

Optical design with only two surfaces

David Shafer

The Perkin-Elmer Corporation, Norwalk, Connecticut 06856

Abstract

A wide variety of designs are described, using only two optical surfaces, that can perform useful functions with good aberration correction. Several use no aspherics.

Introduction

The widespread use of optical design programs has made it very easy to consider complicated optical systems and study many design variations that would involve an unthinkable amount of time and labor a generation ago. It is a feature of human nature that with these powerful design tools at our disposal, we tend to generate designs that require these tools. It is very easy to lose sight of the many useful optical tasks that can be performed by exceedingly simple optical systems. Many optical system requirements can only be met by fairly complicated designs, but the surprising things that can be done with simple optics make it a very worthwhile area to study.

This paper briefly surveys some designs that have only two optical surfaces. These systems can be designed using the most modest of computational tools and can even be done by hand calculations without too much effort. Many of the systems shown are thought to be new.

Two-mirror telescope

Figure 1 shows one example of a family of two-mirror, three-reflection telescopes that I have described on other occasions¹. It is corrected for spherical aberration, coma and astigmatism, with a nearly parabolic primary mirror and a nearly parabolic secondary mirror. When used as shown, the obscuration due to the hole in the secondary mirror makes this design have limited appeal.

Figure 2 shows a better arrangement — the field of view is all off-set relative to the optical axis so that the light leaving from its second reflection off the primary mirror goes to an image without any interference from the secondary mirror. There is still obscuration from the secondary mirror, but only in the light entering the system, so a much smaller value results than in the Figure 1 design. Furthermore, it is not centered in the pupil, so the effect on the system MTF is considerably reduced.

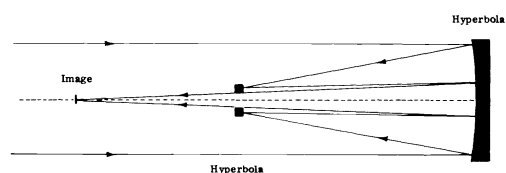


Figure 1. Three-reflection two-mirror telescope.

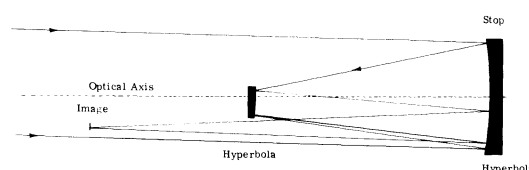


Figure 2. No hole in secondary mirror FOV offset to one side.

This system makes a nice ring-field design and is capable of very high performance with an $f/3$ primary and an $f/10$ system. The primary needs to be only as large as the entrance aperture for ring-field applications. An accessible image location is a desirable design feature that can be obtained by a larger off-set angle for the field of view.

Figures 3 and 4 show another example of a well-corrected two-mirror, three-reflection telescope. The obscuration of Figure 3 is completely avoided by the Figure 4 configuration, which has a centered primary mirror (an ellipse, while the secondary is hyperbolic). This also makes an effective ring-field design. An $f/3$ primary gives an $f/4.5$ system. Since the stop and both pupils are at the primary, its size is not affected by the field of view.

Figure 5 shows one other example of this type of telescope, where it has been configured for stray-light rejection. Figure 6 shows how the primary mirror has a decentered aperture stop on its top section and a decentered Lyot stop on its bottom. The accessible field stop at the intermediate image, the accessible final image and the lack of any obscuration make

OPTICAL DESIGN WITH ONLY TWO SURFACES

this ideal for stray-light rejection applications. A wide-angle strip field is shown here. The image is curved quite strongly due to three concave reflections.

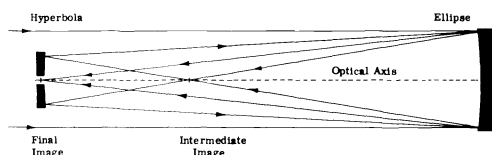


Figure 3. Anastigmatic telescope.
Length = focal length.

