Fizeau interferometry for large convex surfaces

J. H. Burge

Steward Observatory Mirror Lab, University of Arizona
Tucson, Arizona 85721

ABSTRACT

Measurements of large convex surfaces are notoriously difficult because they require auxiliary optics that are larger than the surface being tested. Fizeau interferometry is well-suited for these surfaces because the only surface required to be made to high accuracy is the concave reference surface, which is only slightly larger than the surface being measured. Convex surfaces which are spherical or aspheric can be measured using spherical, aspherical, or holographic test plates. The reference surfaces for these tests must be of good quality and measured to high accuracy. The optical systems that provide illumination and create an image of the interference pattern do not have to be made to high quality. The illumination systems can typically have errors several orders of magnitude larger than the allowable surface measurement errors, so these systems can be made at low cost. Several such systems using low-cost aspheric mirrors and lenses for measuring convex spherical and aspherical surfaces are presented.

Subject terms: *interferometry, optical testing, metrology*

1. INTRODUCTION

Fizeau interferometers are built commercially for measuring a wide variety of optics. These interferometers use interchangeable optics to allow the measurement of a range of surfaces from flat to $f/0.65$. The reference surfaces, typically less than 100 mm in diameter are often pushed with actuators to allow the use of phase shifting interferometry. These instruments have been extremely successful for measuring a broad range of optics, but they cannot directly measure convex surfaces larger than the reference sphere.

Large convex optics can be measured using custom-built Fizeau interferometers that use concave test plates slightly larger than the convex surface. The size of the test plates and sensitivity to illumination errors are minimized by using a small gap, typically a few millimeters, between the test plate and the surface being measured. Because this gap is small, this test is not limited by atmospheric effects and vibration that hinder tests with longer path lengths. Spherical surfaces require spherical test plates, but aspheric surface can be measured using test plates with aspheric reference surfaces, or using test plates with spherical surfaces and computer-generated holograms.

The interferometers for measuring large convex surfaces generally consist of a test plate, an illumination system, an imaging system, and a support system. The test plate has the concave reference surface on one side. The illumination system uses lenses or mirrors to project laser light to the fill test plate with light pointing in the appropriate direction. The imaging system presents an image of the test optic to the film plane or the CCD camera. The mechanical system must allow precise adjustment with high stiffness and stability. If phase shifting interferometry is used, the mechanical system must push either the test plate or the optic being measured.

This paper explains the optical design of these Fizeau test plate interferometers and shows several novel systems that were built at the Steward Observatory for measuring large, fast convex surfaces. Fizeau interferometers with spherical, aspherical, and holographic test plates are reviewed in Section 2. The optical system requirements for measuring large convex optics are developed in Section 3. Techniques for optical design of the test plates, illumination, and imaging optics are given in Section 4. Several examples of systems built at Steward Observatory Mirror Lab for measuring fast spheres and aspheres are shown in Section 5.

2. FIZEAU INTERFEROMETERS

Optical surfaces are accurately measured by combining light reflected from the surface under test with light reflected from a known reference surface. The resulting interference pattern is analyzed to determine the figure of the optical surface. In Newton's classical system, the reference surface is placed in contact with the surface being measured. The Fizeau interferometer uses coherent light to extend Newton's classical system to allow the test plate to be some distance from the optic being measured. This avoids damage from contacting the optical surfaces and allows the same reference surface to measure a variety of optics. A good overview of the Newton and Fizeau interferometers is given in *Optical Shop Testing*.[1]

2.1 MEASUREMENT OF SPHERICAL SURFACES USING FIZEAU INTERFEROMETERS

The common implementation of a Fizeau interferometer is shown in Fig 1. This instrument uses a collimator with replaceable transmission spheres to allow the measurement of surfaces with a variety of focal ratios.[2] The transmission sphere, or diverger lens, is designed so that the light is normally incident for all points on the reference surface. The test optic is then correctly aligned when it is positioned so the light reflects from the test surface at normal incidence as well. The fringe patterns are projected to a camera for measurement and analysis. Highly accurate measurements are made using phase shifting interferometry.[3] The reference surface is pushed with piezo transducers (PZT's) while a CCD camera captures several video frames. The video images are digitized and are used to calculate the surface figure variations.

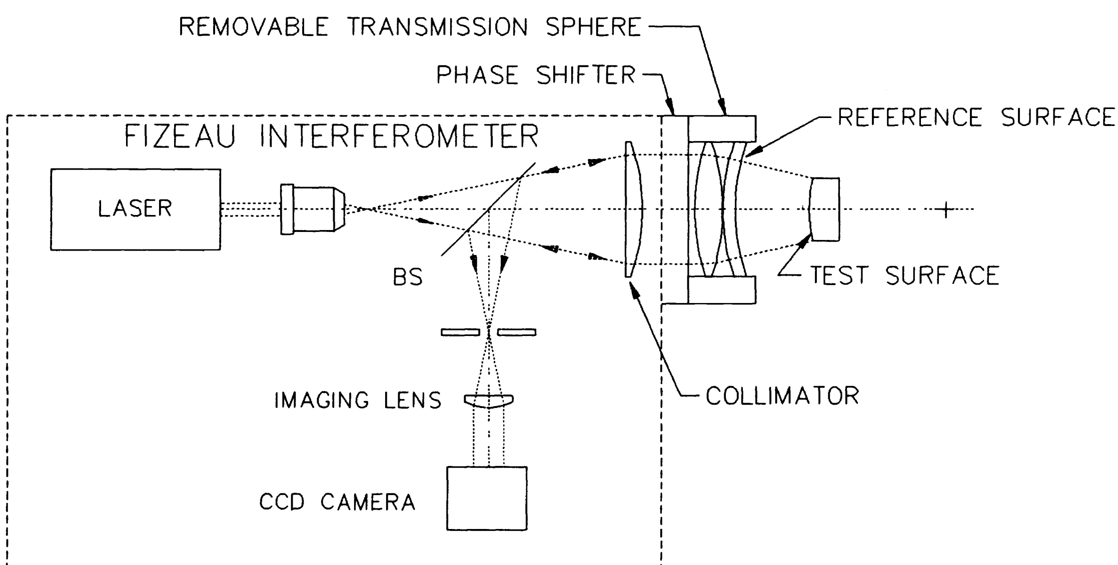


Figure 1. Layout of a conventional Fizeau interferometer.

