Spring 2019

Analysis of Autoguiding for Exoplanet Transit Research at the UNH Observatory

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ANALYSIS OF AUTOGUIDING FOR EXOPLANET TRANSIT RESEARCH AT THE UNH OBSERVATORY

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May 14, 2019

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Abstract

This paper will discuss the proper calibration technique for an autoguider of a CCD[1] camera and the results that follow from successful exoplanet transit observations. A brief background on exoplanets, the transit method, and the analysis of their parent stars through photometry will be examined. The results will be presented in a before and after framework that will visually represent the data improvements from autoguiding as graphical Light Curves (LC). The addition of being able to autoguide at the UNH observatory will work towards providing future students with the possibility of performing follow-up ground-based observations and archiving their work online to aid the entire astronomy community.

[1] A list of all acronyms used in this paper is located in the Appendices section.

1 Introduction

The theory of exoplanet existence has long been a thought in the minds of astronomers and scientists. It has only been recently, that exoplanet existence has been confirmed and observed from telescopes inside and outside of the Earths atmosphere [8]. These extrasolar planets are simply defined as a planet that revolves around a star that is not the Sun in our solar system [12]. Detecting exoplanets has posed an arduous task for scientists for two reasons. One reason being that the exoplanet is so small in size compared to the distances they are being detected at. The second reason is that the light given off by the parent star of which the exoplanet orbits is typically on the order of several billions times in brightness compared to the light given off by the planet [8]. These two challenges combined makes visualizing exoplanets in a photograph of the night sky nearly impossible. It is for this reason that the majority of understanding exoplanets comes from indirect observational techniques.

There are a few different techniques used to indirectly detect exoplanets and each method has its own guidelines that make it a preferred method to use compared to another method. The exoplanet transit method is the process of taking repetitious images of the planet's parent star while the planet comes in between Earth and the parent star, as viewed from Earth. During this time, the planet will block the light given off by its parent star and, when graphed, can be seen as a "dip" in the visible light curve produced by the parent star [9]. This will be the observational technique I will be focusing on due to its success among the various methods and for the reason that the UNH Observatory is both capable of performing this method, as well as improving it.

The use of autoguiding during observational astronomy is an essential component to improving the data yield from exoplanet transits at the UNH Observatory. As time progresses, stars move across the night sky due to the Earth's rotation. Autoguiding allows for the telescope to very accurately track the light produced by a star throughout its journey across the night sky. Without the tracking ability of an autoguider, the observer would be responsible for adjusting the telescopes position to ensure it stays with the star. These adjustments of the telescope typically result in systematic errors and thus flawed data taken of the transit. Additionally, when observing deep space objects that are either very dim or far away from Earth, exposure times are typically set for elongated periods in order to capture more light in a single image than a short exposure would. Longer exposure times lead to an increase in star movement and thus being able to avoid a systematic error by avoiding manually adjusting the telescope is crucial to limited data flaws [2]. This paper will analyze the data and images produced by the technique of autoguiding and assess the information to prove that it is a necessity for students here on campus.

2 Exoplanets and The Transiting Method

To reiderate, an exoplanet is a planet, outside of our solar system, that orbits a star known as its parent star. In January of 1992 the first two exoplanets were discovered, simultaneously, orbiting a pulsar in the constellation of Virgo [13]. The two people credited with the discovery, Aleksander Wolszczan and Dale Frail, made history as being the first people to confirm what many scientists and astronomers had already theorized but had yet to have any overwhelming proof of. This major discovery coming just shy of three decades ago speaks as to how new this area of space science truly is.

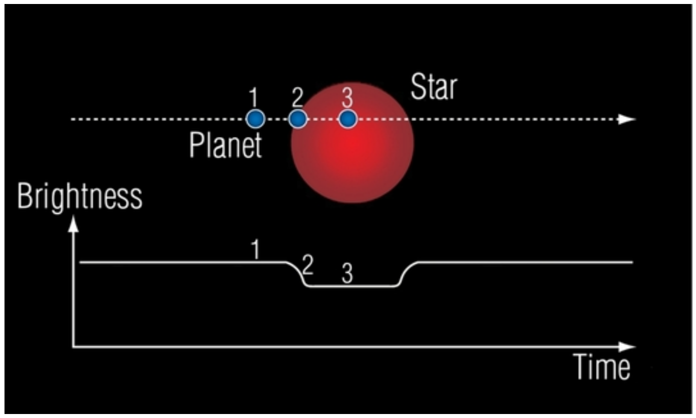

Figure 1: *This image provides a clear visual representation of what is happening when a planet transits in front of its parent star with respect to the Earth's point of view. The light curve shown on the graph, beneath the illustration, is what the images of the night sky produce during a transit when graphed. The process of producing a light curve will be discussed in more detail later on [20].*

