

## Benefits of Freeform Mirror Surfaces in Optical Design

J. Michael Rodgers  
Kevin P. Thompson  
Optical Research Associates  
3280 East Foothill Blvd. #300  
Pasadena, CA 91107-3103  
MikeR@opticalres.com  
Kevin@opticalres.com

### **Extended Abstract**

The capability of modeling anamorphic or freeform optical surfaces has long been part of commercially available optical design software programs. However, designers of cost-effective imaging systems generally avoid using freeform surfaces in the lens model due to the challenges of fabricating and testing such surfaces. If a practical and routine method of fabricating and testing freeform surfaces could be developed, this would remove existing obstacles to designing with such surfaces, and could result in their wider usage. Freeform surfaces offer substantial benefit to the optical designer and the end user by providing additional degrees of freedom that allow lower wavefront error and distortion than can be achieved with the same number of rotationally symmetric surfaces. This is especially true in unobscured mirror systems with tilted and decentered components, in which the oblique ray incidence angles introduce aberrations that are correctable by surface shapes that have different local base radii of curvature in the orthogonal directions. This paper provides examples of the benefits of freeform surfaces in the design of unobscured mirror systems in minimizing wavefront error and distortion.

### ***Introduction***

This presentation will discuss using freeform surfaces in the design of unobscured mirror systems to reduce the aberrations, especially astigmatism, distortion and coma. We will briefly discuss the origin of astigmatism in mirror systems, and the effects on the structure of the aberration across the field due to freeform surfaces. Design examples will be shown illustrating the potential improvement with freeform surfaces.

### ***Astigmatism from oblique rays***

An optical wavefront acquires aberration, especially astigmatism, when it reflects obliquely off a curved mirror that is locally rotationally symmetric. By “locally rotationally symmetric” we mean rotationally symmetric about the surface normal at the point on the surface intersected by the central ray in the beam (chief ray). Because of the obliquity, the mirror appears to have more power in the direction of the field angle. A fan of rays in the plane of the field angle will focus closer to the mirror, than a fan of rays in the orthogonal direction (Figure 1). The axial separation of the best focus for horizontal and vertical ray fans is a measure of astigmatism.

For a locally rotationally symmetric mirror, a field angle whose chief ray is coaxial with the mirror axis (normal incidence) is the only field angle where there is no astigmatism. Off axis, astigmatism increases as the square of the field angle.

### ***Benefits of freeform surfaces***

To avoid astigmatism at a single off-axis field angle, what is needed is a locally anamorphic surface (i.e. not rotationally symmetric about the local surface normal), with a longer radius in the field angle direction than in the orthogonal direction. With the rotationally symmetric surface in Figure 1 replaced by a freeform surface, the vertical and horizontal fans of rays now focus at the same point, in contrast to the astigmatic focus shift as shown in Figure 1. Figure 2 shows an astigmatism map across an extended field of view for the freeform system. The lengths of the line segments in Figure 2 indicate the magnitude of the astigmatism. Note there are two nodes (points where the aberration is zero) in the field. In this illustration, we can zero out the astigmatism for two off axis field angles (mirror images of each other), but for a range of field angles we cannot exactly zero the astigmatism. Distortion and coma also have this node behavior. Thus the key benefit of using freeform surfaces is greater control of the location in the field of nodes in the aberration field, and potentially the larger number of nodes in the field. This level of control allows us to reduce the worst-case wavefront aberration.

### ***Modeling freeform surfaces***

There are at least two ways to model locally anamorphic power. One is to take an axially symmetric surface and add tilt, decenter, and asphericity. In that case the vertex of the surface may be far off of the used part. A simple and extreme example that illustrates the point is the case of a finite object and image point. There is a solution using a rotationally symmetric conic: an ellipsoid tilted  $90^\circ$ . However, it is simpler and more efficient to model the surface without such an extreme tilt and decenter. This can be done by modeling the surface directly as an anamorphic function, an aspheric toroid.

This method of modeling can also help the fabrication process. The anamorphic or freeform surface can be thought of as a decomposition between an axially symmetric surface plus anamorphic deformations, as in the NC State process. If the axis of symmetry of the rotationally symmetric portion is in or near the used part this makes the fabrication easier using a spindle-based method in which the part rotates about an included axis.

