APPLICATION NOTE

Filter Set Prescription
Alan Holmes

August 1st, 2002

SBIG has a color filter set prescription specifically designed to achieve correctly balanced color images for galaxies and nebulae. Our design is sometimes challenged on the Internet in spite of the incredible quality of the color images posted by customers using our filters, so I feel it is necessary to explain the rationale behind our choices. We are not new at this – we were the first to popularize the use of efficient interference filters for color work. Our original filter set back in ST-6 days gave nebulosity images that were too blue, which led to further study on our part and to the filter set we currently use.

For deep sky astronomical color imaging, one has two basic types of objects, stellar and nebular. The stellar objects emit light over a wide range of wavelengths, approximating a blackbody curve with absorption lines superimposed upon it. Nebulae only emit in discrete wavelengths, with the bulk of the emission being at 486.1 nM, 495.9 nM, 500.7 nM, and 656.3 nM wavelengths. I have used a monochromator to view these wavelengths to establish their visual appearance with light levels one can see clearly. The 486 wavelength is an electric blue, the 496 and 500 nM wavelength a blue-green, aquamarine color (but more blue than green), and the 656 nM a very deep red. The important point is that none of these lines are green!

Our old filter set, illustrated in Figure One, was designed such that the 486 line fell completely within the passband of the blue filter, and the 500 nM line was detected about equally using either a blue or green filter.

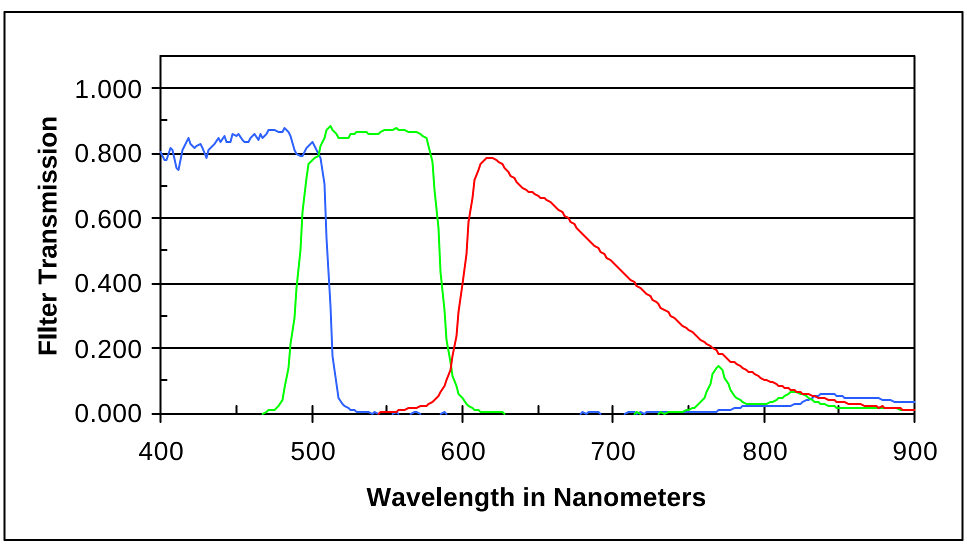


Figure One: Old Filter Set Transmission

This is a common choice, detecting the 500.7 nanometer line with equal sensitivity in both blue and green filters. It is also a wrong choice, at least when imaging with sensors such as the Kodak KAF series, as I shall explain.

We recommend users color balance images taken with our filter sets by taking red, green, and blue images of an out of focus solar type star and adjust the color to white by varying the exposure times and color ratios. With our old filters, the emission nebulosity in the images calibrated this way appeared to always be too blue after balancing the stars to white. The reason that we now understand is that the ratio of nebular signal to stellar signal within each filter's passband was not constant. For example, assume that one has an image where, through a red filter, the red nebulosity is 100 counts and a white star is 1000 counts. Through the blue filter, the blue nebulosity is 100 counts, but the white star is only 500 counts (caused by the blue emission line being at the <u>long wavelength edge</u> of the blue filter where the CCD quantum efficiency is highest). If I balance the star to white by taking a blue filtered exposure 2 times longer, the blue nebulosity is now twice the strength of the red, and will appear too blue. In short, the problem is that blue nebulosity is at the long wavelength edge of the blue passband. You want the blue and green filters to detect the 500.7 nm line with equal counts <u>after</u> color balancing!

