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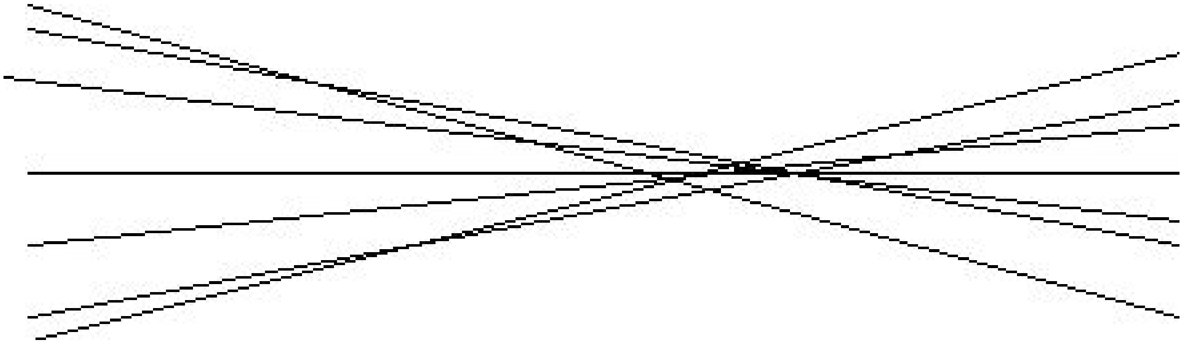
Cloudy Nights Telescope Reviews

Understanding Spherical Aberration

by Thomas Back Click to email author



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There are five different third order Seidel monochromatic aberrations.

1. Spherical aberration
2. Coma
3. Astigmatism
4. Curvature of field
5. Distortion

They are called Seidel aberrations because they were studied in great detail by Ludwig von Seidel, back in the 1850’s, and were named after him. In this essay, we will talk about the first aberration, spherical.

Spherical aberration, simply put, is a variation of focus with aperture. Let’s explain. Take a 6” mirror used in a Newtonian telescope. Any photon that hits the axial point (center) of the mirror comes to a perfect focus, thus zero spherical aberration. For the rest of the mirror to be free of spherical aberration, every photon must strike every point on the aperture of the mirror with the exact same focal length as the axial one. In a perfect 6” f/8 (152.4mm/1219.2mm) mirror, assuming the object is at infinity, or in more real terms, the object distance is far enough away from the mirror, that the light rays are essentially parallel, the only way to achieve zero spherical aberration, is to make the surface a paraboloid. The greater the off-axis distance from the axial point is on the mirror, the more the surface is deformed (parabola), so all the light rays converge to a single point, or an optic with zero spherical aberration.

If this condition is not satisfied, there will be either phase retarded, or phase advanced rays coming off the surface of the mirror that do not fall within that “perfect” point, and will be outside of that point. This is spherical aberration (probably one of the most misspelled words in amateur astronomy, is aberration. More often than not, it is spelled “abberation”).

An optic can be undercorrected, or overcorrected, spherically. A spherical mirror is undercorrected, and a hyperbolic mirror (in a simple Newtonian) is overcorrected. The reason a spherical mirror (or any mirror that is under-corrected) shows undercorrection, is because the marginal (edge) rays focus short, and the mirror does not satisfy the phase requirement to bring all photons from a parallel beam to the exact same focal point, over the entire surface. This is because the distance from the focal point to any point on the parallel beam is not equal to the distance from any other point to the wavefront to focus.

Again, the only curve that satisfies the phase requirement for zero spherical aberration at all points on the mirror is a perfect paraboloid.

So far, we have been talking about third order spherical aberration.

