Practical Tips for Reducing Measurement Errors

Precision polishing equipment is only as precise as the input functions required for surface figure correction. Careful attention to the sources of interferometric errors can optimize the effectiveness of magnetorheological finishing.

by Jay Kumler and Ray Malcom

Lens design software and ray-aiming techniques help evaluate the amplitude-spatial-frequency space over which Twyman-Green and Michelson interferometers make accurate measurements. However, Fizeau interferometers require some reassessment to maximize the effectiveness of emerging manufacturing capabilities such as magnetorheological finishing. The deterministic subaperture computer-controlled processes of advanced finishing equipment can address surface imperfections in smaller and smaller spatial periods, meaning that incorrect test data will produce inefficient convergence and, possibly, finishing cycles that increase rather than reduce surface figure errors.

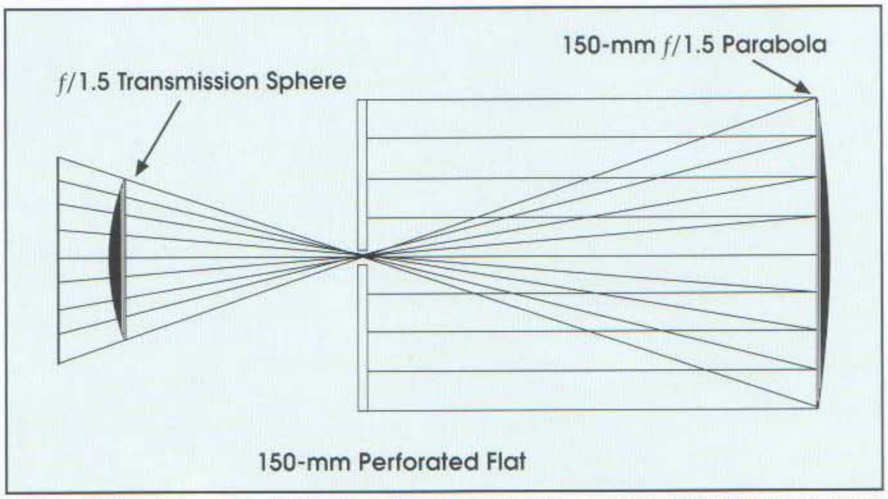


Figure 1. *Testing a parabolic mirror in autocollimation using an f/1.5 transmission sphere can incur mapping errors with ray surfaces per second totaling 0.92 percent. An error of that magnitude would cause a magnetorheological finishing machine to produce midspatial frequency ripple and a less-than-effective hit.*

The magnetorheological finishing process requires two input functions: one to describe the shape distribution and removal rate of the "polishing tool" and another to describe the surface error of the optic to be polished. Both inputs require accurate interferometric data to avoid mapping errors; e.g., magnification, distortion and clocking, and ray-retrace errors. Sources of ray-retrace errors include defocused interferometers, reference surface errors, cavity surface errors, and the transmitted wavefront errors associated with Fizeau transmission spheres.

Fizeau interferometers require users to determine the linear-scale factor of the cavity under test. Small errors in this factor are of little consequence if the test is simply characterizing the surface figure accuracy for final acceptance. However, if the test is supplying surface data to a magnetorheological or similar subaperture finishing machine, incorrect magnifications can be costly.

Errors in linear scaling can come from incorrect knowledge of the physical scale of the surface under test, incorrect cursoring of the image and imperfect imaging; e.g., defocus and distortion of the interferometer. Distortion values internal to an imaging system in a commercial interferometer can range from −0.7 percent at 1× magnification to +0.3 percent at 6× magnification for full-aperture testing; e.g., testing a 150-mm-diameter, concave, *f*/1.5 parabolic mirror (Figure 1) in

Table 1 - Scaling Errors

0.05-mm error in the outer diameter of the parabola	0.05/150	0.03 percent scale factor error
Two-pixel error in the cursor setting	2/300 pixels	0.60 percent scale factor error
Instrument pupil imaging errors (pupil distortion)		0.70 percent
The root sum square of these mapping errors		0.92 percent

autocollimation using an $f/1.5$ transmission sphere can result in a 0.92 percent error (Table 1).

An error in magnification of 0.92 percent on a 150-mm-diameter, concave, $f/1.5$ parabola would cause a magnetorheological finishing machine to miss a 5-mm-wide zone near the edge of the mirror by 0.69 mm, causing midspatial frequency ripple and a less-than-effective hit.