### ***Examples***

Multiple mirror systems necessarily have the beams incident on one side of the surface normal and therefore tend to have astigmatism as one of the limiting aberrations. Therefore using locally anamorphic mirrors is essential for best performance. It is not always possible or desirable to generate the anamorphic shape by highly tilted and decentered rotationally symmetric surfaces. In any case, a surface functional form that is inherently anamorphic, like an aspheric toroid, has the degrees of freedom that more directly control the aberrations (in particular the nodes in the aberration fields). The presentation will show two examples of representative reflective designs using rotationally symmetric surfaces, and anamorphic

(freeform) surfaces. The difference in wavefront quality and distortion will be shown. The generic configurations to be shown are representative of ones that Optical Research Associates has used in the past few years in actual engineering projects. In those projects, we had restricted ourselves to rotationally symmetric surfaces due to existing limitations in fabrication. The performance of our designs would have improved if we had used the freeform shapes. Thus, implementation of the NC State freeform surface fabrication method can have an immediate beneficial impact on real-world projects.

### ***Example 1: Three-mirror imager***

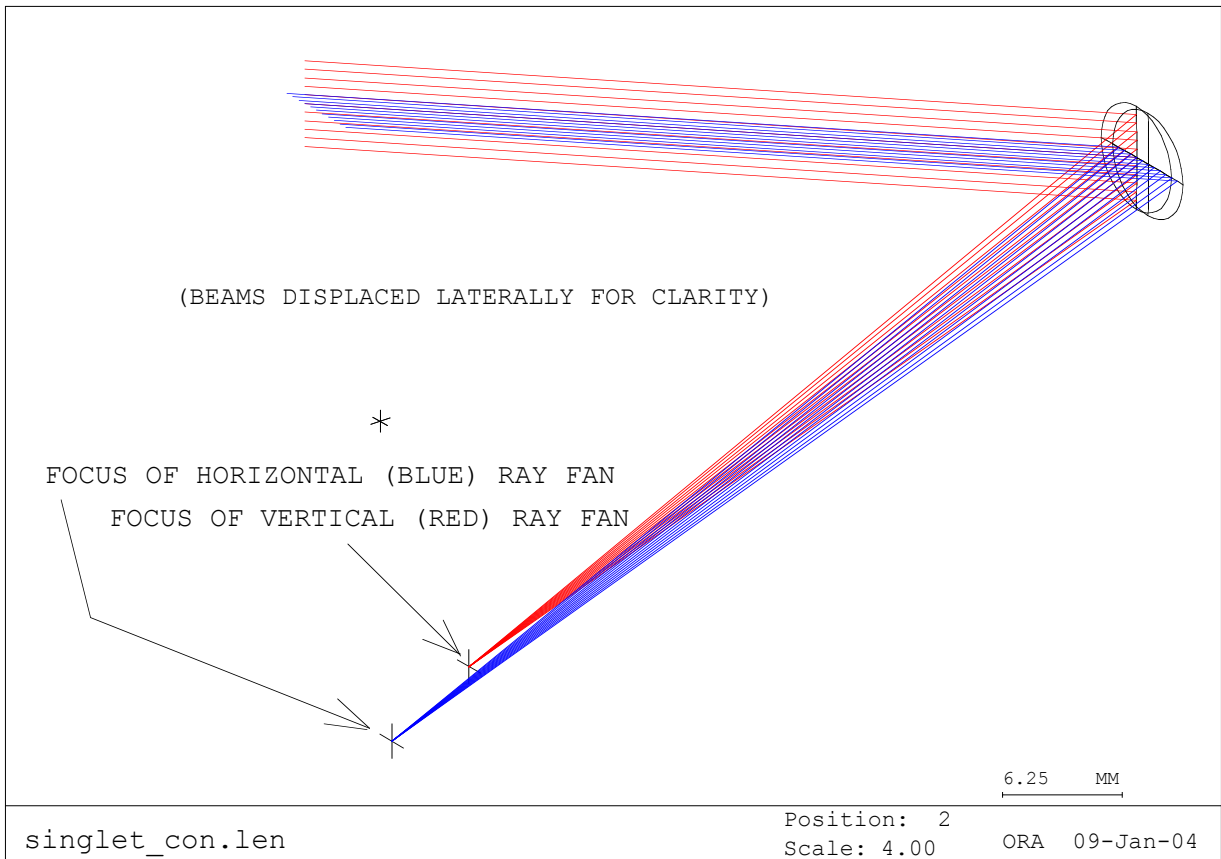
A common three-mirror design form is the reflective analogue of the Cooke triplet, with a positive primary and tertiary, and a convex secondary. The aperture stop is at the secondary in the preferred form.

