DESIGN AND ANALYSIS OF DIFFRACTIVE ASPHERIC NULLS

Steven M. Arnold
Diffraction International, Minnetonka, MN

Diffraction International has developed a general methodology for designing diffractive aspheric null lenses. We use commercially available optical design software supplemented by proprietary extensions that automate the repetitive and laborious tasks.

The methodology is illustrated by three examples involving nulls for rotationally symmetric, off-axis and biconic aspheres. The methods are readily extendable to free form optics.

Null Wavefront from Snell's Law

We design using OSLO™ software because its menus and commands are readily customizable, although our methods are presumably applicable to other commercial optical design software.

We begin each null test design with the desired null wavefront—everywhere perpendicular to the aspheric surface. This null wavefront is most easily modeled by refracting from a fictitious zero-index glass into air at the aspheric surface boundary (Figure 1). The wavefront to the left of the aspheric surface is arbitrary, but a collimated wavefront is most convenient. The raytrace software does not permit the fictitious glass to have exactly zero index because that would make the reverse ray trace indeterminate. OLSO™ allows $n \geq$ 1E-20 whereas ZEMAX™ allows $n \geq$ 1E-10. The OPD error from assuming a non-zero index ε is on the order of εS where S is the range of asphere surface sag.

Starting at the null wavefront avoids the ray aiming and pupil sampling issues that would result if we started from a spherical or collimated (stigmatic) source. A dense bundle of optimization rays can be readily defined to appropriately sample the asphere aperture. Aperture sampling and ray aiming are unaffected by subsequent optimization.

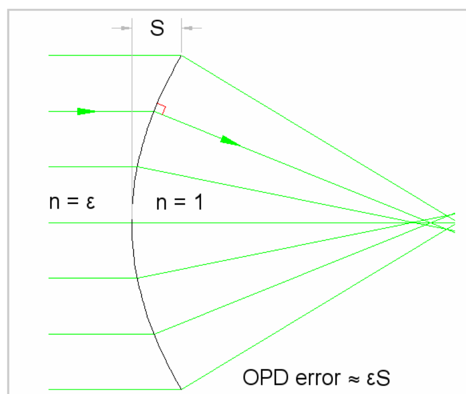

Figure 1: Snell's law and fictitious, zero-index glass yield null wavefront.

Our task is thus reduced to designing a refractive, reflective, diffractive or hybrid null that will bring this null wavefront to near perfect focus or collimation. Design constraints include mating the wavefront to an available interferometer objective while managing pupil distortion, alignment sensitivities, spurious diffraction orders and manufacturing concerns.

Example 1 — Rotationally Symmetric Concave Asphere

Our first example (Figure 2) is a concave, rotationally symmetric asphere with about 35 microns aspheric departure. We locate a CGH (*i.e.* diffractive) null in a converging F/1.5 wavefront and introduce a 2-mm decenter and a 2-mm field stop to block spurious diffraction orders.

