Testing diamond turned aspheric optics using computer-generated holographic (CGH) interferometry

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Abstract

The use of a CNC 2-axis diamond turning machine has enabled a variety of aspheric optics to be fabricated. These optics, which are both reflective and refractive elements, require a testing method equally versatile. Computer-generated holographic (CGH) interferometry is a method ideally suited to this unique, emerging optical fabrication technique. The same mathematical formula used to fabricate the part is used to also design the hologram. The hologram serves as a reference master and is designed for each individual asphere. This method permits even generalized aspheres to be tested with relative ease.

Many aspheres designed for use in infrared systems may be too extreme to be adequately represented by a hologram. This limitation is economically overcome through the use of simple null lenses. These lenses are used to null the lower order aberrations, thus allowing the hologram to cancel the higher order departures.

The limitations of the hologram, the use and design of null lenses, and examples of testing aspheres are given.

Introduction

Conventional production fabrication techniques have been primarily limited to spherical surfaces due to the high cost and long fabrication time involved in hand figuring aspherics. This, in turn, has limited normal shop testing procedures to include the use of test plates and standard interferometers such as the Fizeau, Twyman-Green, and Laser Unequal Path Interferometer (LUPI).

Many different aspheric surfaces, in limited quantities, have been manufactured and subsequently tested using expensive null lenses. These null lenses, usually consisting of many elements, are designed and manufactured to remove the theoretical wavefront error in the piece under test. Testing these null lenses is often a difficult, if not impossible, task in itself. This technique is acceptable if many aspheres are to be manufactured, thus allowing the expense of the null lens to be amortized over many pieces.

Modern manufacturing methods have enabled the production of aspheres to become a reality. These methods include diamond turning, replication, injection molding, and hot-pressed forging. Diamond turning, utilizing a 2-axis CNC air bearing lathe with fringe counting laser feedback, is a particularly powerful fabrication technique. This method allows aspheric elements, both refractive and reflective, to be fabricated in a matter of hours rather than days or months by conventional lapping and polishing. A test method equally versatile and cost-effective is necessary to support this emerging optics fabrication technique. Such a versatile test method is computer-generated holographic (CGH) interferometry. The hologram, designed for a particular asphere, serves as a reference master. Since a null lens is no longer necessary, this technique offers relatively low cost and fast turn around testing in the optics shop when operated by qualified personnel.

Description of CGH Interferometry

The theory and production of computer-generated holograms has been described in the literature.[1,2] The application of computer-generated holograms to the interferometric testing of aspheric optical elements has also been the subject of extensive documentation.[3-5] The interferometer used for this work was jointly developed by Honeywell, Tropel, and the University of Arizona. This interferometer, designed for use in a prototype optics shop, has been described in a paper by Emmel and Leung.[6] Figure 1 depicts the interferometer layout. The first step in producing a computer-generated hologram involves ray tracing the interferometer for the particular asphere to be tested. As illustrated in Figure 1, this involves ray tracing a plane wave vertically through the variable beam expander, large beam expander and focusing lens until the ray intersects the test piece. The beam is then reflected off the asphere, and the aspheric skew rays are then traced back through the test optics. A movable "cat's eye" relay lens is then used to image the test piece at the hologram plane (i.e., the physical plane where the hologram is to be located). The output of this ray trace is an OPD (optical path difference) vs aperture height map for the particular asphere. The maximum OPD may be minimized by suitable choices of the test piece position, test beam F-number, and test piece aperture.

The above ray trace may be performed on many computers and calculators with suitable software. The program used at Honeywell is called GENRAY, and was written by John Loomis while at the University of Arizona. An additional routine then calculates the physical position of the fringes as a function of aperture when this wavefront interferes with a plane reference beam at a predetermined angle. This angle determines the carrier frequency of the hologram by introducing tilt fringes into the interference pattern. This ensures that the diffracted orders will be spatially separated in the focal plane of the hologram relay lens (i.e., this angle is directly proportional to the maximum slope in the aspheric wavefront). The fringe positions are output as X-Y coordinates and recorded on a magnetic tape or disk.

