Imager's Corner

The idea for this editions column came from a reader that was confused and frustrated by the answers they got to a simple question – what kind of astro-camera is better for RGB or colour imaging? I suspect this edition will earn me hate mail from at least one of the two camps, maybe both.

In this edition we will take a look at some of the theory surrounding this question and courtesy of a fellow astro-imager and RASC member, Jason Dain, we will look at an actual data set in addition to the theoretical discussion. Most times when you get into this discussion it is very difficult to *prove* your argument as there are only a few cameras that come in one shot colour (OSC) and monochrome versions. Both Jason and I have used a fantastic OSC camera made by ZWO, the ASI2600MC Pro and Jason is now the proud owner of a shiny new ASI2600MM Pro, a mono version of the OSC camera using the same sensor as the OSC version. This allowed Jason to capture side by side data on the same target, under similar conditions, using the same scope so we have an excellent data set to compare images from both cameras.

When you ask this question on groups such as Cloudy Nights you often get answers like – mono is better because it doesn't have missing pixels like the OSC Bayer matrix does, or the ever favorite OSC is better because it is less work. Neither of these is correct and neither is helpful to a novice trying to decide which camera to buy. There is really a whole discussion you need to have with someone that asks this question. At the top of the discussion points is what qualifies as better? Is it SNR, is it time spent collecting data, is it ease of processing, is it resolution, the list of things needed to answer this simple question really depends on the interests and capabilities of the person asking it and on a good definition as to what qualifies as *better*. Jason and I discussed these questions for a while and came to the conclusion that resolution and SNR for the same data acquisition time would be a good way to rate the differences. Thinking a little more on the topic we realized that resolution depends heavily on seeing and that our typical conditions would leave us seeing limited with both cameras. This left us with the SNR comparison which is what we used for purposes of this evaluation. In a previous edition of Imager's Corner we explored signal to noise ratio and noise in general. If you remember, a 3 dB difference in SNR is about the minimum the human eye can perceive so for the purposes of this experiment, if the SNR of two images varies by less than 3 dB we will claim they are effectively the same.

A little technical detail is required to get an understanding of what camera specifications are important to the discussion and dispel a couple of popular myths. The ASI2600MC version is a full OSC camera that uses the colour version of Sony's IMX571 APS-C format sensor with a

RGGB Bayer mask for colour imaging. The ASI2600 MM version of the camera is identical with two differences of note. First, this version of the camera uses the mono version of the IMX571 APS-C sensor. It is identical to the OSC sensor except it does not include a Bayer matrix. This means that we don't have to contend with trying to compare data from different sensors and do a lot of hand waving to explain why things vary from what was expected. The second difference between the two cameras is the type of optical window used to cover and protect the sensor. The OSC version uses a window that provides both a UV and IR cut-off suitable for full colour imaging using a refractor while the mono version uses a simple clear window that has a broader passband than the OSC version. The optical transmission characteristics versus wavelength of both windows are shown below.

