

Methods of tolerancing injection-molded parts for illumination systems

Mark E. Kaminski^{*a} and R. John Koschel^b

^aBreault Research Organization, Inc., 6400 East Grant Road, Suite 350, Tucson, AZ 85715;

^bSpectrum Astro, Inc., 3450 East Sunrise Drive, Suite 140, Tucson, AZ 85748 and Optical Sciences Center, University of Arizona, Tucson, AZ 85718

ABSTRACT

Injection-molded optical components are used often for commercial illumination systems. This paper discusses methods of how to model the tolerance aspects of such components. Tolerance aspects include surface roughness, source-to-optic position and rotation errors, and surface slope errors. It is noted that all of these tolerance investigations cannot correctly account for errors in the injection-mold process. A method to model deformations induced in the injection-mold process is proposed. The method is based on the laser scan of an injection-molded part, which allows the rebuilding of the surface from the point cloud. This method, while quite accurate, is time consuming, so a second algorithm based upon approximation with a Harvey scatter model is developed that takes over an order of magnitude less in time. It is shown that the approximate model provides results within a few percent if comparisons are done in the far field. Near-field results require the rebuild method that uses the measured point cloud. Additionally, illumination systems comprising multiple interactions with the component surface (e.g., lightpipes) can use the approximate Harvey model.

Keywords: Illumination, nonimaging optics, optical design, tolerancing, Harvey model, injection molding

1. INTRODUCTION

Illumination systems can be fabricated from any number of methods, including: electroforming, stamping, machining, and injection molding. Injection molding is the preferred method for any part to be made in sizable quantities, especially for those systems requiring a higher degree of final accuracy. The tolerancing of such parts is difficult in comparison to lens design, which has accepted methods of tolerancing. For example trade studies on the bending of an element in relation to the manufacturability, cost of the component, and its effect on system performance are common. Illumination system components do not have the same benefit of accepted tolerancing methods due to the complexity of the individual components, the limited volume in which to locate the component, and limited process time during manufacture of the component. The primary force driving the design and thus performance of the illumination system is cost – all aspects of the design must be minimized in time and expense demands in order to reduce cost. This process by its nature introduces errors in the fabrication, which can mean the final system does not meet required performance demands, such as transfer efficiency or illumination distribution profile. Thus, the designer must account for such potential errors in the design process. Accounting for such is typically accomplished by demanding the design system works a certain level above requirements (e.g., test points in the illumination distribution are 25% above minimum requirements). These additional requirements insist the use of more powerful sources and often systems that give up efficiency in order to provide illumination requirements. A more powerful method of accounting for illumination system tolerance errors is to include the potential fabrication errors in the design process. The designer includes such errors in order to study the performance of the system with successive design iterations. With each step the designer can determine if performance approaches system requirements while ensuring that realistic tolerances can be met. If indications show potential tolerance difficulties, the designer can change the approach. Such a method will increase the design time, but at the luxury of reducing the number of fabrication iterations. Design iterations are much less costly than fabrication iterations, typically on the order of one to two magnitudes. A tolerance method constantly being developed by us is presented here. It uses injection-molded plastic parts for illumination systems for illustrative purposes, but slightly modified algorithms could be implemented to handle components made with other processes.

*mkaminski@breault.com; phone 1 520 721 0500; fax 1 520 721 9630; breault.com.

