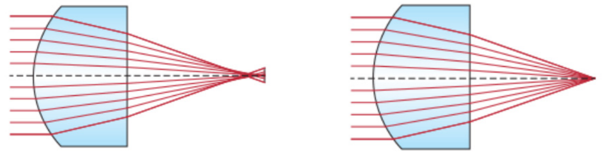
ASPHERE SPECIFICATIONS AND OPTICAL PERFORMANCE

Introduction

Any spherical optical surface, even a perfectly designed and manufactured one, will exhibit spherical aberration. This inherent defect of a spherical surface causes incident light rays to focus at different points when forming an image and creates a blur. This is what aspheric lenses are designed to correct for. (Figure 1)

Figure 1: Spherical Lens on the left compared to an Aspheric Lens on the right



Aspheric lenses can offer an improved spot size several orders of magnitude smaller than spherical lenses. This almost eliminates blur and significantly improves image quality. Aspheric lens elements also enable designers to create higher throughput systems whilst maintaining good image quality in multi-element assemblies. In optical systems, multiple spherical elements can be replaced by a single asphere reducing size and weight without a loss in performance. As manufacturing methods have continued to improve over recent years aspheric lenses have become an essential part of modern optical design.

Any lens with surfaces that are not spherical can be referred to as an asphere, however for manufacturability most aspheres are rotationally symmetric lenses with a radius of curvature that varies from the center to the edge. This geometry leads to unique challenges that are not present in traditional lens manufacturing. A spherical lens is defined by a single radius of curvature and can be ground and polished by a tool larger than the component, working the entire surface at the same time. In contrast the continuously variable radius of curvature of an aspheric lens requires sub-aperture polishing with tools that are small enough to create different local curvatures at different points on the surface.

Both the design and manufacture of aspheric lenses are fundamentally more complex than that for spherical components and it is important to be aware of their unique specifications and what they mean for performance.

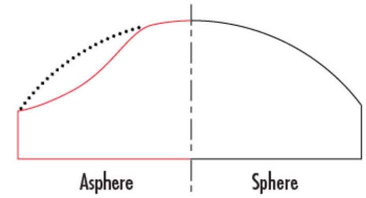
SPECIFICATIONS

An aspheric surface is usually described in terms of its sag which can be thought of as the deviation from a plane at its vertex. The equation is given below:

$$Z(s) = \frac{C^2 s^2}{1 + \sqrt{1 - (1 + \mathrm{k}) C^2 s^2}} + A_4 s^4 + A_6 s^6 + A_8 s^8 + \cdots$$

Z(s) is the displacement of the surface from the vertex at a radial distance of s from the optical axis. The parameter C is the curvature (which is the inverse of the radius of curvature at the vertex) and k is known as the conic constant. The terms A4, A6 and A8 are known as 4^{th}, 6^{th} and 8^{th} order aspheric coefficients. The comparison of an aspheric surface to a spherical one is shown in Figure 2

Figure 2: An illustration comparing an asphere to a sphere



The aspheric surface described by the equation above represents the ideal shape and the goal of manufacturing is to get as close as possible to this. Inevitably there will be deviation from the ideal surface profile, this is known as the asphere figure error or the **Surface Irregularity.** This is calculated by subtracting the ideal surface from the manufactured surface using software and analyzing the residual deviation. This specification is often quoted as a peak-to-valley (P-V) value, which represents the difference between the points of maximum and minimum deviation. However, this can be misleading as it doesn't state how many peaks and valleys there are on the optical surface. A more robust measure of the surface irregularity is the root mean square deviation (RMS) which looks at the absolute difference from the ideal surface at multiple points and calculates an average value for the entire optic. This value can vary from a few microns at commercial grade to a few tenths of a micron at high precision.

