# Optical design of reflective wide-field cameras

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## ABSTRACT

This paper discusses some methodologies that apply to the optical design of reflective wide-field cameras. Among the methods considered are off-axis and eccentric pupil systems, concatenation of systems, tilted component systems, aberration theory, and confocal systems. The goal of the paper is to review design methods. In particular some systems are shown to illustrate two methodologies.

**Keywords**: Optical design, mirror design, wide-field, reflective optics, unobscured

## 1. INTRODUCTION

Reflective systems provide useful solutions to imaging problems due to their achromaticity, large spectrum bandwidth, and achievable aperture size. Often the mirrors in these systems are required to be aspheric in their optical shape to achieve sharp imaging. Since the seminal paper by Schwarzschild[1] in 1905 many different and useful reflective systems have been found. In particular, reflective systems that provide a wide-field at high optical speed and that are unobscured are often needed for a variety of applications. The paper by Rodgers[2] provides a catalogue of useful mirror systems. From an educational point of view a good question to ask is how these reflective systems are designed.

In this paper we discuss reflective cameras that are unobscured and that have a wide-field of view at a relatively fast optical speed. Historically, one way to design these systems is to start with a well corrected axially symmetric system that is used in an off-axis manner or as an eccentric pupil system. This technique, based on axially symmetric systems, is widely used and very powerful because of the inherent axial symmetry which at once helps to obtain sharp images. Several three-mirror anastigmatic cameras have been designed in this way. Ring or annular field systems that are used in optical lithography are another example of this design methodology. A clever technique to design unobscured systems is by concatenating well corrected systems that are already unobscured. In the papers by Rodgers[2] and Cooke[3] we find some examples of this technique.

Although the off-axis or eccentric system methodology is very powerful, it does not tell us about the design possibilities when there is no axial symmetry. In addition, once the axial symmetry is lost new insights into how the aberrations behave is required. Over the years there have been several approaches for understanding systems that lack axial symmetry. Tilted component systems, which are systems that may not have an identifiable symmetry but that are constructed from axially symmetry components, are a class of systems whose aberration properties have been described by Buchroeder[4] and Thompson[5]. In these systems there are no new aberration forms but the field dependence has new field behavior. For example astigmatism can be uniform or linear as function of the field of view and point or line nodes where the aberrations vanish can appear anywhere in the field of view. Theories about non-axially symmetric systems are valuable and insightful. However, with reduced or no symmetry at all there are more aberration terms to control and achieving sharp imagery over a wide-field at fast optical speeds becomes challenging.

It is also possible to gain insight into the behavior of optical systems by constructing an aberration function according to the symmetry of the optical system under study. For example, Sasian[6]

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0277-786X/08/$18 · doi: 10.1117/12.798171

developed a theory for plane symmetric systems which provides the aberrations terms and aberration coefficients for such systems. New insights emerge from such theoretical developments. For example, if a system is constructed in such a way that there is sharp imagery along a given ray (called the optical axis ray) surface after surface, then it is possible to show that such a system can have a reduced number of field aberrations and that the system will behave closer to an axially symmetric system. This type of systems is called a confocal system.

The understanding of all of these methodologies[7] provides the optical designer with a more general insight about optical systems and makes a difference in designing optimum systems. In this paper we illustrate how in practice some of these methodologies are used. Specifically we present a design that relies on the methodology of confocal systems and another design that is an off-axis portion of an axially symmetric parent system. Overall the discussions presented give design insight to those practicing the design of reflective systems.

## 2. THREE-MIRROR SYSTEM WITH FOCAL PLANE ACCESS

In this section we illustrate the technique of confocal systems. We use this technique to provide an easier access to the focal plane of a three-mirror system. We start with a Paul-Baker camera that has a paraboloidal concave primary mirror, a spherical convex secondary mirror, and a spherical concave tertiary mirror as shown in Fig. 1. The system is axially symmetric and is free from the fourth-order wave aberrations spherical aberration, coma and astigmatism. The system has some Petzval field curvature. The radius of curvature of the tertiary is equal and opposite to the radius of secondary mirror. A problem with this system is providing physical access to the focal plane without significantly obstructing the beam directed to the tertiary mirror.