Tips and Suggestions

Practical tips for reducing cavity errors, particularly mapping and imaging errors, include the following:

- Use a surrogate mirror with fiducials deposited on the surface under test to measure linear magnification and pupil distortion.
- Take care to precisely center the surface in the interferometer aperture.
- Make sure the surface is in sharp focus.
- Use fiducials to ensure the "handedness" is correct on the data set.
- Use optical design code to model the cavity and ensure that the sine and scale of the phase data are correct.

Reducing ray-trace errors is also possible if you:

- Model the cavity using ray-trace analysis to determine if ray-retrace errors will be large.
- Minimize the number of tilt and focus fringes in the cavity.
- Check the transmitted wavefront and collimation of the Fizeau transmission sphere. This should be part of the quality assurance calibration schedule for periodic recheck.
- Check the collimation of the interferometer with a shear plate.
- Minimize the cavity length by using a retro sphere with a curvature as near as possible to the test piece.
- Always use retro spheres (concave or convex) inside of real focus. Ray-retrace errors will increase if the cavity goes "through-focus."

Commercial interferometer manufacturers could help end users quantify these errors by:

- Specifying, certifying and providing test data files for transmitted wavefront error of the transmission spheres.
- Providing data files for the sphericity of the Fizeau reference surface (not just hard copy maps).
- Providing information on the theoretical geometric distortion as a function of magnification for each of the transmission spheres offered.

The best way to correct magnification-scaling errors is to calibrate the interferometric setup with a test mirror that has accurate fiducials on the surface under test. Using a surrogate 150-mm-diameter mirror with photolithographically deposited fiducials, one could evaluate and then remove the effects of pupil imaging, defocus, scale error and distortions from local surface slope of the surface under test. The fiducials should also not have bilateral symmetry, so that they can determine the "handedness" of the cavity. Magnetorheological finishing machines need to know if the phase information should be "flipped" left to right, up and down, or if the data should be inverted; i.e., bumps equal holes.

Many aspheric null tests have surface coordinates that are not nominally proportional to the sine of the angle, so the pixel scale achieved in this lateral calibration is not constant. One reason to model the cavity in a ray-trace code is to determine the significance of sine condition violations.

Error types and sources

Surface figure and slope errors of the Fizeau reference surface will influence, respectively, the phase map and hit map of the surface under test. Many commercially available transmission spheres are 0.1 wave peak-to-valley at 632.8 nm. In the example of the 150-mm-diameter, $f/1.5$ concave parabola, the cavity length is approximately 1200 mm if [2 × (150 mm diameter) + 4 × (225-mm focal length)]. Meter-long path lengths are common in Hindle tests and telescope autocollimation tests. Even in the 6-in. mirror example, a 100-μrad slope error will result in a 0.12-mm radial shear in the test cavity.

The magnitude of slope errors in

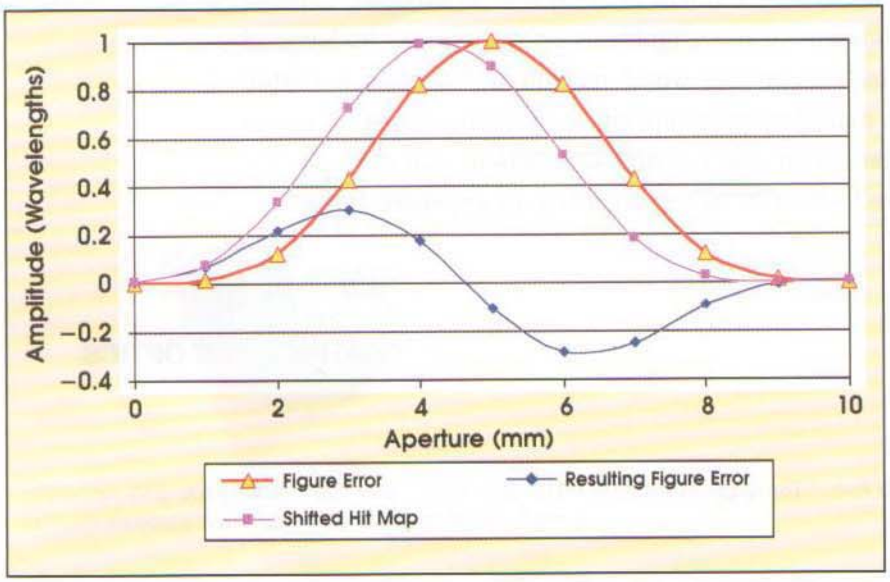


Figure 2. A 0.75-mm shift in a 5-mm-wide zone located 5-mm away from the edge of a parabolic mirror will result in figure errors at approximately twice the spatial frequency with amplitudes of 30 percent under and 30 percent over hit. The mirror becomes choppier, convergence is only 40 percent (1- to 0.6-wave peak to valley) and the errors are more difficult to correct.