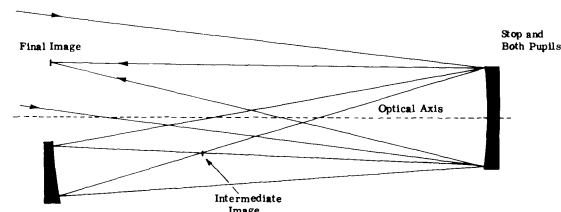


Figure 4. Unobscured version.

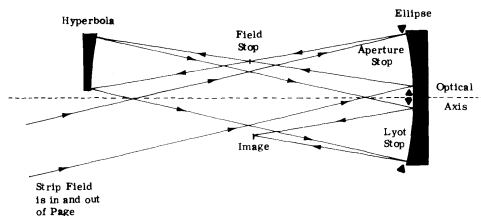


Figure 5. Two-mirror unobscured strip field telescope with stray light rejection.

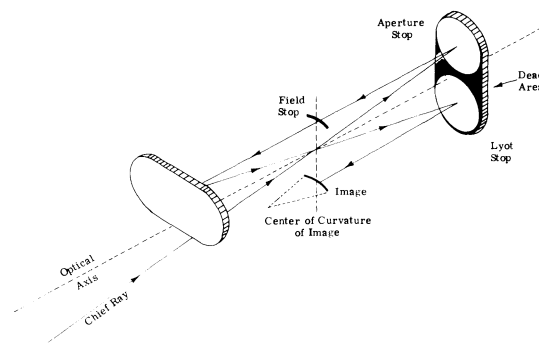


Figure 6. Isometric view.

A two-mirror, four-reflection telescope is shown in Figures 7 and 8². The primary is a fast sphere ($f/1.5$ or faster) and the system is intended for a 10 meter aperture Arecibo-type use with a scanning secondary mirror. The aspheric secondary looks flat but has a long radius. The primary needs to be oversized because of the third reflection.

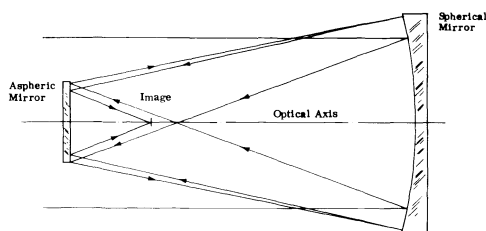


Figure 7. Aplanatic telescope - no 3rd or 5th order spherical aberration or coma.

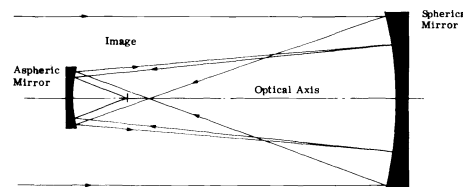


Figure 8. Aplanatic telescope - fifth order coma limits field of view.

A design which looks similar to Figure 7 but, with a larger beam diameter at the third reflection, can be corrected for spherical aberration, coma and astigmatism. However, at fast speeds, such as $f/1.0$ - $f/1.5$, 5th-order coma is much more important than astigmatism correction. The Figure 7 design is corrected for both 3rd and 5th order spherical aberration and coma. In Arecibo-sized systems there is enough room to get at the small image of the instantaneous FOV, which falls in the hole in the beam due to the obscuration from the secondary mirror. Figure 8 shows a version having a smaller secondary mirror and no oversizing required of the primary mirror. Performance is limited by 5th-order coma, which cannot be corrected except in the Figure 7 system. In all cases, the primary remains a sphere.

Poor man's x-ray telescope

Suppose two spherical mirrors with the same radius, one convex and one concave, are placed in contact. Figure 9 shows them slightly separated. If they are in contact, then light cannot enter the system. If it could, however, it would be enormously aberrated after reflection at near-grazing incidence angles from the first mirror. All aberrations would be

then exactly cancelled by the second mirror, since they have the same radius and no separation. The two mirror system would also have no net power either.

