Localized Slope Errors and their impact on image performance requirements

Mark C. Sanson, C. Theodore Tienvieri, and Steven VanKerkhove
Corning Tropel Corporation, 60 O'Connor Road, Fairport, NY 14450
SansonMC@corning.com, TienvieriT@corning.com, and VanKerk@corning.com

Abstract: The performance effect of localized slope errors in an optical system will vary based on the system location as well as their magnitude. This paper looks at a method to model and analyze such errors.

1. Introduction

All methods of manufacturing optical elements produce some type of surface figure errors[1]. Using optical design programs, one may easily model these surface errors. Such surface errors are often low frequency. This paper discusses potential localized slope errors that are not easily toleranced.

Localized slope errors on surfaces can impact performance in small parts of the field and may cause problems if not taken into account during system testing. Localized errors can cause problems not evident in some testing. Consequently, localized errors may be very costly. Examining and understanding the impact of these types of defects may prevent significant problems[2]. Through the modeling outlined in this paper, we are able to develop methods to evaluate the performance degradation for local surface errors.

2. Modeling

By placing a small defect on the surface profile, we can represent a localized error. The size and diameter of this error is varied to change the slope and area of the error in relation to the localized pupil on the surface's clear aperture. Since the errors can occur at any location on the aperture we can move it around to different locations. In the design example used, there was no vignetting. For this reason we are placing the localized slope errors in the center of the elements in this paper. If there is vignetting present, it would be advisable to place the errors at other locations on field optics.

The height and width of the error are varied and placed on different parts of the optical system, i.e. field and aperture elements, to demonstrate the impact on performance (Fig 1). A sample Gaussian surface error (Fig 2) is seen in the graphic below. It is an artificially created error. The surface profile was simulated on a single surface, keeping the surrounding elements perfect. The width of the errors is defined in this paper as the width at the 1/e value.

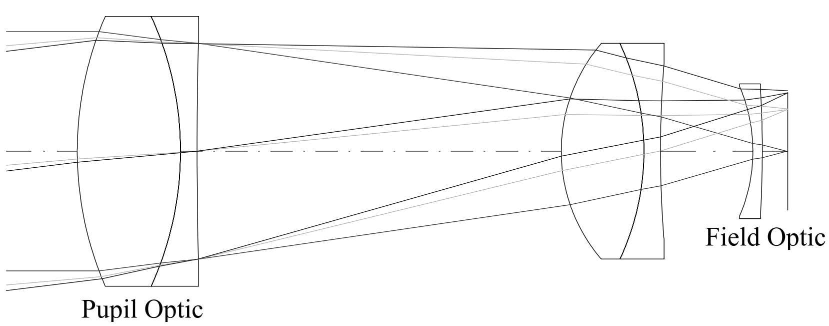


Fig. 1 An example optical system with pupil and field optics

3. Analysis

International Optical Design Conference 2006, edited by G. Groot Gregory,
Joseph M. Howard, R. John Koshel, SPIE Vol. 6342, 634223,
© 2006 SPIE-OSA · 0277-786X/06/$15 · doi: 10.1117/12.692242

For analysis, we examine several factors. These include height and width of the error, pupil size relative to the error, and location in the optical system. We want to be able to understand how all of these factors come into play in the image performance of the optical system. The system used in this example has had its field scaled to a 100mm diameter. A layout of each surface examined is shown. It is a low F/# system with surfaces very close to the pupil and surfaces with small localized pupils. The performance evaluations that we examine are rms wavefront and distortion. The base performance of the system is shown in each chart for reference. Several different ratios of the artifact to localized pupil size are examined. The chart below shows the shape of each artifact to the localized pupil.

