Asphere Metrology

Options for measuring aspheric lenses

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An asphere is an optic that deviates from the spherical form and is defined by the polynomial equation shown in Figure 1. While spherical lenses have long been used because of optical properties that make them easier to manufacture and measure, aspheres can significantly reduce the number of elements, and therefore size and weight of an optical system, as well as many aberrations inherent to spherical lens systems. Optimax is working with industrial partners and researchers to develop manufacturing technology for improving both fabrication and metrology of aspheres. The specifications to which a lens is manufactured are only as good as the metrology available. It is helpful to consider the method of metrology that will be used before setting the tolerances on a lens.

$$z = \frac{Cr^2}{1+\sqrt{1-(k+1)C^2r^2}} + \sum_{i=1}^{20} a_i \left|r^i\right|$$

Z = sag
C = curvature at vertex
k = conic constant
r = radial coordinate

Figure 1: Asphere Equation

This paper will outline the numerous metrology options for aspheres at Optimax, including how they work, any requirements, and what is specified with each method in an effort to help reasonably tolerance aspheres. Effects on the fabrication and cost of the lens will also be discussed. Metrology of aspheres fits into three basic categories: physically measuring the form of the optical surface, reflected wavefront testing, and transmitted wavefront testing. Each category has different methods of testing with varying degrees of accuracy.

Physical Measurements

Before advancements in machining and computer software, aspheres were measured against an already existing physical object of near perfect form. Brass, easier and less fragile to work with than glass, can be cut and shaped into gauges equal in shape to the desired lens but opposite in curvature. Lenses are subjectively judged by how well they fit with their brass gauge counterpart. Now only special cases are measured with brass gauges because there are programmable instruments that can physically measure and provide more accurate data on the profile and form of a lens.
Optimax has two such methods to measure aspheres: a coordinate measuring machine and profilometers.

Coordinate Measuring Machine (CMM)

The FARO Gage Plus coordinate measuring machine, pictured in Figure 2, is a portable arm with six flexible joints. Precision rotary encoders in each joint provide extremely accurate data on the position of the arm.[1] By defining certain geometrical characteristics (such as a plane, a

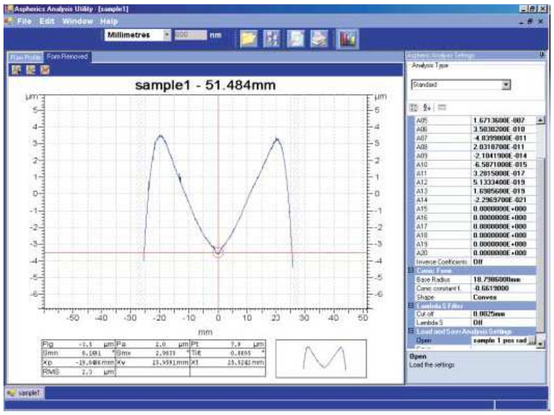
Figure 2: CMM[1]

line, and a point) with respect to the position of the arm, the shape and form of the rest of the lens can be determined using these calibration points. Also, the software can compare the lens to a 3D model and generate a report giving the deviation of the lens from that form.

The CMM is generally used to measure acylinders and torics but can be applied to rotationally symmetric aspheric lenses as well. The arm is portable and has various mounting fixtures allowing it to be utilized without removing the lens from the machine it is being worked on. It is convenient to be able to measure, rework, and re-measure the lens without having to realign it with the polishing equipment. The arm has a 1.2m coverage sphere and, unlike most metrology options, a lens does not need to be rotationally symmetric to be measured by the CMM. If the desired lens is not axially symmetric, the CMM should be a strong consideration. Accuracy, dependent on the linear distance between measurement points, is ±5µm at best.[1]

Profilometry

Optimax has Talysurf profilometers from Taylor Hobson that can be used to measure surface profiles of aspheric lenses. By defining an initial position in the z-axis and a desired length of movement in the x-axis, the machine pulls the stylus across the surface of the part measuring the change in the z-axis throughout that movement. The instrument is pre-programmed with the asphere equation and any other unique characteristics. The data from the stylus tip and from this program are organized to output information about the lens as shown in Figure 3; this information can be viewed as height from the theoretical form as a function of radial distance or separated where vertex radius error and surface irregularity are similar to power and irregularity in a spherical lens. Any tilt inherent to the setup of the machine rather than the lens is removed in this calculation.