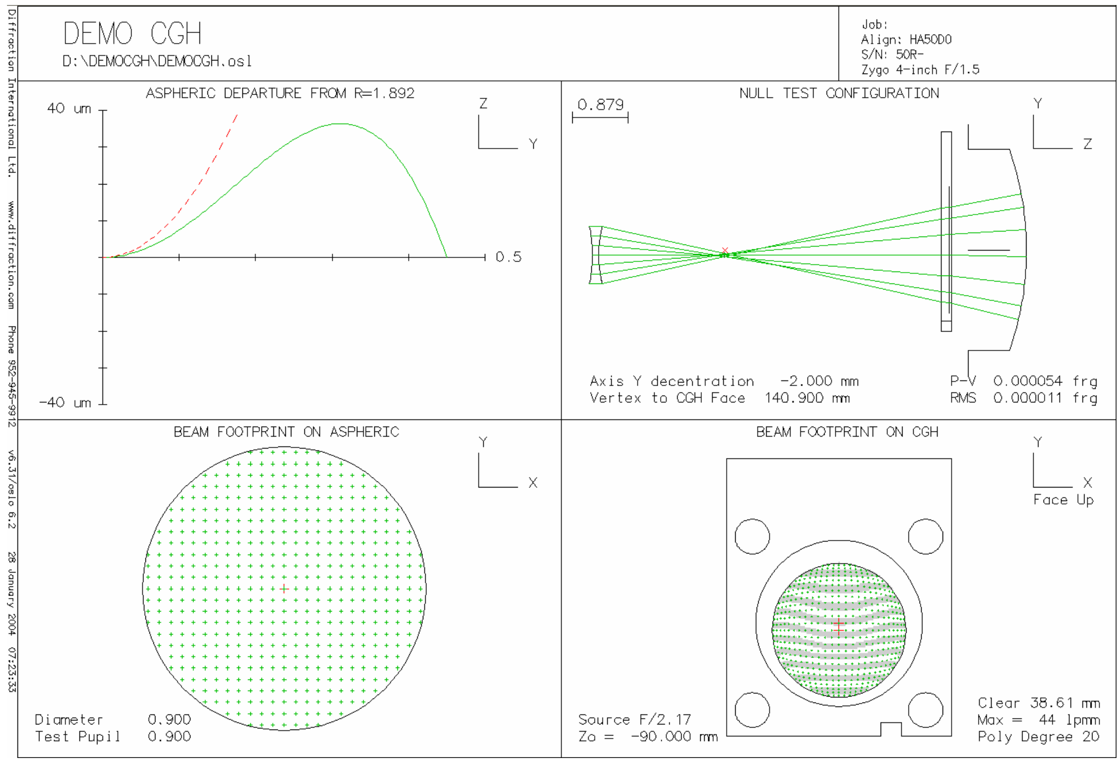

Figure 2. Null test of rotationally symmetric asphere with imposed 2-mm decenter between asphere and interferometer axes. A rectangular grid of rays at the asphere undergoes barrel distortion in propagating to the CGH face. The binary “fringe” pattern is a coarse representation of the CGH grating—the actual spatial frequency is near 44 lpmm.

Table 1. Abbreviated listing of Figure 1 null test design. The CGH diffractive surface has been decomposed into a rotationally symmetric phase function “CGH Phase” centered on the asphere axis and a two-point-source phase function “CGH Carrier” centered on the CGH and interferometer axes; OSLO does not permit both types on a single surface. Phase functions on coincident surfaces add arithmetically. Lens units are inches.

```
*LENS DATA
DEMO CGH
 SRF        RADIUS        THICKNESS    APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ          --         1.0000e+20     1.0000e+14            ZERO       Collimated
 AST          --             --           0.450000 AS         ZERO    *  Aperture Stop
  2      -2.151000        0.100000        0.450000            ZERO    *  Dummy 1st Surf
  3       1.692913        1.984252        0.450000 K           AIR    *  ASPHERIC

  4           --             --           0.039370 K           AIR    *  Field Stop

  5           --          0.118110        1.000000 K      SILICA C *  CGH Backside
  6           --             --           0.760000 K      SILICA C *  CGH Phase
  7           --          1.228740        1.000000 K           AIR    *  CGH Carrier

  8      -4.772047       -4.772047        1.592520 K           AIR    *  4-inch F/1.5

 IMS          --             --         2.5306e-07 S                     Cat's Eye

*TILT/DECENTER DATA
  5       DT     1         DCX       --        DCY     0.078740    DCZ       5.429134
          GC     3         TLA       --        TLB        --       TLC         --
  6       DT     1         DCX       --        DCY    -0.078740    DCZ         --
                           TLA       --        TLB        --       TLC         --
  7       DT     1         DCX       --        DCY     0.078740    DCZ         --
                           TLA       --        TLB        --       TLC         --
*HOLOGRAPHIC OPTICAL ELEMENT DATA
  2       HOR    1         HWV      0.632820
          HV1    1         HX1       --        HY1    -0.078740    HZ1      -3.543307
          HV2    1         HX2       --        HY2        --       HZ2      -3.543307
```

A double pass raytrace model is necessary to check for ghosting from unwanted diffraction orders and accurately model alignment sensitivities. Using OSLO's compiled command language (CCL), we have authored proprietary command extensions (macros) to reverse single pass raytrace models and convert them to double pass (Table 2) with two mouse clicks. This feature is invaluable when it becomes necessary to revise a single pass model.