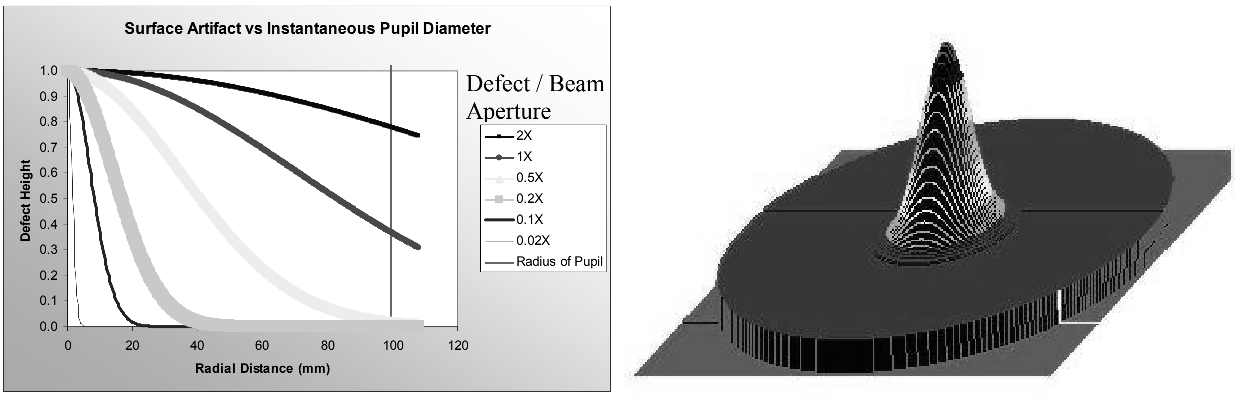


Fig. 2 Sample defect placed on the surface aperture

4. Field Sampling

When testing an optical system, there is often a certain sampling that is done in the field. It can become very expensive to check too many points in a system. Below is a graph of the nominal system value and measurement of a hypothetical system for rms wavefront error and the distortion. There are 21 field points measured evenly across the field. There is only a slight difference in the axial wavefront error between the nominal system and what is measured.

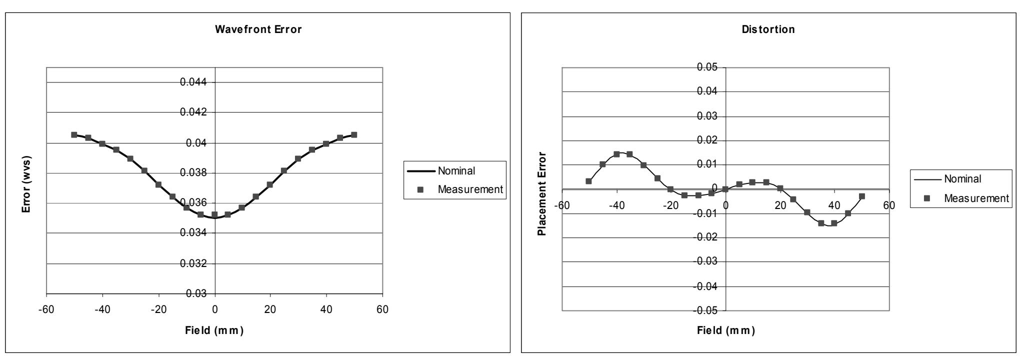


Fig. 3 Wavefront error and distortion plots for the sample lens system

It would appear that the above system performs to the design, but problems with the system performance are seen with a different field sampling. The following charts (Fig. 4) are of the same system, but a higher sampling has been taken in the central 20% of the field. These charts more clearly reveal the effects of a small error on one element in the system. Depending on the actual specifications for the system, this error could be a major problem. This error is right in the center of the field, but the 21 measurement points, which included the axial point, did not reveal them. Note that the distortion is significantly larger in this region, and it is beyond the maximum value in any field point in the nominal system.

