From Design to Assembly: Getting the Most from Your Optical Software

Mary G. Turner, Jon A. Herlocker
Breault Research Organization, 6400 East Grant Road, Suite 350, Tucson, AZ USA 85715

ABSTRACT

Sequential and non-sequential optical codes can be used for much more than the initial design and analysis of idealized optical and illumination systems. The design process usually assumes ideal components, ignoring realistic properties such as surface and volume scatter, Fresnel reflections, and polarization aberrations. These codes can also be used to perform tolerance analysis on these designs to help determine manufacturability limits. An important extension in the use of these programs is to create simulations based on the as-built components which include realistic optical surface and scatter scenarios. For example, modeling the measured optical quality of a fabricated primary mirror surface provides the opportunity to modify other optical or mechanical parameters to compensate for any surface errors, which in turn, can relieve critical tolerance limits. Optical analysis codes can also be used to model the performance of an optical system during assembly and testing to isolate defects and perturbations which cause the system performance to be out of specification. Interferometric or polarimetric data measured at several locations across the field of view can be used in the optical program to help identify out of tolerance components. These capabilities are of particular importance in eccentric systems as well as in polarization critical systems, provided the optical code can realistically model data in this form.

Keywords: Alignment, tolerancing, Lyot filters, c-plates retarders, parabolic concentrators

1. INTRODUCTION

As optical engineers, we often consider our optical software to be a tool primarily for designing imaging or nonimaging optical systems. This is for good reason as this is the task we generally use these tools to accomplish. However, these tools can readily find application in all aspects of optical engineering from the basic layout and design, through tolerancing, manufacture and assembly. Additionally, there are many capabilities in these programs that can also be used to help model "real world" simulations, well outside the idealized performance defined by the original design. These simulations are useful not only for defining tolerances for manufacturing and assembly, but can also be useful determining the optimal design for systems whose configuration, and therefore, performance can change during operation.

In this paper we will look at several ways optical software can be used to help improve the performance of an optical design by considering the effects of more realistic models.

Let's start by considering a very basic optical design. As we all know, the design performance "in the software" needs to be better than actual requirements on the system's performance, no matter what the performance metric. This is to allow for a reasonable set of tolerance requirements on the various optical and mechanical components. The tighter the system's performance requirement, the tighter (read as more expensive) the tolerance ranges become. When initially considering the tolerance analysis of an optical system, it is often reasonable to allow each possible defect to contribute equally to the total tolerance budget. Although this is very useful to get a rough estimate, the final tolerance budget will often be further adjusted among the various error sources, including fabrication errors, material errors, assembly errors, environmental effects as well as the residual design error. Each system parameter that can be identified exactly reduces the total number of tolerance parameters, allowing the total error budget to be shared among fewer parameters. The ability to exactly specify parameter values is often considered to be only available for limited production systems, where budgets allow for exact information including glass melt data, and interferometric information of large optical components.

2. Injected molded parts

Optical System Alignment, Tolerancing, and Verification III, edited by José Sasian,
Richard N. Youngworth, Proc. of SPIE Vol. 7433, 74330N · © 2009 SPIE
CCC code: 0277-786X/09/$18 · doi: 10.1117/12.829202

Consider an injection molded part: the actual surface quality depends on can only be measured after the expensive and time consuming process make the mold is completed. Errors do to microstructure roughness on the tool can be measured and modeled using scatter the scatter models found in many optical codes. One these values have been measured, the results can be applied to future designs as significant changes are unlikely to vary significantly. Tooling errors result in very nonuniform surface shapes that are best defined using complex forms such as Bezier polynomials or NURBs. The following figure shows section of typical injection molded surface. A laser scan was used to determine the shape and this data was used to create a model of the part within a CAD program.