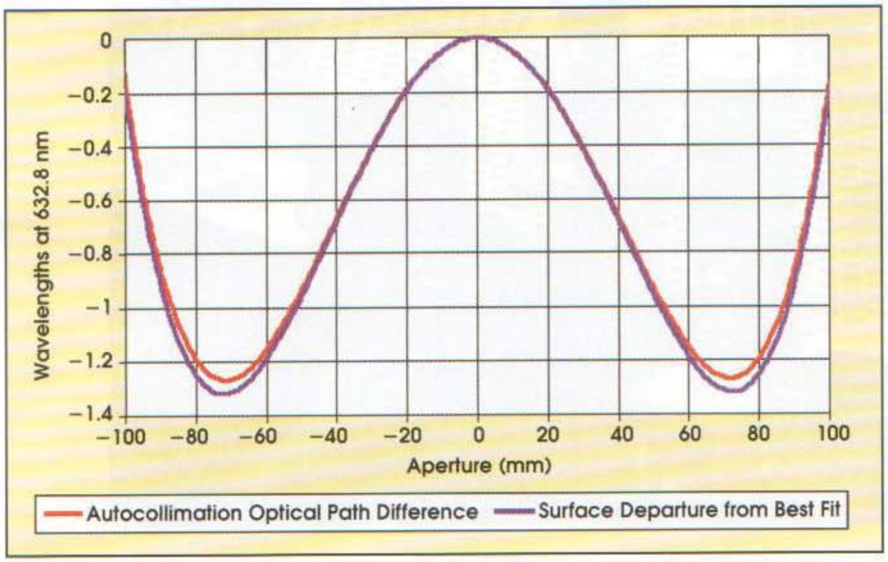
the cavity depends on the relative radii of the reference and test surfaces. If the radii differ greatly, small surface errors can yield sizable measurement errors. Research has demonstrated that if a ball bearing is tested by a 4-in. transmission sphere, the systematic ray-mapping errors will not be canceled.[1] The cavity error will be proportional to the difference between the curvature of the reference and the curvature of the part under test.

Because interferometers are imperfect imaging instruments, defocus and tilt in the cavity combined with the distortion in the imaging system result in measurement error. Distortion of interferometers is a function of the transmission sphere, which means that using the same techniques that evaluate distortion of imaging systems can characterize it. Interferometers using fast (*f*/0.75) transmission spheres have distortion significantly larger than 0.5 percent because the output angle of the sphere is not linear with height. This nonlinearity introduces wavefront error at the rate of 0.17 wave for every wave of defocus when using an *f*/0.75 sphere.

Imperfections of the surface under test also will cause errors in Fizeau interferometers used to evaluate non-null cavities of aspheric surfaces. In many cases, mild aspheres are fabricated from best-fit spherical surfaces and asphered on a magnetorheological finishing machine. A 200-mm-diameter, *f*/4 telescope mirror polished from its best-fit spherical radius and tested in autocollimation will yield significant ray-retrace errors from the non-null cavity (Figures 3 and 4).

Transmitted wavefront error from transmission spheres will introduce ray-retrace error in the cavity. Simply put, rays normal to the reference wavefront do not overlap with rays normal to the test wavefront. To evaluate the magnitude of the transmitted wavefront error, we tested commercially available transmission spheres in autocollimation; i.e., in reverse using a Fizeau reference surface as the cavity retro mirror. Table 2 charts the peak-to-valley irregularity and slope values with tilt and power removed.

Advanced precision polishing



Figures 3 and 4. *Errors in ray-retrace-induced phase measurement from non-nulled cavities must be calculated through the transmission sphere to be modeled correctly. A system that includes an f/3.3 transmission sphere modeled the above data.*