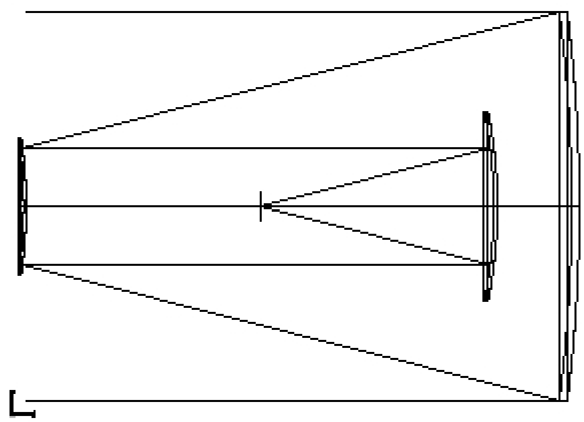

Fig. 1 A Paul-Baker camera

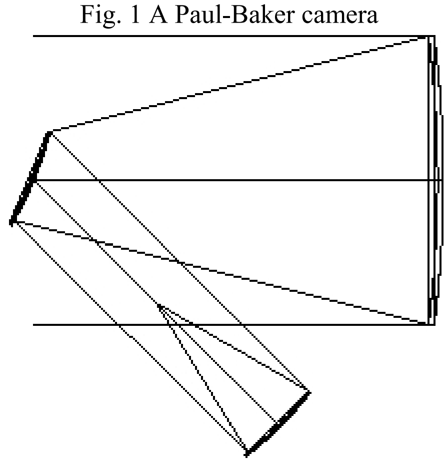

Fig. 2 Mirror system with secondary tilted.

In principle, our starting point is an anastigmatic system. However, our first design step is to change the two spherical mirrors to be paraboloidal, creating a confocal system which is perfectly corrected on axis, surface after surface. The next step is to tilt the secondary mirror so that the tertiary mirror is out of the incoming beam to the primary mirror as shown in Fig. 2. The secondary mirror becomes an off-axis paraboloidal mirror to maintain collimated light between the secondary and the tertiary mirror, satisfying the confocal condition.

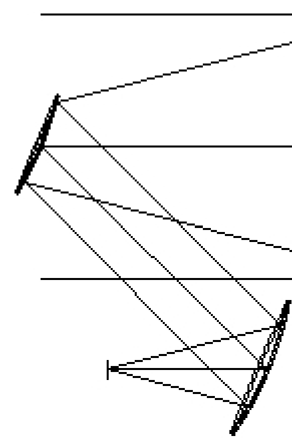

Fig. 3 Mirror system with secondary and tertiary mirrors tilted to allow an easy access to the focal plane.

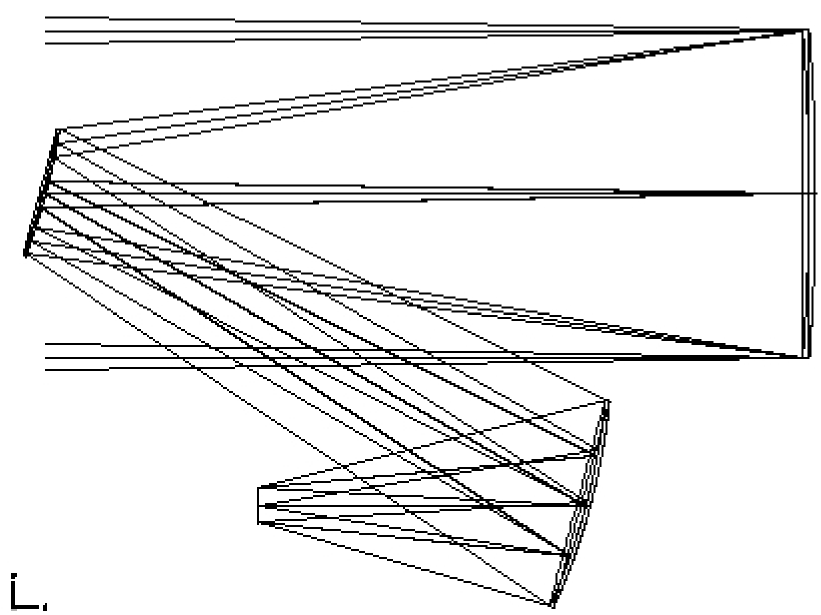

Fig. 4 Ray-tracing optimized system to work at F/3.2

Then the tertiary mirror is tilted to provide easy access to the image plane as shown in Fig. 3. In this step the tertiary also becomes an off-axis paraboloid mirror and continues to maintain the confocal condition. Maintaining the confocal condition implies that the system has no on-axis aberrations or anamorphic distortion[6]. The secondary and the tertiary mirrors have the same tilt but in opposite directions and also have the same base radius of curvature but opposite in sign. As a result the system has no linear astigmatism or field tilt and therefore it behaves almost as an axially symmetric system in terms of low-order aberration analysis.

Performing a ray tracing optimization and allowing the secondary and tertiary mirrors to depart from off-axis paraboloids permits the designer to obtain sharp images; nearly diffraction limited in the visible spectrum. The field is flat and covers two degrees in diameter at a speed of f/3.2 with a system focal length of 500 mm as shown in Fig. 4. Distortion in this system is mainly quadratic with the field and is about 3%. The stop is located at the primary mirror.

The fact that the axially symmetric starting system is anastigmatic results in the optimized system having little or no spherical aberration, linear coma, or quadratic astigmatism. Clearly by using the concept of confocal systems and starting with a well corrected axially symmetric system it is possible to find a useful non-axially symmetric system.