However, there are an infinite amount of degrees of spherical aberration. Fifth order is zonal aberration, which is seen as a bright zone in the star test. There are 7th order, 9th order, and so on, but at these higher orders (with the exception of the 5th order), are not of any real significance. But 5th order spherical aberration can be very damaging to the overall wavefront, depending on the severity.
Now we know that no optical element or system is completely free from spherical aberration, as much as we would want our telescopes to be free from this, and other aberrations. The question then comes up, how well should a telescope be corrected for spherical aberration? That depends on how the telescope is going to be used. If you are only interested in deep sky objects, then aperture is more important than having an optical system that reaches the highest of wavefront accuracy. However, regardless of how the telescope is used, there should be a minimum standard for spherical aberration if the telescope is to be considered “adequate.” There are many ways to measure the surface and overall wavefront quality of a telescope (there is not enough space in this article to go over all the different ways to measure optical quality—it would amaze most amateurs to know how many there are!), but one does stand out above the rest: RMS wavefront/Strehl ratio.

One could ask, why not Peak to Valley? Well, P-V measurements don’t really tell you enough about the entire apertures’ contribution to the final wavefront. You could have an outstanding optical system that has a P-V of only _ wave, but has a Strehl ratio of .99. This is because P-V measures the highest peak, and the lowest valley on the wavefront, and if this _ wave error covers only a few microns of the surface, it makes an unnoticeable contribution to the performance of the optical system. The RMS (from which the Strehl ratio is calculated) covers almost the entire surface (the more data points across the aperture, the more accurate the actual surface wavefront measurement is), and with modern interferometers, the OPD RMS Spherical wavefront can be measured to a very exacting degree. It is generally well accepted that when the RMS wavefront is 1/14.05 wave or better (Strehl .80), the system is diffraction limited. I consider this the minimum standard for a useful astronomical telescope. It will resolve equal double stars at the theoretical limit for its aperture, and will show fair detail and contrast on the moon and planets. This also applies to deep sky work. If the spherical aberration is below this level, it will lower contrast, which is of prime importance in detecting low brightness objects, against the sky background.

On the other end of the spectrum, how good does the spherical correction need to be, to see all the possible information that a given aperture will show?

This will be a point of debate long after this article is old and dusty, but there are ways to determine this.

Again, the Strehl ratio is a good indicator of the degree of spherical correction an optical system should reach, if the only limiting factor is seeing. In all but the best seeing sites, any optic that is Strehl .95 or better, is going to be seeing limited on almost every night. That is 1/28 wave RMS on the wavefront. At Strehl .95, only 3.8% of the light from a star is misdirected to the diffraction rings, instead of the Airy disk. Any energy that is thrown out of the Airy disk, into the diffraction rings, or as noise around the Airy pattern reduces contrast. At about .88 Strehl (see Star Testing Astronomical Telescopes, page 198), an optical system becomes noticeably sharper than an optical system with a Strehl ratio of .80 of less. At .95 or better, it is fully a planetary telescope. Very few commercial telescopes even reach a Strehl of .88, when tested as a full system.

But let us say you live in a near perfect seeing site like the Pic-du-Midi, South Florida, Mount Wilson, La Palma, etc. And you have a very trained eye for subtle planetary detail, and it is a “10” seeing night. At what RMS/Strehl does a planetary telescope stop showing even the lowest contrast details, and any further wavefront improvement is a waste of the optician’s time?

James G. Baker, probably the greatest optical scientist of the 20th century, wrote an article titled “Planetary Telescopes.” In it, he felt that at the lowest contrast levels, under perfect conditions, that around 1/120 wave RMS (~ Strehl .998), no further correction would improve the detail and contrast. I would tend to agree with this, but after testing well over 1000 telescopes of all manner of optical correction and telescope types, this spherical wavefront quality cannot be achieved, although a few optics come very close, but seeing would never allow such quality to be used to any advantage.

In conclusion, any optical system that is corrected spherically to ~ 1/14 wave RMS (assuming coma and astigmatism is under control) is a useful telescope, at ~ 1/30 wave RMS, a great performer, and any telescope from ~1/40 wave RMS to 1/100+ wave RMS, is only limited by seeing.

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