A Fizeau interferometer with a single diverger lens is capable of measuring a variety of surfaces with numerical aperture less than that of the diverger. It can measure convex surfaces with radius of curvature less than that of the reference surface and concave surfaces with virtually any radius. As spherical waves propagate, they remain spherical with only the radius of curvature changing. This fact allows one system to measure spherical optics with a wide range of curvatures.

Since the Fizeau interferometer uses the wavefront reflected from the last surface as a reference, the test and reference wavefronts travel together through the diverger lens and the collimator. This common path feature minimizes the effects of errors in these optics. Errors in these optics affect both the reference and test wavefronts equally, so they do not affect the interference pattern.

The standard Fizeau interferometers are clearly limited in their ability to measure large convex surfaces. To be directly measured, a convex surface must be smaller than the transmission sphere. Some optics with convex surfaces can be measured as concave surfaces by looking through the glass. The most common method for measuring convex spherical surfaces is to make a matching test plate and use the Newton fringes. The concave test plate can then be measured by the Fizeau interferometer without difficulty. This method is risky for large optics because of the danger of damaging one of the surfaces when placing them in contact. Also, the Newton fringes cannot be phase shifted.

2.2 INTERFEROMETRY WITH ASPHERIC FIZEAU TEST PLATES

Convex aspheric surfaces can be measured the same way using concave test plates with aspheric reference surfaces that match the surface being tested. The difficulty with this technique is that it requires the fabrication and measurement of an extra aspheric surface. The concave test plates may be difficult to fabricate, but they can be measured from center of curvature using null correctors[4] or using a conjugate test like the Silvertooth test[5].

The Fizeau test of an asphere works the same way as the measurement of the spherical surfaces. The illumination system must be designed so that the light is normally incident onto both the aspheric test plate and the asphere being measured. This can require an illumination optic with an aspheric surface. It is important to keep in mind that this can be a low-quality surface because of the common path nature of the system.

Unlike the measurement of spherical surfaces, the aspheric wavefronts change their shape as they propagate. There exists a family of surfaces that will look perfect to an aspheric test plate. To fourth order, the relationship between these surfaces is derived by assuming the amount and the form of the aspheric departure remain constant as the wavefront propagates and the diameter D and radius of curvature R change together. The simplification neglects the change in the sixth order term cause by coupling the aspheric phase departure with the aspheric slope departure. For surfaces described as conic sections of revolution with conic constant K, the magnitude of the fourth order aspheric departure a_4 is

$$a_4 = \frac{KD^4}{128R^3}. \tag{1}$$

Taking the differential of (1),

$$\Delta a_4 = \frac{D^4}{128R^3}\Delta K + 4\frac{KD^3}{128R^3}\Delta D - 3\frac{KD^4}{128R^4}\Delta R \tag{2}$$

which reduces by dividing through by (1) to

$$\frac{\Delta a_4}{a_4} = \frac{\Delta K}{K} + 4\frac{\Delta D}{D} - 3\frac{\Delta R}{R}. \tag{3}$$

But as the light propagates we assume that a_4 does not change and that $\Delta D/D = \Delta R/R$, so (3) reduces to the simple expression

$$\frac{\Delta K}{K} = -\frac{\Delta R}{R}. \tag{4}$$

This expression is useful for analyzing the coupling of system errors, but since it is an approximation, it is inadequate for the design of the aspheric test plate. The test plate design is discussed in Section 4.1.

2.3 MEASUREMENT OF CONVEX ASPHERES USING HOLOGRAPHIC TEST PLATES

Convex aspheres can also be measured using test plates with spherical reference surfaces with computer-generated holograms,[6] as shown in Fig. 2. The advantage of this test is that the reference surface is spherical, which can be made and characterized to high precision. The holograms, consisting of annular rings of chrome, are written directly onto the concave spherical reference surface. The positions of the rings are chosen to give the desired shape of the diffracted wavefront, and the width of the rings is controlled to give high fringe visibility. The test is performed exactly the same as the aspheric test plate.

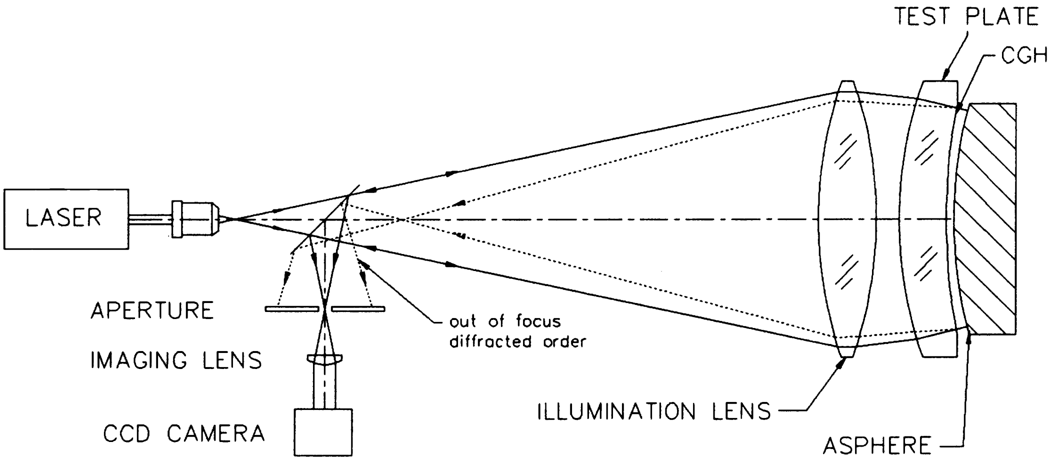


Figure 2. Configuration for CGH test plate measurement of a convex asphere.

