Correlation of mid-spatial features to image performance in aspheric mirrors

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ABSTRACT

Modern techniques in deterministic finishing employ devices, which provide geometrically well-defined removal functions for precision correction of fast aspheres. While stability of the removal function is essential, a commonly experienced consequence of such controlled removal is the creation of a residual trail, or signature of periodic surface "ripples" or textures that correlate to the characteristics of the removal function and tool path. The extent to which this signature exists in both amplitude and spatial frequency can have a profound impact on system imaging performance. Therefore, it is necessary to accurately characterize the spatial frequency content of surfaces and control its impact through proper specifications in order to guaranty image performance. Traditional specifications like Peak to Valley and RMS wavefront specifications cannot fully capture or predict image quality in fast aspheric optics unless perhaps they are specified over precise spatial scale lengths (or frequencies). In this paper we will explore a correlation of surface metrics and image performance using empirical data collected on a variety of fast aspheric mirrors produced by Aperture Optical Sciences Inc.

Keywords: Asphere, Mid-spatial errors, slope errors, encircled energy, image performance, optics fabrication, off-axis parabola, deterministic finishing

1 INTRODUCTION

Manufacturing optics for today's most precise reflective imaging systems requires polishing techniques which enable extreme control over surface gradients and periodic features. This is critical for x-ray optics, which, are used at grazing incidence, high damage threshold laser optics, as well as applications in remote sensing, lithography and many other precision imaging applications. Today's manufacturing techniques for producing fast aspheric optics unfortunately also result in the progressive accumulation of mid and high spatial frequency features during grinding and polishing. The amplitudes and frequencies of such features can ultimately limit image quality. Mitigation of such features can be difficult, costly, and time consuming. However, failure to specify and control periodic errors can result in unexpected loss of image performance. Therefore, as a potential cost driver, designers and users should include tolerances for mid-spatial errors both to ensure performance and also to avoid over-specification of unnecessary (and potentially ineffective) requirements on peak-to-valley tolerances.

1.1 Mid-Spatial Frequency Error

There is no definitive, or globally accepted convention for Mid-Spatial Frequency Error ("MSF") yet. However, it is commonly defined as periodic "ripple" or texture in the surface or wavefront occupying the region between "Roughness" on the high spatial frequency ("HSF") side and "Shape" or "Figure" on the Low-Spatial-Frequency ("LSF") side. We most often see the MSF range defined as 1 mm to 10 mm (1 mm^{-1} to 0.01mm^{-1}) and have adopted this as our own convention at Aperture Optical Sciences Inc.

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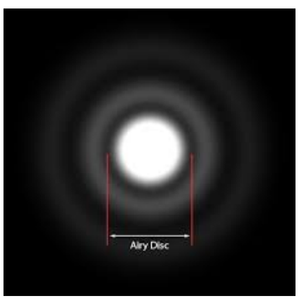
1.2 Image Analysis and Wavefront Error

Fundamental diffraction theory tells us that optics with a perfect form will produce wavefronts and images demonstrating the performance at the diffraction limit. Therefore deviations from the perfect form will begin to distribute energy away from the central lobe of the Airy Disc. Equation 1 below gives the diameter of the Airy Disc and equates to 83.8% of the distributed energy within the point spread function ("PSF"). However, it has long been understood that it is not just the total form error in optical surfaces that defines the shape of the point spread function but also the morphology of form error. Diffraction analysis using fast-Fourier-transform ("FFT") based calculations tell us how to calculate the PSF from wavefront data collected from interferometry[1]. Calculation of the modulation-transfer-function ("MTF") furthermore illustrates how image resolution can be described in the context of periods of spatial scale length. Aikens et al and others have described the correlation between MTF and errors of spatial scale length in wavefronts [2]. However, industrially motivated realities demand the restriction of tolerancing practice to those metrics, which demonstrate the best combination of both effectiveness *and* practicality. Therefore, we restrict our tolerances to those metrics, which are easily measured and provide direct feedback to the manufacturer about how to correct for surface errors. Historically the dominant tolerance for the quality of an optic is the maximum, or "peak-to-valley" ("PV") error variation of its surface or wavefront. Legacy specifications of form error in units of common fractions of fringes (or waves) still dominate technical design specifications, but derive more from optician's test plating practice rather than the capabilities of modern interferometric or image analysis techniques. Still, this tolerancing practice has proven highly reliable for decades for the vast majority of optics. However, it only holds for error of generally low frequency. This has worked so well, for so many years because most optics have "regular" or simple shapes and lend themselves to machines and methods that produce low frequency surface contours. For instance, the most effective practice of making high quality flat and spherical optics use proportionally large work surfaces and low frequency motions to produce surfaces, which are smooth and similarly exhibit surface errors of low spatial frequency. However, as optical surfaces become more complex, such as ultra-lightweight mirrors, and aspherics, the amplitudes of higher spatial frequencies become more dominant [3]. As requirements of image quality become more sophisticated, the specifications may also need to change.