Analysis Type: Standard

A05	1.6713600E-007
A06	3.5030200E-010
A07	-4.0399000E-011
A08	2.0318700E-011
A09	-2.1041900E-014
A10	-6.5871000E-015
A11	3.2015000E-017
A12	5.1333400E-019
A13	1.6985600E-019
A14	-2.2969700E-021
A15	0.0000000E+000
A16	0.0000000E+000
A17	0.0000000E+000
A18	0.0000000E+000
A19	0.0000000E+000
A20	0.0000000E+000
Inverse Coefficients	Off
Base Radius	18.7986000mm
Conic constant 1	-0.6619000
Shape	Convex
Cut off	0.0025mm
Lambda S	Off
Open	sample 1 pos sad

Open
Load the settings

Figure 3: Profilometry Data[2]

The talysurf must measure through the axis of rotation; profiles are normally measured and provided at 0º and 90º on axis, but if more data is desired they can also be measured in other places, at 45º on axis for example. Optimax also has new software available to combine multiple measurements from the profilometer and generate a plot of the full surface of the lens. This allows for asymmetric corrections to be generated to help with final figuring. Optimax frequently uses profilometers for surfaces that are tolerance at ±0.5µm or looser. As the sag of a lens increases or the slope of the lens becomes too steep or too flat, the lens becomes harder to measure accurately. The extreme slopes approach the limits of the resolution of the instrument, which vary depending on the arm length, stylus tool, and current calibration.[2] Possible tolerances are largely dependent on the geometry of each individual lens. A sag table is required to aid in the manufacturing process of every asphere but can be used to tolerance the lens with profilometry. A lens can be toleranced by specifying acceptable microns deviation from the theoretical form as a function of radial distance, or the tolerance can be specified as vertex radius and maximum allowable deviation from theoretical form throughout the profile.

Profilometry is the most common way to measure aspheres at Optimax. Interferometric testing may be impossible for some lens designs or unnecessary for some tolerances. Tighter tolerances increase cost but using the profilometers is generally less expensive if they can obtain the desired specifications.

Surface Testing in Reflection

Profilometry can often provide the accuracy desired or is sometimes the only metrology option for an aspheric lens design, but if tighter tolerances are desired and the geometry is suitable, aspheres can also be measured using interferometers. There are many interferometric methods and it is important to choose one appropriate for the lens design. When testing a lens interferometrically, the most common way to do so is by imaging the reflected wavefronts. Wavefronts are emitted from the interferometer, reflected from the lens, and imaged into an interferogram to be analyzed for surface form and irregularity. There are many different ways to do this depending on the form of the lens, some of which are based on a null configuration, meaning a perfect lens would result in no interference fringes.

The interferometer setup to measure spherical lenses is often only slightly modified to measure aspheres and many of the same principles are applied; a basic understanding of the way spherical lenses are measured will be helpful.

Spherical lenses are tested using a phase shifting interferometer (PSI) and a displacement measuring interferometer (DMI) together in a null configuration so that a perfect lens would reflect a spherical wavefront in such a way that no interference fringes are formed on the interferogram. If any fringes do appear, each represents a deviation from spherical by $\lambda/2$; λ is the wavelength of light used in the test and equal to 632.8nm for the HeNe lasers in the interferometers at Optimax. The PSI analyzes the interferogram from the confocal position to determine irregularity. The resolution of interferometers at Optimax is approximately 0.04 fringes ($\lambda/50$), and 0.1 fringes ($\lambda/20$) is approaching the manufacturing limits of most of the interferometric tests. Any fringes that do form from the reflected wavefront of a spherical lens are interpreted to calculate the power and irregularity.

