# Testing Generalized Rotationally-Symmetric Aspheric Optical Surfaces Using Null Reflective Compensating Components

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## Abstract

A new technique for the testing of generalized rotationally-symmetric aspheric surfaces is presented. The technique utilizes commercially available interferometric equipment and unique aspheric compensating components. For each test, the aspheric compensating component is designed as a null reflective end-mirror in the interferometric cavity containing the aspheric surface under test. The aspheric compensating component can be produced by diamond-machining techniques. The design methodology, limitations of the technique and examples are presented.

## Introduction

New fabrication techniques have provided the optical designer with opportunities to employ unconventionally fast and radically aspheric surfaces. The ability to fabricate aspheric surfaces has always depended on adequate testing techniques. Because of its sensitivity and non-contact nature, interferometric testing has been a preferred method for providing surface evaluation.

Interferometric testing of aspheric surfaces usually requires the use of an auxiliary optical system. When used in conjunction with the aspheric component under test, the auxiliary optical system traditionally known as a null compensator provides a suitably corrected wavefront for analysis. The history of null compensators contains many interesting examples of inventive lens design. (1) Though traditionally important as a means for evaluating astronomical objectives and secondaries, their use is not restricted to these surfaces alone. More recently, the use of synthetic holograms to provide appropriately distorted wavefronts for interferometric aspheric surface testing has expanded the variety of testable surfaces. (2) Together, traditional null compensator and computer-generated holography (CGH) techniques have been the preferred testing methods for aspheric surfaces. The technique described in this paper offers a new choice for surface testing.

This new technique involves the design of an aspheric null compensator as the end-mirror in an interferometric cavity containing the aspheric surface under test. The aspheric nature of the reflective null compensator requires it to be produced by an appropriate technique such as diamond machining.

This paper will review the general methodology of the aspheric null compensator design and present a design example. The design example will include the controlling equations for a null compensator's geometry and several fabricated test examples of different aspheric surfaces. A review of the technique's advantages and limitations will conclude the paper.

## Design Methodology

The design of these new null compensators is based on the principle that "by making one surface of any centered system aspherical, it is possible, in general, to ensure exact axial stigmatism". (3) Schematically, an axial meridional ray fan can be traced from an object conjugate to the aspherical surface under test and then to the reflective null compensator. By using the null compensator as a non-shearing retro-reflecting end-mirror, with the appropriate aspherical geometry, the rays can be returned to the original axial conjugate. The selection of an appropriate object conjugate is the first step in the design.

Three factors influence the choice of an appropriate object conjugate. First, the size of the wavefront caustic produced by the meridional ray fan will restrict the position of the conjugate. Second, for the testing of a single surface in reflection, the null compensator may obscure some of the mirror under test. The size of the permissible obscuration may further restrict the choice of conjugate. Third, the use of convenient alignment surfaces on the surface under test and null compensator may make a particular conjugate preferred (e.g. infinity).

After selecting an appropriate object conjugate, a meridional ray fan is traced from the object conjugate off the surface under test and beyond (see Figure 1). An evaluation of the wavefront caustic produced by this ray fan will suggest an appropriate axial (vertex) distance from the surface under test to a null compensator. This distance is selected to minimize the size of the null compensator and to keep it outside the caustic formed.