Table 2. Double pass equivalent of Table 1. Surfaces 7 through 11 are defined by surface data and global coordinate pickups of surfaces 5 through 1 respectively.

```
*LENS DATA
DEMO CGH
 SRF      RADIUS       THICKNESS   APERTURE RADIUS       GLASS  SPE  NOTE
 OBJ       --           4.772047      1.000000             AIR     Cat's Eye

  1     -4.772047         --          1.592520 K           AIR   * 4-inch F/1.5

 AST       --             --          1.000000 AK       SILICA C * CGH Carrier
  3        --      P   -0.118110      0.760000 K        SILICA C * CGH Phase
  4        --             --          1.000000 K           AIR   * CGH Backside

  5        --             --          0.039370 K           AIR   * Field Stop

 RFS     1.692913         --          0.450000 RK      REFLECT   * ASPHERIC

  7        --      P      --          0.039370 PK          AIR P * Field Stop

  8        --      P      --          1.000000 PK       SILICA P * CGH Backside
  9        --      P      --          0.760000 PK       SILICA P * CGH Phase
 10        --      P      --          1.000000 PK          AIR P * CGH Carrier

 11     -4.772047 P   -4.772047 P     1.592520 PK          AIR P * 4-inch F/1.5

 IMS       --             --          1.000002 S                   Cat's Eye

*VERTEX COORDINATES AND DIRECTIONS w.r.t. CGH FACE (mm,deg)
                      X            Y            Z          TLA         TLB         TLC
  Cat's Eye          --           --      -90.000000
  4-inch F/1.5       --           --       31.210000       --          --          --
  CGH Carrier        --           --          --           --          --          --
  CGH Phase          --       -2.000000       --           --          --          --
  CGH Backside       --           --       -3.000000       --          --          --
  Field Stop         --       -2.000000   -90.500000       --          --          --
  ASPHERIC           --       -2.000000  -140.900000       --          --          --

*VERTEX COORDINATES AND DIRECTIONS w.r.t. ASPHERIC (inches,deg)
                      X            Y            Z          TLA         TLB         TLC
  Cat's Eye          --        0.078740     2.003937       --          --          --
  4-inch F/1.5       --        0.078740     6.775984       --          --          --
  CGH Carrier        --        0.078740     5.547244       --          --          --
  CGH Phase          --           --        5.547244       --          --          --
  CGH Backside       --        0.078740     5.429134       --          --          --
  Field Stop         --           --        1.984252       --          --          --
```

Our ghost analysis consists of a composite spot diagram (Figure 3) produced by tracing all combinations of diffraction orders through the double pass model. For each combination of orders, the number of rays traced is proportional to the product of the expected diffraction efficiencies. Using proprietary OSLO CCL commands, this analysis is accomplished with two mouse clicks plus a few keystrokes.

We perform a detailed sensitivity analysis which consists of perturbing one physical parameter at a time while optimizing selected compensators (typically alignment of the asphere). The optimization merit function consists of RMS OPD for a dense bundle of rays. Ray failures are excluded from the RMS. To enforce the case of zero tilt fringes in the interferogram, we constrain one reference ray to return to the same field point coordinates. For each such perturbation, we compute interferogram PV, RMS and Zernike decomposition as well as compensator values. Using proprietary OSLO CCL commands, this is all accomplished with two mouse clicks plus a keystroke. We find OSLO's standard sensitivity analysis tools to be not very useful in this task.

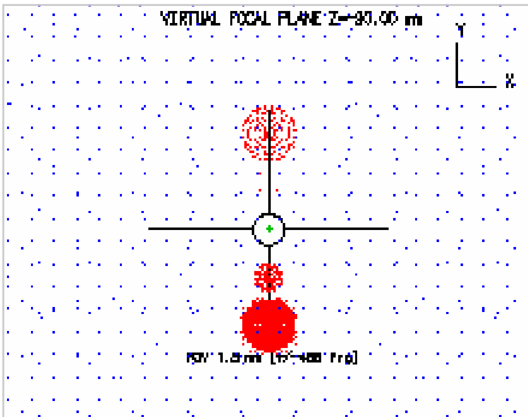

Figure 3. Ghost diffraction spot diagram at virtual focal plane. The central circle contains the design diffraction order (well focused) and represents a 1.3 mm FOV (approximately ±500 tilt fringes).