Typical tolerance parameters that are studied are source variation, surface roughness, source-to-optic position and rotation errors, and shape errors of components. Source variation items include output power, size of the source (e.g., filament length), and geometry of the source (e.g., location of the die within an LED). Thus, the luminance output distribution varies from source to source. The designer must determine the required tolerance aspects of the source variation, which describes the amount of source testing and selection that must be done for manufactured systems (e.g., one must determine the bin categories of LEDs in color, optical power, and electrical input). Surface roughness of manufactured parts can vary from sample to sample, which is especially true for injection-molded parts over the lifetime of the mold tool. So, the designer must investigate various surface roughness levels to ensure the actual part will provide the required performance over the anticipated quality levels of the mold tool. Illumination systems are susceptible to source-to-optic position and rotation errors. Additionally, source-to-optic position and rotation errors are often the largest reason that illumination systems fail to meet performance standards. The designer must ensure that such errors do not compromise system performance over realizable ranges of positional and rotational errors. Shape errors are also a typical error in injection-molded illumination components since the very nature of injection molding leads to deformations. However, it is difficult to model such errors except through prescribed surface variation, especially constant slope discrepancy. Thus, it is difficult to model accurately shape variations introduced through the molding process. These and other errors are compounded by the complexity of the optical surfaces comprising the illumination system. For example, vacuum-metalized, injection-molded plastic reflectors are used in the automotive industry. The reflectors are comprised of many facets over a large area to provide the intensity distribution to meet governmental standards. The individual facets illuminate different parts of the target distribution such that the overlap of all facets in the far field meets requirements. Slope errors of even 1 degree can lead to nonconformance of the part. One-degree slope errors can easily be realized over the extent of such large injection-molded reflectors.

The illumination design process is comprised of the steps shown in Fig. 1. The arrows indicate the schedule of the steps, and, if required, the restart of steps if later results prove negative. In the setup step the performance goals, such as efficiency and uniformity, are determined. Next, baseline analysis determines the trades between obtaining the goals and the geometry requirements. This step is accomplished usually by investigating the etendue of the system. At the end of this step one will have a general understanding of the size and angular extent of the illuminator as a function of the performance goals. Once the etendue of the systems is determined, one proposes conceptual designs in order to meet the goals. Often a literature search proves useful at this step, but it is not always needed dependent on the experience of the designer. The concept study investigates possible optical designs, and one is selected for final design. Concurrent to this step optimization and tolerancing is done in order to maximize the performance of the design while ensuring that it can be manufactured to meet the modeled results. Finally, the optimized, toleranced system is fabricated and tested. If all steps are done correctly the manufactured system will agree with the modeling, and the system can go to production. The “question mark” in Fig. 1 indicates that the tolerance step is not always performed to completion due to time constraints, difficulty in analyzing all potential tolerance parameters, and lack of understanding of the important parameters to be analyzed.

In the next section the technique for doing a tolerance investigation of an illumination design is discussed. Limitations of including shape variation, or what is hereafter called deformations, is also broached. The third section discusses a method of including shape variation based upon laser scan measurement. A lightpipe example

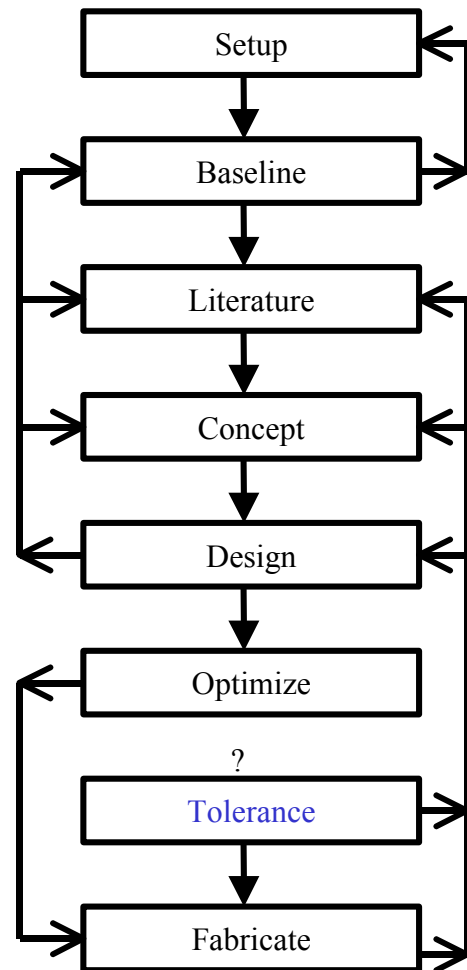


Figure 1. Typical schedule for the illumination design process.

is used to highlight this section. The fourth section proposes an approximate method for including deformations based upon the Harvey model for specular scatter. Within this section a comparison to the system introduced in Section 3 is provided. Finally, Section 5 provides conclusions.