The problem is even more complicated than my simple example illustrates. For example, what if I doubled the red filter passband, extending it out into the near infrared? My sensitivity to the emission line at 656 would be <u>unchanged</u>, but yet the star counts in the red filter would double. Now, color balancing on a white star would require me to double the blue exposure, doubling the blue nebulosity counts relative to the red nebulosity!

To calculate a new filter set, I modeled the problem using a Microsoft Excel spreadsheet. I input a star spectrum based on an equivalent blackbody temperature, and modified it by the transmission of the atmosphere, for a clear night and a star at the zenith, and the quantum efficiency of the KAF-0401 detector (the ST-7E CCD at the time). I input potential filter spectral passbands into this model, and determined how many counts would result for a solar type star with each filter. To model the nebular response, I input a 1000 photon line at 486 nM, a 3000 photon line at 496 nM, an 8000 photon line at 500.7 nm, and a 5500 photon line at 656 nM. These proportions came out of the Astrophysical Quantities Handbook (C.W. Allen) for the typical intensities of these emission lines in planetary nebulae. I then determined the nebular signal I would see, after white balancing, using the red, green and blue filters and adjusted the passbands so that the counts in each of the blue and green filters was the same as with the red filter. I also made it so the blue and green response to the 500.7 nm line was similar <u>after</u> color balancing. I am assuming here that, on the computer screen, one count of blue and one count of green will yield a blue-green point twice as bright as 1 count of red. If this assumption is true, then my filter choice will produce a visual response comparable to the photon flux in each region, as seen from outside earth's atmosphere. I ignored the photopic response of the eye, which isn't appropriate for such faint objects anyway. If I did not ignore it all planetary nebulae would be strongly blue-green, which does not seem to be what is considered true color in the community. The eye is ¼ as sensitive to 656 nm as 500 nm. “True” color is very much a philosophical concept for emission line objects too faint to see!

Figure Two shows the relative photon flux versus wavelength for a blackbody spectrum of a 5900 degree kelvin star. The blue is slightly overestimated by this model due to the many absorption lines in that area. Figure Three shows the atmospheric transmission as a function of wavelength, assuming only Rayleigh scattering and a sea level site. Figure Four shows the QE curve for an ST-7E/8E CCD. The new filter set transmissions are illustrated in Figure Five. Table One gives the counts I calculated using the new filters before and after balancing. I do not perfectly achieve my goal, but its close!