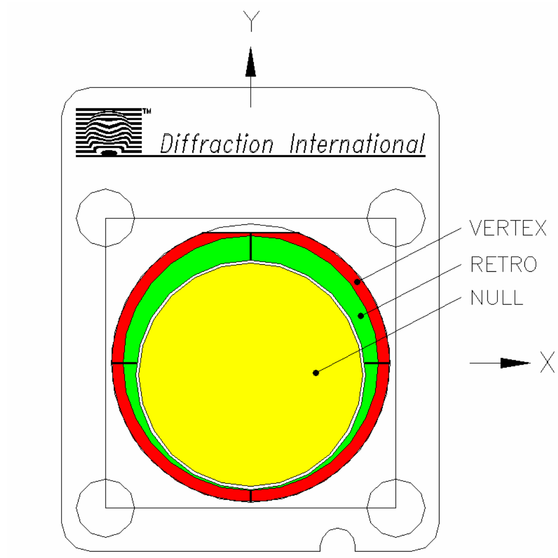

Figure 4. CGH aperture layout.

This CGH incorporates a retro-reflecting, annular grating for alignment of CGH to Fizeau sphere and a vertex-focused alignment spot for visually centering the asphere and confirming its distance (a check on base radius).

Example 2 — Concave Off-Axis Biconic (IRMOS M4)

Our second example is the concave, highly off-axis, biconic M4 mirror of the James Webb Space Telescope/Infrared Multi-Object Spectrometer (IRMOS). This mirror measures 94 mm by 76 mm and is centered about 227 mm from the parent axis. The design was somewhat complicated by the need to work with the M4 mirror in a vacuum dewar and the CGH and interferometer. The design also needed to work for testing outside the dewar.

Disliking user-defined surfaces, we needed to first request that the biconic surface type be added to OSLO. Once that had been implemented, modeling of the null wavefront was no more difficult than for any rotationally symmetric asphere—it just followed from Snell's law.

Our design (Figures 5) is a bilaterally symmetric null test from center of curvature with the CGH null in a converging F/1.5 wavefront. We (belatedly) imposed a constraint that the M4 backside datum surface, the dewar window and the CGH all be parallel. The CGH has a maximum spatial frequency of about 42 lpmm. The pupil distortion is fairly minimal. The design was optimized for use outside the dewar. After adding the 22.55-mm thick dewar window, substituting vacuum for air inside and respacing the M4 mirror, the design residual (to be compensated by a software null) was only about 0.6 fringes.

This CGH null incorporates several alignment features (Figure 6). These include a retro alignment aperture, a collimated wavefront perpendicular to the M4 backside datum surface and two focused spots at the prescribed locations of fiducials on the datum surface. The focused spots were used to align marks against which the datum surface was later registered.

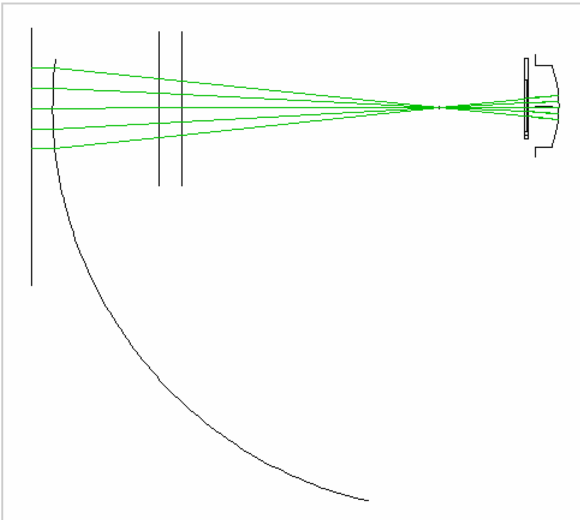

Figure 5. This null test of the highly off-axis biconic asphere IRMOS M4 begins with a datum surface that is the back side of the M4 mirror. Two parallel dummy surfaces represent a dewar window parallel to the CGH face. This design is optimized for use in air (without window), but can be respaced for testing in a vacuum dewar with only about 0.6 fringe of residual aberration.

