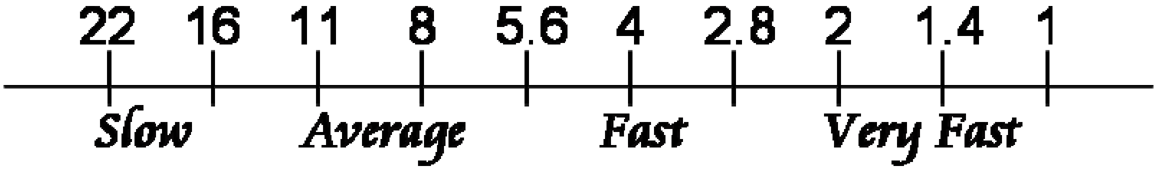
Fast Astrograph Considerations or “More Aperture for a Given Image Scale and Focal Length”

The dictionary defines an astrograph as a telescope designed for the sole purpose of astrophotography. As an amateur, for me, the term “sole purpose” is a bit constraining. Not to offend but I don’t think we amateurs do anything with a sole purpose. What telescope hasn’t had an eyepiece at the image? Maybe telescopes like the Oschin 48” Schmidt at Palomar, but this is only because its design with the curved image inside the tube makes visual astronomy nearly impossible.

To me a more fitting definition replaces “sole purpose” with the words “primary purpose”, making a more appropriate astrograph definition “a telescope designed with the primary purpose of astrophotography”. With this definition pick a telescope, attach a camera, use it most often for astrophotography and you own an astrograph. You’ll know your telescope has become an astrograph, when your star parties become astrophotography sessions, and you spend the night socializing between pictures instead of at the eyepiece.

So what is a fast astrograph? It is the one that gets there more quickly because it has a larger aperture for a fixed focal length. Like a camera lens an astrograph’s speed is represented by its focal ratio or F/number. Faster astrograph systems have smaller focal ratios. Smaller focal ratios equate to shorter exposures for the same extended object to the same depth. Focal ratio is simply the focal length divided by the entrance aperture diameter, thus a 6” aperture telescope with a 48” focal length is F/8, and a 12” aperture with 48” focal length is F/4. Photographers have standardized on a scale where each smaller F/stop value is a factor of 2 faster than its next larger value. Thus for nonstellar extended objects, like nebula, an F/8 system requires twice the exposure as an F/5.6 system for the same extended object to the same depth because the F/5.6 system has a larger aperture and both systems have the same focal length.



Roughly speaking a slow system is F/16 or slower like F/22, an average system is F/16 or faster than say F/11 or F/8, and a fast system is F/5.6 or faster like F/4 or F/2.8, etc. These are rough definitions, if you think your F/11 Schmidt Cassegrain is fast, who am I to argue, you will still need 8 times the exposure at F/11 than your friend with an F/4 system photographing same extended object to the same depth. . Notice I said like a camera lens thus both telescopes have the same focal length and image scale; so your friends F/4 system has a correspondingly larger aperture. You don’t get something for nothing. Fast Astrographs are all about the largest aperture for a given image scale and focal length.

With so many very fine commercial optical systems available why would anyone make their own? There are as many answers to this question as there are home made telescopes. Anyone who has gone to the effort knows the answer and has experienced the deep satisfaction of viewing and sharing the mysteries of the universe with an instrument of their making. There is something primal about the transformation of a rough piece of glass using grit, pitch, and polishing compound into a pristine exceptionally precise optical surface. Amateur and professional opticians apply the same tools, the same effort and care using traditional methods that are antique by any standard but fundamental to an industry that's changed our world.

With a few successful telescope systems under your belt you are ready to take on the greater challenges, how about a larger telescope, how about a faster telescope, why not a faster larger telescope.

