Transmission Sphere Selection

Introduction

A typical application for a GPI or VeriFire interferometer is the examination of spherical surfaces. A concave or convex spherical surface can be inspected for surface figure and irregularity by placing its center of curvature coincident with the focus of a transmission sphere. This Application Brief provides a basic understanding of transmission sphere selection for spherical surface testing.

What are Transmission Spheres?

A transmission sphere is used to transform the collimated output beam of the interferometer mainframe into a spherical wavefront, and is used as a beamsplitter to divide the laser light into separate reference and measurement wavefronts. ZYGO transmission spheres are designed to snap into the accessory receptacle located on the interferometer mainframe, or an auxiliary receptacle remote from the mainframe, in the collimated output beam.

The last surface of each transmission surface acts as the "master surface," commonly referred to as an aplanatic surface. The quality of the reference wavefront is dependent upon the figure quality of this master surface. The master surface reflects approximately 4 percent of the laser light back into the mainframe, to form the reference wavefront.

The remaining laser light, in the form of a high quality spherical wavefront, acts as the measurement beam. As illustrated in Figure 1, this wavefront converges to a focus in front of the transmission sphere and then diverges on the other side of focus. The converging and diverging portions of the beam can be thought of as a library of precise spherical wavefronts with a limited range of converging radii and an infinite range of diverging radii.
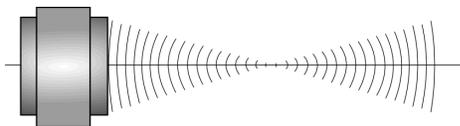

Figure 1

Transmission spheres are lenses, and as such are described using conventional lens nomenclature. One of the most significant parameters of a lens is its relative aperture, or speed. This is defined as the ratio of the focal length to the entrance pupil diameter (f/D) and is usually referred to as the f/number (f/#). A lens whose focal length is 8 inches (200 mm) and whose entrance pupil diameter (aperture) is 4 inches (100 mm) is referred to as an f/2 lens. Shown in Figure 2, an f/1 lens has a larger relative aperture (twice as large) and a higher speed than the f/2 lens shown in Figure 1.

The f/1 lens is "faster" than the f/2. The relative aperture or f/# of a lens describes the steepness of the cone angle of the light at the focus of the lens. A narrow cone is conventionally referred to as from a "slow" lens while a broader cone is from a "fast" lens. This convention and nomenclature may be familiar since it is used for lenses of photographic cameras.
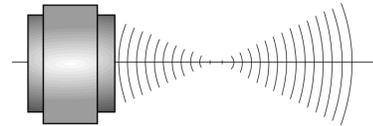

Figure 2

A number of different transmission spheres covering a range of f/numbers and apertures are required to accommodate the full range of convex and concave test possibilities. The reasons for this are explained in the following sections. Transmission Spheres of various apertures and f/numbers are available as standard accessories, and others may be obtained on special order.

Describing the Surface Under Test

Although it is a convention to describe a cone of light produced by a lens in terms of f/#, it is not conventional to describe the "speed" of a concave or convex surface in those terms. Instead, the convention is to use R/numbers. An R/number (R/#) is analogous to an f/#. It is the radius of curvature divided by the clear aperture of the spherical surface, as shown in Figure 3. Therefore f/# and R/#, if they are the same (e.g. f/2 and R/2), describe cones that have the same "speed."
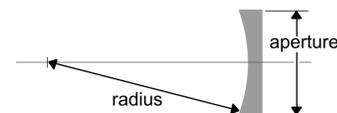
Figure 3

Measurement Scheme

Spherical surface testing is accomplished by positioning the spherical surface to be tested in the beam with its center of curvature precisely at the focus of the transmission sphere. This has the effect of placing the test surface coincident with a spherical wavefront of identical radius. Concave surfaces are tested in the diverging portion of the beam (Figure 4), whereas convex surfaces are tested in the converging portion of the measurement beam (Figure 5). An interference pattern will result when the measurement wavefront, after reflecting back from the test surface, passes through the transmission sphere and into the interferometer where it interferes with the reference wavefront.