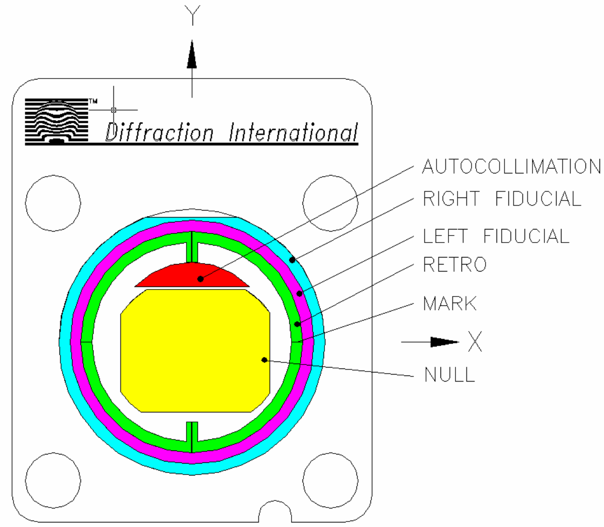

Figure 6. IRMOS M4 CGH aperture layout includes a retro-reflection feature for alignment of CGH to interferometer, an autocollimation feature for defining orientation of the datum surface and dewar window, two annular apertures that focus onto fiducial marks at left and right edges of the asphere aperture and reticle marks to define the CGH coordinate system.

Table 3. Abbreviated single pass listing of IRMOS M4 null test design. Global coordinates reference all components to datum surface ABC.

```
*LENS DATA
IRMOS M4 DWG 2045987 parallel
 SRF       RADIUS       THICKNESS    APERTURE RADIUS       GLASS   SPE  NOTE
 OBJ         --        1.0000e+20     1.0000e+14            ZERO       Collimated
 AST         --            --          60.000000 AS         ZERO       Aperture Stop
  2          --         94.291000     127.433572 KX         ZERO     * Datum ABC
  3     406.882900         --         267.118693 KX          AIR     * ASPHERIC

  4          --         22.550000      76.200000             AIR     * Dewar Window

  5          --            --          76.200000             AIR     * Dewar window

  6          --            --           2.700000 X           AIR     * Field Stop

  7          --          3.000000      25.400000 K        SILICA C * CGH Backside
  8          --            --          17.000000 KX       SILICA C * CGH Phase
  9          --         31.210000      25.400000 K           AIR     * CGH Carrier

 10    -121.210000    -121.210000      40.450000 K           AIR     * 4-inch F/1.5

 IMS         --            --          15.205612 S                     Cat's Eye

*TILT/DECENTER DATA
  2       DT     1          DCX     45.990000    DCY    -47.967000    DCZ        --
                            TLA        --        TLB        --        TLC        --
  3       DT     1          DCX    -45.990000    DCY   -180.706000    DCZ        --
                            TLA     35.300000    TLB        --        TLC        --
  4       DT     1          DCX    -45.990000    DCY     47.967000    DCZ    125.000000
          GC     2          TLA        --        TLB        --        TLC        --
  6       DT     1          DCX    -45.990000    DCY     48.771000    DCZ    402.300000
          GC     2          TLA        --        TLB        --        TLC        --
  7       DT     1          DCX    -45.990000    DCY     50.371000    DCZ    486.000000
          GC     2          TLA        --        TLB        --        TLC        --
```

Example 3 — Convex Off-Axis (IRMOS M1)

Our final example is the convex and off-axis IRMOS M1 mirror. This design is a hybrid null consisting of a symmetric biconvex BK7 singlet located near the M1 and a large CGH in a diverging F/3.3 wavefront. Once again, we found it advantageous to constrain the dewar window and CGH face to be parallel to the M1 backside datum surface. We further constrained the biconvex singlet axis to be perpendicular to the datum surface. The CGH is large so that it can be further from the focus, thereby reducing pupil distortion. The minimum grating spacing is about 37 lpmm.

The alignment feature are similar to those of the M4 mirror. An auxiliary CGH null was created to certify the BK7 singlet in a transmission configuration. The CGH null includes an alignment feature for the near surface of the biconvex singlet.