Figure Two: Relative Photon Flux from a Sunlike (5900 deg K) Star

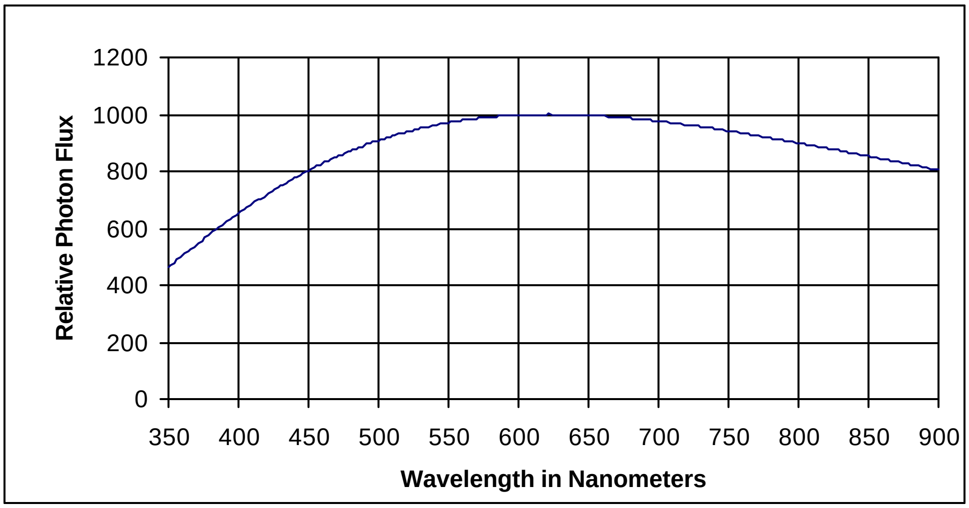


Figure Three: Atmospheric Transmission based on only Rayleigh Scattering

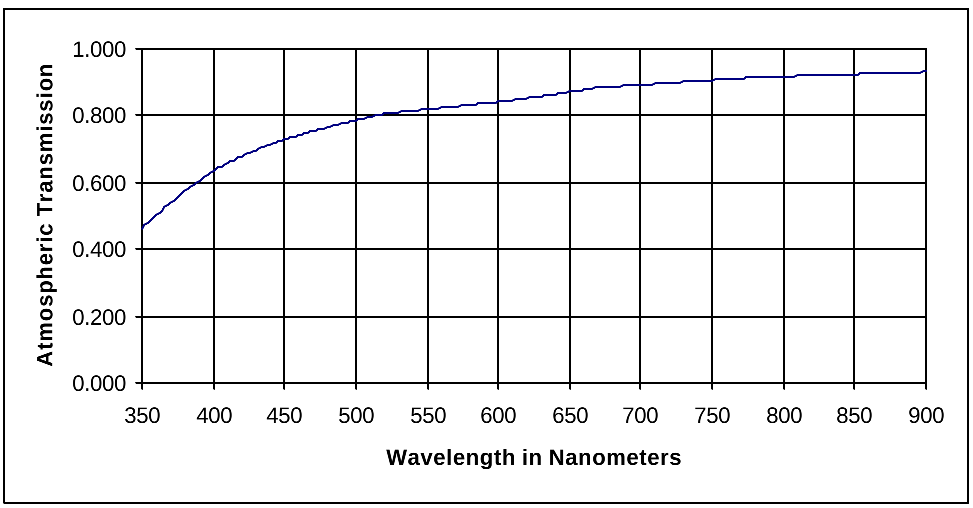


Figure Four: ST-7E/8E Quantum Efficiency Curve

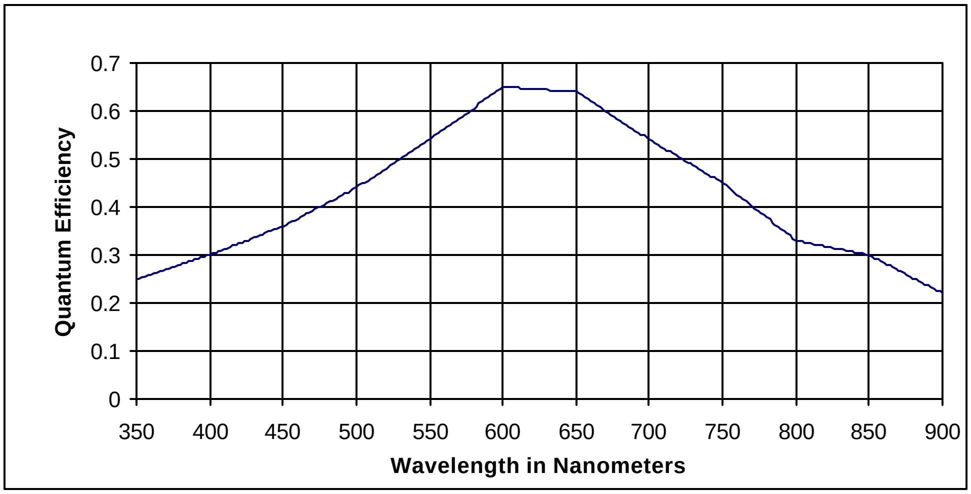
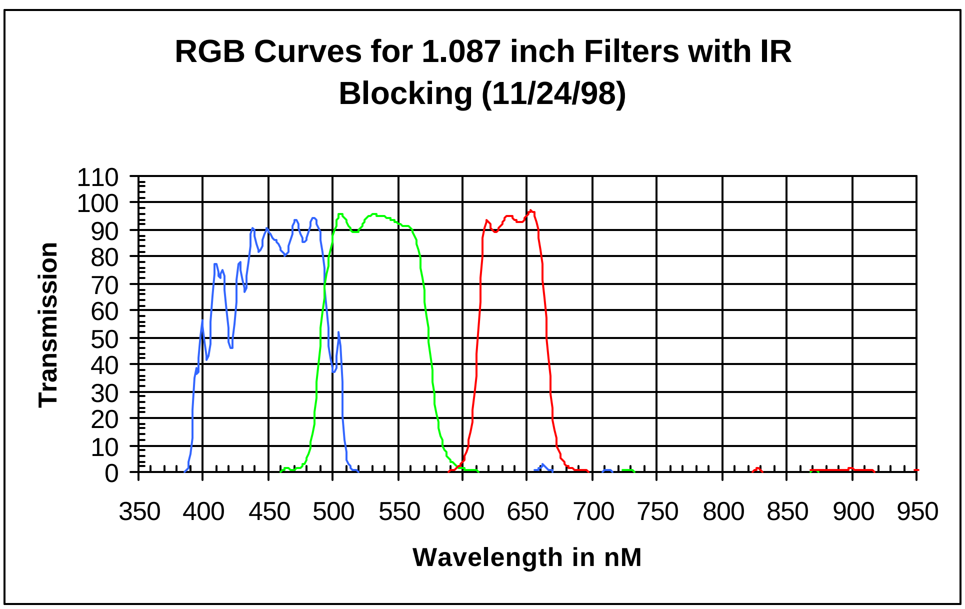
