from late B/A to K, which is a wide range of types. Therefore, effects of star colour in the observations are not unlikely - however, most of them were in the range of F or G stars.

Some of the observations in the dataset were over-exposed. The reason for that can be traced back to a misinterpretation of the upper pixel limit for the *Canon* camera. It was expected to be close to the value of 16383 ($2^{14} - 1$), but it was closer to 14966. The reason for that is unknown - the *Sony* camera on the other hand exhibited the expected maximum value. All *TOI* observations were conducted with a 30s exposure time, which was done for the reasons that the effect of scintillation is minimized (see equation 20), the Poisson noise is smaller and read-out noise is reduced as well, since there are fewer readings per session. Another aspect of saturation that should have been considered, is the "linearity saturation", a characteristic of the detector's linearity, which in most cases can no longer be upheld at specific exposure times. A safe option for exposure is to stop at a maximal count in mid-range, which would be around 8000 for the *Sony* camera, although in most cases linearity will probably uphold up to 90% of the maximal count number (Gary, 2010).

Apart from the mentioned issues of the telescope optics themselves, the flat-field correction has the largest capacity for errors according to (Beck et al., 2019, p. 7). Based on a graph in the paper (see Figure 46), the dominant contribution of error for an average *TOI* from the here discussed data sample would be from the flat. The second largest contributor would be the scintillation noise (I_{rms}), which in turn is the largest contributor in the case of stars like *HD 189733*. For *WASP-33* the error contributions of scintillation and flat noise are about the same.

The reason for the higher scintillation error for brighter stars lies in the exposure time, that is adapted to the magnitude in the graph. The consequence is logical, the shorter the integration time, the stronger the scintillation effects. Apart from the exposure time, the scintillation

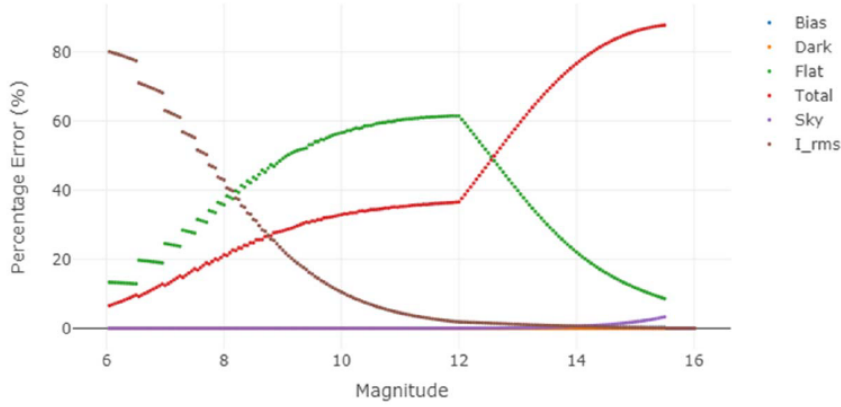


Figure 46: Error contributions to small telescope exoplanet observations (Beck et al., 2019)
(I_{rms} = target scintillation noise)

also depends on other factors, such as airmass and the telescope aperture. The normalized scintillation noise can be quantified as follows (Beck et al., 2019):

$$\sigma_{scint} = 0.004 \cdot D^{-2/3} \cdot X^{7/4} \cdot e^{-\frac{h}{H}} \cdot (2 \cdot t_{exp})^{-1/2} \quad (20)$$

In equation 20, D is defined as the telescope aperture in meters, X is the airmass, H the scale height of the atmosphere (8000 m), and h the altitude of the telescope, which is about 302 m for the Kuffner Observatory⁷⁹. The aperture equals 0.2032 m for the mostly applied *Meade* telescope. Inserting these values into the previously mentioned equation, using the minimal airmass ($X=1$), one would receive a scintillation noise value of $\sigma_{scint} = 0.001439$ for $t_{exp} = 30s$. The maximal airmass value $X_{max} = 1.977$ of the discussed targets (for *TOI-5379.01*) and the same exposure time, equates to a noise of $\sigma_{scint} = 0.004742$. Table 21 shows the calculated scintillation noise for all previously discussed cases, where the noise has been varied with the initial and final airmass value (marked as a subscripted i and f in the noise value in the table) to be compared to the ingress, mid-transit and egress standard deviations and the transit depth.

Table 21 shows that in all cases the scintillation would be an essential part of the noise/standard deviation of the light curve. For the *TOIs* the percentage of scintillation is somewhere between 10 – 37%.

From the listed *TOI* observations in Table 21, *TOI-1717.01* and *TOI-1371.01* are affected the most by scintillation, relative to the calculated light curve standard deviation. For the 5s exposure of *WASP-33*, the percentage is somewhere close to 30 – 40%, while the 2s integration time of *HD 189733* is between almost 50 – 80%. Comparing these values to the brown line in Figure 46, one can see that they come very close to the expectation. For the 50s "exposures" that are actually stacks, the percentage of scintillation noise is somewhere between 15 – 40%, which is similar to the *TOIs*' value mentioned before, which makes sense, since the exposure time is similar.

Adding to the scintillation noise issue posed by different values for the airmass, the photometric

⁷⁹Kuffner Sternwarte Wien: Kontakt. <http://kuffner-sternwarte.at/index.php>, last access: 2022-10-20

Planet/TOI ID	σ_{scint_i}	σ_{scint_f}	σ_i	σ_m	σ_e	ΔF [mag]
TOI-5379.01	0.001630	0.004742	-	0.012566	0.014180	0.01178
TOI-1186.01	0.003189	0.001620	0.018284	0.011026	-	0.00980
TOI-1717.01	0.001954	0.003419	-	0.008933	0.009234	0.00986
TOI-1371.01	0.004555	0.001743	0.014221	0.008655	0.010851	0.01562
WASP-33 b (5s)	0.008855	0.004487	0.021115	0.015885	-	0.01510
HD 189733 b (2s)	0.007711	0.012586	0.015719	0.018798	0.015628	0.02820
WASP-33 b (50s)	0.002800	0.001419	0.006913	0.009669	-	0.01510
HD 189733 b (50s)	0.001542	0.002517	0.006248	0.006069	0.007101	0.02820

Table 21: Scintillation noise for different airmasses (and exposure times)

quality experiences a significant loss for airmasses $X > 1.4$ (Rauer et al., 2008), where the fall is gradual up to $X = 1.6$, before decreasing rapidly towards 2 airmasses. Two of the discussed observations reached airmasses very close to $X = 2$, namely *TOI-5379.01* and *TOI-1371.01*, where the influence on photometry can be considered significant. The other two *TOIs* and *HD 189733 b* reached airmasses close to 1.6 and *WASP-33 b* around 1.7, which can be considered influential but not concerning (see also Table 20 for the respective airmass classification). Many other observations in the list (Table 9), have been observed at high X values, some even with $X > 2$ - a fact that definitely did not help with the respective measurement accuracies.

The main sources of noise according to Castellano et al. (2004) are poisson noise, noise from data reduction (bias, dark, flat), noise from atmospheric scintillation and CCD read out noise. The noise introduced due to image calibration and the CCD read out noise are ideally not above 1 mmag. Equation 17 lists some of that noise for the calculation of the S/N ratio, but leaves out the issues caused by scintillation and the data reduction process, that actually pose the biggest challenge, together with background noise.

Another aspect is atmospheric extinction that increases with the airmass and can influence the instrumental magnitude significantly.

$$m_{obs} = m_0 + k' \cdot X + k'' \cdot c \cdot X \quad (21)$$

Equation 21 (Bozza et al., 2016, p. 102) shows how the primary (k') and secondary extinction coefficient (k'') influence the observed magnitude m_{obs} . The latter coefficient k'' is dependent on the colour of the star. Rayleigh and other scattering processes cause the coefficient to increase with decreasing wavelength. Red stars will intrinsically suffer less extinction than bluer ones (in a wide bandpass). The other variables in the equation are the magnitude above the atmosphere m_0 , the airmass X , the coefficients and the star's colour index c . The colour dependency poses a difficulty that is not easily solved, especially if the colour is unknown

in advance. Additionally, the coefficient varies from location to location, but also with wind speed, direction and air humidity (Bozza et al., 2016). These are the reasons why this aspect has been left aside here, although the colour aspect of extinction can influence the relationship in colour difference between the variable and reference star (Castellano et al., 2004).

Continuing on the path of atmospheric influences on the observation conditions, the yield of exoplanet measurements over the course of the campaign should be discussed as well. According to Beck et al. (2019), the weather in Bayfordbury, Hertfordshire, England from 2015 - 2019 entails 11% of clear nights and 47% of mixed nights. The average clear time was 31% and about half of those nights (15%) were photometric. Comparing these values to this campaign, where all days that were actively sought out for observation (192, excluding everything after 12th August, since the campaign ended with *HD 189733*) and the yield of 26 observations would result in 13.5% of days being usable for observations. This would be similar to the number of photometric nights mentioned earlier, however the real number for the observations in Vienna would be much higher. The days spent by the observer for data analysis, literature work, vacations, sickness, etc. are not considered in the calculated percentage.

The question of the transit yield in the discussed dataset can also be ascribed to the difficulty of the human eye in recognizing a transit engulfed in noise. There are a handful of methods that attempt filtering out noise to lay bare the underlying transit signal. Tingley (2003) lists some of these methods and compares them by applying them to synthetic light curves. Some of these methods include the matched-filter approach in different implementations, the first one ever implemented being by Jenkins et al. (1996). The method is described by Kay (1998) as a detector for an already known signal superimposed with white Gaussian noise. The concept is based on calculating the probability of observations being the result of white Gaussian noise or the result of an underlying signal plus the mentioned noise. A test statistic is formed by taking the ratio of the two states of probability (likelihood ratio), which is then varied for multiple tests within a parameter space, being compared to the dataset each time. Another match approach was conceptualized by Doyle et al. (2000) by including time-based weighting. An entirely different statistical approach is taking the Bayesian method described by Defaÿ et al. (2001), where an unknown parameter is estimated through the maximization of a likelihood-function, improving the estimation by implementing as much prior information as possible. The period of the to be detected signal is fitted by assuming white Gaussian noise and representing the signal as an unknown Fourier series. Kovács et al. (2002) describes a box-fitting (box-least-squares) technique, which is a χ^2 fit of a square-well transit model. With the help of minimization, the transit depth is removed as a free parameter, lessening the computational effort.

Of these mentioned methods, tested on synthetic datasets with transits, the modified matched filter process of Doyle et al. (2000) performed the best at around 46% detection probability, while the Bayesian and the box-fitting approach performed quite poorly in comparison (Tingley, 2003). This is the case although, according to Tingley (2003), the techniques that did not perform well in the test were the only ones discussed in astronomical literature at the time of publication. In the meantime, this fact should be different, since the paper was published in 2003. Today methods using machine learning and AI are gaining more and more relevance and are already able to help in that regard.

Another factor causing difficulty, specifically for *TESS* and its discovered exoplanet candidates is the accuracy of ephemeris, that can vary considerably. The reason for that lies in the space telescope's very short pointing duration of 27.4 days (Ricker et al., 2014), which can cause large uncertainties in the period determination. The number of transits measured on the same star is limited due to the short pointing time. Deeg and Tingley (2017) carried out calculations with a timing error estimator using the expected results of *TESS*. The calculations were undertaken before the launch of the satellite using a number of transit parameters and accuracy variables. The result for different samples of *TOI* candidates were calculated - for the sample of *TOIs* observed in the small telescope campaign here, a variation of the ephemeris ranging from 0.10 – 2.11 hours can occur after a year of the initial detection. This means that a photometric follow-up as soon as possible after detection is recommended, ideally before one year has passed, since the ephemeris uncertainty can multiply to make the measured signal undetectable (Deeg and Tingley, 2017). For the observed exoplanet candidates in this project, there is information on the ephemerides uncertainty (see Table 6), but not on how many times the respective candidate has been observed so far. The majority of transit candidates observed seem to have an uncertainty of 0.0 hours, which is a good sign, but there is no information on whether the signal has been followed-up even once after its discovery. This gives the *TOIs* another aspect of uncertainty - we do not know whether the transit was even fully measurable during the average observation time of 3.42 hours per session in the thesis campaign. This issue will not apply to *PLATO*, since the observation campaigns will last 1-2 years (Nascimbeni et al., 2022).