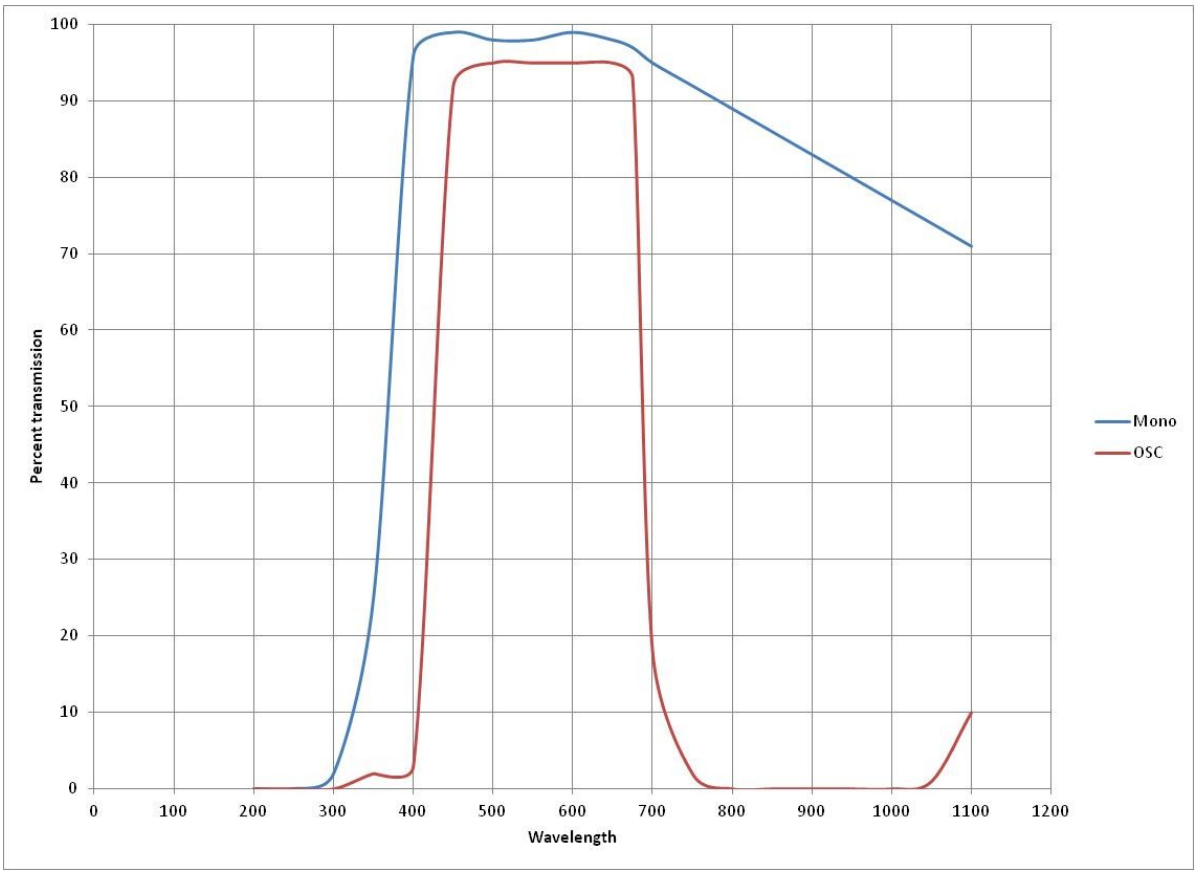

Figure 1 - Optical window transmission characteristics of both cameras. The ASI2600 MC (OSC) version is shown in the top plot while the ASI2600MM version is shown in the lower plot. In both cases the X axis is wavelength and the Y axis is the percentage of incident light transmitted by the window.

At wavelengths longer that 670 ηm, the mono version of the window has a significant transmission advantage. For informational purposes, the wavelength of Hα is 656 ηm and SII emission line is located at 672 ηm. The passband transmission for both filters is similar with the mono version passing 98 percent of the incident light while the OSC version passes about 95 percent. At Hα wavelengths the mono window passes about 98 percent of the incident light

while the OSC window passes about 94 percent. The situation tilts in favour of the mono unit at SII wavelengths with the mono window passing 97 percent while the OSC window starts to roll off passing 80 percent. Although this seems like a large difference it only amounts to -1.7 dB, less than the 3 dB we would need to see to make a noticeable difference in SNR.

Next let's take a look at camera quantum efficiency, the measure of how many incident photons are converted to electrons and detected by the sensor, but to do this we need to compare apples to apples. Many people simply look at the QE peaks for both cameras and attempt to draw conclusions. With manufacturer specifications for both of the cameras we can see that the mono version peaks at greater than 90 percent and the OSC sensor peaks at greater than 80 percent. Since both cameras use the same back illuminated sensor, it is a reasonable assumption that other than sensor to sensor variations the difference is due to losses occurring in the Bayer matrix filters. This makes the simple comparison of QE peaks misleading since you will have to put red, green, blue and probably luminance filters in the optical train of the mono camera to take a colour image. Now in the mono case these can be high quality interference filters with very little loss, something that can't be easily done with the small micro-filters used in a Bayer matrix array. The filter response of the mono colour filters is shown below.