## 3. TWO-MIRROR, OFF-AXIS SYSTEM WITH A LARGE FIELD OF VIEW

In this section an unobscured system using an off-axis section of a well corrected axially symmetric system is designed. This is an obvious method and so the challenge is to find a well corrected system that can be used in an unobscured manner. The steps taken in designing a very large field and optically fast five-reflection, two-mirror system are illustrated. Consider the flat-field, anastigmatic Schwarzschild system that consists of a convex primary mirror and a concave secondary mirror as shown in Fig. 5. Both mirrors are aspheric and have the same magnitude but opposite sign in radius of curvature.

This system can deliver a field of view of several degrees with near diffraction or diffraction limited performance in the visible. Several trade-offs between field of view, optical speed, and exit pupil location are possible. One problem with this two-mirror system is that, depending on the design, it may not have a real stop.

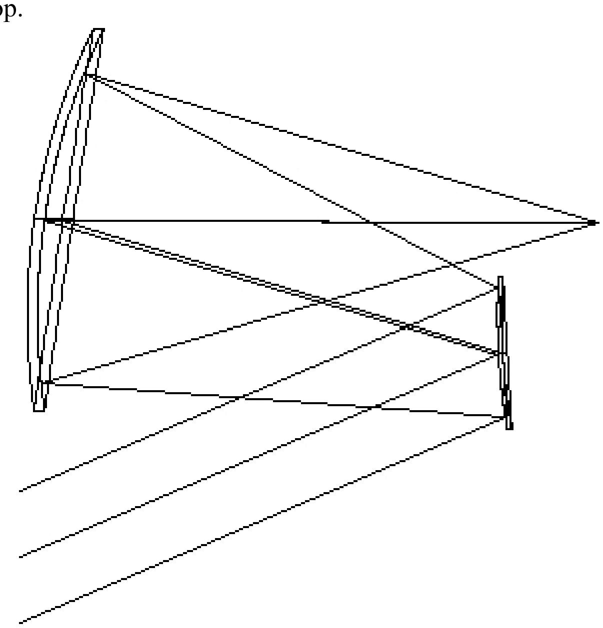

Fig. 5. Two-mirror Schwarzschild telescope

Previously some three-mirror systems have been designed that can be considered an improvement on the Schwarzschild system. Specifically one can split the convex mirror into two convex mirrors, space them, and obtain better performance. Such a three-mirror system is shown in Fig. 6. Alternatively one can add to the Schwarzschild system a concave tertiary mirror and obtain a solution as shown in Fig. 7. This is not the Walrus[8] system showed in Fig. 8 because there is imaging between the secondary and tertiary mirrors.

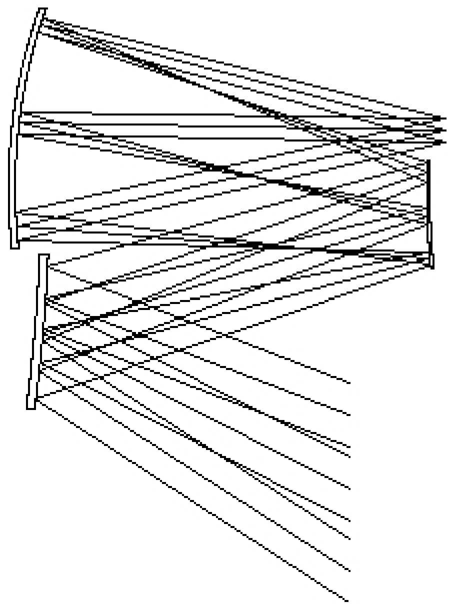

Fig. 6 Schwarzschild system with an added convex mirror covering a radial field of 12 degrees at F/2.

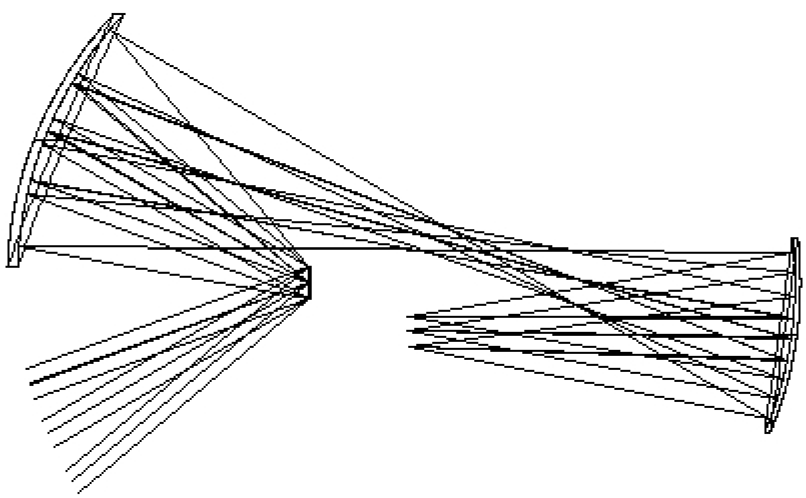

Fig. 7. Schwarzschild system with an added re-imaging concave mirror covering a radial field of 20 degrees at F/3.