The output may be plotted by a variety of digital image plotters. The holograms used for this work were plotted using electron-beam lithography, one of the most accurate methods presently available. This process allows holograms to be plotted at their final size (10-15 mm diameter), eliminating the photoreduction process necessary when using standard plotters. (Due to resolution limitations, photo plotters or laser beam recorders are used to plot the CGH at a larger than usable size. This plot is then photoreduced to the final image size.) The ability to plot the hologram at final size eliminates the introduction of any potential errors associated with the photoreduction process. This procedure allows testing with $\lambda/10$ accuracy for surfaces with asphericities up to a slope of approximately 300 waves per radius. This accuracy is primarily limited by the geometric accuracy of the hologram. The hologram recording process and the limitations involved are the subjects of a paper to be presented in this journal by Kang Leung.[7]

CGH Testing Using Spherical Waves

As in conventional interferometry, most CGH testing is performed using spherical wavefronts. A well corrected lens system is used to convert a plane wave into a converging or diverging spherical wavefront to test convex or concave surfaces respectively. The computer ray trace is then used to calculate the difference in optical path for the aspheric surface as it deviates from a sphere. It is clear that many interferometers could be modified to use holograms, provided the optical prescription is known. The interferometer is then set-up the same as if one were testing a sphere. A Twyman-Green interferogram is obtained of the aspheric surface. In most cases, unless the asphericity of the test piece is slight, this interference pattern will be too complex to be of value to the observer. However, upon insertion of the hologram and proper interferometer alignment, the interference pattern clearly shows the surface fabrication errors. Figure 2 depicts the test set-up for testing a conventionally polished concave f/2 parabola at its center of curvature. (Note that a f/2 parabola is tested at r/4 when at its center of curvature.)

Figure 3 clearly shows the utility of CGH testing over conventional interferometry. As a parabola may be tested conventionally in auto-collimation, this piece was used to qualify the interferometer. Figure 4 shows the test configuration for a convex diamond turned germanium asphere. The test piece is placed in the converging test beam as if we were testing a sphere. Figure 5 depicts the wavefront before and after insertion of the hologram. Figure 6 is an example of a diamond turned germanium generalized asphere (R = 2.639, cc = 0,AD = -0.541E-03, AE = -0.760E-04) tested in an approximately f/1.1 beam. The figure errors and residual diamond turning marks are clearly visible in the CGH interferogram.

Use of Null Lenses in CGH Interferometry

As discussed above, CGH and conventional interferometry normally utilize a spherical beam to illuminate the test piece. The hologram then records the OPD between the asphere and the spherical wave. Due to limitations in the hologram plotting process, at some extreme degree of asphericity the hologram can no longer accurately represent this optical path difference. To economically overcome this limitation, simple null lenses may be used in conjunction with holograms.[8]

The design and use of null correctors have been reported on throughout the years.[9-11] These null lenses, involving many elements, have been designed to exactly cancel the aberrations introduced by a particular asphere. Thus, the results of the interferometric test is a true null if the test piece is perfect. The cost of the design, manufacture and assembly of these null lenses is prohibitive unless a large production run is anticipated or the piece is particularly large and therefore expensive regardless of the test method. Many times the manufacture of one or more aspheres is required, prohibiting the expense of a null lens system. Furthermore, due to the speed of manufacture, many different aspherics may be machined in a day. This requires having a versatile as well as inexpensive test method.