But why a Fast Astrograph? More aperture for any FOV and or Focal Length

Aside from More aperture, images from fast systems have a number of other attractive qualities. First the stars appear suppressed and extended objects like nebula appear enhanced. That is for a given exposure, nebula have improved signal to noise due to the photographic speed of the optical system form a larger collection area and limiting magnitude of point sources is reached quickly. This is because for well corrected systems star images are considerably smaller than a pixel and are under sampled by the CCD. Light from a larger section of the sky is collected along with the star light and overall signal to noise for stars is reduced. Second the exposure needed for a given extended object to a given depth becomes shorter by the ratio of the square of the focal ratios. Thus, an F/5.6 system requires half the exposure of an F/8 system. Again more aperture for the faster system, more light per unit area at the CCD, better SN for a given focal length and image scale. For example I'd rather image with a 20" F/3 than a 6" F/10, both have the same image scale with a given camera, but the 20" F/3 collects a lot more light and that's the point of a fast astrograph.

An amateur astronomer seeks personal satisfaction from using and/or building instruments. As an amateur imager I like to see how objects are connected and relate to one another on a macro scale. For me personal satisfaction comes from making optical instruments, using these instruments for astroimaging, and returning from an imaging session in the field with a pretty picture to hang on the wall. An image that reminds the viewer of how insignificant we are. Finally the design and construction of fast wide field systems is difficult and satisfies the desire for challenge.

A little about the cash management amateur astronomy oxymoron. Commercially fast wide field systems are rare and high quality well corrected systems, when available, are very expensive. Such systems are worth the expense! As an amateur these endeavors are undertaken as a form of entertainment for relaxation and the monetary value of the time spent is not a consideration. The perceived cost of a system is the cash outlay for material without consideration of labor and therefore the completed homemade system seems less expensive. Design and construction of the 8" F/2.6 was relaxing and entertaining for about 400 hours over 6 months. Materials were about the cost of a very good high end 4" refractor from TeleVue. I have made those investments and value both.

OK but why stop at F/2.6 why not build an F/1?

Design Considerations for a fast Astrograph?

There are limitations imposed by Megacity Sky Glow and Spectral Filters. A fast system will require travel or installation at dark sky sites. For fun I have done the experiment, at F/2.6 from the Southern California Megacity, sky fog overwhelms the faint fuzzes in seconds. On a good night from my yard I might see a 4th magnitude star. When you look at the night sky, your ability to see dim stars and the Milky Way is limited by the same sky glow (light pollution) that will fog your film or CCD when you take a picture. For any given camera, the dimmest stars you can capture is a function of the pixel size, the brightness of the star, the diffraction limited star size, and amount of back ground each pixel captures along with the star light. The depth you can probe a nebula is a function of the brightness of the nebula and the brightness of the background sky.

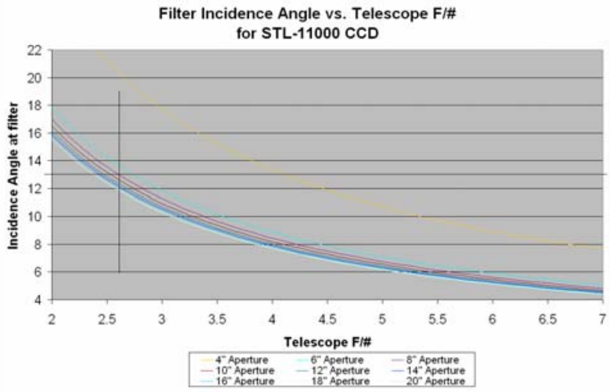
How about using the F/2.6 and a very short exposure, and try stacking 500 frames for each color filter?

You could produce a 15 minute color exposure, right? The raw images from a STL-11000M would consume 5 gig of disc space and take more than 2 hours just to download from the camera. During this data collection series the object will have moved close to 45° across the sky. Many flat frames would be required to correct the ever changing sky glow. A wide field flat frame with spectrally inconsistent sky illumination adds to the color imaging data reduction chore. After all this effort you will have an image whose resolution and depth are limited by atmospheric conditions, your camera, and your telescope. There is little you can do to retrieve nebula that is overwhelmed by sky glow, its a matter of signal to noise. A large number of frames will tend to randomize the sky background noise providing a more appealing image texture for the dark image regions, while adding a small amount of excess read noise from the sensor. But this method will not tease nebula that is overwhelmed by background noise into a useful image.

