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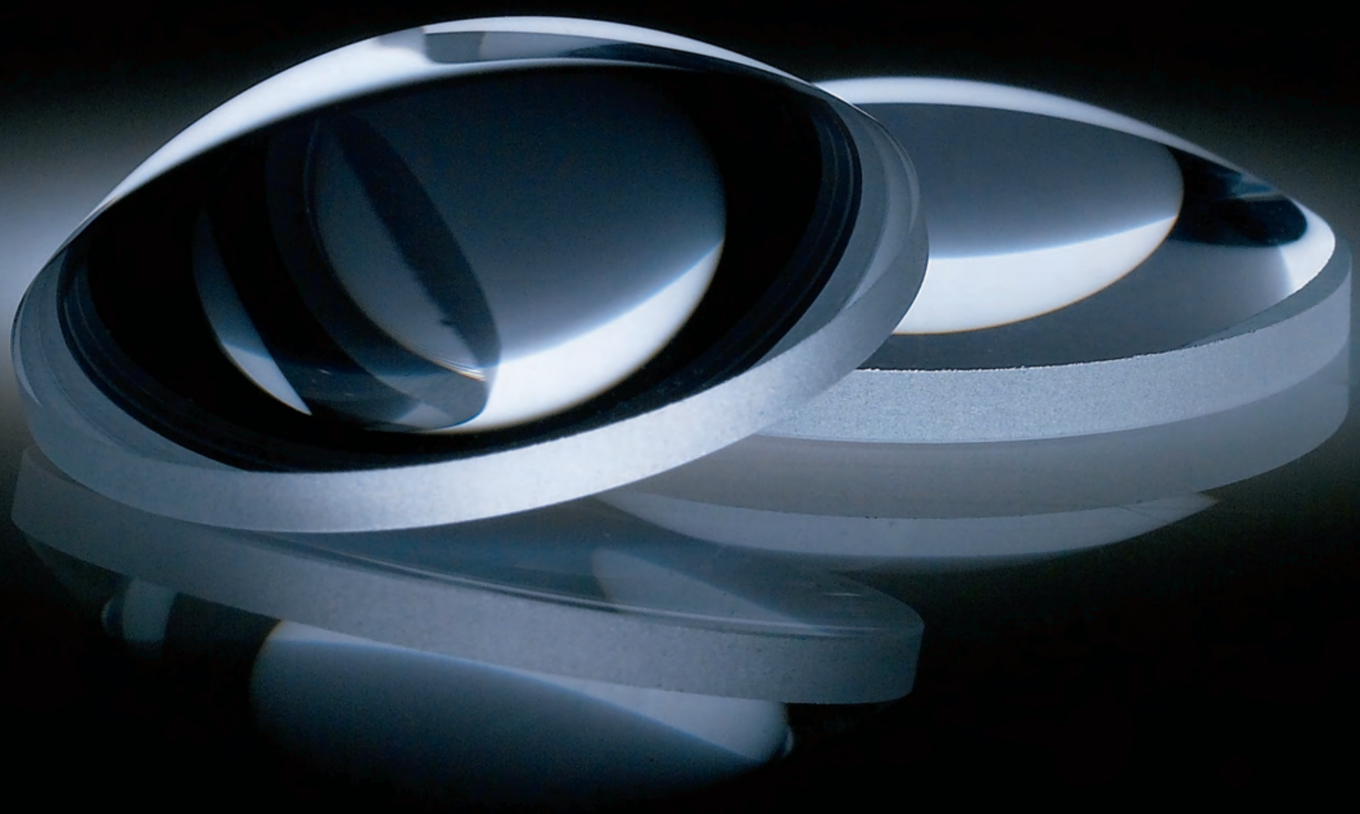

The use of aspherical lenses can improve the performance of an optical system by correcting aberrations that perturb light's wavefront from its ideal spherical shape.

(Image courtesy of Edmund Optics, Inc.)