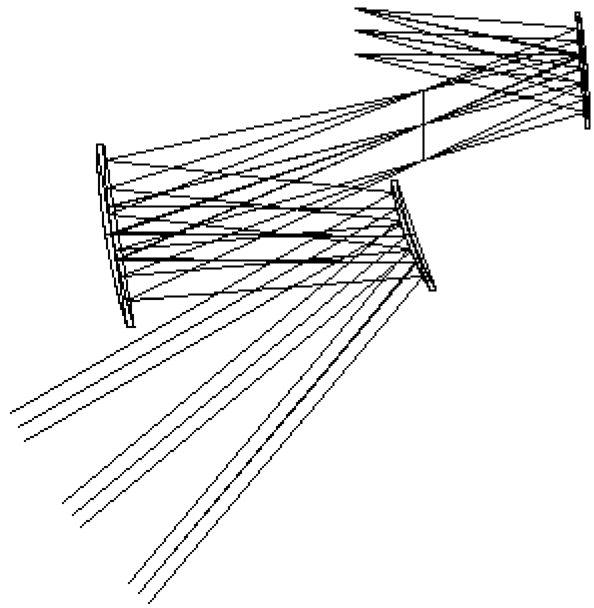

Fig. 8 Walrus three-mirror camera covering 20 degrees in the radial direction at F/4.

It is natural to ask what would happen if two mirrors are added instead of one. Thus another possibility is to add to the Schwarzschild system both a front convex mirror and a rear concave mirror to obtain the system shown in Fig. 9. This system can cover 20 degrees in the radial direction at a speed of F/2 and provides diffraction or near diffraction limited imaging depending on the final focal length. Thus the addition of two mirrors helps to provide better imaging than any of the previous systems.

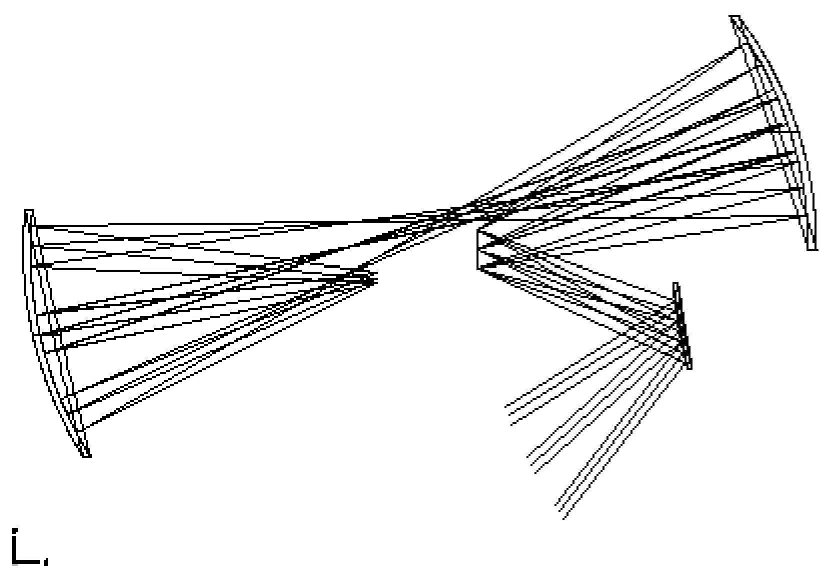

Fig. 9 Four-mirror camera covering 20 degrees in the radial direction at F/2.

Two problems with this four-mirror camera are that the incoming beam to the quaternary mirror is close to the image plane and that the overall system length is long. To solve these problems one can consider folding the system by adding a fifth mirror. With proper design it is possible to have the fourth mirror to coincide with the secondary mirror, and also to have the tertiary mirror to coincide with the fifth mirror. This technique is reminiscent of the Seal camera[9]. The result is the folded camera shown in Fig. 10, consisting of three mirrors with five light reflections between them. There is some loss of performance due to the mirror constraints which results in decreasing the radial field to 16 degrees.

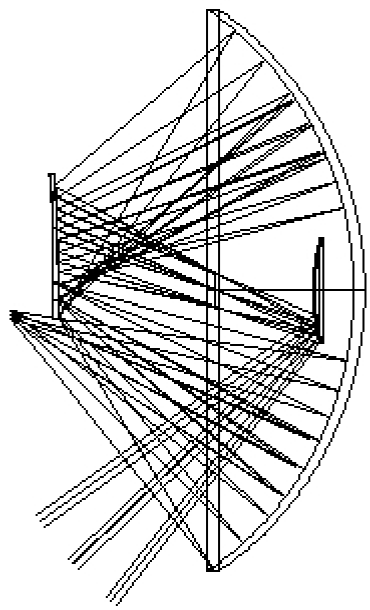

Fig. 10 Folded three-mirror system with five reflections covering a 16 degrees radial field of view at F/2.