Figure 4

Figure 5

Some Constraints

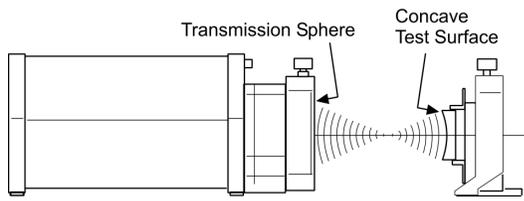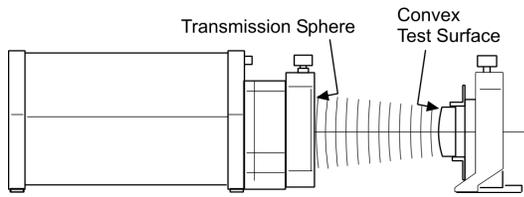In order to measure an entire surface, the cone of light from the transmission sphere must be fast enough to completely fill (illuminate) the test surface. In other words, the f/# of the transmission sphere must be equal to or faster than the R/# of the test surface. If the f/# is slower than the R/#, only a portion of the surface will be tested (Figure 6). The ratio of R/# to f/# describes the percentage of the entire surface measured, for example f/2 and R/l results in 50% coverage.
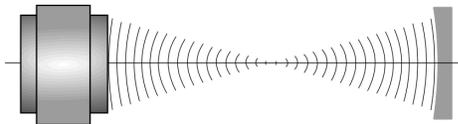

Figure 6

In the converse situation, if the f/# is faster than the R/#, the transmission sphere overfills the test surface (Figure 7).
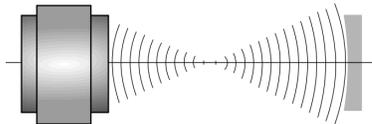

Figure 7

This results in the test surface appearing smaller on the interferometer monitor than it would have if the f/# had been exactly equal to the R/#. The percentage of full-size can be calculated as the ratio of the f/# to R/#. For example, f/5 and R/6 will result in an interferogram that is 88.3% of full size. Of course, if the interferometer is equipped with a zoom feature, such as the 6X zoom of a ZYGO interferometer, the 88.3% interferogram can be zoomed to full size.

The zoom feature is very useful in compensating for any significant mismatch between f/# and R/#, but only when the f/# is faster than the R/#. The 6X zoom can fully compensate for a transmission sphere with an f/# that is six times faster than the R/# of the surface being measured. For example, by using the 6X zoom, and R/12 surface can be made full-size on the monitor even if an f/2 transmission sphere is used to measure it Since even a 50% of full-size interferogram is usually quite acceptable, an R/24 surface can be measured.

From this we can see that from a coverage point of view, only a few transmission spheres are necessary to cover a range of very fast to very slow surfaces.

Referring once again to Figure 1, note that there is no restriction on the radius, diameter, or R/# of a concave surface provided a transmission sphere with suitable f/# is used.

Unfortunately, this is not the case when measuring a convex surface, since the radius of the test surface must be no longer than what will fit between the transmission sphere and its focal point. This distance, which is essentially the radius of the master surface of any particular transmission sphere, increases as the f/# becomes slower for a constant aperture series of transmission spheres. For measuring convex surfaces with radii longer than can be accommodated within that distance, the only alternative is to use larger aperture transmission spheres (such as the 6 inch series) to increase the available radius range without decreasing coverage.

In Figure 8, even though the f/# of the transmission sphere is only slightly faster than the R/# of the convex surface, it is not possible to measure the convex surface in the setup shown because the radius of curvature of the surface is longer than the focal distance of the transmission sphere.
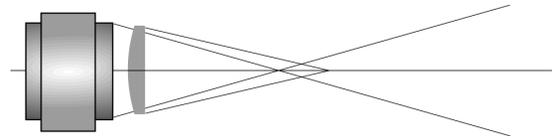
Figure 8

Figure 9 illustrates that by using a larger transmission sphere of approximately the same f/#, the center of curvature of the surface can be placed at the focus of the transmission sphere enabling the surface to be tested.
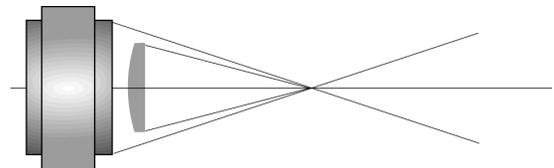
Figure 9

Figure 10 shows that by using a transmission sphere in the same series as illustrated in Figure 8, but with a longer focal distance to accommodate the longer radius of curvature of the surface, a transmission sphere with an f/# slower than the R/# of the surface must be used and full coverage of the surface under test is not accomplished.