The large optics required for this test are the test plate and the illumination optics. The test plate is only slightly larger than the test asphere. It has a concave spherical reference surface and does not require high quality glass. Errors in the illumination system will affect the test if they are larger than the separation of the orders of diffraction and cause the orders to overlap in the interferogram. Ray slope errors of ±1 mrad from the illumination optics are typically permitted.

A second optical configuration for the CGH test is shown in Fig. 3. This uses the asphere in transmission and uses only the reflected-diffracted wave from the test plate. Since this test requires only diverging illumination, it is more economical for solid glass aspheres. The illumination system consists of a low quality null lens, similar to that used for the through-the-back null lens test of the asphere.

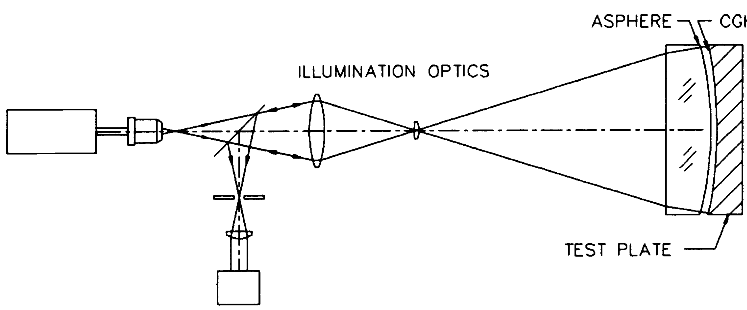


Figure 3. Alternate configuration for CGH test of convex aspheres.

The separation of the orders of diffraction requires a trade-off in the design of the test. Large errors in the illumination optics can be tolerated if a large amount of power is built into the CGH, which causes the orders to be widely separated. However, more power in the CGH requires more rings with tighter spacing, which makes the hologram more difficult to fabricate. A compromise between these two effects has led to hologram designs that allow slope errors of ±1 mrad without causing any order leakage.

Even for a perfect illumination system, the aperture may not be made arbitrarily small because the stop acts as a low-pass spatial filter on the surface measurement. For coherent illumination, the spatial frequency cutoff of the filter is derived using Fourier optics[7] as

$$\xi_c = \frac{\theta_f}{2\lambda} \tag{5}$$

where ξ_c = spatial frequency of cutoff (cycles per meter at mirror)
θ_f = full angular size of aperture, as viewed from the secondary (radians)
λ = wavelength of light (m).

So a 2 mrad wide aperture gives 1700 cycle-per-meter resolution.

3.4 IMAGING DISTORTION

The mapping from the surface to the image plane is important for two reasons. The surface measurements are usually made to guide the fabrication of the part. It is important that the optician knows where the surface irregularities really are so he can effectively polish them out. This is especially true when highly deterministic figuring such as Computer-Controlled Polishing[8] or ion figuring[9] is used. Imaging distortion also causes the low order alignment errors (tilt, focus, and coma) to appear as higher order surface errors.

The mapping in the presence of distortion for an axisymmetric system is approximately

$$\rho_i = m\rho_m(1+\varepsilon\rho_m^2), \tag{9}$$

where ρ_i = radial position in normalized image coordinates
ρ_m = radial position in normalized mirror (object) coordinates
m = magnification from mirror to image
ε = distortion coefficient.

The test usually references the edge of the part, so the coordinates can be normalized so $\rho_i = \rho_m = 1$ at the edge of the mirror, which couples m and ε. The apparent radial shift for such a system is calculated to be[10]

$$\Delta\rho = \rho_i - \rho_m = \frac{\varepsilon\rho_m(\rho_m{}^2-1)}{1+\varepsilon}. \tag{10}$$

The effect of the mapping distortion on low-frequency wavefront variation is analyzed using a polynomial representation. The wavefront may be described as a sum of functions of the form

$$W(\rho,\theta) = \sum_{n,k} a_{nk}\rho^n \cos k\theta + b_{nk}\rho^n \sin k\theta \tag{11}$$

Zernike polynomials are a special case of functions of the type shown in (11) that are orthogonal over the unit circle. The systems treated have circular symmetry so the mapping always preserves the azimuthal angle θ. The mapping of is found substituting $\rho + \Delta\rho$ for ρ in (11), expanding and keeping first-order terms in ε. This results in the mapping relations,

$$\begin{aligned} a_n\rho_i{}^n &\rightarrow a_n(1-n\varepsilon)\,\rho_m{}^n + a_n n\varepsilon\,\rho_m^{n+2} \\ a_n\rho_m{}^n &\rightarrow a_n(1+n\varepsilon)\rho_i{}^n - a_n n\varepsilon\,\rho_i{}^{n+2} \end{aligned} \tag{12}$$

which leads to

$$\begin{aligned} a_{nm} &= a_{ni}(1-n\varepsilon) \\ a_{(n+2)m} &= a_{(n+2)i}(1-(n+2)\varepsilon) + a_{ni}n\varepsilon \end{aligned} \tag{13}$$

where a_{nm} is the coefficient in mirror coordinates and a_{im} is the coefficient in image coordinates. This equation shows that a system with 10% imaging distortion will couple one wave of power into 0.2 waves of spherical aberration..

3.5 MECHANICAL SYSTEM

The test plate must be held rigidly with respect to the optic being tested to avoid vibration problems. The system must allow adjustments of all the required degrees of freedom. For measuring spherical surfaces, only tip, tilt, and focus are required. For measuring aspherical surfaces, lateral translations must also be accommodated. The resolution of these motions should be less than a quarter fringe.

