ABERRATIONS IN OPTICAL SYSTEMS AND THEIR EFFECTS ON THE IMAGE

The five monochromatic (Sidel) aberrations are - spherical, coma, astigmatism, field curvature, distortion.

Optical systems are afflicted with five basic monochromatic aberrations that limit their performance in astronomical observing and astrographic work. Each aberration is explored and its effects explained. Generally the more expensive and elaborate a system is, the more these aberrations are fully corrected. The five Sidel aberrations are generally valid only at one wavelength, but in practice, if they are corrected in the center of the spectrum, they will usually be reasonably well corrected at the ends of the spectrum also.

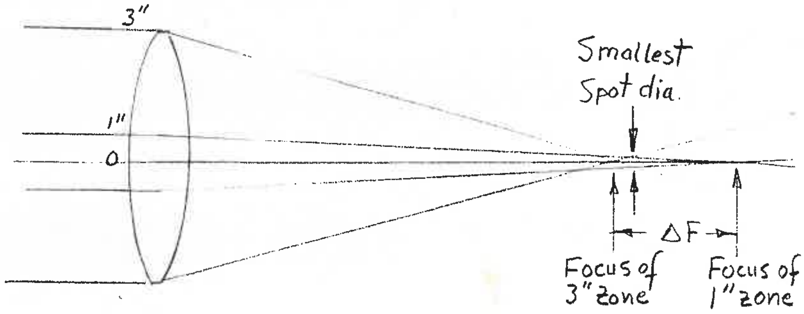
The three chromatic aberrations are - longitudinal chromatic, lateral chromatic, spherochromatism.

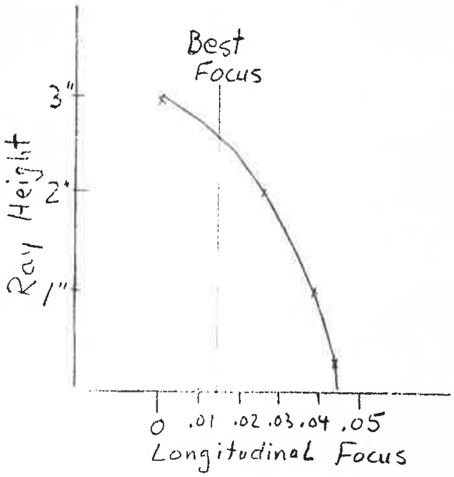
Many lens systems (and some catadioptries) are fully afflicted with chromatic aberrations. Of the three, longitudinal chromatic is the most difficult to get rid of and generally requires expensive exotic glasses. But even the use of exotic glass does not guarantee the elimination of longitudinal chromatic. The glass must be in the right place with the right amount of internal power or bending. Otherwise there is little or no effect (remember the 8 and 10 transistor radios that were produced with some transistors doing nothing at all?).

Some manufacturers would like you to believe that when the C and F (red & blue) colors are brought to a common focus, then all other colors in between are also in focus. Thus they advertise their C-F achromats as being fully corrected. Nothing could be further from the truth. Some manufacturers claim that their lens is optimized differently (such as D-g or e-h). This does not eliminate color, rather it brings one color closer to focus at the expense of another color at the other end of the spectrum. There are no tricks to eliminate color in normal achromatic lenses. The only trick is that some people who have paid exorbitant prices for a normal achromat refuse to "see" the resultant chromatic aberration. Everyone else, however, will see it.

Lateral chromatic and spherochromatism are not generally troublesome unless the design is unusually poor or the lens was not spherically corrected at the center of the spectrum.