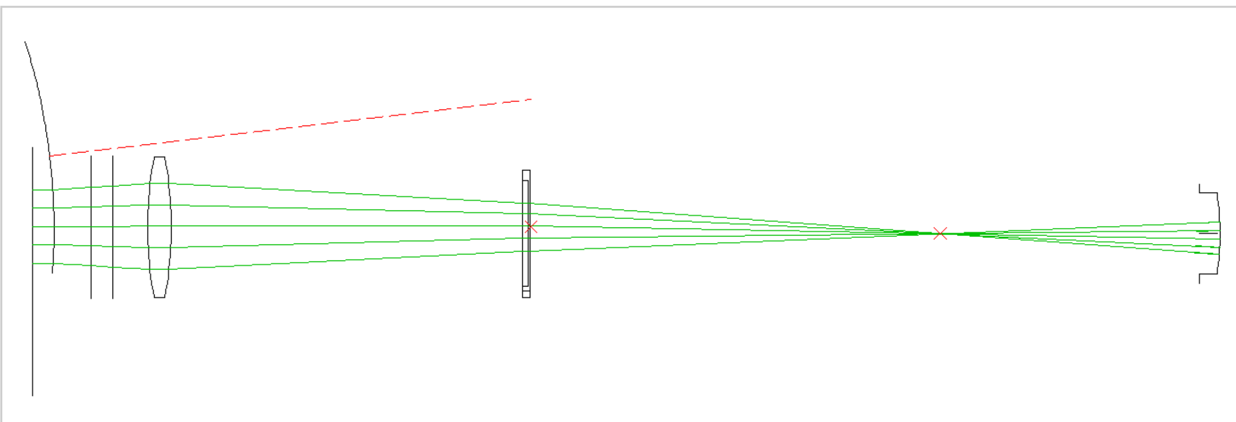

Figure 7. This null test of the IRMOS M1 mirror, like that of the IRMOS M4 mirror, includes constraints for parallelism between CGH, dewar window and M1 backside datum surface.

Reference/Acknowledgement

V. John Chambers, Ronald G. Mink, Raymond G. Ohl, Joseph A. Connelly, J. Eric Mentzell, Steven M. Arnold, Matthew A. Greenhouse, Robert S. Winsor, John W. MacKenty, "Optical testing of diamond machined, aspheric mirrors for ground-based, near-IR astronomy", in **Instrument Design and Performance for Optical/Infrared Ground-based Telescopes,** Masanori Iye, Alan F. M. Moorwood, Editors, *Proceedings of SPIE* Vol. 4841, 689-701 (2003).

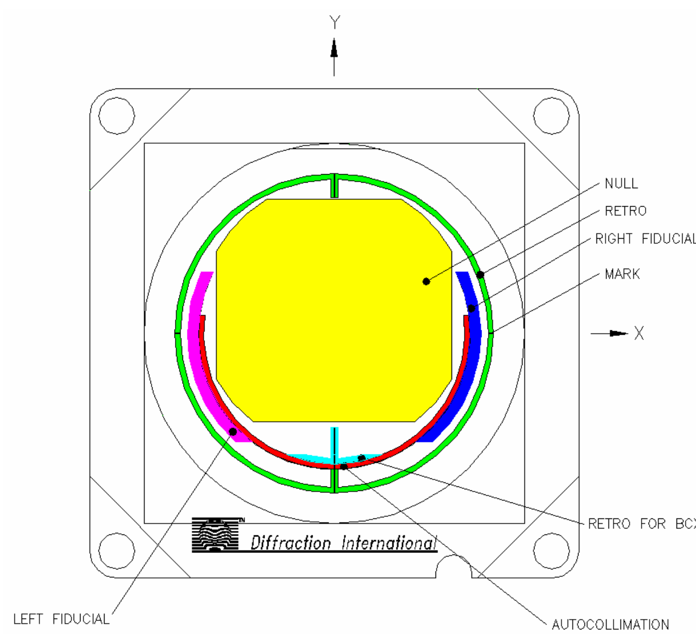

Figure 8. Aperture layout of IRMOS M1 CGH null.