3. SYSTEM REQUIREMENTS FOR FIZEAU MEASUREMENTS OF LARGE CONVEX OPTICS

The system requirements for the Fizeau test are broken into several aspects. The quality of the reference surface directly affects the measurement accuracy. The temporal and spatial coherence of the source must be adequate to give high contrast fringes. Slope errors provide limits on the allowable quality of the illumination optics. The imaging optics should be designed to focus a distortion-free image onto the CCD. The mechanical system should give high resolution adjustment and must push the optic or the test plate to use phase shifting interferometry.

3.1 REFERENCE SURFACE

The most important element of this test is clearly the figure of the reference surface. A bump δS high on the reference surface decreases the optical path difference between the two wavefronts by $2\delta S$. This has the effect of appearing as a bump δS high on the optic being measured. The figure of the test plate need not be perfect, only well-known. Small errors in the figure of the concave test plate can be measured and removed from the test of the convex optic. The accuracy of this operation depends on the accuracy of the reference surface measurement , the accuracy of the mapping from reference surface measurement to the test of the convex optic, and the stability of the test plate figure. The surface measurement will have residual error δS from backing out the test plate surface of

$$\delta S = (\text{surface slope}) \times (\text{mapping error}). \qquad (6)$$

If a 1-m reference surface has slope errors as large as 10 nm/cm and the registration of the test plate measurement is accurate to 1%, errors in the final surface measurement of 10 nm are expected.

3.2 ILLUMINATION SOURCE

The light used must have adequate power, coherence, and stability to perform the measurements. Low-cost helium neon lasers work quite well. The light source must have ample power to give a high signal-to-noise ratio in the detector. The light source must have sufficient temporal coherence to provide high-contrast fringes. The coherence length should be greater than twice the gap distance. The size of the source must be small enough that it subtends an angle less than the allowable slope errors described below. For the holographic test, it is important that the wavelength of the light is known and stable. The error in the measurement of an asphere using a CGH test is described by a conic constant error ΔK

$$\frac{\Delta K}{K} = \frac{\Delta\lambda}{\lambda}. \qquad (7)$$

where $\Delta\lambda$ is the wavelength shift from the expected value.

3.3 ABERRATIONS IN ILLUMINATION OPTICS

Large errors in the illumination system can cause measurement errors. If design or fabrication errors cause the slope of the rays to depart an angle θ from normal on the optic, a surface measurement error ΔS is made

$$\Delta S = t \cdot \theta^2. \qquad (8)$$

where t is the separation between the test plate and the optic. More severe slope requirements are imposed by the CGH test plates. The different orders of diffraction are separated by angles as small as 2 mrad. A stop is placed in the system that passes light with slope errors within ± 1 mrad. If slope errors in the illumination system exceed 1 mrad the light from this region will be blocked by the aperture, causing a hole in the data. It is also possible that a large slope error will shift the aberrated light from a spurious order into the aperture, which will cause a phase error.

High frequency figure errors can cause problems even if the slope is small. Surfaces that are not in focus cause local image distortion and intensity variations that are proportional to the curvature variations in the surface and the distance from the image of the optic. This problem is avoided by designing the optical system so that the difficult optics are imaged near the detector plane.

The test can be phase shifted by pushing either the test plate or the optic being measured. This motion should be linear to a few percent over around a wave of travel. Piezo transducers (PZT's) can be purchased that are ideal for this motion. If used in a set of three, the offset voltages on the PZT's can be varied individually to give a fine tip, tilt, and focus adjustment. It is also useful to build in the ability to rotate the optic with respect to the test plate. This allows the removal of the non-axisymmetric errors from the test.

4. OPTICAL DESIGN OF FIZEAU TESTS FOR CONVEX SURFACES

The optical design of these systems is performed in three steps:

1. determine the test plate reference surface (and hologram) shape;
2. design the illumination system to create a wavefront that fits the test optic;
3. design imaging lenses to create a distortion-free image of the optic onto a CCD.

These steps are described in detail below, and the prescriptions for example systems are given.

4.1 DESIGN OF TEST PLATE REFERENCE SURFACE

The first step in designing a test is to pick the air gap between the test plate and the surface being measured and to find the prescription of this surface. The prescription is trivial for spherical surfaces, but it requires some work for aspherical surfaces. I design these surfaces by simulating a wavefront that exactly fits the shape of the optic being measured, then fit the test plate to this wavefront after it has propagated the correct distance. The wavefront may be simulated using a point source, a dummy aspheric surface, and a few "pickups" in the optical design code.

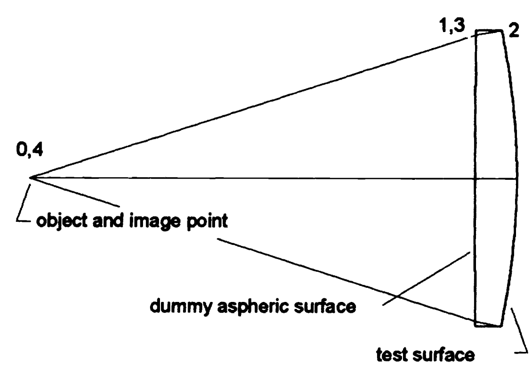
For the test of secondary mirrors, I model the mirror as a solid lens and use refraction at the first (back) surface to create a wavefront that fits the surface to be tested. I model the test surface as a mirror and then impose symmetry to insure that the light is normally incident everywhere on the test surface. The system stop is specified to be at this test surface. The first surface, which is allowed to be a general asphere, has its shape and position duplicated at the third surface using pickups in the design code. The point object location is duplicated at the fourth surface using a thickness pickup. The aspheric coefficients of surface 1 (equal to those at surface 3) are optimized to give a perfect point image at surface 4. Since the system is symmetric, with the point source coinciding with the image point, the rays must strike the reflective surface 2 at normal incidence everywhere on the mirror. This condition is equivalent to the wavefront fitting the optical surface. This method can be performed exactly, so the entire system can be defined in single pass.