For astrophotography in the city the solution is a different telescope with a longer focal length, slower F/number, and narrow band filters. With slower systems and narrow band pass filters you can get very attractive images from the city, something many amateur imagers enjoy doing.

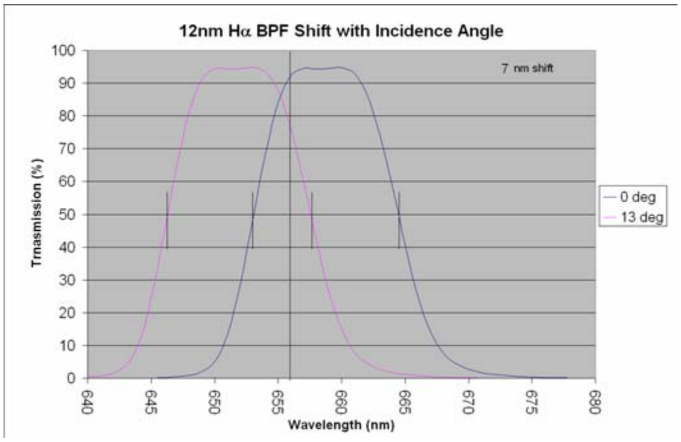
Why not use one of those 6nm filters or something even narrower with the F/2.6?

All dielectric interference filters shift predictably short with increasing angle. The combination of fast F/cone and wide field angles limits the use of narrow band filters to slower systems.



Filters narrower than 13nm will be significantly degraded by the very fast F/cones where the sum of the F/cone and half field angle are greater than about 13°. Again, they are great for slower systems, where slower begins at F/4.

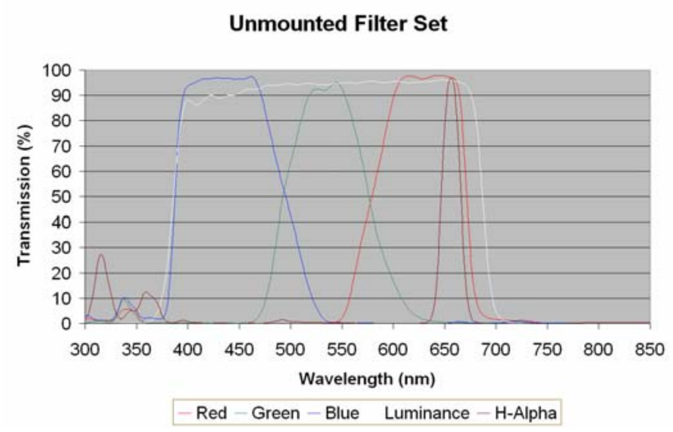
The graph on the right plots the combination of F/cone angle and field angle at the filter for telescope apertures from 4 inches to 20 inches. The vertical line highlights the F/2.6 filter incidence angles for a STL-11000M. From the graph apertures 6 inches and larger, using a STL-11000 CCD, F/number dominates the filter incidence angle. For apertures 4 inches and smaller the field angle dominates the filter incidence angle.



