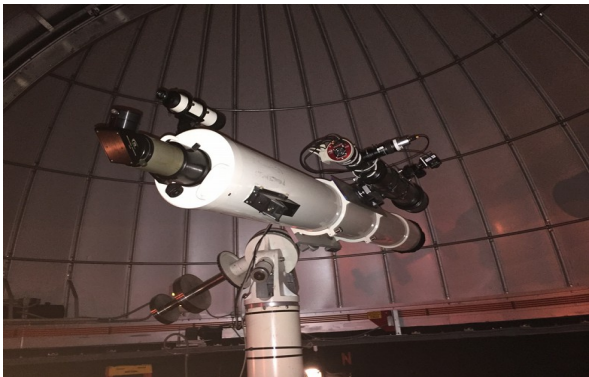


Deep Sky Astrophotography with an Altitude/Azimuth GoTo Telescope Mount An Enhancement for Public Outreach in Astronomy Activities

By: Vance C. Tyree

I am a member of the Los Angeles Astronomical Society (LAAS) and I have been active in public outreach in astronomy as a telescope operator and “Sky Docent” at the Garvey Ranch Observatory (GRO) which is owned by the City of Monterey Park in California.

The LAAS has been operating the observatory for the City of Monterey Park for almost 30 years. I became involved at GRO in 2015 and added a donated 120mm f/8.3 ($F = 1000\text{mm}$) piggyback telescope to the 8” f/12 refractor in the GRO to be used to show live color images of the objects being viewed through the 8” refractor.



Having live images made the public experience significantly better because the GRO is located in a Bortle 8 area only 200 feet from a fully lit baseball, football, soccer playing field, which makes the sky more like Bortle 9++. The piggyback telescope has a deep sky camera (ZWO ASI071MC-cool) and a planetary imaging camera with a 3X Barlow attached to the piggyback telescope through a flip mirror unit that I configured to allow par-focal switching between deep sky imaging and planetary imaging without needing to re-focus the telescope. Our Electronically-Assisted Astronomy (EAA) apparatus has become a popular feature in our LAAS public outreach at GRO.

The heart of this imaging configuration is the camera control software. I am using SharpCap 3.2 Pro, which has a tool to live stack images as they are downloaded from the camera so the observatory guests can watch the deep sky images accumulate while they are waiting in line to view through the 8” telescope eyepiece. Since the GRO is located in an extremely light polluted site and also, since the telescope drive is more than 45 years old (93 arc second periodic error - Yikes!) the sub-exposure time can not be greater than 10 seconds to avoid star trails with such a large periodic error without auto guiding (which can not be done with this old Schaefer German Equatorial drive).

The SharpCap live stack has absolutely no difficulty doing perfect star alignment in real time with this large periodic error as each new sub-exposure is downloaded. Furthermore, we have field rotation caused by imperfect polar alignment which is also perfectly tracked. We have gathered some fairly acceptable deep sky images during this past two years of imaging with the piggyback telescope at GRO (shown below).



M42 – Orion Nebula



IC434 – Horsehead Nebula

These images are fairly noisy, but the noise is not readily visible when displayed on a small screen. It was this imaging experience during this past two years that caused me to rethink my astrophotography experience that I had been assuming to be the “standard method”, with an accurately polar aligned equatorial telescope drive with auto guiding and with relatively long sub-exposures. Subsequent processing of these images to remove the almost overwhelming light pollution using PixInsight is a key element needed to produce the final pleasing images shown above.

When the GRO was closed at the beginning of the COVID-19 outbreak, I set out to create a different astrophotography procedure that takes advantage of what I learned during the past two years of deep sky imaging at GRO. I want to have a method to enable who people participating in public outreach to include Electronically-Assisted Astronomy (EAA) to enhance the public astronomy experience using a telescope on an Altitude-Azimuth telescope drive to be able to do simple low cost deep sky imaging. EAA typically uses non-cooled CMOS cameras to keep the cost of the camera as low as possible. I used the following equipment for the images that will be discussed later in this paper:

Telescope Drive: iOptron AZ Mount Pro which is a GoTo altitude-azimuth telescope drive

Telescope: Astro-Tech AT72ED which is a 72 mm aperture f/6 ($F = 432$ mm) refractor

Camera: ZWO ASI183MC which is a one shot color camera without cooling system. This is a relatively low cost camera that bridges deep sky imaging applications as well as planetary imaging.

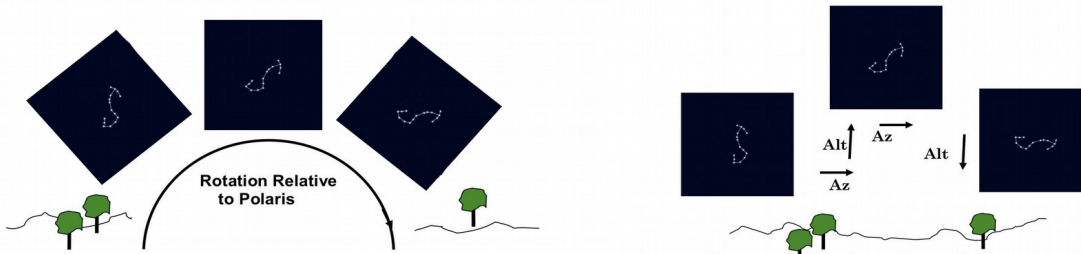
I chose to use an altitude-azimuth telescope drive because it is a very common computer controlled telescope drive that people start out with in astronomy. I wanted to see what deep sky imaging is possible without the need to upgrade to a high cost computer controlled equatorial telescope drive with all of the usual additions like a guide scope.

A photograph of the equipment that I used for all of the deep sky images is included below. I am using a Vixen flip mirror unit to make it possible to switch between an eyepiece and the camera without needing to re-focus. A small helical focuser on the eyepiece port enables focus compensation for observers who have different visual acuity needs without disturbing the camera focus.



What are the Imaging Limitations using an Alt-Az drive?

Field Rotation: Field rotation results when the sky objects are being tracked using an Altitude/Azimuth telescope drive or using an equatorial drive that is not accurately polar aligned. This rotation is best illustrated using a diagrams:



An Altitude-Azimuth telescope drive places the camera frame into an orientation with the camera horizontal axis parallel to the azimuth motion and the camera vertical axis parallel to the elevation axis. As the sky object is tracked through the sky on a curved path with this camera frame orientation, as shown in the diagram on the right, we see the sky object rotates within the camera frame. An Equatorial telescope drive has the camera frame orientated parallel to the Right Ascension and Declination axes so the camera frame does not rotate in the camera frame as the sky object is tracked through the sky (diagram on the left).

The largest professional telescopes (like the 10-meter Keck) are driven with an Altitude-Azimuth drive because these large telescopes are so massive that an Equatorial drive system is not practical. Professional telescopes resolve the field rotation issue by using a computer controlled camera rotation system that rotates the camera at exactly the same rate as the field rotation occurs so the image that is recorded appears as though the camera is on an Equatorial drive system. Even though camera field rotation systems are available for amateur telescopes, they are very expensive and are much heavier than a small telescope drive can handle. So, is there another way to correct field rotation in our small telescope case?

Camera Control Software comes to the rescue. SharpCap 3.2 Pro. has a “Live Stack” tool that takes a series of images at a given sub-exposure time (as specified by the user) and averages them together to produce a reduced noise image. Live Stack accomplishes this function in real time and uses a group of stars detected in the first image in the series to register all subsequent images in the series of images by translating and rotating the subsequent images to make sure that any drift and/or rotation is removed before averaging the new image with the previous images. SharpCap Live Stack is capable of correcting out the field rotation in images gathered by a telescope/camera combination driven on a computer controlled Altitude-Azimuth telescope mount. This will work as long as the star images are round, or very nearly round which will place a limit upon maximum sub-exposure time.

Field rotation rate can be calculated as a function of observing latitude, Earth’s angular rate, and azimuth and altitude of the object being imaged. With this field rotation rate we can calculate the number of pixels a star will drift due to field rotation during a given exposure time and a given the image chip size (actually, chip diagonal) and pixel size. A more appropriate calculation is to determine the maximum exposure time for a specified number of corner pixels drift and this calculation is entirely independent of the telescope focal length. So, as you would expect, larger pixels will allow for longer sub-exposure time, for the same size image chip. We can view the pixel size impact upon the sub-exposure time is in the following table that compares two different CMOS cameras.

