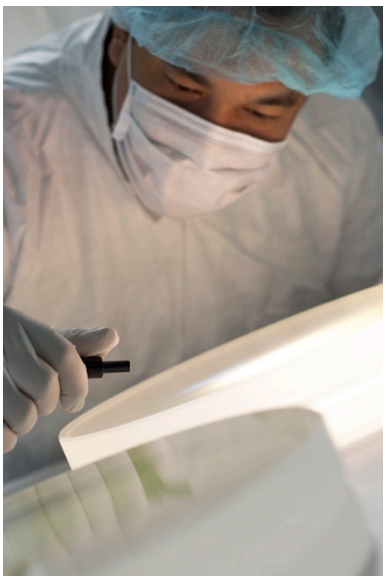
Aperture Optical Sciences

INTRODUCTION



Controlling quality of off-axis parabolic mirrors requires tolerances that are both traceable to performance and verifiable by measurement. Primary aspheric parameters for off-axis parabolic (OAP) mirrors, include the conic constant (k), focal length (f), off-axis angle (OAA or "θ") and off-axis distance (OAD). We defined these in our application note, "Specifying the Geometry of an Off-Axis Parabolic Mirror[1]".

Getting the OAP configuration right may be the first step, but determining appropriate tolerances is next. What then are reasonable assumptions for tolerances on these key parameters and how are they measured? Intuition might suggest applying tolerances of angle and distance as one would for a spherical optic. However, because the primary design parameters in an asphere are interdependent, it is not always practical or even possible to verify these quantities by independent measurement as you may for a sphere or flat optic. Therefore, if something so fundamental as focal length or off-axis angle cannot easily be verified, how can the quality be guaranteed? This application note explains how AOS addresses this fundamental question. Our answer may surprise you.

INTERDEPENDENCE

Unlike physical features such as radius of curvature or diameter, f_s, θ, and OAD can only be measured relative to an incident wavefront. Without the means for relating the incident wavefront of light directly to the mechanical datums, there is no way to detect small errors in f_s, θ, or OAD. Furthermore, errors in θ, will manifest as errors in f_s or, OAD, or both. In fact, these quantities are inseparable and interdependent. Like pressing on a pillow, you cannot alter one parameter without causing multiple possible permutations of the other two. Let's look at an example:

The off-axis distance, focal length and off-axis angle are defined with respect to each other:

$$\text{Off Axis Distance: } OAD = f_s \sin\theta$$

Therefore, error in Off Axis Distance could be the result of any number of error permutations in f_s, $and\ \theta$.

$$dOAD = \sin\theta df_s + f_s \cos\theta\ d\theta$$

When under test interferometrically, adjusting off-axis distance will change whatever the focal length and off-axis angle are measured to be. Thus the only way to know error in one of these parameters is to fix the other two – or explain the magnitude of error relative to possible worst-case combinations of the other two parameters. This consequence presents a great inconvenience to defining clear tolerances on a manufacturing design drawing. So how can one establish fixed quantities for these tolerances?

OUR SOLUTION

The simple answer is we don't. Instead we treat each of these parameters as "basic" and then measure the total resulting error in form of the optic. Here's how we do it.

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First, we must establish measureable datums. We build these into the geometry of each optic we design. This provides for a coordinate system measureable by a coordinate measuring machine (CMM) or profilometer. In an OAP, this is typically the rear surface, diameter (or an edge in a rectangular component), and clocking flat on the edge of the OAP (figure 1).