The technique used at Honeywell follows that of Wyant and O'Neill.[8] It is sufficiently simple and inexpensive to allow steep aspherics to be tested with relative ease with little additional cost. For the purpose of discussion, it will be convenient to measure the asphericity of a test piece in terms of the departure (sag) from a "best fit" sphere. This best fit sphere is simply the sphere radius which minimizes the sag difference between it and the asphere. The maximum value of this sag difference is then a measure of the asphericity of the test piece. As previously mentioned, the wavefront slope in the hologram is limited to approximately 300 waves per radius. This physically corresponds to approximately 40 waves departure from the best fit sphere (λ = 6328.Å). If the best fit departure exceeds this value of 40 waves, a "null" lens is used to reduce the asphericity. The term "null" is used as it is not a null lens in the true sense, it is simply a single element introduced into the test arm to convert the spherical wave into a wavefront which more closely matches the test piece (for the remainder of this discussion the term null will be used). An important point to mention here is that it is not necessary to have a well corrected test beam as in conventional interferometry. It is only important that errors in the test beam are known by design or measured after fabrication. The design errors will automatically be accounted for when the aspheric skew rays are ray traced through the interferometer. The fabrication errors can be fit to a polynomial and also be included in the hologram. The null lens is designed using any lens design program.

In its simplest form the null lens is chosen to compensate for the spherical aberration in the aspheric test piece. This null lens is then ray traced along with the interferometer optics as a normal hologram would be designed. The effect of the additional lens is to reduce the peak-valley OPD needed to be encoded in the hologram. Some examples will best illustrate this technique. Figure 7 depicts the test set-up used for a concave diamond-turned generalized asphere with overcorrected spherical aberration (R = 2.603 in., cc = 0.78385, AD = 0.6662E-03, AE = -0.2218E-03). The best-fit sag difference for this asphere is 68 waves, which was too great to encode in a hologram. A simple null lens was designed using ACCOS (prescription R_1 = 0.92 in., R_2 = 0.9703 in., C.T. = 0.308 in., airspace to asphere = 3.459 in.). This reduced the peak-valley OPD to 7 waves, easily encodable in a hologram. This lens system was then raytraced and a hologram designed and manufactured.

Figure 8 demonstrates the resulting null wavefront using both the null lens and CGH (this asphere has a central hole machined in it). The price for such a null lens is a modest $200. The fixturing is equally inexpensive as the only critical tolerance is the air space necessary for the raytrace (see Figure 7.)

Several other aspheres have been diamond turned and successfully tested with such a set-up. Table 1 lists the prescription of the surface, the null lens design and the peak-valley OPDs associated with, and without, the null. A hologram was then used to remove the remaining wavefront error to produce a true null test.

TABLE 1

λ = 6328 Å

TEST PIECE PRESCRIPTION	OPD (λ's) W/O "NULL"	"NULL" LENS DESIGN (BK7)	OPD (λ's) W/"NULL"	TEST CONFIGURATION
R = -7.188 CC = -1.057	60	R_1 = 8.8318 in. CT = 0.268 in. R_2 = 0.7846 in. T(Air) = 8.568 in.	6.5	Fig. 7
R = -3.07 in. CC = -2.99 AD = -0.101 AE = -0.0036 AF = -0.229 AG = 0.0075	105	R_1 = 1.223 in. CT = 0.248 in. R_2 = 0.5688 in. t(Air) = 0.9096 in.	11	Fig. 9
R = 10.675 CC = 40.605 AD = -0.0102 AE = 0.0071 AF = -0.00907 AG = 0.0047	64	R_1 = -1.5313 in. CT = 0.2439 in. R_2 = 1.8599 in. t(Air) = 0.100 in.	33	Fig. 10
R = 10.175 in. CC = 214.72 AD = 0.0036 AE = -0.0566 AF = -0.0233 AG = 0.0292	107	R_1 = 0.7171 in. CT = 0.150 in. R_2 = 0.5688 in. t(Air) = 2.98 in.	16	Fig. 7

Summary

The use of precision diamond turning allows a multitude of aspherics to be manufactured quickly and inexpensively. This has placed demands on optical testing to be equally fast and inexpensive without a loss of accuracy. Such a test method is CGH interferometry. The use of CGH interferometry allows simple but precise testing of even generalized aspherics. This is facilitated by end-to-end computer modeling which requires only the aspheric coefficients of the test piece to generate a hologram. The use of electron-beam lithography enables holograms to be plotted at their final size, thus eliminating the need for photoreduction.

