CCDware

HOW TO TAKE GREAT IMAGES

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The allure of taking pictures of objects in the night sky is a powerful attraction to many amateur astronomers. Whatever the equipment base, there is a desire to optimize the results. While there have been many articles and books on the subject of processing, in Adobe PhotoShop® for example, precious little has been written about acquiring the image. If the quality of the acquired data is not optimized, the processed result can never correct poor data.

There are some fundamental techniques that, once understood, can significantly improve results. Essentially there are only three things we need to do to get good images – focus, track and expose. Sounds simple, doesn't it? This is not unlike what we do with a conventional camera when we are trying to photograph a moving target. But when it comes to starlight, the problem gets a lot more involved for a number of reasons and we need to use a computer to solve these problems dynamically.

Focusing

We have all experienced focusing for visual use. We adjust the focuser using a back-and-forth movement of the focuser to achieve as sharp an image as seeing will allow. After a little experience, we get a feel for a given telescope and eyepiece and can "snap" the object into focus, to the degree the atmosphere ("seeing") allows. We all know how critical focus is to see detail in an object. The better the focus, the more we can see. In fact, many objects can't be seen ("detected") if the telescope is far out of focus. How much of the object we see ("signal"), is directly dependent on how good the focus is. After viewing it for a while, we move on to another object and repeat the process. We generally don't notice if the focus point changes or even if it does, it is no big deal since we can easily enough refocus it by viewing the object through the eyepiece.

Focusing is a whole different thing when it comes to CCD imaging. First off, we can't see exactly what the camera sees in real time. Regardless of how fast a camera can take an image and present it on the computer screen ("downloads"), it is never fast enough to achieve that "snap" focus we get by eye. Thus we have to resort to more elaborate techniques by using the computer to see what the camera is seeing and adjust the focuser appropriately. Thus we need a way for a computer to control the focus, a focusing program on the computer to focus and a camera control program to control the camera.

Secondly, a CCD camera is incredibly sensitive. We count individual photons with the camera, not the thousands of photons per second we see by the naked eye or the millions of photons per second we see during daylight. So to get the night time signals to a reasonable level so that it can be detected, we need to take very long exposures. Total exposure time for the moon can be as short as ¼ second. For deep sky imaging of faint galaxies, it can be many hours! In order to maintain the ability to detect these weak signals, we need to insure focus is maintained, once achieved.

Focus changes due to a number of things. If we put an optical filter in between the telescope and eyepiece, perhaps to reduce light pollution, we refocus the telescope, never knowing or caring whether the focus point changes. If the aluminum tube of the telescope contracts as the evening cools down, and they all do, the focus point shifts and we have to refocus. Some telescopes, especially larger ones, will slightly change focus as the telescope changes its orientation, due to mirror movement, tube flexure and other factors. These factors become important during the typical long exposures we take with a CCD camera.

Given the length of the exposures and the fact that we use different filters to develop color images, we need to either insure focus is unchanging over temperature, telescope position and filter selection or make periodic adjustments to focus. The former is most difficult to achieve even with expensive telescopes and special filters (called “parfocal”, which means the focus point is unchanged with different filters). For high quality imaging, some sort of focusing during the evening is used by amateur and professional observatories alike.

So let’s summarize our focusing challenge:

- Initially focus using something other than our eye with a camera that doesn’t give the immediate feedback our eye/hand system requires when we are operating visually.
- Insure the focus is stable for long periods of time in which temperature and telescope orientation can change.
- Maintain focus as different filters are inserted between the telescope and the camera.

Tracking

Tracking refers to the telescope’s mount tracking a stellar object as it moves across the sky. As anyone who has ever observed through a telescope without a tracking mount can tell, objects really seem to go flying out of the field of view (“FOV”) pretty quickly. The views from the top of the ladder on a big Dobsonian are spectacular but fleeting. For more modest size telescopes, mounts have motors and appropriate control electronics that track the night sky by moving at the stellar (“sidereal”) rate. Of course, we need to align the mount to the north celestial pole (“polar alignment”) but once we do, we can achieve somewhat stationary object in the eyepiece. With good polar alignment and a tracking mount, we can observe an object for as long as we wish.

However, for CCD imaging, the problem gets more complex. If the tracking and polar alignment is not perfect, and it never is, the images will smear (“trail”) during long exposures. The demands of CCD imaging on the telescope mount are much higher than for visual use.