At the same time, the increase in uncertainty over the course of a year can also be seen as a motivation to establish wide-ranged transit follow-ups operated by scientists. With large-scale measurements of new planetary candidates in the form of a network or a "swarm" a maintenance of ephemeris could be undertaken, which would save time for large observatories to observe small Earth-sized planets around M-dwarfs (Zellem et al., 2020). This leads us back to the original intention of this project.

The aspect of using DSLR cameras for measuring a transit event is still something rarely executed, especially in the world of professional astronomy. A few decades ago the thought of using ordinary cameras instead of sophisticated CCDs was unthinkable. In the meantime, the CMOS sensors in digital cameras have reached a level of data quality that can keep pace with the professional sensors - especially regarding affordability. However, since DSLR cameras cater to capturing every-day life situations and not objects in space, the sensor is overlaid with a Bayer filter, that separates the pixels into three channels (RGB). This attribute of the CMOS sensor however poses a challenge, since it can cause large systematic errors. Particularly for photometry, the interaction between the RGB colour-sensitive pixel pattern and the PSF is a cause for concern. Combined with tracking inaccuracies during imaging, the pixelisation in the shape of the Bayer-Matrix can cause variations in the flux measured by the detector - a big problem for precise brightness measurements (Gee et al., 2021). Additionally, DSLRs have lower quantum efficiency and a smaller full-well capacity, which are both sources of Poisson noise (Zhang et al., 2016). The DSLR cameras are also not cooled, which causes

a stronger dark current - a factor that increases with temperature, as mentioned before. As literature suggests (e.g. Gee et al. (2021) and Zhang et al. (2016)), most exoplanet transit observation campaigns with DSLR cameras reach a photometric accuracy of $\sim 1\%$ for each of the colour channels. This is possible despite the presence of tracking errors, enabling high precision photometry with this type of sensor (Gee et al., 2021). This would make large scale campaigns for exoplanet candidates possible, however considering the frequency of *TOIs* with $\Delta F \geq 1\%$ is limited (see Figure 44), a full campaign for *TESS* candidates is difficult. Zhang et al. (2016) suggests that a higher accuracy (10 mmag to 4 mmag) can be reached by combining the channels with weighted or simple addition. No reference in literature could be found for quantifying the errors or issues caused by debayering interpolation, as applied in this project. The method however intuitively suggests similar outcomes as for weighted addition. A side-note regarding the observation of *HD 189733 b* with a DSLR camera: the measurement has been shown before by Littlefield (2010).

8. Conclusion

To come full circle with the project's purpose, let us revisit the goals that were attempted to be achieved in this project. The attempt to assess false positives from the observed sample of *TOIs* was not possible, since none of the stars exhibited clear signs of contamination (such as an eclipsing binary) or of any other stars/objects being in the vicinity of the target. This fact however, does not indicate a failure in this aspect of the project - theoretically the higher focal length and the higher number of arcseconds/pixel as compared to the space telescopes is an advantage where false positives can surely be excluded in the future. Undeniably, the small-telescope community could help with this endeavour of finding false positives - especially a large number of citizen scientists would increase the likelihood of detecting such an event. The key messages or main statements arising from this work were firstly how many planetary candidates can be observed by one person in 6 months and secondly, an estimate of a rate of validation of *TESS Objects of Interest* for the given circumstances - i.e. weather, instrumentation, light pollution, moon, data reduction, programs applied, and more factors that were discussed so far. Furthermore, a duration and precision for the *PLATO* follow-up campaign was to be estimated.

A total number of 26 observations were executed, counting the two test observations and the two *TOIs* that were not analysed further. That means we are left with a yield of 26 observations/6 months for one person. As an aside, more observations would have theoretically been possible, but since the project does not only involve observing but also analysing the data and reading literature, not every opportunity of good weather was used to full capacity. Apart from that, personal reasons, such as recuperating from long observation nights that can be very tiring - especially if repeated many times in a short time frame - have to be taken into account. Therefore, the sample of observations can be regarded as a relatively realistic sample for a follow-up citizen scientist who wants to dedicate most of their time to observing planetary candidates.

Rate [per yr.]	By observation	$\sigma < \Delta F$	$\sigma < 2 \cdot \Delta F$	By detected transit
TOI obs.	48	4	10	0
all obs.	52	8	14	2

Table 22: Estimated rates of observation or validation by one person in one year

Table 22 has listed the estimated rates of "validation" by one person in one year. The first row of values corresponds to all observed *TOIs* and their rate of validation per year. The columns start from the most optimistic approach of answering the question on the left to increasingly pessimistic towards the right.

In case one is asking for the coverage of planetary candidates by one person in one year, one can answer with 48 observations, since 24 *TOIs* could be observed over 6 months. The second row includes the two conducted test observations, which would leave us with 52 observations (from 26 per 6 months).

The second and third data columns attempt to answer the question with achieved accuracy;

firstly with standard deviations of the generated light curves that were smaller than their respective transit depths and secondly with standard deviations that are smaller than twice the respective transit depth, in order to give an idea how many light curve dispersions of the observed sample were close to the expected transit depth. Two of the *TOIs* had smaller dispersions than their respective ΔF - adding these to the two test observations in the second row that would equate to 4 (values for the year are doubled). From the next column one can postulate that three more *TOIs* would have accuracies that are close (less than two transit depths) to the ΔF value.

The final column goes by the number of detected transits, which was not achieved for the *TESS* candidates, however one of the test observations was successful within the 6 months (2 per year). But the measured transit is an already known planet with attributes (regarding brightness and transit depth), which are rare in the *TESS* sample (see Figures 43 and 44) and therefore might not be very representative to a hypothetical *PLATO* field of candidates, even though brighter stars are being aimed for.

Precision	Min σ	Max σ	Mean σ
[mag]	0.006	0.085	0.022
[%]	0.515	7.508	1.961

Table 23: Precision of the *TOI* light curves (minimum, maximum and average of σ values)

For the achieved precision of *TOI* light curves, Table 23 has listed the respective values. The average light curve dispersion (σ) of all *TESS* candidate observations (last column) is about 2%, which is higher than in other literature, where about 1% was reached (Zhang et al. (2016), Gee et al. (2021)), however under observing conditions with less light pollution and with a brighter sample of targets. Looking at the best case scenarios of the campaign though, about 0.5 – 0.6% is the lowest magnitude dispersion (for *HD 189733 b* it was about 0.6%), which can be seen as a formidable value (first data column). The maximum value of 7.5% is however very imprecise, values around 5 – 6% are not uncommon, but can be traced back to clear issues, e.g. saturation with the Large Refractor or insufficient reference star quality.

What do these numbers mean for the future *PLATO* mission? *PLATO* is expected to yield about ~ 4000 planets ⁸⁰, specifically for stars with $V < 11$ mag (similar to the discussed sample ⁸¹), which means that a citizen science follow-up mission would have to employ 77 observers a year when going only by successful observations to reach 4000 candidates. Going by achieved accuracy, somewhere between 286 – 1000 scientists would be required to observe all 4000 candidates in one year. This is an optimistic approach, because the worst case scenario of 4 observations/person/yr was taken as a minimum. However, there is another caveat to this calculation: the number 4000 is the estimation for the confirmed planet yield of *PLATO*, which would imply a significantly higher number of candidates before being confirmed. The

⁸⁰see footnote 18

⁸¹PLATO mission, ESA: *Planet Yield*. <https://platomission.com/2018/06/04/planet-yield/>, last access: 2022-10-26

limit of observing all candidates in one year has been chosen, since Deeg and Tingley (2017) mentioned, that the ephemeris of a *TESS* candidate needs to be followed up within a year. This issue is however more specific to the *NASA* mission, since *PLATO*'s pointing will remain the same for at least one year (as opposed to *TESS* with 27 days). Therefore, when ignoring that requirement, the same follow-up campaign could be accomplished e.g. by 60 – 200 observers in 5 years.

All this is of course an estimation, many of the candidate stars would also have $V > 11$ mag, with which a high level of accuracy is unlikely reachable, when it comes to the instrumental set-up applied here. If one were to continue with this simple configuration of telescope and detector, the stellar magnitude should be ideally below 8 – 9 mag and the transit depth higher than 1%. However, only a handful of *PLATO* "objects of interest" will satisfy this requirement.

Nevertheless, considering the similarity of *TESS* to *PLATO*, regarding the instrumentation, the target magnitudes, but also specifically regarding transits with a period of < 15 days (due to 27 day pointing cycle of *TESS*) the two missions can be considered highly comparable. This means the here observed sample would be eminently representative of future *PLATO* candidates as far as follow-up at short periods is concerned. However, the importance of follow-up with small ground-based telescopes will be even higher for the upcoming *ESA* mission, since much longer periods of planetary candidates (due to pointings of 1-2 years) are planned and therefore transit events of certain candidates are much rarer. This means that due to the direction, season of detection and the location of large telescopes, many of the high-tier instruments might not be able to catch that event. Therefore, a "swarm" of small telescopes around the globe is even more important, since a high coverage of the earth with observationally ready citizen scientists would peak the probability of a follow-up success for the long-period *PLATO* candidate. Considering the outcome of this observational campaign, the importance of many observers has been strengthened. Since there are many factors that contribute to a highly accurate measurement, the likelihood of success with as many observers as possible is peaked as well. Looking at the number of observations out of the 22 analysed *TOI* measurements, that reached a desirable accuracy (about 5/22, $\sim 23\%$), the continuous activity of observers appears to be essential. This counts not only for external factors, such as weather etc. that cannot be controlled by the (citizen science) astronomer, but also for the applied instrumentation and as a means of staying in practice and improving the observational techniques constantly. This was the case for this campaign as well - unsurprisingly, the expertise and automation of measurement execution was at its highest when the campaign came to an end. The learning curve can also be considered to have risen quickly, throughout the campaign period - at the beginning it was at its most exponential point, especially considering that this was the author's first observational campaign.

As a recap of the previous chapters, the most likely limiting factors of this observation campaign, more precisely to the accuracy of the light curves, were the background noise caused by moon and city lights, the pointing drift combined with the image curvature, that created trends in the light curves, the pixel interpolation due to debayering and lastly scintillation noise. These factors are of course the likeliest reasons for a lower precision out of the ones that were studied here in detail - other important factors that have not been discussed and that play a

decisive role in the measurements cannot be excluded. For example, in some cases that were not discussed in detail, the limitation was saturation of the target.

As a final remark to future attempts of capturing planetary candidate transits, some aspects that could be improved on would be the following: precise polar alignment is essential, preventing a movement of the star across the image in the series can minimize the variation in brightness. Added to the precise alignment, that either requires a lot of time or specific instrumentation, an installation for auto-guiding, which feeds information of occurred tracking errors back to the telescope motor, would minimize the movement from pixel to pixel.

A larger aperture for the telescope would also result in higher signal and angular resolution. The theoretically necessary higher signal for a successful *TOI* detection can be estimated from the successful transit measurement of a 7 mag star with a 2-second exposure. A star of magnitude 7 is about ~ 16 (15.85) times brighter than the average *TOI* at 10 mag (see equation 15, which would require an aperture that is about $\sqrt{16} = 4$ cm larger. This holds true since the signal of an object increases with the area of the pupil, therefore by the squared aperture. This means that a 10 inch *Meade* telescope might have already made some difference, at least when only considering the required signal.