Spherical Wavefront Interferometry with Zernike Subtraction

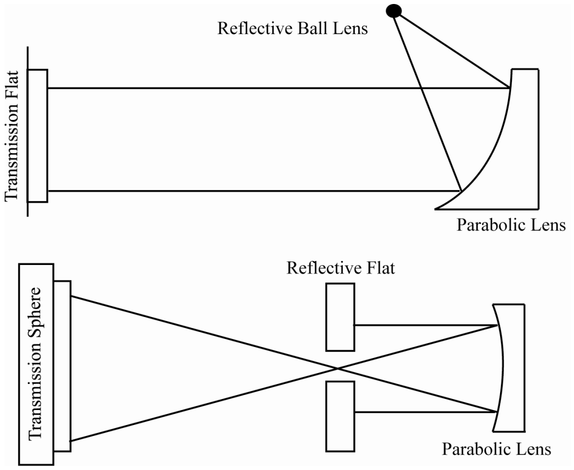
An asphere can be tested in the same way as a sphere if the departure from spherical is mild enough that the fringes formed by the interferometer do not violate the Nyquist condition, which states each fringe must cover two or more pixels for the pattern to be accurately resolvable by the sensor. A spherical wavefront reflects from an aspheric surface and fringes form based on the surface’s deviation from spherical; the larger the deviation or local slope, the more fringes that form in a smaller area, and the larger the fringe density. This is not a null configuration; there is an expected fringe pattern and an actual fringe pattern, and these are compared, if the Nyquist condition is not violated, to determine the form of the lens. One way this can be done is with Zernike based aberration subtraction. Allowable departure for this test varies proportionally to the diameter of the lens but depends mostly on the angle of localized slope. A large departure in a small area, which indicates a steep local slope, can lead to irresolvable fringes densities.

This test is straightforward but can only be used for extremely mild aspheres. Approximately x/mm spherical departure is the limit of this test, but departure needs to be considered for the fringe density of each particular lens design. With this test, tolerances as small as 0.1 fringes ($\lambda/20$) are sometimes possible, but uncertainty may vary with the form and departure of the asphere. Specifications can be set for both vertex radius and maximum deviation from aspheric form.

Null Testing of Ellipse/Parabola

While all aspheres are defined by the general asphere equation, some are varied only by k, the conic constant. When the higher order terms are zero and $-1 \leq k < 0$, a special null test may be applicable. By properties of the equations for the surface form of lenses that are portions of conics such as paraboloids or ellipsoids, they bring collimated light to focus at certain conjugate points or foci.[4] Using this property, there are two ways to perform null testing.

Figure Five: Null Testing of Parabolic Lenses



By placing a reflective surface concentric to the focus, collimated light is focused onto and reflected off the conjugate point and reflected from the optics back to the interferometer. This is a null configuration. Two possible setups are shown in Figure Five; there are many different setup options to choose from when using this test.[5]

This test is performed using the PSI and DMI setup together. It relies on the optical surface being defined by a first order aspheric equation with a conic constant greater than or equal to -1 and less than 0. Tolerances as tight as 0.1 fringes ($\lambda/20$) can be achieved. Vertex radius and deviation from aspheric form can be specified. Tolerance is based on the form of the optic and tighter tolerances will lead to a higher final cost.

Custom Null Optics: Computer Generated Holograms or Spherical Null Lenses

Custom null optics, a computer generated hologram (CGH) or spherical null lenses, can be aligned externally with the interferometers to measure an asphere defined by an even order polynomial. A collimated beam passes through the transmission sphere and then a converging or diverging wavefront is diffracted by the CGH into an aspheric wavefront matching the ideal aspheric surface. A spherical null lens or lens system can be used in the same way as a CGH if there is a design that creates the correct shape and aberrations in the wavefront. These two setups are shown in Figure Six and Seven. The beam is reflected from the aspheric surface and back through these elements to be interpreted by the interferometer. It is recommended the aperture of the null elements be slightly larger than the clear aperture of the optic to ensure the entire area is both imaged and corrected accurately. Ensuring the quality at the edge of the clear aperture of the optic is extremely challenging when the apertures match. The lens must have a clear aperture area that can be tested with an available transmission sphere.