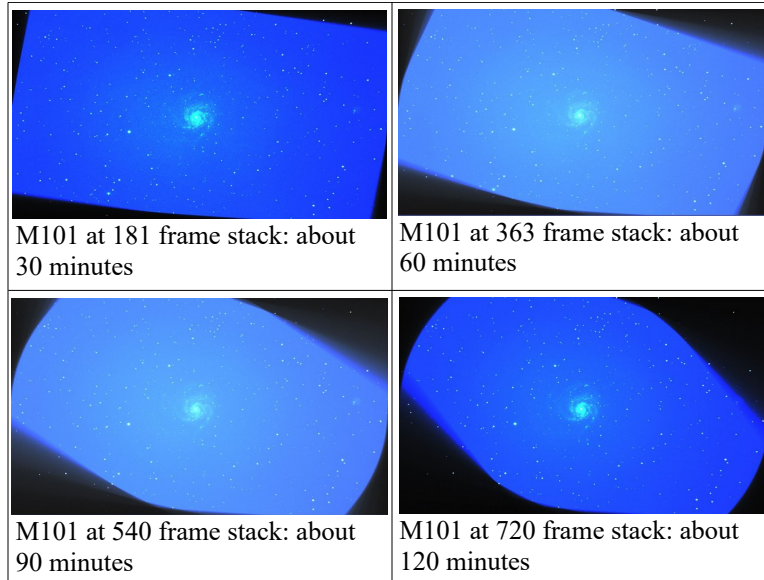
For a Latitude: 34.1585 deg.	For Obj. Azimuth = 19deg	For Obj. Altitude = 60deg		Calculated 3 pixel Drift Exposure Time
Camera	Pixel Array	Array Size (mm)	Pixel Size	Exposure Time
ZWO ASI183	5496 X 3672	13.2 X 8.8	2.4 um	7.95 sec.
ZWO ASI071	4944 X 3284	23.6 X 15.6	4.78 um	8.88 sec.

Even though the chip size of the ASI071 is about 1.8 times larger than the ASI183, the larger pixel size of the ASI071 partially compensates for the larger diagonal such that the 3-pixel drift time is close to the same. Both cameras will work well with a sub-exposure time of 10 seconds. This is an instance where a larger chip and larger field of view does not result in a shorter sub-exposure time. I should point out that the corners of the camera frame are typically not usable in the final image because the corner area will be removed (cropped out) after a long Live Stack time (e.g., 30 minutes) because of field rotation over the duration of the total Live Stack time. As you will see, using software to correct for field rotation will end up with only about the center half to two thirds of the image frame with a clean image that can be cropped out for further image processing.

The Practical impact of Field Rotation:

Let's look at what field rotation does for several different total live stacking times. I took a series of images of M101 (chosen because of its large surface brightness range) using an altitude-azimuth Go-To

telescope drive with an Astro Tech AT72ED telescope (focal length = 432 mm and 72 mm aperture at f/6) with a ZWO ASI183 MC camera (2.4 um pixels, QE=83%, 5496 X 3672 pixels). Sub-exposure time was 10-seconds – a little longer than what was calculated above – but you will see why this slight increase is not significant. These images are stretched using only the SharpCap Live Stack histogram as-viewed screen stretching. The stack times are snap-shots saved from one long 120 minute live stack session.



One thing that becomes very clear from these four aggressively stretched images is the field rotation forces us to severely crop the camera image frame to get a clean image. I can't stack more than about 720 frames without causing undesirable field size reduction. We are left with slightly less than half a frame height of useful imaging area. Object sizes need to be less than half a frame height in order to allow for the field rotation cropping requirements for stacking times up to about 60 minutes (3600 seconds).

Short Sub-Exposure and Camera Read Noise

As we have determined above, the sub-exposure time is limited by how much star motion is permitted in the corners of the image sensor. For the cameras that I use, this sub-exposure limit is 10 seconds. So, let's explore what implications this exposure time limit has upon the quality of images that can be obtained.

I need to point out that the primary limitation on short exposure deep sky imaging is related to the photon arrival rate (photons per second per square meter) of telescope aperture. By using information provided for precision astronomical photometry I can calculate the number of photons that a telescope will focus upon the CMOS image sensor for any object for which the brightness is known. Most good electronic sky chart software has an extensive database on object brightness. So, I can use this information to calculate how many photo-electrons will be deposited in a camera pixel as a function of sub-exposure time and the telescope aperture and f-ratio. I can take the camera specifications for read noise and then compare the RMS electron read noise with the number of photo-electrons that arrive in a pixel during the sub-exposure and estimate whether the incoming photons produce a larger number of electrons than the camera generated read noise. I can now estimate whether a star image or a nebula image will be buried in noise and thus be indistinguishable from the read noise. I won't dwell upon the mathematics of this whole process, but I have encapsulated the mathematics into a spreadsheet that calculates this for star images and diffuse nebulae. The spreadsheet produces numbers that serve only as an estimate of whether various objects will record well in short exposure images, but there are certain special characteristics in human

vision that lead to seeing objects that are near the read noise level. These special properties will be revealed in image examples later in this article.

We have two general classes of objects that we want to image:

- 1: star images (such as globular clusters and open clusters).
- 2: diffuse nebulae which can be divided into two types including fluorescence emission nebulae (for example M8 or M20) that emit narrow band emission spectra of ionized gas, and diffuse black body continuum emission such as galaxies.

So, let's look at these two classes of objects:

1: Star images appear on the image sensor in a tight cluster of photo-electrons covering a small number of pixels. The telescope concentrates incoming photons into a small circle (or spot) whose diameter is determined solely by the telescope f-ratio. The number of these photons within the spot size is a function of the star brightness in magnitudes.

2: Diffuse nebulae have a distributed brightness over some area in the sky. They are, therefore, imaged as a distributed brightness over some area of the image sensor. So, since a lens (telescope) images angles in the sky to be exactly the same angles viewed on the sensor, the brightness of a diffuse object has the same brightness per square arc-second on the sensor (in square arc-seconds) as it does in the sky. This has implications related to how large the pixel should be in square arc-seconds through the telescope. If the pixel subtends an angular area larger than a square arc-second then the pixel collects more photons from the diffused image. For example, if you choose a telescope with a focal length that has a camera sensor pixel area of 2 square arc-seconds then there is a gain in sensitivity relative to read noise. Unfortunately, that sacrifices image resolution. On the other hand, if your telescope focal length causes the pixel to have an angular area of 0.5 square arc-seconds then you will need a longer exposure time to collect enough photons to overcome the read noise. There is some advantage to having a pixel area of one square arc-second in order to maximize the resolution of your telescope while making best use of the diffuse object magnitudes per square arc-second at the pixel level. I will give specific examples of how this works along with some interesting observations of how the human eye tends to compensate for some of the signal-to-noise ratio limitations suggested by simply calculating the ratio of the read noise to the received photo-electrons in a pixel.

Before we get into the details of what cameras and software will be needed for deep sky imaging on an altitude-azimuth telescope drive, I want to discuss the limitation on imaging imposed by **Field Rotation**. If we use only software to correct for field rotation, then we need to understand that field rotation imposes camera exposure time constraints that limit sub-exposure time to the order of 10 seconds (for my specific cameras). So, that means that images of very low surface brightness objects will be noisy and have a grainy appearance even after stacking several hundred images. Bright deep sky objects and, for the most part star clusters, will generally look nearly as good as can be imaged with a polar aligned, guided equatorial telescope drive. Even the grainy images of faint sky objects will look OK when viewed on a small screen like a smart phone. But, don't expect to get deep sky images that look like the finest images published in an astronomy magazine or in "Astronomy Picture of the Day". I am describing an imaging method that gets you started in astrophotography with the simple low cost astronomy gear that I mentioned at the beginning of this article.

What do typical images look like from an Urban Back Yard using an Altitude-Azimuth Telescope drive?

Let's look at a black body continuum emission object:

Now we need to look at the processed M101 image to see how much we gain in image quality versus total stack time. It's an example of a diffuse object with an emission characteristic similar to a black body continuum emission object. I chose to use M101 because it has a low calculated surface brightness object (calculated surface brightness of magnitude 24.2 per square arc-second), but it also has a large surface brightness range point-to-point within the galaxy image. I want to use this brightness range to show the impact of the 10-second sub-exposure time upon the noise level in the final processed image.