The diffraction limit is defined by the Airy Disc diameter or minimum beam waist ($1/e^2$)

*Airy Disc Diameter (D) =2.43932 *λ* (f/#)* *(Equation 1)*

The Airy disc contains 83.8% of the total diffracted energy.

Figure 1 and Equation 1: Airy Disc Diameter

Consider the figures below which show common "large-tool" and "low-frequency" motion based polishing methods (figures 2 and 3) and contrast this with methods for making fast aspheres (figure 4). As steep aspheric profiles drive methods towards smaller finishing tools with pin-point precision such as are employed with robotic polishing, ion-beam figuring, or Magnetorheological finishing, higher frequency features and textures are created. This changes the fundamental assumptions of how well PV and rms statistics predict image performance.

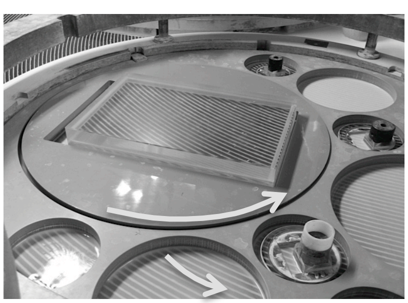


figure 2

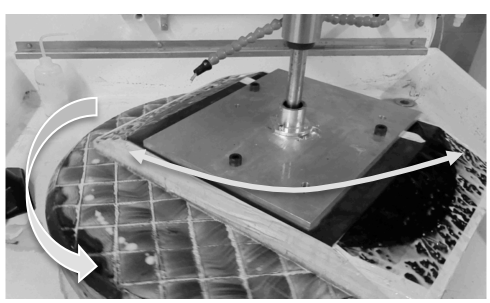


figure 3

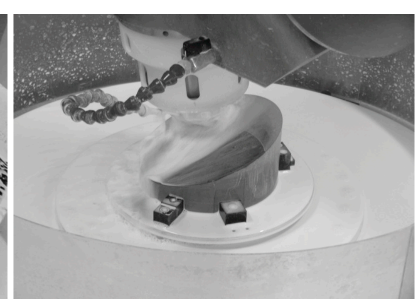


figure 4

figure 2: planetary motion on a large format planarization machine

figure 3: rotation and low frequency stroke / oscillation on a conventional spindle polisher

figure 4: raster motion of a small robotic polishing tool on a steep parabolic mirror surface

The questions therefore are:

- At what point do our specifications of PV and root-mean-squared (“RMS”) wavefront error fail to fully predict image performance?
- Is there a better, industrially friendly, set of tolerances that can be practically implemented with higher reliability? Or, do we simply need to specify form and wavefront over ranges of spatial frequency to combat ripples and textures produced by modern methods?

To explore & illustrate this point consider the example data maps for an F/1.5 parabolic mirror vs. a comparable mirror shown in figures 5 and 6. Both mirrors were produced by AOS recently. Both data maps have very similar results for PV and RMS error. The F/1.5 parabola (figure 5) has a peak-to-valley error of 0.288 waves and rms error of 0.043 waves. The second optic (figure 6) has errors of 0.267 and 0.046 waves respectively. However, the errors in the surface shown in figure 4 appear more uncorrelated and complex. If we calculate the PSF at the test wavelength of 633-nm, we see a very different result. The Encircled Energy metric is useful to quantifying what is visually obvious. The encircled energy function of the F/1.5 parabola predicted a focal spot diameter of 18 microns while the other mirror predicted a focal spot diameter of only 3.2 microns. The optic in figure 6 is therefore close to the diffraction limit, while the optic in figure 5 is more than 8x the diffraction limit. The “smooth” mirror would thus provide superior image quality even though the PV and RMS form measured to be equivalent. This example provides a compelling case to discover what else in the wavefront description is different, and can we better characterize the surface or wavefront with a tolerance that will better predict the resulting performance.