When considering the influence of surrounding temperature, a cooled detector with one colour channel instead of three would increase the precision to an extent that a value below 1% could be reached. Gary (2010) has shown that this is possible - of course there are more approaches that can be taken to improve, for example using more sophisticated techniques to analyse the data. Using background extraction as an extra step before applying the differential photometry or eliminating noise statistically after generating the light curve, just to mention two possibilities.

Zellem et al. (2020) show that a 6-inch telescope suffices to observe a variety of *TESS* candidates as a swarm of telescopes, reaching very high precision. A star with 11.3 mag and an approximately 2% transit depth can be measured up to a precision of 0.6%. This is a comparable precision to the best observations in this work. However, Zellem et al. (2020) also use a self-developed and sophisticated transit data reduction tool for citizen scientists called *EXOTIC: The EXOplanet Transit Interpretation Code*, that automates a plethora of steps that were done manually here and are intricately solved in the code. Therefore, it is possible that maybe even a dimmer star could have been observed in this project, just with a large enough transit depth. Furthermore, the mentioned code could suggest another factor that comes into play, namely the use of the data reduction program. Maybe for the purposes of this endeavour a more sophisticated transit reduction tool would have provided more accurate results. Nevertheless, the aim of the project here was to explore the possibilities of measuring transit light curves of planetary candidates with minimal requirements for easy citizen science application.

Acknowledgements

I want to give my special thanks for the possibility of being part of this project to Dr. Günther Wuchterl, head of the Kuffner Observatory Association and to Prof. Dr. Werner Zeilinger. Dr Wuchterl introduced me to the wonders of the Kuffner Observatory - its instruments and its history, while Prof. Zeilinger was the pillar of the theoretical approach to the project. Together, the two are the architects for the project's conceptualization. They readily supported me throughout this project - whenever I got lost, they prodded me in the right direction.

I also want to thank my parents and family, who are always by my side, wherever I go and no matter what I do.

Abstract (German)

Dieses Masterarbeitsprojekt handelt vom Versuch der Bestätigung von Planetenkandidaten des NASA-Weltraumteleskops *TESS* (genannt *TESS Objects of Interest (TOIs)*) mit kleinen Teleskopen als Leistungsabschätzung einer Follow-Up-Mission für *PLATO*. In der Verantwortung der Kuffner-Sternwarte Wien steht nämlich die "*PLATO Citizen Contribution to Photometric Follow-Up*", deren Aufgabe es ist, "Citizen-Scientists" ("Bürgerwissenschaftler") und professionelle Astronomen für Nachbeobachtungen der voraussichtlich im Jahr 2026 startenden *ESA*-Mission zu engagieren. Bevor dies geschehen kann, sollte jedoch zunächst getestet werden, was mit instrumentellen und softwaretechnischen Minimalanforderungen in diesem Bereich zu erreichen ist. Die Methode der Exoplanetenentdeckung, die hierbei angewandt wird ist die Transitmethode, dessen Hauptkonzept es ist die Verringerung der Helligkeit des Sterns durch den vorbeiziehenden Planeten zu quantifizieren.

Die zu beantwortenden Fragen dieses Projekts sind zunächst, wie viele Planetenkandidaten innerhalb von sechs Monaten von einer Person mit einem Hintergrund in Astronomie nachbeobachtet werden können. Weiters soll eine Bestätigungsrate für die Kandidaten erörtert werden und eine Vorhersage zur Dauer und der Genauigkeit einer solchen sogenannten "Citizen Science"-Mission getroffen werden.

Dafür wurden zwei an der Kuffner-Sternwarte selbst befindliche Teleskope für Helligkeitsmessungen herangezogen: Einerseits der *Große Refraktor* in einer der beiden Kuppeln der Sternwarte - ein Linsenteleskop aus dem 19. Jahrhundert mit 27 cm Aperturweite - und andererseits ein sogenanntes Amateurteleskop auf Stativ mit 20,32 cm (8 Zoll) Durchmesser in Schmidt-Cassegrainscher Bauweise (*Meade LX50*). Die beiden Teleskope besitzen in Kombination mit den ausgesuchten Detektoren (Kameras), Eigenschaften, die für die Bestätigung der Exoplaneten - zumindest der Erwartung nach - behilflich wären. So haben die Teleskope im Vergleich zu den Weltraumteleskopen, mit denen die Kandidaten entdeckt wurden, einen sehr kleinen Abbildungsmaßstab (wenig arcsec/px), der es möglich macht einen Stern und seine Umgebung höher aufzulösen. Das könnte zu einer Bestätigung oder Falsifizierung der von den Weltraumteleskopen vorhergesehenen hypothetischen Planeten aus Transitevents führen.

Bei den für die Beobachtungen angewendeten Detektoren handelt es sich um handelsübliche Spiegelreflexkameras in unterschiedlicher Ausführung - nämlich einerseits die *Canon EOS 5D Mark II* und andererseits die *Sony $\alpha 7$ III*, welche einfach in der Fokalebene der Teleskope

befestigt wurden.

Das Ergebnis waren 26 Beobachtungen über den geplanten Zeitraum von sechs Monaten, wobei zwei dieser Messungen als Tests dienten. Diese waren nämlich keine *TOIs*, sondern bereits bestätigte Planeten, die im Vergleich zu ihrem Stern einen großen Radius (hohe Transittiefe) besitzen und um einen viel helleren Stern als den durchschnittlichen *TESS*-Stern kreisen. Als Bearbeitungsprogramm für die gewonnenen Bilddaten wurde *Siril* gewählt, welches ein beliebtes Programm in der Amateurastronomie ist und aufgrund der Handhabung als benutzerfreundlich bzw. einsteigerfreundlich eingestuft werden kann. Dieses Programm besitzt die Option mit differentieller Photometrie, also in diesem Fall mit einem Ensemble an Vergleichssterne, die Veränderung der Helligkeit des veränderlichen Sterns über die Zeit zu vermessen und diese als Lichtkurve darzustellen.

Aufgrund der hohen Zahl an Beobachtungen und der daraus entstehenden Menge an Ergebnissen/Daten wurden vier der genauesten Messungen der *TOIs* und die beiden Testmessungen als Vergleich genauer besprochen und in einer Vergleichsstudie erläutert. Mit dem Begriff "genaueste Messung" ist hier die Streuung (Standardabweichung) der Datenpunkte in der Lichtkurve im Vergleich zur erwarteten Transittiefe gemeint.

Es wurde eine Liste an Faktoren für die Vergleichsstudie zur Hand genommen, nämlich welche die als Ergebnis aus der Datenanalyse direkt von *Siril* ausgegeben wurden, andere die wetterbedingt Einfluss auf die Datenqualität nehmen und solche die indirekt aus ausgegebenen Daten hergeleitet wurden. Die Qualitätsparameter waren folgende: die Magnitude (V), die Transittiefe (ΔF), das Verhältnis der Gaußfunktionsamplitude für die PSF zum Sternhintergrund (A/B), ein von *Siril* ausgegebener Wert für die FWHM, die Rundheit der Sternabbildungen, das Signal-zu-Rausch-Verhältnis (SNR), die Luftmasse X , die Mondphase, die bereits erwähnte Standardabweichung (Streuung) der Datenpunkte in der Lichtkurve, der Fokus der Beobachtung, Bewölkung, die Beobachtungsrichtung (da im Osten die Stadt Wien für stärkere Lichtverschmutzung sorgt), die Vergleichssterne und die Bewegung des Sterns über den Detektor über den Zeitraum der Beobachtung. Dies sind einige Faktoren, welche anhand von Vergleichen untereinander, aber auch mit den Testaufnahmen verwendet wurden, um Schlüsse zu deren Qualität ziehen zu können. Weiters wurde bei Lichtkurven, die einem Transit ähnelten, sogenannte "Off-Target"-Lichtkurven erstellt, welche Eigenschaften der Vergleichssterne verdeutlichen sollen, die den Transit nachahmen würden und daher das Signal als Transit falsifizieren würden.

Zu den *TOIs* konnten keine eindeutigen Hinweise auf Transitsignale gefunden werden. Zwei Beobachtungen kommen doch sehr nahe an solch eine Behauptung heran, jedoch sind andere systematische Fehler wahrscheinlich für das Signal verantwortlich (siehe "Off-Target"-Lichtkurve). Letztendlich war das Ergebnis, dass die größten Fehler wohl vom Hintergrundrauschen (Poisson, Mond, Lichtverschmutzung), der Szintillation, aber auch womöglich von den drei Farbkanälen, die alltägliche Kameras besitzen, kommen. Einer der stärksten Effekte ist aber vermutlich der Drift des Sterns über den Detektor, aufgrund von unzureichender polarer Achsenausrichtung. Der Stern wird hierbei, speziell beim Schmidt-Cassegrain-Teleskop verschiedenen Bereichen der intrinsischen Bildfeldwölbung ausgesetzt aber auch der unterschiedlichen Eigenschaften individueller Pixel sowie ungleichmäßiger Flatfieldkorrektur.

Eine der Testbeobachtungen, nämlich von *HD 189733 b* war jedoch erfolgreich - ein Transit konnte gemessen und auf die *Exoplanet Transit Database (ETD)* hochgeladen werden. Dies wäre bei erfolgreicher Messung auch für die *TESS*-Kandidaten so vorgesehen gewesen.

Die Ergebnisse für die durchschnittliche Lichtkurvengenauigkeit waren im Bereich von 2% zu finden, wobei die besten Aufnahmen sogar auf 0.5% in der Photometrie kamen. Für die Rate der Bestätigungen musste man aufgrund des Mangels an erfolgreichen *TOI*-Transitmessungen auf die der ausreichenden Genauigkeit zurückgreifen. Somit wären 4 – 14 Messungen pro Jahr pro Person möglich, was für 4000 erwartete *PLATO*-Kandidaten eine erhebliche Menge an Beobachtern für eine Nachbeobachtung innerhalb eines Jahres nach sich ziehen würde. Wenn man in der Rate nur die Anzahl der Beobachtungen nehmen würde, wären dies letztendlich 52 beobachtete pro Person pro Jahr.

Abstract (English)

This Master's thesis project is about the attempt to confirm planetary candidates of NASA's *TESS* space telescope (called *TESS Objects of Interest (TOIs)*) with small telescopes as a performance assessment of a follow-up mission for *PLATO*. The Kuffner Observatory in Vienna has the responsibility as part of the "*PLATO Citizen Contribution to Photometric Follow-Up*" to involve citizen scientists and professional astronomers for follow-up observations of the *ESA* mission, which is expected to launch in 2026. Before this can happen, however, the feasibility of such observations should first be tested with instrumental and software minimum requirements. The method of exoplanet detection applied here is the transit method, the main concept of which is to quantify the reduction in star brightness caused by the passing (transiting) planet.

The questions to be answered in this project are, first, how many planetary candidates can be identified within six months by a person with a background in astronomy. Furthermore, a confirmation rate for the candidates will be discussed and a prediction on the duration and accuracy of such a so-called "citizen science" mission will be made.

For this purpose, two telescopes located at the Kuffner Observatory itself were used for brightness measurements. These were the *Large Refractor* in one of the two domes of the observatory - a lens telescope from the 19th century with 27 cm aperture - on the one hand and on the other a so-called amateur telescope on a tripod with 20.32 cm (8 inch) diameter in Schmidt-Cassegrain design (*Meade LX50*). The two telescopes, in combination with the selected detectors (cameras), have properties that would be helpful for the confirmation of exoplanets - at least according to expectation. Compared to the space telescopes with which the candidates were discovered, the telescopes have a very small imaging scale (few arcsec/px), enabling a higher resolution of the star and its surroundings. This could lead to a confirmation or falsification of the hypothetical planets predicted from transit events detected by the space telescopes.

The detectors used for the observations are commercial DSLR cameras of two different types - namely, on the one hand the *Canon EOS 5D Mark II* and on the other the *Sony $\alpha 7$ III*, which were simply attached to the telescopes at the respective focal planes.