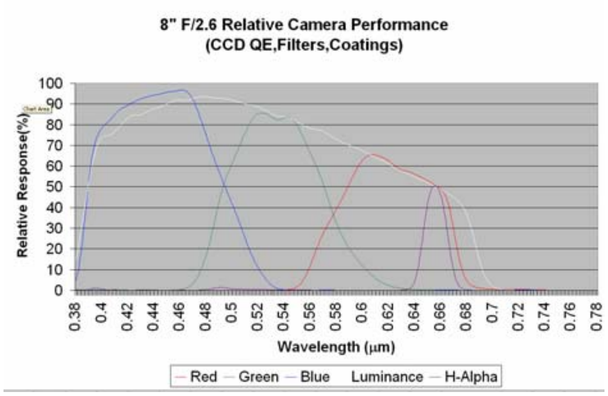
Performance of an H-alpha band pass filter (BPF) is provided in the graph for 0° and 13° incidence angle. This example filter works for fast systems only because the filter manufacturer centered the pass band a little long. The filter pass band shifts with increasing angle toward shorter wavelengths and at 13° has marginally acceptable transmission at Ha. This filter is a good candidate for a range astrographs with apertures 8" and larger operating at F/2.6 or slower.

I suppose you could design a system that places the filter in nearly collimated space to reduce the incidence angles to the sum of a now smaller F/cone plus half-field angle for large aperture systems. Or design a telecentric system for the wide field smaller aperture systems. I looked at several of these approaches and was unable to balance color and distortion without adding significant complexity; maybe you will have better luck.

Thus, with the simple consideration of filters alone the limit to photographic speed of a fast camera is a balance between the angle shift of dielectric band pass filters and the desire to use them for light pollution tolerance.



While on the subject of filters the graph on the right are spectral measurements of LRGB Ha filters shipped by a reputable filter manufacturer. It’s a pleasure to note the quality of the delivered product matches the advertised performance! I have measured filters from most of the high end manufacturers that service amateur imagers and they are all very good. The other thing to note is the transmission in the blue extends well short of 400nm with some ripples 370nm and shorter. Note from the graph that the Near IR end of the spectrum is blocked well below 700nm, and is therefore not of concern.



The graph to the left combines the filter transmission, the telescope transmission, and the CCD quantum efficiency into an overall spectral sensitivity of an example astrograph. Using these filters the astrograph will need good optical performance across a spectrum from 375nm to 700nm. Other measured filters have the short wavelength cut off closer to 400nm, but in all cases the blue spectral band pass exceeds the performance of most commercial systems. The point here is blue image quality will suffer if the optical system of the astrograph is not well corrected to at least 400nm. To overcome this one could use a supplemental minus blue filter in the form of thin film coatings or a Shott GG400 or GG420 colored glass filter to help mitigate the problem.

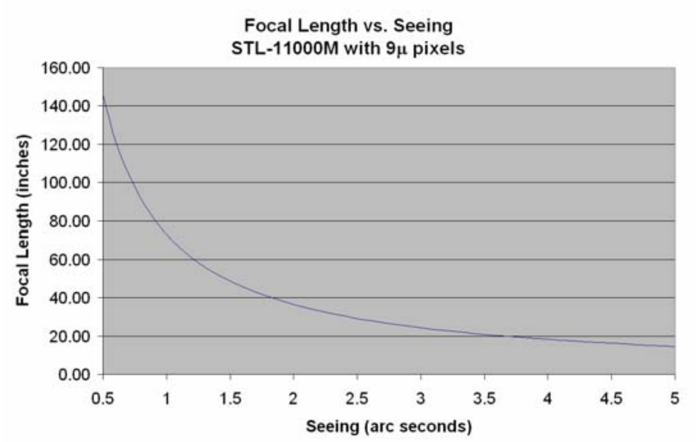
Another concern is the performance of antireflection coatings on the optical elements near the image. The CCD cover and chamber windows can have substantial reflection creating halos around stars. This condition is worse for fast systems. The dominant factor is again the steep incidence angles. Here the performance of the AR coatings are compromised at higher incidence angles. At these high angles the coatings will likely have reduced bandwidth and increased reflection in band. This will result in greater reflection at the blue and red ends of the spectrum and a slight increase every where else. With more reflected light emanating from the optical surfaces at the high incidence angles reflecting back to the CCD, halos will result being brightest in the blue and red and present in the green. Second, star images for well corrected systems are small and again due to the large F/cone angle reflected light spreads quickly creating halos from surfaces very close to the image. Even systems using AR coatings with 0.1% reflection will have halos present in the deepest exposures. Don't blame the manufactures its the limits of physics at work. These conditions exist in all systems but are more pronounced and therefore a clear disadvantage of fast systems. My apologies to anyone fond of halos around stars. My wife has a halo that I am very fond of.

