An Unusual Two-Mirror Telescope: A Diamond Machining Example

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ABSTRACT

This paper will examine how optical designers can use diamond machining techniques to design, test, and construct multimirror optical systems. An unusual two-mirror telescope will be used to demonstrate the advantages of these techniques. A review of the use of non-traditional surface descriptions, a diamond machining approach to aspheric surface metrology, and techniques for system construction and assembly will be described.

INTRODUCTION

The design, testing, and construction of an unusual two-mirror telescope will be described in this paper. This telescope is presented to highlight how diamond machining techniques can be applied to each phase of the development of a multimirror optical system. Although only intended for demonstration, this telescope has excellent performance over a relatively wide field of view and may be suitable for less academic applications. What makes this telescope unusual is its use of nontraditional aspheric surfaces.

Aspheric surfaces are found in many diverse infrared optical systems. From thermal imagers to high-power laser systems, optical designers are incorporating aspherical surfaces into optical systems. Peter Hall writes:

> "For aspheric surfaces to be used in optical systems, it is necessary that two conditions be satisfied: (1) there must be tangible benefits to the system being designed, and (2) the aspherics must be available at a realistic cost relative to the remaining system cost." [1]

Diamond machining is a well-established optical fabrication technology for the production of aspheric surfaces.[2] It is widely used to directly fabricate optical surfaces on materials from infrared transmitting crystals to soft reflective metals. Because the diamond machining process is deterministic, it affords a means for manufacturing aspherical surfaces not available by traditional stochastic processes. This feature is generally regarded as the technology's greatest advantage. However, diamond machining offers more than just the ability to produce aspheres.

This paper will examine how diamond machining techniques can be applied to several specific phases of multimirror telescope developments. Using the two-mirror telescope example, techniques for optical design, metrology, and multimirror assembly will be examined. The use of nontraditional surface geometries to more appropriately define optical surfaces will be reviewed in the context of this telescope's design form. Because these unusual surfaces require special metrology considerations, an interferometric technique utilizing other diamond machined optical surfaces will be examined. In addition, the advantages made possible by the diamond machining of integral reference and mounting surfaces in the assembly's mechanical design will be reviewed.

NON-TRADITIONAL ASPHERIC SURFACES IN OPTICAL DESIGN

Many optical designers utilize aspherical surfaces in systems only as a last resort when an all-spherical design fails to satisfy the optical requirements. Designs that result from the inclusion of a necessary asphere generally represent a compromise to the original all-spherical design form. Results improve when aspherics are included from the beginning of the design phase. In the initial design, the aspheric is typically represented as a conic of revolution or by the addition of an axisymmetric quartic term. If, after the correction of the primary (Seidel) aberrations with these aspheric representations, residual higher-order aberrations need additional correction, then more even-order terms in a polynomial representation (i.e. sixth, eighth, tenth, etc.) are incorporated into the surface geometry. The optimization of these higher-order coefficients is generally left to an appropriate computer optimization routine employing exact ray traces and carefully defined merit functions. In general this is how many aspherics are treated in the optical design process.

Occasionally in the optical literature, references are made to aspherical surfaces that are selected in a more deterministic fashion. These aspherical surfaces are exact mathematical solutions to specific design problems. Familiar examples of these aspherics are the traditional Gregorian reflective conics and the Cartesian "oval" refracting surfaces. Examples of more complex deterministic designs range from laser beam irradiance redistribution systems to generalized two-mirror telescopes.[3],[4] In these systems the descriptions of the aspherical forms are derived explicitly from the initial geometrical considerations. For these applications the most appropriate aspheric forms may not be represented by traditional descriptions.

Diamond machining allows the optical designer freedom from the restrictions that are imposed by traditional aspheric descriptions. The diamond turning machine tool is capable of creating virtually any optical surface that possesses rotational symmetry, lies within the range of the machine tool's motions, and provides for a sufficient clearance path for moving parts. The freedom to use the most appropriate aspherical surface descriptions is available because of the computer numerically-controlled nature of the diamond turning machine. The only requirement is a satisfactory algorithm to generate a series of coordinates to define the surface accurately and guide the machine tool.