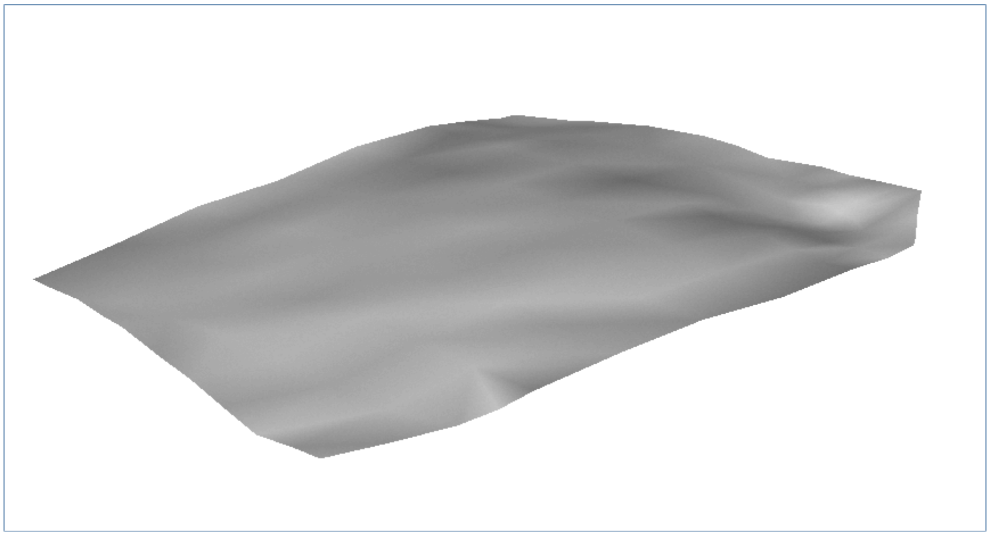


Figure 1 Surface as rebuilt in CAD

Although it is possible to use the information from the laser scan directly in optical software to analyze the performance, it is more efficient to develop scatter based model of the surface for the analysis. The following figures compare the performance of the nominal design with that using a model of the actual surface and that using the scatter model. Note the high level of agreement between the modeled and simulated surfaces. By developing scatter models to represent the errors, including rippling and frequency variations, a tolerance analysis can be performed in advance of the actual tooling process to determine the effects of such defects on the system performance. By varying the parameters of the scatter model, a reasonable understanding of the effects of these errors on system performance can be simulated.

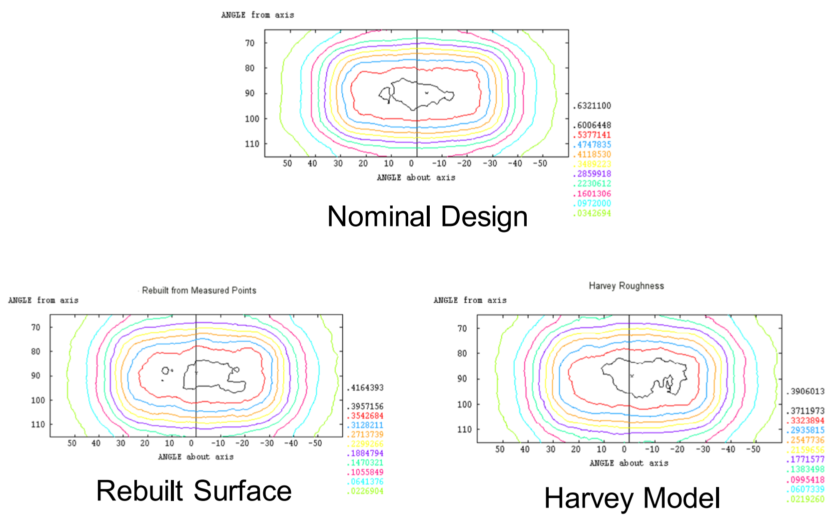


Figure 2 Comparison of nominal, modeled and simulated data

3. Isolating tilt and decenter errors in assembled systems

Optical software can be used to provide useful feedback during the assembly of optical systems. This is especially true during the alignment of nonaxial systems. Small errors in the position of off-axis components can introduce significant amounts of aberrations, including coma and astigmatism, into the system. By entering Interferometric information from several points across the field of view, optical software can help isolate the placement errors. Although, in theory, to exactly isolate the position errors requires a set of wavefront information equal to the total degrees of freedom, in practice, a much smaller number of data sets is actually required to isolate the major error sources. The figures below show the nominal, perturbed (misaligned) and iterated performance of a three mirror anastigmat. As a simple test, the second and third mirrors were both decentered and tilted in both X and Y.