Consideration of atmospheric stability :

The utility of any imaging system will be a function of its sensitivity to atmospheric conditions. What good is an imaging system capable of resolution to 0.25 arc second if the seeing at your observing site never is that stable. Long exposures are an integration of the conditions present during the exposure. The RMS conditions over your normal exposure should set expectations for limiting magnitude and resolution. Resolution and limiting magnitude for stellar and extended objects are nonlinear functions of the conditions during the exposure. The resolution limit is well understood by those doing planetary imaging, where a final image is the composite of the few best resolution images from tens or hundreds of candidates. The limiting magnitude is a bit more complex function of background sky glow and the distribution of star light from the PSF core to neighboring pixels. Thus, when designing an astrograph consideration for the average seeing during an imaging session and the average annual seeing conditions at your observing sites, are necessary inputs.

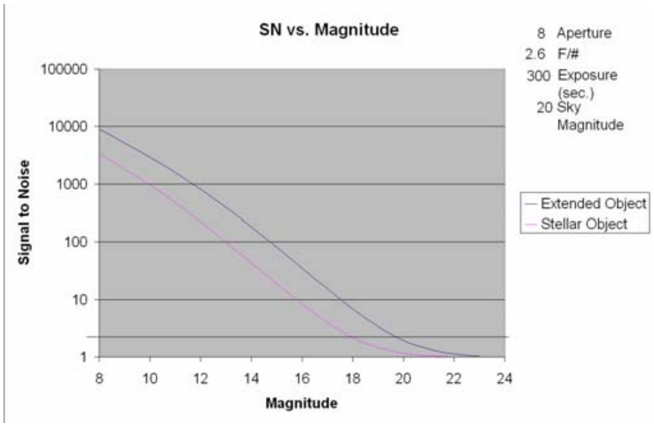
Balancing image scale and seeing:

A casual amateur imager like myself would like some assurance that during the precious monthly new moon there is a high probability of getting a few deep sky images. Observing conditions at sites I frequent, ranged from rock steady "much better than 1 arc second" to a "boiling 4 arc seconds". Average seeing conditions are in the <1 to 3 arc second range. For extended exposures of 5 to 15 minutes it seems these integrated seeing conditions range from 1.5 to 4 arc seconds. These site specific seeing conditions can be used to determine the instantaneous field of view (IFOV) of the CCD for maximum image detail under average site conditions. From this the image scale and system focal length can be calculated.



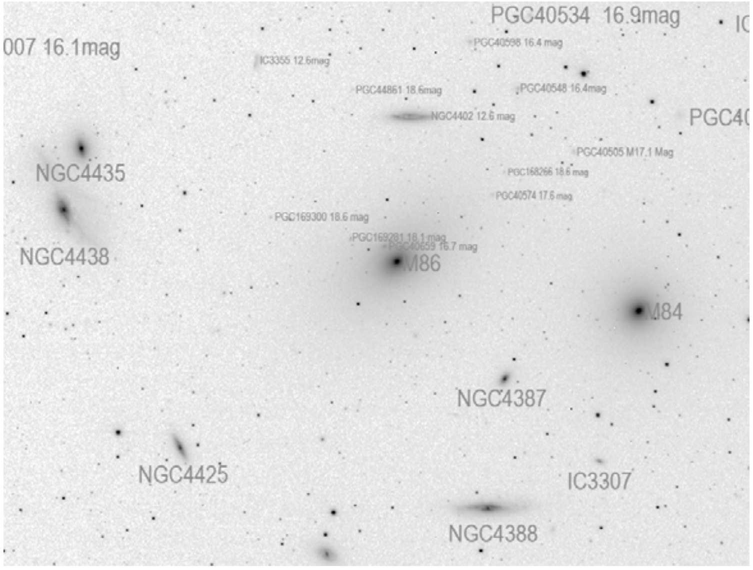
The graph to the right expresses the relationship between seeing and focal length for a 9m pixel CCD. From the graph and considering my seeing sites conditions of 1.5 to 4 arc seconds, the range of optimal focal lengths is about 18" to 48". Once again, optimal here is a system that functions with minimal limitation from seeing and therefore maximizes the amount of extended object detail for the average conditions during most available nights throughout the year. Clearly there will be nights with conditions far better than the system can capture and a few where a lesser system is more appropriate. You might choose to select a higher resolution system so that those few spectacular nights are not wasted, as an amateur its a matter of personal preference.