DESCRIPTION OF THE TWO-MIRROR TELESCOPE

The telescope examined here is based on a traditional design type -- the Schwarzchild flat-field anastigmat.[5] The form of this design, using all conic surfaces, has been reviewed in the literature.[6] The use of two conic surfaces with this design form permits the correction of four primary (Seidel) aberrations. Using this design as a starting point, the mirror surfaces have been made strictly aplanatic by the technique developed by Korsch and Warner.[7] Figure 1 shows an on-axis meridional ray fan traced through the system along with the optical description.

Optical Description	
- focal length	54 mm
- back focal length	130 mm
- mirror separation	108 mm
- entrance pupil dia.	42 mm
- speed	f/1.29

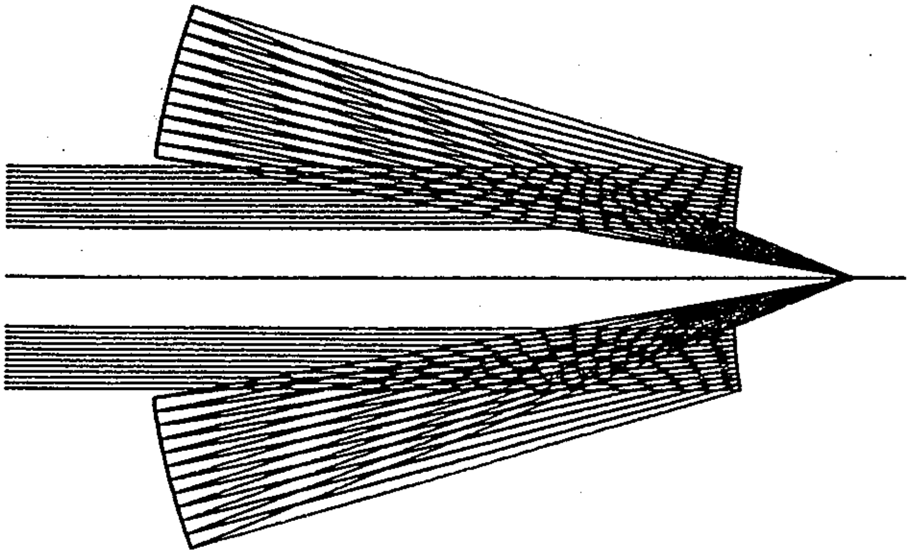
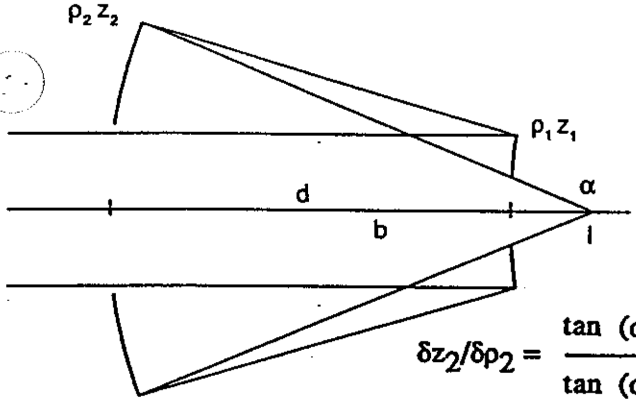


Figure 1 On-Axis Meridional Ray Fan

In this form the aspheric surface geometries for both the primary and secondary surfaces are described by appropriate differential equations. The simplified form of these equations used for the diamond machining of these surfaces and the optical schematic are shown in Figure 2. In this representation the surfaces are completely defined by their axial separation (d), the system back focal length (b), and the system effective focal length (f). These parameters relate this form to the original Schwarzchild representation. The ratio of mirror separation to focal length (2 to 1) ensures that Seidel astigmatism will be zero. Coupled with the ratio of back focal length to focal length ($1+\sqrt{2}$ to 1) will ensure that the Petzval sum is zero.