The current limit to the amount of asphericity which may be encoded in a hologram is approximately 40 waves departure from the best fit sphere. Test pieces which exceed this value require the use of an additional null lens. This lens, also computer designed, is used to remove much of the wavefront OPD. The hologram is then designed to cancel the remaining aberration. This method economically allows testing of steep aspherics, making it a valuable asset in the optics laboratory.

Acknowledgements

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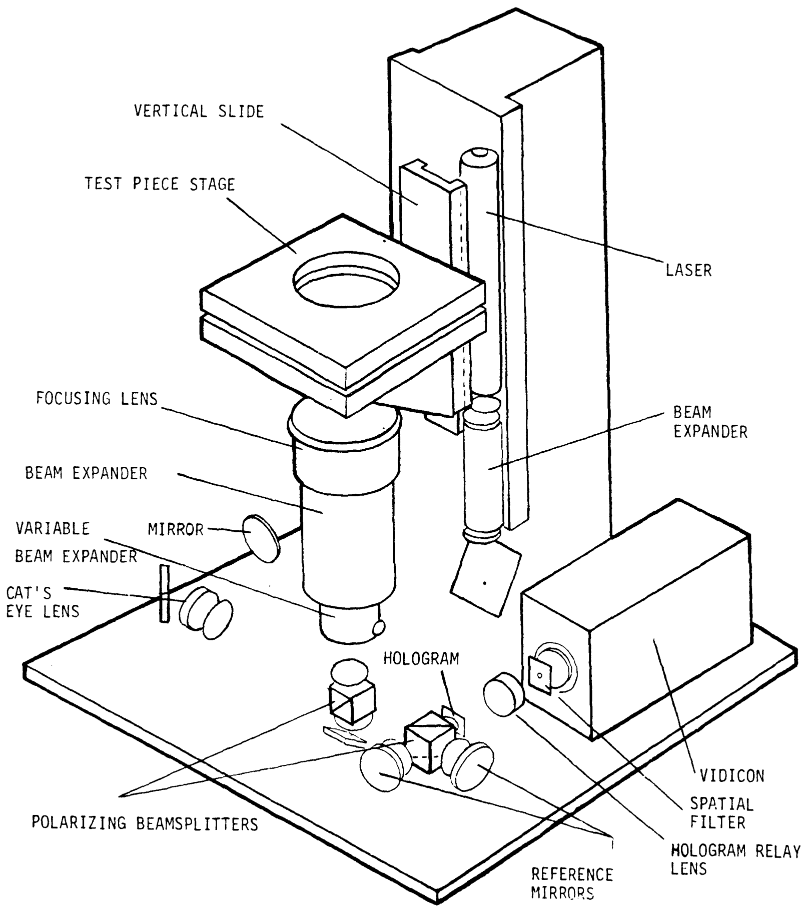