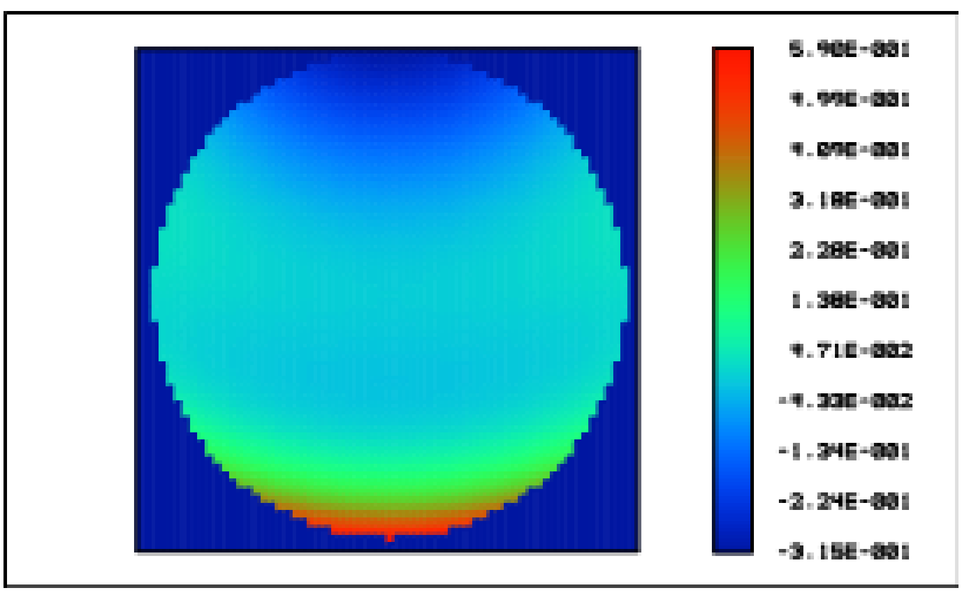


Figure 3 Design performance on axis

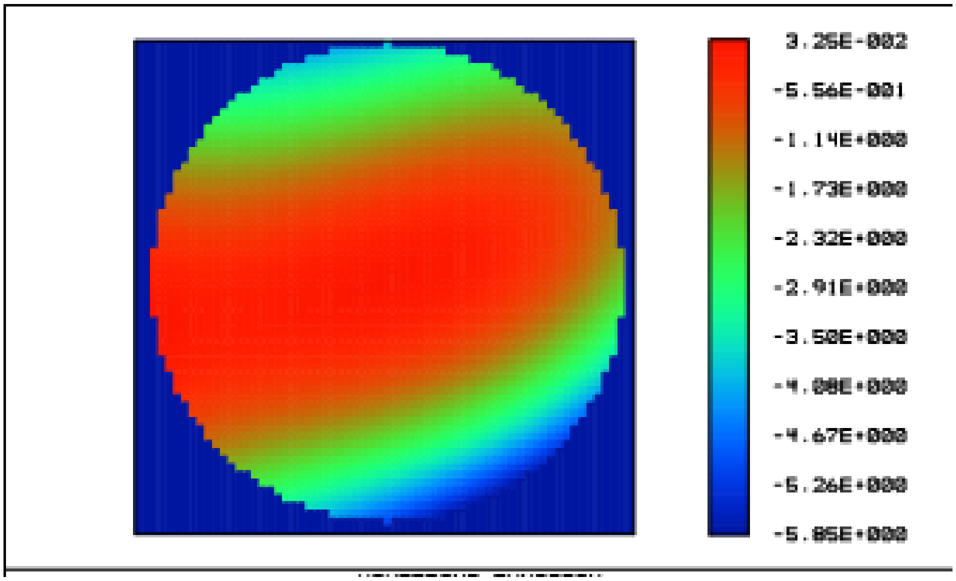


Figure 4 Misaligned system performance on axis

The table below shows the input perturbations as well as the results of the analysis.

Table 1 Comparison of simulated and calculated errors

	Simulated errors				Calculated errors			
Secondary	-0.2000	-0.2000	-0.2000	-0.2000	-0.2073	-0.1925	-0.2005	-0.1999
Tertiary	-0.2000	-0.2000	-0.2000	-0.2000	-0.1870	-0.1809	-0.2008	-0.1996

As you can see, the optimization was readily able to isolate the causes of the degradation in the systems performance. The wavefront map for the reoptimized system is shown below.

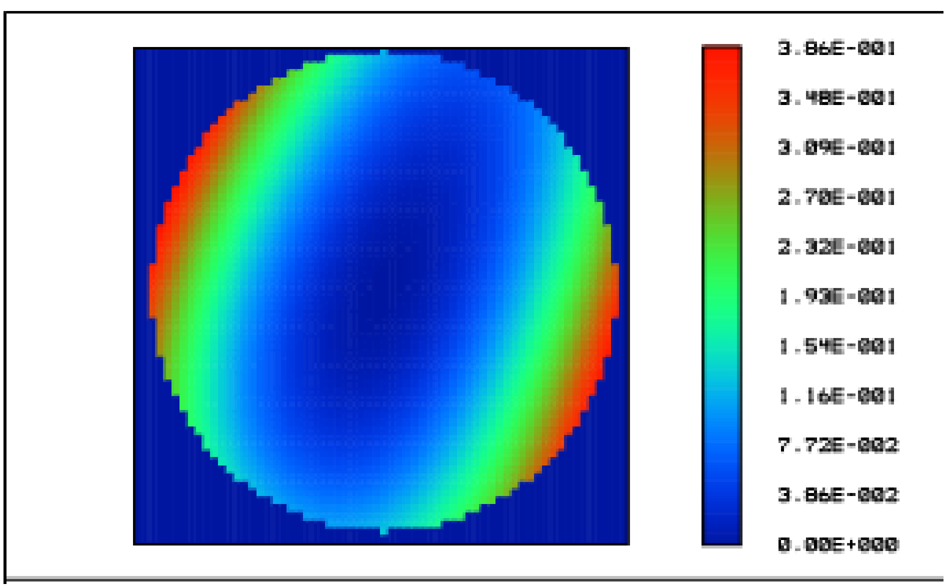


Figure 5 Performance of realigned system

The process used in this example is to modify the original design file to have sufficient configurations for each set of wavefront measurements. Zernike polynomial information is input into each configuration, in this case at the entrance pupil location. Each configuration represents one field point. After optimization across the configurations, the tilt and decenter information indicates the defects which would have caused the input wavefront errors. I

4. Polarization devices

4.1. Lyot filter in an uncollimated beam

A three-stage quartz Lyot filter with a base order of 5, designed for a center wavelength of 590 nm, is illustrated below.

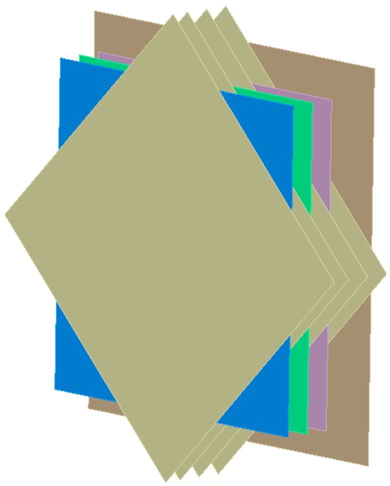


Figure 6 Lyot filter

It is relatively simple to calculate the on-axis transmission spectrum for a given filter design. The performance for a general uncollimated source is more involved, and is a distraction from typical system design activities. Modern analysis tools enable the simulation of the general case using raytrace-based analysis. The following series shows the effect of uncollimated illumination for a series of beam semi-angles. The analyses were carried out by polarization ray tracing at 201 points in the spectrum, taking only a few minutes to complete all the cases. The deviation from the on-axis behavior is not very pronounced at 5 degree beam semi-angle, but beyond that could be a significant factor in system performance.