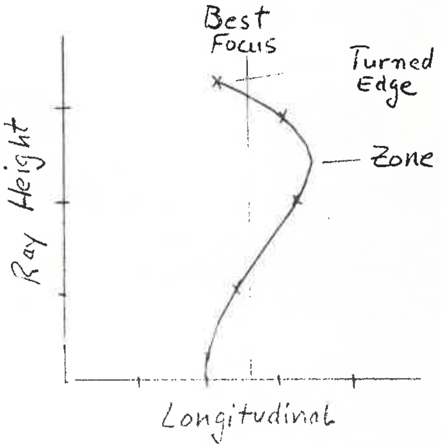
LONGITUDINAL SPHERICAL



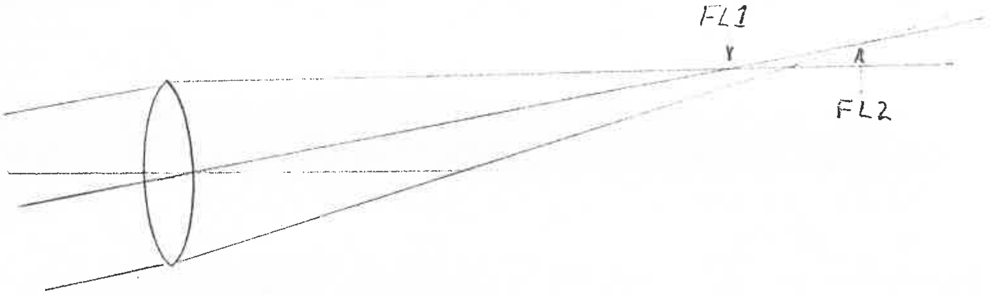


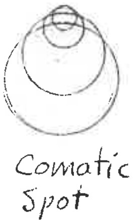
This plot shows a lens with simple third order spherical aberration. The inner focus point is longer by about .04" than the outer. It is called third order because the plot of ray ht vs. longitudinal position follows approximately a third order equation such as $x = y^2$. Because of this it is relatively easy to figure out where the best focus occurs - approximately 1/4 of the distance between the outer meridional ray and the inner axial ray. The smallest spot can be calculated as 1/4 F/Focal Length.

When a system is composed of two or more airspaced optical groups (airspaced being defined as large distances that are a substantial fraction of the optic's clear aperture), the resultant aberrations may include fifth order terms. Fifth order aberrations must be graphed to determine the best focus. Fifth order spherical can also be described as zones (raised zones or turned edge). Generally, for the same longitudinal error, a fifth order spherical curve is much more injurious to the image than a third order error.

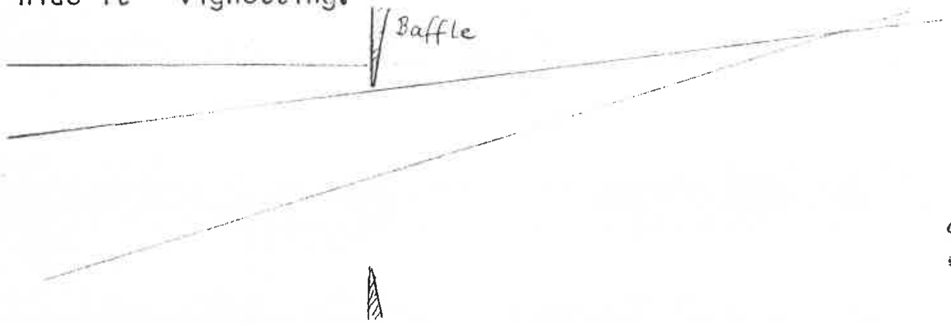


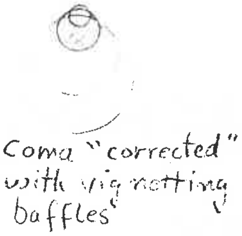
COMA





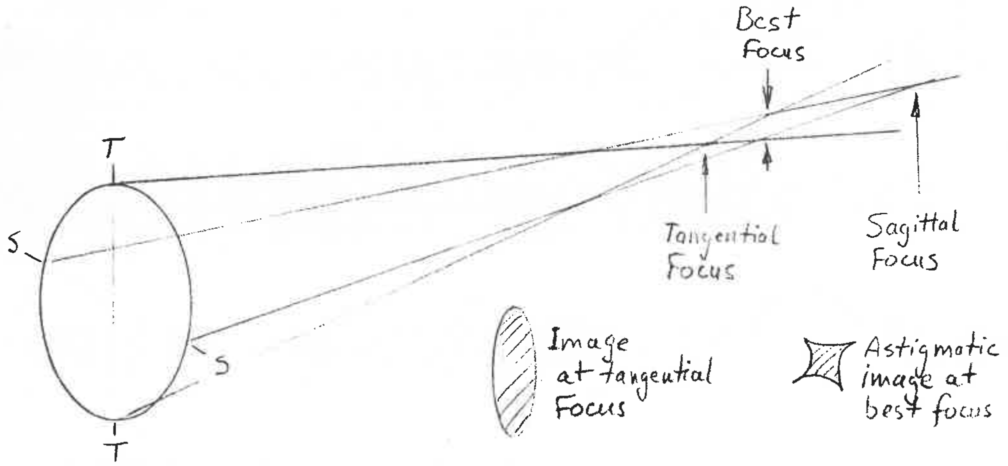
A lens exibits coma off-axis when the effective focal ratio varies across the lens. Coma can arise in simple systems when the lens is not properly "bent", or is bent to minimize some other aberration such as spherical. The Littrow objective is one such example where the lens curves were designed to be easily tested. This design eliminates spherical, but coma remains. Coma also arises in most compound systems where the element spacing is not optimized. The most famous example is the Schmidt-Cassegrain design with the corrector plate placed near the secondary. Here, coma correction was given up in favor of a short compact design. The coma of this system would be very troublesome to the observer were it not for a favorite design trick used to hide it - vignetting.