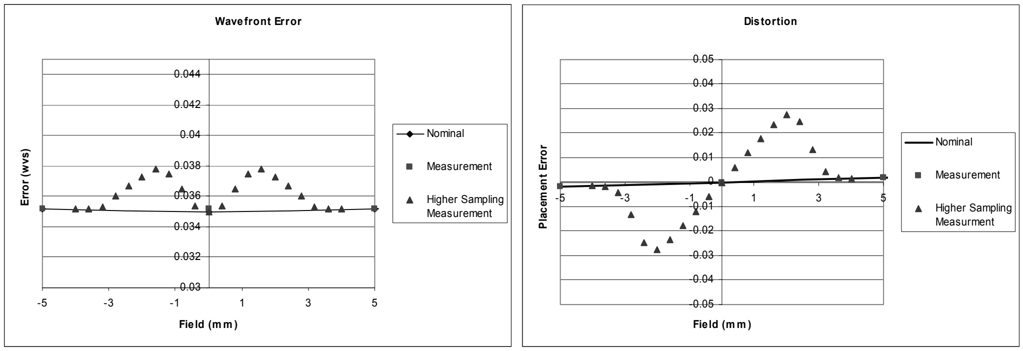


Fig. 4 The same plots as seen in figure 3, but with a higher field sampling in the central 20% of the field

This failure provides the justification for a thorough analysis of localized slope errors. We must be able to prevent errors on the surfaces that would create large errors only seen with very high sampling of points in the field.

5. Pupil Element Surface

We first look at a surface near the pupil of the optical system.

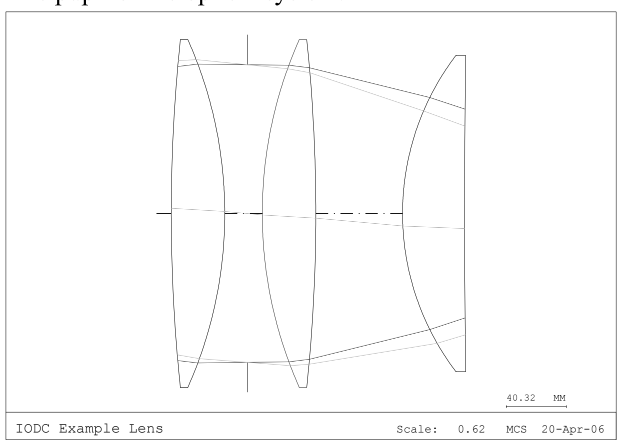


Fig 5 Pupil Optics

The first surface on the middle element in Fig 5 has the error applied to it. It is very close to the pupil of the system. The errors produced from different width bumps are seen in the charts. The errors have greatly varying effects. The largest diameter bump (smallest slope) is like a very small radius change and does very little to the wavefront or distortion of the system. As the bump width decreases, the localized slope error increases and results in different effects on the system. With the bump diameter (1/e value) the size of the instantaneous pupil, a magnification change results, but there is no wavefront error. However, this effect changes as the diameter decreases. The wavefront error and distortion changes are large when the bump diameter is 0.5X or 0.2X the localized pupil diameter. The distortion error lessens with a further reduction in the bump to localized pupil diameters. With an essentially sharp spike, 0.02X ratio, both the distortion and wavefront errors are very small. Note that the wavefront errors are fairly uniform across the field.