If the mirrors are then slightly separated to allow light to enter, the system acquires power and will focus the light a long way off, as in Figure 10. The aberrations no longer cancel exactly, but nearly so. For any given mirror separation we can choose the radii of the mirrors and the separation of their centers of curvature to optimize the aberration cancellation and define an optical axis parallel to the incident light. Since the mirrors still have nearly the same radius in the optimized design, the Petzval surface of the system is flat. Since the two surfaces are also very nearly concentric, the performance does not change with field-angle very fast. For slow $f/\#$ applications, this design has good performance and is orders of magnitude less expensive than conventional X-ray telescope (or microscope) designs. An alternate version has the concave mirror first and then the convex one.

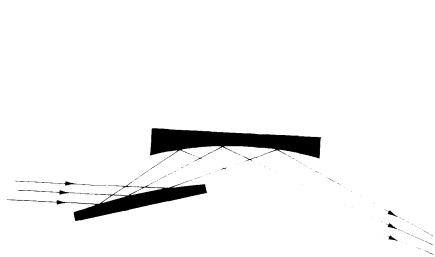


Figure 9. Two spheres of same radius, nearly in contact.

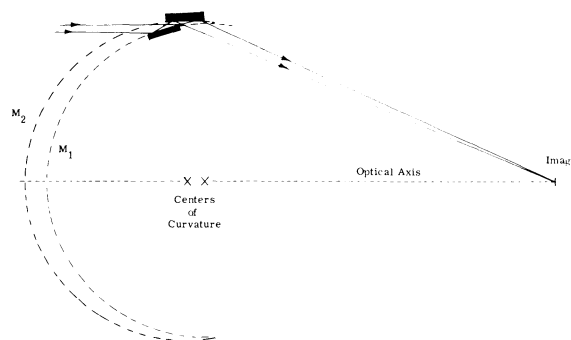


Figure 10. Poor-man's X-ray telescope. Two spherical mirrors.

Zoom relay system

A zoom relay system is shown in Figure 11. It is used with a decentered pupil so as to make it unobscured. This design, with two aspheric mirrors, is corrected for spherical aberration and coma at two separate zoom positions. By choosing the location of the two aplanatic magnifications relative to the total magnification range, one can minimize the change in aberrations during zooming.

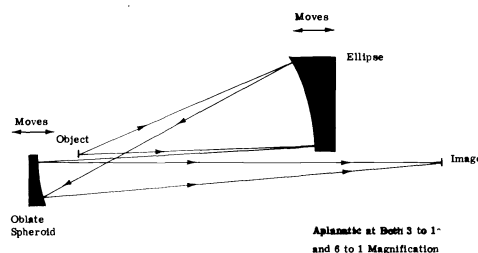


Figure 11. Varifocal aplanatic relay.

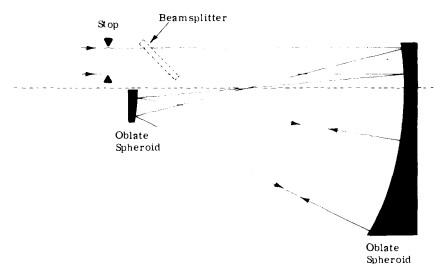


Figure 12. 3-D imaging system. 5 reflections - 2 mirrors.

3-D imaging system

While it may seem difficult to believe, considering the simplicity of the system, the design shown in Figures 12 and 13 is corrected for all the 3rd-order aberrations for all conjugate distances. It is a unit-magnification system with five reflections between the two aspheric mirrors. **Figure 12** shows the design used with parallel input light. Here it is shown with a decentered pupil that makes it unobscured. Light is retro-reflected and retraces its path, so the output is co-linear with the input. The stop position shown is imaged back onto itself. For any other stop position, the entrance and exit pupils will not coincide. A beam splitter, shown in the drawing, would allow access to the output of this distortionless, flat-field anastigmat.

Figure 13 shows how the same system looks when used at a conjugate distance such that the object and image coincide. An intermediate image is formed right on the concave mirror,

OPTICAL DESIGN WITH ONLY TWO SURFACES

which retro-reflects the light path. For any other conjugate distance, the object and final image would not coincide.

Since this system is corrected for all the 3rd-order aberrations for all conjugates, it provides a well-corrected image, at unit magnification, of a three-dimension volume of space. If anyone can think of a use for such an unusual system, I would be most interested in hearing of it.

