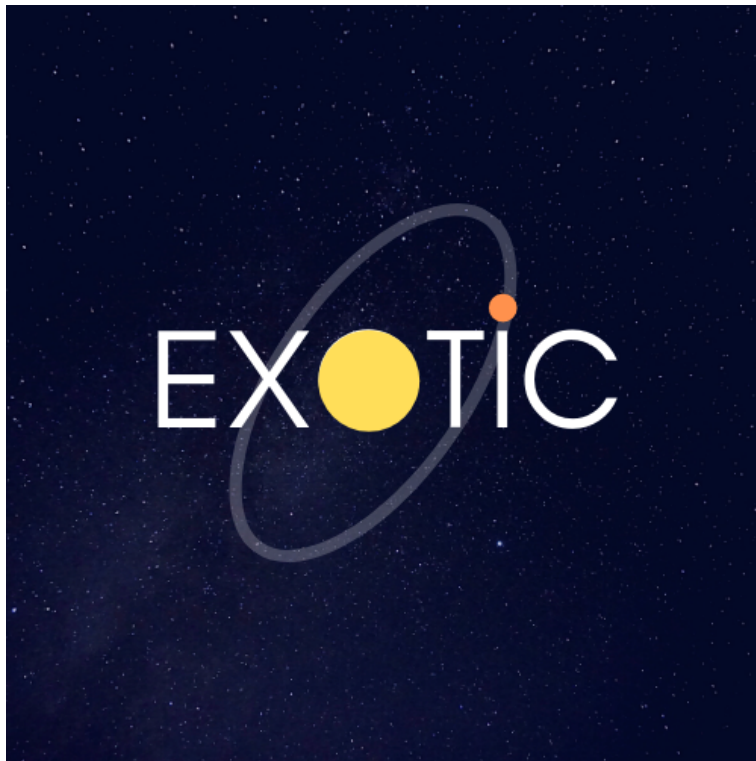


# Exoplanet Watch

## Observers Manual



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Please be careful while observing! **NEVER** point a telescope or optical device at the Sun without proper training and equipment. Doing so may result **serious** injury and permanent blindness.

# 1 Introduction and Overview

Welcome to the Exoplanet Watch Project. As a backyard Astronomer, YOU can help NASA study planets beyond our solar system! This manual is designed as a resource to instruct both beginning and advanced observers on how to begin participating with Exoplanet Watch, primarily through the observation of Exoplanets. As a brief overview, this document will cover the basic ideas and processes behind exoplanet Photometry, walk through the required equipment as well as recommended observing systems, detail the data acquisition process as well as potential pitfalls and issues one may encounter, and finally the data reduction process in which your observations are turned into identifiable light curves of the planet observed. As such, this document is split into three primary sections. The first section is designed for observers with little to no experience, and will cover the necessary astronomy one must know to observe our night sky as well as an overview of how exoplanet Photometry works. While aimed at the novice, the more experienced astronomer is still recommended to review this section as needed. The second section will cover the observing with an Equatorial Coordinates tracking mount based system. If you are loaning a telescope from NASA's Jet Propulsion Laboratory, your equipment will match the exact setup detailed, although the information included is generalized for many different systems. The final section will cover the steps after you have made your observations and will cover calibration frames, the data reduction process using our "EXOplanet Transit Interpretation Code" (EXOTIC) software, and the process of submitting your data to the AAVSO (American Association of Variable Star Observers) Exoplanet Watch Database. Throughout the document there will be included indicators to designate when any information is exclusive to a particular observing system, as well as indicators for when an accompanying video has been created for a certain subject or topic. These additional resources can be found on the Exoplanet Watch website (<https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/overview/>). This manual is a constantly evolving document and aims to efficiently and succinctly cover everything one will need to know to observe an exoplanet from a backyard, but astronomical observing is a complicated and nuanced endeavour. Additionally, this manual is only one of many different resources available to help begin your observational journey - we recommend one such excellent reference created by Dennis Conti aimed at exoplanet observation, which can be found on (<https://astrodennis.com>). Please reach out and contact us either through Slack, email, or another preferred method with any questions, concerns, or suggestions you may have. Clear skies!

# **SECTION 1 : BASICS OF OBSERVING**

## 2 Exoplanets, Lightcurves and Photometry

First things first, before we start detailing how to perform these exciting exoplanet observations, we need to ensure we understand what it is we are observing and the underlying process behind it. Exoplanets are planetary bodies orbiting stars other than our own, and are of an interest to astronomers for a wide range of reasons, including the search for extra terrestrial life. You can learn more about Exoplanets and their properties on NASA's Exoplanet Exploration website. While Exoplanets can be detected in several different ways, the observations we will take all involve the transit method of observation. Transit detection of exoplanets falls under the broad category of Astronomical Photometry, which simply refers to the capture and study of light. In our case, we are carefully recording the light of a star over some period of time, measuring the total amount of light, or flux, we receive on some sort of detector. Generally, we perform these measurements using sensitive digital cameras paired with large telescopes, and then use software to precisely record the star brightness over time. As an exoplanet orbits around its host star, there is a chance that it will "transit" the star from our perspective, occulting some small amount of starlight. We can measure this small change in brightness and record it as a dip. Once several continual observations are made of this periodic dip, we can conclude that a planet may exist around the star, and can follow up with additional detection methods and observations. While the duration of a transit depends on several different factors, these events usually last on the order of several hours. This means that if our camera is capturing an image of the star every 60 seconds, we may collect several hundred different images that all provide a single measurement of brightness. By combining these all together into a coherent measurement, we can accurately display the brightness of the star over a given time interval, exposing the dip associated with a planet passing along the disk of the star

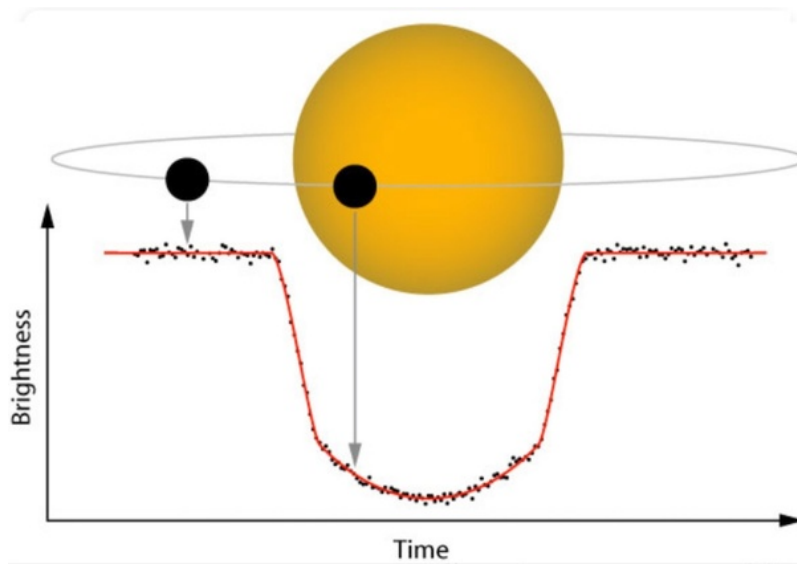


Figure 1: A characteristic light curve produced by a transiting exoplanet. Star brightness is initially flat, then begins to dip rapidly as the planet passes in front of the star (ingress). Brightness remains reduced until the planet moves across the disk of the star and passes out from in front of it (egress) during which the brightness rapidly increases back to normal levels

## 3 All about our Tools, Detections, and Data

### 3.1 Telescopes and Light

Let's now explore in further detail the equipment and methods used in capturing these transits. As mentioned, almost all detections are performed using a sensitive digital detector, often in the form of either a CCD or CMOS camera sensor. While these two technologies have slight differences in the way they operate, both are designed to capture and record our starlight over a defined interval in order to periodically measure star brightness. In order to get the starlight to the detector, we must pair it with a sufficient telescope. Telescopes have two important defining characteristics - their aperture and focal length. The telescope aperture refers to the diameter of either the lens objective or primary mirror used to capture light. The bigger the aperture of the telescope, the better the light collecting power. As such, a telescope with a larger aperture will be able to detect dimmer stars than that of a smaller aperture. The second important characteristic is the focal length, which tells us the field of view of the telescope, or how much of the sky it is capable of observing. When we combine these two factors by dividing the focal length by the aperture, we have the focal ratio. The focal ratio tells us the "speed" of a telescope, with a lower focal ratio corresponding to a quicker speed. As an example, a focal ratio of 10, which we call F10, is exactly 4 times slower than a focal ratio of 5 (F5). The speed of a telescope is a common describing factor and is used to determine how fast a telescope can gather light for a specific field of view. One may think of a two telescopes with a fixed focal ratio, say 1000 millimeters. A telescope with a 100mm mirror will have a focal ratio of 10, while a telescope with a 200mm mirror will have a focal ratio of 5. As mentioned, the telescope with a larger mirror, or aperture, has a greater light collecting power and thus the faster focal ratio for the given focal length. While these are important characteristics of a telescope to understand, for our purposes we simply need to know numerical values for these properties.

### 3.2 Cameras and Detectors

Now that we know a bit about telescopes, let's talk about the camera sensors used and the types of pictures we take. Since the stars we want to record are often quite dim, most of the photos we take to record brightness are long exposures, in the range of 30, 60 or even 120 seconds. While we often choose the exposure time based mainly on what is required to pick up the light from the target star, we have a few special considerations that we must watch out for when choosing this number. These cameras will often have either both a digital gain and offset number that you can set, or just a digital gain. These factors determine how the camera treats a photon hitting the detector and how it is recorded. At a simple level, these digital cameras are simply a grid of many pixels that act as buckets, collecting photons as they fall onto the sensor. The gain and offset determine how many photons are required to record a single increase in the bucket count. Our pixel buckets can only contain a certain number of units, which we call ADU, or analog to

digital units. Using the right gain and offset can be important when planning to image stars of varying brightness, as a pixel's response to a photon can vary depending on how "full" its bucket is. We want our pixel buckets to exhibit a "linear" response - this means that a detected photon properly corresponds with a single "drop" in our metaphorical pixel bucket. Its important for our pixel measurements to remain linear, as this is required for careful and accurate Photometry. While dependent on the sensor technology and type of camera, a good rule of thumb is to keep the "bucket" of our pixel below 50 to 60 percent of its full well, or maximal value. For pixel "buckets" that have fully filled, the pixel is then known as "saturated" and cannot record any additional photons that may impact the pixel. Saturation, non-linearity, and pixel response is a complicated subject - we only wish to emphasize that one must be careful when choosing a combination of exposure time and gain in order to ensure proper pixel values. Other important properties of these cameras include the quantum efficiency, which determines the sensitivity of the camera and the percentage of photons that are actually detected versus those that land on the sensor. Some cameras have what we call a bayer filter attached as well, which is simply a grid of red, green and blue color filters designed to produce a color image from the camera. A camera with a bayer filter will require extra steps known as "debayering" when reducing the data from the camera, which we will cover in a later section. Note that both recommended setups from the Exoplanet Watch team use a camera with such a bayer filter. Finally, let's talk about the picture format which we use with these cameras. All cameras designed for astronomical observation are likely to use the .FITS File Extension file format, which is a flexible image format which can store both image data and accompanying metadata information in what we call the ".FITS File Extension header." .FITS File Extension files are a convenient and easy image format to use, but may not be readable by standard photo editors or image viewing software.