Figure 1. CGH Interferometer

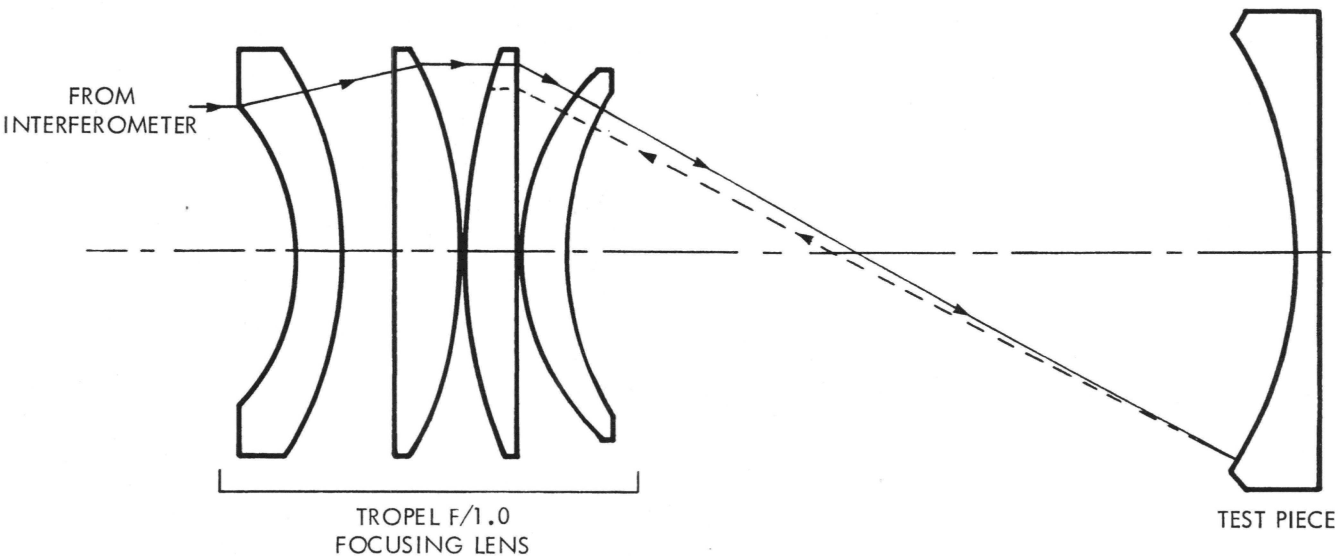
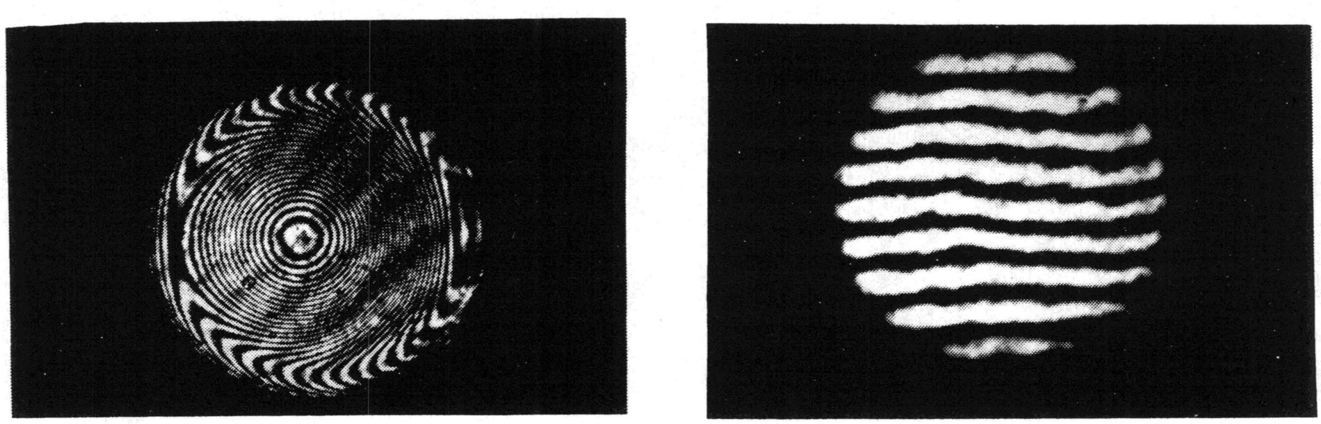


Figure 2. Test Configuration for Concave Parabola

F/2 PARABOLA TESTED AT ITS CENTER OF CURVATURE

W/O CGH

With CGH



Twyman-Green Interferogram Showing Approx. 40 Waves Spherical Aberration and Defocus. Figure Error of Parabola is Undetected.

CGH Interferogram Showing Approx. 0.15 Waves P-V Figure Error.