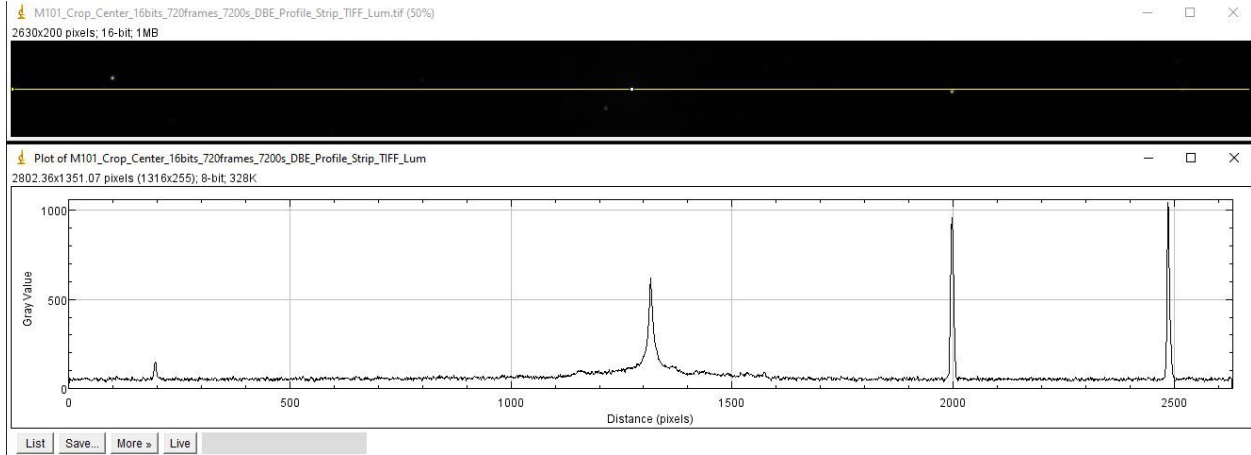
We need to understand that the camera read noise sets a limit upon the lowest brightness that can be captured by the camera so the image of the object is distinguishable from the read noise. Even though there are some standard guidelines related to the read noise versus the signal photons (usually read noise is no more than 10% of the signal photons), the signal photons are still detectable by a persons eye because the low Signal to Noise Ratio (SNR) portion of the image fits into the overall scheme of the image context.

Let me illustrate this concept. Let's start with the fully stretched (and cropped – 720 frames stacked and aveaged) M101 image with several overlays.



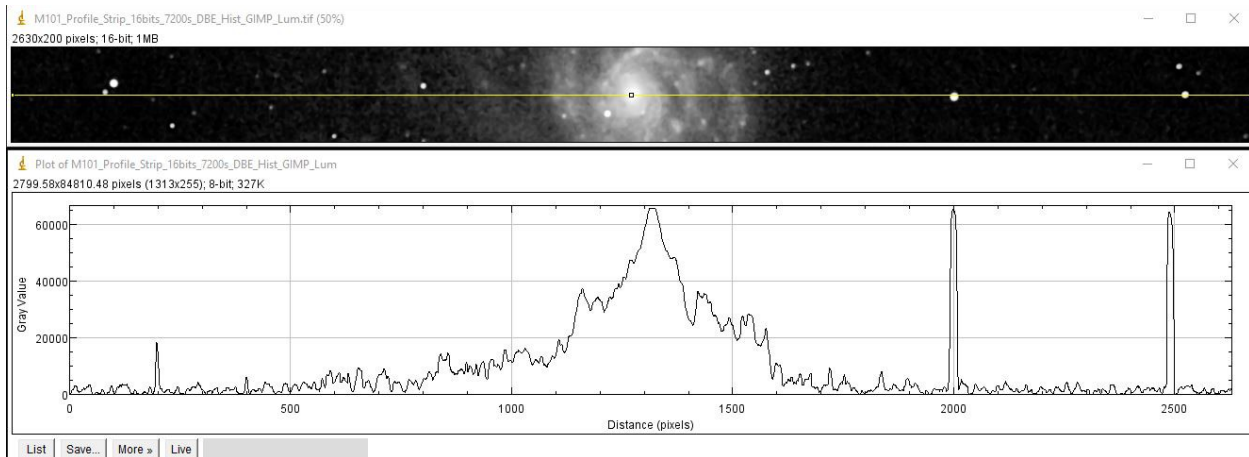
I have a gray box that represents a profile cropping box (full frame width 200 pixels high, centered on the galaxy core) that will be used in Image-J to measure a single pixel wide profile through the center of the galaxy. The yellow line represents the profile line along which the

brightness of the pixels are measured. I labeled three stars that touch this line with their cataloged magnitudes. The star on the far right is centered on the yellow line and it has a brightness of magnitude 13.4. I will use this star as a reference star to gauge the galaxy peak brightness to use as a reference for the brightness along the yellow line.



Now, we will go back to this image, shown above, before any stretching in brightness has been done, but after only the DBE tool in PixInsight has been applied to remove the light pollution. I then placed a profile box at the exact same location with the yellow profile line in exactly the same position as above. The diagram in the image below is the brightness profile in the center line of the profile box. I have included the M101 image within the box, but it is not visible because there has been no brightness stretching in this 16-bits per color image. A broad brightness spike in the center is the galaxy center. The profile line just clips the edge of the star image on the left side (at about X=200 pixels), and it also just clips the first star on the right. However, the star on the far right side is centered on the yellow profile line. Except for the star at the left side and the two stars on the right, the brightness profile below about 600 pixels in X and above about 1800 pixels on the right is dominated by read noise. Roughly, the brightness profile between X = 600 pixels and X = 1800 pixels contains light from the galaxy. I have to admit, that region containing the galaxy doesn't seem to be very promising for extracting an image of M101. Also, that reference $m = 13.4$ star is nearly twice as bright as the galaxy core (by nearly a magnitude).

Keep in mind that catalog listings of non-stellar, extended objects are listed as an integrated brightness of the extended object as if all of its light were concentrated into a star image. So, M101 lists in the catalog at magnitude 7.77 which is clearly different from our reference 13.4 magnitude star. Put into this context, you can see why it is difficult to image M101 using 10-second sub exposures. But I did get an image, and even though it is very noisy, it is recognizable. The brightness profile of the fully stretched M101 image is shown below, which shows only the illuminance portion of the color image:



You can see a glow in the image of a faint outer arm of M101 at about $X = 800$ and another faint arm at about $X = 900$. These two features are barely twice as bright as the read noise at around $X = 500$ – essentially read noise plus the about the same magnitude of photon noise in the galaxy arms – yet our eyes see the galaxy arms in the full color image. Various amounts of histogram stretch and curves stretch within PixInsight and in GIMP, stretching the brightness over the entire dynamic range of a 16-bit per color dynamic range, took the light pollution removed (DBE) image in which the M101 was not visible to being visible with lots of structure in the final image.

So why is it possible to clearly see very faint galaxy arms that are only slightly brighter than the read noise? I don't have a complete answer to this question, but I can speculate based upon the characteristics of the galaxy spiral arms and characteristics of the read noise. Read noise is a random noise created during the process of reading the number of electrons that the photons generated in a pixel. This read noise has absolutely nothing to do with the color filter on the pixel, so it will on the average be exactly the same for all pixels regardless of what color filter is above the pixel and appear as uniform at all colors after the image is has been rendered full color by the de-Bayer processing. However, the galaxy spiral arms contain a high number of young hot stars that contain lots of blue light as well as hydrogen emission regions (HII regions) that are very red. These “colorful photons” are averaged with the “perfectly white” read noise leading to a slight amount of color that your eyes can easily perceive. Also, there is the knowledge that we have about galaxy structure and that we expect to see as we follow the brighter segments of the spiral arms into the region that is fainter (and nearly equal to the read noise) region that helps us to visualize the noise corrupted colored region.

My M101 image is certainly not as good as what we can get with a polar axis aligned equatorial telescope mount with auto-guiding and long sub-exposures, but it is good enough to use in a public outreach event. In fact, much shorter stack times can be useful for illustrating the structure of deep sky objects using an altitude-azimuth telescope drive during a public outreach event. A snapshot of M101 as viewed during the live stacking in SharpCap resulted in this image in which there was only live histogram stretch, color balancing and black point clipping to produce this image as it would be seen by people attending an astronomy public outreach event.



It's a 30-minute stack of 10-second sub-exposures – as viewed live on the PC screen. Moreover, the structure of M101 is clearly visible after only about 5 minutes of live stacking even though M101 is not visible through the eyepiece on the telescope (Astro Tech AT72ED) through which this image was stacked because of the light pollution. People on the wait line to view through the eyepiece get so excited at watching these faint images develop that they'll lose their place in line to see what happens.

Now, let's look at a star cluster object:

I chose M92 which is a globular cluster in Hercules because the image contains a very faint asterism that I call the “teardrop”. It is a group of very faint stars that range in brightness from $m=16.4$ to about $m=12.8$ and is not easily visible by eye in small telescopes but it is usually recorded in astrophotographs.