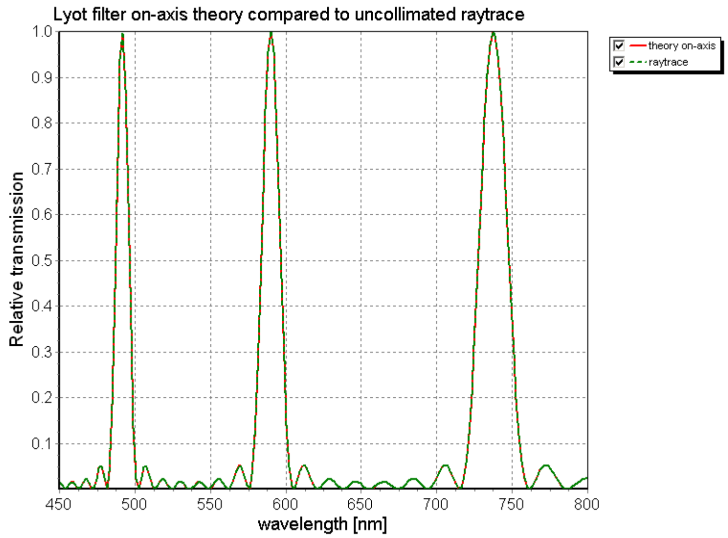


Figure 7 5 degree beam semi-angle

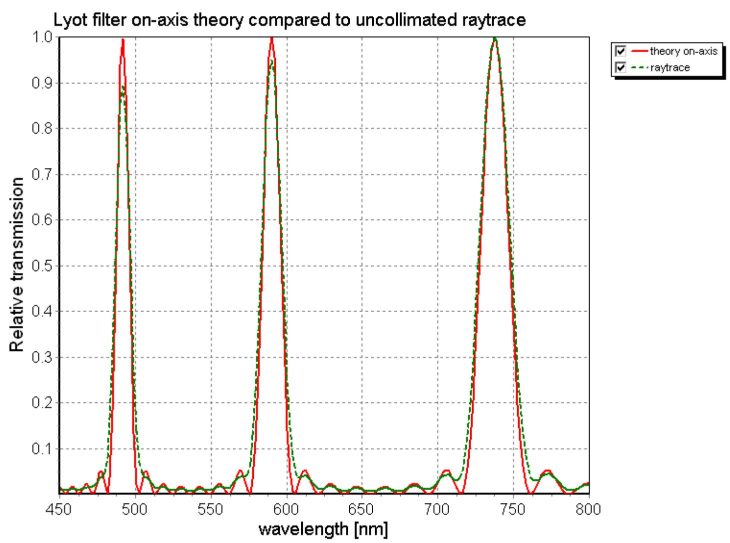


Figure 8 15 degree beam semi-angle

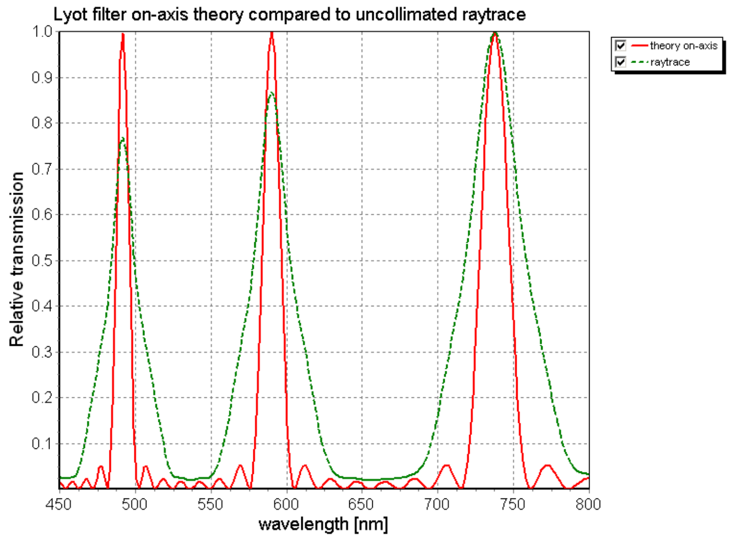


Figure 9 30 degree beam semi-angle

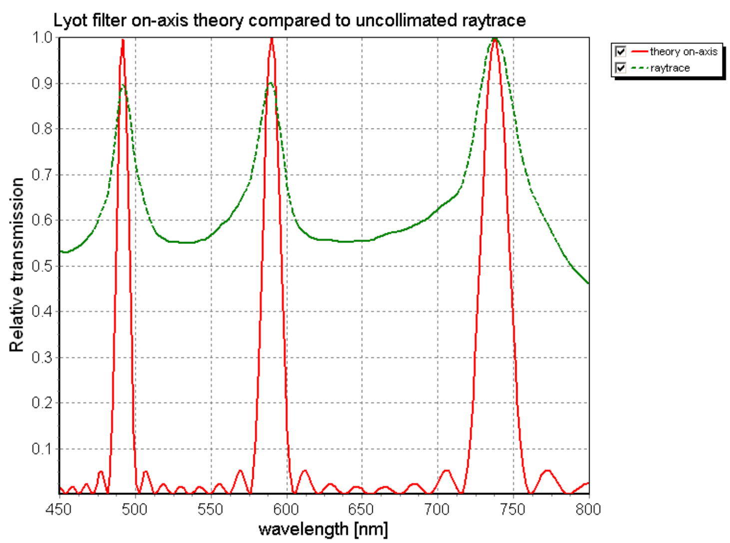


Figure 10 60 degree beam semi-angle

4.2. Optical axis irregularities in a thick c-plate retarder

A three-micron retardance c-plate (retarder with its optical axis out of the plane), inserted between crossed polarizers, is expected to produce several orders of polarization interference for a wide-angle beam in the visible region. The expected result for a nearly-hemispherical direction-cosine space, produced by a simple polarization raytrace, is shown here. It has the fundamental form of a Maltese cross, with the polarization interference superposed. The wavelength of the simulation was 550 nm.

