Astrophotography 101

By Lee Green

Astrophotography is taking pictures of the sky. Like any other photograph, light from an object is focused by a lens and by placing a receptor in the focal plane, the image is recorded. In astrophotography, the camera lens is replaced with a telescope. While the traditional receptor was photographic film, more recently CCD chips have replaced film.

There are unique challenges to successfully image objects in the night sky. The subjects are very small and are often dim so it can be difficult to obtain a good image. The small size of the object requires us to increase the magnification of the optics so the image is large enough to record. Increasing magnification reduces brightness since the light is spread over a larger area. Coupled with the inherent dimness of many objects, the exposure time must be increased to compensate. It is not uncommon to have exposure times of several hours to gather the light from these distant objects.

When exposure times are increased, it becomes important to keep the image still. This can be a daunting requirement since the sky is always moving due to the rotation of the Earth. A telescope must be precisely aligned to the Earth's axis and rotated in the opposite direction to keep it pointed in the same celestial direction. And since many scopes are equipped with equatorial mounts and motor drives, the hard work is done by our equipment.

Long exposure times also introduce a variety of other problems. Wind gusts or a misplaced foot can jiggle the telescope off target. Clouds and planes have a chance to pass into the field of view. Ambient light and any stray light source can ruin an exposure.

Telescope

The telescope is mostly irrelevant to this discussion. Any optics can be used. Of much more importance is the telescope mount.

The mount provides a way to aim the scope at the target and to follow the target over time. Modern computerized mounts have drive motors, maintains their own clocks and have an internal databases of object to help get you pointed in the right direction. As the Earth spins on its axis, the sky appears to move from East to West and the mount provides the means to follow the movement of the stars.

The equatorial mount provides the means to follow the movement of the stars. Equatorial mounts must be aligned with the Earth’s axis. This sounds like a simple requirement, but can be challenging to achieve since there is no exact reference point. Equatorial mounts utilize two separate motors to keep the telescope pointing in the same direction. The Right Ascension motor moves the scope slowly from East to West to counteract the spin of the Earth. The Declination motor lets you point the telescope at different objects. If the mount is not precisely aligned with Earth’s axis, the target will slow drift.

The fork mount, or Alt-Azm mount, provides of a simpler construction, but requires a more complex movement. The fork mount must be mounted on a flat, horizontal surface and its motors move in two directions. The left-right movement adjusts the azimuth and the up-down movement adjusts the altitude. Because this configuration does not align with the Earth’s axis, the movement from one moment to the next must be adjusted to approximate the movement of the target and over time, the image will tend to rotate. It is still possible to use the Alt-Az mount for astrophotography by mounting it on a wedge which aligns the mount with the Earth’s axis. In this configuration, the Azimuth aligns to right ascension and the Altitude aligns to declination.

Camera

CCD cameras for astrophotography operate in a similar manner as other digital cameras, but are housed in special bodies that can be mounted in place of the telescope's eyepiece.

Each CCD chip is a two-dimensional grid of light sensitive pixels. Each pixel is like a glass and as photons strike the pixel, the charge in the cell fills up. When the exposure is completed, the charge levels in the grid are read and the grid is emptied in preparation for the next exposure. The size of the array determines how many "mega-pixels" the camera has. For example, a chip that has 2000 rows and 1500 columns in each row would be a 3 mega-pixel chip.

The "well-depth" indicates the amount of charge at can be held before a pixel is saturated. The amount of charge is read as a value that is typically 16 bits in size which can range from 0 to 65535. When a pixel saturates, the well is full and additional light will cause the pixel to spill over to its neighbors in a process called "blooming." Newer CCD chip have anti-blooming circuitry built in that prevent the pixel from spilling over.

In addition to reacting to light, pixels will also react to heat generated by the circuitry and will register a small charge in the absence of light. This "dark current" varies for each pixel, the duration of the exposure and the ambient temperature. Often the cameras contain cooling circuits to keep the chip at a lower temperature to reduce thermal noise. The good news is that the thermal noise can be removed from your images by taking an exposure with the shutter closed and subtracting this "dark frame" from the other exposures.