The result was 26 observations over the planned six-month period, with two of these measurements serving as tests. These two were not *TOIs*, but already confirmed planets, having a large radius compared to their host star (high transit depth) and orbiting a much brighter star than the average *TESS* star.

Siril was chosen as the image processing program, which is a popular tool in amateur astronomy and due to the handling can be classified as user-friendly or beginner-friendly. This program has the option of measuring the change of the variable star's brightness over time with differential photometry, i.e. with an ensemble of comparison stars, and to display that change as a light curve graph.

Due to the high number of observations and the resulting amount of results/data, four of the most accurate measurements of the *TOIs* and the two test measurements were discussed in detail within the framework of a comparative study. In this case, the term "most accurate measurement" means the best dispersion (standard deviation) of the data points in the light curve as compared to the expected transit depth value.

A list of factors was used for the comparative study, namely those that were directly output by *Siril* as a result of the data analysis, others that have a weather-related influence on the data quality and such parameters that were indirectly derived from the output data. The quality parameters were as follows: The magnitude (V), the transit depth (ΔF), the ratio of the PSF amplitude to the stellar background (A/B), a value for the FWHM output by *Siril*, the roundness of the stellar images, the signal-to-noise ratio (SNR), the airmass X , the moon phase, the already mentioned standard deviation (scatter/dispersion) of the data points in the light curve, the focus of the observation, cloudiness, the direction of observation (since in the east the city of Vienna provides for stronger light pollution), the comparison stars and the movement of the star across the detector over the period of the observation. These are some of the factors that were used to draw conclusions on the light curve quality by comparing the results among the *TOIs* and also with the test observations. Furthermore, for light curves that resembled a transit, so-called "off-target" light curves were created, which should highlight properties of the comparison stars that would mimic the transit and therefore falsify the signal as a transit.

However, no clear evidence of transit signals could be found for the *TOIs*. Two observations do come very close to such a claim, however other systematic errors are probably responsible for the signal (see "off-target" light curve). Ultimately, the result was that the largest errors probably come from background noise (Poisson, moon, light pollution), scintillation, but also possibly from the three color channels that the applied cameras have. One of the strongest effects, however, is probably the drift of the star across the detector, due to insufficient polar axis alignment. The star is exposed to different ranges of intrinsic field curvature, especially in the Schmidt-Cassegrain telescope, but also to the different properties of individual pixels as well as non-uniform flat-field correction.

However, one of the test observations, *HD 189733 b*, was successful - a transit was measured and uploaded to the *Exoplanet Transit Database (ETD)*. This approach would have been taken for the *TESS* candidates as well, if the measurement had been successful.

The results for the average light curve accuracy were in the range of 2%, with the best images even reaching 0.5% in photometry. For the rate of confirmations one had to resort to that

of sufficient accuracy due to the lack of successful *TOI* transit measurements. Thus, 4 – 14 measurements per year per individual would be possible, which for 4000 expected *PLATO* candidates would entail a substantial amount of observers for follow-ups within a year's time. If one would consider only the total number of observations in the rate, this would result in 52 observed per person per year.

A. Light Curve Figures

As part of the appendix, all generated light curves, that have not yet been presented can be found. This involves the light curves with their original integration time of 30s for the *TOIs* (see section A.1). The original exposures of *WASP-33 b* (5s) and *HD 189733 b* (2s) can be found in chapter 6.5.

The section following that one lists all stacked/binned light curves of the observations that have not been discussed further. These binnings were only applied to a handful of light curves, that were not saturated and where an improvement could have been expected. These *TOI* light curves exhibit integration times of 60s (binning of 2, see section A.2).

The final section of the appendix contains the light curves generated for the saturated observations, where a star that was not over-exposed and fitting reference stars were chosen in the green channel to create a light curve. This was done to check whether a better accuracy could have been reached than with the saturated target (see section A.3). Their results were discussed in the shape of their resulting σ values (see Table 11).