- PV Form Error = 0.288λ
- RMS Form Error = 0.043λ
- RMS Gradient = 14.8 µrad
- Diameter at 80% encircled energy criteria = <u>18 µm</u>

- Diffraction limit = 2.3µm

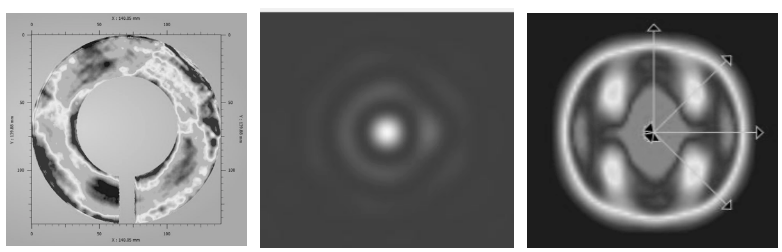


figure 5: Errors in F/3 Parabola

- PV Form Error = 0.267λ
- RMS Form Error = 0.046λ
- RMS Gradient = 1.8 µrad
- Diameter at 80% encircled energy criteria = <u>3.2µm</u>

- Diffraction limit = 2.3µm

figure 6: Comparative Optic of Similar PV and RMS quality

It turns out that if we examine the RMS gradient for these two data sets, we see a dramatic difference – particularly if we look to the mid-spatial region. The rms gradient for the parabolic mirror measured 14.8 µrad, while the data set for the other “smoother” mirror, measured 1.8 µrad. *Therefore, in this case, RMS gradient appears to be a better predictor of image quality than PV or RMS surface form error.* The higher gradient error in the parabola is indicative of higher mid-spatial error. In our companion paper “Fabrication of SiC Aspheres with low mid-spatial error”[3] we describe how manufacturing processes, particularly for fast aspheres, produce higher mid-spatial errors (and thus gradients) than spherical and flat optics. Thus, if fast aspherics are prone to larger gradient error, if may be that much more necessary in such cases to apply gradient tolerances, to ensure image performance.

The manufacturing of fast asphericss requires the use of small-tool based processes to figure steep aspheric shapes We might expect to generate spatial frequencies in the surfaces on the same scale as the “1- 10-ish mm” size polishing tools we employ [3]. We similarly expect to see more ripples in the data as a result of the residual errors generated by tool paths. While we can see these features in the phase data of the form error, the slope of these features is even more pronounced. Furthermore, while we expect to see sharp slopes at the edges of optics, an elevation of the rms slope error (a.k.a. rms gradient) tells us how pervasive such features are throughout the surface or wavefront. The remainder of this paper therefore, will explore empirical data on aspheric optics we’ve produced over the past two years and will compare the predictive relationship between low-frequency PV and RMS statistics of surface form and mid-spatial rms gradient data with the encircled energy calculated from the raw data sets. We will furthermore show examples this for fast, medium, and “slow” f-number aspheres polished using “small-tool” robotic polishing technology.

2 DATA

Three example aspheres produced by Aperture Optical Sciences Inc. over the past year are presented. Interferometric data was calculated in the form of both surface metrics (PV Form, RMS, RMS Gradient) and calculated image quality metrics (Encircled Energy). Our intent was to identify which surface metric correlated better with encircled energy. All three test optics were parabolas, the first two are off-axis and the third is on-axis. The first is F/5, followed by a F/1.7 and the third is F/0.65. Data is presented at multiple points during the manufacturing sequence from the time the surface measured between approximately 1 wave RMS to 0.1 wave RMS. Using the calculated diffraction limit focus diameter as a lower boundary condition, focal spot diameter was measured as a function of PV surface form, RMS surface form, and RMS gradient to discover which metric of surface error tracks best with focal spot diameter. Focal Spot diameter was measured using the encircled energy (“EE”) function calculated from the wavefront data measured with a Zygo DynaFiz interferometer and processed with MetroX (Figure 6). Since the diffraction limit is calculated based on an 83.8% total energy assumption, we used this as the EE criteria (instead of the more typical 80% criteria).