For a long exposure, the dark current can become a significant component of the value and because of the dim nature of the objects we are trying to photograph, exposure times tend to be of long duration. So instead of taking a single 1 hour exposure, common practice is to take 60 exposures of 1 minute and to combine them together by "stacking" the individual frames into a single image.

Typically, CCD chips are monochromatic since they will react to any light that strikes the pixels. In order to take a color photograph, light must be sampled in red, blue and green light. This is usually accomplished by placing a color filter in front of the CCD and taking exposures for each color. A color image is the result of stacking four exposures, one without a filter for the brightness (luminance), and one each with red, green and blue filters. This is known as LRGB imaging. Color cameras have color filters covering individual pixels which allow all four channels to be sampled in a single exposure.

That's the theory. In practice, you must be diligent, persistent and patient to obtain quality images

Focusing

Getting your target into focus can be harder than you might expect. The primary problem is that you cannot look through most astrophotography cameras when they are in place. You must actually take some test images while you adjust the focus. While some programs assist in this process, it can still be difficult to achieve optimal focus.

One common practice is to use a “focus mask” to assist getting good focus. The mask will shape the light as it passes through the optics and result in a recognizable pattern that indicates the quality of the focus. The traditional mask is the Hartmann mask which has three holes, either circles or triangles. When the telescope is out of focus, the three holes are seen in your image. As you bring the telescope to focus, the holes in the mask converge to a single point.

A newer mask, called the Bahtinov mask, causes the light to be diffracted into a star-burst pattern. As focus is changed, the central line moves across the center of the pattern. Perfect focus is achieved when the diffraction lines converge into three intersecting lines.

Another potential problem concerns the filters you might use to take a color image. All filters will introduce an additional layer through which light must pass. This will be enough to change the focal length of your optics enough to throw the image somewhat out of focus. There are special filters, called “par-focal” filters, which avoid this problem although they can be rather expensive. In practice, the amount of change to your focal length is small and the effect can be ignored.

Exposure times

Exposure time must be calibrated to the brightness of the target. Because CCD cells have a limited amount of charge that can be held, this imposes a limit to the length of an exposure. Also, extraneous light such as light pollution will build up over time and further limit the maximum exposure time.

For extremely bright objects, such as planets, the maximum exposure times are often limited to a few 1/10^{ths} of a second. For dim objects such as galaxies and nebulae, exposure times in the range of several hours can be needed to build up enough signal to overcome the inherent noise.

Guided vs. Unguided exposures

Unless your mount is precisely aligned to the Earth’s axis, your target will drift over time leading to elongated images. Typically, good polar alignment allows you to expose images for several seconds before stars elongate. Beyond a few seconds, it is necessary to perform guiding.

Guiding provides a feedback loop for positional information to be used to adjust the mount’s position. Guiding requires the use of a second ‘guider’ camera and a software program that can control your telescope’s direction. Several CCD camera models contain a second CCD chip that can be used as the guider. The second CCD is often mounted in the same camera body adjacent to the main CCD and provides for “on-axis guiding.” You can alternately use a second telescope that is mechanically linked to the first for “off-axis guiding.”

During an ‘on-axis’ guiding session, the typical process is that you position the scope so you have the desired object positioned on the main CCD. At the same time, the guider CCD must be pointed at an appropriate “guide star” that is used as a fixed position. It is often necessary to rotate the camera to position the guide star and the main target properly. Whenever the camera is rotated, the guiding software must be retrained to the new orientation. When guiding is engaged, the guide star’s position on the guider CCD is monitored through successive exposures and any variations in position are used to change the speed of your telescope’s motors. These adjustments compensate for the movement to return the star to its original position.

When guiding is engaged and functioning correctly, it is possible to take exposures that are arbitrarily long, even several hours in length. In practice, it is more common the take a sequence of shorter exposures and to combine the results by “stacking” images together.

Image Calibration

Inherent noise in CCD system is introduced into the image. Dark noise and Bias noise are always present and must be compensated for best image quality. As discussed in the Camera section, “dark frames” must be taken to model the thermal noise inherent in the electronic circuit. Your dark frames must have the same exposure duration and binning as your images.