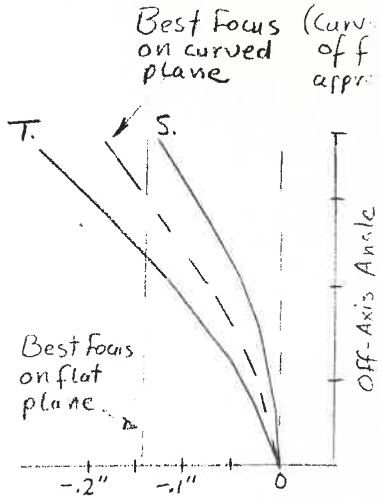




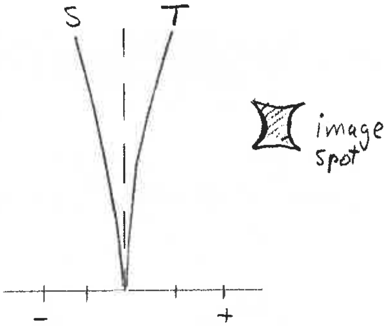
By carefully vignetting the off-axis pencils with well placed (computer generated) baffles, the off-axis image can be made to look quite sharp. The trouble with this method is the equivalent aperture will be less than the full aperture of the system (in some systems only 50 to 60% of the light reaches the edge of field).

ASTIGMATISM

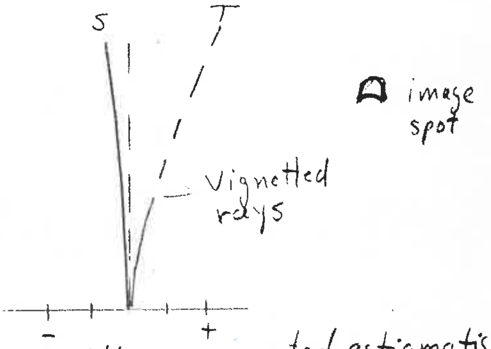




Astigmatism arises in an optical system when the rays from the top and bottom of the lens converge at a shorter focus than those from the edges of the lens. If these focal points are plotted against off-axis angle, the resultant plot shows a rapid separation of the tangential from the sagittal focus. The lens shown above has no coma and is therefore "aplanic", i.e. it focuses on a single plane, albeit curved in this case. The best focus on a curved plane results in the smallest image, although it would not be round. In compound optical systems, the tangential and sagittal can be placed symmetrically around a flat plane to allow the use of a flat film format. The resultant image will still have astigmatism, but it will look symmetrical, although growing in size with off-axis angle. A properly placed baffle with tangential overcorrected will allow the designer to vignette the offending rays and thereby achieve even smaller off-axis images, at the expense of off-axis illumination.