Figure 3. Example of CGH Interferometry

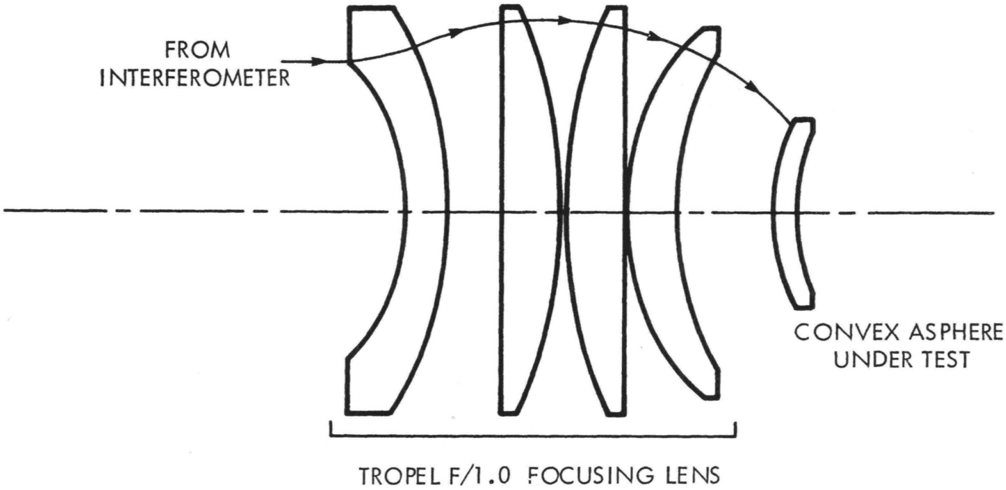
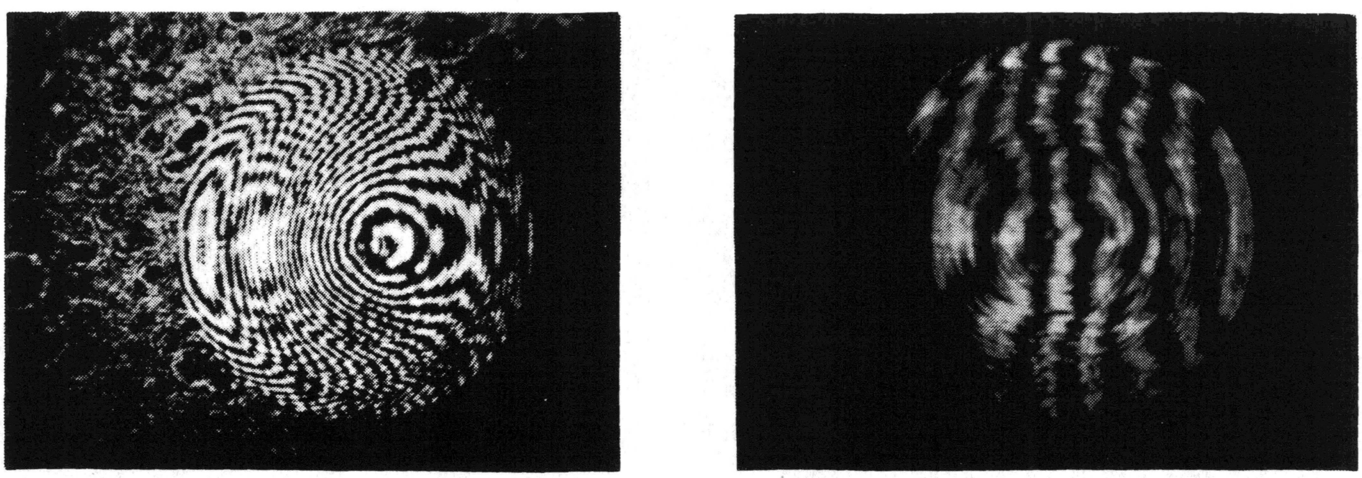


Figure 4. Test Configuration for a Convex Asphere

DIAMOND TURNED ASPHERIC DETECTOR LENS

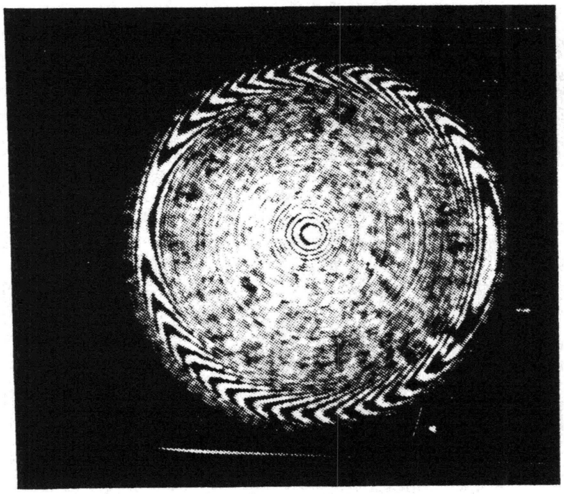
R = 14.6456
CC = - 0.21127 (ELLIPSE)



Twyman-Green Interferogram of Diamond-Turned Asphere Showing Departure From Sphere.