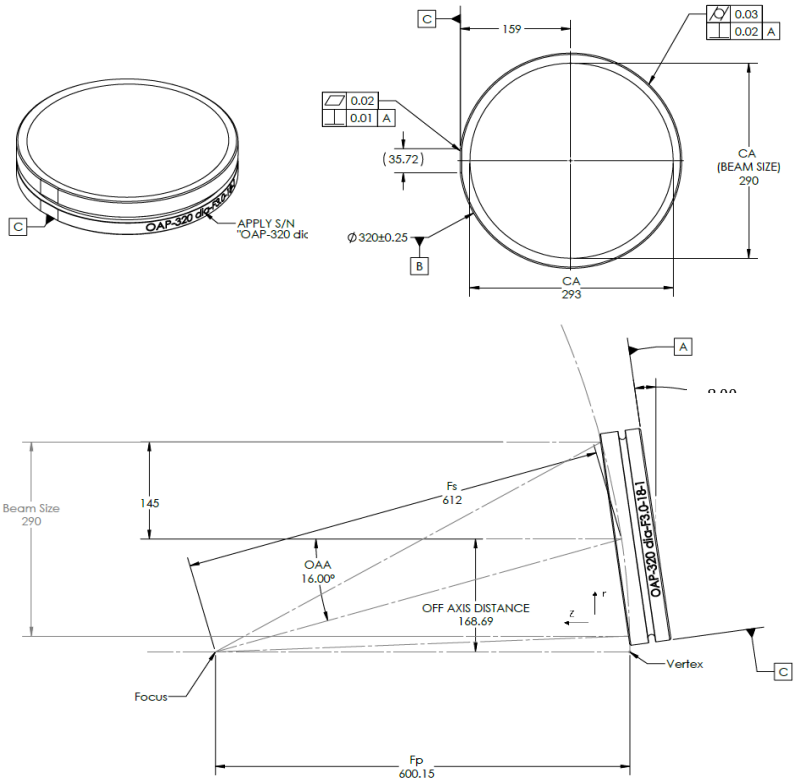

figure 1: Typical AOS Datum Definitions

Next, we take all of the primary dimensional parameters including conic constant to be "Basic". We reference these "basic" dimensions to the defined datums.

> *A **basic dimension** is "a theoretically exact dimension, given from a datum to a feature of interest. In Geometric dimensioning and tolerancing, basic dimensions are defined as a numerical value used to describe the theoretically exact size, profile, orientation or location of a feature or datum target*[2].

Finally, we apply a tolerance to the total departure from this perfect theoretic form much in the way ASME Y14.5 standards define "Surface Profile", ⌓. Said another way, assuming that the primary parameters k, f_s, θ, OAD are exactly at their nominal values, we set a limit on how much the actual surface can depart from this defined form.

> *"**Profile**" tolerances are used to define a tolerance zone to control form or combinations of size, form, orientation, and location of a feature(s) relative to a true profile*[3]*. The graphic*

shown in figure 2 illustrates the concept of a tolerance zone above and below the ideal surface.

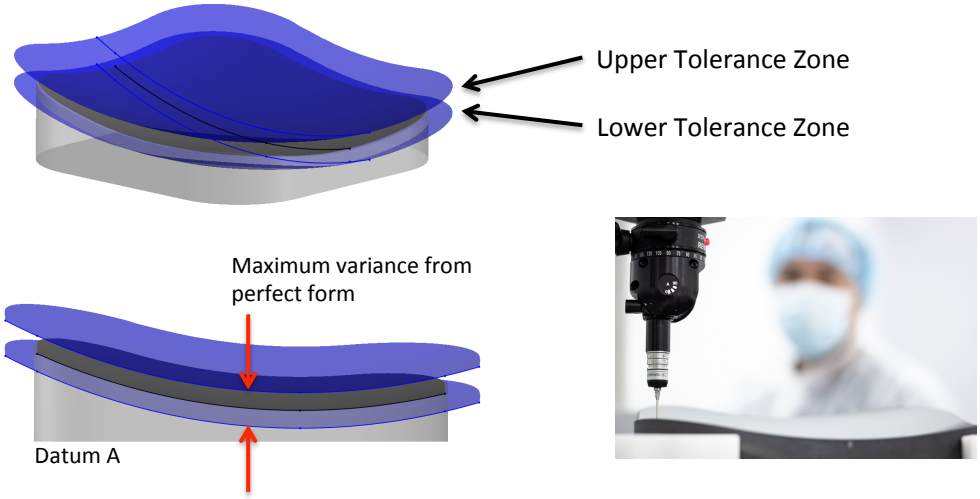

figure 2: Surface Profile

We probe the optical surface and collect a cloud of data points with a coordinate measuring machine (CMM). After fitting these points together and determining the difference between our measured surface and the theoretically perfect surface defined by the basic dimensions, we arrive at the "profile error".