Signal to Noise:
There is but one desired source of signal, its the light from the object of interest. Noise is the unwanted signal that does not emanate from the object of interest. Signal to Noise is a simple ratio of Signal/Noise. There are many sources of astro imaging noise a few are listed below.



Sky glow: The graph to the right is an attempt at portraying the relationship between signal to noise and magnitude for the 8" F/2.6 astrograph under dark sky conditions and a 300 second (5minute) exposure. There are some who feel the threshold of detection is SN of 2 where on the graph there is an unlabeled horizontal line. This suggests that this astrograph should record stars to better than magnitude 18.5. With the tools I have for measuring images I can regularly image stars to magnitude 17.5. This suggests a threshold SN of greater than 3.

In most images there are faint galaxies slightly dimmer than magnitude 18. Suggesting a SN for extended objects closer to 4. Clearly the sky background could have be brighter than estimated. The sky background magnitude per arc second was determined by judging visual limiting magnitude and using an established relationship to sky background brightness. There are a number of excellent papers on the web explaining the method.



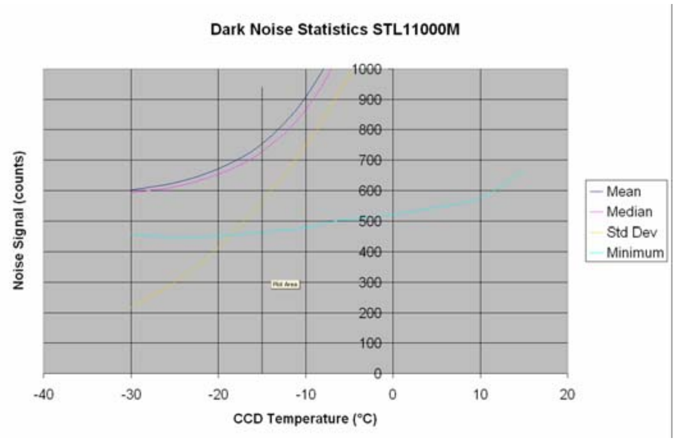
These galaxy images are a small section of a larger 5 minute luminance exposure of the Virgo Galaxy Cluster near the popular M84 and M86. The image was taken February 2006 with an 8" F/2.6 astrograph from dark sky's in the California Desert. It is negative to aid in seeing faint galaxies. Background sky conditions were estimated to be magnitude 21. Detectable are galaxies to only magnitude 18.6 supporting the suggestion that the SN for extended objects is closer to 4. Sky-6 has charted galaxies magnitude19 and dimmer that are not distinguishable from the sky glow background of this image.

The appearance of the dimmest galaxies is that of fuzzy patches, their angular extent covers many pixels and is noticeably different than the crisp pixel core of the dim stars.

This image was selected because there are several galaxies near magnitude 18. To reduce clutter not all of the galaxies visible in the image are labeled.