The above image of M92 is a 30 minute stack (180-frames of 10-second sub-exposure). The “teardrop” asterism is just below the cluster and above a bright star. I have cropped out the “teardrop” asterism and labeled the star brightness of many of the stars in the image.



A magnitude 16.4 star is shown on the left that is easily visible. The spreadsheet calculates that this star is about 17% of the read noise, just slightly worse than the desired 10% of the read noise. It is clearly visible along with two fainter stars that are not included in the hundred million star database in Sky Safari 6 pro. However, the fully stretched magnitude 16.4 star image has pulled this star brightness up to a level that makes it easily visible, but clearly corrupted by noise.

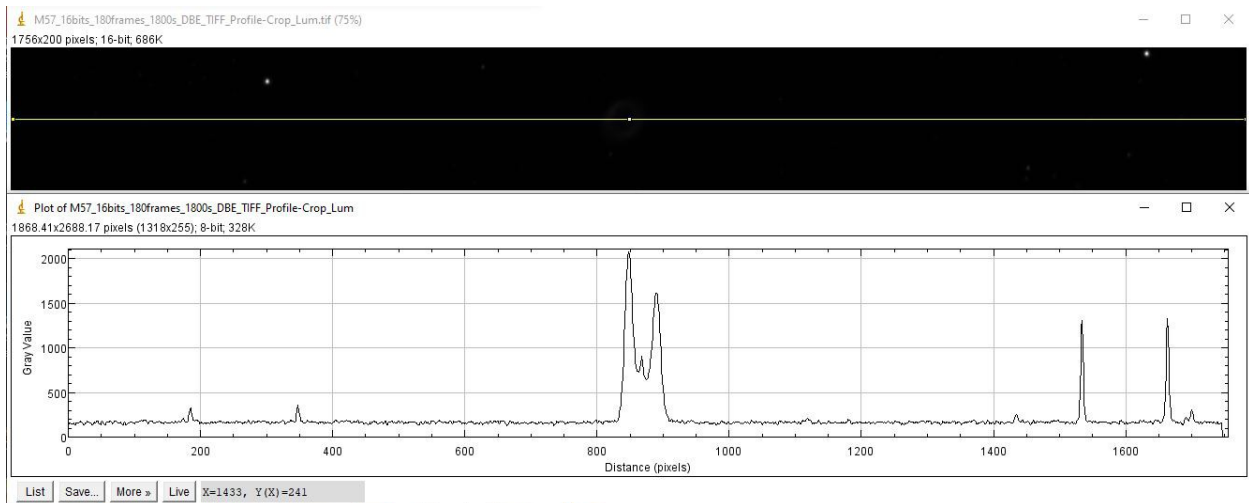
Finally, let's look at some emission nebula objects:

I have selected two categories of emission nebula objects to image that have some very different characteristics: Planetary Nebulae and HII regions where stars are forming. They both contain spectral emissions that are produced by fluorescence of very low density gas that is illuminated by very hot stars that are rich in highly ionizing ultraviolet light.

The first object is M57, which is a planetary nebula – an expanding shell of gas from a star that has reached the the end of its hydrogen fusion fuel supply and is fusing heavier elements while most of its mass is concentrated in a hot white dwarf. M57 is listed in catalogs as being a magnitude 8.8, but its surface rightness is 17.9 mag./square-arcsecond. This is considerably brighter than M101 discussed above and also emission light is concentrated into a smaller area in the sky, so it will record with higher SNR than M101. M57 brightness stretched inside a profile measurement strip is shown below:

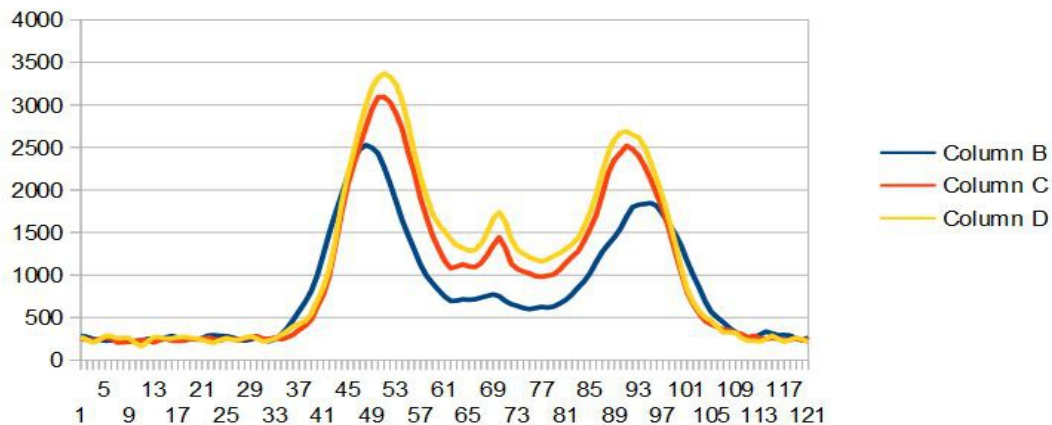


Let's take a look at the profile plot of the illuminance layer of M57 with M57 in raw form after the light pollution has been removed.



The entire range of its brightness profile is well above the background read noise, so the 10-second sub-exposure captures the classical image of M57 including the small spike in brightness in the center that represents the magnitude 15.7 central star. I think it's interesting to take a more detailed look at the M57 brightness profile at each of the three (RGB) color channels:

M57 Profile Plot (B: Red - C: Green - D: Blue)

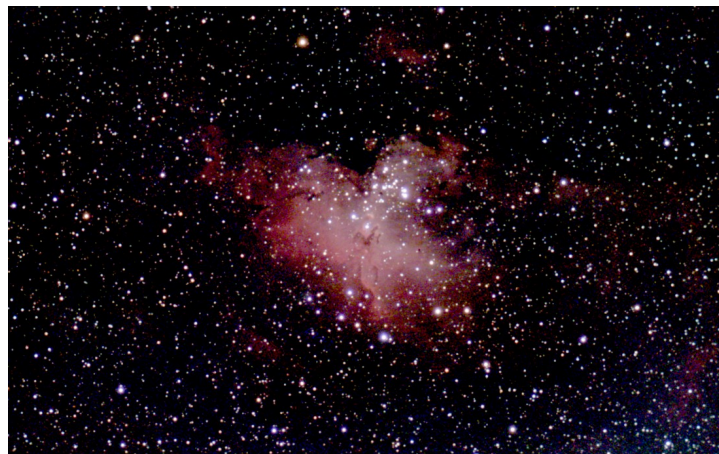


We all know that the classic color image of M57 has a red outer ring around the outer edge of the image. You can clearly see that the red channel brightness profile is lower in brightness than the green and blue channels, but we get the red fringe because the brightness profile of the red channel is wider than the green and blue channels. Also, we see the central star has much less red light (barely a bump) than green and blue light which highlights the fact that it is a hot white dwarf star. It also explains why M57 has a distinctly blue-green center region as seen in this tight crop of M57. The small difference between the red channel and the green/blue channels is significantly enhanced during the histogram stretching process that is used to pull the image into the full dynamic range of the 16-bits per color.



We will now take a look at two HII emission nebulae (M16 and M17) which were both chosen because they have a high amount of red hydrogen alpha light and because they both have a large surface brightness range.

The first emission nebula object I will discuss is M16 (Eagle Nebula). Images of M16 taken with long sub-exposure time will show a large extended faint nebulosity that will not be easily seen in the 10-second sub-exposures that I am using in this discussion. For comparison, take a look at the following M16 image on Astrobin: (<https://www.astrobin.com/418872/>). I am placing an M16 image below that is a stack of 360 ten-second sub-exposures.



If you compare this image with the image of M16 in the astrobin link you will see that the very extended nebulosity is missing in this image. However, this loss in faint nebulosity is expected because the faint nebulosity will be buried in camera read noise and other noise. Still, this is not too bad for the very short sub-exposure time and severe light pollution.