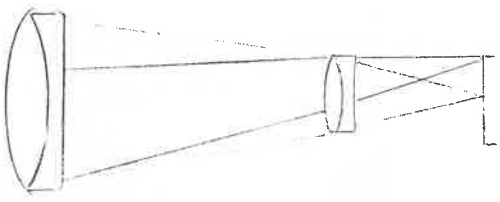


Aplanic Flat-Field lens



Lens with overcorrected astigmatism with vignetting baffles

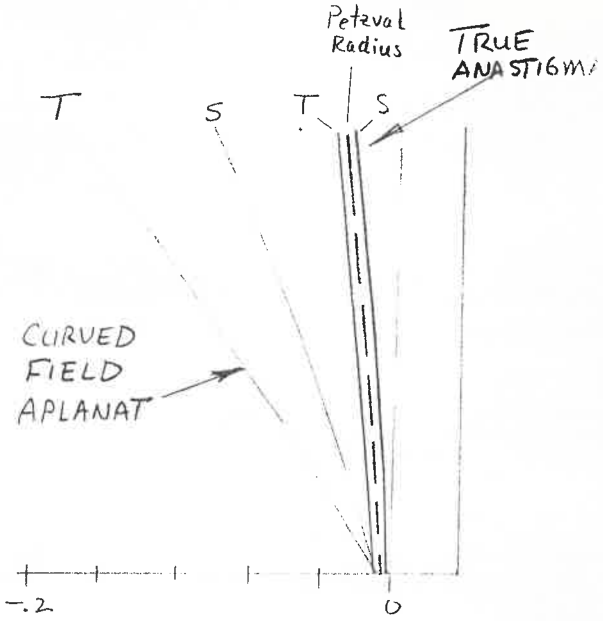
Some examples of flat field aplanic systems are Orthoscopic and Plossl Oculars. By using the vignetted design, some optimized Plossl Oculars have achieved better edge definition at the expense of image brightness. Other examples of aplanic systems are the Petzval 4 element designs, and objectives with single element field flatteners near the film plane.



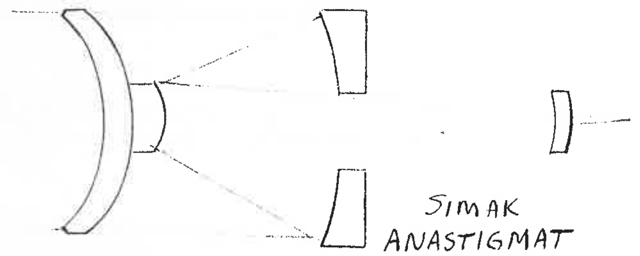
Petzval design with vignetting
Flat Field Aplanat

Lens with field flattener
Flat Field Aplanat

FIELD CURVATURE

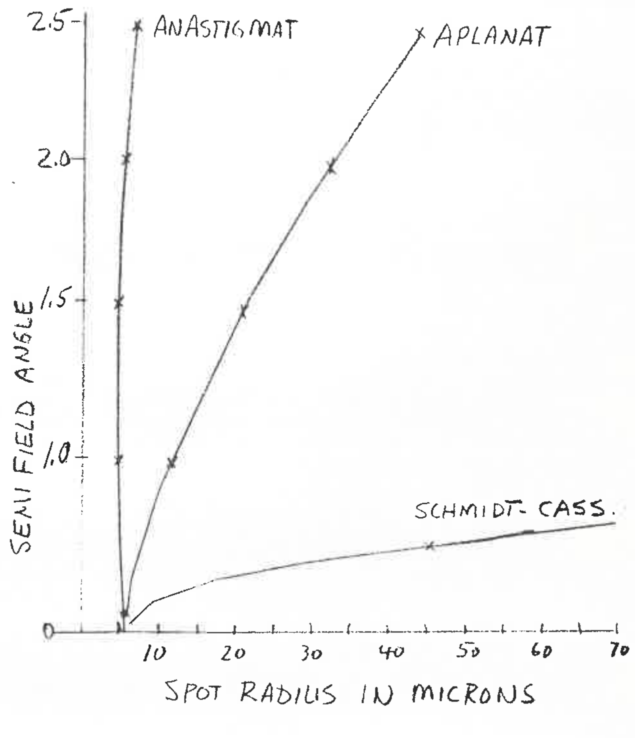


In the absence of coma and astigmatism, all normal single grouping lenses have field curvature. In compound systems, the curvature is the sum of all the individual elements. A rule of thumb is that the magnitude of the Petzval radius is approximately 1.5 times the focal length of the lens. Thus, the Petzval radius is defined as the radius where the Tangential and Sagittal focus would be the same, and then there would be no astigmatism at all at any off-axis angle (as long as the film plane is bent to the Petzval radius). Such a lens would be known as an aplanic anastigmat. The images on the Petzval radius would be perfectly round and diffraction limited. On a flat plane the images would appear more and more oval, although smaller than a normal aplanat at best focus. To correct the Petzval field curvature, all that is needed is a single element field flattener near the film plane. The images are then diffraction limited at any place on the film plane. A lens of this type is a true flat field anastigmat. Examples of this type of system is the Simak Catadioptric system, and lens systems employing an anastigmat correcting lens with field flattener near the film plane.