In some cases, it may be necessary to accept less than full coverage in order to accommodate a particularly fast surface with long radius. Convex measurement situations usually are the determinant of why a variety of transmission spheres are required, since they are more restrictive than the relatively simple concave cases.
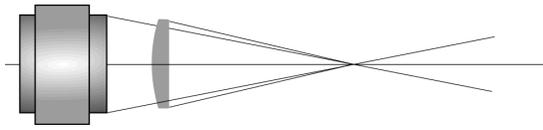
Figure 10

Table I provides information about the distance to its focal point for each available transmission sphere.

The rules for percentage coverage and for percentage of full-scale as explained above for the concave case, apply equally to the convex case.

The Standard Series

Transmission Spheres with various f/numbers are available in 4 inch and 6 inch aperture diameters. Each unit is provided in a snap-in cell and with a storage case. Many transmission spheres are available with maximum system error ranges from $\lambda/10$ to $\lambda/20$ (λ = 632.8 nm) over the clear aperture.

For most applications, 4 inch Transmission Spheres selected from the f/0.75 to f/11 range provides sufficient flexibility for measuring both concave and convex spherical surfaces. If you are using an attenuation filter the measureable part radius is reduced. Contact ZYGO if you have questions or require special transmission spheres.

The maximum convex diameter and radius test surface that can be accommodated by each transmission sphere are provided in Figure 11 and Table I.

R_1 is the radius of the TS reference optic.
D_1 is the TS clear aperture ($R_1 \div f/\#$).
D_0 is the housing opening diameter.
R_2 is the maximum measurable convex part radius when part diameter is larger than D_0.

Figure 11

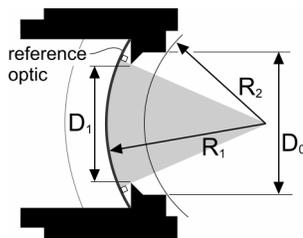| Input Aperture	Output f/#	R_1 (mm)	D_1 (mm)	D_0 (mm)	R_2 (mm)
4 inch	0.65	38.7	59.5	62.0	36
4 inch	0.75	48.2	64.3	65.5	45
4 inch	1.5	121.2	80.8	93.7	115
4 inch	3.3	298.0	90.3	89.2	282
4 inch	7.2	681.7	96.0	98.1	674
4 inch	11.0	1039.2	97.1	100.4	1030
6 inch	0.8	80.0	100.0	104.9	77
6 inch	1.1	123.3	112.1	128.4	118
6 inch	2.2	290.0	131.8	164.1	274
6 inch	3.2	475.8	135.9	164.1	458
6 inch	5.3	776.4	143.8	164.1	761
6 inch	7.2	1045.0	145.1	164.1	1022

Table I

The Converger/Diverger Series

A diverging transmission sphere has a measurement wavefront that is convex, has a virtual focus and is therefore useful for testing mid-range concave spherical surfaces (Figure 12). The radius of the test surface must be equal to or longer than the radius of the diverger in order to be able to comply with the requirement to set its center of curvature coincident with the focus. Since each diverger in the series has a radius 1 meter longer than the previous one, the test path for any surface falling in the range of the series need not be any longer than 1 meter.
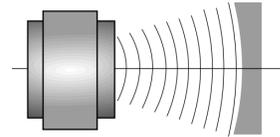
Figure 12

The long radius converging transmission spheres produce a converging measurement wavefront for testing mid-range convex surfaces. Each has a real focus, and therefore the test surface must have a radius equal to or less than the radius of the converger. The long radius Converger and Diverger series of transmission spheres is listed in Table II, along with data describing the radius covered by each.