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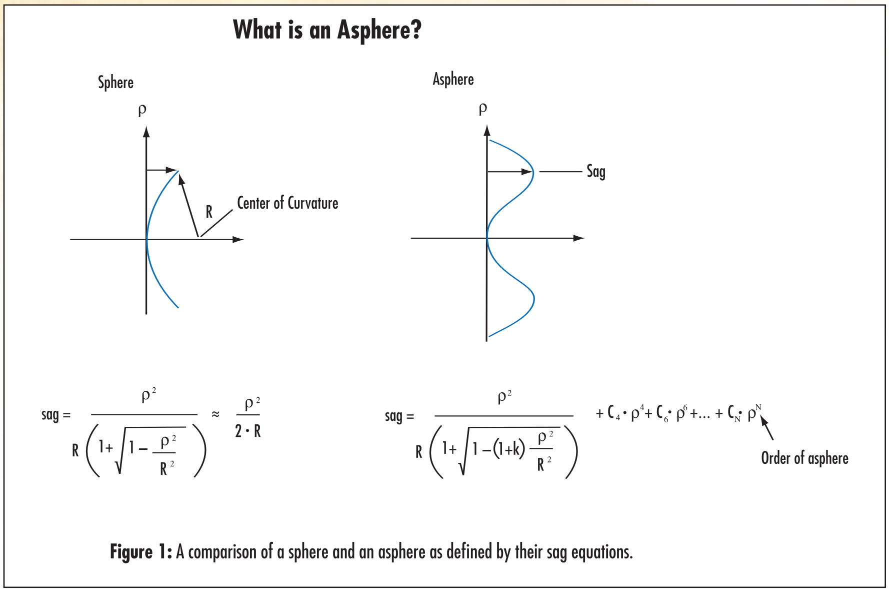
Using Aspheres To Increase Optical System Performance

In a perfect imaging system, light exists as a spherical wave that converges to form a point image. However, in practice wavefront aberrations act to perturb the wavefront from its ideal spherical shape, which can degrade image quality. The appropriate use of ashperical lenses in an optical system can improve performance with a minimum addition of optical elements.

High performance optical imaging systems require good "image quality", a loose term that refers to the ability to resolve fine image detail. Optical engineers quantify this ability by using metrics such as MTF (modulation transfer function), Strehl ratio, spot size or wavefront error. The highest possible image quality occurs when the light exiting the optical system has a perfectly spherical wavefront. Deviations from that spherical wavefront are called "aberrations" and virtually all practical optical systems have them.

Advanced optical systems with large fields of view and "fast" apertures are especially prone to having significant optical aberrations. (Fast means a low F/# or F-stop, which is the ratio of focal length to collecting diameter.) Before the advent of aspheric manufacturing, optical engineers used many spherical surfaces to balance aberrations, and the literature is filled with many such multi-element design forms that utilize all spherical elements, such as the Cooke Triplet, Double Gauss, etc. Computer controlled manufacturing coupled with computerized metrology, however, has now enabled the fabrication of aspheric surfaces that allow aberrations to be balanced with fewer optical surfaces.

A fundamental definition of an asphere is a surface that does not have a spherical shape. A sphere is simply defined by its radius of curvature, R. Familiar aspheric forms come from conic sections such as the ellipse, parabola, or hyperbola, and are characterized by the conic constant (k) or eccentricity (ε) of the conic. It is convenient to express the shape of an aspheric surface in terms of its "sag" (deviation from a plane at its vertex) and its aperture radius, ρ (Figure 1). By



$$\text{sag} = \frac{\rho^2}{R\left(1+\sqrt{1-\frac{\rho^2}{R^2}}\right)} \approx \frac{\rho^2}{2 \cdot R}$$

$$\text{sag} = \frac{\rho^2}{R\left(1+\sqrt{1-(1+k)\frac{\rho^2}{R^2}}\right)} + C_4 \cdot \rho^4 + C_6 \cdot \rho^6 + \ldots + C_N \cdot \rho^N$$

Figure 1. A sphere and an asphere are defined by their sag equations.