A prescription is shown below in Fig. 4 that demonstrates the use of the dummy surfaces to create a wavefront that fits a 350-mm diameter test surface that has 43 μm aspheric departure. The residual wavefront errors using this definition are only 0.0002 λ P-V.

Having defined surface 1 to create the wavefront that exactly fits the test surface 2, it is easy to design the test plate and the illumination optics. The aspheric test plate may be defined by modifying the above prescription slightly. The test asphere must be allowed to transmit the light, and the test plate reference surface is inserted to reflect the light. Once the position of the test plate is chosen, the prescription can be determined by optimizing aspheric coefficients to create a perfect wavefront at the image point An example showing the design of an aspheric test plate for the 350-mm optic described above is shown in Fig. 5. Note that the relationship given in (4) holds, but higher order coefficients were required to improve the fit.

System/Prescription Data

Surf	Type	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD	Infinity	540.1638		0	0
1	EVENASPH	20989.28	50	BK7	337.228	0
STO	STANDARD	-879.39	-50	MIRROR	350	-1.003597
3	EVENASPH	20989.28	-540.1638		337.228	0
IMA	STANDARD	Infinity	0		0	0



Maximum Field : 0
Primary Wave : 0.632834
Lens Units : Millimeters

SURFACE DATA DETAIL:
Surfaces 1 and 3 : EVENASPH
Coeff on r 4 : -2.378856e-010
Coeff on r 6 : 4.692385e-016
Coeff on r 8 : -5.879904e-022
Coeff on r 10 : -7.195934e-028
Coeff on r 12 : -3.816741e-036

INDEX OF REFRACTION DATA:
BK7 1.51508803

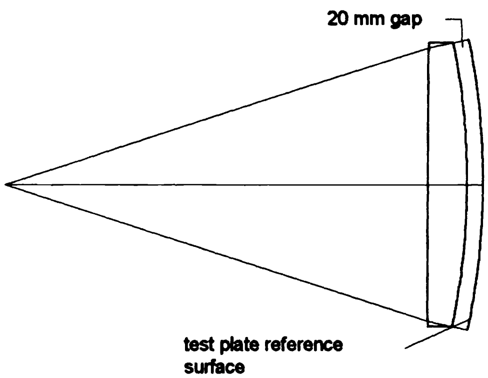
Figure 4. Optical system for defining wavefront that fits the aspheric surface to be tested.

The residual wavefront error in this simulation is 0.0001 λ P-V.

The design of the holographic test plates is more complicated. The radius of curvature of the test plate must also be chosen. Since the hologram compensates the difference between the test plate and the asphere being tested, the test plate radius can be changed and accommodated by changing the power in the hologram. The choice of this power is made as a tradeoff between separation of the orders of diffraction and sensitivity to writing errors in the hologram. More power in the hologram causes the spurious orders of diffraction to be more widely separated so larger errors in the illumination system can be accommodated; however, this also causes the ring spacing to become smaller which increases the hologram's sensitivity to writing errors. Typically the power is chosen to keep the orders separated by at least 2 mrad, which results in maximum line spacing of around 300 μm.

System/Prescription Data

Surf	Type	Radius	Thick	Glass	Diameter	Conic
OBJ	STANDARD	Infinity	540.1638		0	0
1	EVENASPH	20989.28	50	BK7	337.228	0
STO	STANDARD	-879.39	20		350	-1.003597
3	EVENASPH	-899.39	-20	MIRROR	357.806	-0.98128
4	STANDARD	-879.39	-50	BK7	350	-1.003597
5	EVENASPH	20989.28	-540.1638		337.228	0
IMA	STANDARD	Infinity	0		0	0



Primary Wave : 0.632834
Lens Units : Millimeters

SURFACE DATA DETAIL:
Surfaces 1 and 5: EVENASPH
Coeff on r 4 : -2.378856e-010
Coeff on r 6 : 4.692385e-016
Coeff on r 8 : -5.879904e-022
Coeff on r 10 : -7.195934e-028
Coeff on r 12 : -3.816741e-036
Surface 3 : EVENASPH
Coeff on r 6 : 2.330726e-018
Coeff on r 8 : -1.680927e-024

INDEX OF REFRACTION:
BK7 1.51508803

Figure 5. Optical system for designing aspheric test plate.

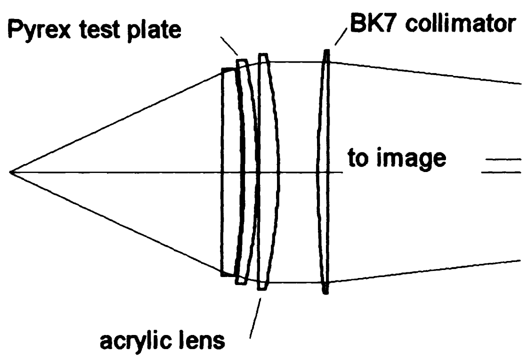
4.2 DESIGN OF ILLUMINATION SYSTEM

The design of the illumination system uses the same dummy surface to create the wavefront that fits the asphere. The reflective surface is removed allowing the wavefront to be transmitted through the test surface. The illumination optics are simulated and optimized to bring this light to a good focus. The required quality of the focus depends on the allowable slope errors. The imaging distortion is minimized by optimizing for linear mapping between position on the test optic and the slope of the image ray.

This design method is exactly the same for designing a null corrector. An example of the holographic test of the 350-mm optic is shown in Fig. 6. An aspheric acrylic lens and a glass collimator are used for this illumination. The holographic test uses reflected diffraction from the hologram to create the reference wavefront. The illumination system is designed using only the test wavefront, which is not diffracted by the hologram. The reference wavefront will, of course, be designed to be coincident with the test wavefront.