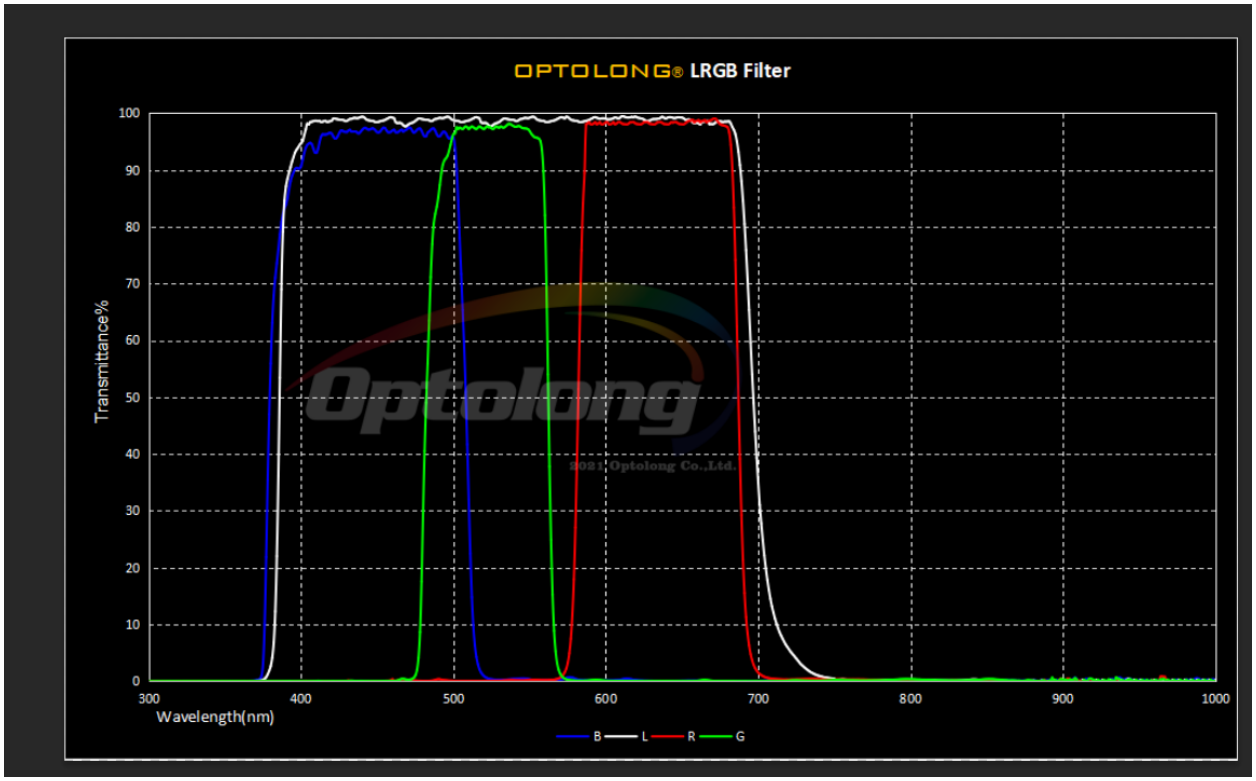

Figure 2 - Transmission characteristics of Optolong's LRGB filter set used in this experiment.

The transmission characteristics have to be combined with the QE plot of the mono sensor to compute overall quantum efficiency in order to compare it with the OSC camera.

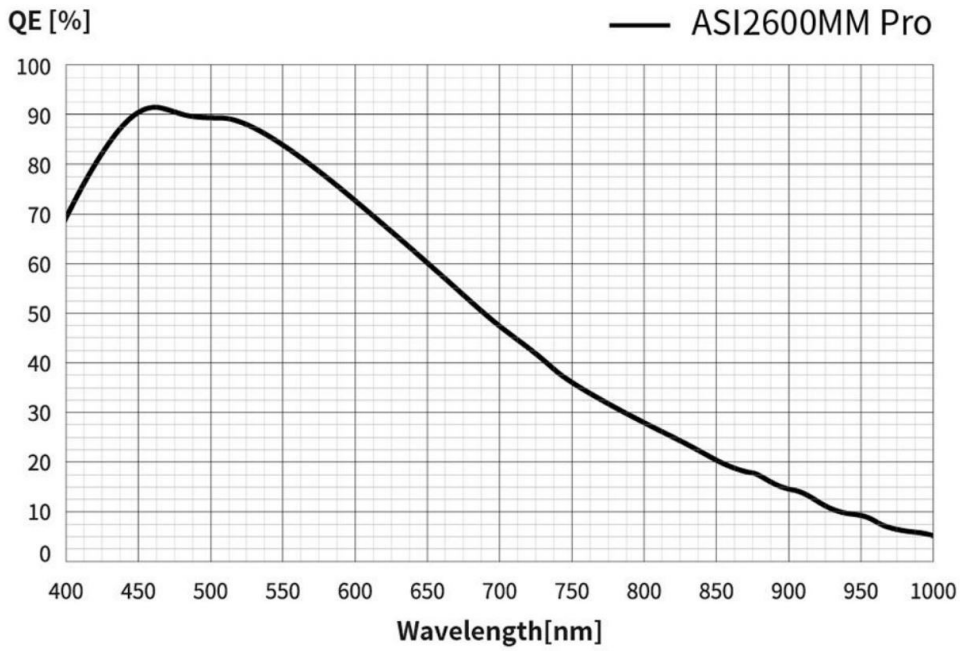

Figure 3 - Absolute quantum efficiency plot of the Sony IMX571 APS-C sensor.