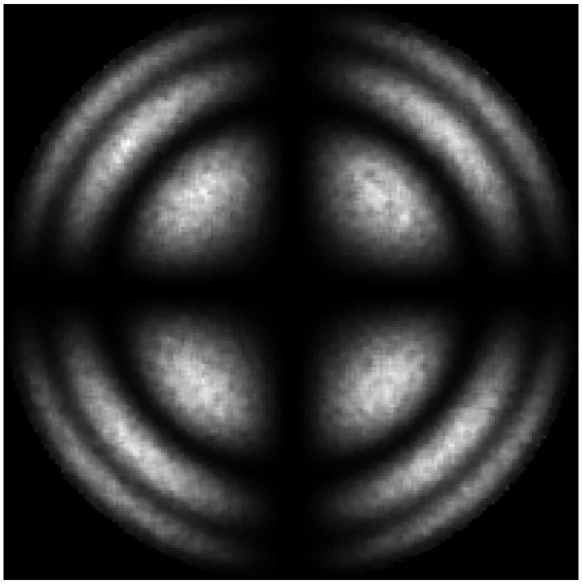


Figure 11 Polarization interference of ideal c-plate

A localized defect in the optic axis alignment in the c-plate was also simulated. This defect consisted of "wander" of the optic axis with respect to the device axis with a maximum deviation of 8 degrees. In this example, the plate was stratified into 8 layers.

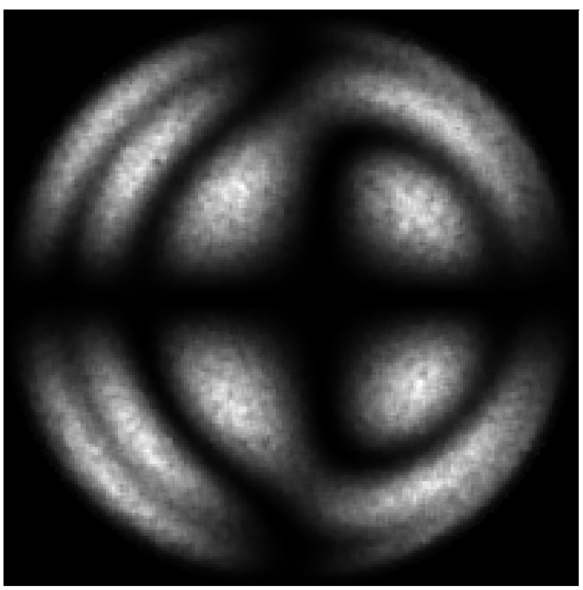


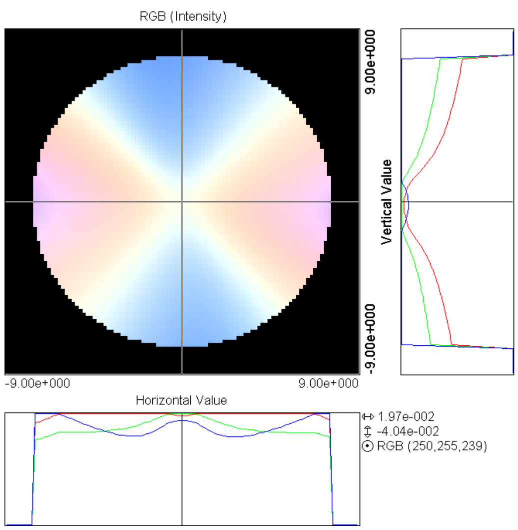
Figure 12 Polarization interference of non-ideal c-plate

The effect is to reduce the effectiveness of such a plate as a compensating layer, as for instance in a liquid-crystal cell. This would result in serious viewing anomalies for a display using such devices.