As mentioned before, the exoplanet transit method is one of many methods used to indirectly observe exoplanets orbiting around their parent star. There are two different kinds of transits; a primary transit and a secondary transit. A secondary transit occurs when the exoplanet transits completely behind the parent star from the Earth field of view. A primary transit is the one depicted in Fig. 1 and the only type of transit that was observed for the use of this paper [20]. Both types of transits can be examined to yield important qualities about the exoplanet in question. By examining secondary transits, scientists are able to map together the light spectrum generated by an exoplanet. This is done by examining the light spectrum produced from the parent star, both, when the exoplanet is completely shielded from Earth's view and when the exoplanet is visible [20]. This strategy can provide insight on the exoplanet's atmospheric composition as well as the temperature it gives off. Another way to measure the atmospheric composition of an exoplanet is by studying the light given off by the parent star that penetrates through the atmosphere of the exoplanet. This light is absorbed by the planet's atmosphere at a variety of wavelengths and degrees. Scientists can then generate an absorption spectrum of the transit depth at multiple different wavelengths [20]. Atmospheric composition is a very interesting quality to observe because it leads to more insight on what is going on beneath that planet's atmosphere and even more interestingly enough, if the atmosphere is one that could potentially harbor life.

It is certain that there are several unique characteristics that make studying and observing exoplanets essential to our understanding of space and the systems that inhabit it. The transit method can also determine information regarding a planet's orbital period [10]. For example, here on Earth, we have an orbital period of roughly 365 earth-days. An orbital period can then be used to determine the distance between the exoplanet and its parent star. This information can provide some deeper knowledge regarding the specific solar system it is in when comparing this foreign system to what we have already learned from our own solar system.

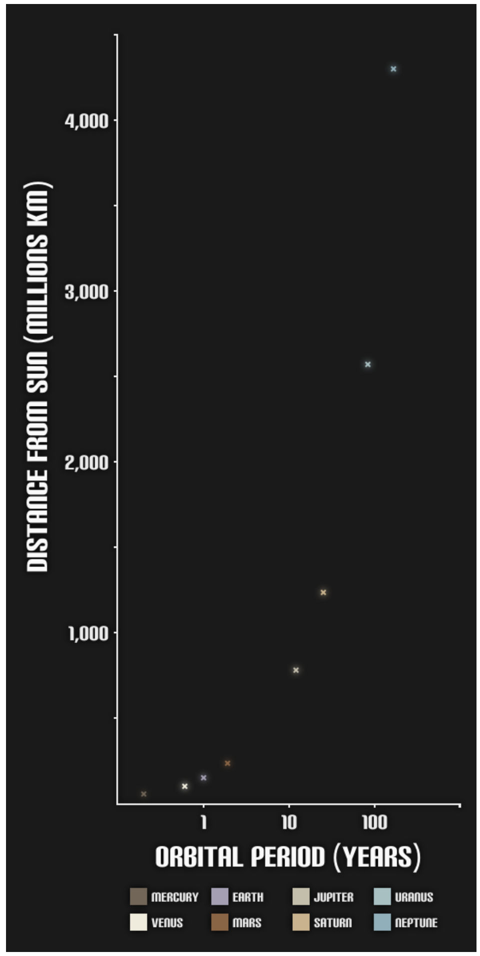

Figure 2: *This graph shows the astronomical distance between each planet in our solar system and the Sun plotted against the accepted orbital periods of each planet. The data points show a unique exponential trend among this relationship between the two characteristics of planets [5].*

From the graphic provided in Fig. 2, it is evident that there is an exponential trend among the planets in our own solar system. By using our own solar system as a guideline, this specific trend could lead astronomers on where to continue their observations in a specific system. For instance, if it is discovered that there is an exoplanet found to have a really large orbital period, similiar to one like Jupiter in our solar system, than astronomers could continuously monitor the brightness of this parent star because our solar system would be an indicator that there are likely planets with a much smaller orbital period, located closer to the parent star. Despite the complete hypothetical nature of this example, studying exoplanet transits allows for this possibility to be available. This is just one application of many characteristics that can be understood from transiting exoplanet systems.

Since the discovery of the first exoplanets in 1992, there have been numerous missions by multiple different space agencies around the world; all with the same goal of discovering new exoplanet systems. One of the most prominent missions was the Kepler and K2 missions exacted by NASA in 2009. The goal of the Kepler satellite was to monitor over 100,000 stars in the Milky Way Galaxy in order to detect Earth-sized planets located in the nearby stars habitable zones [15]. Habitable zones are defined as the area far enough away from the parent star that conditions of life can be sustained. Kepler had lasted for about 4 years until two of the four reaction wheels on the spacecraft had been lost and brought an end to its mission. K2 was the follow-up mission that lasted for an additional 4 years and continued the work set out by the Kepler mission by detecting exoplanets using the transit method [15]. The missions are regarded as highly successful and in their years of studying the surrounding starfields have a combined 2,700 confirmed exoplanets. This goes along with the nearly 3,000 possible candidates to be confirmed exoplanets in the future [14].