To make matters even more confusing, manufacturers usually give relative quantum efficiency information for OSC sensors where the peak QE is scaled to 100 percent as shown below for the colour version of the same sensor.

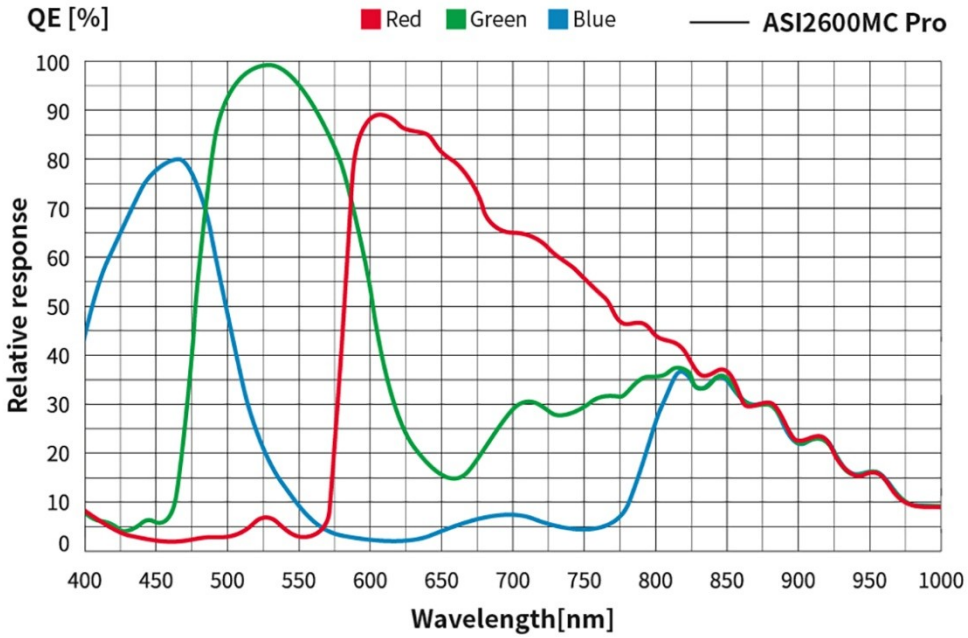

Figure 4 - Relative quantum efficiency plot for the colour version of Sony's IMX571 APS-C sensor.

In order to convert this to absolute quantum efficiency the plot must be multiplied by the absolute value for the peak (80%). Once we have the absolute quantum efficiency for both cameras, the OSC data needs to be scaled by the optical window response and the mono camera data needs to be scaled by both the optical window response and the LRGB filter responses giving the apples to apples comparison plot .