### **3.3 Miscellaneous Considerations**

Additionally, there are several smaller, albeit still important considerations one must be aware of when talking about observational equipment - these include control computers, power setup, and dew management. Lets first begin with equipment control. This is generally done through a central control computer which runs all the necessary software and drivers to communicate with the mount, camera, and all other auxiliary items. Managing all these different components can be difficult, which is why astronomers often rely on programs known as "sequencers" which facilitate communication between all pieces of equipment as well as provide a main "control panel" to schedule and initiate observations. Additionally, managing the time that observations are made at is important when measuring exoplanet transit parameters. Ensuring that your control computer is running on proper, synced time is important, and we will have a section dedicated to ensuring that proper time is kept during observations. Most astronomical equipment is designed to be used with the Windows Operating system, which is why we highly recommend using a Windows machine for running your equipment. As such, this manual has been specifically prepared for those using a Windows environment. If you would like to use another operating system or do



not have access to a Windows machine, please reach out to our team and we can direct you on the best path forward. Our next consideration is powering our setup. This can be as simple as running an extension cord, or as complicated as a regulated battery with a distribution system. We recommend using main power with the provided AC-DC transformer bricks provided for each piece of equipment when possible. In addition to the actual observing equipment, you will need to be able to power the control computer along with any other miscellaneous pieces of gear, from headlamp to hand warmer. This leads us to our last important consideration, which is recognizing the climate and conditions one must observe in. A common issue when performing observations in a humid climate is dew, which has the potential to form on telescope objectives, interfering with data collection. This is usually solved by using either a dew shield or dew heater strap. A dew shield acts as a passive form of prevention, while a dew heater will actively heat your telescope objective to prevent dew, requiring an additional power source.

### **3.4 General Required Celestial Knowledge**

The final piece of this broad overview of observing equipment and methods will be detailing how we track and image our target stars as the night sky changes. While both the telescope and camera are necessary to make our observations, nothing is possible if we don't have adequate tracking abilities. After all, if you can't find your target star, how are you supposed to observe it? As you probably know, our night sky is not static - the Earth rotates at 15 degrees an hour, and thus our sky is constantly rotating about the North Celestial Pole (Celestial Poles (NCP and SCP)). The Celestial Poles (NCP and SCP) is currently located close to the star Polaris, which is why we call it the Pole Star. If you are in the northern hemisphere, everything in the sky rotates about this point. If you are in the southern hemisphere, the sky similarly rotates about the South Celestial Pole (SCP) which is located nearby the star Sigma Octantis. It is important for you to know the location of your hemisphere's celestial pole, so you can accurately follow the motion of the stars during the night. A few additional terms that are important to know are both the meridian and the celestial equator. The meridian refers to the line directly above you, passing through the zenith, that splits the eastern half of the sky from the western half. The celestial equator is similarly the line that splits the celestial north from the celestial south. It is important to begin familiarizing yourself with these concepts, and they will quickly become second nature as you begin to make astronomical observations.

As mentioned, the rotation of the sky poses a problem for astronomers, as we require a way to keep a star still as we try to take pictures of it. To overcome this, astronomers use pieces of equipment called tracking mounts, which are designed to mechanically move at the exact opposite rate that our night sky rotates in order to effectively keep the spot you're observing still in the sky. There are two different types of tracking mounts: an Equatorial Coordinates based system and altitude-azimuth based system. These two mounts rely on two different coordinate systems that we use to classify the sky. The Equatorial Coordinates coordinate system has two axes, Right Ascension and Declination, which originate out from the celestial poles. The second type

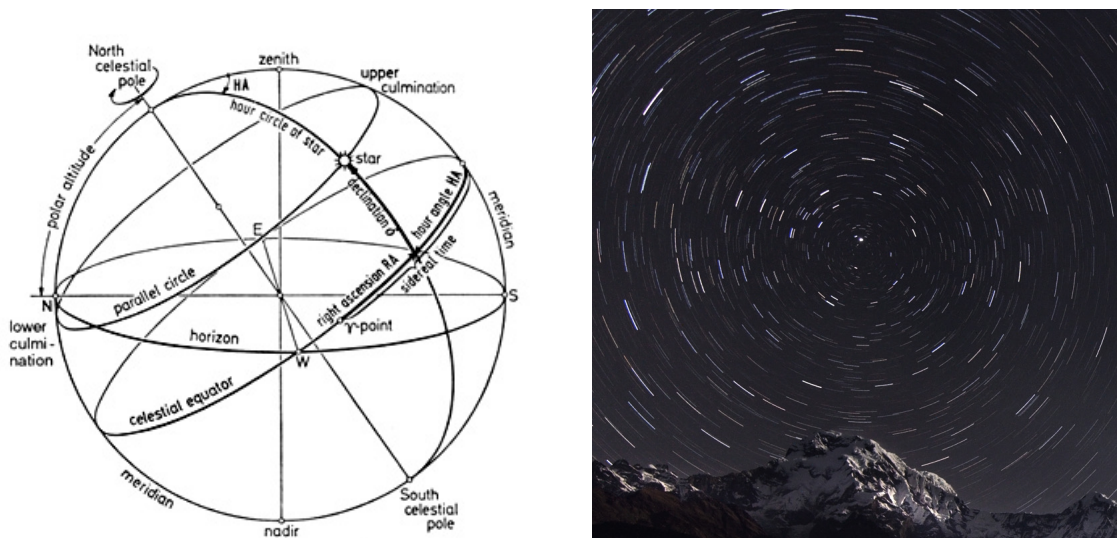


Figure 2: A depiction of our night sky from an observers perspective, with important features labeled along with an example of the sky's rotation about a celestial pole

of tracking mount is uses the altitude-azimuth coordinate system, which is based on your local reference frame. It has two axes, altitude and azimuth. Altitude measures how far an object appears above the horizon, while Azimuth measures how far the object is from the north. We will cover these two different tracking systems and subsequent tracking mount types in much greater detail in the following sections. Understanding both of these coordinate systems and how they relate to celestial motion and the objects we image is extremely important - as such, we find it necessary to dedicate an entire section to their explanations. Having a solid foundation in celestial coordinates, tracking methods, and general celestial motion will make your life much easier when planning and carrying out any sort of observation, so we wish to stress the importance of this knowledge. As mentioned previously, without proper tracking, we can't do all the fun science involved with our exoplanet in the first place if we can't even find the exoplanet!

## 4 Celestial Coordinates, Tracking, and Finding Our Target

### 4.1 The Equatorial Coordinates Coordinate System

To begin our discussion on coordinate systems and the way we keep track of objects in the sky, we will introduce what is known as the Equatorial Coordinates Coordinate System. This system was created by astronomers in order to give celestial objects like nebula, galaxies, and exoplanets a fixed coordinate position one can refer to in order to always know their location in the sky. As such, it is important to note that Equatorial Coordinates coordinates are **absolute** - the coordinate position of an object in the sky does not change regardless of one's position on the Earth(for almost all stars, ignoring the effects of parallax). One may also think that an object's position in time is also fixed, but this isn't quite true as Equatorial Coordinates Coordinates rely on a geocentric reference frame, with fixed positions relative to the Earth's projection out onto the stars. The

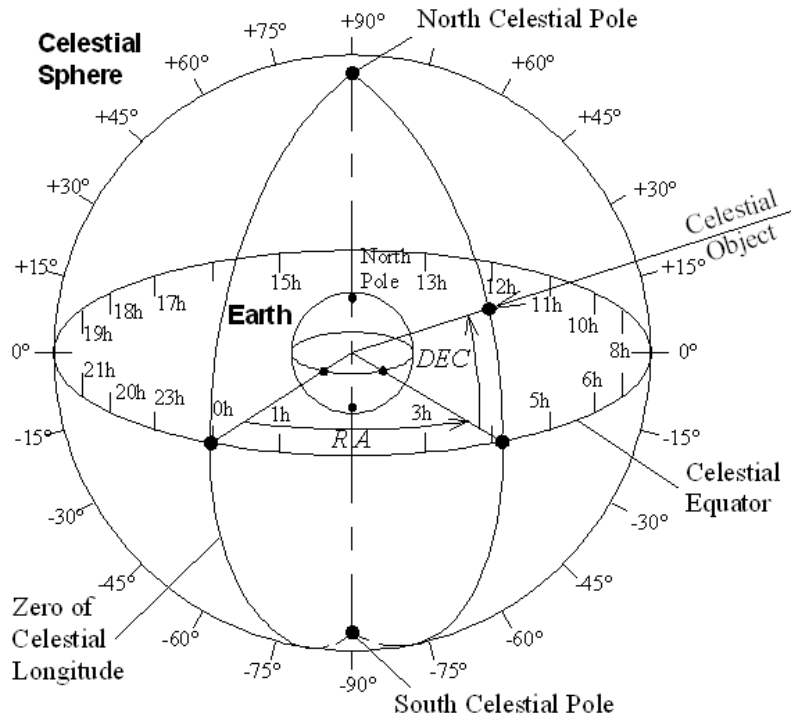


Figure 3: The Equatorial Coordinate System projected out onto the Celestial Sphere. Note the two important pole positions and the relative definition of Declination and Right Ascension in relation to this positions

position of stars relative to this projection change very slowly over time due to the precession of the Earth's pole as well as the effect of axial nutation. While this may sound complicated, no need to worry! We simply wish to stress the idea that the sky is a moving, dynamic system, even with regards to the common coordinate systems we use to classify the location of objects. Since the position of objects change over time, Astronomers define an "epoch" every 50 or so years defining the exact position of the Equatorial Coordinates coordinate grid for a given date, and subsequently the position of any celestial object. Realistically, one will not need to concern themselves over the exact details of the Equatorial Coordinates epoch in use - it is common to either use J2000 or local(exact) Equatorial Coordinates coordinates, and the observing software used will take care of the details between the two depending on which is desired. As for how these coordinates are defined, we start with two axes, Right Ascension (RA) and Declination (Dec). Declination ranges from +90 to -90 degrees, measuring the angular distance from the celestial equator either up to the Celestial Poles (NCP and SCP) or down to the SCP. Similarly, Right Ascension measures the angular distance eastward along the celestial equator, ranging from 0 hours to 24 hours. Any celestial object will have a (RA, Dec) coordinate pair which remains fixed over time, changing only due to long term effects mentioned previously. For our purposes we may consider these coordinates as static for our object. As the name implies, Equatorial Coordinates Mounts are designed around Equatorial Coordinates coordinates, and work by aligning to a celestial pole, which enables us to track objects by moving in Right Ascension only. Equatorial Coordinates Mounts also remove the issue of field rotation, which is a phenomena that occurs with altitude-azimuth mounts as the

position of stars rotate over time. Crossing over the meridian is important as well for Equatorial Coordinates mounts, requiring what we call a "meridian flip" to avoid our telescope from hitting the tripod over time. Equatorial Coordinates Coordinates can be quite confusing at first - the best way to familiarize yourself is to observe the motion of the sky as well as use an Equatorial Coordinates mount frequently and become comfortable with the different positions over time as it tracks for a given coordinate pair. The mount motion will be quite different depending on how close the target is to the celestial equator or poles, so try playing around with several different targets to get a feel for the mount and its motions before planning a exoplanet observation. We again wish to stress the importance of understanding the Equatorial Coordinates coordinate system for any sort of observing - it is necessary in order to find your desired target!