2. METHOD OF TOLERANCE ANALYSIS OF ILLUMINATION SYSTEMS

Performing a tolerance analysis of an illumination system is crucial to ensure that the manufactured system meets performance metrics. The designer follows the process shown in Fig. 1 or a similar method. The design through tolerance steps are often done in an iterative way, such that modifications to the design are tolerated before finishing the whole design. An iterative process makes sure that the final geometry that one is approaching is tolerable of typical errors, or the process can be restarted to provide such. The tolerance step is comprised of two techniques:

1. Parameter sensitivity: important parameters are noted during the various steps of the design process. These important parameters are the items that greatly affect system performance, such as source-to-optic position. It is crucial that the designer investigate how the system reacts as these important parameters are varied individually. The designer can then ascertain the allowable variance of the parameter while still maintaining performance metrics. Parameter sensitivity should be investigated upon the completion of each design iteration.
2. Monte Carlo analysis: the important parameters or a pared down list dependent on the results of the parameter sensitivity are used in this step. Random perturbations to each of the parameters are made and the system performance is determined. Each parameter is randomly varied over the allowed ranged determined during the parameter sensitivity. Several iterations are performed in order to map out the parameter space. With this method the interdependence of the parameters can be ascertained, and the range of parameter variation can be updated. The statistics of sampling the merit space and the desired accuracy determines the number of iterations that are done. Monte Carlo analysis should only be performed at the end of the design process. At times it can show problems in the design that must be addressed, but with a properly designed system (i.e., one that follows a schedule similar to Fig. 1) these circumstances will be minimal.

Upon the successful completion of these tolerance steps, the design is sent for manufacture. Figures 2 and 3 show the parameter sensitivity plots for two of five variables determined during the design process of an illumination system. This system is illuminated by LEDs, and scattered light is collected at a neighboring detector. The important parameters are the limitation of direct cross talk (i.e., light that goes directly to the detector) while maintaining a high transfer efficiency. Figure 2 shows the size of a baffle that limits the cross talk, while Fig. 3 shows the lateral source-to-optic position error. Two cases are plotted in each figure. The upper curves are the illumination over the full target, while the lower curves show the illumination over the central 20% of the target region.

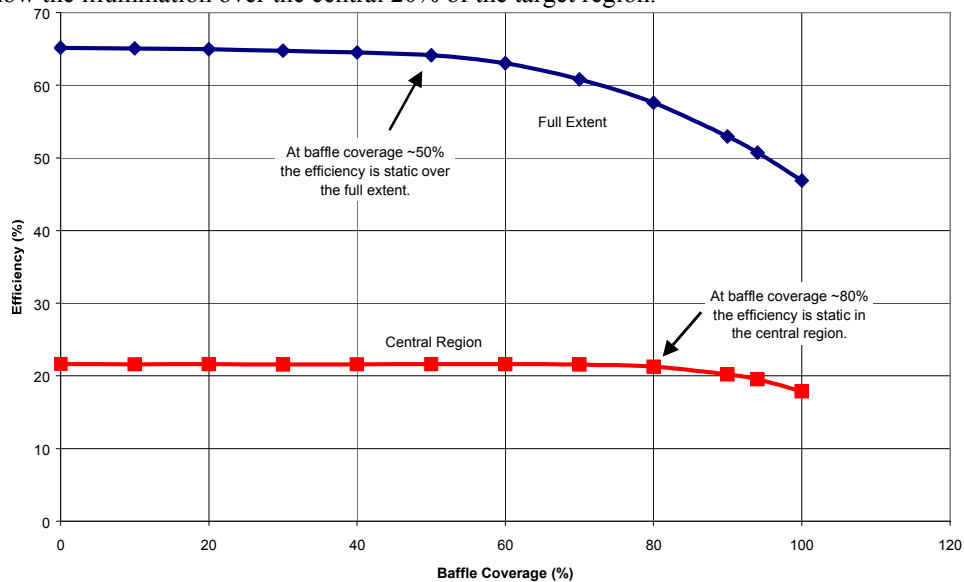


Figure 2. Effect on system efficiency by the baffle size. It was determined that this variable has minor effect on system performance.