Now, let's discuss my image of M17 (Omega or Swan nebula) and look at it with a little more analysis to give you an idea of what impact read noise has upon the H2 emission when the image

is stretched into the full dynamic range of the 16-bits per color from image processing. Here is the M17 image from my basic equipment:

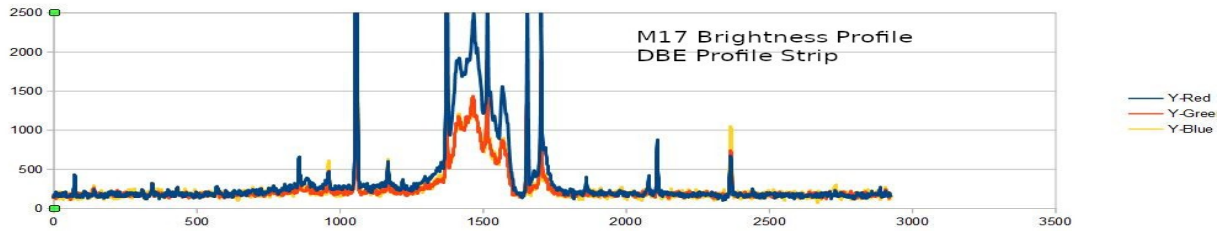


There is a fair amount of faint nebulosity in this image, but this has been stretched out of a brightness level that is very close to the background read noise. For comparison, take a look at the M17 image from a one-shot color DSLR camera on astrobin: (<https://www.astrobin.com/283986/0/>). The faint nebulosity is not as noisy as the image above because of the longer sub-exposure time used in the astrobin image.

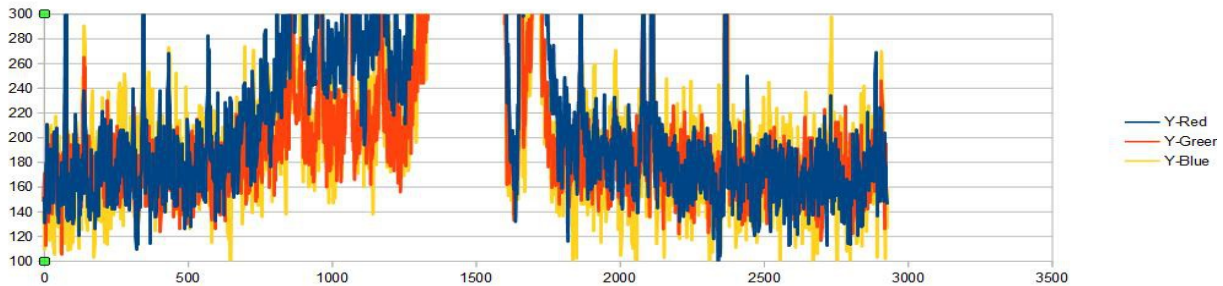
I did some analysis of my M17 image after the Dynamic Background Extraction (DBE) in Pixinsight to see how much noise is present in the dark sky compared with the red nebulosity in the M17 image. Here is the profile strip with only DBE and also the profile strip with DBE and histogram stretch to show M17.



At this point let me remind you of what I said about the faint M101 galaxy arms being visible because of the presence of “colorful photons” in the very faint galaxy arms even though they are essentially at the read noise level. In the case of M17 and other HII objects the “colorful photons” are very distinctly red, so this phenomenon of seeing very faint nebulosity that is very near the noise level is greatly aided by the color in the nebulosity. Take a look at these brightness profile plots of M17 taken on exactly the horizontal center line of the above DBE profile strip where I clipped off the bright star peaks:



This next profile plot is brightness range limited in Y to 100 to 300 to show more clearly where the “colorful photons” deviate from the more neutral gray background.



The first thing to notice in these brightness profile plots is that the brightest portion of M17 peaks at about 2000 ADU out of 65535 ADU maximum in the 16-bit image, or about 3% of the total brightness range. That's why M17 is below visual threshold in the DBE only profile strip. Looking at the range limited brightness profile, the read noise and other imaging noise has a median value at around 165 to 170 ADU. The second thing to notice is that the red channel graph (blue line) starts to turn upward at around pixel 600 to 700 on the X-axis. After that point the red channel is about 100 ADU above the general noise. And then from that point on the full M17 nebula becomes (depending upon the color channel) at least 200 ADU above the general noise level by about a factor of two. However, it's generally accepted that a good signal to noises level goal is that the nebulosity should be about ten times the general background noise for a good image. The very brightest portion of the “Swan body” clearly meets this guideline, but the extended nebula does not meet the guideline. Yet, I can clearly see the faint M17 nebulosity in the histogram stretch profile strip.

If I zoom in on a region in the histogram stretch profile between about pixel 500 to about pixel 750 and do a 200% zoom on this section where the red channel is becoming brighter in the profile graph, you will see that the image is very noisy (grainy).



I can say that it is not a very pleasing image, but I do clearly see the rising red channel brightness. Now, If I apply a Median Blur with a radius of 3 pixels, the image looks much smoother while the very dim stars are minimally damaged by the blur function. Here is the result of that median blur operation:



So, the combination of “colorful photons” , median blur and additional application of Curves in GIMP produced the image shown at the beginning of this section on M17.

There is more that we can learn from this M17 image because we have a case where we have profile measurement through both a very faint nebulosity that is only twice as bright as the noise and also through a nebulosity region that meets the guideline that good signal to noise ratio (SNR) is achieved when the nebula brightness is such that the read noise is only 10% of the total signal. I can now take that information along with the camera and telescope that I am using and calculate both the threshold nebula brightness and the “good SNR” brightness using the photon flux spreadsheet that I mentioned earlier in this article.

By using a few example images of different types of deep sky objects I have shown that even though an altitude-azimuth telescope drive forces a ten second sub-exposure limit on imaging, you can get some reasonably pleasant images of deep sky objects. Much of the success of this imaging procedure rests upon a perceptual property of human vision that enables us to see a surprising amount of detail in image features that are nearly buried in image noise. So what happens if we use a short focal length telescope?

The interesting property of field rotation in an altitude-azimuth telescope drive is that the amount of rotation where trailed star images occur in the corners of the camera frame is independent of optics focal length and depends only upon the length of the camera sensor diagonal. If you have a DSLR prime focus camera lens with a focal length of, say, 135mm and an aperture of f/2 then we can image a 5.6 degree by 3.7 degree portion of the sky with a plate scale of 3.6 arc-second pixels with the ASI183MC camera, enabling you to image the entire Cygnus Loop in one frame. The challenge will be that the very low surface brightness of the the Cygnus loop may make it difficult to do the imaging in a light polluted urban sky. It will be an interesting experiment. Whether or not imaging the Cygnus Loop is possible, there are hundreds of objects that can be imaged using this altitude-azimuth telescope drive system.

CMOS Camera Selection

CMOS cameras have a significant advantage over CCD cameras in this application because they have lower read noise and the read-out time is very short (several milliseconds versus several seconds). I don't have experience with very many CMOS cameras other than several from ZWO and a couple from QHY cameras, but camera selection is primarily governed by what SharpCap 3.2 can support. Supported cameras are listed in the SharpCap web site (<https://www.sharpcap.co.uk/sharpcap/cameras>).

The most important camera parameters that will determine how well the camera will perform with 10 second sub-exposures include *high quantum efficiency* and *low read noise*. First of all, quantum efficiency is important because when you are imaging very faint objects, you can't afford to waste photons as a result of low camera quantum efficiency. So, quantum efficiency should be greater than 50%. Second, very low read noise is important because with short exposure time because objects with very low surface brightness must have a signal level that is significantly greater than the read noise in order that the object photon signal will be distinguishable from the read noise. Read noise can not be accurately calibrated out as we do with dark current and flat-fielding. Sometimes setting the camera gain to be higher than the "Unity Gain" point (where photo-electrons are digitized to be one electron per Analog-to-Digital converter Unit, or ADU) can result in significant reduction in read noise in some cameras. Higher gain will result in reduced native camera dynamic range, but averaging a very large number of images will effectively make up for this dynamic range loss.

Camera physical sensor size is also very important because of field rotation when imaging using an altitude-azimuth telescope drive. I gave two examples of cameras with different pixel size and different image frame diagonal sizes earlier in this article. The ZWO ASI183 is better with short focal length telescopes (focal length the order of 400 to 500 mm) while longer focal length telescopes (800 mm to about 1500 mm) will have better performance with the ZWO ASI071 (at nearly twice the cost of the ASI183). I don't think you need to get too bogged down over optimizing the camera if you already have a CMOS camera that you use for planetary imaging. The important thing is to do imaging. You can select objects that will match their angular size in the sky to the size of the camera that you already have. If you are buying a camera, then the ASI183 is a good match because it has small pixels and a large number of pixels so it can be used for deep sky objects as well as planetary imaging by using sub-framing to better match the camera to the planetary image size. Sharp-Cap 3.2 supports camera sub-framing for most of the cameras in its list of supported cameras.