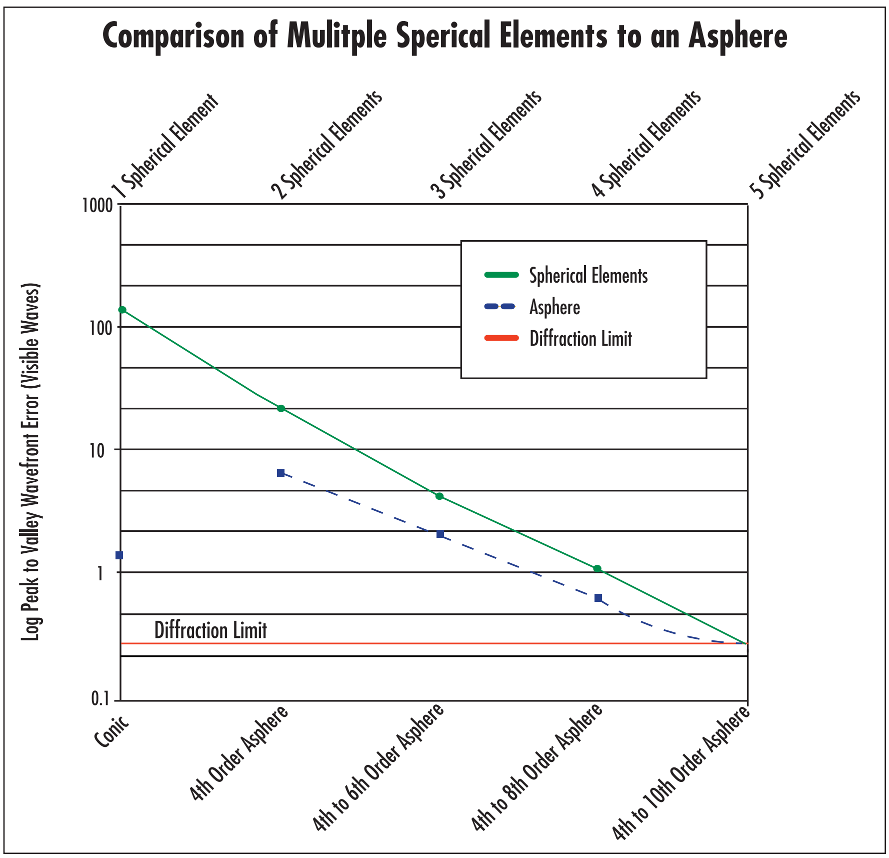


Figure 2. Wavefront error comparison for a multi element spherical system to a multi order aspheric polynomial. The aspheric element has one spherical side.

Using Aspheres

Asphere Placement in Double Gauss Assembly

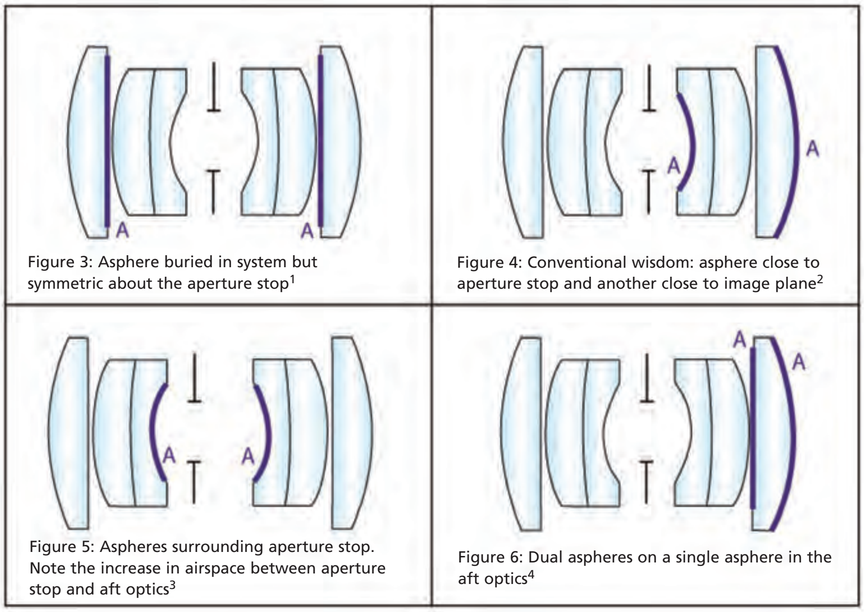


Figure 3: Asphere buried in system but symmetric about the aperture stop[1]