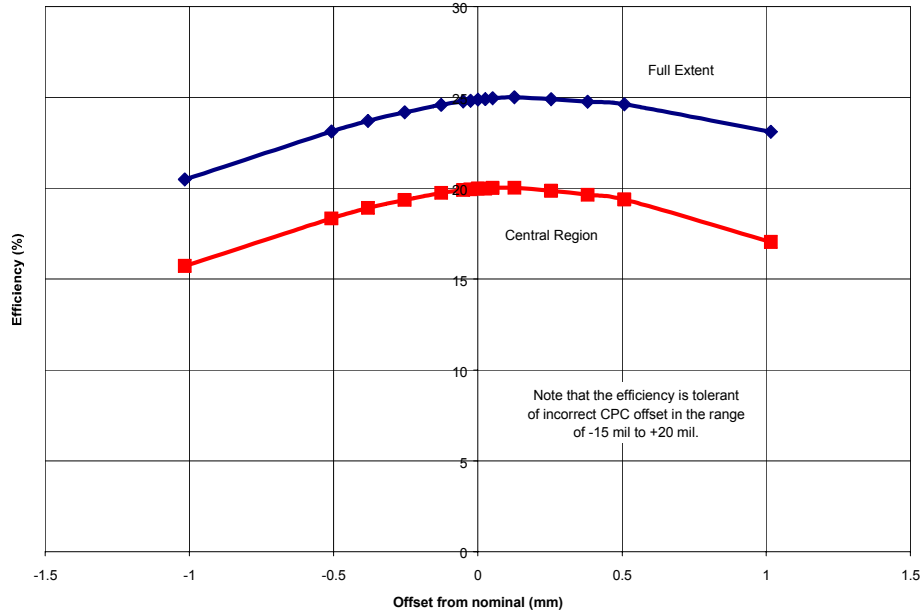


Figure 3. Effect on system efficiency by the source position. This parameter dominates system performance.

It was noted during the tolerance analysis that the baffle size had little effect on system performance, thus it was not investigated in the Monte Carlo analysis. The source-to-optic position error dominated along with source rotation error in the performance of the system. Figure 3 shows that lateral position errors of -15 mil to $+20$ mil could be tolerated before it compromised system performance. This parameter range was used in the Monte Carlo analysis. Four results for the Monte Carlo analysis are shown in the plots of Fig. 4. These results are random perturbations, and once again it showed the lateral source position error and source rotation dominated system performance; however, while the allowable lateral position errors maintained their parameter sensitivity range, the rotational errors had to be constrained by a factor of two. The detector in each case is shown as the circle in each of the plots.¹