4.3. Color casting in a simple liquid crystal cell

The retardance of a simple liquid crystal cell varies significantly with illumination angle, and also with wavelength due to dispersion. Examining a liquid crystal cell in the "on" state under broad-wavelength, broad-angle illumination is an important task in liquid-crystal display design. Using a typical twisted-nematic liquid crystal cell layer between crossed polarizers is expected to yield high transmittance at the design wavelength, and for a suitable range of wavelengths across the visible region. As the illumination tends off-axis, the states emerging from the liquid crystal material will generally vary with wavelength, leading to color variation, or "casting," when a broad spectrum is applied.

This effect is illustrated by tracing an equal-energy white source through a cell, and rendering the color assuming a CIE E illuminant. An illumination semi-angle of 75 degrees was used, with source sampling the visible spectrum uniformly at 25 nm intervals. This should yield transmitted white on-axis, and may lead to shifts from white otherwise. An RGB rendered view, and the corresponding CIE 1931 chromaticity diagram, assuming 10-degree observer model, are shown below. The first example assumed a display visualization conversion gamma of unity to emphasize the color shift through enhanced saturation. The second renders the result using a more realistic conversion gamma of 2.4, to better simulate the logarithmic behavior of human perception at the cost of some subtlety in the observation.



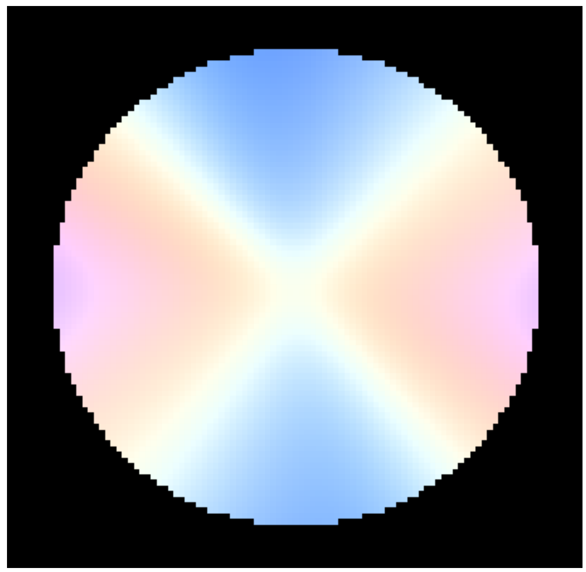


Figure 13 150 degree source angle, Gamma = 1

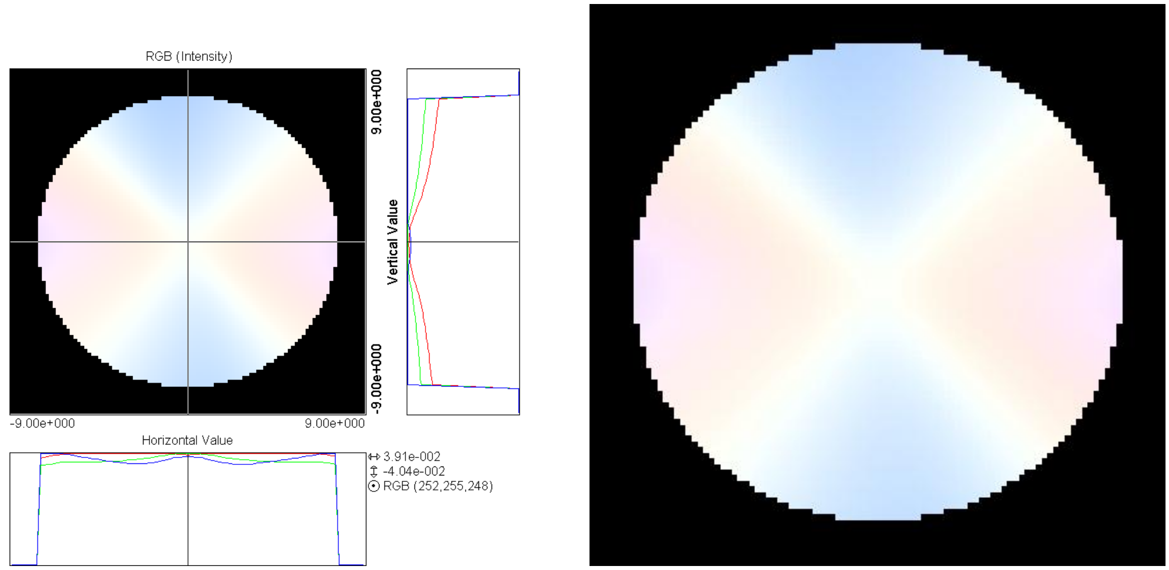


Figure 14 RGB data for 150 degree source angle, Gamma = 2.4

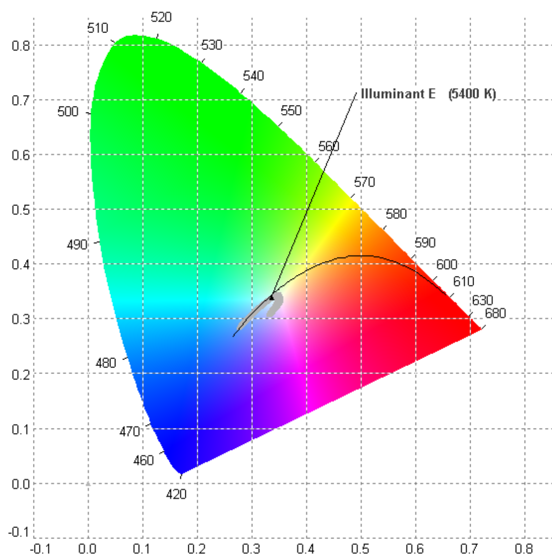


Figure 16 Chromaticity diagram

5. Solar concentration systems

5.1.1. Surface deformations in solar concentrators

In order to properly calculate the efficiency of solar concentration systems, it is important for the analytical model to simulate not only the as manufactured shape and position of the components, but also to simulate the surface effects in operation due to stresses, such as heat and weight. One method to do this is to apply a deformation to the surface of the reflector, in this case a parabolic trough.