These numbers are even more astounding when comparing the Kepler and K2 missions to the total overall confirmed number of exoplanets (3952). Additionally, of those nearly 4,000 exoplanets 3,080 were discovered by utilizing the transit method [14]. The current-day statistics exemplify just how important the Kepler/K2 misions were to creating our encyclopedia of exoplanets. Furthermore, the success of the transit method to have been responsible for detecting nearly 75% of all exoplanets speaks to the reliability and dependency of this method in exoplanet research.

3 Photometry

Capturing images of the exoplanet transiting in front of it's parent star is just the first step of detecting exoplanets. The images taken by the CCD camera are stored as FITS images. A FITS file acts as an image that stores information within the same file as the image taken [19]. When taken of a star that is experiencing a planetary transit, the FITS image will store necessary information regarding the brightness of a star displayed as a count of pixels. These FITS images are then taken through a photometry software where the light given off by objects inside the image are measured [22].

During my senior lab class in the Fall of 2018, my lab partners and I were able to observe and record images for a total of three separate transits. Prior to the transit event, we made sure to have roughly 45 minutes of images taken before the transit begun (ingress) [14] and 45 minutes of images after the transit had completed (egress) [21]. The purpose of recording an ingress and egress for a transit is to prove that for a period of time, the brightness of a star was dimmed due to some object coming in between the star and the Earth's FOV. The egress and ingress, when graphed, will illustrate a constant brightness that is recognized as the star's true brightness. When the transit is occuring, the light given off by a star will show a decrease and this will be demonstrated graphically as a "dip". All of these components put together produce a LC. Fig. 1 shows an extremely simplified version of a planetary LC in the bottom portion of the image.

The process of producing a LC given the FITS images compiled during a planetary transit is the goal of photometric astrophotography. When analyzing the light given off by the three transits recorded last semester, my lab partners and I used a software called AIP4WIN. This software tracked and measured the light pixels produced in each one of the images we had taken. AIP4WIN analyzed our FITS images by having us select a reference star and a minimum of two check stars. The reference star was to be chosen due to its large size and high luminosity compared to the stars around it. This star was used by the program as a pixel-reference star to the target star that we were interested in. The companion stars were to be chosen due to their similiar brightness to that of our target star. We then ran the program and followed along with the program's ability to track the positions of each selected star in the star field. The photometry results were then presented for our target star in terms of variable brightness minus comparison star brightness and comparison star brightness minus check star brightness. We then took this data and imported it into an excel sheet that was created by Lewis M. Cook entitled "AutoPlot-short" that was provided to us by Professor Gianforte. This excel sheet allowed for the data mentioned above to be inserted into pre-determined cells in order to produce a LC.