SIMAK ANASTIGMAT

STARFIRE LD ANASTIGMAT

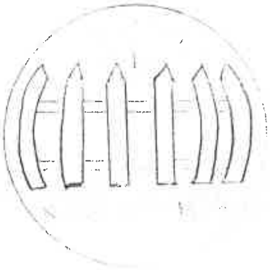


DISTORTION

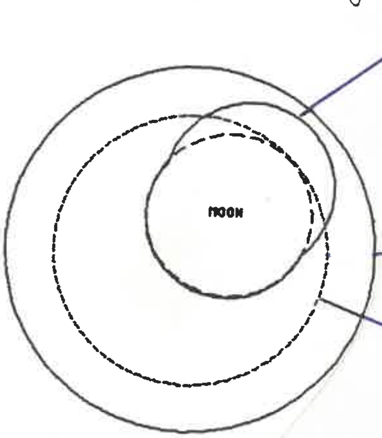
To be a true astrographic objective, the lens system must have the same magnification or effective focal length at any off-axis angle. Otherwise stellar distances as measured on a photographic plate would be different at different places on the plate. This is the one defect of a lens system that is not immediately noticeable to the amateur astronomer. Distortion does not affect the image sharpness at all. It only affects the position of the image.

In the film plane, an image with an angular diameter of a1 will correspond to an image height of h1. If the angular diameter is doubled to a2, then h2 must also be twice high as h1. Therefore, a lens that images a 1 degree circle at 1 inch diameter on film and a 2 degree circle at 2.2 inches has measureable pincussion distortion. If the image is 1.8 inches high, the lens has barrel distortion. A true astrographic lens will image the 2 degree circle at exactly 2.000 inches. Any deviation is expressed as percent distortion. Usually simple lenses have no measurable distortion. Lenses with zero power anastigmatic field flattener elements also usually have no distortion. Some aplanic flat field systems such as telephoto camera lenses usually have quite measurable distortion.

Oculars generally have severe distortion. Some ultrawide field oculars have such severe distortion that they show an enlarged apparent field when the actual field seen is nowhere near as big. These oculars will show straight pickets as curved outward, and will show circular objects toward the edge of the field as oblate objects. An ocular with 15% distortion may show an 80 degree field, but the field is actually 15% smaller, thus being only 68 degrees.



Barrel Distortion

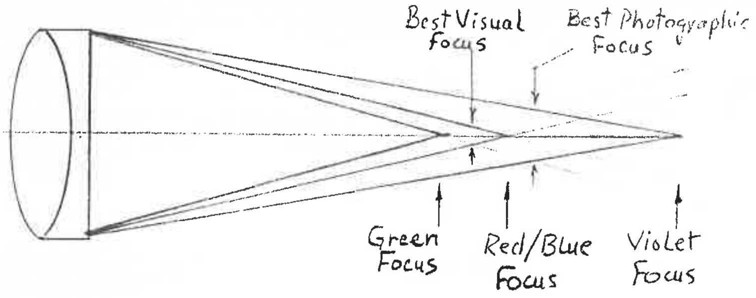


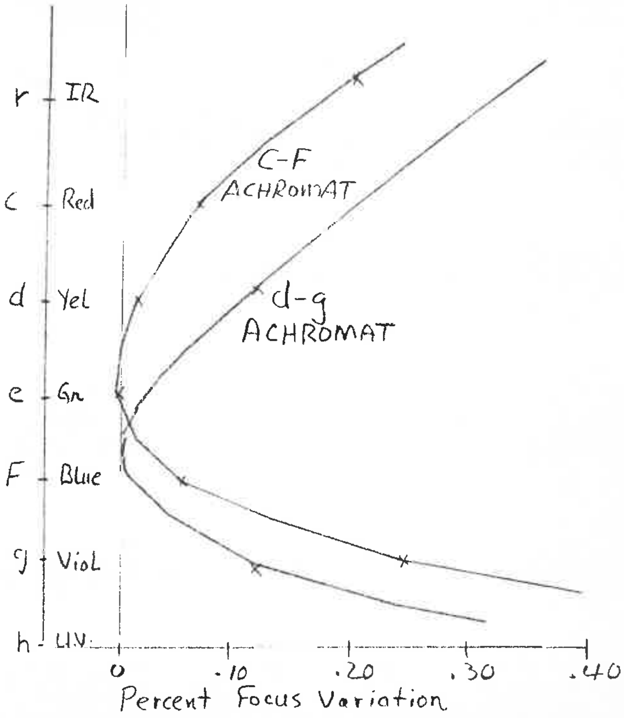
Distortion has increased Moon's diameter near the edge of the field.