The reflective triplet was optimized using standard rotationally symmetric aspheric surfaces (CODE V<sup>®</sup> surface type ASP), and also with anamorphic aspheric surfaces (CODE V surface type AAS) with the same order. In both cases the envelope and other constraints were the same. The resulting AAS design has about half the average RMS wavefront error of the ASP design. In the wavefront error plots to be shown in the presentation we see indications of node structure, as the ASP field has one broad region of minimum wavefront error, and the AAS field has two. The node structure is more pronounced as we look at Zernike astigmatism (terms 5 and 6), as shown in Figure 3. In the AAS design, astigmatism goes to zero near the top and bottom of the field of view. The ASP design has only one node, though the region of low astigmatism is broad. As noted in the Figure 3 caption, we can convert the one node in the ASP design to two nodes by changing the surfaces to AAS type and then targeting the appropriate Zernike polynomial coefficients to zero at two particular points in the field.

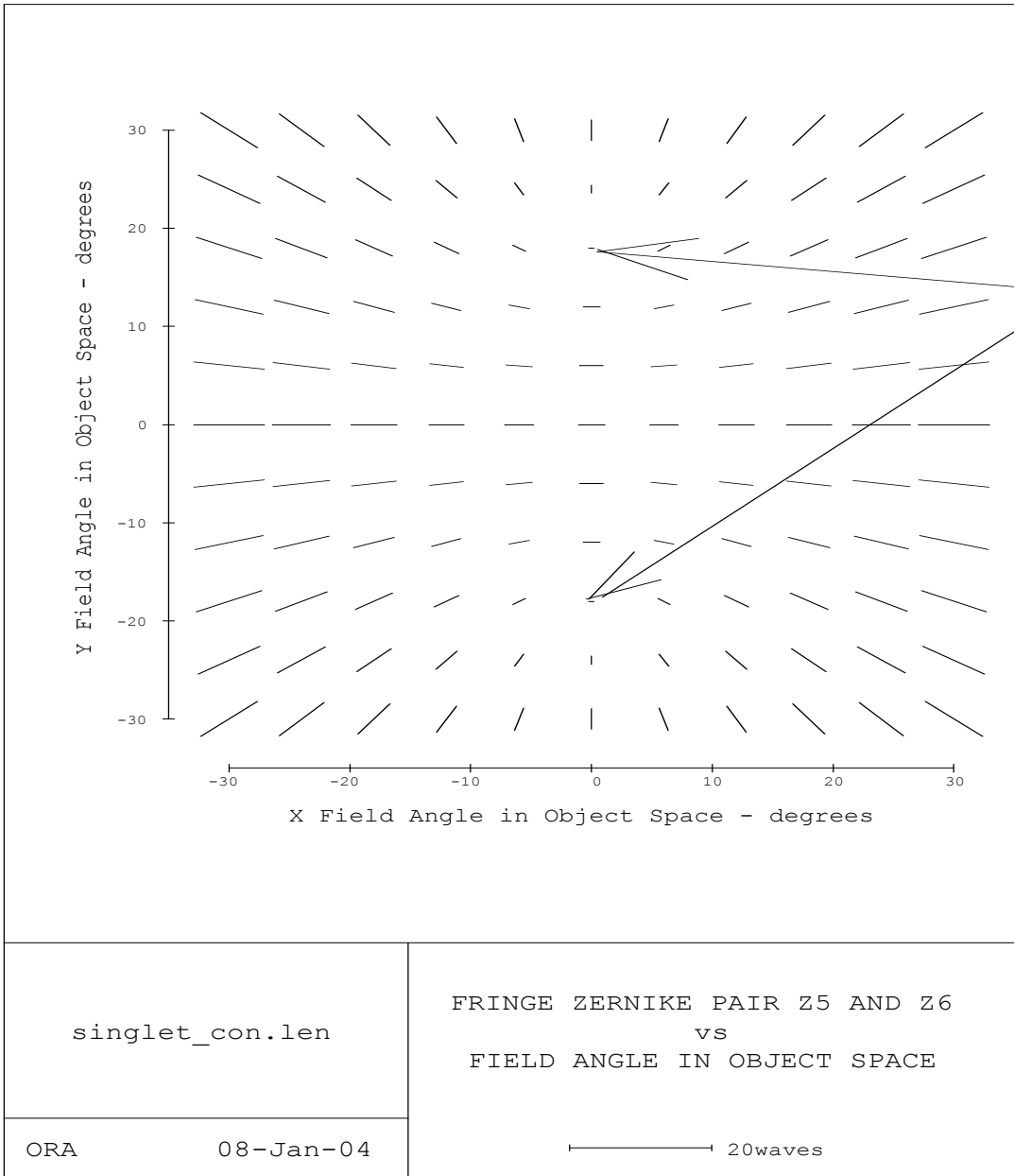
### ***Conclusions***

For fundamental reasons relating to the aberration effects of wavefronts incident obliquely on curved mirrors, freeform surfaces offer greater aberration control than rotationally symmetric surfaces. We show realistic examples of unobscured reflective imaging designs in which freeform surfaces can enable us to achieve a design with about half the wavefront error than can be achieved with rotationally symmetric surfaces, for the same number of mirrors and the same packaging constraints. Implementing a fabrication process for freeform surfaces should allow immediate benefit to the designers and users of high-performance imaging systems.