A.1. Light Curves with Original Integration Time

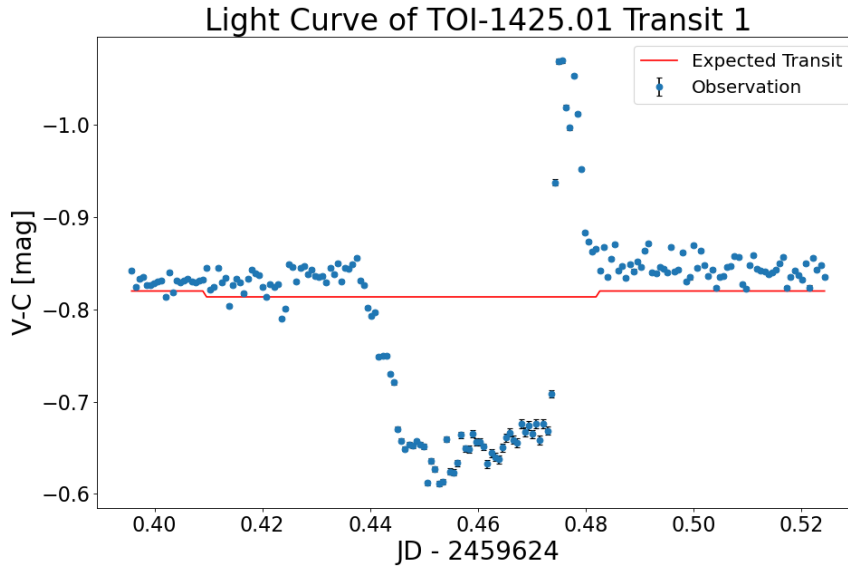


Figure 47: Generated light curve of TOI-1425.01, first observation

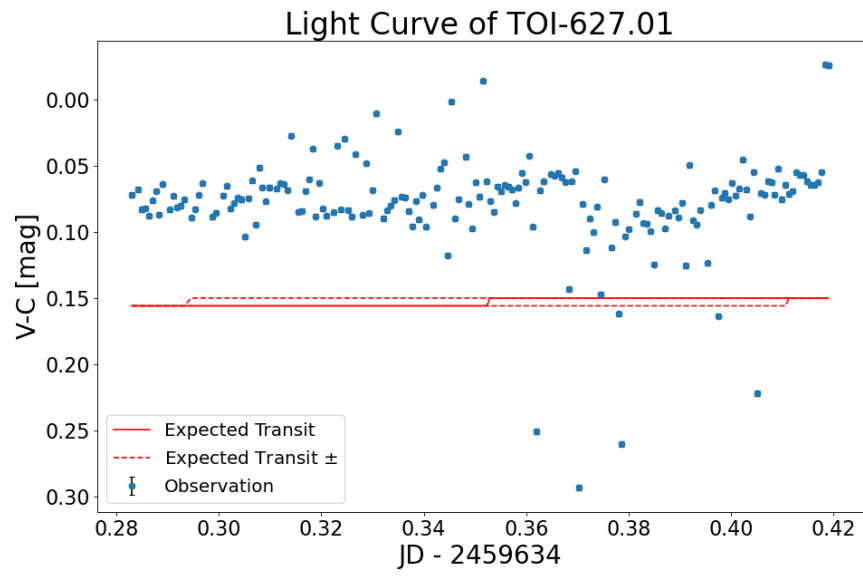


Figure 48: Generated light curve of TOI-627.01

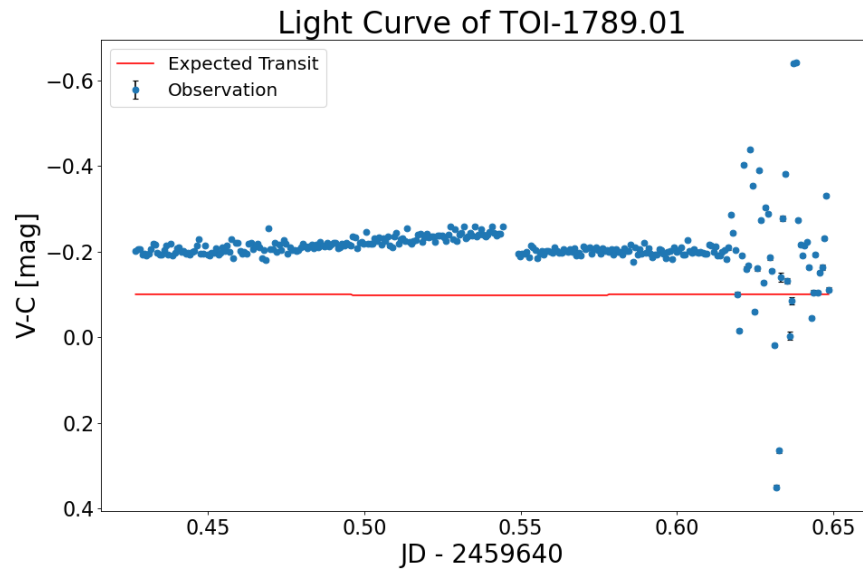


Figure 49: Generated light curve of TOI-1789.01

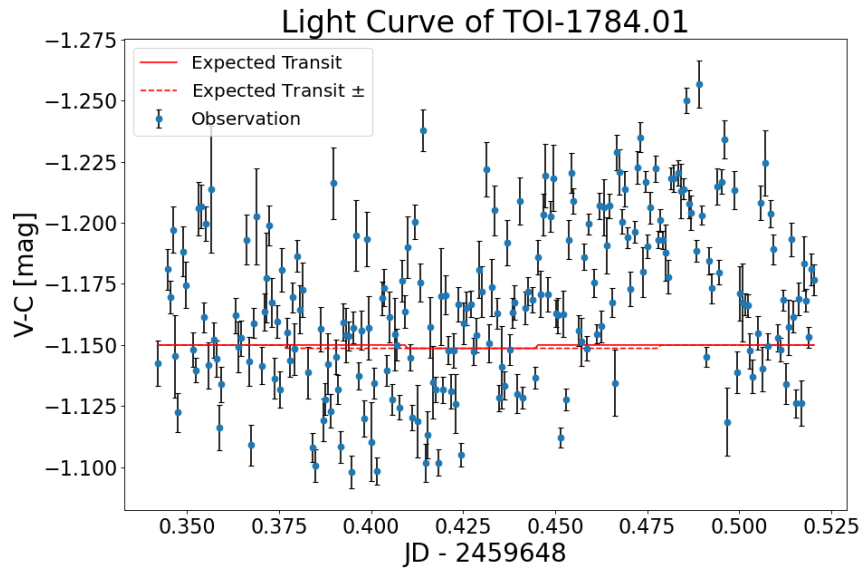


Figure 50: Generated light curve of TOI-1784.01

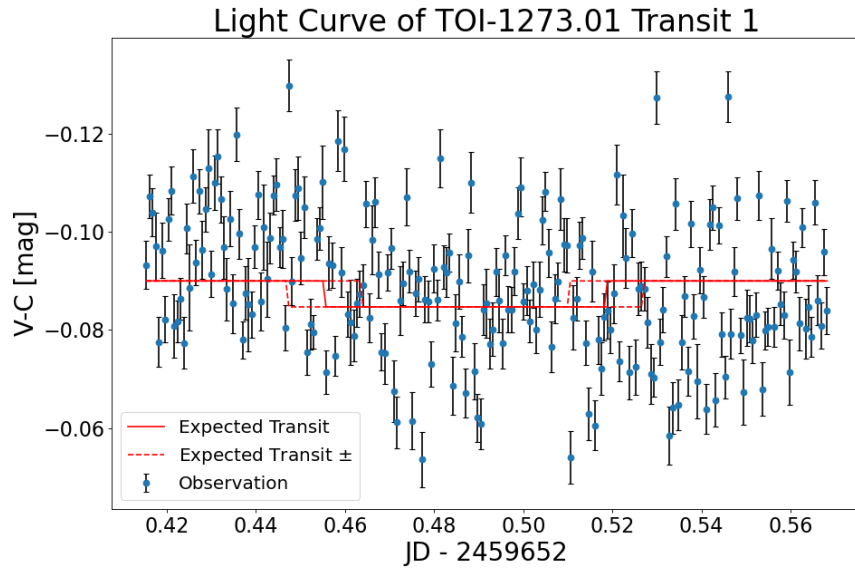


Figure 51: Generated light curve of TOI-1273.01, first observation

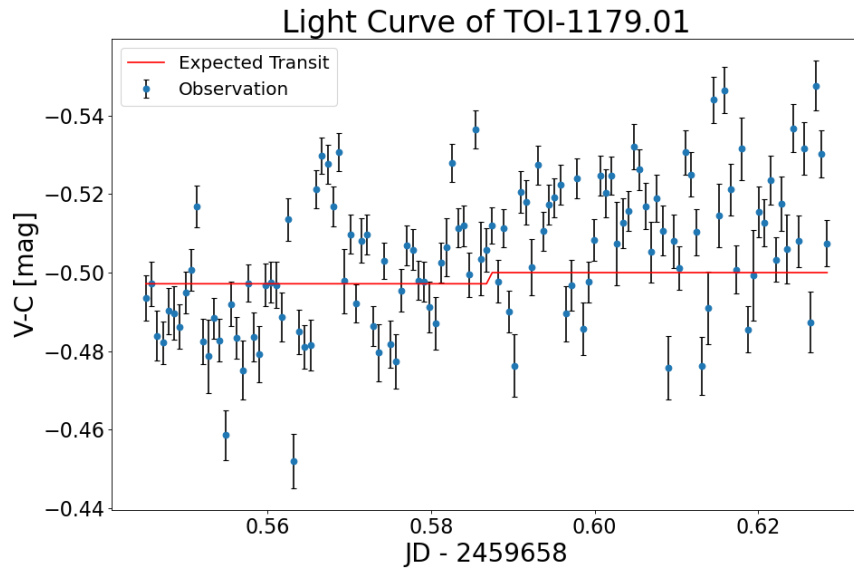


Figure 52: Generated light curve of TOI-1179.01

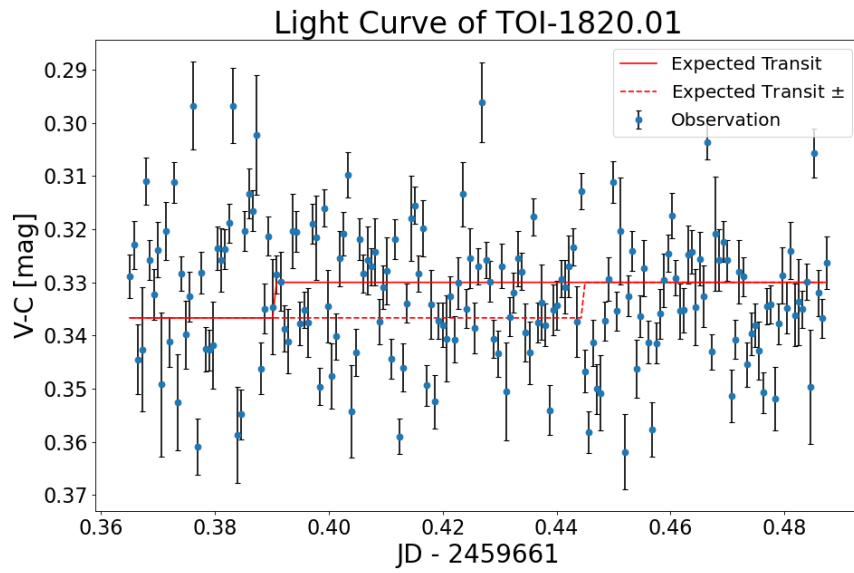


Figure 53: Generated light curve of TOI-1820.01

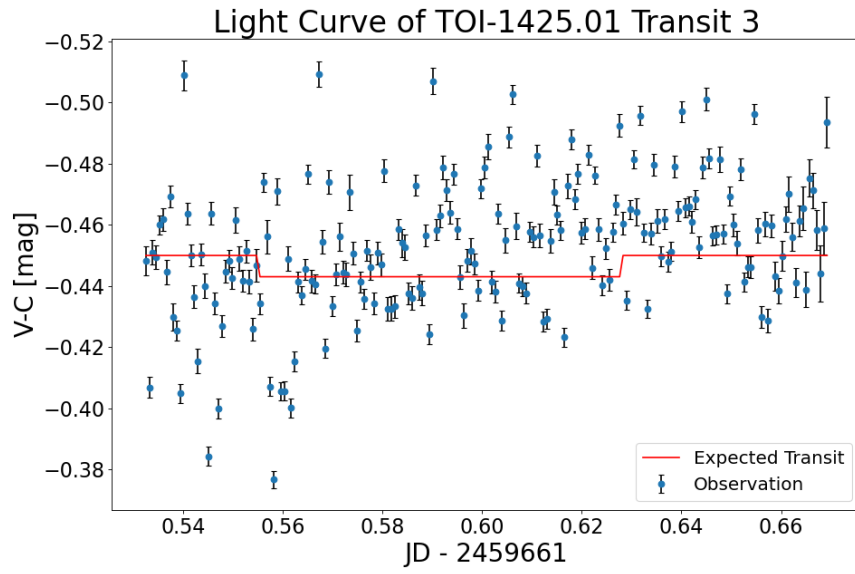


Figure 54: Generated light curve of TOI-1425.01, third observation

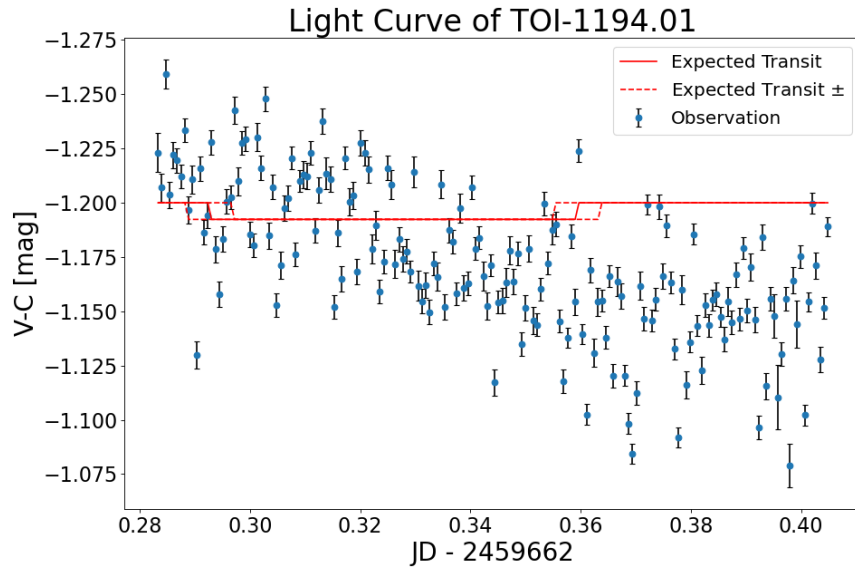