The data map below represents the residual error in the surface form + measurement uncertainty between the as-manufactured surface and the perfect nominal design (k, f_s, θ, OAD). This method is effective for measuring how well the manufactured optic form agrees with the intended design. We can typically know this within a few microns. Having established compliance with the design form, we are now free to set up an interferometric test to measure the reflected wavefront error, and evaluate the optical level quality to an even higher level of scrutiny. We'll discuss measurement of reflected wavefront error in an upcoming application note.

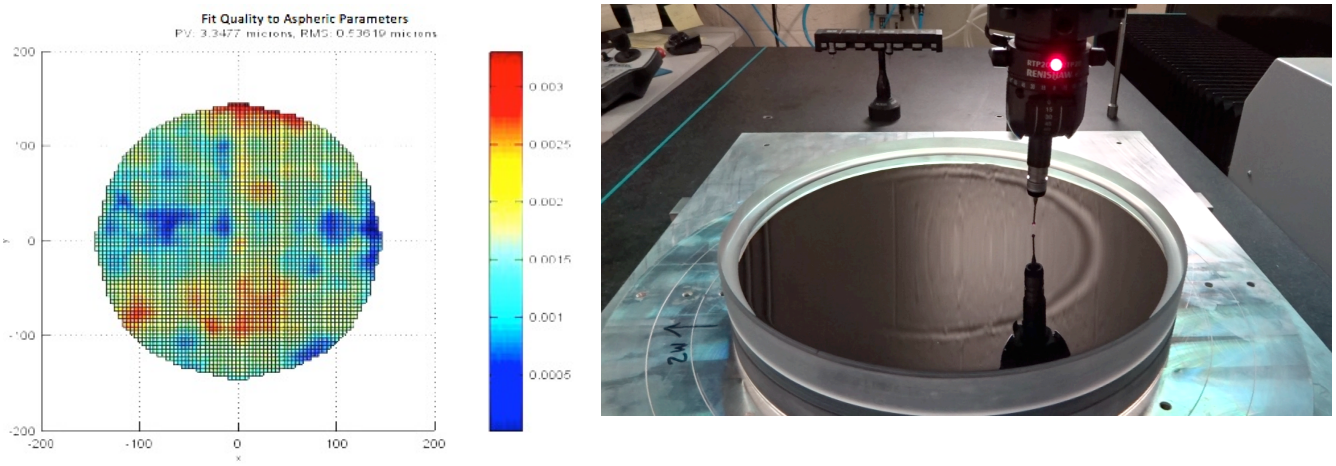

figure 3: AOS Data Map Showing Fit Error to Aspheric Design

CONCLUSIONS

The method illustrated provides a means of applying a global tolerance limit for constraining allowed variances in primary dimensional parameters of general aspheres including off-axis parabolas. Using this method, AOS can control surface profile to < 0.005 mm uncertainty of the theoretic perfect designed asphere. How error + uncertainty tolerance impacts the performance will vary by design and application and can be further explored through simulation.

AUTHOR

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Flemming has been working in the field of optics engineering and manufacturing for over 35 years and holds degrees in Optics from the University of Rochester, and Manufacturing Engineering from Boston University. Mr. Tinker is a specialist in optics manufacturing & management involving innovative technologies. Please address inquiries regarding this technical application note to info@apertureos.com. Thanks also to Dan Dunn for offering the elegant pillow / bean-bag analogy, and to Ryan Smith for support with process and graphics.

[1] https://apertureos.com/off-axis/specifying-the-geometry-of-an-off-axis-parabolic-mirror/
[2] ASME Y14.5M-1994 Dimensioning and Tolerancing
[3] ASME Y14.5-2009 Page 158