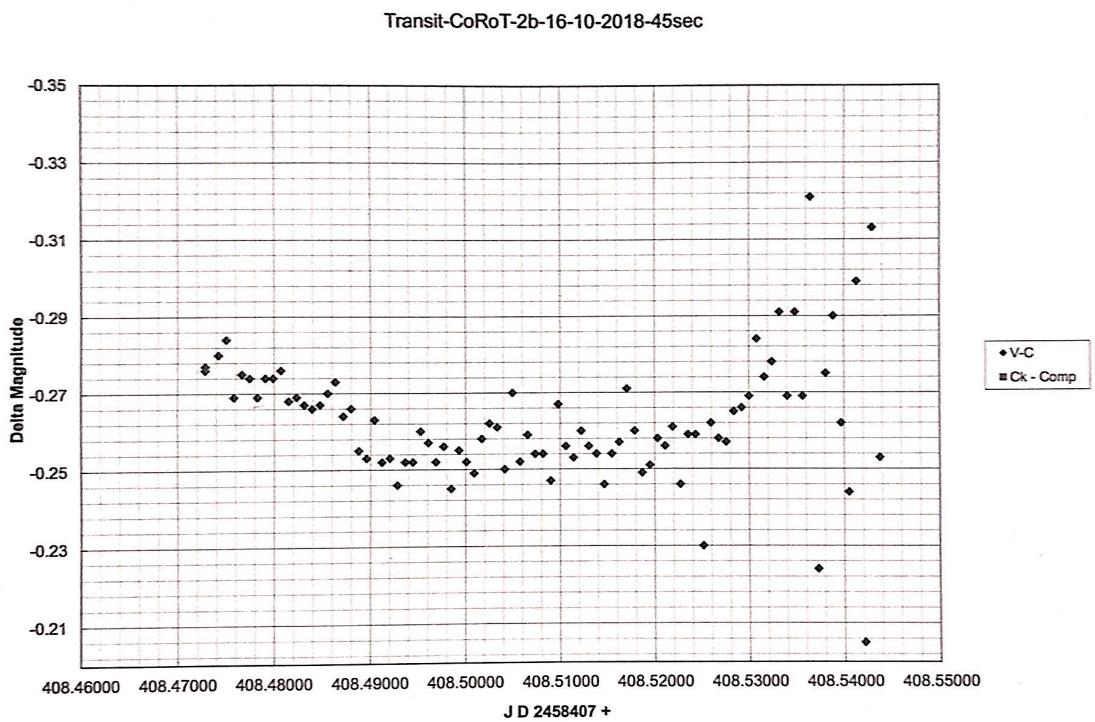

Figure 3: *This LC was produced by my senior lab group last fall. The images taken were the result of a non-autoguiding session for the star CoRoT-2. The y-axis represents the brightness of the star in magnitudes and the x-axis represents the the time of the recorded brightness in terms of the Julian calendar.*

The LC produced in Fig. 3 was the best of the three my group had worked on. Just before the x-axis point of 408.49, there is a noticeable decrease in brightness compared to the points before this time interval. This area represents the transition from pre-ingress to transit. The time interval at 408.53 represents the end of transit and transition into egress on the graph as well although this is harder to notice due to the random dispersal of points. Unfortunately during the end of the transit and the recording of the egress, the weather conditions shifted and cloud coverage began to shield CoRoT-2 from our telescopes view. Despite the success of verifying the exoplanet transit and confirming an exoplanet is orbiting around CoRoT-2 as published on the Exoplanet Transit Database, the LC we produced is extremely inadequate for professional publication. This LC was the result of manual guiding during transit since autoguiding had yet to be set up and therefore was unavailable to us at the time. Even without my explanation on where the ingress and egress, begin and end, it is completely possible to not even recognize a LC on the graph at all. The application of autoguiding for exoplanet transits will provide much more convincing evidence that an exoplanet is transiting in front of its parent star.

4 Autoguiding Applications

Autoguidng during exoplanet transit research allows for cleaner images containing much more accurate data than images where autoguiding was not used. What actually is being done during a session of autoguiding is that the CCD camera and telescope communicate electronically with one another to essentially track a specific target star in the night sky [2]. This is made possible by selecting the target star through the astronomy software, SkyX Professional, and allowing for the telescope to keep the pixels generated by the target star in a specific range.

This is important because exoplanet transits take time. All exoplanets have various lengths of time it takes them to come into the Earth's line of sight with their parent stars and thus dim the amount of light given off by their star from our viewpoint here on Earth. As time progresses during a transit, the Earth is simultaneously rotating around its axis. These two factors result in the depiction that a star can move throughout the night sky from our view on Earth. Although during the several hours needed for most transits, the movement may not seem too drastic when looking at the scale of how big the night sky is. However, when focusing a telescope on a tiny, yet specific, patch of the night sky, every little movement is important.

By allowing for the telescope to track the target star on its own, relinquishes the possible mistakes that can arise from having an observer aimlessly readjust the telescopes field of view using a remote hand-controller. When autoguiding, the telescope's field of view (FOV) stays locked, keeping all the stars surrounding the target star on the same image. This prevents the star field drift phenomenon mentioned earlier which without autoguiding, could result in a series of images where stars of importance for photometry could be lost and ruin the measurement of light [6].

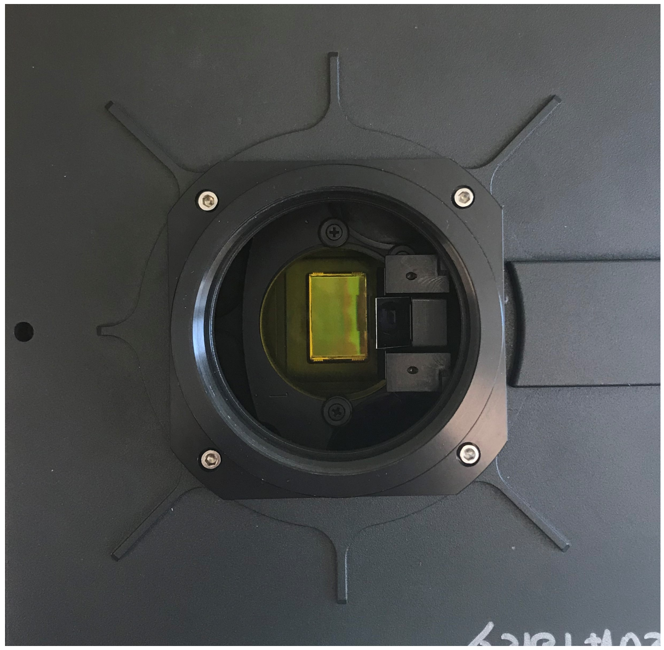

Figure 4: *This image is of the lens for the STXL-6303E CCD camera at the UNH Observatory. The image depicts the main chip, the blue light exoplanet filter, and the pick-off mirror used for autguiding.*