Because thermal noise is not constant, it is required to take multiple dark frames to adequately model this noise. A handy rule-of-thumb is that you should take dark frames that are equivalent to the exposure time for your images. At a minimum, you should have at least three dark frames and ideally, you would want to have ten. The good news is that dark frames are not affected by the filters, so you can use a set of dark frames for all images with the same exposure time.

Dust and other imperfections in the optical system also introduce image noise and can be compensated using ‘flat-fields.’ The flat field image is simply an image of a uniform light source. Optical imperfections alter the smooth image and can be used to adjust your images to partially compensate for the distortions. The shape of the distortions depends on the type of optics you are using. For refractor telescopes, the distortions appear as circles and with Schmitt-Cassegrain telescopes, they appear as doughnuts.

The biggest problem in using flat-field calibration is the ability to have a uniform light source. While there are manufacturers who make uniform light sources, these tend to be expensive. One common alternative is to use twilight as the even illumination source. While effective, this technique requires good execution due to the fast change of intensity of the sky.

Image Stacking

Typically you will take a sequence of images. To combine the images, they are often “stacked” to build up the image quality and to smooth random noise. In order to be stacked, the image positions must be precisely aligned. Stacking can be used to increase the signal by summing the images. To reduce image noise, stacking can be performed to provide the “median” signal.

Image Processing

Once you have aligned and stacked the images, further processing is often performed to enhance the image quality. Several techniques exist to assist in the process, including Stretching.

Stretching an image is a technique for expanding the dynamic range of you image across the available values of intensity. This is used most often to enhance the faint details in an image. A perfect stretch would result in the dark areas having a zero value and the brightest areas having the maximum value. Programs like Photoshop have excellent tools for stretching the image. In Photoshop, the Levels command provides a linear stretch and the Curves command provides non-linear adjustments.

In advanced processing techniques, the goal is to improve the quality of the image by adjusting it in various ways. There are a variety of mathematical calculations that can be applied to the image data. Some of these will reduce noise, while other will enhance the signal. Among these adjustments are three techniques, Kernel Filters, Unsharp Mask and Deconvolution.

Kernel filters are the simplest matrix operations. Each pixel in an image is replaced by a simple average of the surrounding pixels. In a 3x3 kernel filter, nine pixels are used to calculate the resulting value. The effect is a “low-pass” filter in that quickly changing pixels are smoothed out. This is often used with noisy images to preserve the large-scale structures in an image and removing tiny spikes.

Unsharp Mask is a matrix transformation that is used to improve the inherent blurring that occurs when an image is sampled by a CCD. It operates by adjusting each pixel in the image with a new value that contains the pixel itself and portions of the surrounding pixels. While this technique is very effective, it can hollow out areas around stars, so it should be used lightly.

Deconvolution is a term that refers to any of several techniques that provide mathematical processes that attempt to reverse a ‘point spread’ due to blurring and out of focus images. The Point Spread refers to the tendency for a point light source, such as a star, to spread out to a circle. This occurs for several reasons including out of focus conditions and the refraction of light as it travels through the atmosphere. The further out of focus or the more turbulent the atmosphere, the larger the circle. Two techniques are the Maximum Entropy and the Lucy-Richardson algorithms will improve the image quality, but can introduce additional artifacts if applied too aggressively.

The final step in processing the image is to create the published version. To do this, you may want to crop and rotate the image so it provides a pleasing presentation. You may also want to export the image and change its format so that it is of reasonable size. Often, the final image is resized and converted to a JPEG file to minimize the file size.

Let the Fun Begin

Taking photos of the sky is a challenging and rewarding activity. There are many considerations you need to be aware of to achieve the best photos. It takes practice to learn the techniques for taking good photos and there is a learning curve associated with each aspect. I would encourage you to jump in and try your hand at taking some photos. Each attempt will help you see the effects. Don’t be discouraged by results that are not to your liking. Instead, see if you can identify why the image failed to meet your expectations and learn what steps will help you avoid the problems next time.

I will always try to assist any way I can. Please feel free to contact me or, better yet, join me at an imaging session.