Dark noise (thermal noise) from the sensor. A sensor will generate electrons in the absence of signal/light. Fortunately this form of noise is predictable and can be subtracted from the image. Thus dark frame subtraction is a standard part of image processing. For a CCD the amount of dark noise is a function of temperature. The colder the CCD the less dark noise is generated, the less precision is needed for the cooling control, and the less impact dark frame subtraction will have on the final image.

The graph to the right is data collected from an SBIG STL-11000M. The graph is a summary of 20 minute dark exposures made at temperatures from 0°C to -30°C. Statistics were generated for each temperature from an average of three exposures using the full CCD frame.



The "mean" values are the average of all pixels sampled. The "median" is the value where there are an equal number of pixel values above and below. The "StdDev" is the range the pixels have above and below the mean value. The "min." is the minimum value that any sampled pixel has.

From the graph it is evident that the rate of increasing benefit from cooling diminishes with lower temperatures. That doesn't mean that more cooling is wasted just that its net impact on noise is reduced. I have standardized on -15°C as my imaging temperature. Clearly a lower temperature would reduce the average (mean) dark noise. But the -15°C temperature allows consistent results that are independent of ambient seasonal variations and remain within the cameras ability to air-cool. Again its a matter of preference your imaging conditions and desires are likely different than mine. I could standardize on a lower temperature using SBIG's available water cooling but haven't had the nerve to hook up yet.

Shot Noise: A sensors detection of photons and conversion to elections is a statistical process. If many images of the same object and same duration are taken then averaged there will be a predictable variation in the intensities between images. We cannot predict the amount that a given image will vary, or if a particular image is the true object intensity, we can only predict the range that the images will vary from the average. This statistical variation variation is called shot noise. The magnitude of shot noise is plus or minus the square root of the signal. For example if the object has an average intensity of 3,600 units the shot noise will be plus or minus 60 units.

Bias noise: This noise is generated by the conversion of electrons to a digital word and communication of that word. A bias frame is generated by commanding the camera to take its absolute shortest exposure. Bias noise is generally quite small and some amateur imagers don't bother with bias correction. My preference is to correct using bias frames.

Optical System noise, Flat Frame: The light that strikes the sensor surface has made the perilous journey across time and space being attenuated by everything in its path, its trip through your optical system is no exception. Scattered and reflected light from optical surfaces mirrors lenses, windows, filters all contribute to a reduction in signal and increased noise.

Fast Astrograph Considerations Summary :

While we are asking for things, might as well make a list...

The system should have greater than 80% of the star energy in the 9m pixel for ½ well at seeing limit.

The system must be portable and components a one man lift.

Rugged, no collimation or other adjustments "in the field" other than object positioning and focus.

Stable performance and focus over temperature and altitude.

Par-focal filters, no refocus required with filter change.

Sealed for dust, dew, and frost resistance.

Use existing G11 mount.

Good color correction with a useful spectral range from 375nm to 750nm.

Flat field, with lateral color < ¼ pixel, small longitudinal color, low distortion for full 35mm frame, sum of all to be less than <1/2 pixel.

Low vignetting for minimal flat frame artifacts and uniform sky penetration over field of view.

Long back focal length to minimize modification of CCD camera (STL11000M).

Manufacturable with limited shop tools.

You can't always get what you want, so what should be compromised? It seems my ideal system would be between F/2.5 and F/4 with a focal length between 16 inches and 50 inches. Such a system would have an aperture between 4 inches and 20 inches. This is a very wide range of systems.

There are of course other considerations. Those wishing to photograph small dim galaxies or other objects requiring image scale will need correspondingly longer focal lengths and better seeing conditions. Those attracted to very wide fields will want a shorter focal length camera lens, and should consider placing the filters at the entrance aperture of the lens. Lunar and planetary folks need an entirely different system. My desire is the greatest detail of extended objects using the SBIG STL-11000M at Southern California dark sky sites under average conditions.