Figure 55: Generated light curve of TOI-1194.01

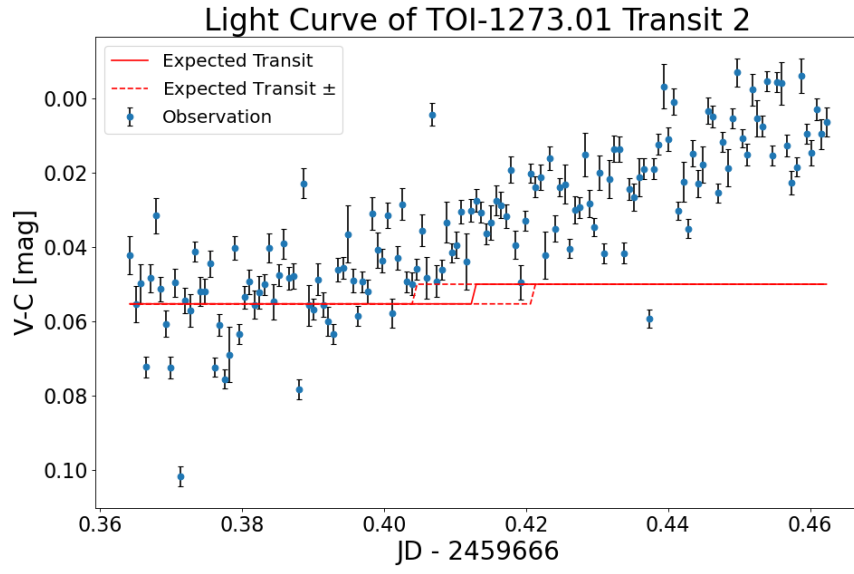


Figure 56: Generated light curve of TOI-1273.01, second observation

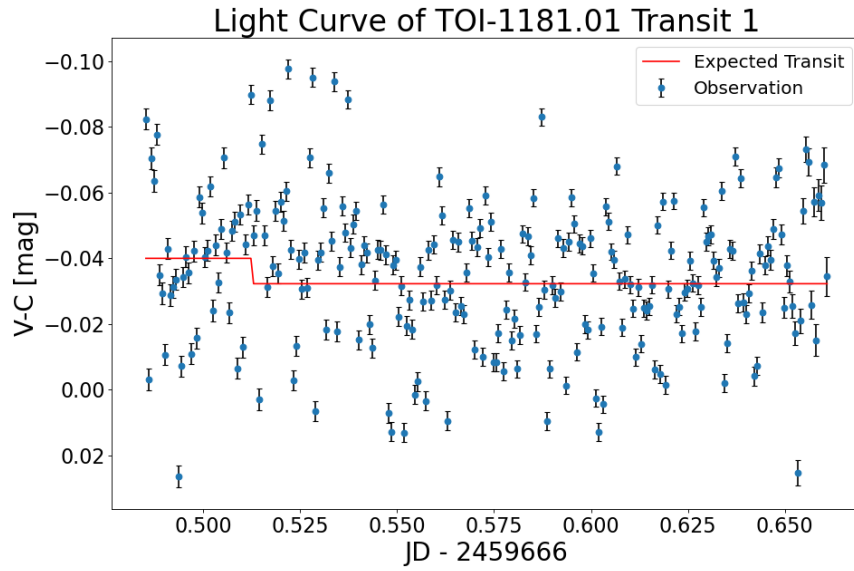


Figure 57: Generated light curve of TOI-1181.01, first observation

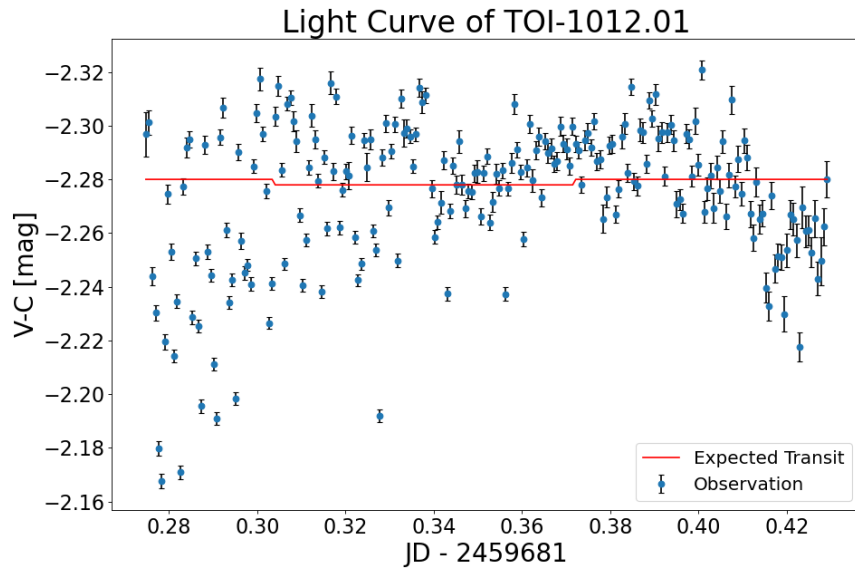


Figure 58: Generated light curve of TOI-1012.01

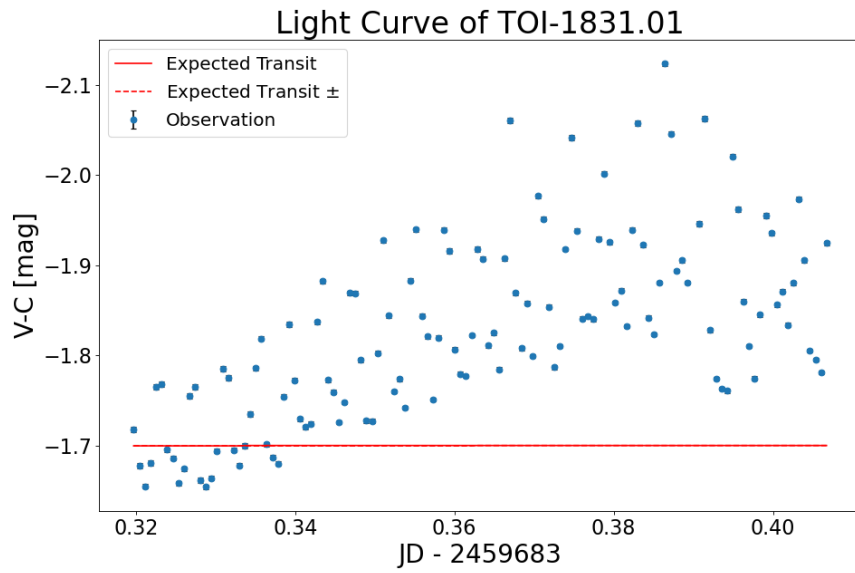


Figure 59: Generated light curve of TOI-1831.01

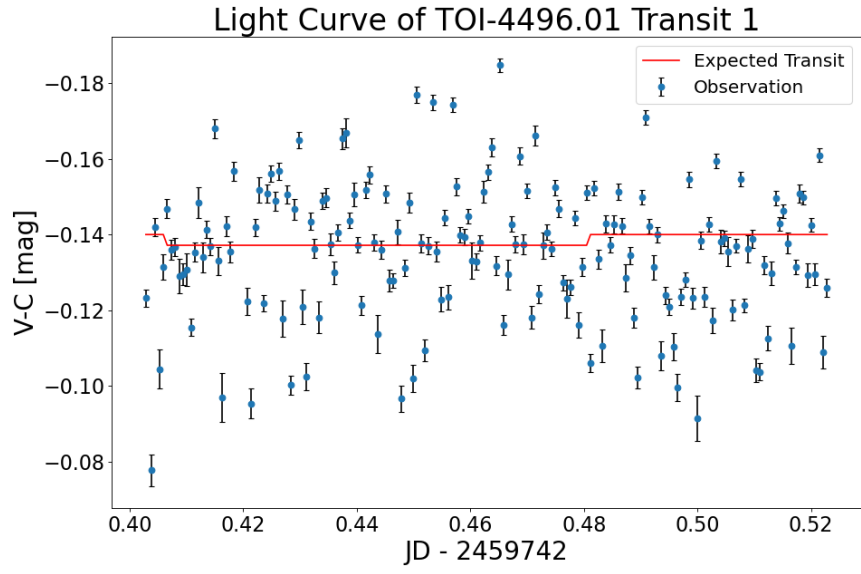


Figure 60: Generated light curve of TOI-4496.01, first observation

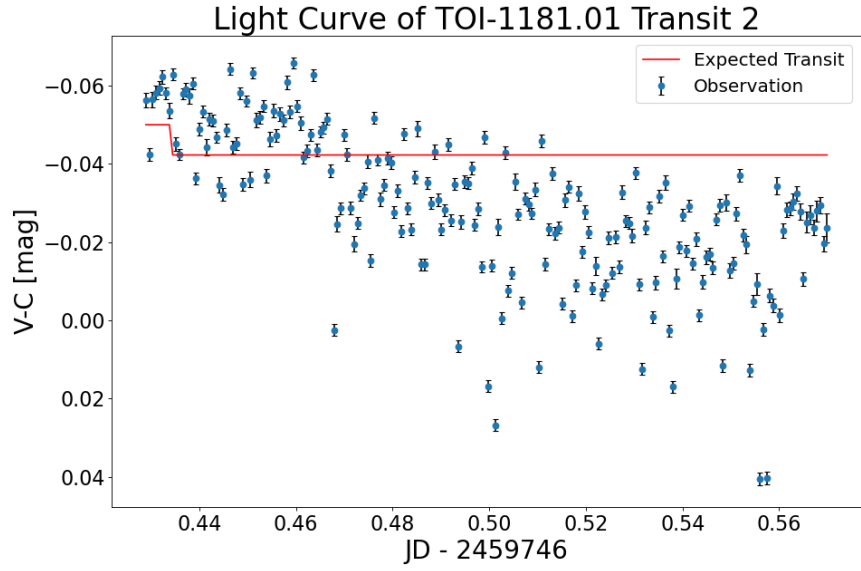


Figure 61: Generated light curve of TOI-1181.01, second observation

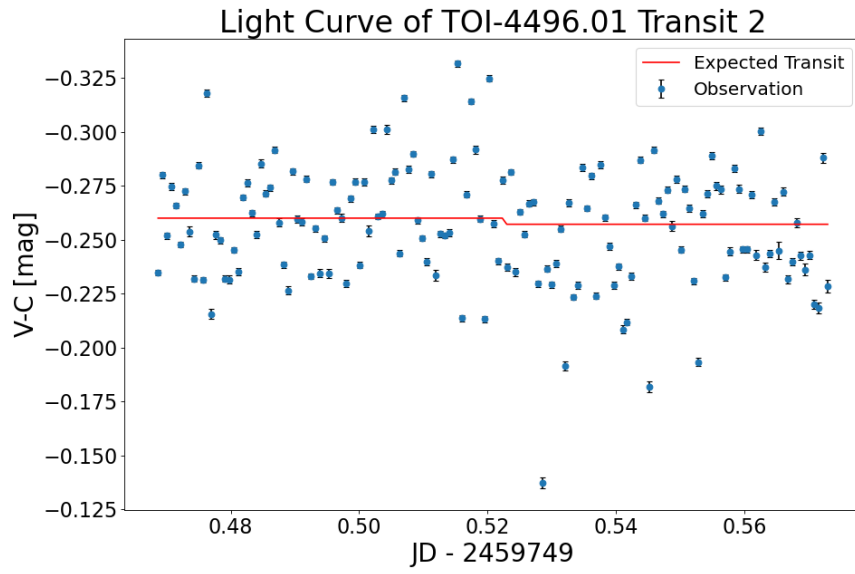


Figure 62: Generated light curve of TOI-4496.01, second observation

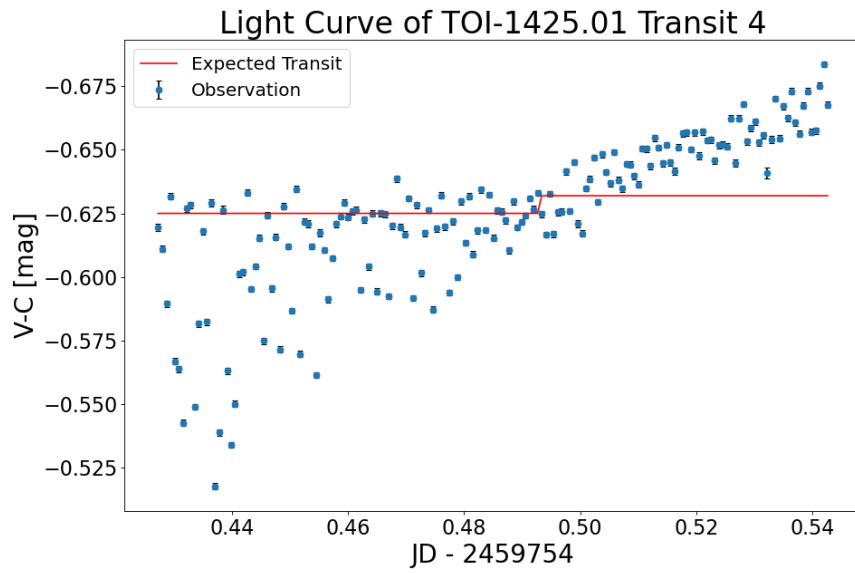


Figure 63: Generated light curve of TOI-1425.01, fourth observation

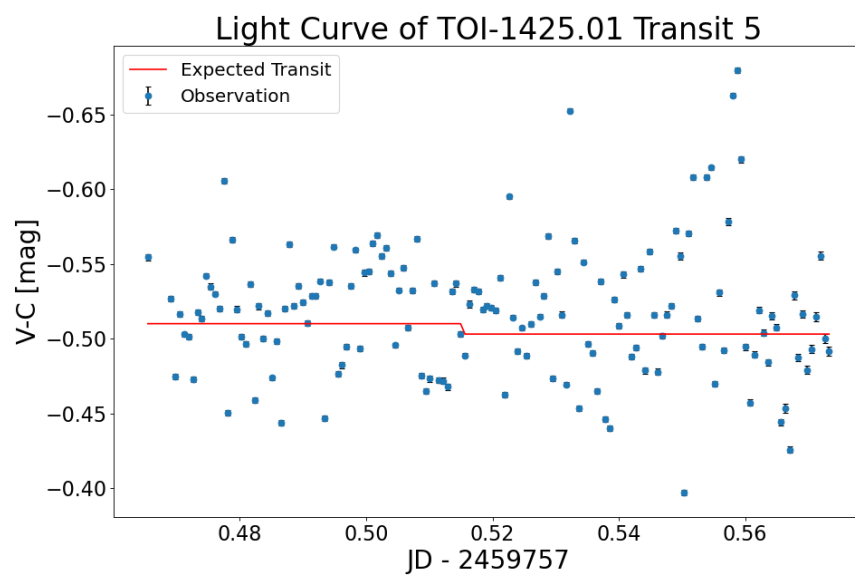