High end amateur and professional systems get around this limitation by a number of sophisticated techniques. One way consists of modeling the pointing error of the telescope all over the sky, which includes the polar alignment error, and adjusting the pointing based on this model. The pointing model can be extended to tracking by using similarly advanced techniques so that the tracking rate can be adjusted so that, based on the model, the object can remain stationary on the camera for extended periods of time. If the system resolution (See Exposure, below), is not too high, then successful imaging can be achieved. This type of imaging is called Unguided Imaging.

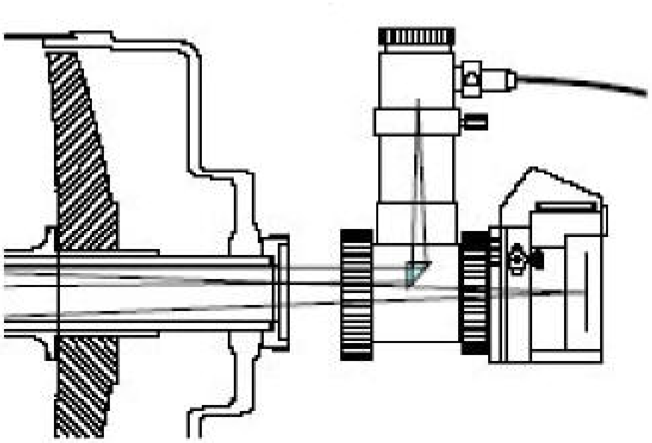
For more modest equipment sets, good results can be achieved by a technique called “guiding”.

Guiding consists of using essentially two cameras. One camera, the “imager”, looks at the object you wish to image. A second camera, the “guider”, looks at a specific reference star. By connecting the telescope mount to a computer and connecting the guider to a computer and having a suitable guiding program, we can begin to solve this problem. The guider looks at a specific star, the “guide star” and notes its position on the guider camera. We calibrate the guiding program so that we know how much the guide star moves in response to a specific command from the guiding program to the telescope. Then we start the guiding program to track the guide star. As the guide star moves, the guiding program attempts to move the telescope in a direction to bring the guide star back to its original position. This is the basic process of guiding.

There are two basic ways of implementing guiding, at least at the amateur level. Here are the basic techniques:

Self-guider

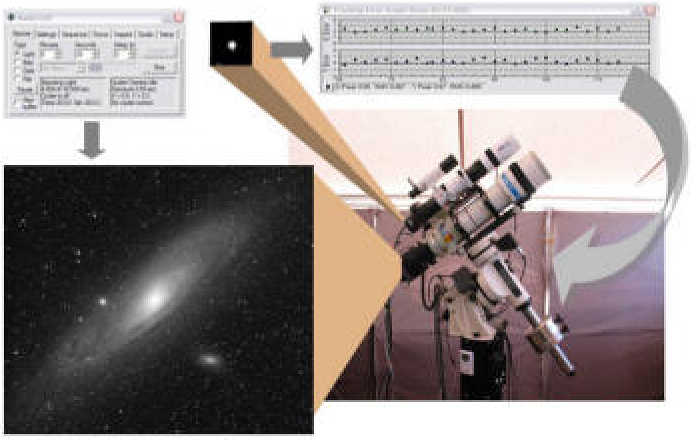
Here the guider camera and the imaging camera share the same telescope optical path. The guider camera samples a portion of the light outside of the imager’s FOV. SBIG has a patent on a unique arrangement in which the guider and imager are in the same housing. This arrangement provides an all-in-one package.



Off-Axis Auto-guider Configuration

External Guide Scope

There the guider looks through a small telescope (“guide scope”) that is hard-mounted to the main scope. The imager looks through the main scope.



External Auto-Guider Configuration

Professional techniques get considerably more sophisticated and will not be discussed here.

An autoguider has one additional problem. Since the guider is behind any filters, the guide star signal will be reduced depending on the filter in place. This is usually addressed by either selecting a sufficient exposure time for the lowest transparency filter or manually adjusting the guider exposure depending on the filter chosen.

We know that when we look at an object that is low on the horizon, we don’t see as well as when the object is overhead. This is due to the amount of atmosphere (“air mass”) we are looking through. Planetarium programs give the air mass of an object for various altitudes normalized to a value of 1 at the zenith. It is instructive to see how the air mass changes as an object gets closer to the horizon. An air mass of 2 indicates we are looking through twice as much atmosphere as at the zenith and occurs at an altitude of 45°. The effect of the atmosphere can be seen with the naked eye if you look at a bright star that is close to the horizon. The star seems to flicker and even change color. This is nothing more than the atmosphere acting as an optical element (“refraction”) changing the position and color of the star as the atmosphere moves. To take good images, we need to be imaging through the least amount of atmosphere as possible, consistent with exposing for long times of course.