#### 4.2 The Altitude-Azimuth Coordinate System

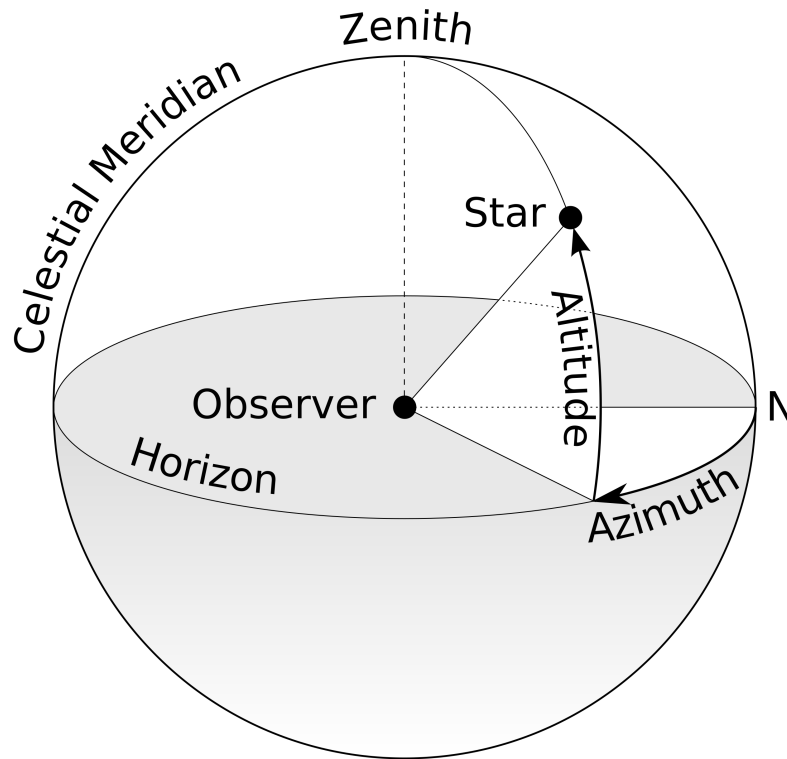


Figure 4: A simple depiction of the Altitude-Azimuth Coordinate System given an arbitrary observer. Note that the relative position of the observe defines the coordinate system, with the zenith/horizon and northern position defining our two axes of azimuth elevation

Now that we have a grasp over the popular and ever important Equatorial Coordinates coordinate system, we can discuss another, easier to understand coordinate system called the Altitude-Azimuth System, or Altitude-Azimuth Coordinates for short. Much like its Equatorial Coordinates partner, the Altitude-Azimuth Coordinates system is a method of noting coordinate positions for celestial objects in the sky. Importantly, this system is defined by the user's local position, and is thus a **relative** coordinate system. The relative nature of this system is its greatest disadvantage,

although it does play an important role in celestial mechanics and observational astronomy. In order to fully understand the position of an object in the sky, both its Equatorial Coordinates coordinates and local coordinates will be necessary - the Equatorial Coordinates coordinates give the object's absolute position, while its Altitude-Azimuth Coordinates coordinates give us its relative position for our location as well as an intuitive sense of its position in the current sky. The Altitude-Azimuth Coordinates Coordinate system is defined with two Axes, Altitude and Azimuth. Altitude ranges from 0 degrees starting at the user's given horizon all the way to 90 degrees, directly above the observer at their zenith. Azimuth similarly starts at 0 degrees measured from true north, and increases eastward all the way back to the origin (0 to 360 degrees.) Altitude-Azimuth Coordinates Tracking systems work based off this coordinate system, and move in both altitude and azimuth over time in order to keep an object stationary. Altitude-Azimuth Coordinates systems suffer from what is known as "field rotation," in which the rotational motion of the sky interferes with long exposure photography, resulting in trailed stars the further out one goes from the center tracked object. Quantifying the amount of field rotation experienced for a given altitude and azimuth is more difficult than we wish to go into for this manual, but it is important to know that field rotation presents a major issue for the relatively long exposures we need to make for exoplanet Photometry, and thus any observing system utilizing an Altitude-Azimuth Coordinates mount will require special considerations.

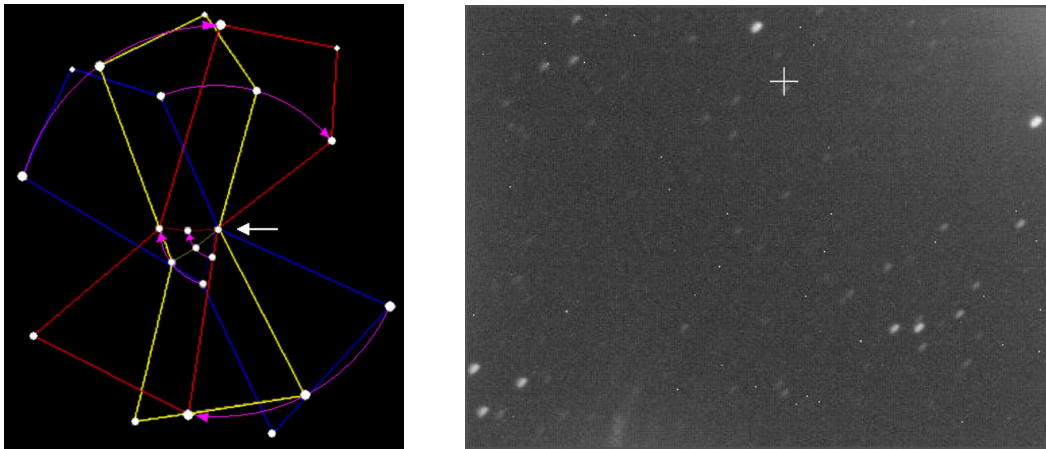


Figure 5: (Left) An example of the Orion Constellation undergoing field rotation about the center belt stars. (Right) An example image exhibiting field rotation taken with our observing system

### 4.3 Practical Coordinates and Airmass

Given that we now understand these two common coordinate systems found in observational astronomy, we can talk about their practical applications to exoplanet Photometry. All transiting exoplanets have a host star associated with them (there are exoplanets out there without a host star, but these cannot be detected using the transit method) and these host stars will have associated Equatorial Coordinates coordinates denoting its position in the sky. These coordinates will almost always be given in a Sexagesimal Coordinates form due to the importance of "degrees" and

their relation to the number 60. Both Right Ascension and Declination are expressed using 3 subsequent numbers, denoting the degrees, arcminutes, and arcseconds where 1 arcminute is 1/60th of a degree and 1 arcsecond is 1/60th of an arcminute. A Declination coordinate is usually expressed purely in degrees, arcminutes, and arcseconds while Right Ascension is generally expressed as hours, minutes, and seconds (referring to hours, minutes, and seconds of arc, with 24 hours corresponding to a full 360 degrees) as a matter of convenience. Thus, an example Equatorial Coordinates coordinate pair may be: **(RA) 10h19m38.02s, (Dec) -09d48'22.6"** which corresponds to the host star Wasp-43 and its associated exoplanet. This information is all one needs to point a properly aligned tracking Equatorial Coordinates mount to the desired target star. Similarly, Altitude-Azimuth Coordinates coordinates may be given in the same Sexagesimal Coordinates format, but are more likely to be given as a pair of decimal degree values. As such, an example Altitude-Azimuth Coordinates coordinate pair may be **(Az) 251.354929 (Elv) -4.425617** which happens to be the coordinates of Mars in Anaheim, CA at local midnight on December 1st, 2021. Again recall that as Altitude-Azimuth Coordinates is a relative system, specifying the time and location is required in order to transform between Altitude-Azimuth Coordinates and Equatorial Coordinates coordinates. Our practical discussion of the coordinate systems and their relation to our desired exoplanet targets wouldn't be complete without mentioning the existence of what is known as "Airmass." Airmass is (as the name implies) a term used by astronomers to quantify the amount of atmosphere a telescope is looking through for a target. Since the Earth is a sphere, this quantity is a function of the target elevation, with the minimum Airmass of "1" corresponding to directly above, or zenith. A larger Airmass is detrimental to astronomical observations in a number of different ways, and a good rule of thumb is to try and avoid imaging objects below 30 degrees elevation. As such, the local position of the desired target star plays an important role when playing out observations of an exoplanet. Other local factors, such as local view obstructions, relative location to the moon, and rise/set times all influence planning an observation.

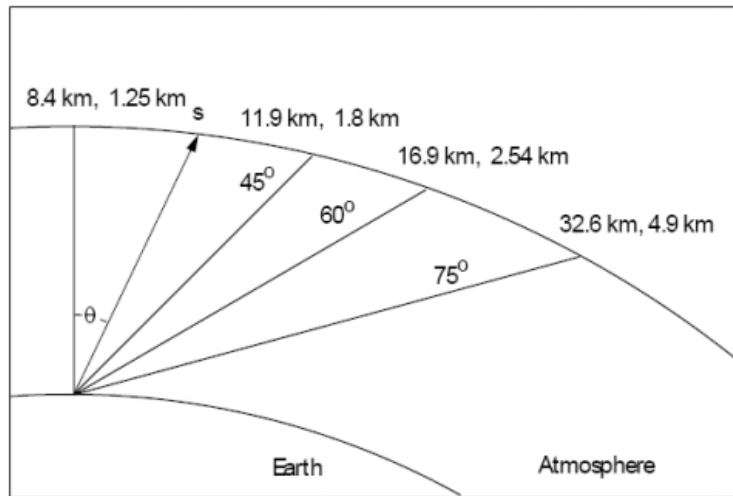


Figure 6: The importance of observing altitude given the relative Airmass one must observe through. As you observe lower in the sky, the percentage of atmosphere one must peer through increases

## 5 Safe Observing Practices

With this, we have covered much of the textbook introductory knowledge one needs to start performing exoplanet observations. What remains, however, is some practical information to ensure that both you and the equipment remain as safe as possible. Fortunately, making exoplanet observations isn't a dangerous activity, but there are several important factors one should always take into account before deciding to set up for a transit observation. The first and most important consideration is one's personal safety. As stressed at the start of the manual, you should **NEVER** point an optical device at the Sun. This includes your telescope, binoculars, and eyes. There is **NEVER** a reason to look at the Sun without proper specialized equipment designed for the express purpose of making Solar observations. The vast majority of astronomical equipment is not safe to use for this purpose, and doing so may seriously injure yourself as well as permanently damage both your telescope and camera. Please take this warning seriously - it only takes a single second of inadvertent Sun exposure through a telescope to permanently blind yourself for the rest of your life. It is also important to be knowledgeable and aware of one's observing environment. Please make sure that you are properly dressed and equipped for an observing session and are located in a safe, suitable environment. This means knowing the weather forecast and the temperature range expected for the night - please be responsible while performing your observations! Similarly there are a number of rules one should follow to ensure that your equipment remains safe. The most important consideration here is being aware of the weather and planning your observation sessions appropriately. While most astronomical equipment is designed to endure environmental exposure to a certain degree, you should always be aware of the chance of rain or snow. If you are not sure whether the weather will be suitable for observing, it is better to hold off and wait until conditions are more appropriate. Cloudy nights happen, and cloudy nights with unexpected rain also happen!