The autoguider used at the UNH observatory comes pre-assembled in the filter wheel that is attached to our CCD camera. This means that the autoguider works independently, as a separate CCD chip from the main CCD chip. As seen in Fig. 4, the illuminated, yellow rectangle is the cameras main chip. The yellow shade of the chip comes from the circular filter placed above the chip that is designed to filter out the blue light given off by exoplanets before the main chip registers the light from the star. The autoguider is not pictured here, however, the mirror located directly to the right of the main chip is used during an autoguiding session. This 'pick-off' mirror is designed to capture the light directed on the camera lens and reflect it towards the autoguider chip. This allows for the autoguider to work with the main chip on the CCD camera and track the star throughout the night sky.

5 Calibration Process

The first step in calibrating the autoguider came by allowing the telescope mount and CCD camera assembly to communicate with one another through the SkyX Professional software. Fortunately, the camera was already set up to work with the mount due to students working at the observatory in the past. The drivers for the Filter Wheel had to be updated before the SkyX program could connect and recognize the autoguider chip as a functioning piece of the camera. Despite the rather easy connection that was made in order for the computer to connect to the autoguiding chip, the images taken by the chip proposed strenuous errors for some time.

After analyzing the FITS image produced by the autoguider, Professor Gianforte and I noticed the autoguider was not collecting any light information. The image produced continually displayed a black frame and when opened under NASA's FITS Liberator 3 software (an application used to open and display FITS data), showed no data ever recorded in the image. We concluded the image taken that yielded no data may have been a result of extremely faint stars along with cloud coverage to shield them even more from the autoguider. Staying rather optimistic, we followed this discovery up by slewing to the moon the next night we were out at the observatory. This next session saw much clearer conditions from the night sky than before and the moon was in its full phase so it was the brightest object in the sky that night. We were shocked to find out the image taken by the autoguider was the same as before, fully blacked out with no signs of light data at all.

The realization of aiming at such a bright object in the night sky and collecting zero light data from it was where our concerns began to increase. Our initial thought was the autoguider was not picking up any data because there must be something blocking the path of light that is normally directed towards the chip. After disassembling the camera, it was clear that nothing had been blocking the autoguider chip and our guess was incorrect. However, this lead to the next possible solution that the autoguider was not receiving any light data because the pick-off mirror that directs light towards the chip was not extending far enough into the FOV of the main chip. I posted on website support forums for both Sofwatre Bisque[2] and Diffraction Limited[3] in search of guidance for where to go from here. After posting Fig. 4 on a forum and expressing the concern that the pick-off mirror may not be extending far enough, I received a response from Doug, an employee at Diffraction Limited, who assured me that the pick-off mirror was not our issue [11]. Doug was extremely helpful throughout the consistent errors I ran into and offered potential solutions nearly everytime. Following his comment that the pick-off mirror was not the issue, Doug had suggested ensuring all the hard-wired connections between the camera and telescope mount were fully plugged in and debugged the sensors within the autoguider ensuring it was not a factory malfunction when producing the components.

After discussing the continual errors with Doug for about a week, we finally were able to move onto calibrating the autoguider after solving the data-less image issue. Doug had suggested on the forum post to "make sure [we] have set the guide camera to 'External'" considering the specific camera and filter wheel model we were using treated the pieces as two individual parts [11]. We had tried to ask for guidance on where to find this setting as the pathway had changed depending on which version of SkyX Professional you were using. We were able to locate a post on Software Bisque's forum where one of the owners named Matt had given straightforward directions on where to locate the setting [3]. After adjusting this setting, images taken by the autoguider began to detect incoming light. It was very unfortunate to have so much time spent on observatory sessions and troubleshooting, when in the end it was one setting that had held us back the entire time. Nevertheless, Professor Gianforte and I were fortunate enough that we were able to move onto the actual calibration of the autoguider chip.

[2] The company that designed the SkyX Professional Software

[3] The company that owns SBIG Imaging Systems (designed our camera model)

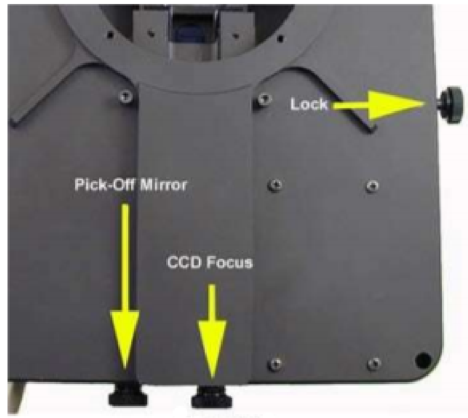

Figure 5: *The image shows the three knobs responisble for controlling the calibration process of the autoguider. The semi-circle located at the top of the image is the opening to the lens that is pictured in Fig. 4. These two images make up the whole picture of the filter wheel [18].*