Encircled Energy (EE) describes the radius (not diameter) of a circle enclosing a specified % of total energy of the point spread function (“PSF”). However in this case, to enable a comparison with the diffraction limit, we are reporting a “diameter” of energy rather than the radius.

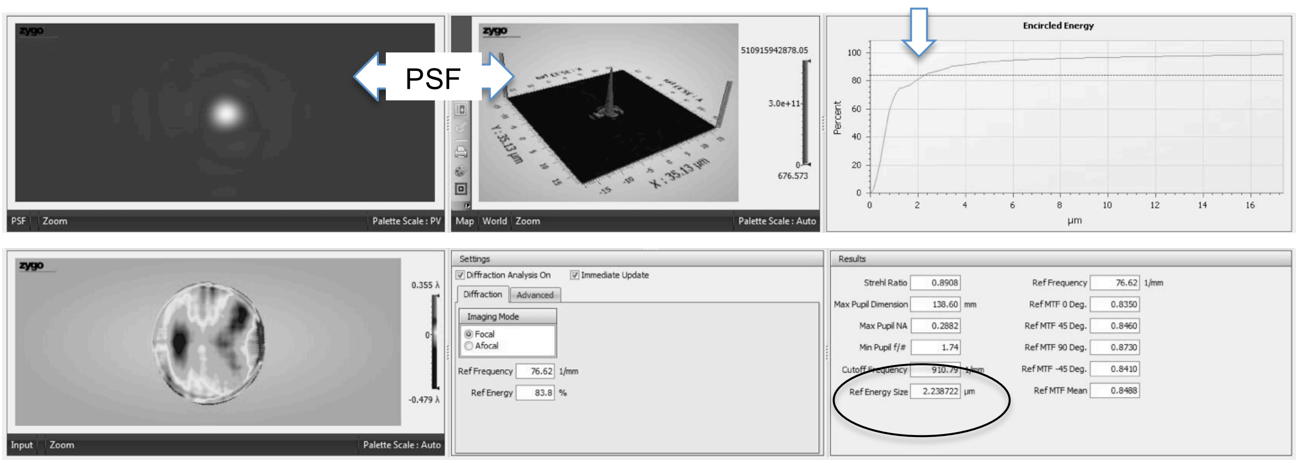


Figure 7: Point Spread Function and Encircled Energy Data Format from Zygo MetroX

2.1 Example 1 (mild asphere): 20-degree, F/5 Off-Axis Parabola

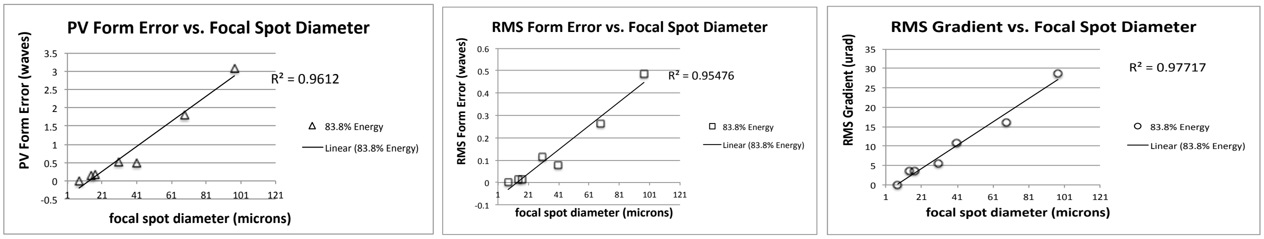


figure 8a-c: Comparison of surface measurements vs. calculated focal spot size for a mild asphere

2.2 Example 2: (fast asphere): 45-degree F/1.7 Off-Axis Parabola

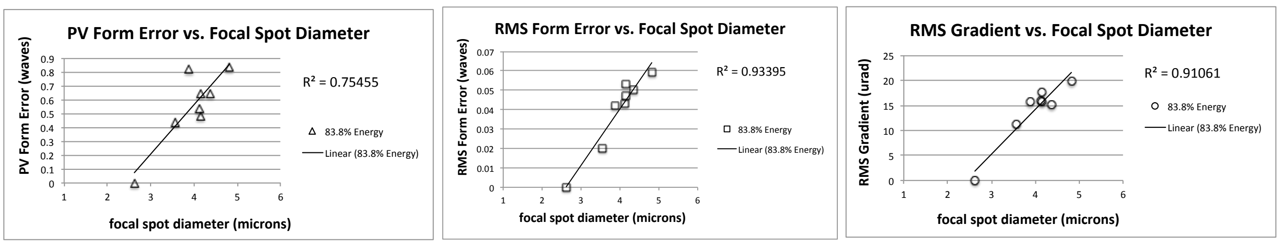


figure 9a-c: Comparison of surface measurements vs. calculated focal spot size for a fast asphere