For a CGH, which is created like a diffraction grating where line patterns are drawn into glass using an electron beam or laser lithography, there are some limitations on local slope and spherical departure due to the fabrication of the CGH that limit the use of this test.[6] However, these limitations are broad in comparison to other methods and CGH may be the only option to interferometrically measure certain asphere designs. Each CGH is specific to the aspheric design it is measuring, so considering cost, it is often a better option when multiple lenses are being produced. Alignment of the system is extremely important for a CGH test and can induce error into the measurements if not setup properly.[6] A CGH can have a 10 week lead-time and may cost more than $10,000. When using a CGH, the tightest recommended tolerance is 0.25 fringes (λ/8) because of setup induced alignment errors that are sometimes difficult to identify and eliminate. It is important to have an accurate way to align the interferometer, CGH and lens, such a fiducial or some other means, to minimize this error as much as possible. Using a CGH, a lens is often specified with a radius tolerance at the vertex and an irregularity tolerance as deviation from aspheric form. A CGH may cost more or take longer than other options, but if the asphere cannot be measured any other way interferometrically, it is a good choice to provide a tighter tolerance than is available with profilometry.

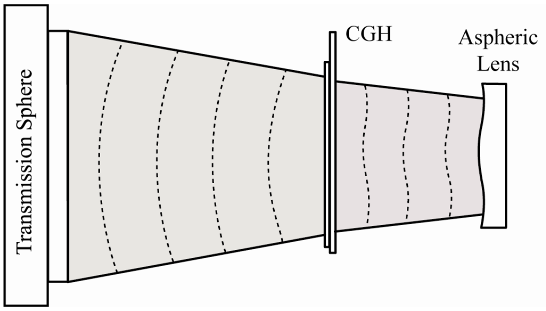


Figure Six: Null Testing with a CGH

Using a spherical null lens or lens system is based largely upon the ease and ability to manufacture and certify the lenses, and the time and difficulty of this task affects the cost of the final asphere. The tolerance also depends on the system of null lenses. The error in the null lenses as well as the overall alignment of the test setup needs to be considered. The interferometer can measure parts to a tolerance as tight as 0.1 fringes (λ/20) but because of difficulty and errors inherent to the test setup this is not always possible. This may be a good choice for testing the asphere if the spherical null lens system is readily available or easily manufactured. It is less expensive than other options for custom null optics and sometimes easier than more complicated interferometric methods.

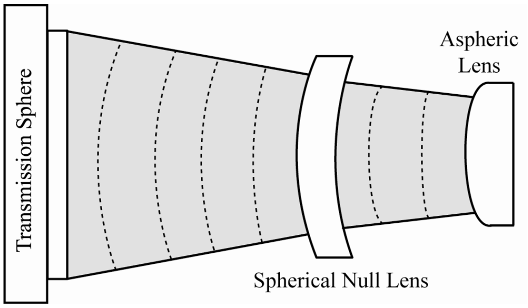


Figure Seven: Spherical Null Lens in Reflection

Subaperture Stitching Interferometer for Aspheres (SSI-A)

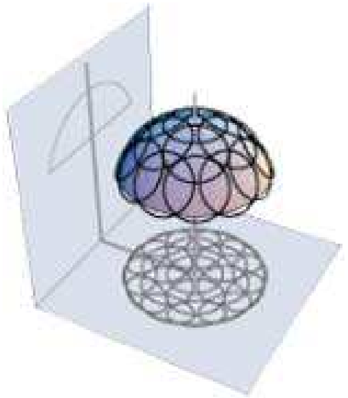


Figure Eight: Lattice[8]

Subaperture stitching was originally developed to overcome the size limitations on spherical lenses in basic interferometer setups. However, the new software of the SSI-A from QED allows this technology to be applied to measuring aspheres. A major issue with aspheres on interferometers is the steep localized slope and spherical departure which leads to irresolvable fringe densities. The SSI can “zoom-in” using a slower f/number transmission sphere and image smaller portions of the part.[7] The motion capability rotates the lens, capturing a collection of subapertures called a lattice. The lattice, shown in Figure Eight, is determined by the part geometry.[8] The localized slope in each subaperture should be such that the fringe density is resolvable for the imaging sensor.[7] The Nyquist condition must not be violated; this principle is one criterion that guides the software in suggesting a transmission sphere and determining a lattice. The lattice of subapertures is then stitched together using multiple overlapping areas to minimize error. Because the part is moved/rotated with respect to the interferometer, errors from the transmission sphere and setup are also identified and subtracted.