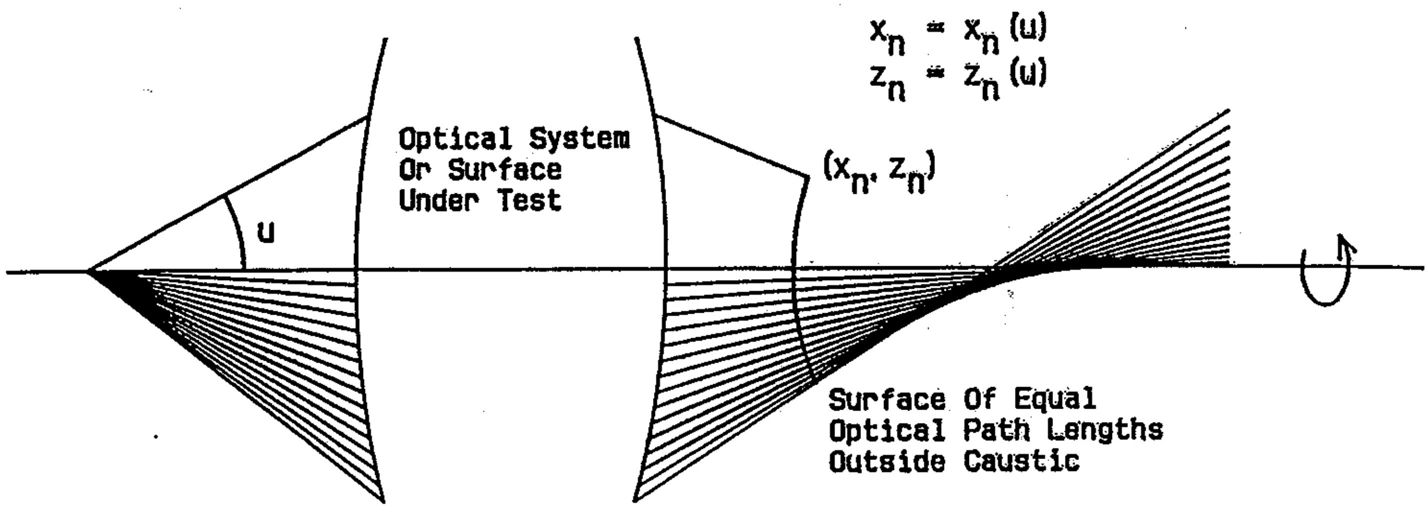



Figure 1 – Design Methodology

Having determined a position of the null compensator, the total optical path length for the axial ray is determined from object conjugate to null compensator. The axial meridional fan is then retraced. The position where each ray has the same total optical path length as the axial ray will then define the aspherical surface coordinates of the null compensator. These surface coordinates are thus defined parametrically as functions of object angle (u) for both their position along the optical axis (z) and as their height above the optical axis (x). For an infinite object conjugate, the surface will be defined parametrically as a function of input ray height above the optical axis.