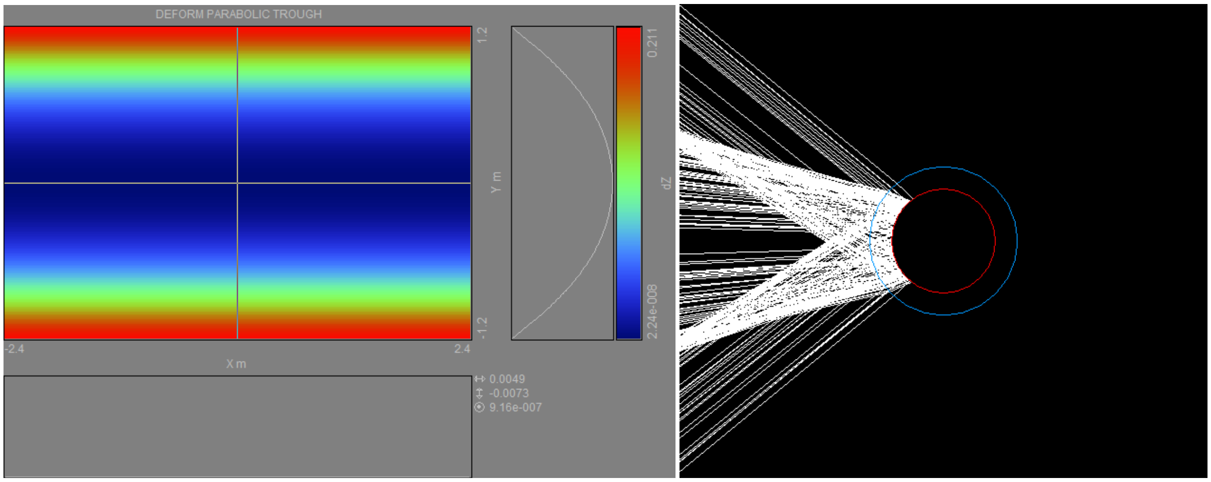


Figure 17 Deformed parabolic trough and energy distribution

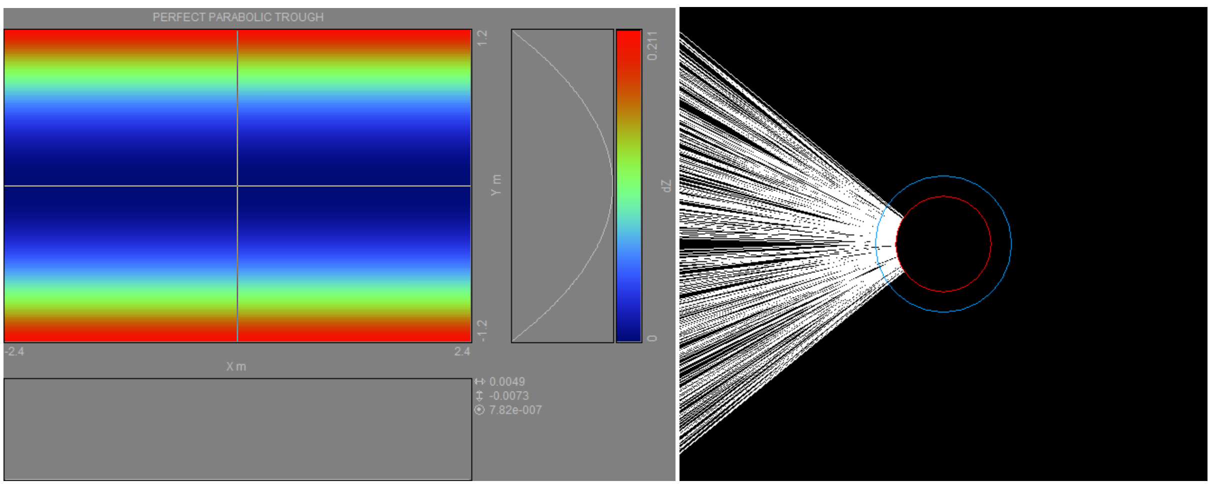


Figure 18 Ideal parabolic trough and energy distribution

By considering thermal and other stresses in defining the surface shape, it is possible to enhance the overall efficiency of the systems by modeling more realistic day to day system variations.

5.1.2. Simulating heliostats

In heliostats, the mirror or array of mirrors must track the sun's position in order to redirect and concentrate the energy on the target surface. Errors in the positions of the mirror elements can result in significant reduction of efficiency. In order to reduce costs, lighter weight materials are preferred, but these materials often have increased susceptibility to deformation and movement. By considering these effect in the design analysis, collector size and location can be optimized to maximize the total energy collection while maintaining the lowest cost for the collector.