It is also possible to maintain the radial field equal to 20 degrees by reducing the optical speed to F/2.5. In addition, the primary mirror can be located in close proximity to the tertiary and fifth mirror so that the three mirrors could be manufactured with diamond turning technology as a single two-curvature mirror. Thus the end result would be a two-mirror camera with five reflections as shown in Fig. 11. The stop aperture is real and is located after the primary mirror. The image lies in a flat surface and the image quality is shown in Fig. 12 with wave-fans at a wavelength of 0.55 micrometers. The wave-fans show that near diffraction limited performance should be expected. The focal length is 6.375 mm, the entrance pupil diameter is 2.55 mm, the camera length is 65.2 mm, and the large mirror diameter is 97.5 mm.

This camera has a very small entrance pupil diameter in relation to its physical size and is similar to a fish-eye lens in this regard. The advantage is that in azimuth it covers a field of about 165 degrees. Thus the camera has field coverage of almost an annular strip of the horizon in the order of 165 degrees in azimuth and 20 degrees in the radial direction. The image height for the largest field position of 56 degrees is 5.17 mm so that the complete image field of the camera can be acquired with a CCD. The specifications for the camera are given in the Appendix. All the mirrors have been allowed to be aspheric surfaces up to the eighth-order. No effort has been made in controlling distortion which is about 7% or effort in fully optimizing for imaging performance, as clearly there is a trade-off between field coverage and optical speed.

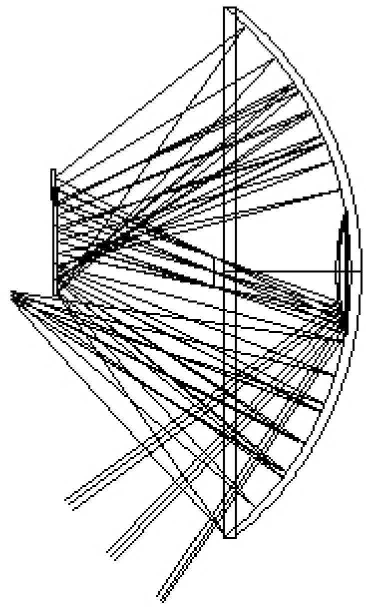

Fig. 11 Folded two-mirror system with five reflections covering 20 degrees radial field of view at F/2.5.

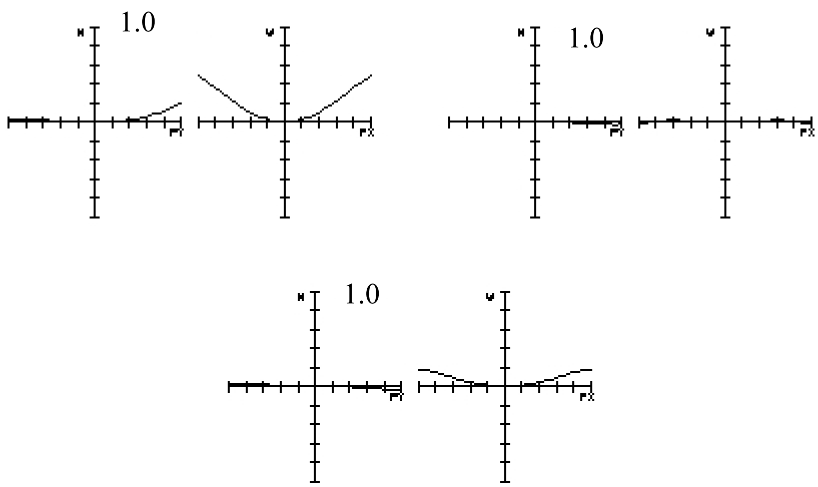


Fig. 12. Wave-fans at 36, 46, and 56 degrees off-axis with a scale of one wave.

Notably, in this type of camera light that arrives at the focal plane is not reflected back to the source but reflected side ways to a light trap. Therefore, unlike many systems, there is no cat's eye retro-reflection.

## 4. ALTERNATE SYSTEMS

In optical design it is a good practice to compare different solutions to a given problem. For the case at hand it is not so obvious which other systems can provide similar performance, that is delivering an unobscured F/2 or F/2.5 beam over a large field of view. The Seal system is showed in Fig. 13 and was designed as a folded version of the Walrus camera. There are four reflections and three mirrors. The large concave mirror is elliptical in shape and produces the second and fourth light reflections.

The primary mirror is spherical and the tertiary mirror is a folding flat. The Seal camera operates at F/4 with a radial field of 20 degrees. As pointed out by Owen[9] the Seal system can deliver almost a half annular field of view as also shown in Fig 13. It is not a full half annular field of view because at the field extremes the image plane overlaps with the light beams before and after the primary mirror.