Calibrating the autoguiding chip required two important adjustments as laid out in the instructions manual: adjusting the pick-off mirror and adjusting the CCD focus of the autoguider chip [18]. The first step involved adjusting the pick-off mirror with the telescope in order to align the mirror with the optical axis. This step was necessary to ensure the mirror did not stretch the resolution of the images produced. In order to properly adjust the pick-off mirror, we set the main camera chip to focus mode, which allowed us to take continuous photos one after another. The purpose of this is not to save every picture taken, but instead use the continuous updating of photos to get the sharpest possible focus without blur. This action is done frequently at the observatory as it is necessary to change the telescope's focus from viewing objects through the eyepiece to using the CCD camera to observe systems in the night sky. We set the exposure time limit to a short 3 seconds so our wait time in between images was not too long or too short and began rotating the pick-off mirror knob counter-clockwise, which was the direction of the main CCD chip. We watched for the mirror to produce a shadow on the updated image. This was a sign that the mirror was vignetting the image and had been expanded too far out into the FOV of the main chip. Upon recognizing the shadow in the image, the insturction manual indicated that we should slowly rotate back clockwise until the shadow was completely gone and lock the knob in place [11]. Unfortunately for us, we had rotated the knob clockwise and counter-clockwise multiple times each and were never able to see a shadow vignetting. Again, we took to the support forums of Diffraction Limited where Doug had suggested that if no shadow was appearing that he recommended we rotate the knob as far counter-clockwise as allowable to ensure the pick-off mirror was able to intercept the light that was directed to the main CCD chip.

Adjustment of the CCD camera's focus was next. This step required extreme attention to detail due to the fact that how good of a camera's focus is directly correlated to how clean and detailed the images produced are. This was a relatively straightforward task, as adjusting the CCD focus for the autoguider is the same process I have performed over and over again while prepping for transits using the main CCD chip. Professor Gianforte and I headed out to the observatory one night and began this focal adjustment by aiming at some of the brightest stars available to us: Capella, Vega, Spica. Due to the poor visibility conditions, the autoguider was only able to recognize these stars at unnecessarily high exposure lengths. This lead us to decide to slew to the moon and try focusing the autoguider by using the moon's surface. After receiving over-exposure images at short time frames of a couple seconds, we began pushing the limits of how short of an exposure time our camera would allow for us. We settled on an exposure time of 0.005 seconds and the image produced was astounding to me at first sight.

Figure 6: *This image of the moon was taken by the autoguider chip at an exposure time of 0.005 seconds.*

For me, being able to visualize this image after all the error debugging and troubleshooting Professor Gianforte and I had done over the past several weeks was a sign of relief. Although fully calibrating the autoguider took me a lot longer than I had anticipated, it was a major accomplishment to get the autoguider working and focusing exceptionally well. I took my time adjusting the focus knob for the CCD chip of the autoguider to make sure I could get the image as sharp as possible. After settling on a focus, I tightened the lock knob pictured in Fig. 5, all the way in order to keep the two adjustment knobs from moving. THis was done to ensure they are never accidentally rotated in the future.

6 Results and Data

As mentioned before, autoguiding will allow for cleaner, data-filled images of the light exposed by a parent star. Autoguiding has success due to the ability of the telescope mount to communicate with the CCD camera and lock onto the pixels generated from the star. This allows for the star to stay in the FOV of the telescope and as it moves throughout the night sky, the telescope mount adjusts its position to follow the star. Truly successful autoguiding lies within the polar axis of the telescope mount. By aligning the polar axis of the telescope with the north celestial pole of Earth, the observer can be certain that the autoguider will follow the parent star and reference stars near the edge of the telescope's field of view will not be lost. The polar alignment along with the use of autoguiding will ensure that the field of view of the star field is held fixed in respect to the CCD chip's pixels. [17].

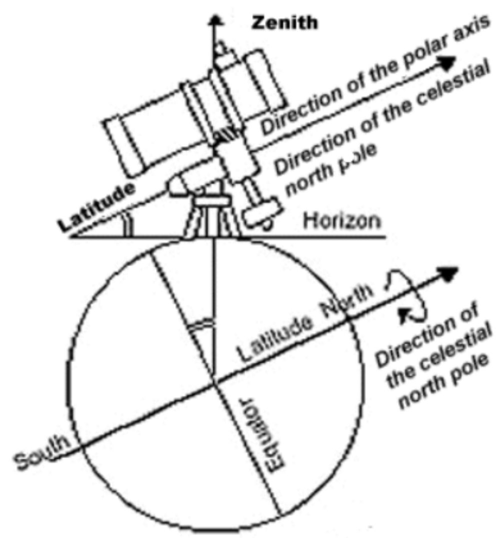

Figure 7: *This image expresses the paragraph above in a visual format. The understanding of Polar Alignment is important because it plays a large role in how successful autoguiding can or cannot be [17].*