Camera Control Software

As I have mentioned several times, SharpCap 3.2 Pro has some highly desirable performance advantages compared with most other camera control tools. In particular, the most important characteristic in SharpCap is the Live Stack capability which can track drift and frame rotation and assemble a final averaged image with round star images. Live Stack offers some star quality parameters that can be used to reject images that are of lower quality because of glitched caused by telescope drive gear periodic error of other factors that produce non-round star images during a sub-exposure.

In addition to the star quality filters, SharpCap Live Stack has a histogram stretch tool that can perform real-time image stretching, so you can monitor the accumulating image stack while the stacking is in progress. There is also a set of color correction sliders in the Live Stack image stretching tool to allow adjustment of the image color balance in real-time. This, in addition with the display histogram stretch tool, it is possible to watch the slow improvement of the image quality while the Live Stack progresses. There is an option to save this “As Viewed” image in addition to the full raw FITS stacked image after the Live Stacking has accumulated for a long period of time.

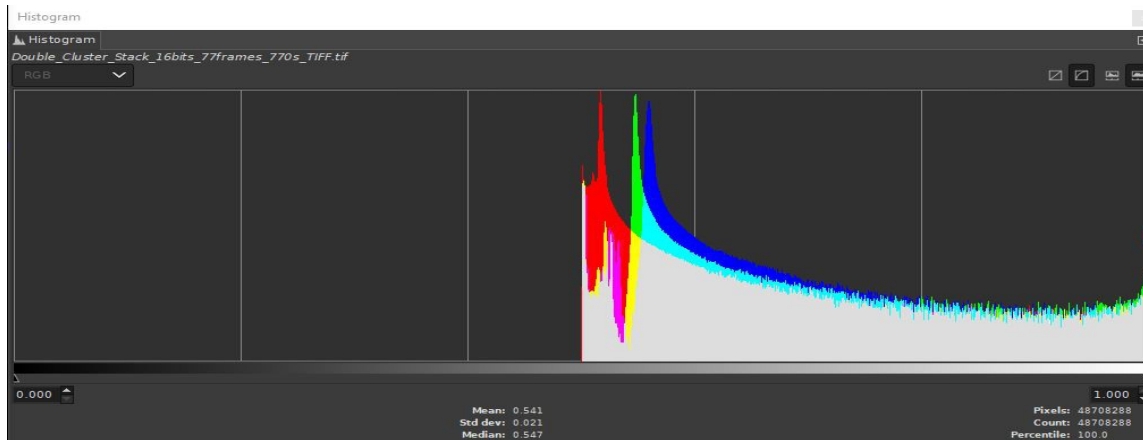
Some or all of these characteristics may be available on other camera control software tools, but I have not yet taken the time to search out which of the many camera control software tools will have properties similar to what SharpCap offers.

Image Processing Procedure

Stacked images taken at a dark sky location can be processed using relatively simple methods using Photoshop, GIMP (a free Image processing tool similar to Photoshop), or any of the many astrophotography processing tools. However, when deep sky images are taken in an urban area with severe light pollution, it is necessary that light pollution be removed before any further image processing is done. For a reminder, we are dealing with a large light pollution signal linearly added to the deep sky image so the light pollution can be removed if we know exactly how much of the total signal is the light pollution signal. In theory, that is relatively easy to do because we know that in most deep sky images because there are large areas of pure darkness in the image.

We can easily see that urban light pollution includes a strong color bias which, if not corrected, will imprint the light pollution color on the deep sky image. So we can't simply set a black point to remove light pollution. A histogram of the light pollution in a Double Cluster image from a Bortle 9 urban site shows how much color shift exists.

The very large red, green and blue peaks in the histogram below show the color shift problem with the light pollution. We can see that about half of the brightness dynamic range is taken up by the light pollution. Our deep sky object color data is located only a small number of ADU (Analog to Digital converter Unit) values above the light pollution peaks in the above histogram. We need to subtract out the individual light pollution color channels by the amounts shown in the histogram near the peak of each color channel. Simply setting the black point on the total illumination will, in this particular case, remove almost all of the red and a significant portion of the green from the deep sky image.



Another problem with the light pollution is that there can be brightness gradients. These brightness gradients have two different origins. One is the vignetting in the optical elements in the imaging optics, which can be calibrated out by doing a careful flat-frame master image. The other cause is the presence of non-uniform haze in the sky which reflects or scatters different amounts of light within the camera chip field of view. Fortunately, most deep sky objects can be imaged within a camera field of view of the order of 1.5 degrees by 1.0 degrees, so the non-uniform light pollution scatter is rarely an issue if the telescope is pointed far from a bright object such as the first quarter moon.

Let's look at what can be done to remove the light pollution. The only sensible solution is to remove the light pollution by accurately measuring the brightness and color of the light pollution and subtract it from the image. This will remove the light pollution without causing a severe color shift in the deep sky object.

In my opinion, the best solution to the light pollution removal is to use PixInsight. PixInsight is a powerful astronomical image processing software package that is essentially the “Photoshop” of astrophotography. Many of the tools in PixInsight are very difficult or impossible to implement within Photoshop or any other general photography image editor. The tool in PixInsight that can remove the light pollution is Dynamic Background Extraction (DBE). By setting some parameters in DBE and creating about 50 sample boxes (avoiding star images and nebulosity in the deep sky object) in the light polluted image, it will create an exact copy of the light pollution in the image (with accurate brightness and color). My Double Cluster image with the sample boxes for DBE is shown below:



We can now accurately subtract the created light pollution image from the original image to create a deep sky image without the light pollution. My Double Cluster as output image from DBE is shown below includes some brightness stretching using "Histogram Transform" in PixInsight to bring out the very faint portions of the image.



This rather simple process, unfortunately, comes at significant cost. The software license for PixInsight costs 230 Euros (\$250 to \$270, depending upon the exchange rate) which can be a barrier for people who are just starting out in astrophotography.

I have been developing a processing method that can approximate the results that are obtained

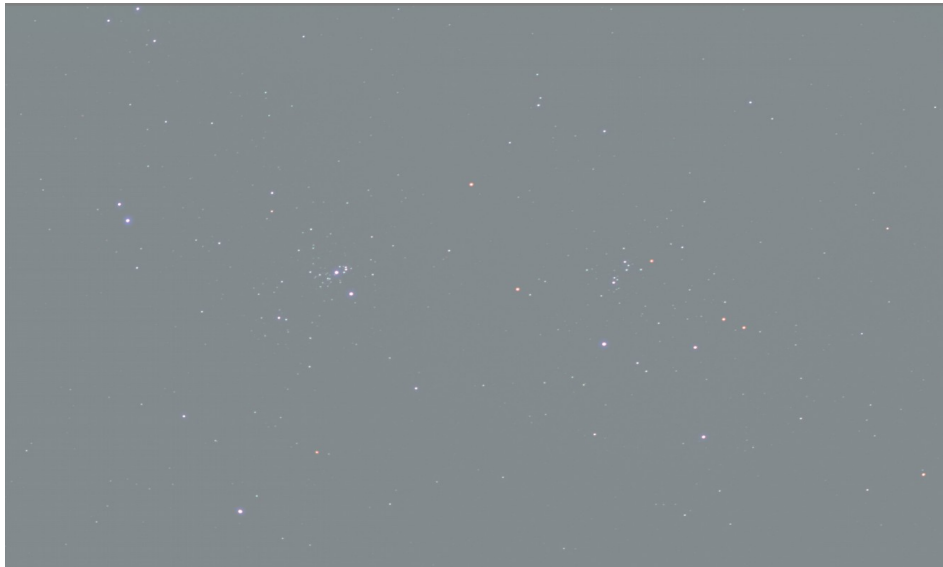
with PixInsight using an image processing tool that can be installed at no cost. That tool is called GIMP (<https://www.gimp.org/> - The current version is V2.10.20). It is a fairly close match to Photoshop in its image processing tool sets. The method that I will describe will also work in Photoshop or other general image processing tool with similar capability if you already have it. By the way, the PixInsight license fee is much less than what one would pay for Photoshop.

One essential requirement for the image processing tool to be useful for light pollution removal is that it must be capable of processing images with at least 16-bits per color channel, preferably 32-bits per channel. GIMP can process images with 16-bits per color channel. A very large dynamic range is critical to being able to remove light pollution and leave enough deep sky object dynamic range to stretch the brightness without creating “banding” (gaps in the brightness levels) in the histogram of the processed image. Banding creates some rather unpleasant color and brightness artifacts in the final image.