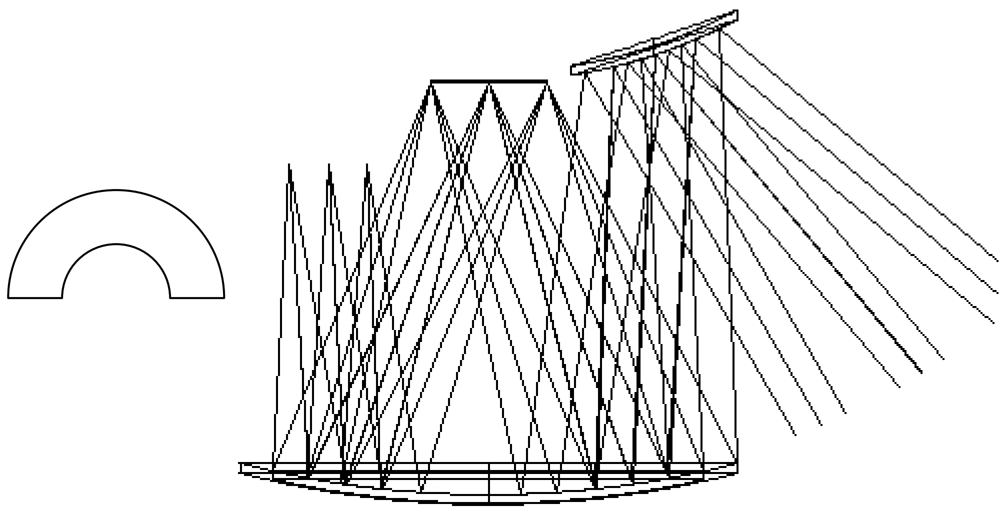

Fig. 13 Owen's Seal camera and its half annular field of view.

Cook[10] has shown that an improvement in optical speed over the Seal system can be obtaining by allowing the mirrors in the Seal system to be all aspheric and independent. Optical speeds of up to F/1 can be obtained. Fig. 14 shows a Cook system optimized at F/2 over a radial field of view of 20 degrees. In terms of image quality this system does not perform as well as the system of Fig. 10 and looses the ability to provide the almost full annular field of view because the secondary and quaternary mirrors have different curvatures and optical shape. However, it does have the very important features of being very compact, about one fourth the size of the camera in Fig. 10 and of being telecentric in image space.

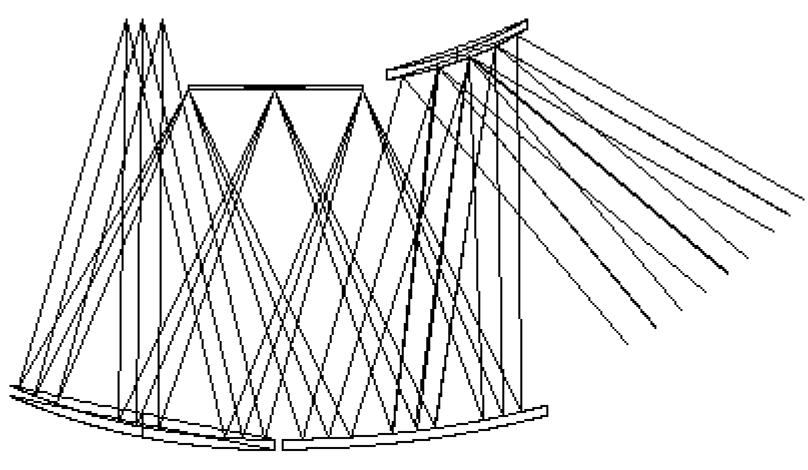

Fig. 14 Cook's fast and compact imaging camera.

When the secondary and quaternary mirrors in Cook's camera are constrained to be the same then the image quality degrades and lower optical speeds can be provided resulting in Owen's Seal F/4 camera. Alternatively, one can split the primary convex mirror into two mirrors to create extra degrees of correction and obtain a five reflection camera as shown in Fig. 15. This camera still can provide almost a half annular field of view. However, two disadvantages are the fifth reflection and the increase in the transverse size. In addition, some careful baffling is required in this type of systems to avoid stray light reaching the image plane.

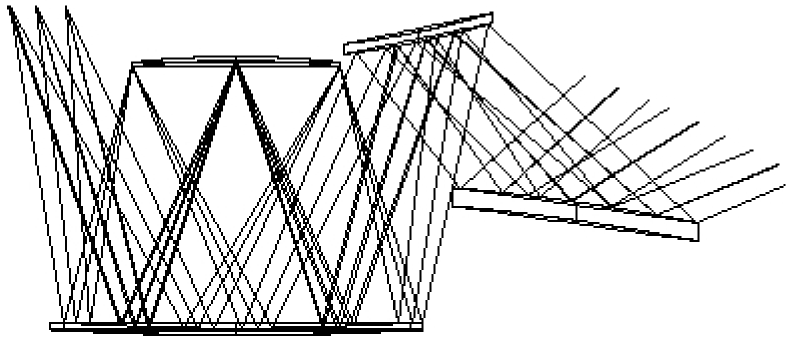

Fig. 15 Four-mirror five reflections camera with half annular field strip at F/2.5 and 20 degrees radial field of view.