Figure 64: Generated light curve of TOI-1425.01, fifth observation

A.2. Light Curves Stacked

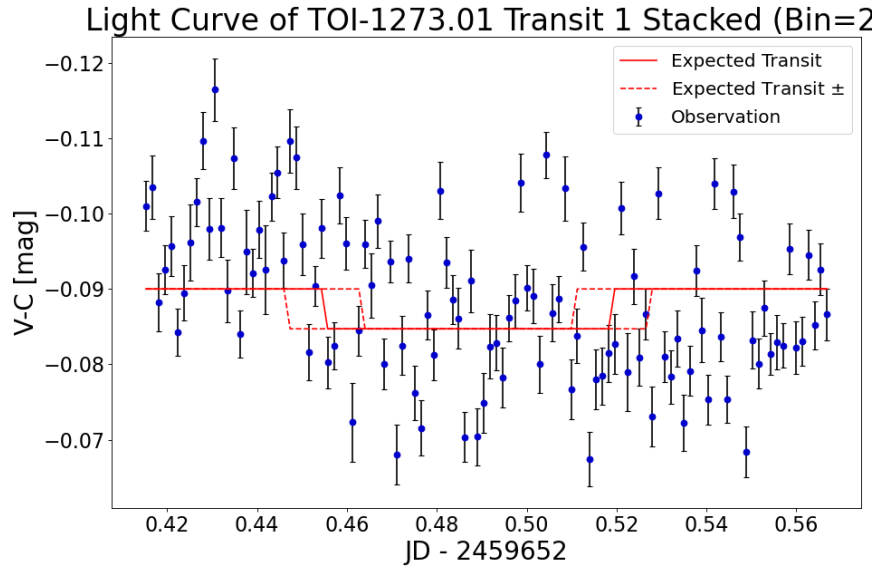


Figure 65: Stacked light curve of *TOI-1273.01* first observation, with bin=2

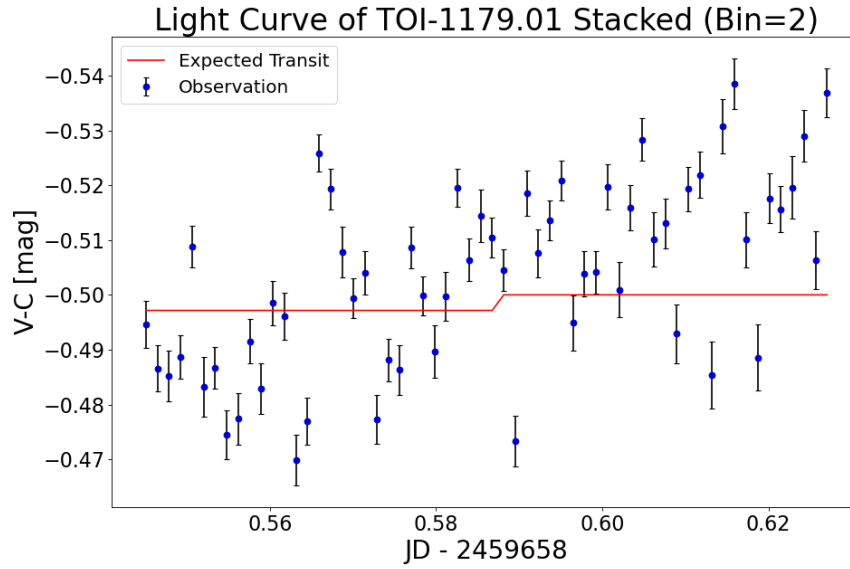


Figure 66: Stacked light curve of *TOI-1179.01* with bin=2

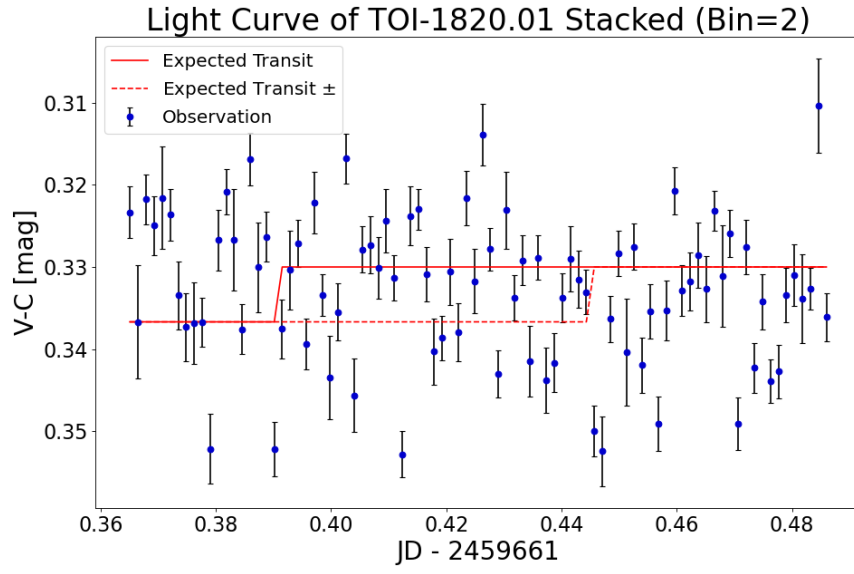


Figure 67: Stacked light curve of *TOI-1820.01* with bin=2

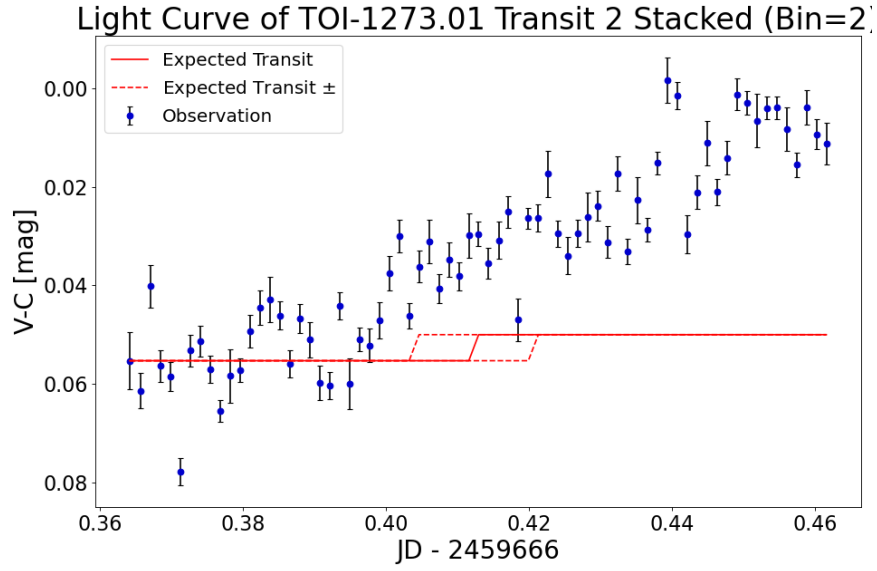


Figure 68: Stacked light curve of *TOI-1273.01* second observation, with bin=2

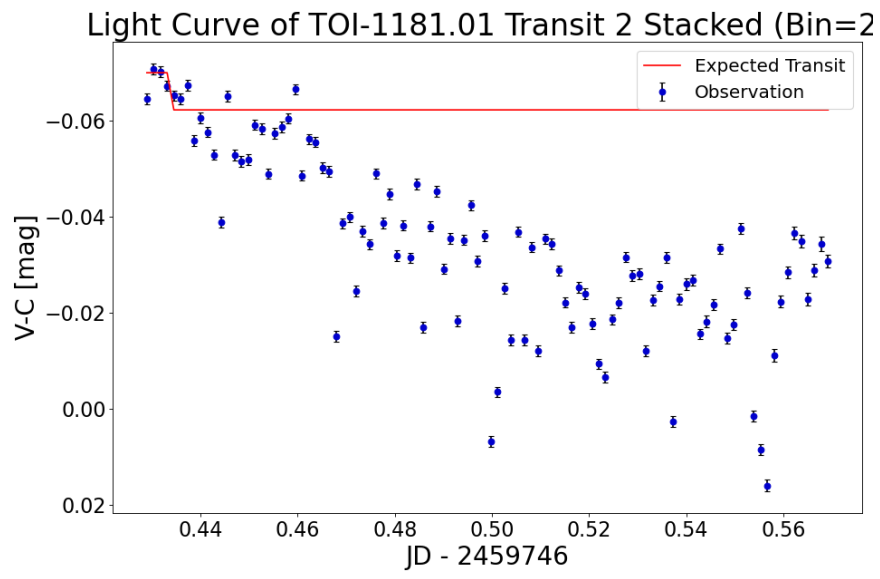


Figure 69: Stacked light curve of *TOI-1181.01* second observation, with bin=2

A.3. Light Curves for Accuracy

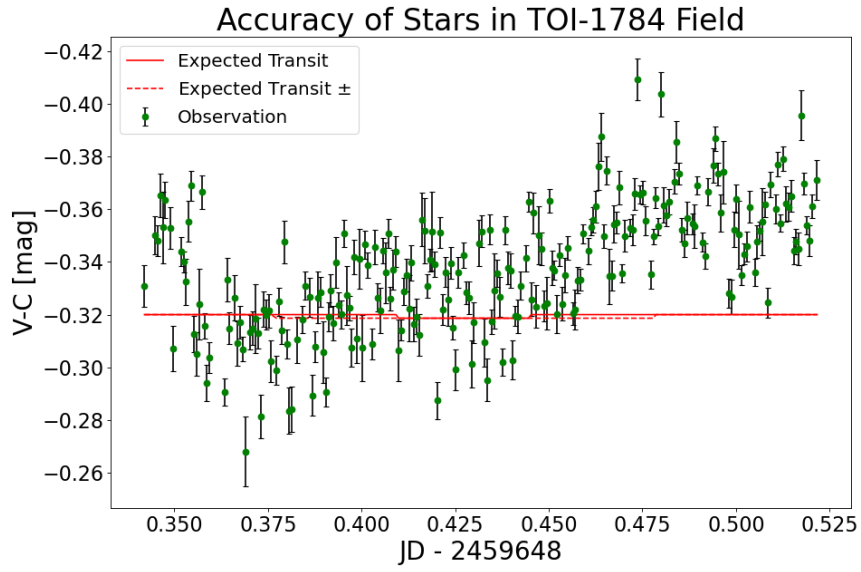


Figure 70: Accuracy light curve of *TOI-1784.01*

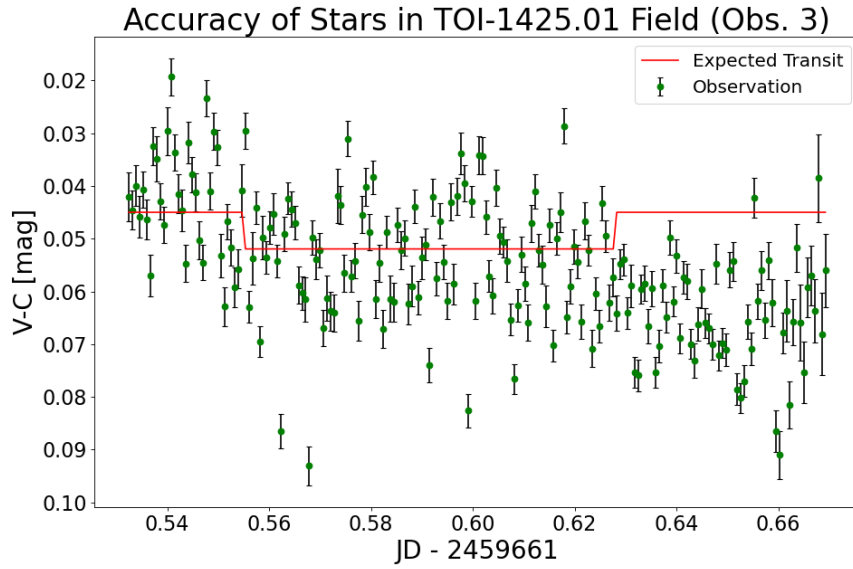


Figure 71: Accuracy light curve of *TOI-1425.01* third observation