Whilst the surface irregularity gives a great indication of lens performance there is still a substantial amount of information missing. Looking at the entire optical surface the deviation from the ideal shape at any particular point will not be constant. In addition, the sub-aperture grinding and polishing techniques used in asphere manufacturing can create repeating patterns and structures within the surface irregularity profile known as mid-spatial frequencies. Another key specification that follows on from this is the irregularity slope or **Slope Tolerance**. This value puts an upper limit on the rate of change of the asphere figure error, describing how quickly the deviation from the ideal form can change within a given window. Typical values range from 1 μm/mm at commercial grade to 0,15 μm/mm at high precision. The window size is an important part of the specification and must be chosen to be less than the wavelength of the mid-spatial frequency being targeted but large enough to avoid counting higher frequency variations such as surface roughness or instrument noise.

PERFORMANCE CONSIDERATIONS

All optical systems have a theoretical performance limit known as the diffraction limit. Strehl ratio is a specification used to compare the real performance of an optical system with its diffraction-limited performance. For aspheric lenses and other focusing optics, Strehl ratio is defined as the ratio of peak focal spot irradiance of the manufactured optic to the diffraction-limited peak irradiance[1]. The industry standard threshold to classify a lens as "diffraction-limited" is a Strehl ratio greater than 0,8.

Strehl ratio can also be related to RMS transmitted wavefront error using the following approximation, where is RMS wavefront error in waves[2]. This approximation is valid for transmitted wavefront error values < 0,1 waves.

$$S = exp[-(2\pi\sigma)^2]$$

The Strehl Ratio of an optic is highly dependent on the accuracy of its surface which can be quantified in terms of the Surface Irregularity and Slope Tolerance described in the previous section. First, consider the spatial frequency of the figure error. When surface irregularity is modeled as a rotationally-symmetric cosine function, we can explore the resulting Strehl Ratio as a function of RMS surface irregularity for a variety of cosine periods (Figure 3 and Figure 4).

Figure 3: Radial cosine irregularity maps on a 25 mm diameter f/2 asphere surface. The cosine periods from left to right are 20 mm, 10 mm, and 5 mm

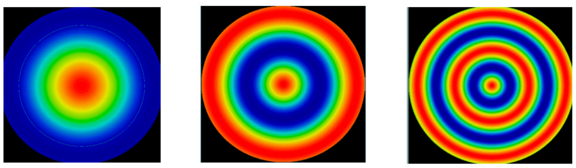
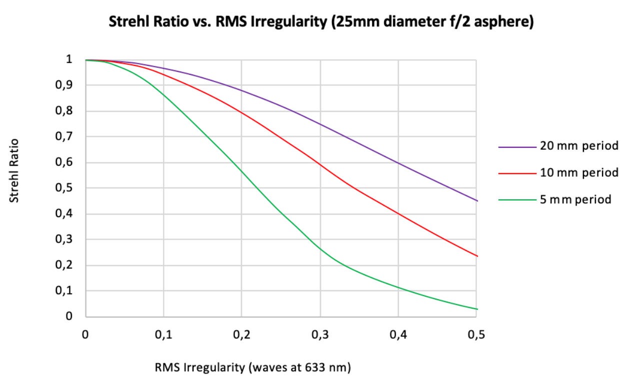
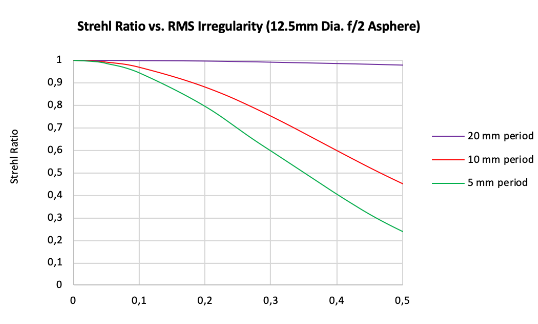


Figure 4: For a particular RMS surface irregularity, the more cosine periods over the aperture of the asphere, the lower the Strehl Ratio.