## 5. FULLY ANNULAR FIELD SYSTEM

In the previous systems the radial field of view for the largest field position is beyond 60 degrees and it is interesting to consider cameras that both reach 90 degrees in the field of view and that are fully annular. By trial and error, simplifying, and changing the specifications of the previous four-mirror camera one can arrive at the camera design of Fig. 16. This is a three-mirror camera with a convex primary mirror, a convex secondary mirror, and a concave tertiary mirror. The camera works at F/4 and covers a radial field of view of 30 degrees, from 60 to 90 degrees, and an azimuthal field of view of 360 degrees which results in a panoramic camera. Wave aberration residuals are in the order of two waves in the visible for a focal length of 25 mm. Note that the camera has significant barrel distortion and as this aberration is linked to pupil coma we observe the Slyusarev effect in the incoming collimated beams that change their cross section size. The specifications for this camera are given in the Appendix. All mirrors are prolate ellipsoids in their optical shape but the use of polynomial terms improves the optical speed to F/3 as shown in Fig. 17.

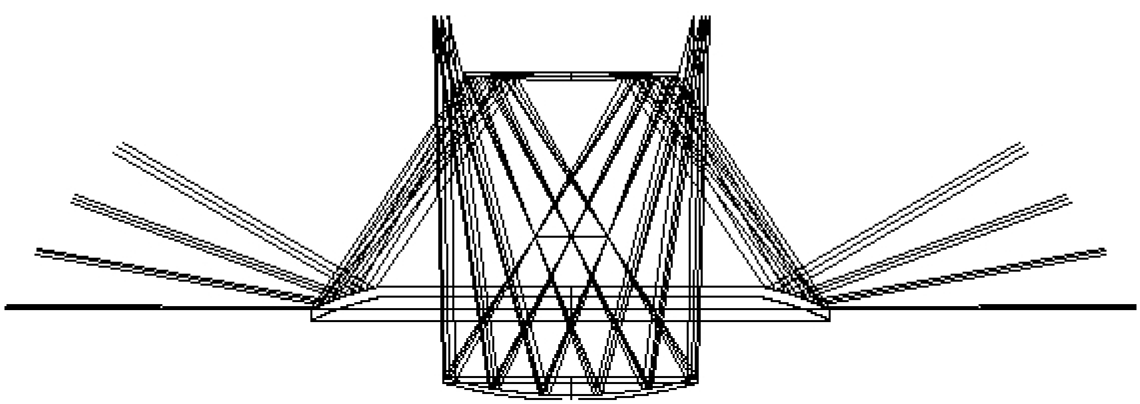

Fig. 16 Three-mirror, fully annular field of view camera at F/4.

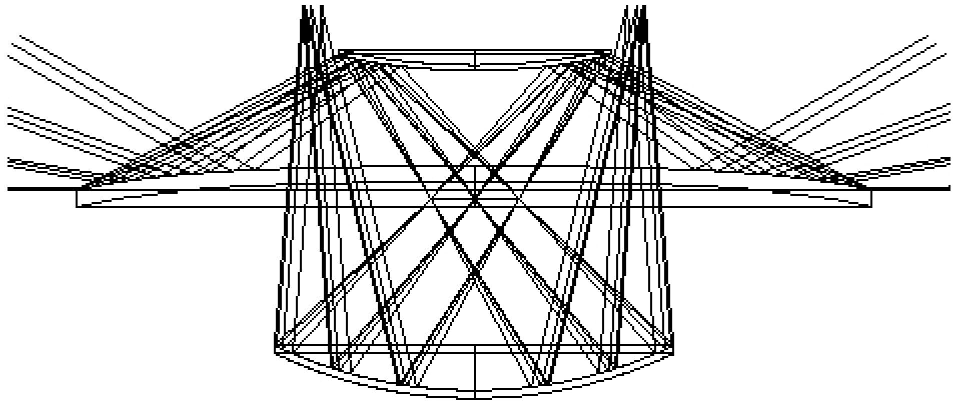

Fig. 17 Three-mirror, fully annular field of view camera at F/3 with polynomial aspheric surfaces.

If the azimuthal field is reduced to less than 360 degrees, for example less than 180 degrees, then faster optical speeds are possible with this design. Alternatively, the radial field covered can be decreased, for example from 50 to 70 degrees, and obtain a speed of F/2.5 as shown in Fig. 18.