The lens can be no larger than 250mm in diameter and must be rotationally symmetric to be measured with the SSI-A; 50 μm is approximately the largest allowable spherical departure, but local slope and fringe density need to be considered specific to each lens. The tightest tolerance that is recommended to be specified is 0.1 fringes ($\lambda/20$). This is an absolute test since the surface is measured without respect to anything other than the theoretical form. Vertex radius is sometimes measured with profilometry on parts where surface irregularity is measured with the SSI. The SSI cannot calculate both radius and irregularity with respect to one another.

Zygo VeriFire Asphere Interferometer (VFA)

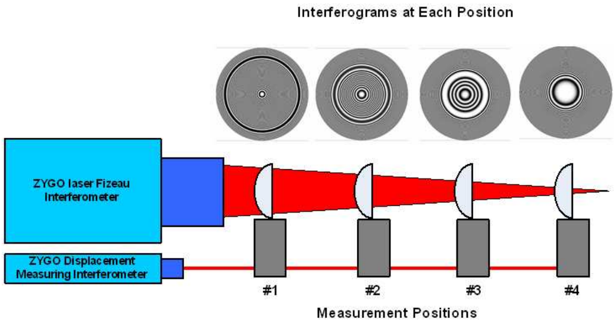


Figure Nine: VFA Scan[9]

The Zygo VeriFire is a new technology for measuring aspheres that uses both a PSI and DMI but in a different arrangement. Using spherical wavefronts from a transmission sphere, the optic is moved along its symmetrical axis and multiple interferograms of the part are captured in annular zones as shown in Figure Nine. The zone on the part and the position of the stage are corresponded based on where the optical surface and spherical wavefront will have a common tangent (the wavefront is normal to the surface in that zone). Therefore the reflection will produce an interferogram with a resolvable fringe density that can be interpreted using the Fizeau interferometer. The zones, rather than being stitched together using overlapping apertures like the SSI, are put together based on their relative apex to the zone distance and scan position determined with the

DMI.[9] Because of the DMI capabilities, the surface irregularity and apex radius are measured together and relative to each other.

The lens must be axially symmetric, have a measurable apex and defined aspheric equation, and cannot have reversing curvature to be measured with the VFA. The area to be imaged can have a diameter ranging from 1mm to 130mm; 800µm is nearing the maximum allowable spherical departure, a much larger allowable departure than any other interferometer without additional custom null optics.[10] It is still important to verify that local slope and fringe density are not issues. The smallest recommended tolerance with this method is 0.1 fringes (λ/20).

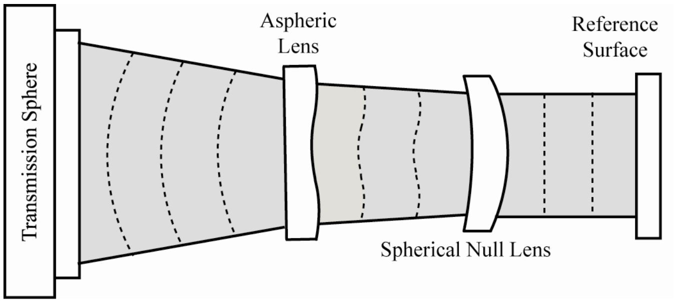
Lens Testing in Transmission

The simplest of all transmitted tests is an uncomplicated image quality test – using the lens to form an image and subjectively and visually determining if it is good enough for the intended application. There are also ways to quantitatively measure a lens in transmission using interferometers.

Transmitted Wavefront Error

A quantitative way to measure overall performance of a lens in transmission with finer resolution is to measure the transmitted wavefront error (TWE). This method tests the total lens function, including both surfaces and material defects.[11] Using the same setup that is used to test spherical lenses, a well-behaved asphere can be tested by TWE. A lens is well-behaved if the design has approximately less than 50µm departure and the change in slope is less than 0.5µm/mm. In this test, a spherical wavefront is transmitted through the asphere, reflected from a plano or spherical reference surface, and transmitted back to the interferometer. With a well-behaved asphere in this setup, the interferometer is able to accurately interpret the wavefront and resolve interference fringes to measure errors in the aspheric lens.