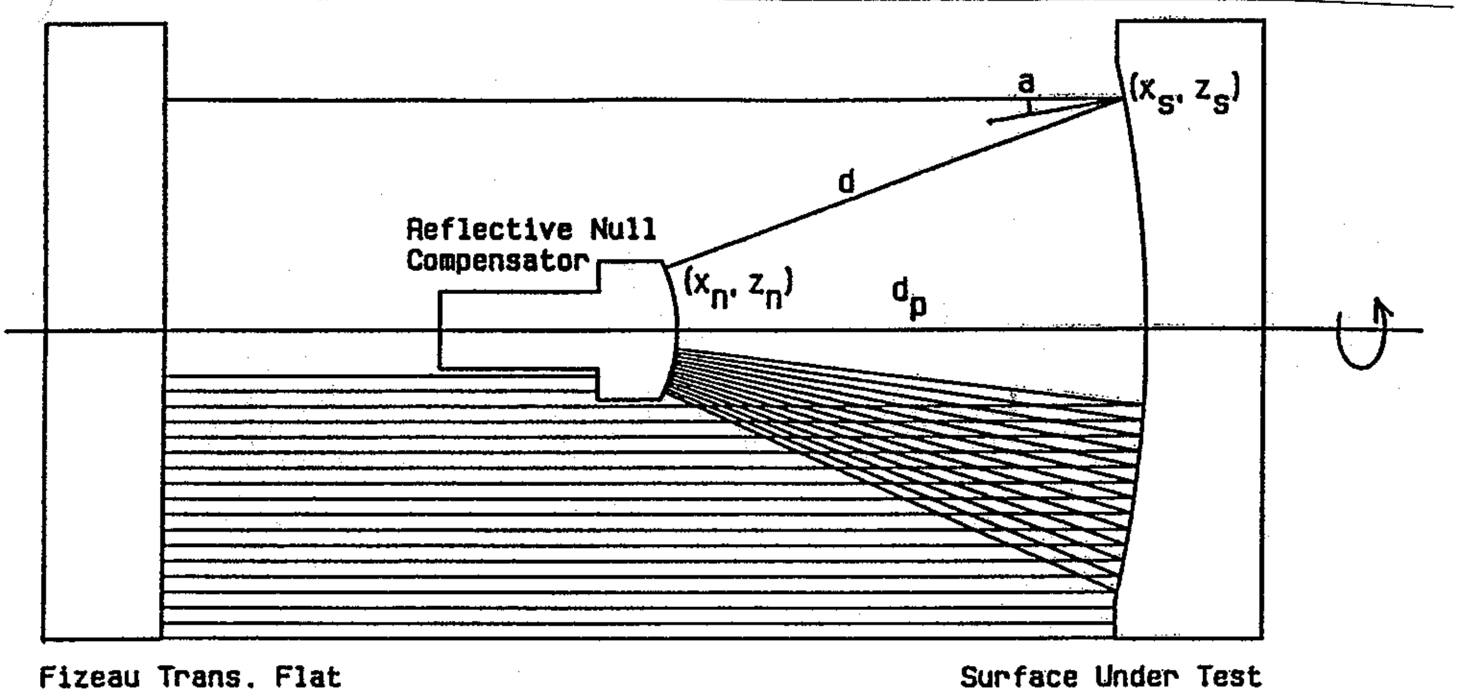
Surface coordinates must satisfy the following conditions: The function of height from the optical axis (x) must be monotonic in object ray angle (u). A differential analysis of the surface coordinates must show that the surface will not exceed the limits of fabrication accuracy. Finally, the overall size of the null compensator must be neither too large in obscuration nor too small to preclude fabrication. It is often helpful to represent the surface by a closed form sagitta approximation to aid in this analysis.

## Design Example

The design example chosen for this paper is the testing at an infinite, object conjugate of a rotationally-symmetric concave reflective generalized aspheric surface. This has been the most common application of this form of testing to date. Many concave optical asphered germanium and silicon lens surfaces have been tested in reflection this way, in addition to front surface mirrors.

Figure 2 describes the optical geometry of the test. Because an infinite conjugate is used, ray paths are calculated from the vertex of the aspheric surface under test. The generating equations for the parametric expressions that describe the null compensator's surface are shown below (equations 1 through 5). In this sign convention used all quantities are positive except the sagitta (z) of the null compensator. With this convention a machining tape can be prepared from the parametric expressions directly.

Four sample surfaces were fabricated along with their corresponding null compensators. The first surface was a parabola of revolution (f/1.14). The second was a sphere, chosen for its ability to be tested conventionally for comparison purposes. The third surface was an oblate ellipsoid. It was selected because oblate ellipsoids are the only family of conic surfaces of revolution that cannot be tested conventionally at axial conjugates. The final surface fabricated was an aconic surface of revolution. It was created by adding an absolute-valued cubic polynomial term to the first surface's parabola. Specific descriptions of the four surfaces are given in Table 1. Information about the degree of surface asphericities is described in Table 2. The caustics formed by each surface for an infinite object conjugate are shown in Figure 3. From these caustics appropriate vertex separations were selected.