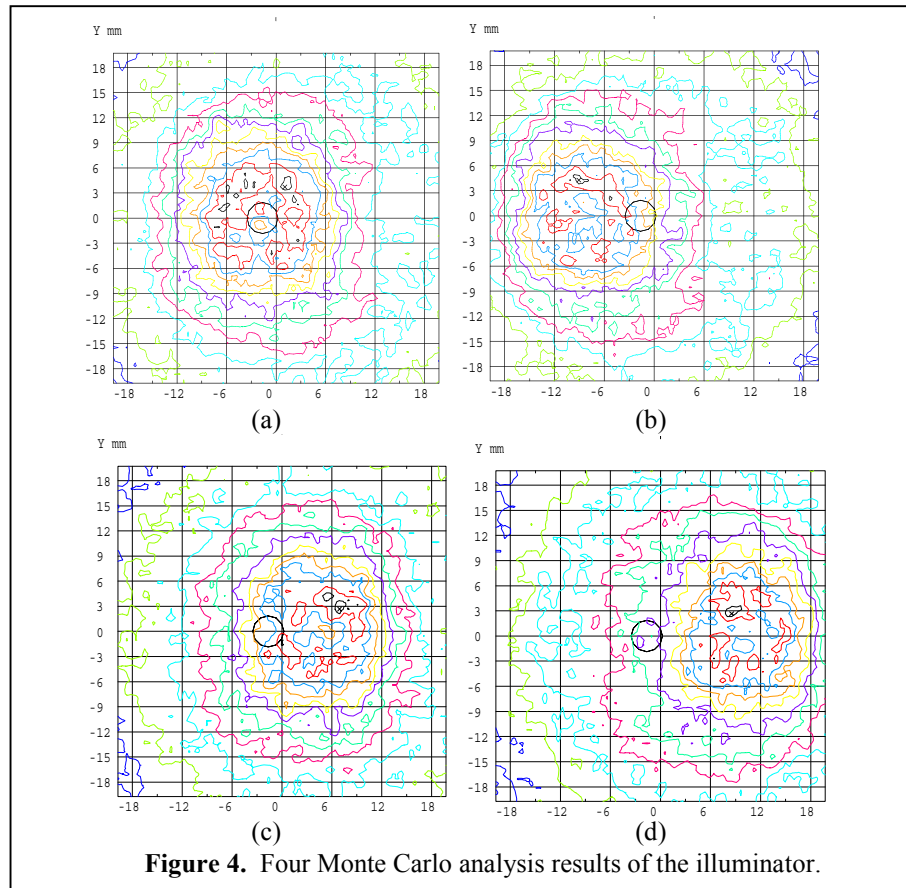


Figure 4. Four Monte Carlo analysis results of the illuminator.

Now that the Monte Carlo analysis is complete, the design can be sent for manufacture. However, one parameter that likely has not been successfully investigated is random perturbations of the shape of the injection-molded part. One could do this step during the previously described tolerance steps, but you need an algorithm for doing such. In fact, one should base such an analysis on the specifics of the injection-mold capability of the manufacturer. This process can be accomplished by measuring a witness sample made by the manufacturer. Note that any injection mold will vary over time, from machine to machine, part geometry, environmental parameters, material characteristics, and so forth. Thus, this witness sample provides a baseline of the expected deformations created during the injection molding. The next section describes a method that we employed to integrate the molding process into our design and tolerance process.

3. DETERMINISTIC METHOD OF INTEGRATING INJECTION-MOLD DEFORMATIONS

Deformations occur during the injection-mold process due to the cooling of the part. The greater the duration that the part is held in the mold tool, the more likely it is to maintain the design shape. However, the longer the time that part is held in the tool, the greater the cost of each part. Thus, the process time is typically minimized. This leads to sinks, warps, and ripples on the surface of the part. These deformations of course lead to nonconformance to the design model. Deformations are especially detrimental for reflectors and lightpipes.

As an example of the process we will use a lightpipe design that did not have the luxury of a shape deformation analysis. The fabricated lightpipe had substantial leakage before it arrived at the remote emission region. This leakage caused the part to not meet intensity requirements, so it was not a viable solution. We then set upon a path to determine the culprit for the lacking performance. Two methods for measurement of the part were studied: computer measurement method (CMM) and a laser scan. A laser scan was chosen because it supplies a multitude of points at higher resolution than obtainable with CMM.² In fact over the lightpipe we had over 100,000 points in the cloud. From this point cloud we can rebuild the surfaces and then perform a ray trace to determine expected performance with the deformations. The major detraction of laser scanning is the accuracy of the measurement. Loosely, the accuracy is on the order of 50 microns, which is often not suitable for rebuilding the part in an optics model. Additionally, we could not use all points within the cloud because of the large number. Thus we took points in a local neighborhood, averaged them together, and placed the rebuilt point at the centroid. With this method we were able to obtain better accuracy at the expense of resolution that was not desired. The rebuilt surface for a $3 \times 3 \text{ mm}^2$ parabolic region is shown in Fig. 5. The ripples that extend over the surface lead to a 7-degree slope error, which amounts to a 14-degree propagation error due to the reflective nature of the lightpipe. We speculated that these deformations across the parabola were the reason that the part was failing. The results using (b) the rebuilt surface are shown in Fig. 6 along with (a) the nominal design and (c) the measured lightpipe. Note that the other surfaces within the lightpipe design were not rebuilt, or in other words they maintained the nominal design shape. Figure 6 shows excellent agreement between the measurement (c) and the rebuild (b), especially the peak intensity value of 0.39 cd to 0.42 cd respectively. The nominal design had a peak intensity of 0.63 cd. The laser scan and resulting analysis showed that the leakage was caused due to light not conforming to the critical angle that provides total internal reflection.