Figure 4: Conventional wisdom: asphere close to aperture stop and another close to image plane[2]

Figure 5: Aspheres surrounding aperture stop. Note the increase in airspace between aperture stop and aft optics[3]

Figure 6: Dual aspheres on a single asphere in the aft optics[4]

[1]Japanese Patent 63-070,2216 [2]Japanese Patent 08-220,439 [3]Patent 5572365 [6]Patent 4726666

Figures 3-6. Alternative approaches to asphere placement in Double Gauss lens assembly.

including even ordered polynomials (C_2, C_4,.... C_N) to the surface shape, optical engineers have garnered considerable power to eliminate aberrations from the optical system.

Asphere vs Multiple Spheres

The power of aspheres can be demonstrated by comparing their ability to correct aberrations with spherical elements, as shown in Figure 2. The comparison contrasts an aspheric singlet with varying polynomial degree to a set of spherical lenses in an F/1.25 system with a 4° full field of view using Schott N-BK7 and monochromatic light. The axial or central beam's wavefront error is shown plotted versus number of elements and the aspheric polynomial. A rule of thumb derived from the Rayleigh Criterion states that a diffraction limited spot can be achieved for wavefront error that is smaller than a quarter of the wavelength of light. As shown in the figure, it takes five spherical elements to achieve quarter wave performance while it can be done with a single element with a 10^{th} order aspheric element.

There are standard locations for placing aspheres in an optical system. Theoretically only two aspheres are required for good imagery for fast, wide field of view systems[1].

Placing one asphere near an aperture stop or a pupil will correct spherical aberration, which is a variation in focus location with aperture height. This is a rotationally symmetric aberration and is constant across the field of view. The aperture stop is the ideal location for asphere placement since that location affects all fields of view simultaneously.

A second asphere placed at an intermediate image will correct field aberrations, such as coma and astigmatism. These are non-rotationally symmetric aberrations. Intuitively, having an asphere at an intermediate image allows the field to be directly mapped to the optical surface.

These ideal placements are not always practical in a real optical system. For instance, many commercial optical systems allow control of the aperture setting by using an iris, which is a moving part requiring space for mechanical actuation. In these cases it's not feasible to place an asphere directly on the aperture stop. Instead, it must be placed as close to the aperture stop as possible.

Similarly, it is not advisable to place an optical surface at an intermediate image, because dust on that surface or surface imperfections will be imaged to the detector plane. So in practice an asphere is placed close to an intermediate image to correct field aberrations. This is easily done if the optical system is a re-imager, meaning there is a focus inside the optical system. Some system requirements have tight packaging or cost specifications, however, which do not allow for an intermediate focus. In these cases an asphere is placed as close as possible to the image plane.

Dueling Aspheres

Without the ideal locations available for aspheres, the lens designer has to be careful not to design in "dueling aspheres" that can inadvertently drive up system cost. The cost of an asphere roughly corresponds to its fabrication difficulty, and practitioners of asphere manufacturing use aspheric departure as a metric for how difficult an asphere is to make. This departure is the maximum difference from a best fit sphere and is specified in microns or waves. Dueling aspheres increase each other's aspheric departure requirements.

As an example, let's imagine that the entrance pupil (image of the aperture stop in object space) is on the front surface of the optical system and the exit pupil (image of the stop in image space) is at the aft optical surface. These two surfaces are conjugate to one another. This is a fancy way of saying that placing a scratch on the front surface will image onto the back surface. If aspheres are placed on both of these surfaces they may duel one another. For instance, one could end up with a design where the front surface has an asphere with +53 waves of departure, while the back could have -50 waves. The all spherical equivalent could simply have -3 waves of spherical aberration and it could be corrected by placing one asphere of +3 waves on either the front or the back surface.