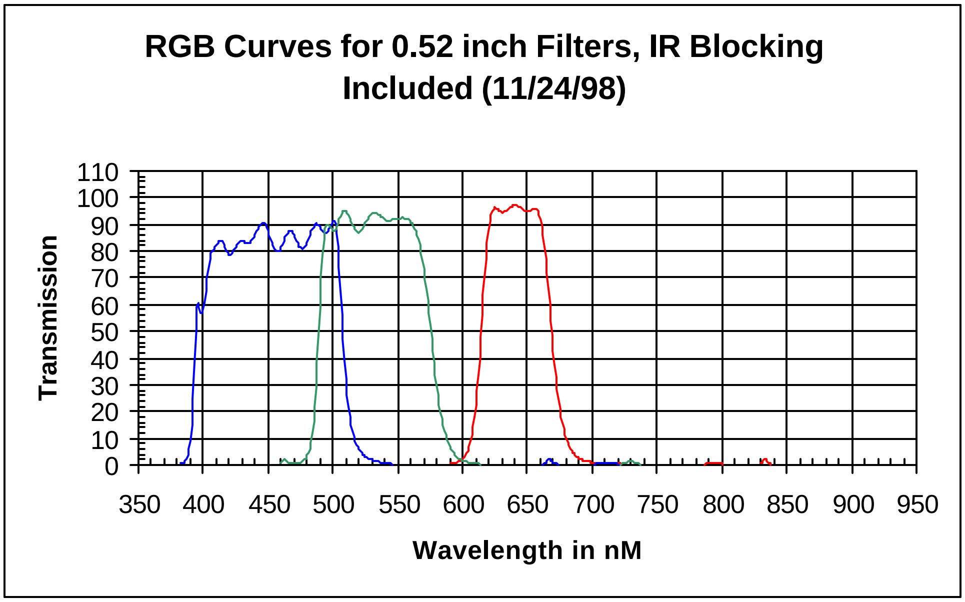


Table One: Results of Numerical Integration

Results of Numerical Integration		Red	Green	Blue
Integrated Star Counts before Balancing		14793	15331	9994
Integrated Nebular Counts before Balancing		2718	3539	2010
Balancing Factors		1	1	1.6
Integrated Star Counts after Balancing		14793	15331	15990
Integrated Nebular Counts after Balancing		2718	3539	3216