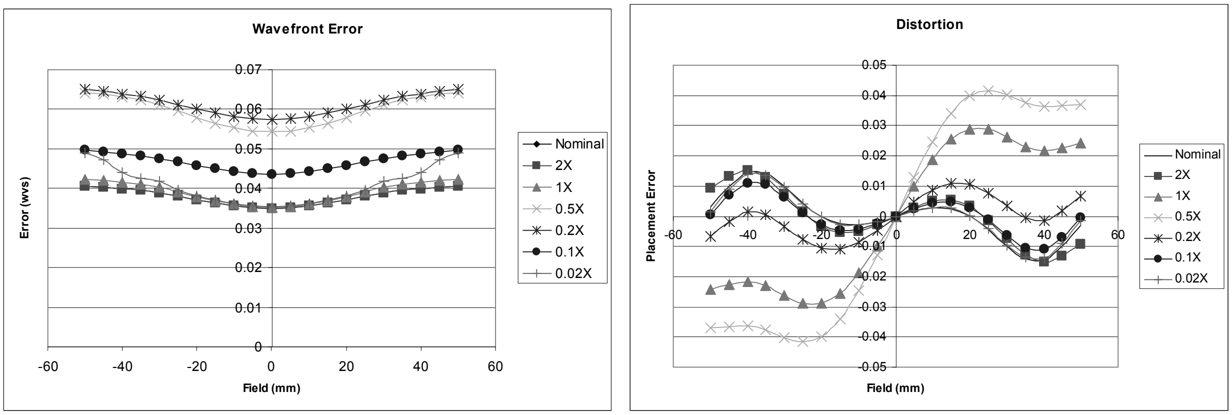


Fig. 6 The wavefront error and distortion plots for the pupil element case

In this example the bump goes from being like a slight radii change to a small defect that becomes integrated by the pupil. In between these extremes, the detriment to the system performance is very large. Surface defects that would need to be caught in optical fabrication are fairly large in diameter. The very small narrow defects on a near pupil surface are not a concern in this system in terms of wavefront error and distortion.

6. Field Element Surface

The next surface that we consider is adjacent to the cover plate in figure 7 below. The surface is very close to the field and the instantaneous beam size is relatively small relative to the optical aperture.

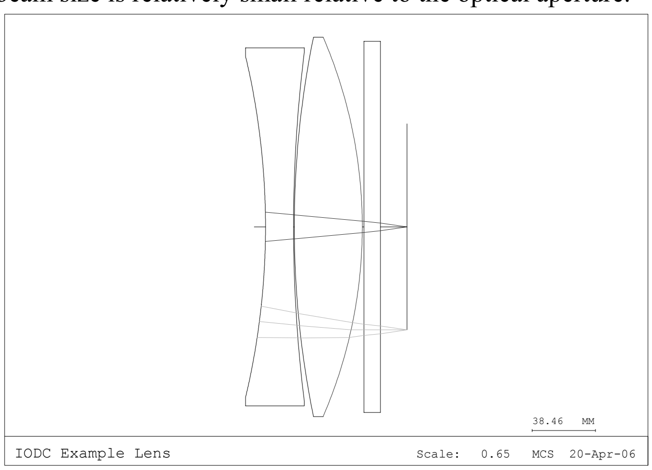
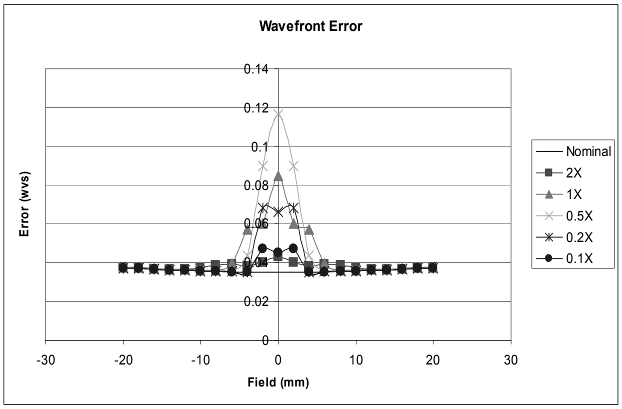


Fig. 7 Field Optics

For this surface the wavefront and distortion outside of the inner 20% of the field is not affected at all. The instantaneous beam for a field point quickly moves off the center of the optic, so the following charts of the system performance have been reduced to the sub-field of interest. We still are showing 21 field points for the hypothetical surface across this reduced field. This paper addresses the argument for our approach in the field sampling section. We are focusing in on the central region for a clearer understanding of the effects. We still must take into account the field sampling used in the actual system when looking at defects from this surface.