When I first started out working on this thesis back in December, I had set some far-reaching goals for myself when discussing the possibilities of how far I could take this research with Professor Gianforte. The path to success was constantly interrupted by various communications errors among the observatory equipment and even moreso the weather experienced here in Durham during the months of Winter and early Spring. Although roadblocks faced among the technology may have set us back a couple days, the visiblity and wind conditions of winter prolonged observatory visits longer than expected. It is for these contributors that I was never able to fully complete what I had set out to back in December. That being said, all the work I had put in over the past couple months was not for nothing. Following the calibration of the autoguider which produced Fig. 6, I am able to say the UNH Observatory has a fully functional and operational autoguider chip that is ready and waiting for future undergraduate and graduate students.

Although I personally was unable to perform a transit while autoguiding on the target star, I still want to discuss the benefits that can be obtained from the use of autoguiding rather than experimenting in astrophotography without the use of an autoguider. As mentioned before, autoguiding gives the telescope the ability to follow the star's motion across the night sky and keep it centered within the telescopes FOV. This is especially the case when observing deep-space, dim stars. For these stars it is typical to expose the camera's lens for a longer period of time in order to analyze the dim light source as long as possible. The electronics inside the CCD camera are cooled to reduce the noise they generate in order to use these dim stars as guide stars [1]. As time progresses, the star follows a particular path through our night sky and the autoguiding chip allows for this path to be constantly at the center of the FOV visualized by the telescope and recorded by the camera's main CCD chip. By invoking the autoguider during a transit session, the periodic error experienced by the telescope in either the right ascension or declination direction can be accounted for and corrected to prevent impedance that is added to the data of a FITS image when manual guiding is performed [4].

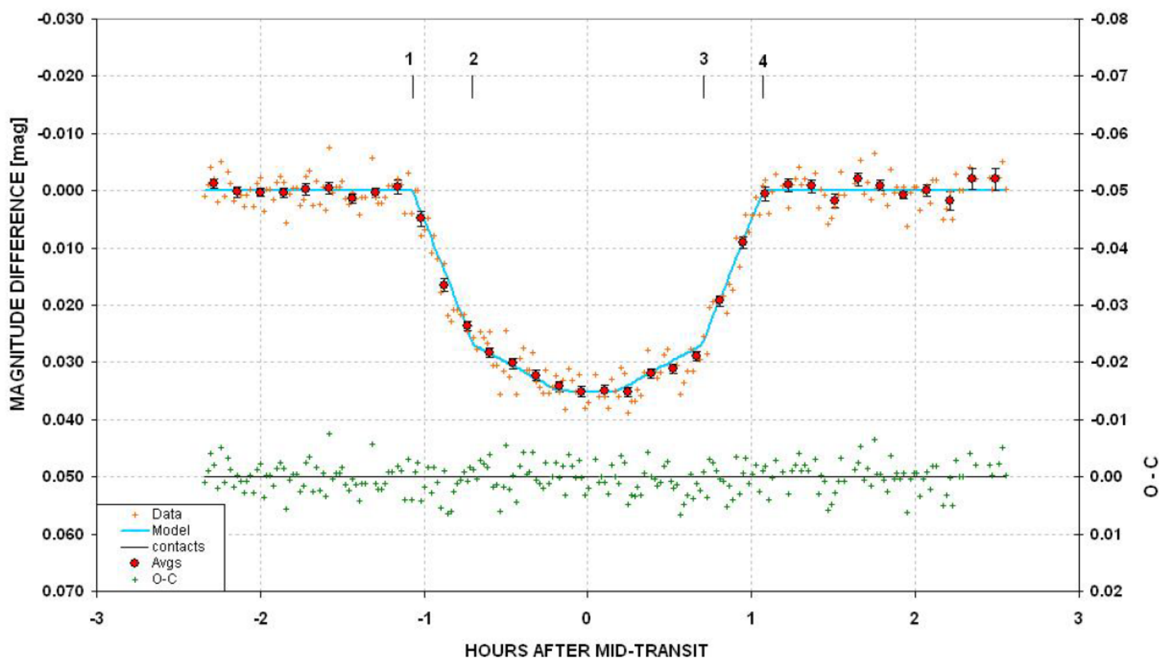

Figure 8: *This LC appears on the cover of Bruce Gary's "Exoplanet Observing for Amateurs" Third Edition and represents what a Professional LC should look like [7].*

Correcting the periodic error naturally present from slight discrepancies in telescope movements is a large advantage of autoguiding. Fig. 8 demonstrates a linearly consistent ingress and egress along with a proper decrease in magnitude experienced by a parent star with a transiting exoplanet. It is much more convincing that an exoplanet is transiting around this star in comparison with Fig. 3. Although Fig. 3 showed indications of a LC there is too much inconsistency in the data that give the appearance of a random scattered plot. By having the technology and ability in place to produce a LC such as the one Bruce Gary did in Fig. 8, students at UNH will have the potential to assist the astronomy community by submitting LC's to internet databases and update various characteristics associated with LC's like duration and depth.