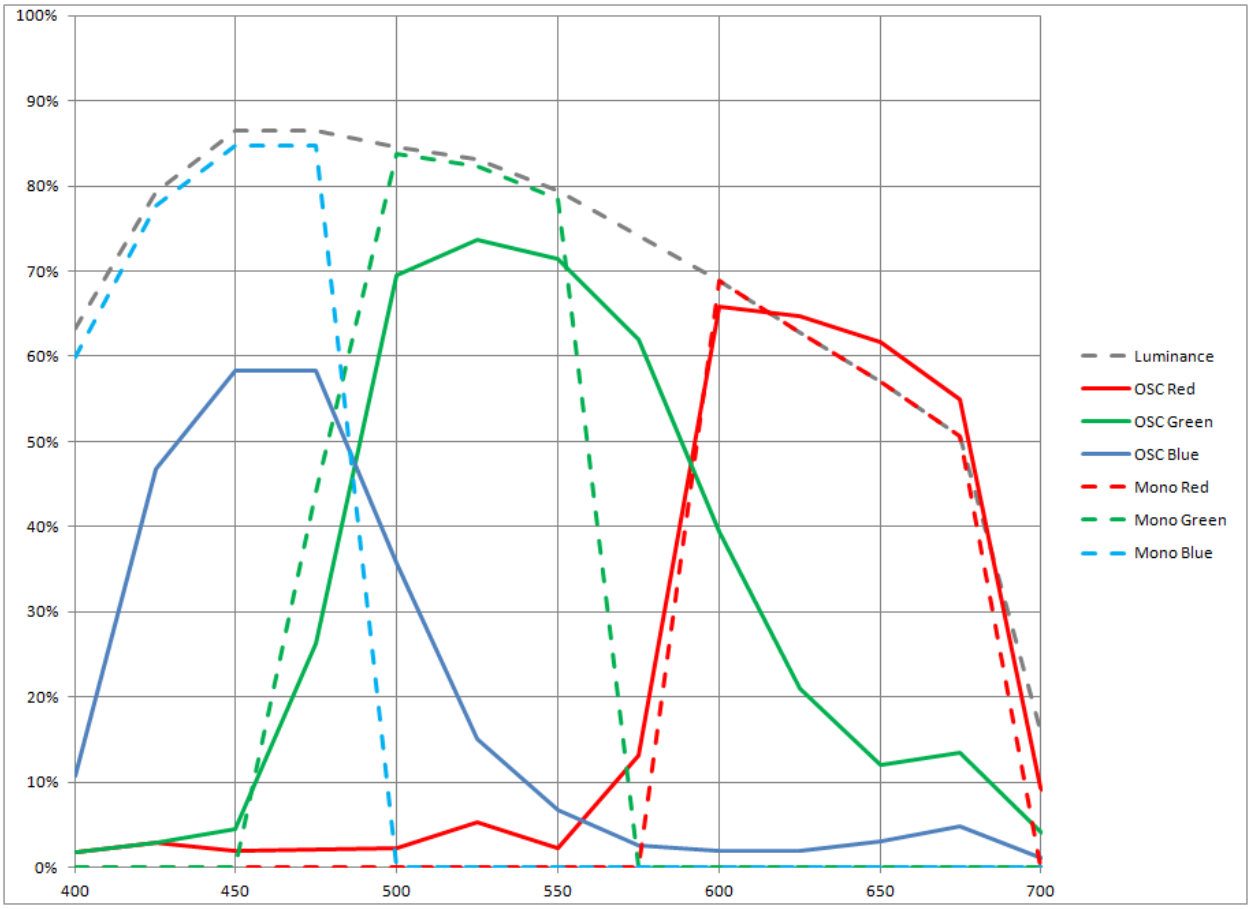

Figure 5 - Fully scaled QE plots including filter and optical window effects for both the mono and OSC cameras.

As you can see there isn't much difference until you hit the blue end of the spectrum. Here the interference filters used with the mono camera are clearly superior with a 3.2 dB difference between the two systems in the band from 425 ηm to 475 ηm. For the rest of the visible band both cameras are virtually the same with less than a 3 dB difference between them. There is certainly nothing in the specifications of these two systems, once the mono filter transmission data is taken into account, to lead the reader to expect any better performance at Hα frequencies (where emission nebulae shine) from one camera over the other.

Band	Red 650 ηm	Green 525 ηm	Blue 460 ηm
Difference OSC relative to mono	0.7 dB	-0.9 dB	-3.3 dB

Table 1 - Difference in dB at the band centers (OSC relative mono)

Table 1 shows the difference in QE at the band centers in dB, calculated by $20*\log(QE_{OSC}/QE_{mono})$.

Finally, let's take a look at the effect of those *missing* pixels due to the Bayer matrix on the image. With the majority of the resolution of the OSC camera coming from the green channel, which has half the pixels, one would expect half the resolution of the mono camera when used

with the same optical system. The question becomes what will seeing allow? Using my Esprit 120 and the ASI2600MC Pro, my calculated resolution is 0.92 arcseconds per pixel. Since the camera is an OSC device using a RGGB Bayer matrix I'll get about half that resolution so let's call it 1.84 arcseconds. This means that under ideal conditions I should be able to resolve objects 1.84 arcseconds apart. Examine the image of Epsilon Lyrae taken with this setup.