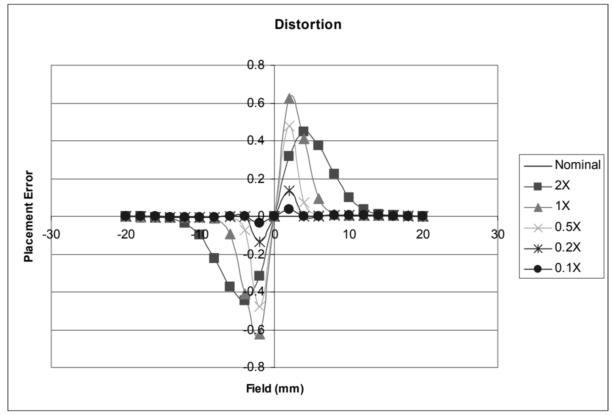


Fig. 8 The wavefront error and distortion plots for the field element case

The effects from a localized slope are very pronounced on this surface. The distortion errors are localized about the central region of the field. The larger the slope of the error, the closer the peak of the distortion error is to the axis. However, the magnitude of the error seems to peak when the ratio between the defect and the localized pupil is 1. The wavefront error extends far from the axis with the larger bump widths similar to the distortion, but the peak of the wavefront error is found when the ratio between the bump and localized pupil is 0.5.

These charts are useful to understand the sampling needed for the system testing and the defect size allowed from manufacturing.

7. Intermediate Element Surface

The final surface type that is considered is in between the pupil and field. The concave surface of the middle element shown in figure 9 has the error placed on it.

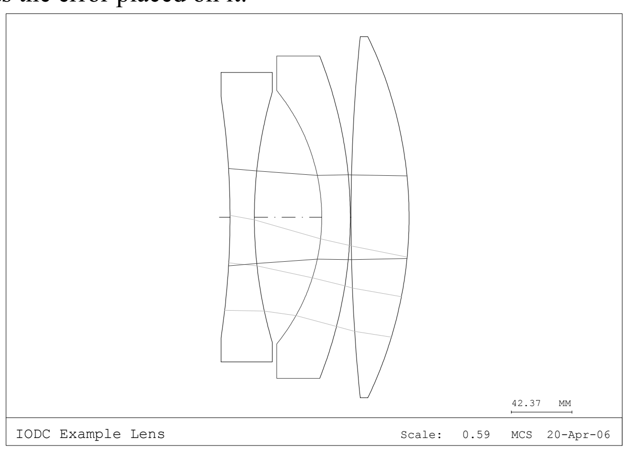


Fig. 9 Intermediate Optics

The errors placed on this surface result in an effect between that of the pupil and field optic. Both magnification and distortion errors result. The distortion errors are less like the 3rd order distortion seen in the pupil optic. The wavefront error is mainly over a large region in the center of the field, and it is a much more uniform error over the region than the field optic. Like the surface errors on a pupil surface, the narrowest errors do not cause a problem with wavefront error and distortion. This is due to the small error being integrated over the pupil. However, on this surface those narrow defects are many times smaller than on the pupil optic because the pupil is smaller. This requires tighter surface figure tolerances of this surface as compared to those with a larger instantaneous pupil.

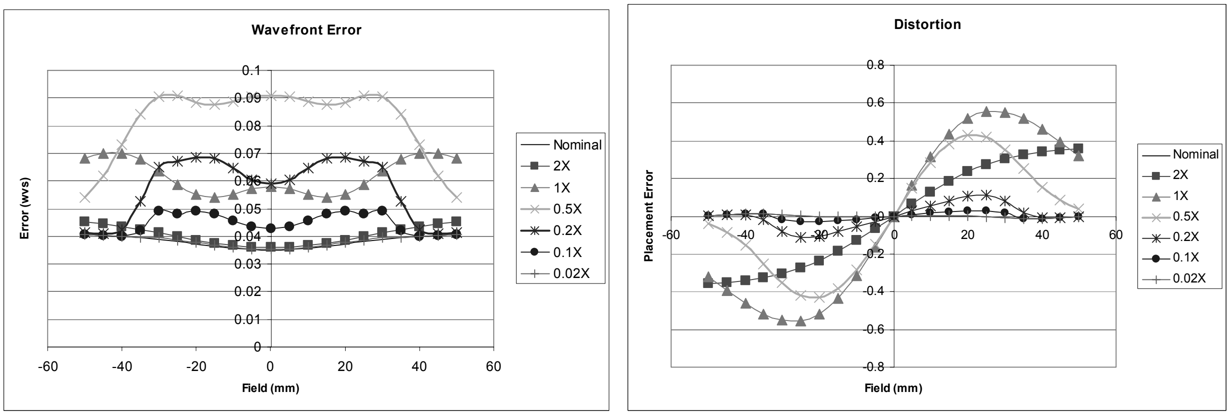


Fig. 10 The wavefront error and distortion plots for the intermediate element case