$$\cos\alpha = \pm\,(1 - \rho_1^2/f^2)^{1/2}$$

$$\delta z_1/\delta\rho_1 = \rho_1\,\frac{2b - f(1+\cos\alpha) - 2z_1}{-2d\cdot f\cdot(1+\cos\alpha) - \rho_1^2}$$

$$\tan(\alpha/2) = \rho_2/\{[\rho_2^2 + (b - z_2)^2]^{1/2} + b - z_2]\}$$

$$\sin\alpha = \rho_2/[\rho_2^2 + (b - z_2)^2]^{1/2}$$

$$\delta z_2/\delta\rho_2 = \frac{\tan(\alpha/2)\cdot(b - 2d - z_2 - \rho_2/\sin\alpha) - (f\sin\alpha - \rho_2)}{\tan(\alpha/2)\cdot(f\sin\alpha - \rho_2) + (b - 2d - z_2 - \rho_2/\sin\alpha)}$$

Figure 2 Telescope Surface Equations

The geometrical performance of this system remains diffraction limited in the visible until the field is totally vignetted, which occurs at a half-field angle of seven degrees. The aspheric departure of the mirrors from their aplanatic Seidel conic solution is approximately one wave in the visible. This departure from the Seidel conic surfaces is anticipated because of the relatively fast speed of the system (i.e. f/1.29). Although an approximation to this exact solution is possible by a polynomial expansion, the direct representation of the surfaces by their appropriate differential equations avoids inherent errors in curve fitting routines. This also ensures that the surfaces described yield the global design minimum to the original optical design criteria. The surfaces were diamond machined from their differential equations using a standard numerical technique.[8] The accuracy of the numerical integration was kept below the resolution of the machine tool by an appropriate choice of integration step size. A machining surface increment was chosen to yield a sagitta error of no greater than 100 angstroms (i.e. the machine tool resolution).

A DIAMOND MACHINING TECHNIQUE FOR ASPHERIC METROLOGY

Using such unusual surface geometries obviously poses special metrology considerations. Ensuring testability of aspherical surfaces is generally the optical designer's task. Depending on the aspherics, several metrology techniques are available. The most common being stylus contact methods and null methods. Commercial contact instruments, such as Rank Taylor Hobson's Form Talysurf [9], are capable of evaluating many generalized aspheric surfaces when the surface's sagitta and clear aperture dimensions lie within the instrument's range. Null techniques have been employed to measure a broad range of aspheric surfaces. These techniques involve the use of a null optic (e.g. a computer-generated hologram or lens system) to compensate for wavefronts reflected or refracted by aspherical surfaces.

One new technique is the use of a null aspheric mirror to provide the wavefront compensation for an interferometric surface test.[10] Diamond machining provides a ready means for the fabrication of such a null mirror. Because concave mirrors are particularly amenable to this form of testing, a null mirror was created to test the telescope's secondary. The primary was then tested with the secondary as the telescope was assembled. Clearly the introduction of another aspheric complicates the evaluation of the test results since in general the null's geometry is unknown. In this instance, the accuracy of the null's geometry was verified on a Form Talysurf.

For this test of the secondary mirror the null is used as an interferometric cavity end-mirror with the secondary mirror within the interferometric cavity. The equations that describe the null surface and a schematic of the test are shown in Figure 3. The surface of the null optic is defined parametrically as a function of ray height of the input collimated wavefront (i.e. radial distance on the secondary). The choice of axial separation of the secondary and null was chosen to insure the null optic did not obscure the secondary's surface and the null resided outside the caustic formed by the secondary. The evaluation of the resulting interferogram used a scale factor of one fringe equivalent to one-quarter wave of secondary surface error after the effects due to imperfections of the null optic were removed.