The problem here is that the meridian bisects the region of least atmosphere. This is one of the reasons most professional observatories use a variation of a fork mounted telescope. With this design, it is possible to image continuously through the meridian. Of course such precision fork mounts are quite expensive as they are difficult to construct. At this point in the development of amateur equipment, the most cost effective mount style, in terms of precision per unit cost, is the German equatorial mount (“GEM”).

Fork Mounted Telescope

German Equatorial Telescope Mount

When tracking an object from east of the meridian, something must be done when the meridian is reached with a GEM. Manual operation consists of stopping until the object has crossed the meridian. Then the user reacquires the object from west of the meridian. This is called “flipping the meridian”. A typical GEM will slew to the direction of the north celestial pole and come back from the west to the target. In the course of doing this, the object will be rotated 180°. If the user is doing guided imaging, the guider must be recalibrated. If the user is using a self-guider, the assembly must be rotated by 180° to reacquire the guide star and then the guider must be recalibrated. As a consequence, most guided imaging is not done through the meridian. Even with unguided imaging, the images taken west of the meridian will be rotated 180° from those taken east of the meridian. Motorized rotators are available that can make part of this easier but they all still require user intervention.

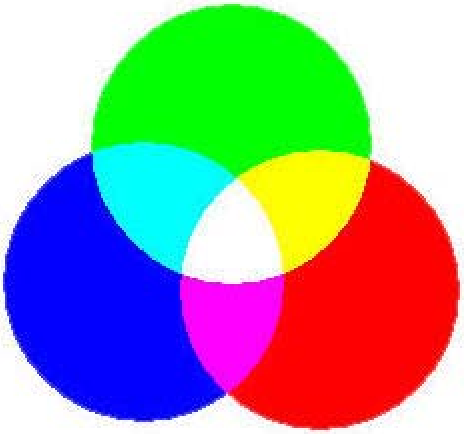
Let’s summarize our tracking challenges:

- Guiding
- Autoguiding through different filters
- Flipping the meridian with GEM’s
- Image rotation

Exposing

When we look at an object visually, a lot of natural technology is taking place. The brightness sensors in the eye (“rods”) are accumulating intensity (“luminance”) information. The number of rods determines the detail (“resolution”) of what we see. The longer we look at something, the more detail we see. This is the result of the eye-brain system accumulating or integrating the photons that impinge on the retina over time. This is why the longer we look at something, the more detail we see. The eye is also averaging the atmospheric movement (“seeing”) to bring out more detail.

Now, when we look at an object that is bright enough to stimulate the eye’s color sensors (‘cones”), a more complex process takes place. There are three types of cones which are, broadly stated, sensitive to specific colors, nominally red (“R”), green (“G”) and blue (“B”). Again, through the eye-brain system, the signals from these sets of cones are combined in the brain to what we see as color. Through the relative addition of the RGB cones, we “see” color. This is an additive system that is best illustrated by the diagram below.



Additive Color System

Some basic relationships can be seen here. Red plus green gives yellow. Red plus blue gives magenta. Blue plus green gives cyan. Red plus green plus blue gives white.

Additionally, we have a lot more rods than cones so we have more resolution capability in black-and-white (luminance) than in color.

Electronic imagers attempt to emulate the eye’s basic technology. We effectively replace the rods with an array of sensors (“pixels”, a contraction of picture elements). The number of pixels determines how many points we can see on the image. We use the same array in combination with R, G and B filters to simulate the cones. Unlike the eye, with this arrangement we have all the pixels available for each color and can get the maximum resolution through each color filter. In principle, we could take three images, one through each filter, and have a nice, color image. Unfortunately it isn’t that simple. Here again, we take our cue from nature.

The RGB filters are less transparent than the clear or luminance filter so the signal is weaker. For dim images, we take luminance exposures and data filtered through RGB filters. This is called an LRGB image. We trade off resolution for sensitivity when taking RGB data but not when taking L data. Of course for bright images, we can take the RGB data at maximum resolution and simplify our remaining tasks a bit.

With certain assumptions, we can make the resolution/sensitivity trade-off by combining a number of pixels into one "super-pixel". This technique is called "binning". 2x2 binning, means we have combined 4 pixels into one super-pixel; 3x3 binning means we have combined 9 pixels into one super-pixel. 1x1 binning is another term for unbinned. For dim objects, the L data is binned 1x1 and the RGB data is binned 2x2.