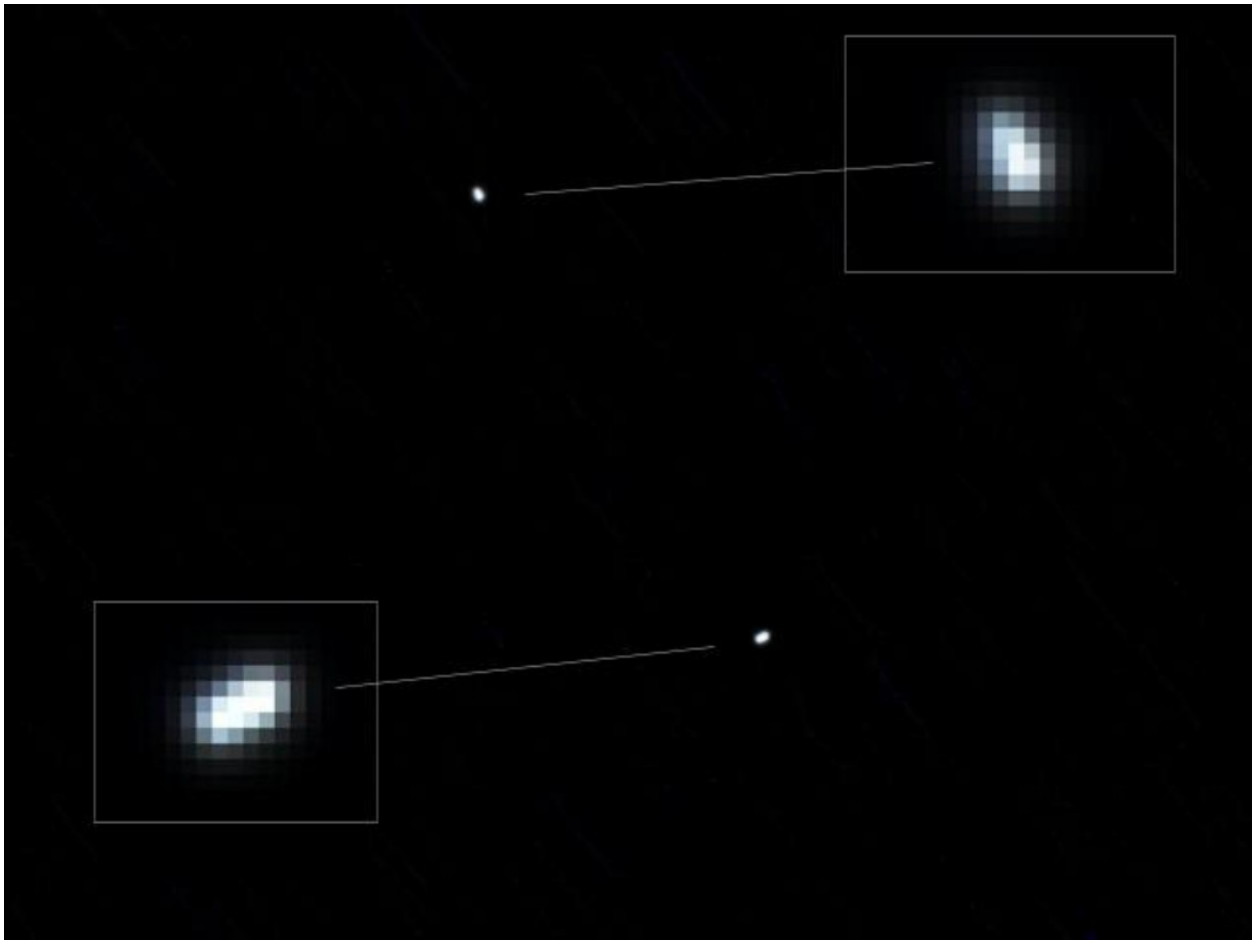

Figure 6 - Image of Epsilon Lyrae taken with a ZWO ASI2600MC Pro and an Esprit 120 APO refractor.

Now I'm sure we can argue whether the individual stars are resolved, but I think we can agree that even at 2.3 arcseconds of separation, seeing is still limiting what can be achieved. This means that the resolution loss due to the Bayer matrix, under most observing conditions (at least here in the Maritimes), is swamped due to seeing. With seeing being the limiting factor the mono camera will have about the same resolution as the OSC unit.

With the resolution question out of the way, the question becomes one of what the *missing* pixels do to the SNR. To answer this we need a little background in sampling and interpolation. Consider a true image of an object, one that is band limited by seeing. The idea of band limiting means that the image is blurred such that the number of pixels we have can correctly sample a