Surf	Type	Radius	Thick	Glass	Diameter	Conic
OBJ	STANDARD	Infinity	540.1638		0	0
1	EVENASPH	20989.28	50	BK7	337.2319	0
STO	STANDARD	-879.39	5		350	- 1.003597
3	STANDARD	-908.7	33	PYREX	370	0
4	STANDARD	-614.0316	5		380	0
5	EVENASPH	Infinity	48	ACRYLIC	400	0
6	EVENASPH	-614.0316	100		400	0
7	STANDARD	1244	25.4	BK7	412	-0.586
8	STANDARD	Infinity	2400		412	0
IMA	STANDARD	Infinity	0		0.00804	0

Primary Wave : 0.632834
Lens Units : Millimeters



SURFACE DATA DETAIL:
Surface 1 : EVENASPH
Coeff on r 4 : -2.378856e-010
Coeff on r 6 : 4.692385e-016
Coeff on r 8 : -5.879904e-022
Coeff on r 10 : -7.195934e-028
Coeff on r 12 : -3.816741e-036
Surface 6 : EVENASPH
Coeff on r 4 : 5.783886e-010
Coeff on r 6 : 9.551897e-016

INDEX OF REFRACTION
BK7 1.51508803
PYREX 1.47237912
ACRYLIC 1.48977468

Figure 6. Optical design of illumination system for CGH test of the 350-mm asphere.

4.3 DESIGN OF IMAGING SYSTEM

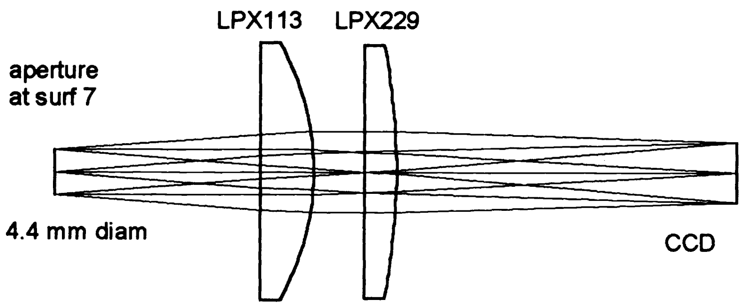
The optics that project the laser are trivial, but the imaging optics require some design. The imaging lenses must collect and focus all the light in the presence of the slope errors in the illumination system. Since only a narrow pencil of rays actually hit each point on the test surface, the residual aberrations in the imaging system will not caused blurred fringes. They will cause distortion in the image.

I design the imaging optics by modeling the system with the test optic as a diffuse source and the stop as the aperture where the light comes to focus. The size of the stop is chosen based on the allowable slope errors in the imaging system. Lenses are then chosen that give a distortion-free image of the test surface, properly scaled, on the CCD array.

An example is given in Fig. 7 for imaging the test of the 350 mm asphere above. In this case, slope errors of ±1 mrad are allowed, which gives a spot diameter up to 4.4 mm.

System/Prescription Data

Surf	Type	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD	-879.39	5		350	-1.003597
1	STANDARD	-908.7	33	PYREX	370	0
2	STANDARD	-614.0316	5		380	0
3	STANDARD	Infinity	48	ACRYLIC	400	0
4	EVENASPH	-614.0316	100		400	0
5	STANDARD	1244	25.4	BK7	412	-0.586
6	STANDARD	Infinity	2400		412	0
STO	STANDARD	Infinity	20		4.4	0
8	STANDARD	Infinity	5.2	BK7	25.4	0
9	STANDARD	-26.351	5		25.4	0
10	STANDARD	Infinity	3.1	BK7	25	0
11	STANDARD	-70.027	33.57678		25	0
IMA	STANDARD	Infinity	0		5.997954	0



Maximum Field : 175mm
Primary Wave : 0.632834
Lens Units : Millimeters

Surface 4 : EVENASPH
Coeff on r 4 : 5.783886e-010
Coeff on r 6 : 9.551897e-016

INDEX OF REFRACTION
PYREX 1.47237912
ACRYLIC 1.48977468
BK7 1.51508803

Figure 7. Optical design of imaging system for CGH test of 350 mm asphere.

5. EXAMPLES OF FIZEAU MEASUREMENTS OF LARGE CONVEX SURFACES

Several interesting Fizeau tests of large convex optics have been designed and implemented at the Steward Observatory Mirror Lab. Layouts from measuring a fast 270-mm-diameter sphere, a 260-mm asphere and a 1.14 m asphere are shown.

5.1 MEASUREMENT OF A 270 MM CONVEX SPHERE WITH 0.6 NA

A fast convex surface of a relay lens for a null corrector[11] is being measured using a test plate with an interesting illumination scheme shown in Fig. 8. A concave test plate is measured using a Fizeau interferometer with an $f/0.6$ diverger. The diverger reference surface quality was determined by measuring a precision ball at many rotation angles. The convex surface of the relay lens is then measured with this test plate using the Fizeau and diverger only for illumination and imaging. An imaging element is fit to the relay lens with the outer surface nearly concentric with the test plate. For the relay lens measurement, there are four nearly concentric surfaces. To avoid spurious fringes, the Fizeau reference and the imager surface are tilted and the reflections from these surfaces are blocked. The test plate is pushed using PZT's and phase shifting interferometry is used to allow a high resolution measurement.