## 6 Putting it all together

With this quick overview, we are ready to walk through the steps required to observe an exoplanet! A typical observation run will follow this pattern: we begin our night by checking the transit candidates which are observable from our location. Not all transits are suitable for observing, and we will have to choose based on a variety of factors, including star magnitude, transit depth, transit duration, and the percentage of observable baseline. Once an exoplanet transit has been decided on, we record its necessary information, from finder charts to coordinates, and then begin setting up our equipment. We will detail where you can find this information for a given exoplanet in the following section. We ensure that our mount is properly aligned to the sky as needed, and then ensure that both the camera and telescope are properly attached and balanced. With this, we are close to beginning our transit observation! However, we first must ensure that the telescope is properly in focus and that the camera is functioning correctly. Once we confirm that everything

is working correctly, we locate our target star which hosts the exoplanet and begin a sequence of many photos to record the transit event. This is usually done using some sort of sequencing software which facilitates communication between the camera and tracking mount to ensure that the system remains on target for the duration of the transit. At the end of the observation run, we should have several hundred individual photographs each measuring the brightness of the star for a given time interval. In addition to these science photos, we will also take what we call calibration frames in order to correct for various errors throughout the process. We can then take all of these photos and "reduce" them to a useful format, such as a light curve. In our case, we will rely on EXOTIC, which is a data reduction tool built for the express purpose of analyzing transit events. EXOTIC will take our group of photos, perform an intensive measurement process in which the brightness of the target star is carefully measured, and then tell us whether a transit, and thus an exoplanet, was observed. With this, our observation is complete and we are ready to upload the data to be used by the scientific community. This is a broad overview of a complicated process - we will dig into the details in the following two sections, detailing how to observe with both an altitude-azimuth tracking system and Equatorial Coordinates system.



## **SECTION 2 : EQUATORIAL COORDINATES TRACKING SETUP**

## 7 Equipment Overview

This section is designed to guide users through the observing process using Equatorial Coordinates tracking. The instructions presented will be tailored to the exact setup created for the Exoplanet Watch telescope loan agreement, although many combinations of camera, tracking mount, and telescope will likely be suitable for observations. If you have any questions on a certain gear combination, or are having issues with getting set up, please reach out to our team. To begin, we will walk through each major component included with the delivered setup, which are the following:

- CEM26 Equatorial Coordinates Tracking Mount and Tripod
- ASI224MC Color Camera
- C6 Schmidt Cassegrain Telescope

### 7.1 Tracking Mount:

The tracking system of any observing system is widely considered to be the most important piece of equipment. This is because without the ability to properly account for the rotation of the sky in order to track our desired target, no meaningful observations may be made, regardless of the abilities of either the telescope or camera. For an Equatorial Coordinates based tracking mount, a special procedure called "Polar Alignment" is required each time you begin observing to ensure the mount is properly aligned with the motion of the sky at your specific location. We will discuss this important step in greater detail shortly. The mount which we will be using is called the CEM26, or "Center Balanced Equatorial Coordinates Mount 26." While this name may sound a bit confusing, it is simply referring to the weight capacity of 26 pounds, along with the fact that it is center balanced, which is a type of Equatorial Coordinates mount. Another common type is known as the "German Equatorial Coordinates mount," or GEM. If you are following along with your own personal equipment, there is a decent chance you have a mount of this construction, as it is considerably more common than centered balanced mounts. They both accomplish the same task of tracking the night sky, and the differences between the two are meaningless for our considerations. The CEM26 has several important components which all work together to accomplish the goal of tracking. The primary piece is what we call the "mount head," and is what houses the motors and circuitry required to track the sky as well as an attachment point for the telescope. The mount head is split into two axes, which handle tracking for "Right Ascension" and "Declination" respectively. The mount head will also have an attached "Counterweight and Counterweight Bar" which are used to reduce strain on the tracking motors, offsetting the weight of the attached telescope. In addition to the necessary Polar Alignment step mentioned above, the telescope and counterweights must be balanced in a special way each time you use the mount,

which will be covered shortly. Lastly, a tripod is needed to support the mount head and provide a stable base for the remaining equipment. The mount head is generally attached to the tripod with two adjustable bolts, allowing for easy movement of the mount, which is required when polar aligning. Lastly, I wish to stress that all tracking mounts are delicate precision instruments, and can easily be damaged if not given the proper care and respect. It is recommended to review the manuals specific to your hardware before use. Here are a few general safety guidelines when handling an Equatorial Coordinates mount. Before moving your mount, always ensure that the clutches engaging the motors for both axes are in the unlocked position. For the CEM26, the lock and unlock positions are labeled with a convenient switch near each axis. Always ensure that the telescope and mount head have proper clearance from the tripod, ensuring that they never collide. Lastly, in order to safeguard both the mount and telescope, always place the counterweights onto the mount first before any payload.



Figure 7: A labeled CEM26 Equatorial Mount. It is important that you are familiar with all labeled features in order to comfortably and safely operate the tracking mount

Keep in mind that the Equatorial Coordinates mount is the most complicated feature of our observing setup, and will require the most care and consideration when learning the observing

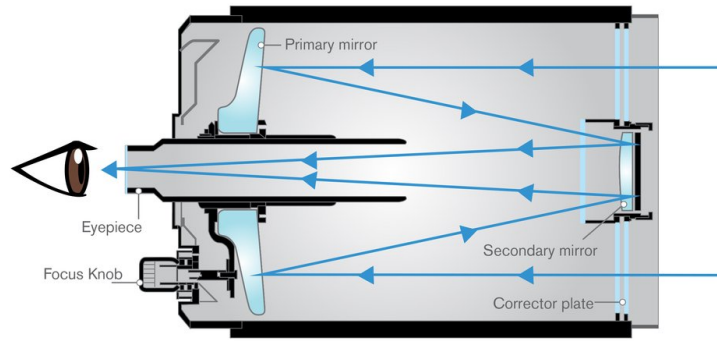
process. Don't be discouraged if it takes several nights to familiarize yourself with these concepts as you begin to become comfortable with the steps needed to align yourself to the sky and the somewhat counter-intuitive motion of the mount. In the following subsections of the manual, we will explain the Equatorial Coordinates coordinate system and these required steps.

## 7.2 Telescope/Optics:

The telescope included with the Exoplanet Watch system is a C6 Schmidt Cassegrain. The C6 simply refers to the size of the aperture, meaning the primary mirror is 6 inches ( 150mm) in diameter. A Schmidt Cassegrain is a common type of telescope, utilizing both mirrors and corrective lenses. The C6 telescope is an F10 system, meaning a focal length of 1500mm. When observing exoplanets, the specific focal length is actually not too important, with the sampling rate of the camera + telescope pair playing a larger role. Sampling is a way of measuring how much of the sky is recorded by a single pixel on the camera, and is measured in arcseconds per pixel ("/px). The C6 telescope paired with our chosen camera gives us 0.5 arcseconds per pixel, which is a relatively oversampled system. We will cover this in more detail when reducing our data, but I want to emphasize that this oversampling means a higher demand on our tracking equipment and the increased likelihood that the stars we observe will appear potentially bloated or elongated. Fortunately, star shape isn't critical when performing Photometry, but these defects can effect some of the steps we follow when observing, making things more difficult. Any telescope with a decent size aperture will likely be suitable for exoplanet Photometry - those with shorter focal lengths and larger sampling rates will be less demanding on our tracking equipment. If you have any concerns about whether your specific telescope is capable, please reach out to our team. For our C6 Schmidt Cassegrain telescope, I want highlight some important features and considerations during handling. Schmidt Cassegrains, or SCTs, are particularly fragile. The corrector lens located at the front of the telescope is critical in the optical design and somewhat delicate, so its recommended you treat the telescope with care. The centered circle located in the middle of the corrector plate is the secondary mirror. The light exits the telescope at the back, which is where we will attach our camera. The telescope is focused using the knob located on the back. These characteristics are the same for all SCT type telescopes, but other designs may vary drastically.

## 7.3 Camera/Detector:

The camera included with the Exoplanet Watch system is a ZWO ASI224MC. This is a camera with 3.75um pixels, which again when paired with a focal length of 1500mm produces a sampling rate of 0.5 arcseconds per pixel. The total sensor size of the 224MC is quite small, meaning the captured field of view is only around 15 arcminutes by 15 arcminutes. Essentially, with this camera and telescope, we look at only a small slice of the sky and will observe only a few stars at a time.



**Schmidt-Cassegrain Telescope**

Figure 8: The light path of a Schmidt Cassegrain Telescope. While one does not need to understand the exact optical properties of the telescope, it is important to understand that the optical tube consists of a front corrector plate, a primary mirror, and secondary mirror. All 3 components must work together to direct the light which we end up observing

The ASI224MC is what we call a "One Shot Color" camera, or OSC for short. This means it produces color pictures using a bayer filter array attached to the sensor itself. A bayer filter array is simply a grid of red, green, and blue filters. In order to produce a color image, interpolation is performed between neighboring pixels to get sufficient color data for each pixel at the cost of spatial information. While important, it is not necessary to understand these details fully while observing, and they will be covered in greater detail when discussing data reduction. Cameras with a larger sensor size will be easier to use as they give a wider field in which we can cross reference stars, along with a greater sample size when trying to perform a "plate solve." Plate solving is an automated process used to center the telescope field of view onto the desired coordinates by matching specific star patterns. The full well capacity, ADC bit depth, sensor size, and quantum efficiency are all additional important factors when choosing a camera for Photometry.



Figure 9: (Left) The ASI224MC "hockypuck" camera. The heart of the camera is the imaging sensor (shown in the center) which is supported by a round housing with a USB3 and ST4 cable port. The front of the camera is threaded to allow us to easily attach it to our imaging train. (Right) An example raw image taken with the ASI224MC. Note that your images will be monochrome before the process of debayering

## 7.4 Assembly and Initial Preparations

(This section has an accompanying video located on the Exoplanet Watch website) Now that we understand our equipment a bit better, we can begin to assemble everything together and prepare for our first observations. Please note that some sort of Windows computer connection is required (preferably a laptop you are comfortable with exposing to the elements). The assembly process for our Equatorial Coordinates system is very simple, and begins with the telescope "imaging train," or the camera to telescope connection. From there we must attach the mount head to the tripod. After that, we can connect our telescope/camera pair to the mount itself, and our system is complete. Once our assembly is complete, we will then cover the necessary software installation.