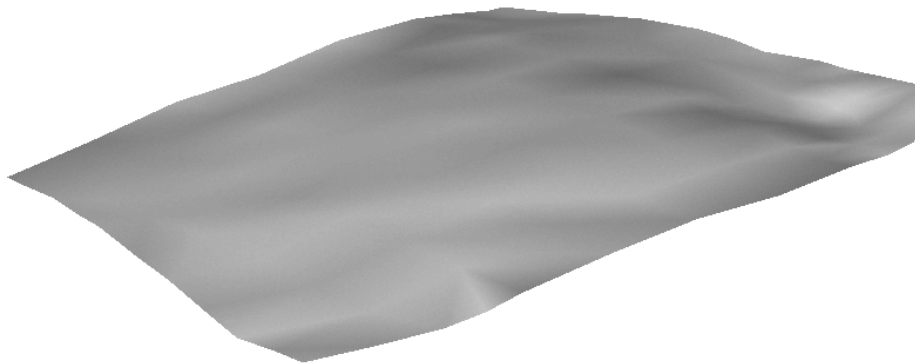
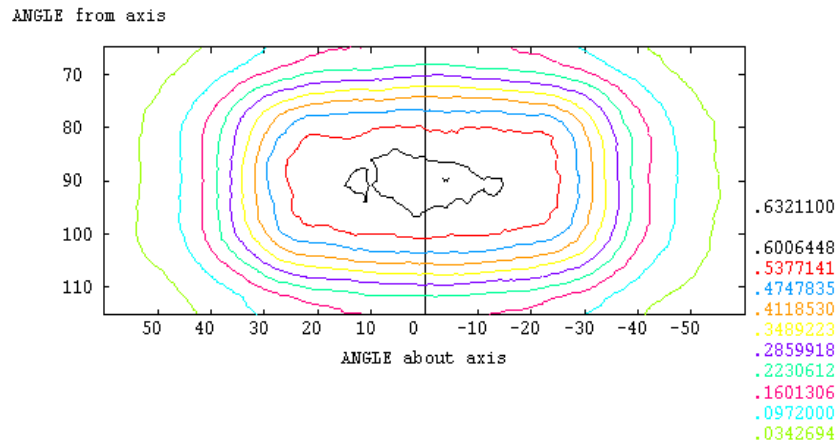
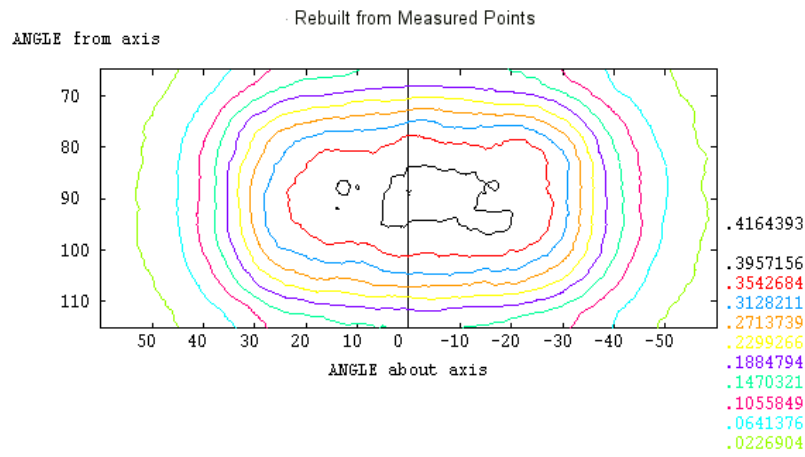