Figure Five: New Filter Set Transmission Curves

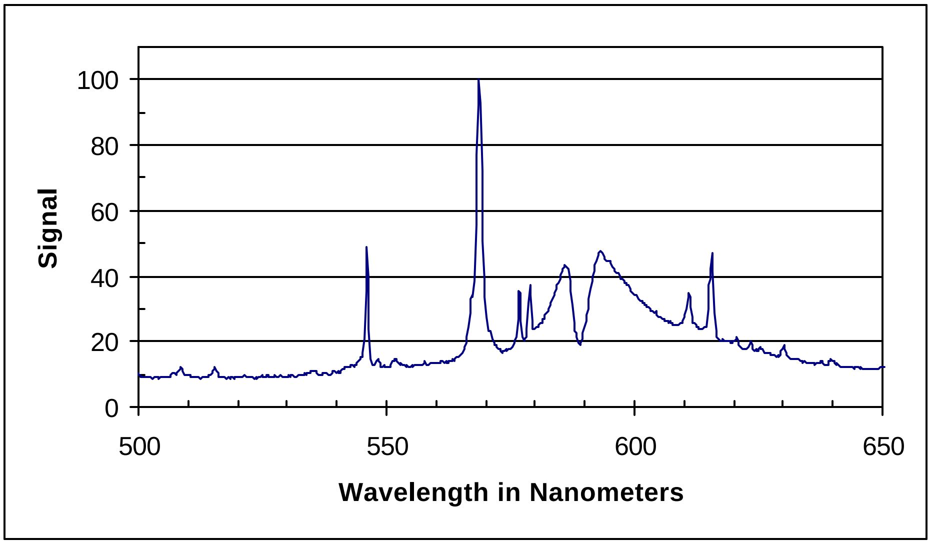




In the new filter set, the red and green passbands have been slightly reduced. The attenuation of red H-alpha nebulosity that occurred in the old filter set has been corrected. The filter prescription is different for the ST-5C and PixCel 237 0.52 inch filters than for the ST-7E and ST-8E 1.087 inch diameter filters. ST-6 users should not use the new filters.

There is a "hole" in the new filter set between 570 and 610 nM. While this may offend the purist, there are no significant astronomical emission lines in this hole. Stars have very wide spectral distributions, as illustrated in Figure Two, so no loss of information results from this hole – you do not miss "yellow" stars (which are yellow-white). However, sodium vapor streetlights terribly pollute this region, as seen in Figure Six, which shows a night sky spectra from my backyard looking above a shopping area. All lines and continuum shown in this figure are pollution – the airglow lines are quite faint on this scale.

Figure Six: Spectra of Light Polluted Suburban Night Sky



The new filters incorporate the IR blocking that required a separate optical element for our old filter set. It is now more convenient to use – one does not have to take out the IR blocker to get maximum sensitivity with the clear filter. There is no IR blocking in the clear filter since our users have said they like all the extra small stars and faint galaxies that are detected with the wider passband.

The exposure ratios for the new filters that should be optimum for a ST-5C or PixCel 237 are approximately 1:1:1 (red:green:blue). The ratios for a ST-7E or ST-8E are approximately 1:1:1.6.

So, I have described the thought process that went into our filter design and exposure ratio choices. We brought out these new filters in 1998. I think it is clear from many of the images collected using our cameras and filters that we have a design capable of beautiful, dramatic images with a pleasing color rendition. It is certainly possible that another choice might lead to slightly better results, but one should not be misled into thinking our design is totally broke based on what one reads on the web. Some of the common objections are:

1) 500.7 nm is not detected with equal sensitivity in both blue and green filters
   -It is <u>after</u> balancing

2) There is a "gap" between the red and green filters
   -The gap in intentional. It reduces the effect of light pollution and misses no important emission lines. The gap was necessary to balance the counts from a sunlike star.

3) An optimum filter set has smooth overlaps
   -Stars have big absorption lines all over the spectrum. The atmosphere has many absorption lines, particularly in the near infrared. Emission nebulae have strong

discrete emission lines. Why is smooth critical when nothing being imaged is spectrally smooth? Optically, the only reason it is important is that you don't want to locate important spectral features on band edges, since the edges might shift with temperature or manufacturing process. In our case, only the 500.7 line is on an edge, for the blue filter. Our specification specifically controls the filter properties at this wavelength.

4) We don't exploit the sensitivity advantage of CMY filters
   -There is no sensitivity advantage to CMY filters. This has been misrepresented in many places, in print and on the web. CMY filters also have the disadvantage of passing two widely separated colors at one time (for the M filter). Atmospheric refraction tends to displace these colors from each other. This problem alone is the kiss of death for CMY imaging on planets. Any filter design that has significant "leaks" far from the passband has this problem. Also, your computer monitor is RGB. Why measure using different colors when you have to convert it later?

5) A different design would produce "truer" color
   Our design has withstead the test of time. We believe our colors accurately reflect the photon flux from an emission nebula from an exo-atmospheric location. Perhaps we should attenuate the blue to make it more representative of what one would see from sea level, or attenuate the red to make it equal energy, not equal photon flux. Or we could drop the 656 nm level by 4X to match the eye's photopic response, or drop it by 360X to match the eye's scotopic (night vision) response. As you can see, "true" color is a philosophical determination. One should not get too passionate about it.

An important final note – all of the discussion above about balancing applies to film-based celestial photography. One should not assume that film pictures are more accurate. One still has to balance the solar-type star color to white!