**Imaging Train:** While "imaging train" implies a number of components connected together, our system is very simple, and consists only of our camera. You will find a 1 1/4 inch "visual back" adapter piece attached to the back of the telescope. In addition to the threaded 1 1/4 inch nosepiece included with the camera, this is all we require for our imaging train. Thread the nosepiece onto our camera using the attached threads, and then insert the nosepiece into the visual back. The visual back has an attached lock screw that you will need to tighten in order to complete the attachment. While the orientation of the sensor does not matter, ensure that the connection is tight enough that the camera will not rotate throughout the night. With this, the camera is properly connected to the telescope and the pair is ready to be attached to our Equatorial Coordinates mount. As the term "imaging train" suggests, if you have additional imaging equipment such field or coma correctors, filter wheels, off-axis prisms etc, your camera attachment method will be more complicated. Correctors will include precise backfocus requirements (distance from corrector to sensor) and filters will need to be placed accordingly with their size relative to the sensor to avoid vignetting effects. If you have your own equipment selection and are struggling to properly construct your imaging train, please reach out to our team and we can assist you. Note that we will cover connecting an Off-Axis Guider in the altitude-azimuth instructions as it is necessary for that setup, but not needed when using an Equatorial Coordinates system.



Figure 10: Existing Imaging train on an assembled observing system. Note the simple connection between visual back, nose-piece, and camera. Note that while this is a simple imaging train, other equipment combinations may have more complex considerations. If using a optical reducer or corrector, certain back-focus (distance from camera to corrector) requirements must be met. Additionally the use of any filters or guiding equipment will complicate the imaging train as well.

**Mount and Tripod Connection:** The process of connecting our mount head to the tripod is very simple as well. Most Equatorial Coordinates mount tripods will have a center "spike" which will guide you as you place the mount onto the tripod, acting as both support to hold the two pieces together as well as a guide for placement. Some tripods may have an additional second spike located at one end of the tripod to specify orientation and guide the azimuth adjustment bolts (see picture below). For our CEM26 mount this is the case, so when lifting the mount onto the tripod ensure that you have the azimuth bolts facing the proper direction, screwed all the way out as to not strike the tripod bolt. Once the mount head is on the tripod, you will need to securely attach it using two bolts located on either side of the mount head. Various mounts will have different attachment methods, but ensuring that the head is firmly and securely on the tripod is critical. Any sort of slop or movement between the tripod and mount head will affect tracking performance and hinder our observations.



Figure 11: Tripod base and the two required bolts to mate the CEM26 Equatorial Mount. Note the locking pin located on the right-hand side. This is used to position the mount relative the the azimuth adjustment bolts and makes for a good guide when positioning the mount

**Telescope and Mount Connection:** With both the telescope/camera pair and mount/tripod pair successfully together, we are almost fully assembled! All that is left now is place the telescope onto the mount. This is done using the angled bar attached at the bottom of the telescope, called the dovetail. The mount head has a saddle attachment for this dovetail at the top of the declination axis, and looks like a large plate with a grooved opening for the bar with two locking knobs at one side. Undo these knobs until the dovetail can comfortably fit inside the assembly, placing the telescope on top of the mount head and then tighten until firmly secured. Do not worry about the exact placement of the dovetail - we will have to balance each axis anyways, which we will cover in the next section. Again it is important to stress that the mount **MUST** have the counterweights attached **FIRST** before the telescope is placed onto the mount head. Failure to do so will likely result in damaging either the telescope or mount. With everything now assembled, the last step

is connecting cables to the computer. First, connect the USB-B cable from the camera port to an available USB port on your imaging PC. Next, connect the tracking mount either through the on-board wifi module or USB connection through the hand controller. Both connection options work equally as well, although you will lose access to the internet while using a wifi based connection. This may impact your ability to use your imaging PC to look up transit parameters as well as perform an internet based platesolve through [astrometry.net](http://astrometry.net).



Figure 12: A fully assembled Exoplanet Watch setup ready to begin observing. Note that the tripod legs are fully extended to give room when Polar Aligning, the counterweight is properly positioned to balance the weight of the telescope tube, and the telescope itself is properly positioned on the dovetail mount.



## 7.5 Software Installation and Testing:

Now that all of the hardware components are ready for observing, we can install the necessary software we will need onto our imaging computer. All of the software we have selected is both safe, free, and easily usable as well as common standards in the amateur community. Note that this installation procedure is tailored to the telescope loan agreement system. Depending on the camera and mount you are using, the needed control software will likely vary and items 1 and 2 may not be the correct. Your items should include proper installation procedures for your specific equipment, but as always if you are having issues please reach out to our team on Slack or by Email at [exoplanetwatch@jpl.nasa.gov](mailto:exoplanetwatch@jpl.nasa.gov). There are several installations that we require:

- [ASI Camera Driver Package](https://astronomy-imaging-camera.com/software-drivers) - <https://astronomy-imaging-camera.com/software-drivers>
- [Ioptron Commander Mount Control Software](https://www.ioptron.com/Articles.asp?ID=332) - <https://www.ioptron.com/Articles.asp?ID=332>
- [ASCOM Platform 6.5](https://ascom-standards.org/) - <https://ascom-standards.org/>
- [Nighttime Imaging 'N' Astronomy Sequencing Software](https://nighttime-imaging.eu/download/) - <https://nighttime-imaging.eu/download/>
- [ANSVR Plate Solving](https://adgsoftware.com/ansvr/) - <https://adgsoftware.com/ansvr/>
- [ASTAP Plate Solving](https://www.hnsky.org/astap.htm) - <https://www.hnsky.org/astap.htm>
- [Time-Sync](https://www.speed-soft.de/software/time_sync/) - [https://www.speed-soft.de/software/time\\_sync/](https://www.speed-soft.de/software/time_sync/)

The first two items are drivers and support packages required to run both the camera and mount. These drivers then interface with the third item, ASCOM, which is a flexible platform designed for interfacing astronomy equipment together. The last item, Nighttime Imaging 'N' Astronomy, is the software which we will be interacting with to plan our observations and facilitates control of the camera and mount. Follow the link for the ASI camera drivers and install the Native Driver package labeled "ASI Cameras." This will install the needed software to run the ASI224MC camera. Next, follow the link for the Ioptron Commander software and install the "Commander and ASCOM Driver Installer." This will install the needed software to control the mount. These drivers then require installation of the ASCOM Platform, following the third link. Click the download button on the right-hand side labeled "Platform 6.5SP1" and follow the install procedure. Lastly, click the last link and download the latest stable release of Nighttime Imaging 'N' Astronomy. Currently this is Version 1.10 HF3. With this, all the required software should be installed and working. The remaining items are additional support software needed while running the primary sequencing software, Nighttime Imaging 'N' Astronomy. Their usage will be covered in subsequent sections

**Initial Testing:** Now that the system is properly assembled and we have a formatted imaging computer, we can do a trial run to make sure all of the equipment is working as intended. Our first step is to make sure that both the mount and camera are connected to the laptop, and the

mount is plugged in, turned on, and receiving power. Connect the hand controller included with the mount in the appropriate slot located on the mount head. The hand controller should power on and give you some information about the state of the mount. Ensure that the displayed time, latitude, and longitude are all correct. Now using our imaging computer, launch the Nighttime Imaging 'N' Astronomy, which we will use to check both the mount and camera. Once Nighttime Imaging 'N' Astronomy is open, you will be asked to load a profile. You can simply exit out of this menu and choose to set up a profile for convenience at a later time. Nighttime Imaging 'N' Astronomy will now display a list of equipment options. We first want to connect our ASI224MC camera in the "Camera" tab located under "Equipment." You should be able to locate the camera from the drop down menu and then press the "connect" power icon. Once this is completed, Nighttime Imaging 'N' Astronomy has control of the camera and will allow you to choose various settings such as gain and offset. We will set these later. Now navigate to the "Telescope" tab located under "Equipment." You should see "Ioptron" in the dropdown menu, followed by a long list of mount names. This is the Ioptron Commander software used to connect our mount. As you did with the camera, press the power icon to connect the mount. A bright red window with yellow text will appear, asking for the "RS - 232 / USB Port." The window will initially be set to whatever previous COM port used for connection, or "Auto Detection." While the automatic detection is usually fine, we recommend navigating in Windows to "device manager" and finding the specific COM port number that is tied to a "Serial USB adapter." This is our mount cable, and Ioptron Commander needs to know the COM port number in order to properly connect. Once you've given the proper COM port, hit OK and a new red window will appear, giving mount information similar to the hand controller. With this, both the mount and camera are connected and ready to be controlled through Nighttime Imaging 'N' Astronomy. You will have to go through this equipment connection process each time you launch Nighttime Imaging 'N' Astronomy. If you have any trouble finding/connecting either the mount or camera, we recommend first restarting Nighttime Imaging 'N' Astronomy, and then double checking the above software installations. If these issues persist, you may have a more serious issue involving either COM port connections, ASCOM, or faulty cabling/hardware. Please reach out to our team and we can assist if this is the case.

**Camera/Mount Testing:** With everything connected, we can now test to see if our camera is properly functioning. Using Nighttime Imaging 'N' Astronomy, navigate to the "Imaging" tab. From here, using the right hand panel labeled "Imaging," we can tell the camera to take pictures of any desired exposure time. The actual photos we take here are unimportant - we just want to ensure that the camera is properly taking photos and we can download that data. As the camera finishes each picture, the large image pane to the left of the tab should update, showing each image. As long as images are displaying and updating over time, we know our camera is properly functioning. As for our mount, as long as Ioptron Commander is properly connected, we will assume everything is working correctly. Before we can properly test the mount by Slewing

to a location, we need to make sure both the Right Ascension and Declination axes are balanced, which we discuss in the next section.

## 7.6 Mount Firmware and Potential Updates:

Throughout the software installation process, you may find various pieces of equipment requiring firmware or software updates. The most important of these, if prompted, is the CEM26 tracking mount. Upgrading the firmware for the mount can be a difficult process - if you are receiving a telescope loan agreement setup, all software/firmware should already be updated to the latest version. The process for upgrading firmware can vary depending on the mount version and current upgrade software published by Ioptron. Please refer directly to their website and subsequent firmware upgrade guidelines, following them exactly as instructed: [http://www.ioptron.com/v/firmware/CEM26\\_GEM28\\_FirmwareUpgradeInstruction.pdf](http://www.ioptron.com/v/firmware/CEM26_GEM28_FirmwareUpgradeInstruction.pdf). If you encounter any issues throughout this process, please stop the upgrade process and reach out to the Exoplanet Watch team, as this may be a sign of faulty equipment or a larger issue.