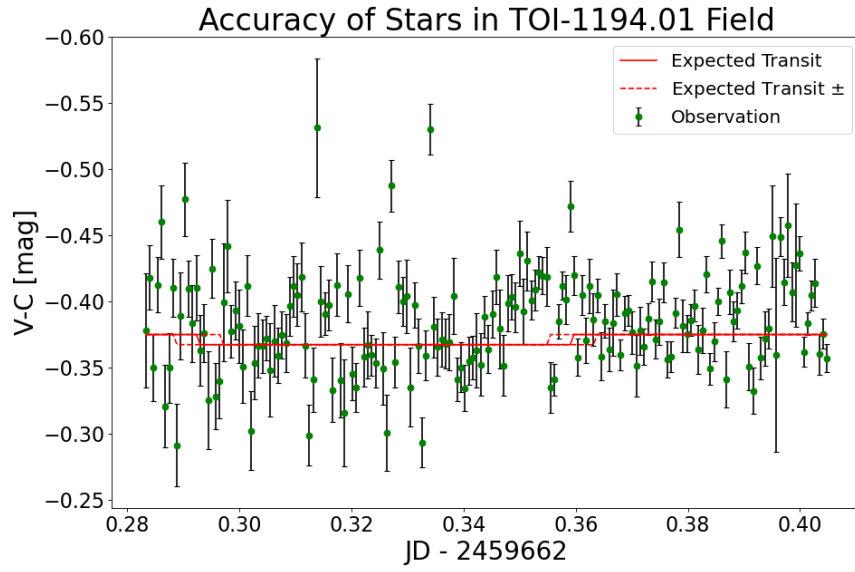


Figure 72: Accuracy light curve of *TOI-1194.01*

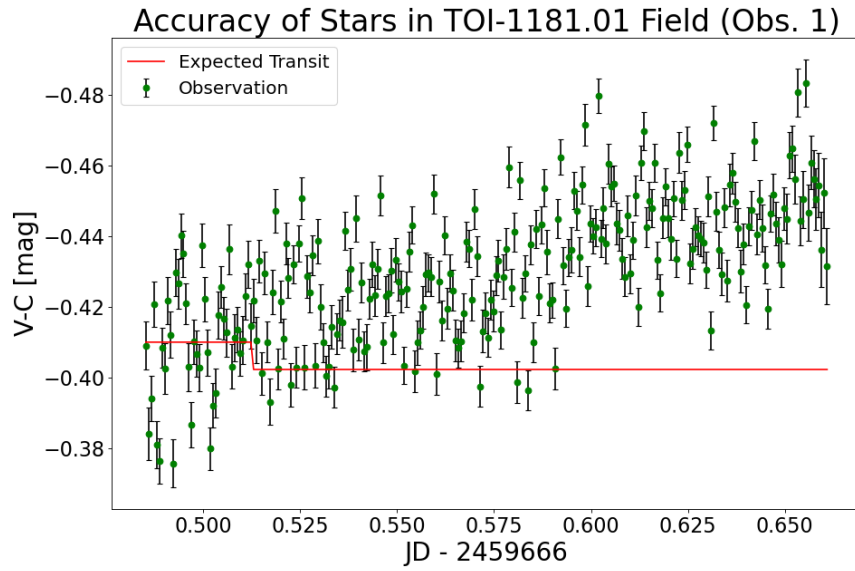


Figure 73: Accuracy light curve of *TOI-1181.01* first observation

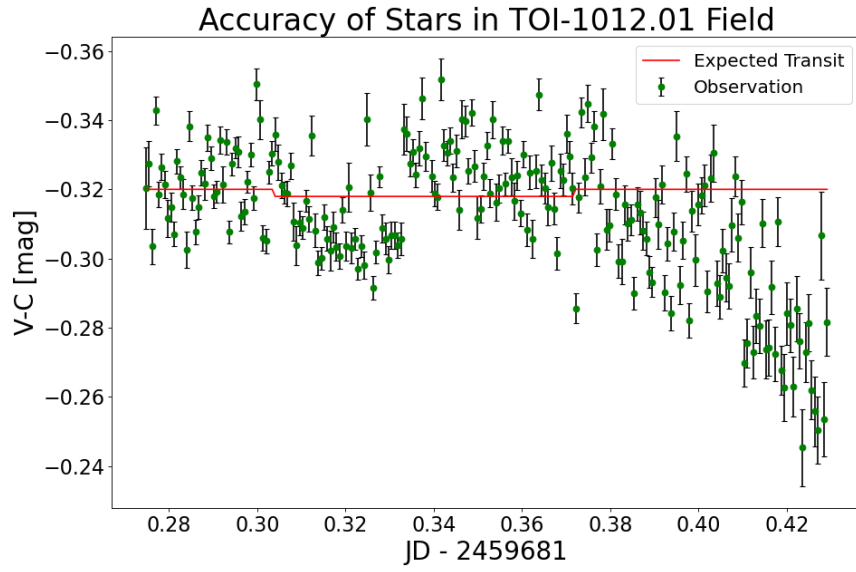


Figure 74: Accuracy light curve of *TOI-1012.01* observation

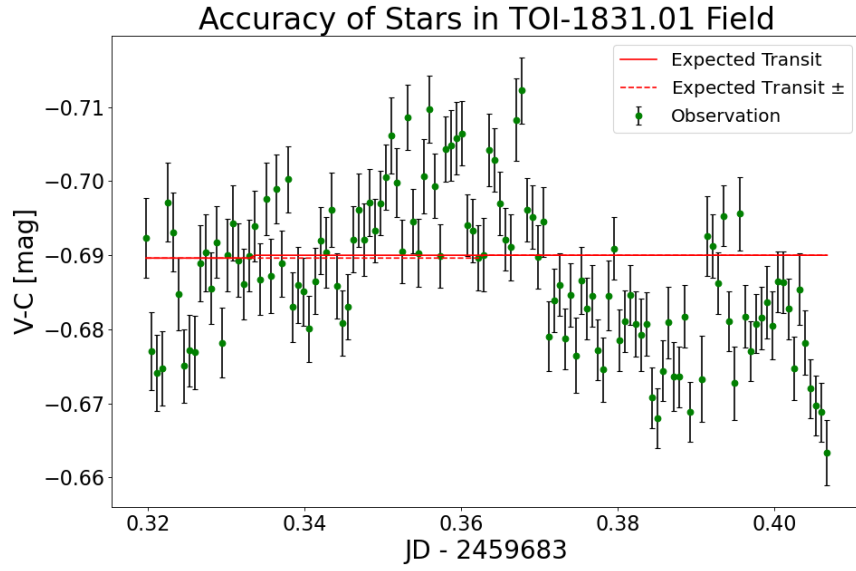


Figure 75: Accuracy light curve of *TOI-1831.01*

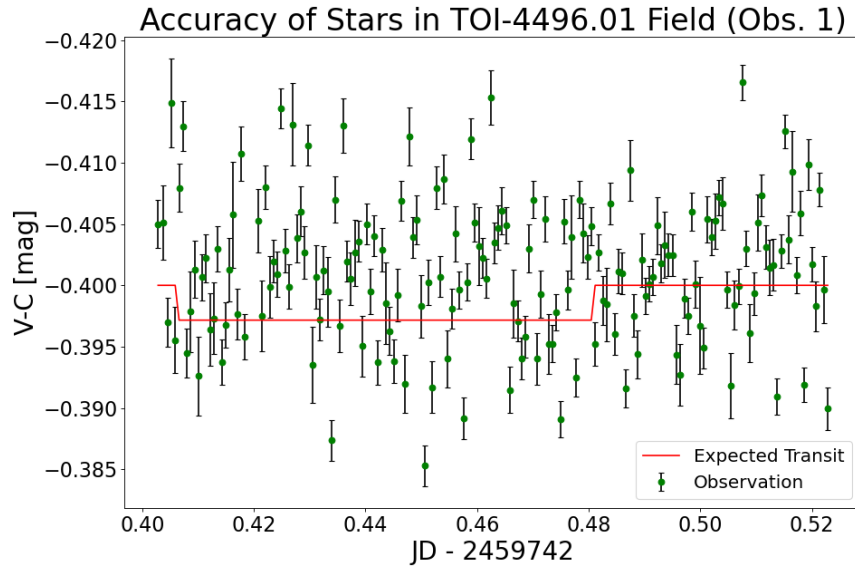


Figure 76: Accuracy light curve of *TOI-4496.01* first observation

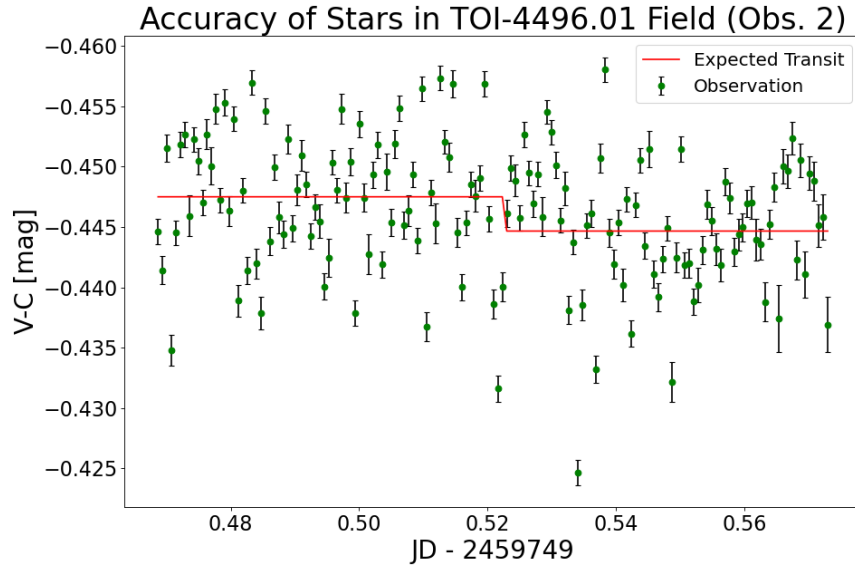


Figure 77: Accuracy light curve of *TOI-4496.01* second observation

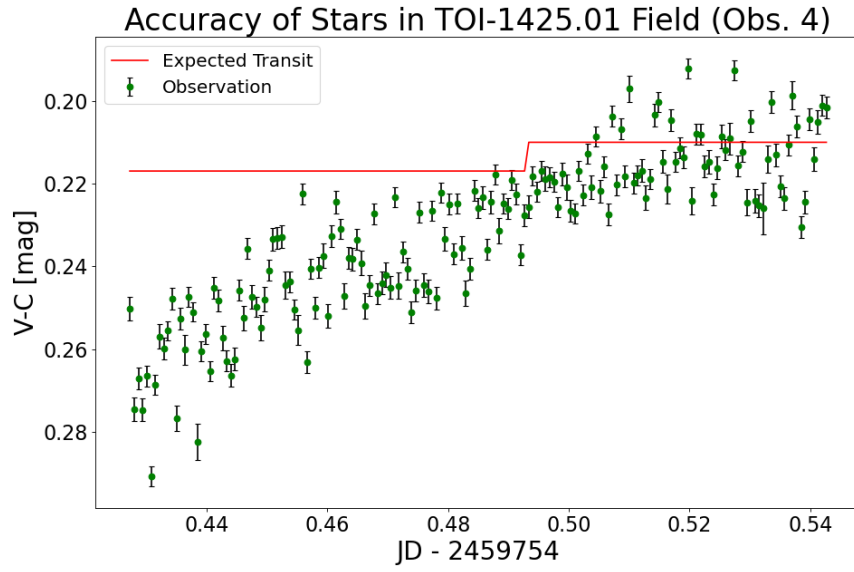


Figure 78: Accuracy light curve of *TOI-1425.01* fourth observation

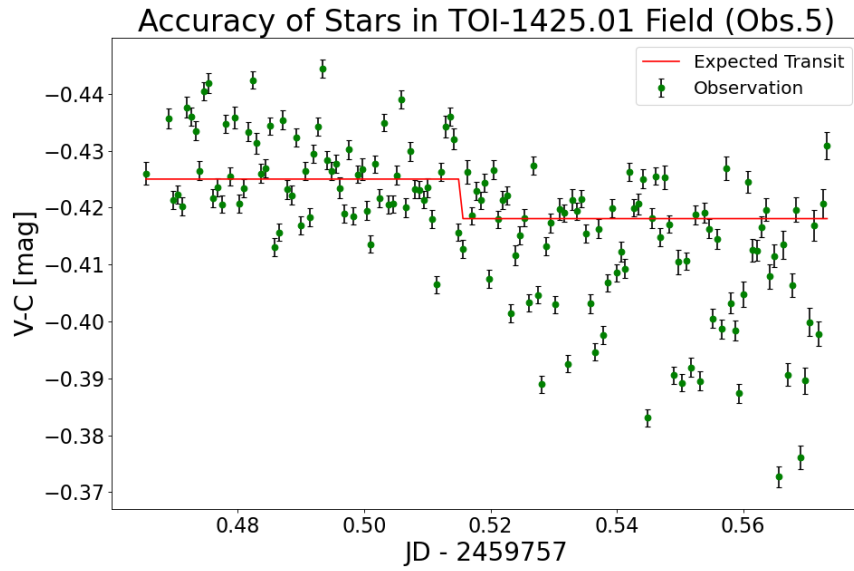


Figure 79: Accuracy light curve of *TOI-1425.01* fifth observation

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