$$z_s = z_s(x_s) \qquad \{\text{eg.} \quad z_s = \frac{cx_s^2}{1+\sqrt{1-(k+1)c^2x_s^2}} + a_1x^4 + a_2x^6 + a_3x^8 + a_4x^{10}\} \qquad (1)$$

$$a = \tan^{-1}(dz_s/dx_s) \qquad (2)$$

$$d = d_p + z_s \qquad (3)$$

note: $z_s$ is positive

$$x_n = x_s - d\sin(2a) \qquad (4)$$

$z_n$ is negative

$$z_n = d_p - z_s - d\cos(2a) \qquad (5)$$

Figure 2 - Design Example

| title | c | k | a | dia. |
|---|---|---|---|---|
| Paraboloid | 1/8.0 in$^{-1}$ | -1.0 | 0.00000 in$^{-2}$ | 3.5 in |
| Sphere | 1/8.0 in$^{-1}$ | 0.0 | 0.00000 in$^{-2}$ | 3.5 in |
| Ellipsoid | 1/8.0 in$^{-1}$ | +1.0 | 0.00000 in$^{-2}$ | 3.5 in |
| Aconicoid | 1/8.0 in$^{-1}$ | -1.0 | 0.00125 in$^{-2}$ | 3.5 in |

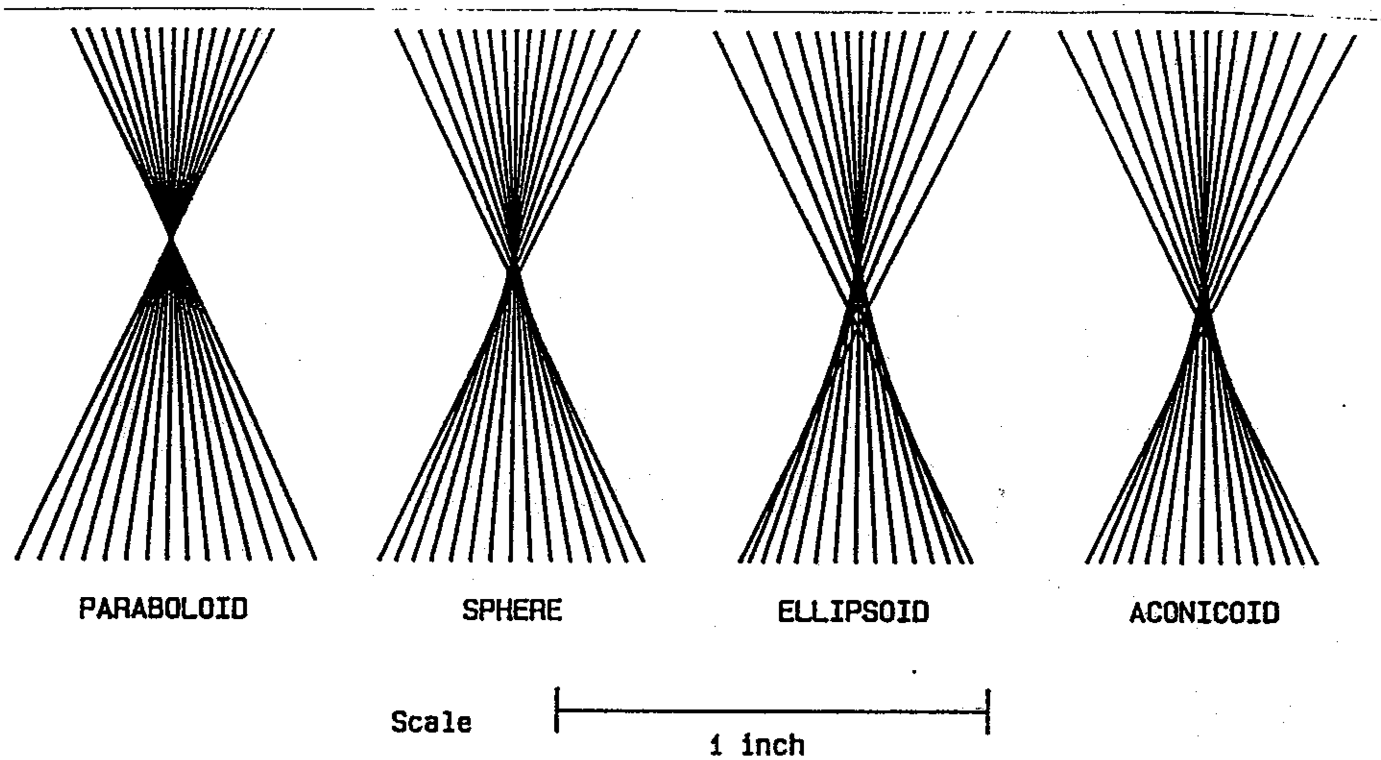
$$z_s = \frac{cx_s^2}{1+\sqrt{1-(k+1)c^2x_s^2}} + ax_s^3$$