## 7.7 Proper Timekeeping:

In order to ensure our measurements for each observed transit are as accurate as possible, we need to make sure we have proper time records for each transit data-point. While the time for each exposure is properly recorded in the .FITS File Extension header and then reduced through EXOTIC, we need to make sure that our control computer time is actually accurate, as the sequencing software recording this time into the .FITS File Extension header relies on the control computer's local time. Several websites are available to check current "Proper" time, such as <https://time.gov/>. There are a few ways we can make sure that your recorded local time is correct and synced with a time server. The first method is navigating to the "Change date and time settings" tab in Windows, and then clicking onto the "Internet Time" tab. From here you can choose to "Synchronize with an Internet Time server" which should update and sync your machine's local time. Doing this each time before an observation will become quite tedious however, so we recommend using a local time syncing app which will contact an available server to sync with at a given interval. There are numerous such software programs that perform this action - we recommend "Time-Sync," which can be found in the software download section. Simply install the app and set the sync interval desired. Your local time shouldn't require syncing more frequently than every day, unless your local machine has noticeably deviated from proper time in the past or has some other issue with timekeeping. Note that this process will require an internet connection. If you wish to observe in a location without steady internet, please ensure that your local machine is properly time synced before beginning your observations.

## 7.8 Balancing The Mount

(This section has an accompanying video located on the Exoplanet Watch website) Balancing the mount is an important procedure that you must follow each time you adjust either the telescope dovetail connection or the mount counterweights. Attempting to Slewing the mount without properly balancing BOTH the Right Ascension and Declination axes can potentially damage or stall the mount motors, so understanding the balancing process is very important. While important, the balance procedure is fairly simple, and once you've balanced the mount a few times it will become second nature. Be careful when performing these procedures! You will be unlocking the clutches for both axes, allowing parts to move under their own weight. Its important that you are careful and ensure that nothing hits the tripod or falls off the mount head. When balancing, we always start with the Right Ascension Axis. Recall that RA is the active tracking axis for an Equatorial Coordinates mount, and is connected with the counterweight bar and counterweights. In order to balance RA, we start by unlocking the RA motor clutch and carefully moving the RA axis until both the counterweight and telescope are parallel with the ground, forming a horizontal line. If RA is unbalanced, you should notice the mount swing either towards the telescope or towards the counterweight, just like a seesaw. Our goal is to balance out this motion, such that when the telescope/counterweight pair is hanging in our horizontal line, no motion is observed. We do this by adjusting the counterweight position on the counterweight bar, moving it either up or down as needed. If, with the clutch unlocked, the mount remains stable in this horizontal position, RA is properly balanced. If you are struggling achieving balance with your specific telescope/counterweight pair, you may require either an extension bar or additional counterweights. For the loan agreement system, this should not be an issue. Additionally, if you observe significant backlash when tracking in RA, you may want to slightly unbalance the mount towards the East - this will help keep the tracking gears meshed at all times.

Once RA has been successfully balanced, we must balance Declination. This is done by unlocking the Declination clutch, and then again leveling the telescope/counterweights in a horizontal line. You may keep the RA clutch locked for ease of use during this process. You should observe the Dec axis/telescope swing either to the front or to the back of the telescope. Just like with RA, we want the Dec axis to be able to freely hang without motion in either direction. This is done by adjusting the telescope dovetail position, moving it either forward or back as needed. Again, be careful that the telescope does not fall during this process! We recommend returning the telescope to an upright position before making any adjustments. Once both RA and Dec are properly balanced following the above process, the mount is ready to Slewing and support our telescope. (Note - for those using equipment outside of the recommended setup. It is possible that you may need to balance in a 3rd axis - this is covered additionally in the balancing video.) The last required step in managing the mount before beginning our exoplanet observations is performing Polar Alignment.



Figure 13: Equatorial Mount Balancing Position for both Right Ascension and Declination. Note that we assume the vertical Z position is already balanced, which is true for the Exoplanet Watch setup and is generally true for any telescope that is symmetric about the dovetail

## 7.9 Polar Alignment

(This section has an accompanying video located on the Exoplanet Watch website) With our equipment assembled and balanced, we are almost ready to begin making exoplanet observations. The last step we need to follow is necessary in order to have our mount properly work. Recall that as our mount is based on the Equatorial Coordinates coordinate system, it must be aligned with either of the celestial poles. If you are in the northern hemisphere, this is the North Celestial Pole (Celestial Poles (NCP and SCP)) located close to Polaris, the Pole Star. Polaris helps make our Polar Alignment process easy, and is a needed reference star during the process as you will see shortly. Polar Alignment in the southern hemisphere is a bit more difficult, as there is not a nice bright star which we can use as reference like Polaris. Instead, the southern hemisphere can use a star aster-ism located near Sigma Octanis, or rely on software derived alignment methods. We wish to stress that for first time observers, Polar Alignment can be a difficult and stressful process. Dont get discouraged! While difficult at first, Polar Alignment is very important to ensure the mount is tracking properly. Once you've gone through the process a few times, it becomes second nature. We can break the Polar Alignment (PA) process down into two primary steps. The first step is roughly pointing the mount towards the north in the right orientation, and adjusting the altitude of the Right Ascension axis such that it is roughly aligned with the celestial pole. The second step is finely tuning this alignment, using either a visual Polar Alignment scope or software. For our CEM26 mount, we will rely on a visual PA scope. This is a small telescope built into the Right Ascension axis, and can be looked through to align ourselves against Polaris or Sigma Octanis. More advanced mounts may have a camera designed for Polar Alignment built in, or rely

on some other method of alignment.

**Rough Alignment:** As stated above, the rough alignment process requires that we point the mount/telescope roughly in the direction of the celestial pole. In the northern hemisphere this is north, and south in the southern hemisphere. You can do this using a compass, or rely on the stars themselves using familiar constellations. Both Cassiopeia and The Big Dipper are commonly used to locate the Celestial Poles (NCP and SCP) (Polaris) as they are generally visible for those in the northern hemisphere and are nearby the pole. Depending on the level of light pollution in your area, finding Polaris may be somewhat difficult for the very first time, especially if you just starting to orient yourself with the sky. We want the mount pointing towards the celestial pole, with the counterweight end facing forward. Once the mount is pointed roughly in the correct direction, we need to raise the altitude of the Right Ascension axis. The celestial pole will always be located at an altitude equivalent to your latitude. For example, a Californian observer with a latitude of +33 degrees will observe Polaris 33 degrees above the horizon. You can find your latitude and longitude easily through a variety of sources, such as <https://www.latlong.net/>. As such, this observer wants to adjust their mount using the altitude adjustment bolt until the Right Ascension axis is inclined 33 degrees from the horizon. Most mounts, including our CEM26, will have an indicator showing the current inclination of the axis. Please note that if your tripod is not perfectly level, this indicator will not be accurate. Once your mount is pointed roughly towards the celestial pole, and the Right Ascension axis is raised to the appropriate inclination, we can move on to fine alignment.

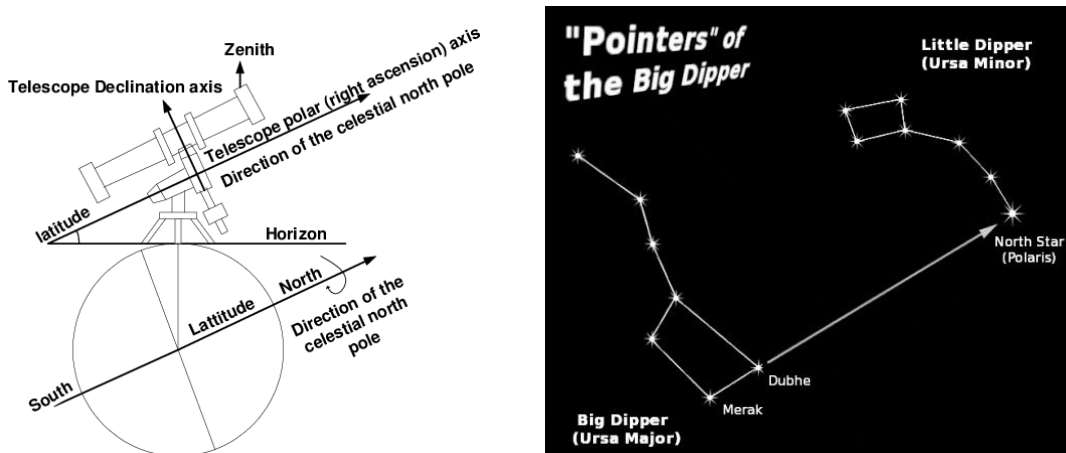


Figure 14: Polar Alignment in the Northern Hemisphere. Once you have properly adjusted the mount altitude to match your latitude, use the big dipper to help find Polaris. Once you have the mount pointing towards the North (or South) Pole Star, you are ready for fine polar alignment

**Fine Alignment:** With the mount roughly aligned, we must now finely adjust both the azimuth position and altitude position of the mount using the appropriate bolts on the mount, following cues from either a polar camera or visual scope. The general process is the same for both, and

only differs in how you view the pole star to make adjustments. Since our CEM26 mounts have PA visual scopes, we will walk through the visual process. First, uncap the covers for the PA scope. These are located underneath the motor housing for Declination and on front of the counterweight bar attachment point. Some visual scopes may require an illuminator cable in order to provide light to the reticle located inside the PA scope. Look through the PA scope - you should see a red indicating reticle with various concentric circles. This is our reference for placing the position of Polaris, and thus achieving Polar Alignment. If the reticle is blurry, focus the polar scope by twisting the threaded piece at the opening of the scope. As you twist out further, the focus point should change. Adjust the focus until you can clearly see the indicator circle. At this point, we are ready to properly center Polaris. Using the mount Hand Controller, navigate first to Alignment and then Polaris Location. This will display where Polaris should be placed on the reticle. Hopefully, you can already see Polaris through the visual scope. If not, you will need to adjust either azimuth or altitude until found. Polaris should be the brightest star seen by a large order of magnitude, and will appear obvious. This can be a tricky process - we recommend first checking the altitude/latitude inclination and level of the tripod. If these look correct, slowly adjust the azimuth bolts, checking both to the left and to the right of your current location. Once Polaris is found, simply place the star at the position indicated on the hand controller. Try to be as precise as possible - good Polar Alignment is essential with this setup, especially if you want to have any sort of automation throughout the exoplanet transit. Bad Polar Alignment will mean your target star will drift over time, requiring manual recentering. If polar aligning in the southern hemisphere, the procedure will be similar to the one outlined above. Instead of Polaris, your reticle will be designed for use with Sigma Octanis and the surrounding stars. It is not uncommon for beginners to polar align on a star that is not Polaris - you will be able to determine if this is the case if you start to observe significant drift over short periods of time as you begin a transit observation. While difficult at first, we wish to re-emphasize that Polar Alignment is critical, and it does get easier over time!