(I have moved from speaking of images to speaking of data. What comes from a CCD imager is a string of digital data in the form of a computer file that has to be properly calibrated and in many cases assembled with other files to get to a picture. This is a more appropriate term as will become apparent.)

The next question is how long the exposure should be. The longer your exposure is, the more signal you get. This is akin to looking in the eyepiece longer and seeing more detail. With CCD imaging however, there are many factors at work that conspire to limit your exposure time. Some are due to the imperfect nature of the equipment and just occur. I will list them here but to explain them all in detail is beyond the scope of this document. See the references at the end for further information.

- Dark current: This builds linearly with exposure time, is a function of the CCD imager's temperature and contributes noise to the image. If the dark current saturates, it can not be calibrated out.
- Saturation: If the exposure is too long, portions of the object can saturate, causing a loss of information in the saturated region.
- MFO's: Miscellaneous flying objects, such as airplanes, satellites, cosmic rays. The probability of an MFO crossing your FOV increases the longer your exposure time.
- Cosmic ray hits: This manifests itself as a bright spot on the CCD imager and is more severe at higher elevations.
- Tracking: The longer your exposure time, the longer your mount has to track accurately or the longer your guider has to guide accurately without a reset.

These limitations are surmounted by taking a number of shorter exposures ("sub-exposures") and then combining them in an appropriate manner.

So why not take a large number of short images? For bright objects, this is a good option but for dim objects, we are limited by one over-arching characteristic of the CCD imager – readout noise.

Recall we spoke of data above. Each pixel can have a specific value but determining that value has an uncertainty in measuring or reading that value. That uncertainty is called noise. If you look at a weak TV signal, you see what is sometimes called “snow”. That is noise, due to the signal not being strong enough. Similarly, you hear static when you listen to a distant signal on the radio. Every time we measure the data in a pixel, there is some uncertainty, noise that comes primarily from the electronics used to measure the pixel. This is called readout noise and is a major limiting factor on any CCD imager. Low values or readout noise are sought since they determine a number of key performance parameters, one of which is how short an exposure can be.

Thus a strategy emerges. You want to expose long enough so that readout noise is not a problem but short enough to minimize the previously mentioned problems. There is a trade-off that depends on a number of factors.

First, how bright is your sky (“sky glow”)? Sky glow brings its own noise due to the uncertainty in the arriving photons. So, if your sky glow is much larger than your readout noise, then there is little value in exposing longer. What are the characteristics of your CCD imager? By these key characteristics, you can determine an optimal sub-exposure length. Here are the factors you need to make this determination:

- Sky glow: The brightness of your sky background in electrons per minute (e/min.)
- g: The gain of your imager in electrons per ADU (e/ADU)
- Ron: The readout noise of your imager in electrons (e)

A calculator is available to lead you through the determination of your optimal sub-exposure length here:

http://www.ccdware.com/resources/subexposure.cfm

CCD imaging chips are not perfect. There is a sensitivity difference from pixel to pixel. This difference gives rise to what is called “hot” and “cold” pixels. Hot pixels accumulate signal much faster than average and cold pixels accumulate signal much slower. Thus an image of our data will have a number of “salt and pepper” effects that will detract from the image. Also our imperfect camera may have some other low level artifacts that are a function of electronic limitations that will limit how low in signal we can go. While the hot and cold pixels can be somewhat relieved by processing, there remains “warm and cool pixels” that become hard to distinguish from the desired object. These imperfections can be lumped under the title of “pattern noise”.

A technique to minimize this effect is called dithering. The scope is moved very slightly between images. When the sub-exposures are aligned and combined, the pattern noise does not line up. Assuming the scope is moved appropriately and the sub-exposures are combined properly, the pattern noise is either eliminated or greatly reduced.

Calibration

Calibration consists of removing predictable factors from our image. Because of our imperfect CCD imaging chip, we have to contend with dark current as described above. Additionally, most telescopes do not have a perfectly uniform light transmission across their FOV. This is generally not detectable by eye but is easily detectable by a CCD imager. Each of these effects can be reduced by the process of calibration.

Dark current is removed by arithmetically subtracting a master dark frame from the sub-exposure. A dark frame is an exposure made at the same camera temperature as the light sub-exposure and for the same duration as the sub-exposure. A master dark frame is obtained by combining a suitable number of individual dark sub-exposures. The optimal number is determined by the calculator mentioned above. Each pixel of the master dark frame is subtracted from each pixel of the light frame to remove the dark current.