Table 1

| title | difference from central paraboloid | difference from central sphere | difference from best-fit paraboloid | difference from best-fit sphere |
|---|---|---|---|---|
| Paraboloid | 0 | -94 | 0 | 23 |
| Sphere | +94 | 0 | -24 | 0 |
| Ellipsoid | +193 | +99 | -50 | -25 |
| Aconicoid | +269 | +175 | -40 | -15 |

differences expressed in waves ( 1 wave = 632.8 nm)

Table 2




Sample Caustics

## Alignment Considerations

As with all other null compensator tests for aspheric surfaces, especially holographic tests, component alignments are critical. The use of conjugate-centered reference surfaces to simplify alignment considerations cannot be overstressed. Below is a description of the alignment procedure for the design example that takes advantage of these reference surfaces. Because of the use of these reference surfaces on both the optical component under test and the reflective null compensator, the time required to position components for testing has been reduced to several minutes.

Component alignment has been greatly simplified in this example by the choice of an infinite object conjugate. Surrounding the clear aperture of each aspherical surface under test is an annular flat perpendicular to the optical axis of the aspherical surface and fabricated in the same machining set-up. On the rear surface of each corresponding null compensator is a small annular flat, likewise perpendicular to its compensator's optical axis. These reference surfaces are the key to the ease of alignment.

After the Fizeau transmission flat of the interferometer is adjusted to the optical axis of the interferometer, the null compensator is placed in the center of the interferometer's aperture. Only two degrees of tilt (x,y) are required to square the compensator's null surface to the interferometer plano wavefront. Next, the component under test is aligned in a mount with five degrees of freedom, x,y,z translation and x,y tilt. First the reference surface of the component is squared to the interferometer's plano wavefront using only the two tilt adjustments. Next, the two components are centered by translating the component under test in the x and y directions. Finally, the alignment is completed by focusing the component under test to the null compensator using the z translation. A photograph of the testing set-up is shown in Figure 4.

In the final interferogram of the component test, there are three separate interference patterns. The most centrally located pattern will be from the null compensator's reference surface. The large middle interference pattern will be of the surface under test (tested in double reflection) and the null reflective compensator's surface (tested in single reflection). The outermost pattern will be from the reference of the surface under test.