**FIGURE 1: ASTIGMATISM IN A SINGLE MIRROR**

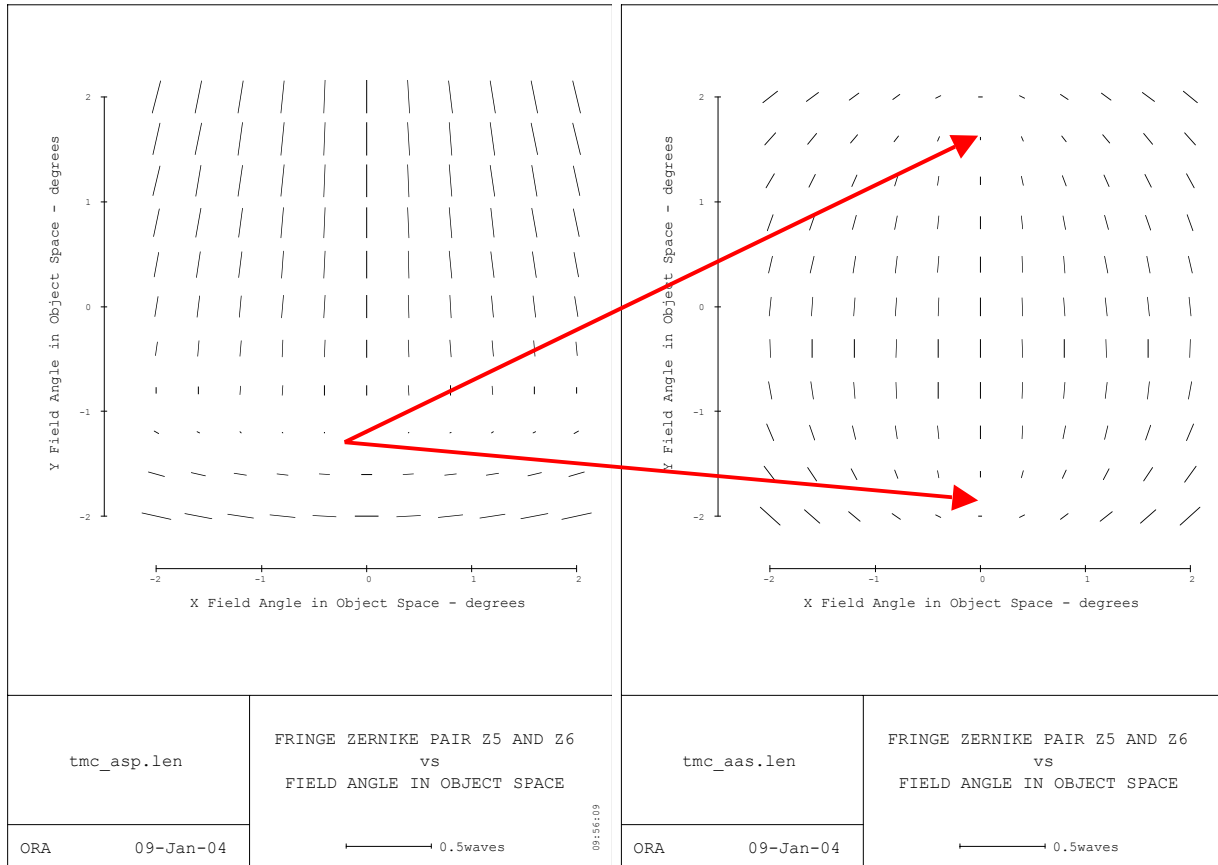


**FIGURE 2: FULL FIELD DISPLAY OF ASTIGMATISM  
IN ANAMORPHIC MIRROR. TWO ZEROS ARE CREATED**



15:54:30

**FIGURE 3: ASTIGMATISM FIELDS (ZERNIKE TERMS Z5/Z6)  
REFLECTIVE TRIPLET**



Rotationally symmetric aspheres

Anamorphic aspheres

Optimization of the design, using specific Zernike coefficients as the targets, can place nodes at particular user-selectable points in the field, as shown above. The one-node solution with a rotationally symmetric design (left) can be transformed into a two-node solution with a freeform design (right).