2.3 Example 3: (ultra-fast asphere): 0-degree, F/0.65 On-Axis Parabola

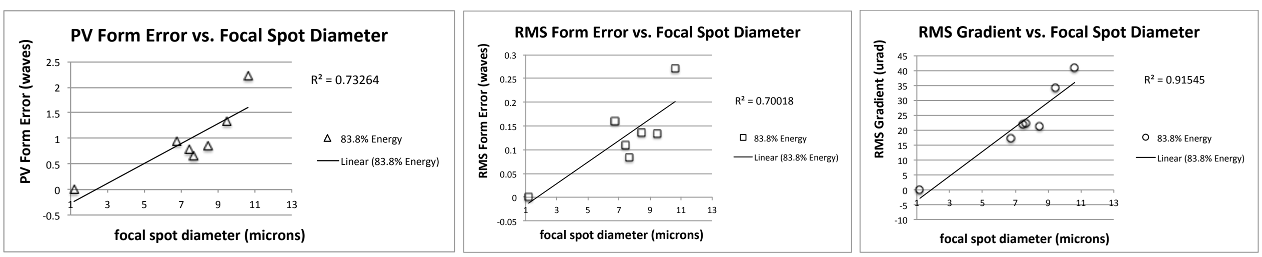


figure 10a-c: Comparison of surface measurements vs. calculated focal spot size for an ultra-fast asphere

Using the “coefficient of determination” (R^2) in a simple linear fit as a means to compare the data we can observe that the correlation of PV, RMS and RMS gradient is about equivalent for the mild asphere. This means that for this case, the PV, RMS and RMS gradient all appeared to be equal predictors of image quality with results of R = 0.96, 0.95, and 0.98 respectively. Thus one, could use any of these tolerances and expect that as you decrease the tolerance, you can expect to receive a proportional improvement in imaging performance. RMS gradient did, in fact exhibit the strongest correlation, but the amount of differentiation is small.

However, as we compare the results for the fast asphere, RMS Form Error and RMS Gradient maintained a strong correlation with image quality with R^2= 0.93 and 0.91 respectively, while the correlation of PV to image quality declined sharply with R^2 = 0.75. It would thus follow, that even if the PV error worsened or improved, the impact on image performance would be unclear. However, tolerancing with RMS form error or RMS gradient would provide a more reliable indicator of image performance.

The final case for the ultra-fast asphere showed a strong correlation only for RMS gradient at R^2 = 0.92. While comparatively R^2 = 0.73 and 0.70 for PV and RMS form error respectively. Therefore, in the case of the most extreme aspheric example, where we would expect gradient errors and mid-spatial errors to be most dominant, image performance was only weakly correlated to the PV and RMS form error.

3 CONCLUSIONS

As an indicator of image quality, RMS gradient as a metric showed the most consistent correlation and the most reliable predictor of image performance. This correlation became more pronounced as the aspheric surfaces became more extreme. This paper reflects only a small statistical sampling of data, and a wider study may be required coupled with further analytical explanation. It should also be noted that few customers choose to specify surfaces using RMS gradient, therefore, manufacturing practices are optimized typically around PV specifications. However, as we see more specifications for RMS gradient appear in drawings, we see them still coupled to a PV specification despite the fact that they do not always appear to be proportional. If specifications were more often written in terms of thresholds of mid-spatial amplitudes or surface gradients, or even image quality itself, our manufacturing practice would certainly change. Unfortunately, it may also be the case that by specifying optics with a PV specification alone, users of fast aspheres may not be getting the performance they model or expect. Ensuring optimized performance may require driving down surface gradients and mid-spatial amplitudes. This is no surprise to many designers, however, hopefully this data will encourage further study on the topic and will lend towards a rethinking of the urgency of spatial frequency based surface tolerances in aspheric optics.

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