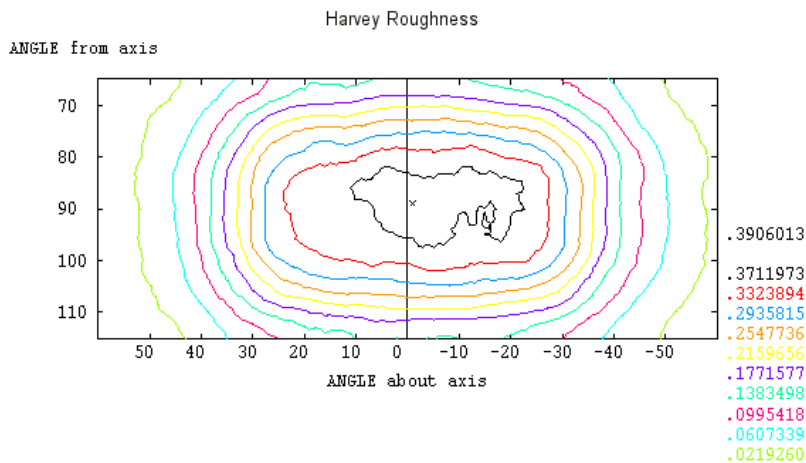
Figure 5. Rebuilt surface of the $3 \times 3 \text{ mm}^2$ parabolic section of the lightpipe. Note the ripples that extend over the surface when in fact the nominal design had a smooth surface. The surface was rebuilt in a CAD program and then imported into the optical analysis package.



(a) Intensity distribution for nominal optical design.



(b) Intensity distribution for rebuilt optical design.



(c) Intensity distribution for measured optical design.

Figure 6. Intensity distributions for (a) the nominal optical design, (b) the rebuilt optical design, and (c) the measured optical design. The units are in candela (cd).

The primary limitation of rebuilding the surface was the time involved to determine rebuilt illumination distribution (Fig. 6.b). It took over an order of magnitude longer to calculate this distribution, thus its utility is limited. A better method must be found that at worst approximates the expected illumination distribution at a fraction of the time cost. Therefore, we investigated using a Harvey scatter model that can be applied to the surfaces of the illumination system. A Harvey scatter model is used for “specular” scatter, or in other words lightly scattering surfaces, for which the amount of flux scattered away from the specular direction is minimal.³ The deformations we need to model are not small, resulting in 7-degree slope errors with a substantial amount of flux. However, we expect the distribution to appear as a “top hat”, with fairly uniform scatter over the maximum deformation angle and a sharp cutoff beyond it. This type of distribution can be modeled with a Harvey model. In the next section we discuss the basics of the Harvey model technique that we developed.

4. HARVEY METHOD OF INTEGRATING INJECTION-MOLD DEFORMATIONS

We noted from Fig. 5 that there was a ripple of random amplitude and frequency; therefore, we setup a periodic ripple structure within a CAD program to model the rebuilt surface. Figure 7 shows how the frequency and amplitude were defined. Note that the frequency is half the normal period. This definition was due to no requirement that an individual ripple had to pass through the nominal zero before another maximum or minimum was realized. This surface was then imported in an optical analysis package. The amplitude and frequency maxima were determined from the measurements described in Section 3. Figure 8 shows the intensity distribution results for four cases for the distribution of the ripple:

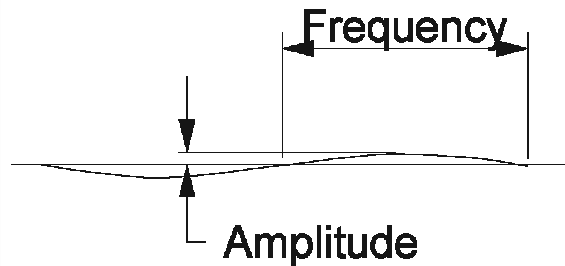


Figure 7. Definition of frequency and amplitude of a software-developed ripple model.