$$\alpha = \tan^{-1}(\delta z_2/\delta\rho_2)$$

$$t = t_p + z_2$$

$$\rho_n = \rho_2 - t\sin(2\alpha)$$

$$z_n = t_p - z_2 - t\cos(2\alpha)$$

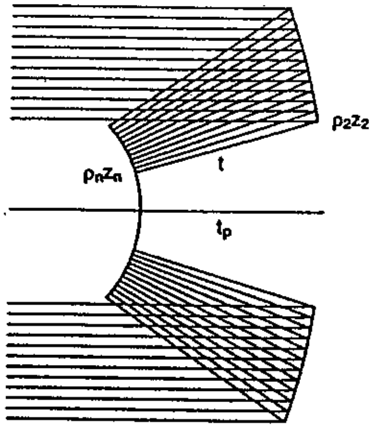


Figure 3 Null Asphere Surface Equations

Diamond machining is used in this test to do more than just make the null aspheric. The use of precision reference surfaces machined into the component under test and the null aspheric greatly simplify alignment of the test configuration. The photograph in Figure 4 shows this test configuration. Note that only two degrees of tilt are required to align the rear surface of the null asphere to the axis of the interferometer. The rear surface of the asphere is perpendicular within arc second accuracy to the asphere's axis of rotation by virtue of a diamond machining vacuum holding technique. The mounting surface on the secondary mirror has been machined plano and orthogonal to the secondary's asphere and is used to tilt the secondary to the interferometer's axis. The remaining three degrees of translation are used to center the secondary to the null asphere and adjust for the proper axial separation (focus). By using these reference surfaces to avoid testing errors related to misalignment, the time to set up the test configuration has been greatly reduced.

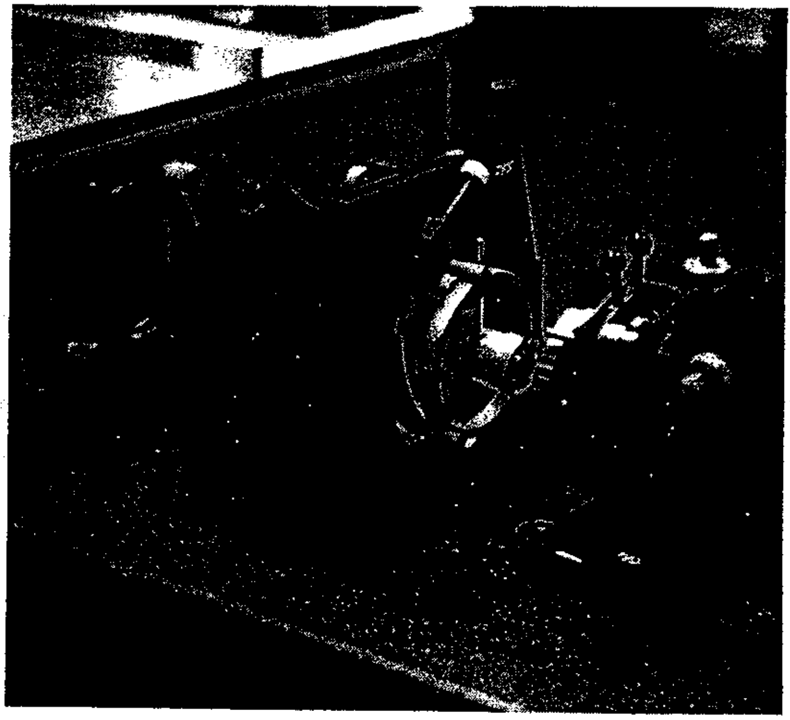


Figure 4 Secondary Mirror Test Configuration

DIAMOND MACHINE TECHNIQUES FOR MULTIMIRROR ASSEMBLY

In a centered optical system incorporating an aspherical surface it is important to maintain the aspheric's rotational axis colinear to the system's optical axis. For this two-mirror telescope both aspherical mirror axes need to be colinear and the surfaces maintained at the precise axial separation distance. This has been accomplished in a three-piece assembly by using integral mounting surfaces machined in conjunction with the optical surfaces. Diamond machined reference and location surfaces on the primary mirror, secondary mirror, and barrel housing have removed the need for positional adjustment of the mirrors at assembly.

It should be noted that no attempt has been made to suppress stray light in this assembly design. This could be accomplished by the use of an appropriate light baffling scheme. But in this Schwarzchild flat-field design form with central holes in both primary and secondary mirrors appropriate baffling would require central light stops on spider supports. To ermit the unobscured interferometric evaluation of this telescope no light stops have been included. For any practical application of this telescope the control of stray light should be carefully considered.