Lessons Learned

A literature and patent search on camera objectives that utilized aspheres shows mostly telephoto systems designed in Japan during the 80's and 90's. Most of these camera lenses are derivatives of the Double Gauss lens, which doesn't have an intermediate image and usually contains an iris. It is interesting to note that the various locations of aspheres in these designs did not conform to the "theoretical optimum locations". Several classes of asphere location emerged and they are re-plotted as they would appear on an ideal Double Gauss lens in Figure 3 through Figure 6.

Figure 5 is an interesting case since the form breaks the Double Gauss symmetry about the aperture stop. The increase in airspace between the iris and the aft optics allows the second asphere to reduce the field aberrations due to the beam wander over the aperture with changing field, while the asphere near the stop minimizes spherical aberration.

Figure 6 is appealing because of a cost savings due to the aspheres being located on a single element. If the element is glass molded this approach can yield tremendous cost reductions compared to two aspheres.

One could argue many of these cases set up dueling aspheres. Perhaps instead of "dueling" aspheres these are "split" aspheres, where the aspheric departure is distributed between two surfaces.

Empirical Case Study

In the 1960's Sloan and Hopkins studied the addition of aspheres to the Double Gauss[2]. They assumed that an aspheric plate could be placed at the aperture stop. We have repeated this exercise but expanded the number of cases to include cases found in the patent literature mentioned above. We followed the original paper's convention, reporting optical performance in terms of MTF at 15 line pairs/mm. (Higher contrast is better since it means a *sharp* resolution). This was conducted by using an automated lens design program that iterated to maximize the optical performance. These solutions were not solved in a closed form fashion.

Case	Surface # (number in matrix is aspheric departure in µm, *shows inflection)											Error Function	MTF 15 lp/mm Axial	MTF 15 lp/mm Edge
	1	2	3	4	5	6	7	8	9	10	11			
1												1.69	44%	32%
2	2										6	1.44	46%	26%
3					1		3					1.49	39%	30%
4						4						1.59	45%	32%
5	4						7					1.47	43%	33%
6					5						10	1.42	52%	30%
7									5			1.47	60%	35%
8	6					22						1.50	29%	27%
9						30					17	1.39	52%	36%
10	40	25										1.44	50%	43%
11										305*	468	1.01	75%	36%
12						5				270*	406	1.00	73%	43%

Singlet Doublet Iris Doublet Singlet

The above table captures the results of this study. There are eleven optical surfaces (including a plate at the iris) in the Double Gauss and these are represented by columns. Each row in the table represents a different configuration in terms of placement of the asphere. The numbers under the surfaces show the aspheric departure in microns.

The last three columns capture the optical performance or relative error function (RMS Wavefront Error — the lower the better) and MTF at the center and edge of the field of view.

Conclusion

The results show that aspheres can offer a great increase in optical performance. Some of these solutions, however, defy theoretical wisdom of asphere placement. The most promising solution for asphherizing a Double Gauss, for instance, utilizes a double asphere on the last element. In this solution one aspheric surface has an inflection point (convex at the center, concave at the edge). An inflection asphere is more difficult to manufacture but it offers an excellent performance increase. The asphere with the inflection has the axial beam covering only the convex portion while the off-axis beams wander to the edge of the asphere. The inflection point attempts to correct astigmatism at the edge of the asphere, while controlling field curvature and spherical aberration at the center.

When designing an optical system with aspheres, then, it is important that the lens designer keep an open mind about the placement of the aspheric surfaces. They should also carefully monitor for dueling aspheres to reduce stress on aspheric fabrication. If used correctly, however, aspheres can reduce size and weight of an optical system by minimizing the number of elements required to achieve good image quality.

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2 "Design of Double Gauss Systems Using Aspherics", T.R. Sloan and R.E. Hopkins, Applied Optics 1911, Vol 6. No. 11, November 1967