target with at least two pixels (preferably more) in any direction. This criteria means that we are, at least, critically or Nyquist sampled. Sampling with fewer pixels will produce alias artifacts that may or may not be noticeable. Now think of a mono sensor as an array of buckets collecting water during a rain storm. If the rain is falling at a constant rate over the array of buckets, each one collects the same amount of water (lets use one litre for this analogy) over the course of the storm. Using the same analogy for an OSC sensor, for any one colour channel we would cover alternating buckets so they cannot collect any water. Now in any direction (X or Y), at the end of the storm, we would have a bucket with one litre followed by a bucket with no water followed by another bucket with one litre and so on. Interpolation is the method used to guess at how much water would have been in the covered buckets if they were left uncovered during the storm. In this case it is as simple as looking at each of the buckets surrounding the empty one and seeing that they have one litre in them. It is a pretty safe bet that the empty bucket should have had one litre as well. Mathematically we could do this by linear interpolation. When the system has two dimensions we use bilinear interpolation which is generalization of linear interpolation to two dimensions. Now let's think of what happens when the rate of rain fall in not constant over the array of buckets. In this case the covered bucket could have collected more or less water and we get an error from our interpolation. This is where the concept of band limiting comes into the equation. If we take a porous sheet and place it over the entire array of buckets and move it around randomly during the storm, it will act to average out the variations bucket to bucket, removing the rapid changes that occur over short distances during the storm and again our simple linear interpolation can give us a useable estimate of how much the covered buckets would have collected. This is what seeing does for our light collection; it blurs or averages out rapid pixel to pixel variations and allows interpolation to produce an accurate estimate of the value for the *missing* pixels due to the Bayer matrix. There is a very slight error produced when the illumination changes direction from increasing brightness to decreasing brightness and there are more complicated interpolation algorithms to handle this situation. There are whole rafts of algorithms, some locally adaptive and some not, that strive to produce a more accurate representation of the missing pixels, but either simple bilinear or bicubic interpolation does an excellent job, when the sampled signal is band limited. Seeing works so well, in most locations, to band limit that the error is reduced to where it can be ignored with virtually no impact on SNR. Generally speaking an interpolator feeds the data through a low pass filter (bilinear or bi-cubic) to fill in the missing data. This is an important point when seeing is the limiting factor; the interpolation process will improve SNR because of the effects of the interpolation filter and this may give the OSC devices a boost that helps to overcome the slight loss of sensitivity.

There are lots of mono to OSC camera comparisons available on a variety of websites, but many try to treat the OSC camera as if it were a mono system ignoring the requirement for interpolation. They usually do this by creating *super pixels* using binning and then compare the

resultant number of pixels collected by this imaginary pixel to the result of binning the same number of pixels in a mono camera. This type of comparison doesn't work because it completely ignores the fact that if you have an evenly illuminated grey background then the OSC pixels misses two thirds of the incident photons due to the Bayer filter removing those from two of the colour bands. If you find it necessary to compare an OSC sensor to the luminance of a mono camera you must create a luminance image from the interpolated colour channels for the result to be comparable. The requirement for interpolation is simply inherent in the way an OSC sensor was designed.

Well enough of the theory, let's look at some real world data to see what, if any, difference we can detect in the SNR of images taken with a mono and an OSC camera where all other aspects of the system are the same except for one sensor having a Bayer matrix. The data set Jason acquired over several nights consists of hours of exposure on M45 with both the OSC and mono versions of the camera using the same scope, an Esprit 100. In both cases the sub-exposures were 180 seconds. Remembering our test criteria of best SNR for the same total exposure time, we started by analyzing a single calibrated frame off both cameras. Each frame was linearly stretched so as not to change the SNR by multiplying each pixel by a constant so an area containing just background could be selected for measurement. The SNR was measured in a small 29 by 29 pixel window in several places around the image and the values presented here are the average of 8 readings. The signal is simply the average value of the pixels within the measurement window and the noise is the standard deviation. Table 2 and Table 3 summarize the results for both cameras.

Mono	Average	Deviation	SNR linear	SNR dB
R	3694	416	8.879808	18.96807
G	3205	366	8.756831	18.84694
B	4505	444	10.1464	20.12624

Table 2 - Single frame SNR data for the mono camera

OSC	Average	Deviation	SNR linear	SNR dB
R	4125	306	13.48039	22.59405
G	6951	462	15.04545	23.54811
B	4427	324	13.66358	22.71129

Table 3 - Single frame data for the OSC camera

The SNR of the OSC camera exceeded the mono camera by a statistically significant amount in the red and green channels while the blue channel dropped below our 3 dB limit required to safely say there was any difference. These results are actually expected as discussed in the text analyzing the camera and filter combinations at the start of this edition. The OSC image was debayered to produce the colour channels. As part of this process interpolation is used to fill in the missing pixels and the interpolation filter (bicubic in this case) removed some of the higher

spatial frequency noise producing a higher SNR value. The advantage in the blue channel is reduced by the higher system QE in the blue channel as shown in Figure 5 and the additional photons converted to electrons in the mono system just about cancel out the inherent advantage of the OSC interpolation. This trend continued for a stack of three images as well.