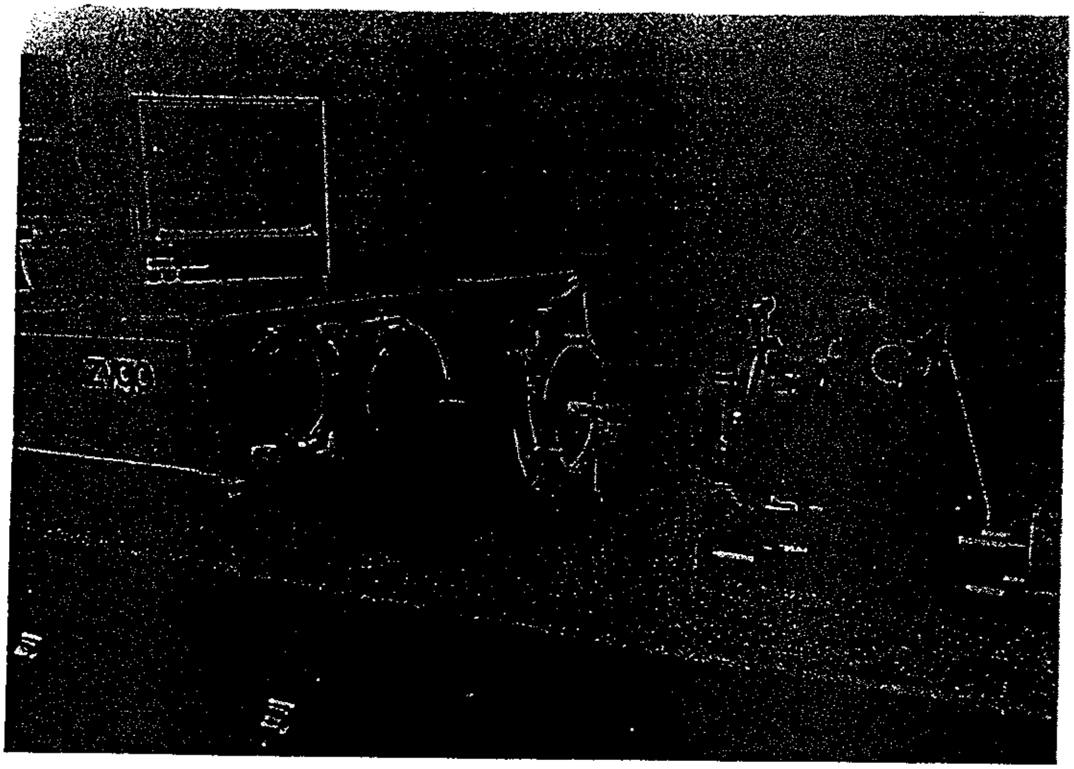
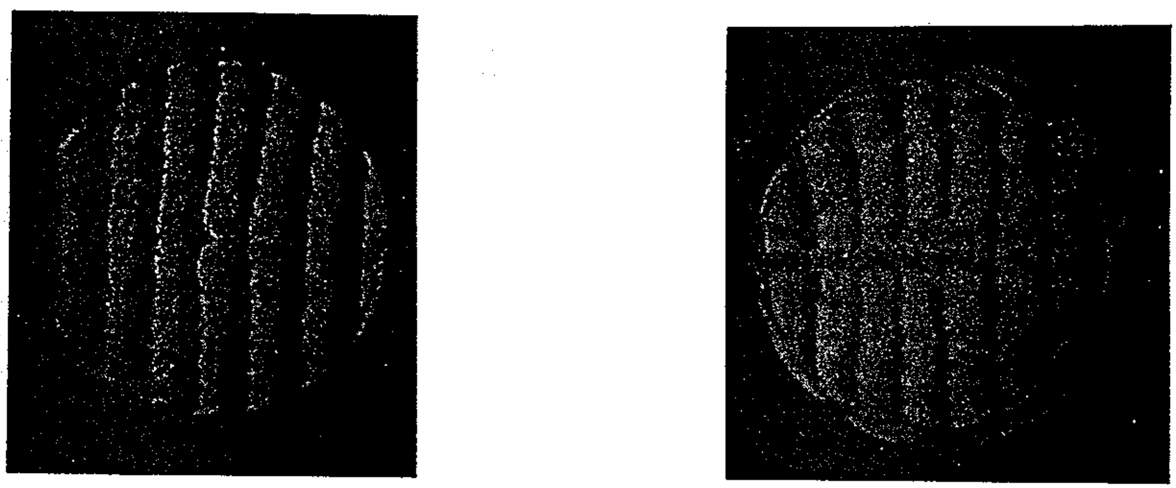


Figure 4

## Sample Evaluations

All test samples were machined on a Pneumo Precision Model MSG-325 Diamond Machining lathe. In the combined interference patterns for each surface tested there was less than one fringe of error in the resultant wavefronts. The interference pattern is interpreted as: one fringe of error in the wavefront is caused by one-quarter wave of surface error from the surface under test added to (in either a plus or minus fashion) one-half wave of surface error from the null compensator. Because the spherical surface is capable of being tested conventionally, its resultant interferograms are shown below in Figure 5.