CGH Interferogram Showing Residual Figure Error.

Figure 5. Example of CGH Interferometry



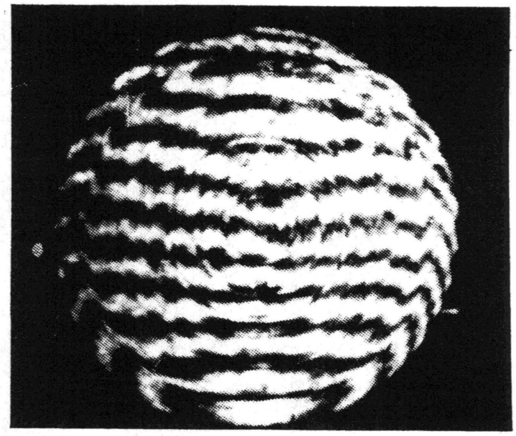


Figure 6. Interferogram of Aspheric Imager Lens (a) Without and (b) With Hologram

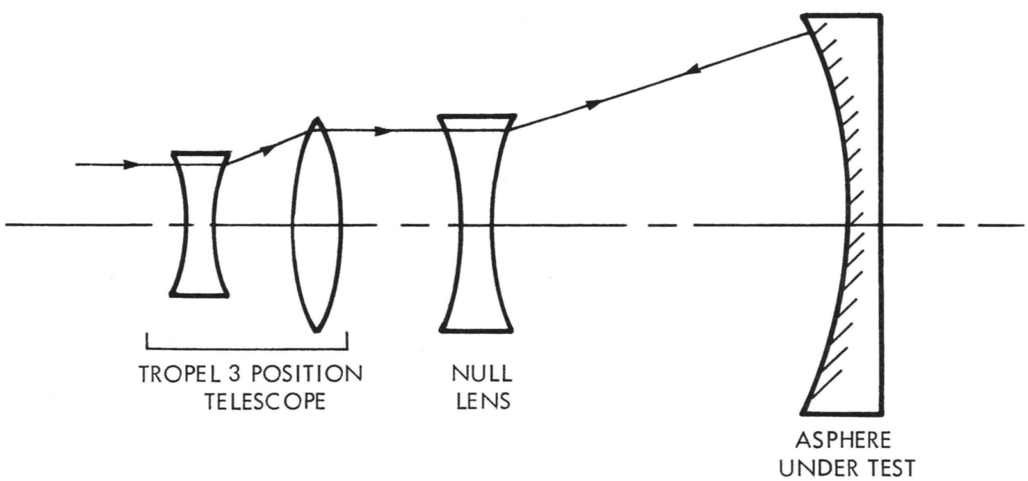


Figure 7. Null Lens for Concave Element with Overcorrected Spherical Aberration