Apparent Field of View

Actual apparent Field of view

LONGITUDIAL CHROMATIC ABERRATION





Longitudial Chromatic Aberration, also known as secondary color, is the most troublesome aberration that lenses posess. Even though achromats are corrected so that the red C wavelengths focus at the same point as the blue F wavelengths, the extraneous colors of yellow, green and violet can be as many as 5 to 10 waves in error. It is rather distressing when optics are touted to be corrected to fractions of a wavelength when only one color is actually that sharp at the focus, and everything else is 2 orders of magnitude off. The manifestation of this error is of course the blue-violet or purple halo that rings bright objects in an achromat. Placing the point of correction at a different color hardly fixes this. Thus the celebrated D-g achromat may have less of a blue halo, but the resultant red and green halo is much more obnoxious and damaging to fine planetary detail. Only focal ratios of f15 or longer and at apertures of 4 inches is the secondary color under control. For larger faster lenses, it is necessary to introduce an abnormal dispersion glass into the design.

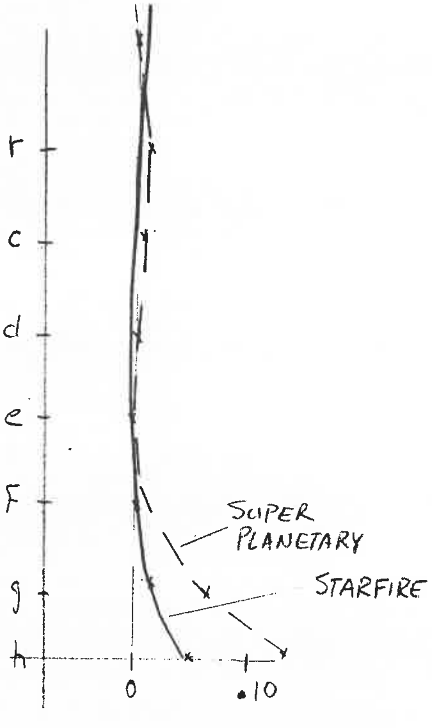
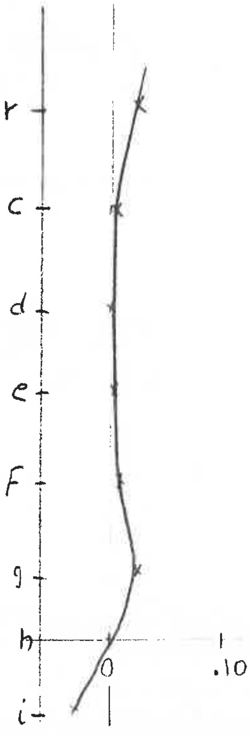
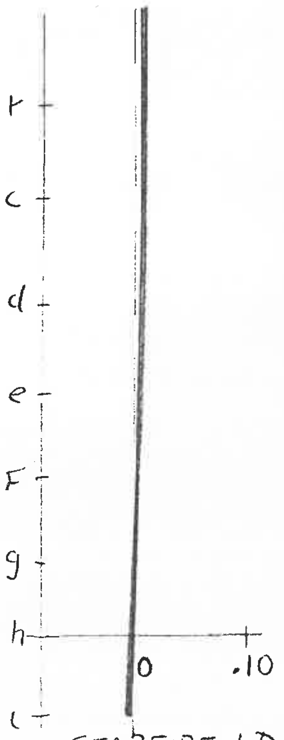


PHOTO VISUAL TRIPLETS



AIRSPACED PLANETARY TRIPLET



STARFIRE LD ANASTIGMAT

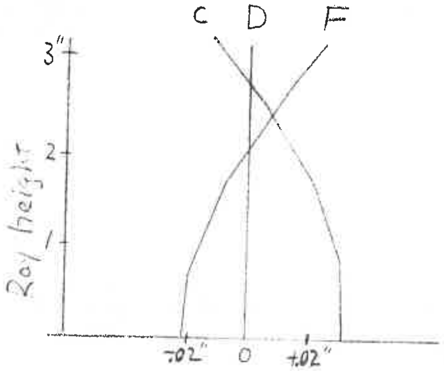
LATERAL CHROMATIC

Lateral Chromatic aberration shows up as the separation of the colors off-axis. Thus stars will image as short spectra at the edges of the field. This is generally not a problem with astronomical objects, but shows up in compound systems such as telephoto lenses and oculars. There is no quick fix to this except to address this in the beginning of the lens design.