Sphere Tested Conventionally
1 fringe = 1/2 wave (surface error)

Sphere Tested with Null Compensator
1 fringe = 1/4 wave (surface error)
+ 1/2 wave (null compensator)

Figure 5

The interferogram taken using the null compensator has a reduced contrast when compared to the conventional interferogram. This is due to propagated scatter from the multiple diamond-machined reflections. The interference pattern also displays higher wavefront gradients. This likewise results from the three-fold increase in reflections.

## Additional Applications

The technique of using these null compensators is not restricted to the testing of single reflective aspheric surfaces. They can also test transmissive components that produce uncorrected wavefronts, or sub-assemblies of components that yield aberrated wavefronts. The aspheric nature of these null compensators also permits the testing of corrected systems at more convenient conjugates than those at which the system is intended to function. Similarly, a system corrected at one wavelength can be tested at a more convenient wavelength by designing the aspheric null compensator to correct the resultant spherochromatism. These null compensators have been used in system testing where key components (domes or internal windows) are missing from the system.

One very useful application of the technique is in component alignment. A series of null compensators can be designed for the progressive assembly of an optical system. For instance, three null compensators might be used in the assembly and test of a catadioptric optical system consisting of a primary and secondary mirror, field flattener lens, and internal detector windows. One null compensator might be used to test the primary mirror in position. After the removal of the compensator and the insertion of the secondary mirror, a second null compensator can be used to properly align and test the primary and secondary mirror as an uncorrected system. This null compensator can then be removed as the field flattener lens is inserted, and another null compensator can be used to position this component. Such a progressive assembly and test of components can simplify the diagnosis of a troubled system.

## Limitations

The technique of using aspheric null compensators has two principal limitations. One limitation, the certification of the aspheric compensator surface, is not a severe problem if the null compensator is designed to be either small or, by the appropriate choice of conjugates, nearly flat. A small compensator can be contact probed to optical accuracies by a device such as the Rank Taylor Hobson Form Talysurf, and a nearly flat compensator can be tested for out-of-flatness. Probing may be destructive, but this is not a serious limitation since null compensators are used only for testing and not as final system components. Asymmetrical errors in the test can be traced to either the compensator or the surface under test by rotating one component.

Even in those cases where the null compensator does not lend itself to contact surface testing, there are several reasons to respect the accuracies of the compensator. Since the compensator is generally small, requiring little time for diamond machining, errors due to machine tool geometries and thermal considerations are minimized. Since the diamond tool sweep used in null component fabrication is generally much less than that used to produce the aspheric surface under test, errors due to diamond tool out-of-roundness are minimized. There are no fabrication errors associated with incorrect tool radius (nose) compensation because an error in this respect will generate a different, but equally valid, compensation surface. (These surfaces are analogous to system testing with a reference sphere where the exact radius of the sphere is unimportant.) Fabrication errors due to poor aspect ratio and mounting problems can be eliminated by proper compensator mechanical designs.

The other major limitation of this technique is obscuration. This can be minimized by the choice of initial test design conjugates. Likewise, it is possible to design the test to work at a finite conjugate with the object conjugate at the center of a perforated aspheric null compensator (in a similar fashion to testing a paraboloid with a perforated reference flat or a Hindle-type test). Appropriate test conjugates will often permit obscuration-free testing of off-axis generalized aspheres and primary mirrors with central holes.

## References

(1) Offner, A. "Null Tests Using Compensators", Chapter 14 in Optical Shop Testing, ed. Daniel Malacara, John Wiley and Sons, 1978.

(2) Wyant, J.C. "Holographic and Moire Techniques", Chapter 12 in Optical Shop Testing, ed. Daniel Malacara, John Wiley and Sons, 1978.

(3) Born, Max and Emil Wolf, "Principles of Optics", Pergamon Press, 1975, pg. 197.