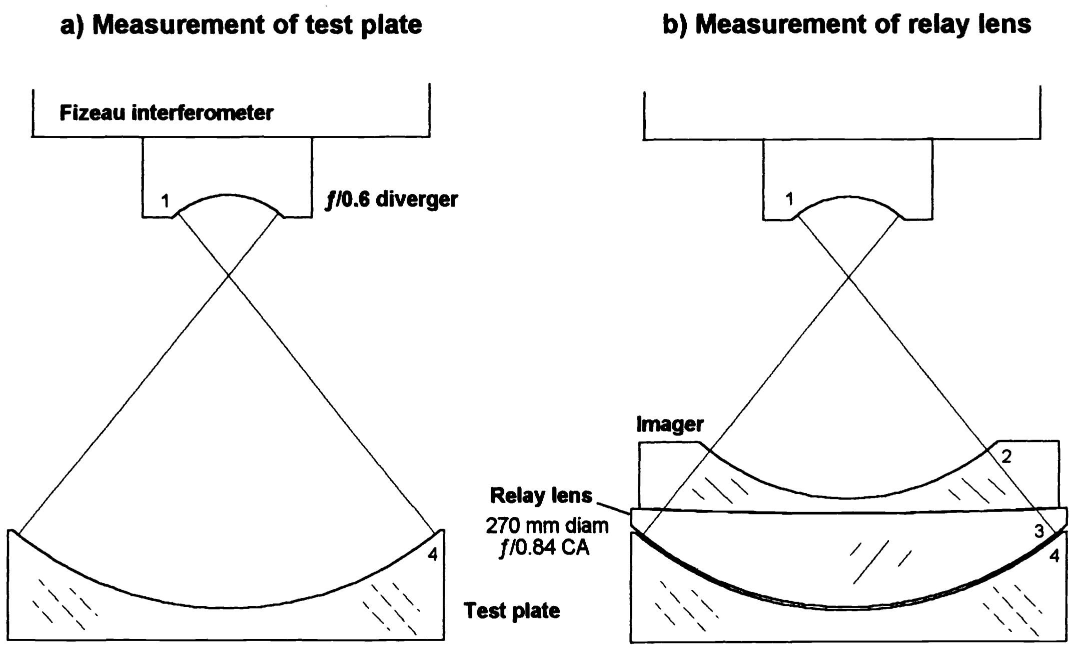


Figure 8. Measurement of a fast convex surface using a test plate. a) The concave test plate is measured using a Fizeau interferometer. b) The fast convex surface (3) is measured against the test plate (4). For this measurement, surfaces 1 and 2 are tilted so the reflections from these surfaces can be blocked.

5.2 CGH TEST PLATE MEASUREMENT USING A REFRACTIVE ILLUMINATOR

A low-cost refractive illumination system was implemented for the holographic test of a 260 mm convex secondary from the Multiple Mirror Telescope.[12] The system layout for this test is shown in Fig. 9. A plano-concave Pyrex test plate was held in a cell with a plano-convex acrylic lens. Acrylic was chosen for the aspheric lens because it is an inexpensive material and it is easily worked. The typical problems with the softness, inhomogeneity, and instability of acrylic do not significantly degrade its performance for illumination optics.

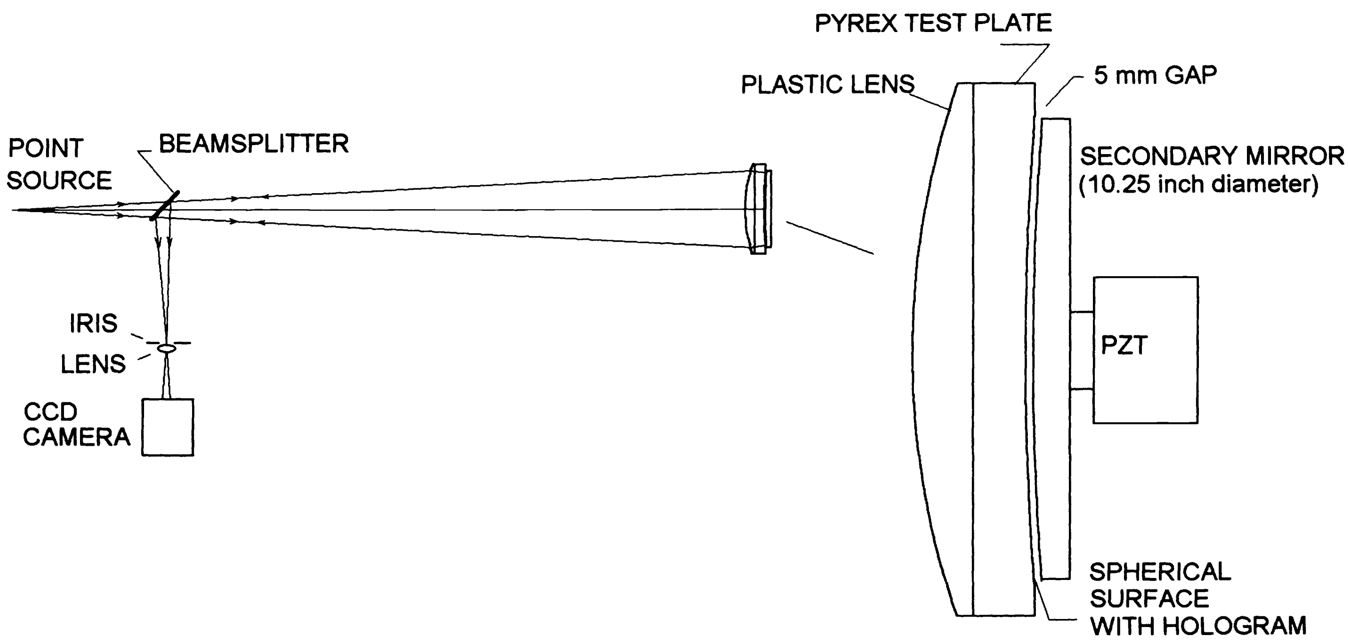


Figure 9. Layout of optical system for measuring a 260-mm asphere.