Size	F/#	Radius (mm)	
		Maximum (or shorter)	Minimum (or longer)
4 inch	f/15 Diverger		-1500 Concave
4 Inch	f/15 Converger	+1500 Convex	
4 inch	f/25 Diverger		-2500 Concave
4 inch	f/25 Converger	+2500 Convex	
4 inch	f/35 Diverger		-3500 Concave
4 inch	f/35 Converger	+3500 Convex	
4 inch	f/45 Diverger		-4500 Concave
4 inch	f/45 Converger	+4500 Convex	
4 inch	f/80 Diverger		-8000 Concave
4 inch	f/80 Converger	+8000 Convex	

Table II

Practical Help

The task of optimizing the selection of transmission spheres to measure a broad range of surfaces needs to be done when initially purchasing an interferometer. The following are practical hints, gained through years of experience.

If you are faced with the task of identifying die most suitable transmission spheres to purchase, it is suggested you fill in the worksheet form provided at the end of this note. Referring to the example below, note that the first six columns organize information about the surfaces you want to measure. Without this information, you cannot make an informed choice about the proper transmission sphere(s) required for your application. Specifically these are: part identifier, diameter (clear aperture), radius of curvature, surface R/# (which is the radius of curvature divided by the diameter), and whether the surface is concave (CC) or convex (CX).

In the following columns, select the transmission spheres that have an f/# that is equal to or faster (smaller) than the part R/#. This will assure full coverage of the surface. Enter the results as shown in the example and explained in the legend. Note that concave and convex surfaces can be measured with a range of transmission spheres, especially if you have the capability of the 6X zoom. The value of R_1 for each transmission sphere is listed in each case to assist you in avoiding the radius limitations for convex testing.

For CC (concave) test optics divide R/# by the f/#. Results over 1 indicate full coverage; results under 1 indicate the % of partial coverage.

For CX (convex) test optics divide R/# by the f/# the same as for CC optics, but also compare the radius of the TS (R_1) to the radius of the part. For full coverage both criteria must be met.

After you have completed the worksheet, a review of the results will greatly simplify making the choice of the optimum combination of transmission spheres. In the example, a 6 inch f/1.1 TS can measure all surfaces. Since it is more economical to use the smaller 4 inch series, the possibility of using only the 4 inch f/1.5, and accepting the reduced coverage in one case, should be considered. Alternatively, the use of the 4 inch f/0.75 in addition to the 4 inch f/1.5 provides full coverage for all concave surfaces, but not all convex surfaces.

If you need assistance or if you want someone to review a completed Worksheet form, contact your Zygo representative. ZYGO offers a free calculator for these functions; just ask for the ZYGO Transmission Sphere Selector Tool, OMP-0495.

Example of Completed Worksheet

	List Surfaces and Data To Be Measured					R₁ mm	4 inch						6 inch					
							38.7	48.2	121.1	298.0	681.7	1039.2	80.0	123.3	290.0	475.8	776.4	1045.0
ID	DIA	RAD	R/#	CC	CX	f/#	0.65	0.75	1.5	3.3	7.2	11	0.8	1.1	2.2	3.2	5.3	7.2
1	50	100	2	✓				✓	✓	60			✓	✓	91			
2	50	78	1.6		✓			x	✓	48			✓	✓	✓	✓	✓	✓
3	22	100	4.6		✓			x	✓	✓	64		x	✓	✓	✓	✓	✓
4	22	64	2.9	✓				✓	✓	88			✓	✓	✓	91		
5	40	45	1.1		✓			✓	73				✓	✓	50			
6	40	200	5	✓				✓	✓	✓	✓	✓	✓	✓	✓	✓	94	

In this example:
✓ means surface can be fully measured
x means the CX (convex) radius is too long to fit in test cavity (RAD $\geq$ R₁)
A number is the percent coverage when TS is slower than R/# (number is equal to R/# $\div$ f/#) (i.e. 1.1 $\div$ 1.5 = 73%)

Worksheet

	List Surfaces and Data To Be Measured					R₁ mm	4 inch						6 inch					
							38.7	48.2	121.1	298.0	681.7	1039.2	80.0	123.3	290.0	475.8	776.4	1045.0
ID	DIA	RAD	R/#	CC	CX	f/#	0.65	0.75	1.5	3.3	7.2	11	0.8	1.1	2.2	3.2	5.3	7.2