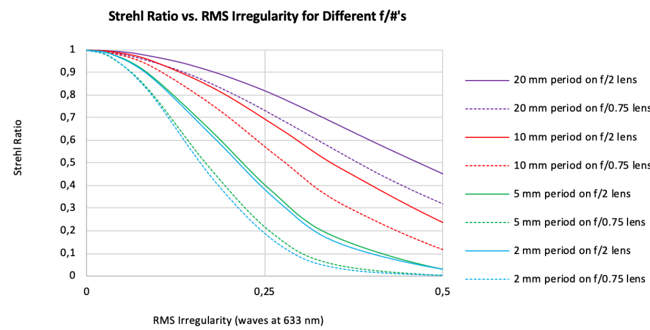
The key factor here is not the period of the cosine in mm, but the number of periods over the aperture of the lens. For a given sub-aperture tool used in asphere manufacturing, smaller diameter aspheres will have less Strehl Ratio degradation compared to larger diameter aspheres (Figure 5).

Figure 5: This 12,5 mm diameter asphere has significantly less Strehl Ratio degradation compared to the 25 mm diameter asphere in Figure 4.



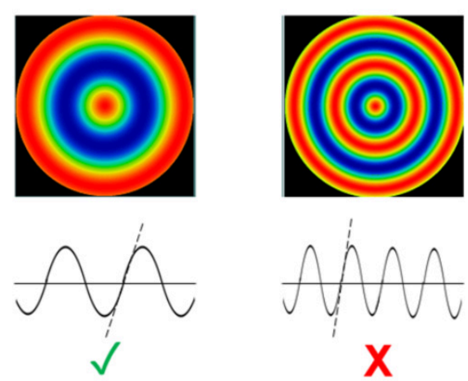
The impact of surface irregularity on Strehl Ratio is also dependent on the f/# of the lens. As a general rule, faster aspheres, or aspheres with smaller f/#'s, have greater sensitivity to surface irregularity's impact on Strehl Ratio. For example, Figure 6 compares an f/2 lens to an f/0,75 lens (both with 25 mm diameter).

Figure 6: Comparing dotted lines to solid lines shows that a faster asphere (smaller f/#) has greater degradation compared to a slower asphere (larger f/#) over a given cosine period.



It is clear from the examples above that the underlying structure of the surface irregularity can have a substantial effect on the Strehl Ratio of a lens, particularly higher spatial frequencies. The Slope Tolerance is a simple and effective way to constrain this. For a given PV irregularity limit, higher slopes are associated with higher spatial frequencies on the surface. So by constraining both the surface PV irregularity and its slope the allowable number of periods is reduced (see Figure 7).

Figure 7: If a surface irregularity map has a PV specification along with a maximum slope specification, this creates a threshold to reduce the impact of higher spatial frequency content on the surface, as higher spatial frequency errors.



For a more direct evaluation of spatial frequencies a specification called the Power Spectral Density (PSD) can be used. This function is computed by analyzing the Fourier transform of the surface irregularity map which gives a two dimensional plot of the surface in terms of spatial frequency components. Placing tolerances on this plot will therefore directly limit the number of periods.

CONCLUSION

Aspheric lenses are an extremely powerful tool for improving the performance of optical systems whilst also reducing the number of elements and consequently size and weight. From medical equipment and microscopes to smart phones and autonomous vehicles they are increasingly important across all optics enabled industries.
It is important to appreciate the complexities of asphere manufacturing. An aspheric surface cannot be made in the same way as a spherical one, a range of sub-aperture grinding and polishing techniques must be used to create a variable curvature. These methods create additional issues that need to be monitored and controlled to maximize the performance of an aspheric lens.

The irregularity is always an important parameter as any deviation from the ideal form will lead to increased transmitted wavefront error and a decrease in performance. There are, however, secondary effects to take into account, in particular the mid-spatial frequency of the surface irregularity profile. A surface with higher frequencies will have reduced performance when compared to an identical surface with lower frequencies. This effect is more pronounced for larger lenses and lenses with a smaller f/#. For this reason it is important to consider the shape of the surface irregularity over the entire lens aperture to understand the true impact that the surface irregularity will have on performance. Tools such as the Power Spectral Density function and the Irregularity Slope value provide a useful way to constrain spatial frequency effects and to really push performance at higher levels of precision.

When specifying complex optical components like high quality aspheres there are many other factors to consider as well as the ones described in this article. Final results can often depend on choosing the right manufacturing partner with the appropriate experience, tools, and metrology to be successful.

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