8. Amplitude Variation of Field Optic

The effect of the amplitude of the surface artifact is very similar on each of the surfaces. Here we look at the variation on the field optic. The increase in the peak distortion increases linearly with the height of the artifact, while the wavefront error is relatively small with minor artifact heights. The charts are for a bump diameter to surface pupil diameter ration of 0.5.

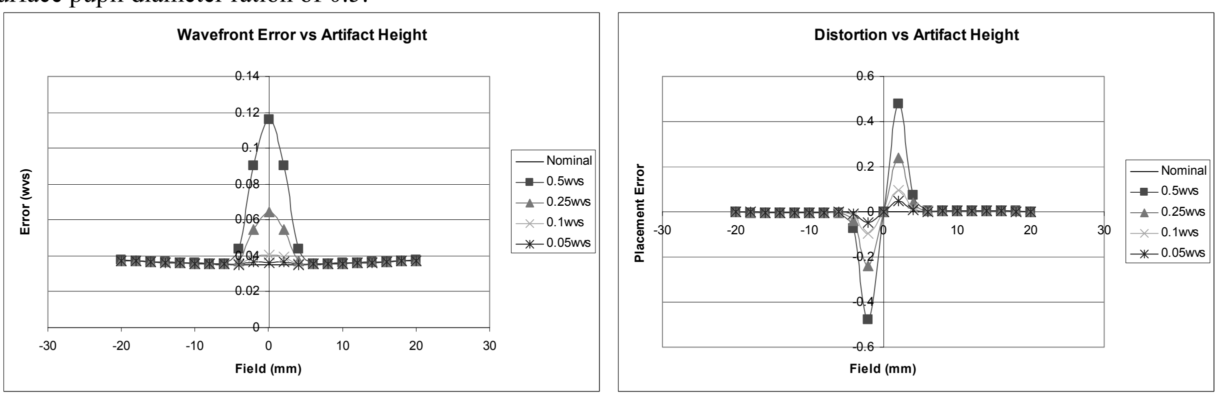


Fig. 11 Plots showing the effects of defects of different amplitudes

Examining both the amplitude and diameter of the local errors on each surface is important. The overall shapes of the errors produced across the field are determined by the ratio of the defect to instantaneous beam size, while the magnitude of the errors is determined by the height of the artifact.

We must consider not just the magnitude of the performance drop, but also the area in the field that is affected. This area determines the number of field points that need to be sampled in testing to adequately quantify parameters across the field of the system. The field optics have the most impact on the required amount of field sampling. The very localized errors reveal this impact.

9. Summary

The localized slope errors can cause severe performance loss in high precision optical systems. These errors would require extraordinary system level testing in order to ensure that all points in the field meet system specifications. Properly modeling a localized slope error reveals the effect of the errors. From this analysis, we can determine where the localized slope errors have the largest impact on the performance of the optical system. The analysis also assists the development of a method to judge the individual surfaces of the system based upon their position in the optical train and defect size.

Performing the analysis may reduce the time of testing of the optical system. If the impact of localized slope has been reduced to acceptable levels, the amount of testing through the field can be lessened. Thorough analysis of localized slope errors and testing of individual optical surfaces are necessary to achieve this advantage.

10. References

[1] A. Tabenkin, "Surface finish: a machinist's tool. A design necessity," in *Modern Machine Shop*, 71 (March 1999), pp. 80-88
[2] Richard N. Youngworth and Bryan D. Stone, "Simple estimates for the effects of mid-spatial-frequency surface errors on image quality," in *Applied Optics*, Vol. 39, No. 13 pp.2198-2209.