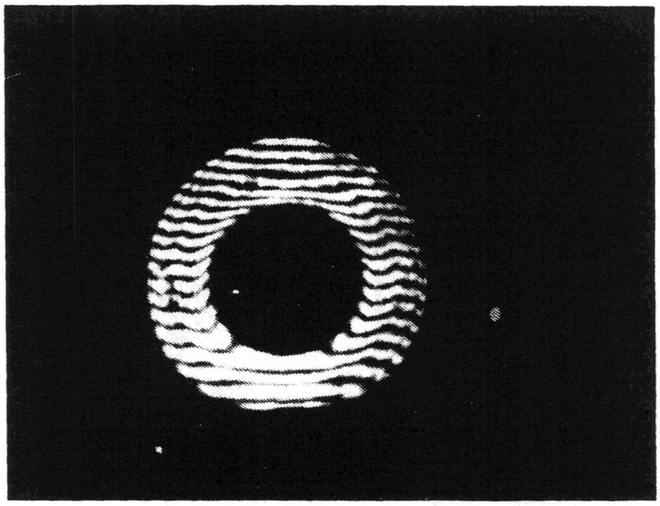


Figure 8. Interferogram of Aspheric Primary with Null Lens and Hologram

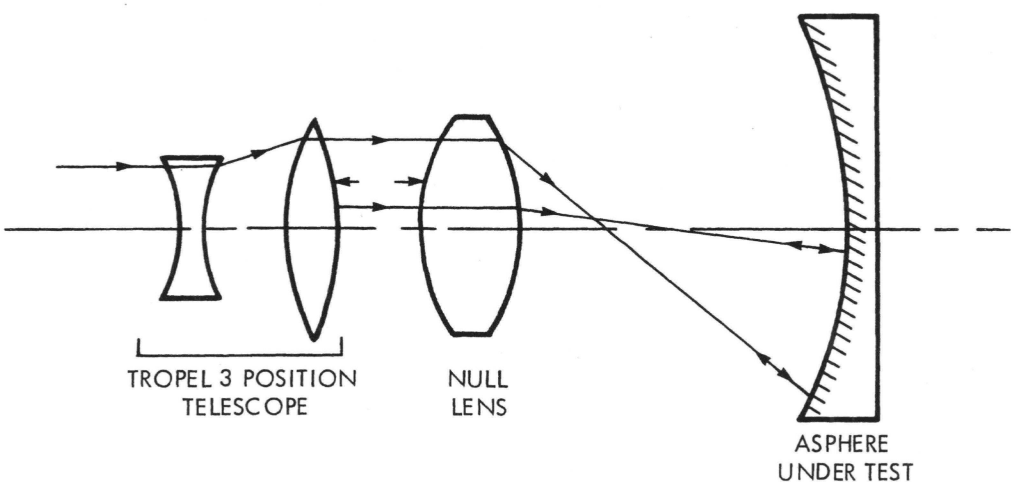


Figure 9. Null Lens for Concave Element with Undercorrected Spherical Aberration

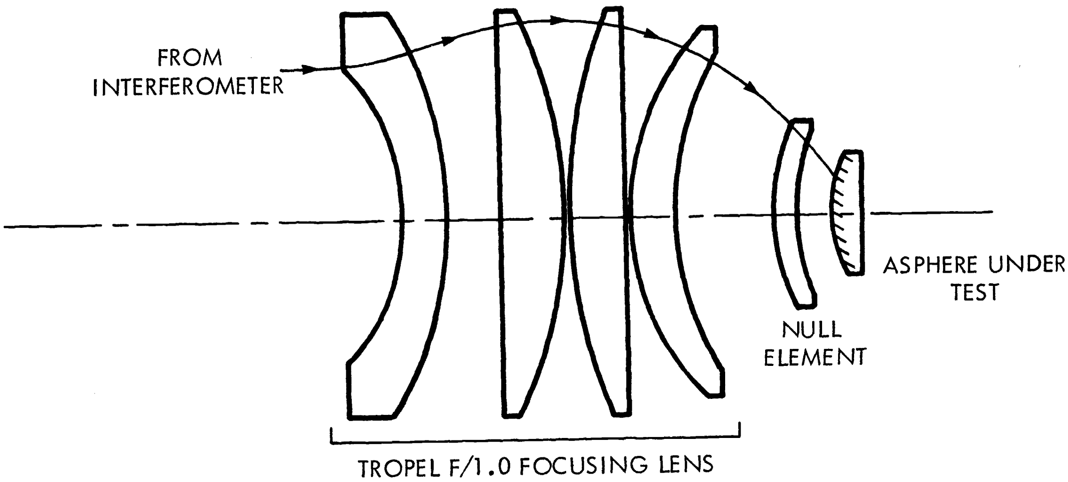


Figure 10. Null Lens Configuration for Convex Asphere