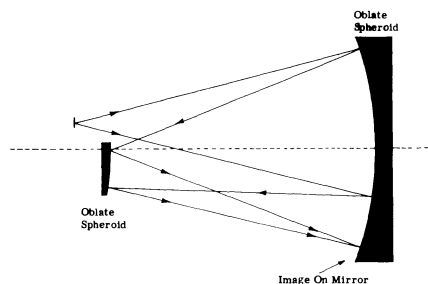


Figure 13. Finite conjugate version.

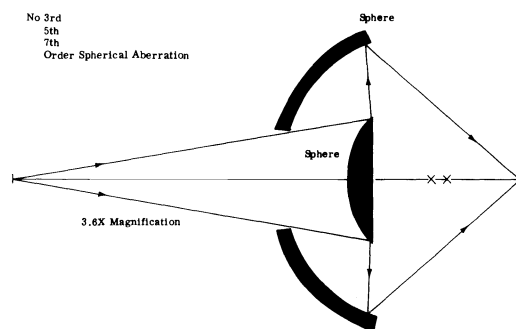


Figure 14. Fast $f/\#$ relay.

Fast $f/\#$ relay

Two nearly concentric spherical mirrors, when used at about 3.6X magnification, as shown in Figure 14, can be corrected for 3rd, 5th and 7th-order spherical aberration³. Since these orders can be separately controlled, they can be used to balance 9th-order spherical aberration to provide very high performance on-axis at fast $f/\#$ speeds. Since the spheres are nearly concentric, the system has much smaller coma than an elliptical mirror used at the same magnification and $f/\#$. The obscuration is about 50% diameter. At other magnifications, third- and fifth-order spherical aberration can be eliminated with non-concentric spherical mirrors. Seventh-order is also zero for only the magnification shown — 3.6X.

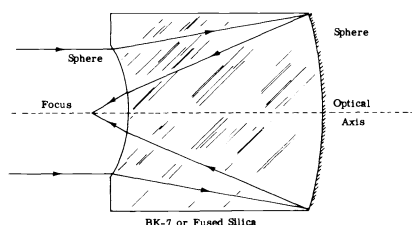


Figure 15. Temperature and wavelength insensitive laser beam focuser.

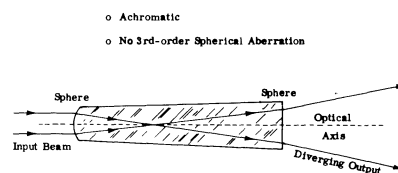


Figure 16. Single element $f/2.5$ beam diverger.

Laser beam focuser/diverger⁴

A single-element laser beam focuser is shown in Figure 15. The two spherical surfaces are nearly concentric. By departing from concentricity, this design can be corrected for 3rd-order spherical aberration and spherochromatism, with very small 5th-order spherical aberration. It is not corrected for longitudinal color, but its lack of spherochromatism means that the performance is extremely insensitive to wavelength changes or uniform temperature changes, assuming refocusing. At $f/1.0$ and a 1.0 inch focal length, it has a $\pm \lambda/20$ wavefront (peak-to-peak) at 0.6328μ . Over a temperature range of $\pm 200^\circ\text{C}$ and a wavelength range of 0.3μ – 2.3μ , the performance changes by less than $\lambda/100$, with refocusing. It can be used with any wavelength laser within its transmission band. Since it is nearly concentric, the design has coma that turns out to be 6 times smaller than that of a parabolic mirror of the same size and $f/\#$. A version with a more accessible focus is possible with a decentered pupil.

A single element diverger is shown in Figure 16. It has two spherical surfaces and is corrected for 3rd-order spherical aberration and longitudinal color, but not spherochromatism. The Figure 17 design, which requires a decentered pupil, is corrected for 3rd-order spherical aberration, longitudinal color and spherochromatism, so neither performance nor focus changes with wavelength or temperature. All three aberrations are corrected with just two spherical surfaces, but the glass must have an index of about $n = 1.71$ (Schott SF-1), while any glass may be used in the other two designs.