The lens was received turned and polished with an unacceptable figure. It had several sharp zones and a large trefoil error from its support in a three-jaw chuck during turning. We corrected the figure by polishing with a full-diameter tool and working the zones locally. The hologram for this test, consisting of 300 rings with spacing varying from 700 μm to 250 μm, was fabricated on a prototype hologram writer at the Optical Sciences Center at the University of Arizona. The secondary mirror was pushed with a PZT to allow phase shifting interferometry. The interference pattern showed nearly perfect contrast allowing low-noise measurements. The mirror was measured to have shape error of 44 nm rms, most of which was due to a quarter wave of astigmatism. The azimuthal component of the hologram error was determined by a rotation test to be 3 nm rms. The comparison of the CGH test results with an independent measurement using a Hindle test demonstrated excellent agreement.

5.3 CGH TEST USING REFLECTIVE ILLUMINATION SYSTEM

Acrylic lenses are ideal for illuminating Fizeau tests of optics up to 400 inches in diameter. Larger diameter lenses are not readily available. The large secondary mirrors at the Steward Observatory Mirror Laboratory will be measured using CGH test plates and a reflective illumination system. This system, shown in Fig 10, uses a 1.8-m aspheric reflector and a small convex secondary reflector. The secondary mirrors are tested face-down in this system since they will be used at this orientation in the telescopes.

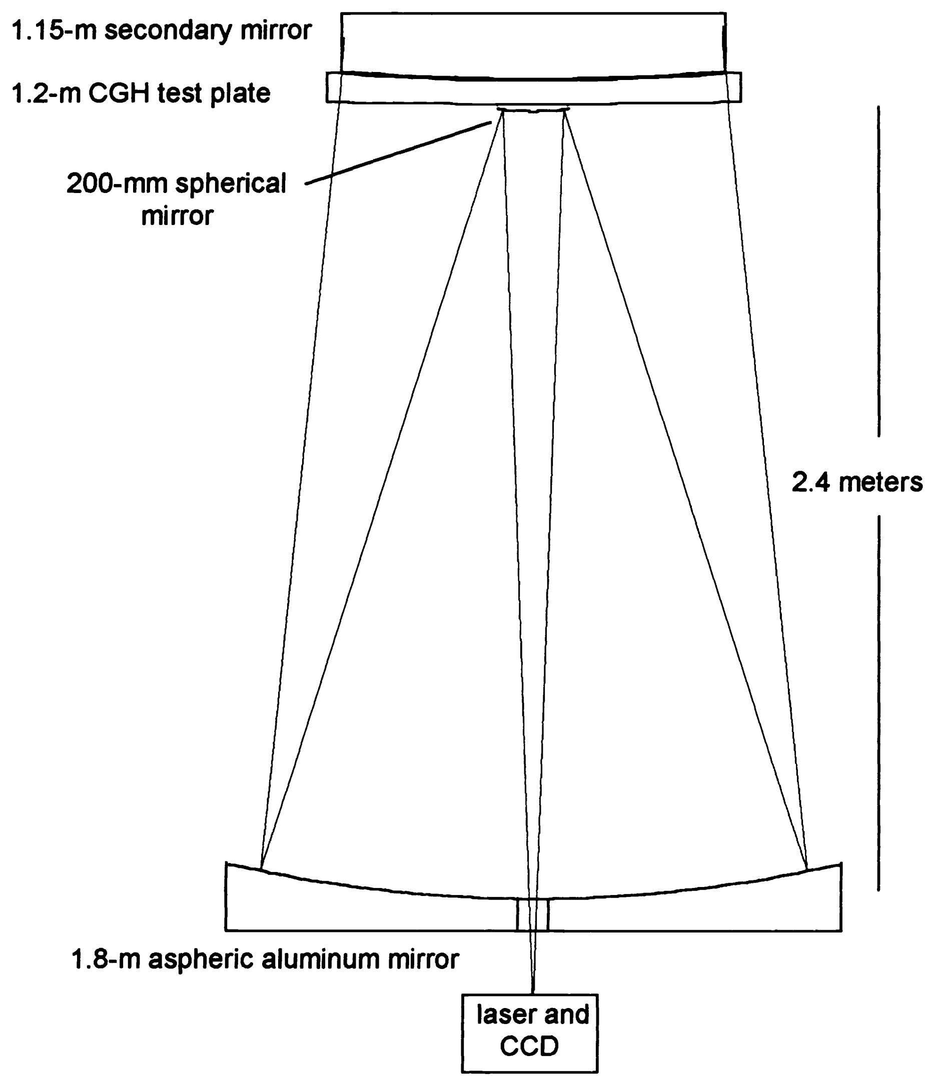


Figure 10. Layout of optical system for measuring a 1200-mm asphere.

The 1.8-m mirror was turned out of a solid disk aluminum on a vertical lathe. It was then ground and polished to give wavefront slope errors less than 0.3 mrad P-V. The ellipsoidal surface (K = -0.42) has 136 μm departure from the best-fit sphere. The figure was tested using a HeNe laser light coupled through a fiber optic as a point source at the near focus of the ellipse, and the images at the far focus were evaluated. This illuminator is planned to be used for measuring four different secondary mirrors. We plan to fabricate a 2.5-m illuminator in the near future for the test of the two more secondary mirrors up to 1.7-m in diameter.

In this test, the test plates are pushed with PZT's for phase shifting. The fine alignment is performed by moving the secondary mirror on a 6 DOF system. Also, the secondary mirrors are supported on an azimuth bearing that allows easy rotation for determining the non-axisymmetrical errors in the test.

6. CONCLUSION

There is no easy way to accurately measure large convex surfaces. The Fizeau interferometer can achieve high accuracy at a reasonable cost using low-cost, low-accuracy illumination optics and a single precise concave reference surface. Random testing errors are minimized by keeping the gap between the test plate and the optic small. Systematic errors are mostly limited by the ability to figure and measure the concave reference surface. The errors in the illumination system couple weakly into the surface measurement.

7. ACKNOWLEDGMENTS

The author acknowledges numerous contributions from D. Anderson on the implementation of these systems. Special thanks to Glen, Paul, and Gwelleh.

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