The first **requirement** for this method to work is to accurately **calibrate** your deep sky image with dark-frame images and flat-field images. Dark-frames are simply images made by covering the optics to exclude all light using exactly the same exposure time, camera gain and camera chip temperature that you are going to use for deep sky imaging. If you are using a camera that is supported by SharpCap Pro the creation of dark frames can be done using a tool in SharpCap. Also, Sharpcap Pro has a tool for generating flat field calibration images.

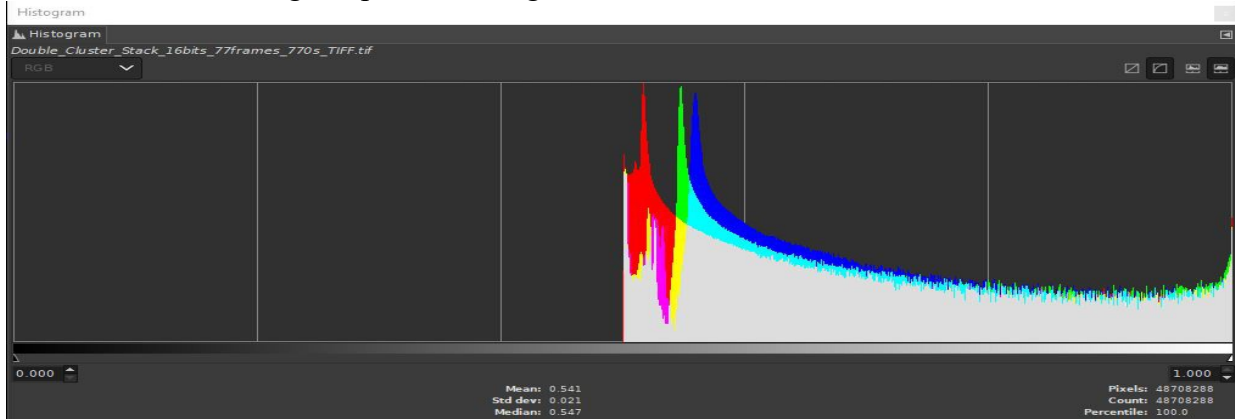
Prepare the telescope with a light diffusing material over the telescope aperture to produce an absolutely uniform illumination over the telescope aperture. There are several methods for doing this, but I will not discuss these in this article. At this point, your calibrated images will have the light pollution very evenly distributed over the whole image frame (presuming there are no other light gradients as discussed above).

With GIMP lauched, we open the stacked and calibrated image. The example Double Cluster image opened in GIMP is below:



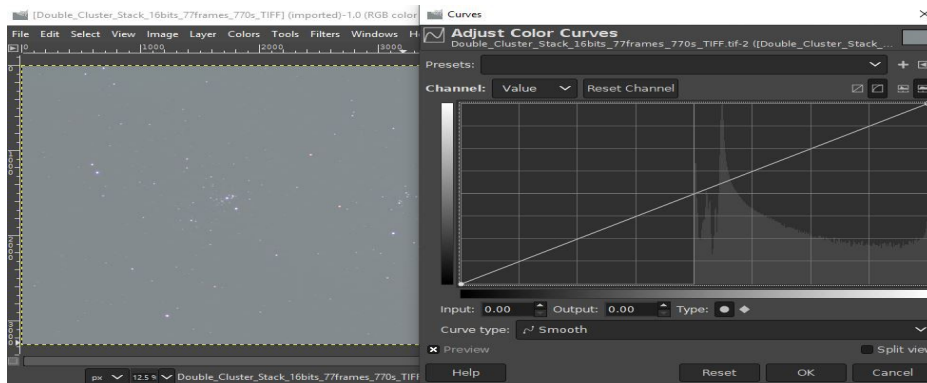
The GIMP-based light pollution removal method is based upon determining the “true zero point” (black point) without the light pollution. This zero point is set to remove the light pollution dark

point offset as is indicated by the offset of the entire histogram from the ADU=0 value. In the histogram of the Double Cluster that was previously shown, we need to take a more detailed look at the individual color band histograms. We can see that the entire histogram distribution is shifted to the right (away from ADU=0) by the light pollution. All of the deep sky data is in the remainder of the histogram plot on the right hand side.

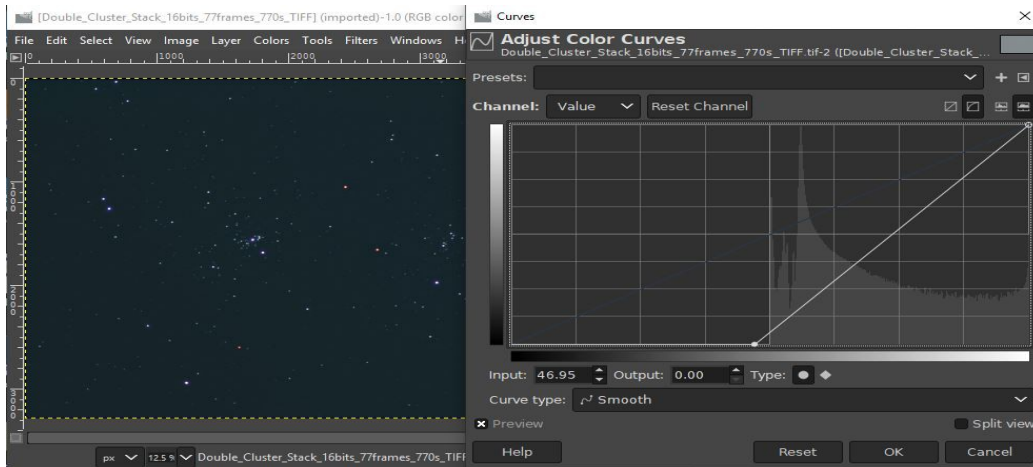


Since the image is calibrated, the light pollution will be the highest peak on the histogram. Also, notice that the three color bands (red, green, blue) have their highest peak at different ADU values. This tells us that the light pollution has a color that will strongly influence the deep sky object color unless the light pollution is subtracted at the three individual color bands. We will be using the Curves tool in GIMP to subtract the individual color band light pollution level.

Let's take a look at the Curves tool. In the screen capture image below, on the left hand side, is our light polluted image. The deep sky image on the left will show the effect that every change in the Curves tool has upon the image if the "Preview" box has a mark in it. On the right hand side of the screen capture is the curves tool that you are using to process the image on the left. Make sure that the logarithmic graph (on the far right of the tool) is selected so you can easily see details in the histogram.

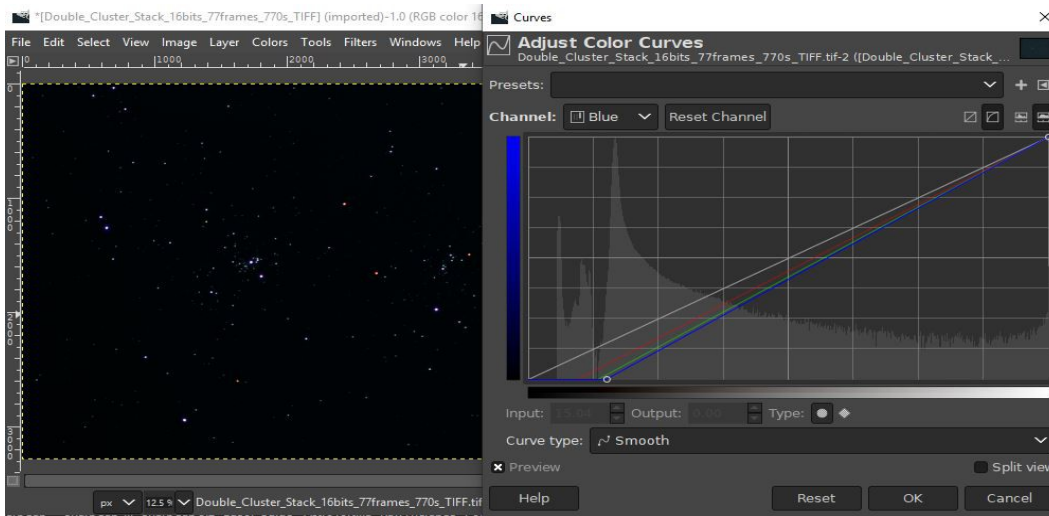


In the above screen capture, I have opened the calibrated Double Cluster image in GIMP and selected the "Curves tool" which shows the histogram of the light polluted Double Cluster image. I can subtract most of the light pollution by sliding the lower left curves black point to the right along the X-axis. You can confirm that you are on the X-axis by looking at the "Output" box beneath the curves graph. The Output should be zero, as shown below:



As you can see from the above image, the background light pollution has been reduced, but the light pollution color remains. Note that the logarithmic scale for the vertical axis is selected as seen in the upper right of the graph. If we take the the black point of the above Curves to just below the sharp rise in the histogram we will remove most of the light pollution and preserve all details in the histogram, while providing more precision in the color selective black point step.