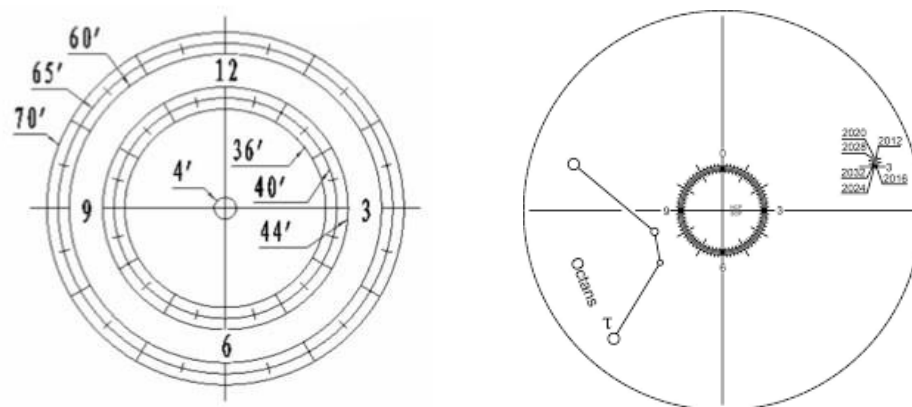


Figure 15: Visual Scope Reticles for both the Northern (left) and Southern (right) Hemisphere. The exact reticle in your equatorial mount will depend on both the company and hemisphere you are located in.

## 8 Capturing an Exoplanet Transit

(This section has an accompanying video located on the Exoplanet Watch website) We are now ready to capture our first exoplanet transit. Remember that each time you set up the telescope system, you need to go through assembly, balance, and Polar Alignment. Both balance and Polar Alignment are very important. You must re-balance any time you remove the telescope from the mount, and must redo Polar Alignment anytime the mount/tripod is moved or disturbed.

### 8.1 Choosing a target:

In order to capture an exoplanet transit, we must choose an actual star to observe. Both the Exoplanet Watch website and the Swarthmore College have transit predictive services. Select an appropriate transit from the target list, getting both the time and the RA/Dec coordinates for the host star. If using the Swarthmore transit finder, note that our telescope system can accurately observe up roughly 12th magnitude stars exhibiting transit depths of 10-15 ppt. Keep in mind that the magnitude scale the astronomers use is logarithmic, and that lower numbers correspond to brighter stars. Telescopes with larger apertures may be capable of more difficult transits. We recommend starting out with a bright star exhibiting a large transit depth for your first few observations in order to get a sense of the equipment's capabilities. The Exoplanet Watch Website lists nightly exoplanet targets to observe.

### 8.2 Nighttime Imaging 'N' Astronomy Sequencing Software Setup:

Once you have a transit with a start time and coordinates, we can set up our Nighttime Imaging 'N' Astronomy sequence. Launch Nighttime Imaging 'N' Astronomy and navigate to the "Sequencer" tab. Here we can plan out our observation. We first want to input the host star coordinates in the appropriate boxes located at the top right. Nighttime Imaging 'N' Astronomy will give you an altitude graph of the target over the course of the night, so you can visualize where our host star is located. Next, under the "Target Options" tab, turn on "Slewing to target." Finally, we need to tell Nighttime Imaging 'N' Astronomy how many pictures to take as well as the camera exposure time. The recommended exposure time will be 30 - 60 seconds for the Exoplanet Watch telescope system. Anything above 60 seconds will likely become limited by the capabilities of our tracking, and significant smearing of our stars will occur. These exposure times should be sufficient for our recommended transit targets. We can tell Nighttime Imaging 'N' Astronomy to take these pictures with the bar of information located in the middle of the page. This bar provides options for number of pictures, exposure time, type, filter, binning, dither information, gain, and offset. First, we must set the gain and offset for our ASI224MC camera. These two fields may usually be left as "0" for gain and "20" for offset. Once this is done, we may leave everything set to defaults



aside from the exposure time and total number of pictures. The total number of pictures will depend on how long your transit is - make sure that you take enough data to properly cover the transit duration as well as a baseline for both the egress and ingress. We recommend following the time duration's given either on the Exoplanet Watch website or through the Swarthmore transit planner.

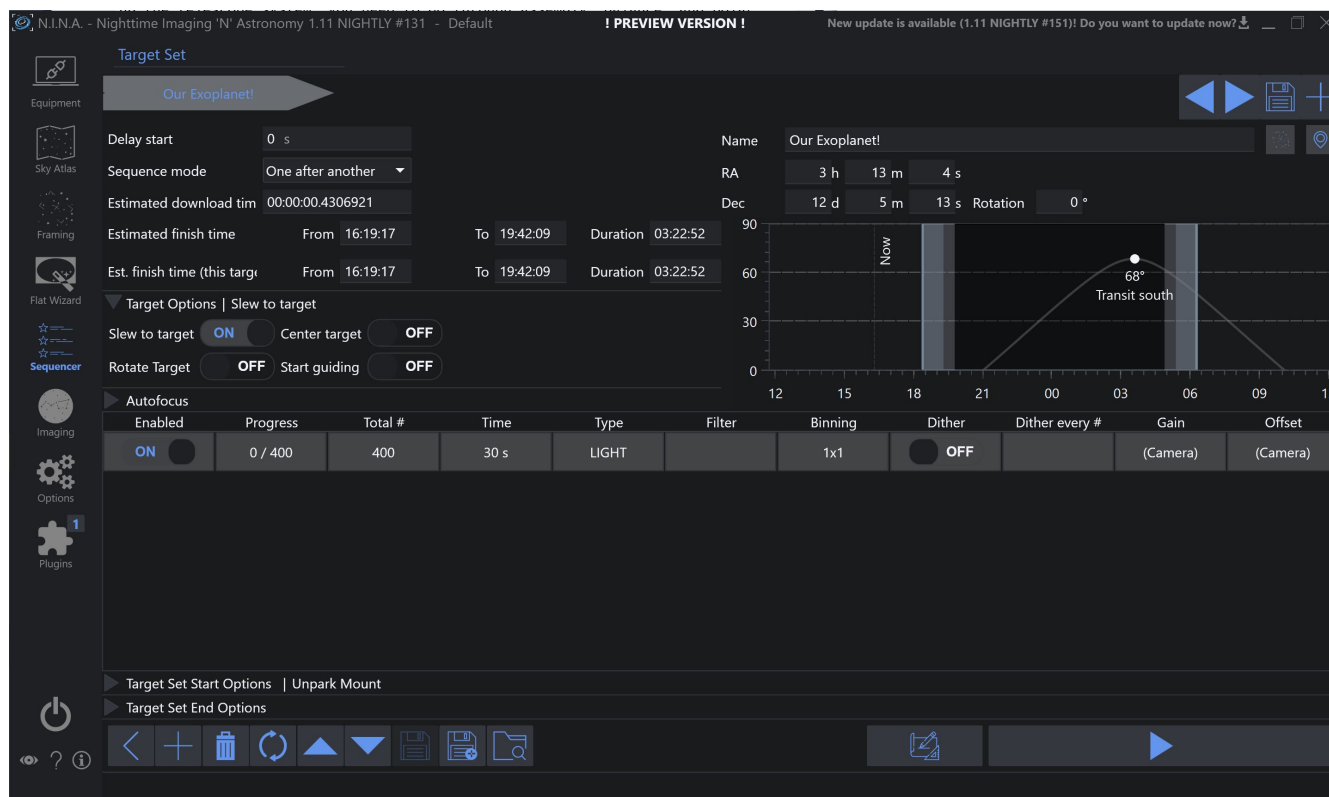


Figure 16: An example sequence in Nighttime Imaging 'N' Astronomy - Note that your UI may look slightly different depending on the version of Nighttime Imaging 'N' Astronomy used, but the sequencing information should be identical

### 8.3 Final Preparations

Before we can start our sequence, we need to make sure the image directory is specified, the telescope is in focus, and we will successfully Slew to the right location. You can specify the image directory in the "Options" tab under "Imaging." You may also specify how you want your file names to appear, although this is not necessary. Next, navigate to the "Imaging" tab and start taking pictures using the right-hand pane. You should hopefully see stars, or out of focus stars in your images. If the camera field appears to be only static, it is likely that the telescope is too far out of focus. Begin turning the focus knob until you begin to see anything resembling a donut. These are out of focus stars. Turn the knob until you can reduce those donuts into tight stars. The tighter/smaller the star appears, the closer to the prime focus point you are. Lastly,

once you are in focus, use the mount hand controller and Slewing to a bright star listed in the hand controller catalog. We want to find a dense star field in which we can compare the telescope's current position with the desired one. Slewing to several stars checking field density - you are more likely to find success Slewing to something along the plane of the Milky Way. If you believe you have a sufficiently dense starfield and everything is in focus, open up the "platesolving" tab and take a 5-15 second exposure. If set up properly, Nighttime Imaging 'N' Astronomy should be able to solve the field and recenter the telescope as needed. If you are unable to successfully Plate Solving, proceed to the next step and check whether the telescope is on target. If not and you are unable to Plate Solving, please reach out to our team and we can assist you.

#### **8.4 Observing the Transit**

Once our sequence is set-up, we are ready to observe! Your observation of the target star should begin an hour or two before the transit is expected to begin in order to capture the baseline star brightness before the exoplanet transit begins. Similarly, you should gather an additional hour or two after the transit is finished in order to establish a proper baseline. To begin the sequence, click the arrow at the bottom right of the Nighttime Imaging 'N' Astronomy sequencer. The mount should Slewing to the target star and the camera will begin taking pictures. You should be able to identify the target star we are observing in the field of view of the camera. You will likely observe periodic motion and blurring of our stars as the mount tracks through the period of its worm gear. This is normal, and is different than the type of motion we want to avoid, such as long term drifting. Continue observing until the transit has finished and a sufficient number of frames post egress have been collected (based off the transit times on the Exoplanet Watch/Swarthmore website). You should now have a collection of .FITS File Extension image files that we are ready to reduce!

## **SECTION 3 : DATA REDUCTION**

## 9 Calibration Frames

In the above sections, we walked through the collection of what we call "light" frames, or the pictures which contain the important transit data we care about. In addition to light frames, astronomers can also take optional calibration frames which help improve the quality of the collected data. These are dark frames, flat field frames, bias frames, and occasionally flat dark frames. In this section, we will briefly cover each type of calibration frame, why they are needed, and how you can take them in addition to your lights.

**Bias Frames** Bias Frames are very short "0" second exposures used to characterize the basic response of the camera. It measures any fixed pattern noise or base issues with the camera such that we can subtract these out. Bias frames must be matched to the appropriate gain and offset used for any light frames. Biases are simply taken by covering the camera and taking several "0" second exposures through Nighttime Imaging 'N' Astronomy. Generally we recommend taking roughly 50-100 bias frames. If covering your camera is not an option (i.e. it is connected to your telescope,) covering the optical tube may be acceptable as well. Generally bias taken this way should be done at night to ensure that the chance of "light leaking" into the camera frame is minimized. We recommend always checking your bias frames before calibration, as you should with each individual calibration frame. Bias Frames will look different depending on what camera you are using, but generally will reveal a random noise distribution with fixed pattern effects, such as potential banding.