7 Conclusions

While it is clear that autoguiding for exoplanet transit research is not essential for successful observation, it is a necessity for producing data and results beyond an amateur level. Despite falling short of my goal in which I would be able to successfully record an autoguided transit session and produce a clear and detailed LC, I am still extremely satisfied with the patience and perseverance by Professor Gianforte and I to overcome the obstacles of inherent errors and poor weather conditions in order to provide a fully functioning autoguider at the UNH Observatory. We concluded our last observatory session of the semester with smooth connections between the Autoguider and telescope, the CCD chip on the autoguider recognizing incoming light information, and confirmed the autoguider's ability to differentiate stars from hot pixels.

For a future student looking to take the autoguider a step further and continue the work that has been laid out in this paper, the next steps should be geared towards calibrating the autoguiders ability to track a star's movements and then follow-up with a transit session. Though the autoguider was able to recognize a star following an exposure time, Professor Gianforte and I ran into an error when attempting to calibrate the auotguider FOV prior to star tracking. We are still unsure as to why this error was occuring because after researching the issue, all the solutions posted online were set in different parameters than SkyX was allowing us to choose.

8 Future Research

It is clear that autoguiding is a necessity to taking exoplanet transit observations at an advanced level. The use of autoguiding along with the progress made by fellow students Tom Ireland (Image Calibration) and Nick Larose (Observatory Depth Level) the observatory here at UNH will have techniques available to future students that will make their work more professionally appealing. Observing exoplanet transits for a professional astronomer meets all these requirements for the reason being that the images produced are far superior in terms of data and clarity than without using these techniques. Additionally, in Senior Lab for Astronomy-focused majors, they will be required to perform a lab that consists of observing multiple exoplanet transits and attempting to produce a LC. Given the advancements we have made to improve the astronomical methods used at the UNH observatory, future students will have the ability to utilize the techniques provided by our work to their benefit.

With the University's Observatory having these new and advanced methods of observing the night sky available, future students will have the possibility of reaching out to exoplanet survey teams or even publish their work they will do onto varous exoplanet databases. NASA's current TESS mission (Transiting Exoplanet Survey Satellite) that was launched in

April of 2019 and is serving as a follow-up mission to the previously retired Kepler mission. The goal of TESS is to continue the discovery of exoplanets in nearby star systems using the transit method [16]. This will be possible because they will be using professional astronomer techniques to minimize the error in their images to be as little as possible. Professor Gianforte and I had visited MIT's Haystack Observatory in October of 2018 where we connected with one of the Haystack's employee who is working directly on the TESS mission. This is when the idea of performing follow-up ground-based observations of the new discoveries TESS will be making was theorized for future students. It was the thought of this possibility that had convinced me on examining exoplanets further. To be able to leave a sort-of legacy here in the UNH Physics department by improving the facilities around me for future students has been an indescribable enjoyment.

9 Acknowledgments

I would like to offer an extreme thanks to my thesis advisor Professor John Gianforte. If it were not for John guiding the astronomy-focused physics students to perform such interesting labs in the Fall of 2018, I would never have discovered how exciting exoplanet research can be. I also want to thank Doug of Diffraction Limited, whose help in finding solutions to the consistent errors that continued to pop-up during the calibration phase were essential to my troubleshooting. Additionally, I would like to thank fellow students Tom Ireland and Nick Larose for their efforts at working towards making the UNH Observatory a more prestigious setting.

10 Appendices

10.1 Equipment

- STXL 6303E CCD Camera from SBIG Imaging Systems
- FW8G Filter Wheel with built-in Autoguider connected to the 6303E SBIG Camera
- Celestron C14, 0.35m SCT
- Paramount MX+ GEM
- The SkyX Professional - Astronomical Software for Observatory Control

10.2 List of Acronyms

- CCD - Charged Coupled Device
- SBIG - Santa Barbara Instruments Group. Company that made the CCD camera we have here at the UNH observatory but is now owned by Diffraction Limited
- SCT - Schmidt-Cassegrain Telescope

- FITS - Flexible Image Transport System
- AIP4WIN - Astronomical Image Processing for Windows
- GEM - German Equatorial Mount
- LC - Light Curve (specifically exoplanet-based and NOT for variable stars)
- FOV - Field of View

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