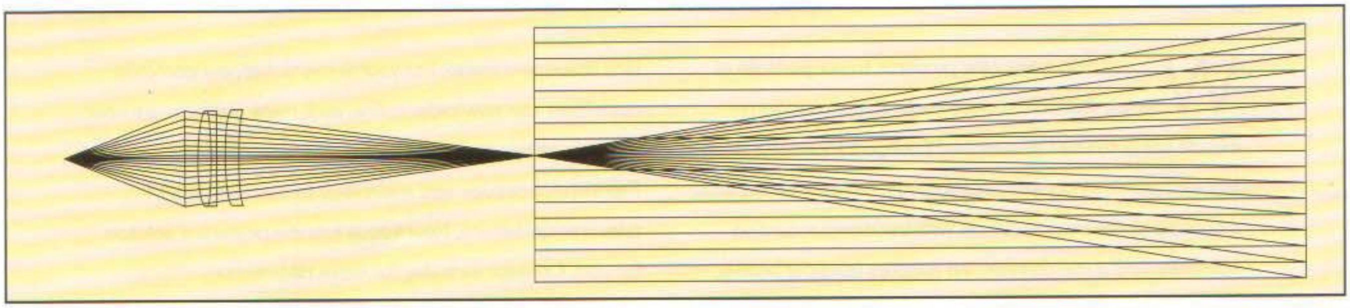


Table 2.
Single-Pass Transmitted Wavefront Transmission Spheres Tested in Collimation

Manufacturers	Serial Number	Focal Ratio	Peak-to-Valley Irregularity (Waves)	Root-Mean-Square Irregularity (Waves)	Power (Waves)	Peak Slope (mrad)	Root-Mean-Square Slope (mrad)
Zygo Series 2		3.3	0.443	0.092	−0.160	75.80	11.35
Jenoptik JenFizar	FP5202	3.3	0.177	0.019	0.136	62.49	5.54
Zygo Series 2	98193	1.5	0.976	0.198	0.743	167.34	25.46
Jenoptik JenFizar	FP5110	1.5	0.105	0.012	−0.317	56.01	8.83
Zygo Series 2		0.75	3.225	0.600	−3.046	266.90	66.59
Jenoptik JenFizar	FM0108	0.75	0.629	0.117	1.918	42.40	13.01

equipment is dependent on the accuracy of the input functions required for surface figure correction. The phase map of the surface under test includes many cavity errors in the phase file, including magnification, pupil distortion, clocking and ray retrace errors. Many of these are manageable as long as the metrologist is aware of the problems and takes the steps required to minimize their contribution. ☐

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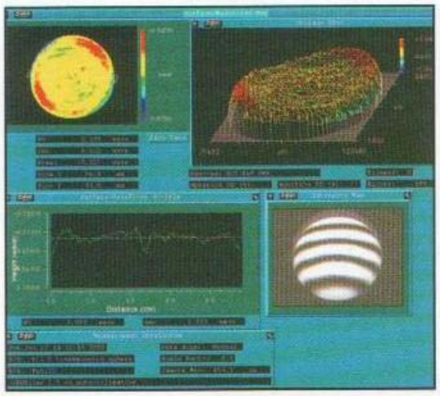

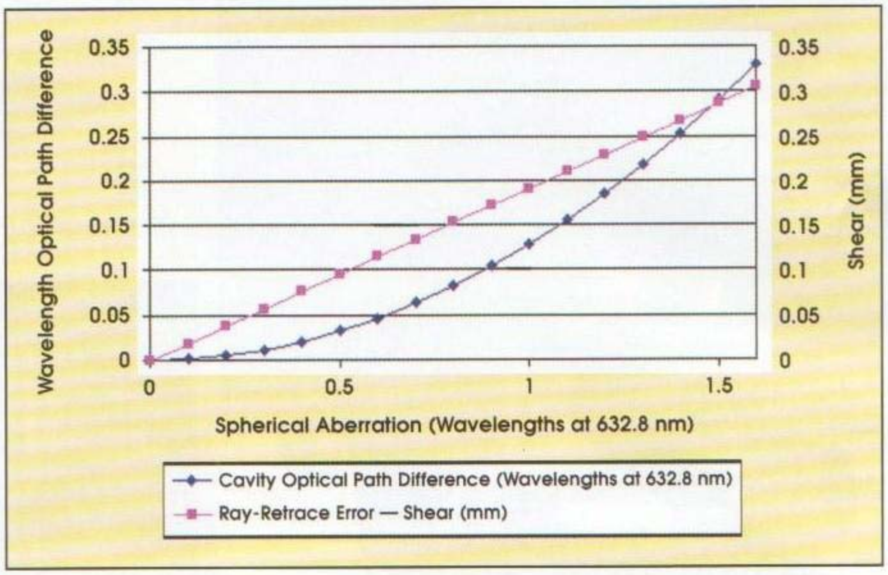

Figures 5 and 6. *To illustrate the effects these error sources have, we tested our 150-mm-diameter, f/1.5 parabolic mirror in autocollimation with a perforated flat and an f/1.5 transmission sphere. This test was a null test, with no residual aberrations if the transmission sphere was perfect and if there were no other cavity errors.*