Figure 5 shows a cross sectional schematic view of this two mirror telescope assembly. Tolerances for these types of diamond machined mounting and reference surfaces have been reviewed elsewhere.[11] Mating cylindrical surfaces for both mirrors and the housing were diamond machined to control decentration. The axial separation and tilt between the components is controlled by shoulder surfaces on the housing and mirrors. These shoulders have been machined to be specific distances from their respective aspheric's vertex positions. Thus when the telescope is assembled the aspherical surfaces are properly spaced. The components were assembled with screws through the mounting faces and secured into the housing, taking care to ensure excessive stress was not introduced.

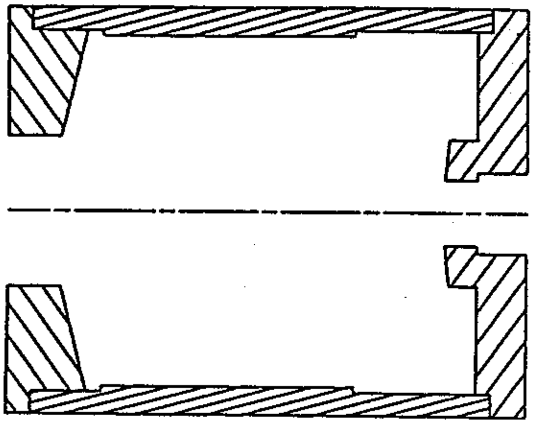
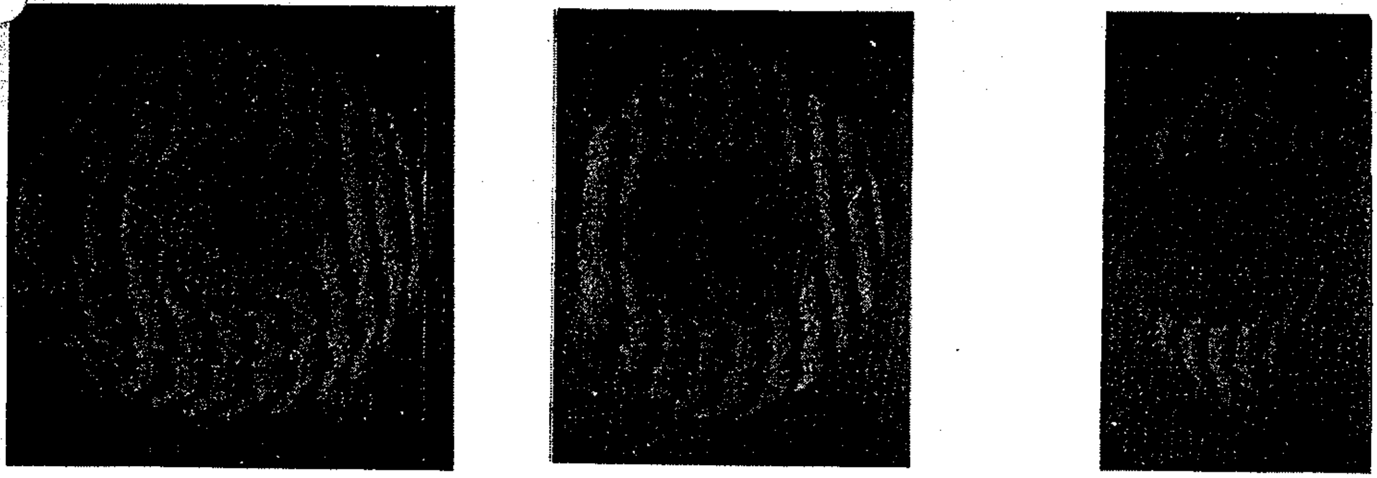


Figure 5 Cross Sectional View of Assembly

Figure 6 shows the results of interferometric testing of the assembled telescope. These interferograms were produced using a Fizeau interferometer (632.8nm) and having a collimated wavefront enter the system and the focused wavefront from the system auto-reflected from a concentric spherical reference surface. These interferograms thus represent a double pass test of the system performance from four diamond machined reflections. The field angles were simulated by accurately indexing the telescope with respect to the incoming collimated wavefront.



On-Axis

2.5 degree field

5 degree field

Figure 6 Telescope Performance

CONCLUSION

This paper has used a two-mirror telescope as an example to demonstrate how an optical designer can use diamond machining techniques to assist in the design, testing, and construction of high-performance infrared systems.

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