Light uniformity is corrected by arithmetically dividing a normalized reference flat field. The flat field is obtained my aiming the telescope at a uniform light source and taking an exposure, making sure the camera is operating in its linear range. Many use artificial light sources such as light boxes, screens, even T-shirts! But there is an available light source that has been shown to be sufficiently uniform for many professional and probably all amateur purposes – the twilight sky at dawn or dusk. There are some complexities in using the twilight sky. First, the sky brightness is changing relatively quickly. Secondly there is only one optimal location for maximizing uniformity. So one has to move fast and continually adjust exposures to stay in the linear range of the CCD. Typically a number of flat field frames are taken to reduce noise (master flat) and a set is taken through each filter for maximum quality.

Calibration consists of creating master dark and flat frames and doing the appropriate arithmetic on a pixel by pixel basis for each sub-exposure.

Ready to go, right?

Let’s assume you want to get the best final image that sky conditions and your equipment allow. You have your scope set up and polar aligned. Your camera is cooled and ready to go. Your telescope is connected to your computer and tracking. Your focuser is connected and you have focused your system. Your object is framed as you like it. If you are doing guided imaging, your guider is calibrating and happily guiding along.

Now that you know your sub-exposure time, you can begin to take a number of sub-exposures, perhaps through each filter. You should focus frequently to make sure you remain in focus. Each time you change a filter you should of course refocus. You should adjust your guide exposure consistent with each filter. Of course, you should move your telescope slightly between each exposure to minimize pattern noise. When you come to the meridian and are using a GEM you can go to the other side, rotate the camera, reacquire a guide star, recalibrate and continue imaging. And when you’re done with your imaging, don’t forget to take your dark calibration data and flat fields. You did turn off your guider and park your scope, right? You need to get enough of each and, in the case of flats, don't forget to take them for each filter for best results. If you want the best, use the morning sky and be ready and alert to un-park your scope, point to the right spot, select the filter and change the exposure as needed. Don't forget to park your scope and turn off your camera cooler and close the dome.

This sounds awfully tedious. What if I miss a step or forget something? How can I be sure to do all this as the night wears on and the coffee wears off? Can I only image when I don't have to work the next day? Is there any way to make this easier? You bet!

CCDAutoPilot2

Let's look at the features of CCDAutoPilot2 aligned with the above challenges and tasks to getting the best image you can with the sky conditions you have and the equipment you are using.

Focusing - CCDAutoPilot2 SureFocus™ Technology

- Focus offsets for each filter
- Focus after each filter change
- Focus periodically on a chosen star outside the FOV

Tracking and Guiding - CCDAutoPilot2 AutoFlip™ Technology

- Change the guide exposure for each filter
- Automatically Image through the meridian
    - Flip the meridian
    - Slew precisely to the original target
    - Restart the guider
    - Rotate the camera (if so equipped)

Exposing - CCDAutoPilot Core Features

- Number of Sub-Exposures
- Binning Mode
- Filter to be used
- Exposure time
- File Name (including sub-directories)

Dithering - CCDAutoPilot2 CleanImage™ Technology

- Guided or unguided dithering
- Optimized dither pattern or random

Dark/Bias calibration frames - CCDAutoPilot2 Core Features

- Number of Sub-Exposures
- Binning Mode
- Filter to be used
- Exposure time
- File Name (including sub-directories)

Flat Fields - CCDAutoPilot2 EasyFlat™ Technology

- Automatic dawn and dusk flats
- Auto-exposure to target ADU level
- Specify the number, filter and binning
- Goes to the right spot on the sky automatically
- Takes as many flats as quickly as possible
- Can also be used with artificial sources (light boxes)

Housekeeping - CCDAutoPilot2 Core Features

- Turn off the guider
- Park and unpark the mount when needed
- Turn off the cooler
- Run an application (to close the dome for example)

Conclusion

CCDAutoPilot2 is an application that arises from my desire as a CCD imager for high quality results. I wanted to get the best possible results from one or many evenings of imaging a target. It represents the culmination of 3½ years of programming for imaging acquisition that introduced for the first time many acquisition firsts in an easy-to-use point-and-click interface with application independence. The CCDAutoPliot2 development team is proud of our history of innovation. We will continue to bring new techniques and technologies to the amateur CCD imaging community to help you achieve the highest quality for your time and effort.

For more information, please visit: *http://www.ccdware.com*