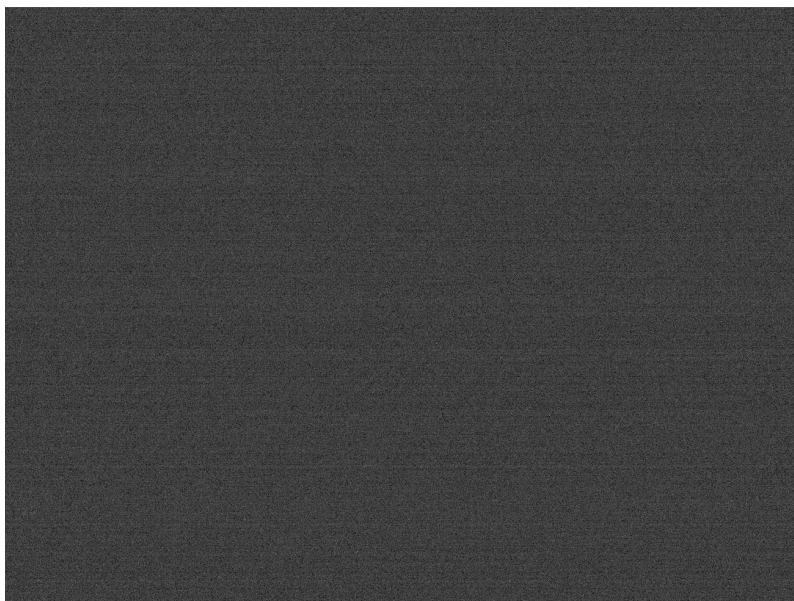


Figure 17: An example Bias frame from the ASI224MC Camera

**Dark Frames** Dark Frames are similar to bias in that they are frames taken when the camera

is covered and not exposed to light. While bias account for any initial existing pattern noise, dark frames are meant for subtracting noise produced by "dark current" as well as artifacts from reading pixel values produced by the camera circuitry known as "amp glow." Dark current is false recordings of light hitting a pixel due to heat causing a response in the pixel. This is why professional astronomy cameras are often cooled to low temperatures, minimizing the dark current. Dark frames must match the exposure time of the light frames, the gain, and the offset. Darks are taken again using Nighttime Imaging 'N' Astronomy, this time taking equivalent exposure times with the sensor covered. Generally we recommend taking roughly 20-30 dark frames. Just as with bias frames, darks make be taken attached to the telescope, ensuring that the environment is dark and no light leaks are occurring. For uncooled cameras such as our ASI224MC, dark calibration may not be beneficial as we cannot precisely control the sensor temperature throughout the course of the night. We recommend trying calibration with both darks and without in order to determine what works best for you if using an uncooled camera, and always using dark calibration if using a cooled camera.



Figure 18: An example Dark frame from the ASI224MC Camera. Here the white corner "amp glow" is made obvious as well as additional "hot" and "cold" pixels

**Flat Frames** While both darks and biases deal with issues inherent to the camera sensor, flat frames are designed to correct issues with the telescope and optics. The total illumination given by the telescope is not uniform across our sensor chip due to imperfect optics, and flat frames are designed to correct for this lack of flatness. As an example, dust on the mirror of the telescope may cast shadows in the form of "dust donuts," appearing as small circles on our camera. Flats will record these dust shadows and divide them out of our image, leaving only the important information we want in our light frames. Flats are usually taken using a uniform light source such as a laptop screen or the evening/morning sky. Point the telescope at your illumination

source and use Nighttime Imaging 'N' Astronomys "Flat wizard" to achieve a proper exposure time (roughly 1/3 to 1/2 the image histogram). Generally we recommend taking roughly 20-30 flat frames. Flats can be a tricky calibration frame to take, and you may find that your flats "uncalibrate" or "overcalibrate" if taken incorrectly. Flat issues can arise due to a variety of issues, from incorrectly matched bias frames to poor/uneven light sources. Troubleshooting flats can be complicated, and additionally flats may not be a requirement for your specific data-set in order to do good Photometry.

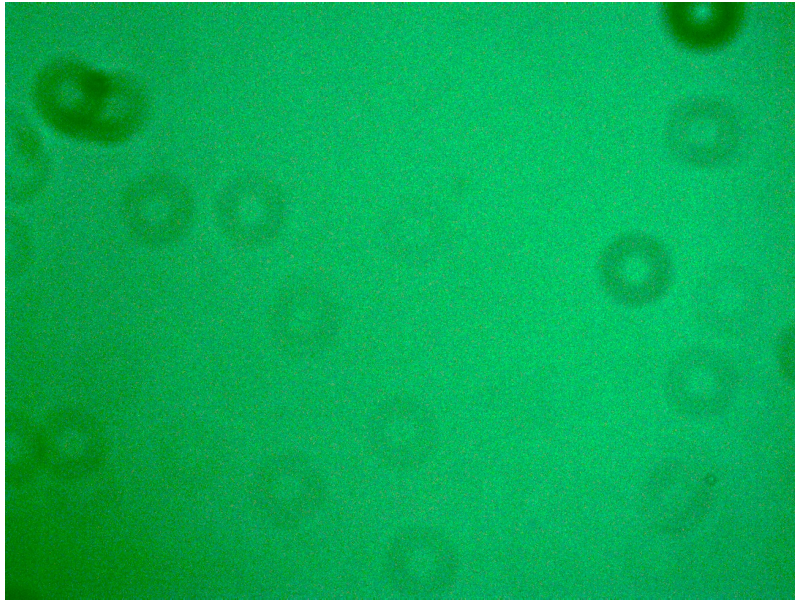


Figure 19: An example debayered Flat frame from the ASI224MC Camera. Here the dust donuts and corner vignetting is clear.

**Flat Dark Frames** Flat Darks are an alternative to Bias frames and should generally not be used unless you have a specific reason(i.e. you find that bias calibration does not work well for your specific setup). If you are observing improper correction using darks, biases, and flats, or have another reason to try flat darks, please reach out to our team.

## 10 Data Reduction using EXOTIC

We can now reduce our transit data using the Exoplanet Watch data reduction tool, EXOTIC. Simply install EXOTIC following the instructions/videos found on the Exoplanet Watch website (<https://exoplanets.nasa.gov/exoplanet-watch>) and follow the data reduction process as demonstrated. EXOTIC is designed to be easy to use, intuitive, and should provide a statistically robust light curve of the transit data. If you are struggling to produce a proper light curve or are having issues with your data, please reach out to the team on Slack and we can evaluate whether this is an issue with your data, EXOTIC, or something else entirely.

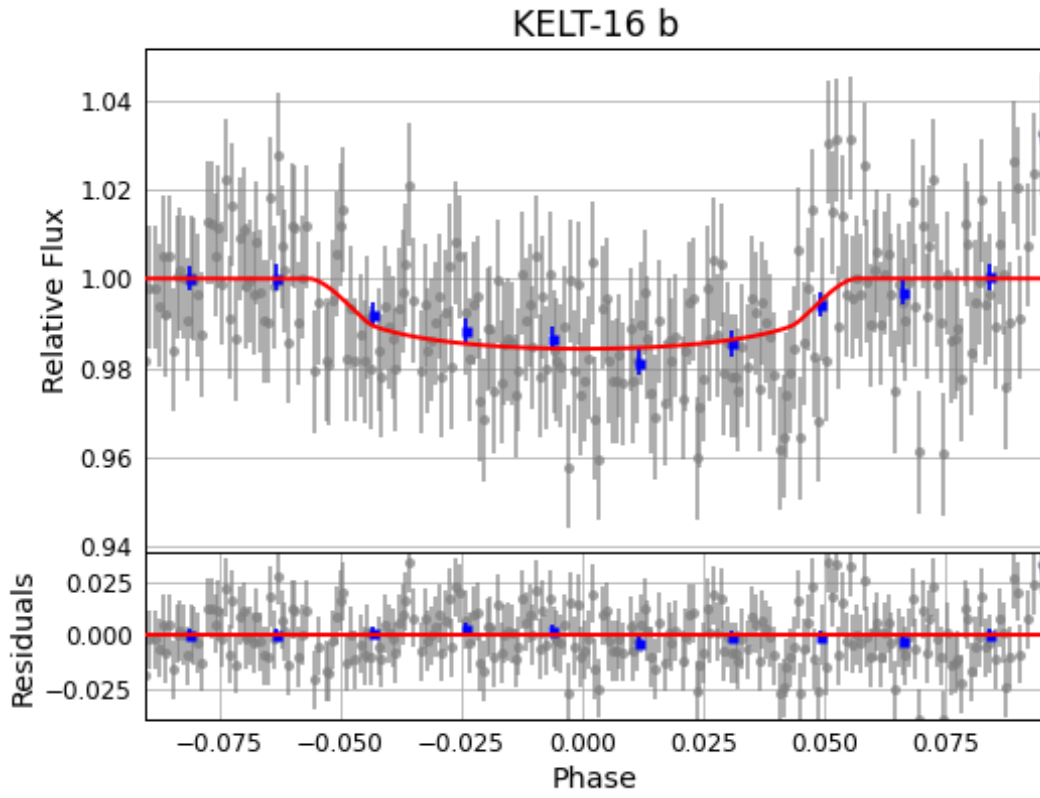


Figure 20: An example of a transit produced using the Exoplanet Watch observing system and EXOTIC

## Glossary

**Photometry** A technique used in astronomy that is concerned with measuring the flux or intensity of light radiated by astronomical objects. i, iii, 2, 4, 9, 16, 17, 34

**Equatorial Coordinates** A fundamental coordinate system often used in Astronomy for locating objects in the night sky. Equatorial Coordinates are absolute relative to the Earth and do not depend on the observers location. i, iii, 5–10, 12, 14–16, 18, 19, 24, 25

**Polar Alignment** Polar Alignment is the procedure one uses to align their tracking mount with one of the Celestial Poles in order to properly track at sidereal rate. Polar Alignment is required for Equatorial Mounts. i, 14, 24, 25, 27, 28

**Nighttime Imaging 'N' Astronomy** NINA is a helpful sequencing software which we can use to coordinate communication between our astronomy equipment. NINA helps us plan and carry out observations in an efficient and convenient manner. i, 21, 22, 28–30, 32–34

**.FITS File Extension** Flexible Image Transport System (FITS) is an open standard defining a digital file format useful for storage, transmission and processing of data that is often used in astronomy to display image data. 4, 23, 30

**Celestial Poles (NCP and SCP)** Two imaginary lines that extend out from the North and South Pole in order to intersect with the Celestial Sphere. The Celestial Poles are the point at which all stars rotate about in the night sky. 5, 7, 25, 26

**Altitude-Azimuth Coordinates** A fundamental coordinate system often used in Astronomy for local positioning in the night sky. Alt-Az Coordinates are relative to the local observer and are useful for interpreting Equatorial Coordinates. 8–10

**Sexagesimal Coordinates** A way of expressing angular coordinates in base 60. We may express an angle in terms of Degrees, Arcminutes, and Arcseconds. An Arcminute corresponds to 1/60th of a Degree while and Arcsecond corresponds to 1/60th of an Arcminute. . 9, 10

**Plate Solving** Plate Solving is a method of measuring the position of stars in an image to determine your exact location in the sky. Platesolving is very useful for finding and confirming an imaging target. 21, 30

**Slewing** The rapid motion of a telescope under computer control as it positions itself to a target. When the telescope is moving faster than its tracking rate, it is said to be slewing. 22, 24, 28–30