Figure Ten: Spherical Null Lens in Transmission



If an aspheric lens is not well-behaved, custom null optics can be used to test in transmission. A spherical null lens or lens system or a CGH can be used in such a way that the wavefront is resolvable for the imaging sensor of the interferometer. One of many possible setups is shown in Figure Ten. The fabrication and design process for the null optics is similar to testing in reflection, so these elements have the same affect on leadtime and cost. While this can take longer and be more expensive, it is often a good choice to test in transmission and evaluate the overall lens performance.

Each lens has an ideal target TWE map and this test produces an actual TWE map as shown in Figure Eleven. Using these maps, a corrective strategy for the lens can be determined. This is a feed-forward process; one side of the lens is modified to correct the sum of transmission errors shown in the TWE map, including any material defects and form error from both surfaces.[11] Therefore, when tolerancing a lens that will be tested using this method, measurements of surface form are not specified because one side may be altered to fix a sum of the errors in the lens, which changes the theoretical shape but corrects the lens performance. An allowable deviation from the expected wavefront is specified; tolerances as small as 0.1 fringes (λ/20) can be achieved, but as always, this depends on the figure and design of the lens being tested.

Figure Eleven: TWE map[11]

While TWE testing is favorable because it evaluates the overall lens performance, there are many requirements for an asphere to be tested in this manner. The interferometer must be able to resolve any aberrations from the lens; if the fringe density exceeds the resolving capabilities of the imaging sensor the TWE map will not be accurate. (The fringe density must not violate the Nyquist condition.) The lens must have an appropriate setup with the interferometer; part diameter, retrace error, and vignetting all need to be considered. The lens must transmit the wavelength of light being used in the test, meaning material must be considered, no paint or blocking wax can remain on the lens, and differences between λ in the test and λ in the application of the lens are pertinent to results. It is important that the lens fits the specifications of the test in order to obtain accurate data and corrective action.[11]

Manufacturing Considerations

How the metrology impacts the manufacturing process is largely dependent on the tolerance set on the optical surface. Most optics are finished with an iterative test, conventional zone polish, test process. Profilometry or less complicated interferometric methods are used to give the optician an idea of the shape of the optical surface and polishing techniques are used to improve the form and surface of the optic accordingly. The lens is repeatedly tested and polished until all tolerances are met. This is the expected process with profilometry and sometimes used with interferometric methods.

Optimax has several deterministic polishing technologies, for example, the AII manufactured by Satisloh and QED’s magnetorheological finishing (MRF) machine and Optimax’ patented VIBE polishing. The AII is an aspherical polisher that can be used in conjunction with any of the metrology options at Optimax. New software can combine multiple profilometry plots or data from the interferometer or CMM to generate a diagram of the surface and form of the optic. A corrective polishing process is determined from this data and carried out by the AII. The AII can polish to an accuracy of λ/10. If a lens is finished with the AII, it is measured and the data is analyzed to generate a corrective process which is carried out in the AII. The part is then measured one more time to verify the lens meets all tolerances. This is feed-forward, faster, and more deterministic than the traditional iterative process. The AII is often used with tighter tolerances on the profilometer or interferometric methods such as spherical null lenses, a CGH, or TWE testing.

The MRF is another method to deterministically polish aspheres. Data from any interferometer can be uploaded and used to achieve a polishing process that can be as accurate as $\lambda/20$. Occasionally, data from the profilometers can be used with the MRF but this is unusual. Like the AII, this is a measure, polish, measure process with the metrology being used.

Another method for polishing aspheres is called VIBE polishing, patented by and unique to Optimax. In this process, a conformal polishing lap is moved in a very rapid vibrating motion. When brought into contact with an optic, very high removal rates can be achieved while maintaining the slope variation across the surface. Optics with more extreme slope variations and reversing curvature that can be very difficult to grey out with other methods but can be polished with ease using the VIBE process.[12]

These testing and polishing combinations above are general examples but not a complete list. The combination of metrology and finishing process is decided depending on each individual lens geometry and the tolerance desired. Each asphere is unique and it is important to consider cost and application of each lens when setting tolerances and choosing metrology.

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