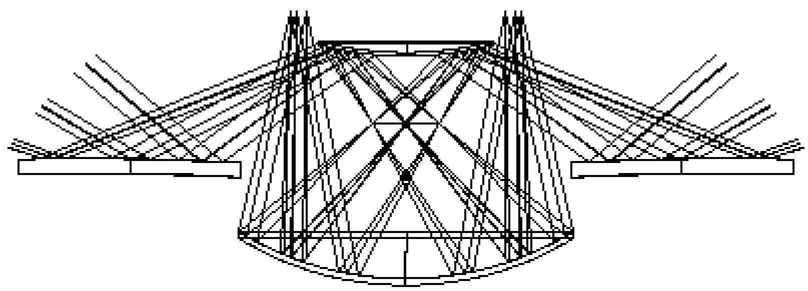

Fig. 18 A three-mirror fully annular field camera at F/2.5 covering a radial field from 50 to 70 degrees.

## 6. SUMMARY

It is not so obvious to some practitioners of optical design how mirror systems are designed. The goal of this paper has been illustrating how some design techniques are used in the design of reflecting systems. The paper does not touch in design issues regarding baffle design, control of stray light, manufacturing, alignment, and testing which are also relevant. This paper in particular has presented the technique of confocal systems to provide access to the focal plane of a Paul-Baker camera. The technique of using an axially symmetric system in an off-axis manner has been used to create some unobscured and relatively optically fast cameras that cover a large field of view. In addition, in pushing the design specifications some other systems have been designed and illustrated that have full annular fields.

## REFERENCES

[1] Schwarzschild, K., “Untersuchungen zur geometrischen optic. II Theorie der spiegeltelescope,” Astronomische Mittheilungen der. Koniglichen Sternwarte zu. Gottingen, 10, 3, 3-28, (1905).

[2] Rodgers, J. M., “Unobscured mirror designs,” Proc. SPIE 4832, 33-60, International Optical Design Conference, (2002).

[3] Cook, L. G., “The last three-mirror anastigmatic (TMA)?,” in *Lens Design*, Warren J. Smith Editor, CR41 SPIE Optical Engineering Press, 310-324, (1992).

[4] Buchroeder, R. A., “Tilted component optical systems,” Ph. D. Dissertation, University of Arizona, (1976).
[5] Thompson, K. P., “Description of the third-order optical aberrations of near-circular pupil optical systems without symmetry,” J. Opt. Soc. Am. A. 22, 1989-1401, (2005).
[6] Sasian, J., “How to approach the design of a bilateral symmetric optical system,” Optical Engineering, Vol. 33, No. 6, (1994).
[7] Sasian, J., "Review of methods for the design of unsymmetrical optics," SPIE Proceedings on Optical Engineering Midwest'90 1396, 453-466, (1991).
[8] Hallam, K., Howell, B., Wilson, M., “Wide-Angle flat-field telescope,” USP 4,598,981, (1986).
[9] Owen, R., “Easily fabricated wide angle telescope,” Proc. SPIE 1354, 430-433, International Lens Design Conference (1990).
[10] Cook, L. G., “Fast folded wide angle large reflective unobscured system,’ US Patent 5,331,470, (1994).

## APPENDIX

TWO-MIRROR FIVE REFLECTIONS CAMERA DATA

| Surf | Type | Radius | Thickness | Conic |
|---|---|---|---|---|
| 1 | EVENASPH | 40.19958 | -22.5 | -1.61789 |
| STOP | | Infinity | -28.75 | 0.0 |
| 3 | EVENASPH | -1779.632 | 53.92634 | -4856.809 |
| 4 | EVENASPH | -63.44275 | -53.92634 | 0.09202441 |
| 5 | EVENASPH | -1779.632 | 53.92634 | -4856.809 |
| 6 | EVENASPH | -63.44275 | -62.43006 | 0.09202441 |

SURFACE ASPHERICTY DATA

Surface 1 : EVENASPH
Coeff on r 4 : 1.2233602e-005
Coeff on r 6 : -1.8265168e-008
Coeff on r 8 : 7.1968229e-011

Surface 3 : EVENASPH
Coeff on r 4 : -3.0765438e-006
Coeff on r 6 : -1.1452155e-009
Coeff on r 8 : -4.2908294e-012

Surface 4 : EVENASPH
Coeff on r 4 : 1.9337197e-008
Coeff on r 6 : 3.2096669e-012
Coeff on r 8 : 4.3949003e-016

Surface 5 : EVENASPH
Coeff on r 4 : -3.0765438e-006
Coeff on r 6 : -1.1452155e-009
Coeff on r 8 : -4.2908294e-012

Surface 6 : EVENASPH
Coeff on r 4 : 1.9337197e-008
Coeff on r 6 : 3.2096669e-012
Coeff on r 8 : 4.3949003e-016

FULLY ANNULAR CAMERA DATA:

| Surf | Type | Radius | Thickness | Conic |
|---|---|---|---|---|
| 1 | STANDARD | 186.0562 | -30 | 16.04629 |
| 2 | STANDARD | -205.6559 | 25 | 12.85757 |
| STO | | Infinity | 25 | |
| 4 | STANDARD | -76.23606 | -60 | 0.4836366 |