The histogram below has the individual color channel black point adjusted to the left edge of the large spike in the histogram for the selected color channel (blue in this case) as shown below:



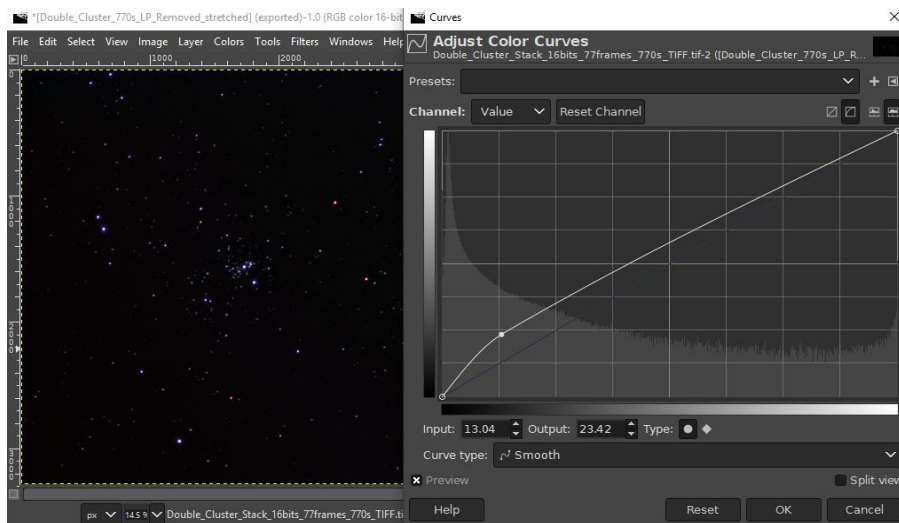
Curves histogram scales the bin count at a particular ADU level into a zero to 100 range and also the ADU range itself (16-bits becomes 0 to 65535) scaled into a zero to 100 range. The key to moving the black point with some degree of repeatability is to find the left edge of the large histogram peak in a particular color channel where it crosses the mid-point in the vertical axis (Y=50). Move the position mark (+) to touch the left-hand edge of the largest histogram peak in a specific color band and read the X-value at that point. Now, move the mouse to the black point

marker on the lower left side of the X-axis, select the black point and drag it along the x-axis (holding the left mouse button) until you read X=(value from above) appears in the “Input:” box below the X-axis. If you have trouble getting the exact target value then select the number in the “Input:” box and type in the correct value. Perform this adjustment of black-point in each of the color channels (red, green, blue) selected in the “Channel” drop-down list at the top of the histogram graph. You will see the result of these black-point selections in the image if you put a mark the “Preview” box.

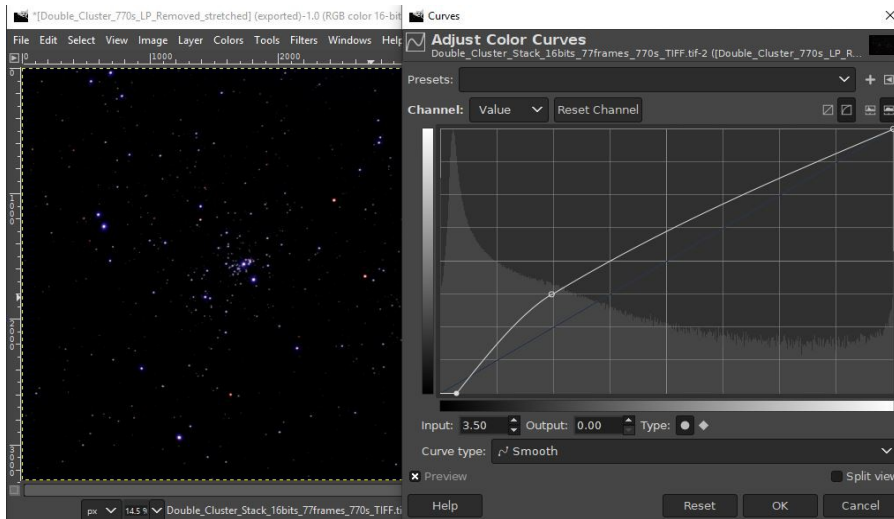
Check to determine if the background is neutral gray-black by viewing the pointer information “Pixel” data over the background (making sure no stars are measured) to see if all three color channels (red, green, blue) are roughly the same ADU level (within about 50 ADU between each channel). If one color channel is too large or too small relative to the other channels then adjust the black point for that channel again until the background is neutral. If you are satisfied with the result, then click OK to perform the adjustment to the image. Your image should have approximately neutral sky background color with the three color channels showing about the same ADU level.

Further applications of Curves can be used to stretch the image dynamic range to show very faint stars or nebulosity. Do not attempt to stretch the image with a single application of Curves. Small incremental stretching with Curves will reduce the amount of bloating in the brighter stars. Use several (2 to 4) modest curves enhancements to achieve the degree of brightening of faint features in the image. The goal is to spread the large histogram peak near the black point out to a higher ADU level, as seen in these three Curves stretches. The three screen captures of 3 applications of Curves to brighten faint stars in the Double Cluster are shown in the three images below:

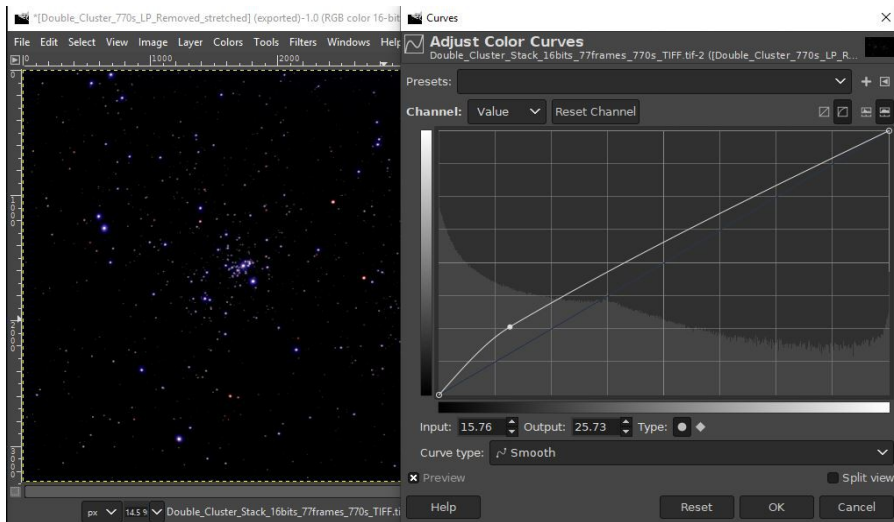
Curves-1



Curves-2



Curves-3



For this image of the Double Cluster, further stretching with Curves will begin to bloat the brighter stars too much. The final result of these curves stretching procedures is shown below:



I need to emphasize that the flat field calibration of the individual camera images before stacking is the **most important step** in removal of light pollution uniformly over the entire image. If you leave any light pollution gradient in the stacked deep sky images then this method of light pollution removal **does not work** because, even though the light pollution appears to be removed, it will be stretched into visibility when you are stretching the deep sky object into a brighter level. As a result of the importance of flat field calibration in light pollution removal, it is necessary to do the flat field calibration **every time** your imaging telescope and camera are used when you set-up your equipment for imaging.

In general, if you disturb the camera-telescope interface in any way (remove the camera from the telescope focuser or change the orientation of the camera in the focuser) the master flat field calibration must be done again. Even if the camera-telescope assembly is never changed (e.g., in an observatory) a new master flat field image must be taken periodically because dust inside the telescope may settle on the camera window producing new “dust doughnuts” that will show up in images calibrated with an old master flat field image.

What is the next step?

I have described a method for creating deep sky images using an altitude-azimuth telescope drive that was never intended for doing long exposure astrophotography. There is no reason to believe that what I have described here is the only way to do this kind of imaging, but it certainly works as described and may serve as a starting point for someone to develop an even better way. Your next step is to start imaging and see what you get. If you are motivated to find a better way, then innovate and let everyone know by writing something describing what you have done. Amateur astronomy is all about having a good time looking at or imaging things in the sky, so don't let anything get in the way of having a good time under the stars at night and let others know what you have learned.