Others

Figures 18 and 19 show two systems fully described in my other paper in this volume. One is a flat-image anastigmat with one aspheric, and the other is a lens with two spherical applanatic surfaces, which introduces Petzval curvature into an optical system, but no 3rd-order spherical aberration, coma or astigmatism. Figure 18 can also be used as a finite conjugate relay system, provided the index of refraction of the lens is chosen correctly.

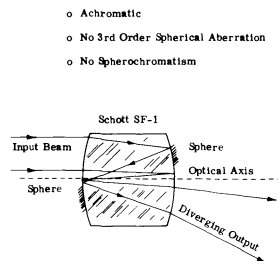


Figure 17. Athermal laser beam diverger.

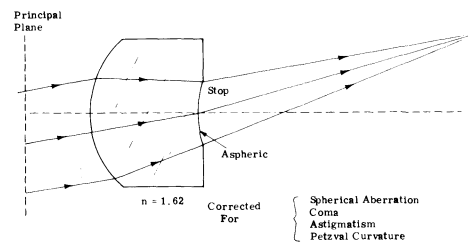


Figure 18. Single element telephoto lens with aspheric.

A laser-fusion clamshell system with two aspheric mirrors is shown in Figure 20 (Shafer, U.S. Patent # 4,179,192). By the use of multiple reflections inside the cavity, the $f/\#$ speed of the point source input is greatly reduced compared to earlier systems, as is the asphericity of the mirrors.

Figure 21 shows a two-mirror laser beam expander/steerer⁵. By choosing the two aspheric mirrors correctly, the small mirror can be pivoted about the point indicated, for beam steering, without introducing either 3rd-order coma or astigmatism into the output beam. Pivoting about the "neutral point" with confocal parabolas introduces astigmatism, but no coma. The design shown has neither.

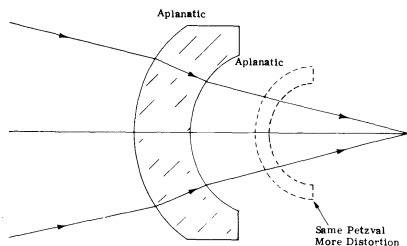


Figure 19. Field flattening element. Both surfaces aplanatic.

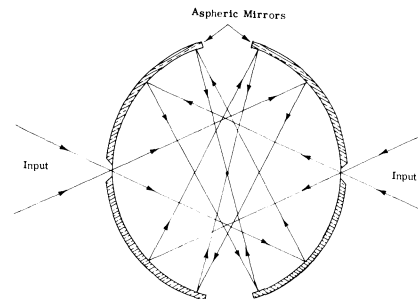


Figure 20. Laser-fusion focusing optics.

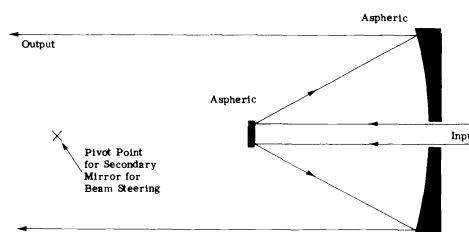


Figure 21. Laser beam expander/steerer.

Conclusion

The designs reviewed here are just a few of the many possibilities that are worthy of attention. Some particularly useful and interesting two-surface designs have been excluded from this paper for future review. It should be clear that not all functions can be performed by these simple systems, but the variety of the examples reviewed here show how much can be done. More complicated systems can also be based on these designs.

References

1. Shafer, D.R., "Anastigmatic Two-Mirror Telescopes: Some New Types," Applied Optics, Vol. 16, No. 5, p. 1178. 1977.
2. Shafer, D.R., "Large Telescope Designs with a Spherical Primary Mirror," Instrumentation in Astronomy, III, SPIE Vol. 172. 1979.
3. Warren Smith, Private Communication. 1977.
4. Shafer, D.R., "Laser Focusing Optics with Extremely Insensitive Performance/Temperature Dependency," Optics in Adverse Environments, SPIE Vol. 216. 1980.
5. Shafer, D.R., "Laser Beam Steerer-Expander," Applied Optics, Vol. 17, No. 22, p. 3584. 15 Nov. 1978.