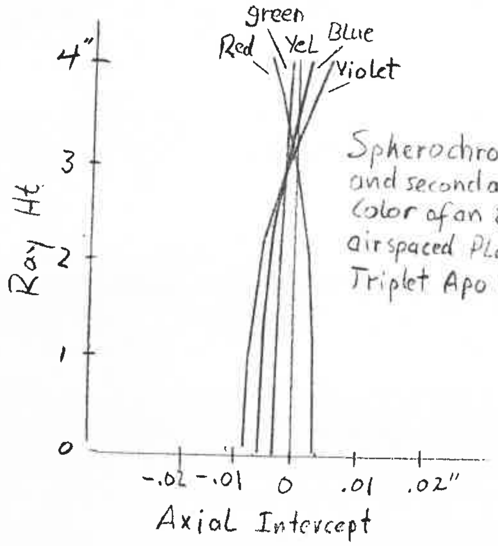
SPHERO-CHROMATISM

This aberration is present in most optical systems that use refractive elements and can limit the effective speed of the system. Two and three element lenses that are closely spaced (airspaced or cemented) will always exibit Sphero-Chromatism. It shows up as undercorrected spherical aberration in the longer red wavelengths and overcorrection in the shorter blue wavelengths.

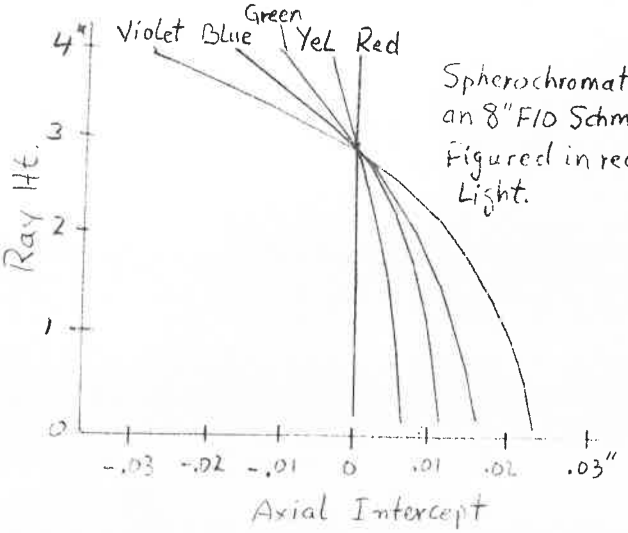
The designer will usually pick the yellow D or green e wavelengths to null the system. The ends of the spectrum are then assigned arbitrary amounts of over and under correction, say 1/4 wave peak. This will then determine the maximum ray height and thus the maximum aperture (or shortest focal ratio). In doublet and triplet lenses the amount of sphero-chromatism can be controlled by proper choice of glasses and spacing of the elements.



In Schmidt-Cassegrains and Maksutov telescopes the Sphero-Chromatism can be quite severe. The reason is that the curves placed on the corrector plate correspond to a perfect null only at one color. At all other colors the index (or bending power) of the corrector plate is substantially different. The mirror, however, does not change in power with wavelength. If the system is spherically corrected in the red (using laser interferometers) then the system is increasingly overcorrected in the yellow, green, blue and violet wavelengths. Although there are no secondary color effects, planetary markings will be smeared and contrast suffers greatly. The amount of spherical error in the blue depends somewhat on system design, but can reach 2 to 3 waves in an 8"f10 Schmidt-Cassegrain and even higher in Spot Maksutov designs (for this reason Spot Maksutovs are limited to slow ratios).



Spherochromatism and secondary Color of an 8"f15 airspaced Planetary Triplet Apo lens



Spherochromatism of an 8"F/10 Schmidt-Cass Figured in red Laser Light.

OPTICAL THROUGHPUT

It is not a simple rule that a larger aperture gathers more light than a smaller one. It depends on how much light is actually transmitted to the eyepiece, which system will show fainter objects. A piece of optical glass such as used in high quality objectives will absorb less than 0.5% (transmit 99.5%) per inch of thickness. Plate glass such as is used in corrector plates will absorb up to 10% per inch of thickness in the visual peak wavelengths. Modern anti-reflection coatings will reduce surface reflection losses in an objective to 1% on the crown and 0.6% on the flint surface. Multi-coated mirrors can transmit as much as 94% (If they are properly applied), whereas normal coatings transmit only 88% of the incoming light. Below is a comparison of light throughput of a refractive and a reflective system:

6 INCH TRIPLET OBJECTIVE		8 INCH SCHMIDT-CASSEGRAIN	Normal	Multi-Coated
Front Surface Loss	- 1.0%	Corrector Surface Loss	- 10.0%	2.0%
Glass Iternal Loss	- 0.8%	Corrector Internal Loss	- 1.2%	1.2%
Rear Surface Loss	- 0.6%	Primary Mirror Loss	- 12.0%	6.0%
Internal Reflections	- 0.2%	Secondary Mirror Loss	- 12.0%	6.0%
Equivalent Clear Aperture	- 5.9"	Secondary Shading Loss	- 14.0%	14.0%
Total Optical Throughput	- 97.4%	Total Optical Throughput	- 50.8%	70.8%
Equivalent Clear Aperture	- 5.9"	Equivalent Clear Aperture	- 5.7"	6.7"

The 6 inch objective gathers slightly more light than a normal 8"SCT, although a fully multi-coated 8"SCT will gather more light than the 6" refractor. However, under actual observing conditions, many amateurs report that they can reach fainter magnitudes on stars and star clusters with the smaller objectives. There is another effect of the SCT's central obstruction that limits the amount of light reaching the stellar image. A central obstruction of the size found in Schmidt-Cassegrains (38% of diameter) will reduce the amount of light in the central Airy Disc from the theoretical 84% to only 60%. This results in an Airy Disc brightness of only 71.4% with the remaining amount scattered into the diffraction rings. On faint stars, where only the Airy Disc is visible, this loss is significant.

6 INCH TRIPLET OBJECTIVE		8 INCH SCT	Normal Coatings w/Central Obstruction	Multi-Coatings w/oCentral Obstruction
Total Optical Throughput	- 97.4%	Total Optical Throughput	- 36.3%	50.6%
Equivalent Clear Aperture	- 5.9"	Equivalent Clear Aperture	- 4.8"	5.6"

The above assumes that the SCT has been perfectly null figured. Assuming that the spherical error is 1/4 wave, then the image brightness of the Airy Disc is reduced even further. The equivalant clear aperture of the 8" SCT can drop as low as 4.5". This may explain why these telescopes are routinely outperformed by smaller aperture refractors.

WIDE FIELD ASTROGRAPHIC REFLECTORS

Wide field photographic telescopes (other than Schmidt Systems) are becoming increasingly popular. They are fairly large aperture and short focal length instruments that promise fast exposure times. Their shortcomings are in the large central obstructions needed to cover the wide field formats that they are designed for. As an example, the 12 inch f5 Simak type of wide field Cassegrain uses a 50% central obstruciton. When the secondary shading is entered into the equation, the system is anything but f5.

12"f5 Simak Cassegrain - 60"EFL
Corrector Reflection & Transmission Loss - 11 %
Secondary Shading Loss - 25 %
Primary & Secondary Loss (assume Multicoat) - 12 %

Total Optical Throughput - 52 %
Equivalent Clear Aperture - 8.7"
Effective Focal Ratio - f7

8"f3.8 Hyperbolic Astrograph - 30.4" EFL
Secondary Shading Loss - 25. %
Primary & Secondary Loss - 24. %

Total Optical Throughput - 51. %
Equivalent Clear Aperture - 5.7"
Effective Focal Ratio - f5.3

SYSTEM PHOTOGRAPHIC COMPARISONS

6"f9 StarFire

Objective - 3 element apochromat
Photographic Systems - aplanic, curved field
Stellar Spot Radius - 1 degree field - 15 u
- 2 degree field - 40 u
Secondary Spectrum Correction - Violet to I.R. 4380A to 10,000A
Sphero-Chromatism - c -.005"
- d .000"
- f +.009"
- g +.015"
Lateral Color - .0001" @ 1 degree
Distortion - less than .01% @ 1 degree
- less than .012% @ 2 degrees

6"f9 StarFire with Field Flattener

Objective - 4 element apochromat in 2 groups
Photographic Systems - aplanic, flat field
Stellar Spot Radius - 1.5 degree field - 10 u
- 3 degree field - 20 u
Lateral Color - .0002" @ 1.5 degrees
Distortion - less than .01% @ 1.5 degrees
- less than .012% @ 3 degrees

6"f12 StarFire LD

Objective - 5 element apochromat
Photographic Systems - flat field anastigmatic
Stellar Spot Radius - 2.5 degrees field - 6 u
- 5.0 degrees field - 7 u
Secondary Spectrum Correction - U.V to I.R. 3600A to 10,000A
Sphero-Chromatism - c -.003"
- d -.001"
- e .000"
- f +.006"
- g +.012"