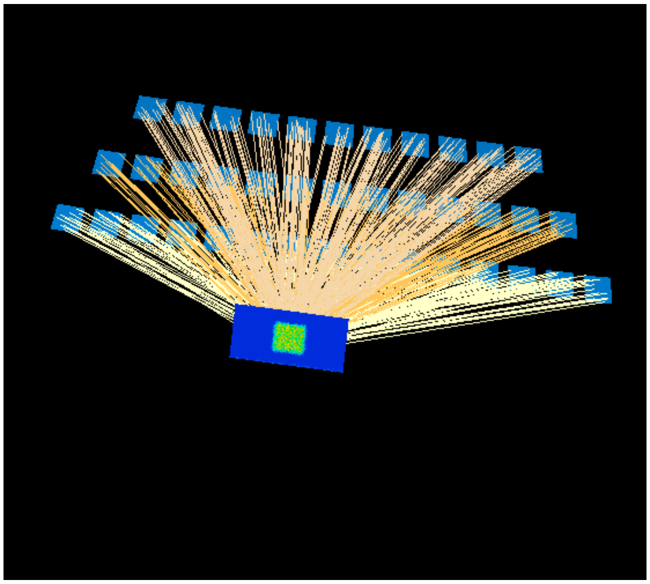


Figure 19 Energy to collector from heliostat (nominal)

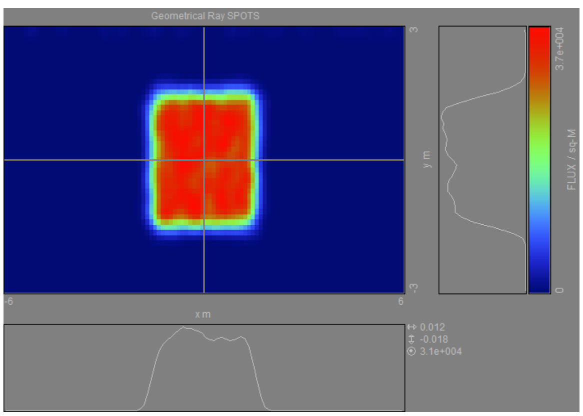


Figure 21 Energy on collector (perturbed)

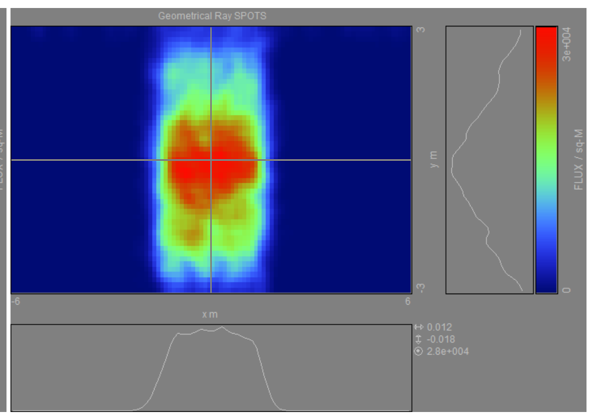


Figure 20 Energy distribution on collector (nominal)

In order to maximize the collection efficiency, the collector needs to be larger. Due to the cost of the collector, setting a reasonable maximum size based on a wide range of operating conditions would provide the most cost effective design.

6. Conclusion

Several of these examples have a commonality other than demonstrating various applications of tolerance analysis to help in the design, assembly and use of optical and illumination systems. In almost all cases, it was necessary for the optical software to interact with data determined using another software tool. This might be interferometry data, CAD files or other information.

Several years ago, a commission was established with the goal of defining a standard for optical design files in order to allow easy exchange of data between the various codes. To the best of my knowledge, this effort has not yet succeeded. Without discussing the relative merits or demerits of this task, it is interesting to see how this is actually being accomplished very quickly, in a more indirect manner, which is bringing a wide range of significant analysis capability to the optical designer. Those of us who have used optical software over the past several years have noticed an ever increasing capability on the part of optical software, especially nonsequential codes, to interact with

CAD programs. This is not only true for optical codes, but for many other types of analytical software as well. This capability to directly import CAD data, which might have been modified as a result of a finite element, flow or thermal analysis program or any other physical analysis tool which can provide valuable data for the optical simulation. A common example would be using SolidWorks to interface programs such as SolidFlow and CosmosWorks to the optical design program. Additionally thin film analysis programs, surface scatter modeling tools and light source measurement tools are also providing data which can easily be input into many optical programs.

REFERENCES

[1] M. E. **Kaminski** and R. J. Koshel, "Methods of tolerancing injection-molded parts for illumination systems," ***SPIE*** *Proc.*of Efficient Illumination System Design **5186**, 61 (Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 2003.)

[2] Advanced Systems Analysis Program (ASAP™) Reference Guide, Breault Research Organization, Inc., 6400 East Grant Road, Suite 350, Tucson, AZ, 85715

[3] ZEMAX User’s Guide, ZEMAX Development Corporation, 3001 112th Avenue NE, Suite 202, Bellevue, WA 98004-8017 USA