Mono	Average	Deviation	SNR linear	SNR dB
R	3680	186	19.78495	25.9267
G	3221	174	18.51149	25.34883
B	4507	205	21.98537	26.84267

Table 4 - Data from stack of three frames for each colour using the mono camera

OSC	Average	Deviation	SNR linear	SNR dB
R	4060	178	22.80899	27.16212
G	6804	228	29.84211	29.49659
B	4374	185	23.64324	27.47414

Table 5 - Data from stack of three frames for each colour using the OSC camera

Next we looked at 1.5 hours of stacked data with very similar results, the OSC providing seeing limited resolution with slightly better SNR.

Mono	Average	Deviation	SNR linear	SNR dB
R	9788	184	53.19565	34.51752
G	8175	164	49.84756	33.95288
B	11701	194	60.31443	35.60842
Lum	14408	130	110.8308	40.89321

Table 6 - 1.5 hours (30 subs @180 seconds per channel) of data from the mono camera

OSC	Average	Deviation	SNR linear	SNR dB
R	12086	187	64.63102	36.20882
G	19667	206	95.47087	39.59742
B	11561	176	65.6875	36.34965
Derived Lum	19609	182	107.7418	40.64768

Table 7 - 1.5 hours (30 subs @180 seconds) of data from the OSC camera

The imaging time for the mono camera to achieve the same SNR as the OSC version, using simple RGB techniques is clearly longer, over three times longer in fact. The effect of the interpolation filter improves the SNR enough in each OSC channel that the mono camera requires a longer exposure to approach the performance of the OSC device for any single channel. Of course no one shoots simple RGB with a mono camera, usually the technique employed is LRGB imaging where a longer luminance exposure is used for detail and shorter colour frames are taken (possibly binned) to do a LRGB combine. We tested this method as well

by restacking 1.5 hours of the luminance data and an hour of each colour, comparing the result to 4.5 hours (the same total exposure time) of OSC data. Using this method we finally achieved close to parity between the two cameras in all but the green channel, keeping in mind that the luminance channel for the OSC is derived from the three colour channels after the fact by my processing software.

OSC	Average	Deviation	SNR linear	SNR dB
R	4178	37	112.9189	41.05533
G	6808	42	162.0952	44.19541
B	3997	35	114.2	41.15332
Derived Lum	6808	42	162.0952	44.19541

Table 8 - 4.5 hours of OSC data

Mono	Average	Deviation	SNR linear	SNR dB
R	4505	41	109.878	40.81822
G	4350	38	114.4737	41.17411
B	4616	42	109.9048	40.82033
Lum	9228	84	109.8571	40.81657

Table 9 - 4.5 hours of LRGB data collected using the mono camera

From both the theoretical analysis and the measured data we can see that the OSC camera actually has a slight advantage over an identical mono camera. There are a couple of caveats to this statement; first the systems must be seeing limited which negates the mono camera's inherent resolution advantage, second the OSC camera image must be debayered to produce a full colour image before things are compared. Where the mono camera should really shine is in narrow band imaging. Here the OSC camera suffers due to the losses from the colour filters employed in the Bayer matrix. For RGB imaging the Bayer filters are matched by the colour filters required for the mono camera. But for narrow band imaging, the Bayer filters represent a loss in addition to the narrow band filters while the mono unit only sees a loss from the narrow band filters. Will this be enough to overcome the noise reduction inherent in interpolation? Maybe Jason and I will tackle this question in a future edition of this column.

To give you an idea of the quality of Jason's data from both cameras, here are the processed mono and OSC images from 4.5 hour exposures. Jason processed the mono version while I processed the OSC data.



Figure 7 - 4.5 hours of LRGB data taken with a mono camera



Figure 8 - 4.5 hours of LRGB data taken with an OSC camera

Most of the differences are due to processing styles with the OSC image showing more background dust and gas with smaller stars. The LRGB mono image is stretched a bit more, but as a result it is slightly less detailed than the OSC version. The blue saturation is stronger in the mono version, no doubt due to the better blue response as shown in Figure 5.

I'd like to thank Jason for all his help with this edition. His high quality data provided a great way to verify the theoretical analysis and shows just how far modern OSC CMOS cameras have come in their ability to capture clean full colour data. To see more of Jason's fantastic images, as well as his terrific daytime wildlife photography, please take a few minutes and visit his Facebook page at https://www.facebook.com/profile.php?id=100010775255799.

Remember, this column will be based on your questions so keep them coming. You can send them to me at b.macdonald@ns.sympatico.ca. Please put "IC" as the first two letters in the topic so my email filters will sort the questions.