- (a) Fixed amplitude and frequency,
- (b) Fixed amplitude and variable frequency,
- (c) Variable amplitude and fixed frequency, and
- (d) Variable amplitude and frequency.

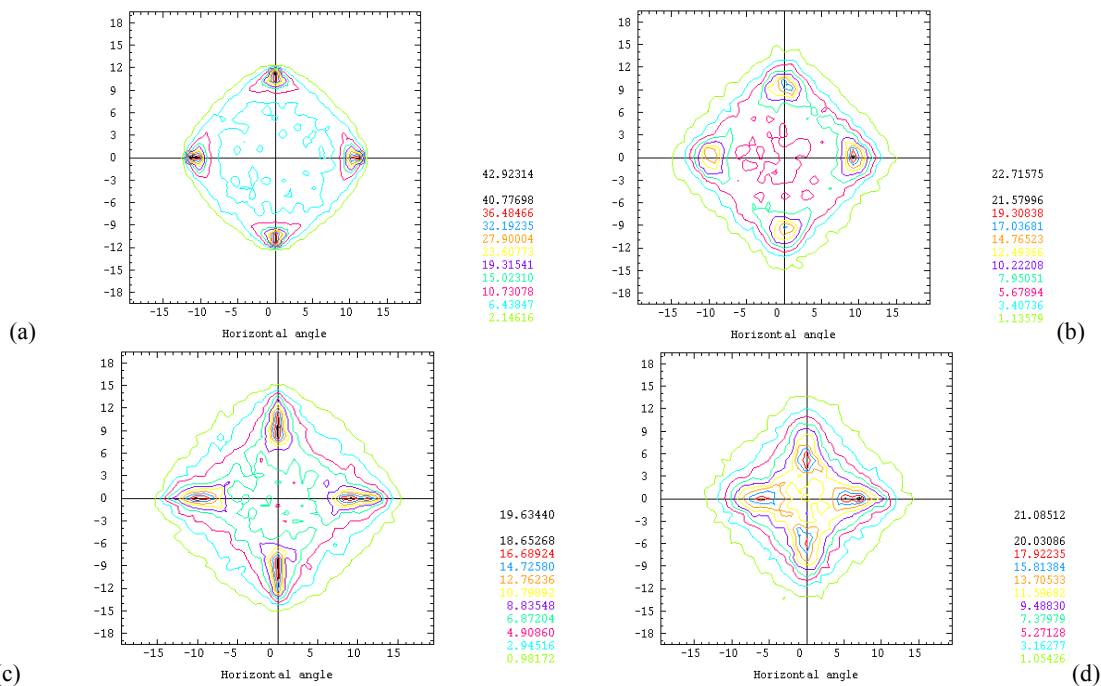


Figure 8. Intensity distributions from a collimated grid of rays for (a) fixed amplitude and frequency, (b) fixed amplitude and variable frequency, (c) variable amplitude and fixed frequency, and (d) variable amplitude and frequency.

Note that Fig. 8 shows a Cartesian symmetry that would not be evidenced in reality. This Cartesian symmetry was due to the selection of control points across the surface. It was later corrected by randomly selecting the control points within an allowed extent of the rippled surface. In order to correct Fig. 8 visually, one can think of the distributions in Fig. 8 as rotatable around the center of each plot and then normalized over the region subtended during the revolution. The results in Fig. 8 are for a collimated grid of rays incident on the nominally flat surfaces. The intensity distributions were saved, which allowed us to determine the amount that each ray was away from the specular direction. This result is directly analogous to scatter measurements.⁴ We applied these four types of ripple distributions for the example developed in Section 3. We quickly determined that the ripple has to be variable over both the frequency and amplitude ranges. Thus, the results shown in Fig. 8.d are used for the following studies.

Using Fig. 8.d we determined the Harvey scatter distribution. The results are shown in Fig. 9 for three maximum amplitude variations of the ripple. The maximum period was held at a value of 1.0 mm for each of these cases. In order to ensure that we properly sampled the perturbation space we compared five iterations for each case. The curves in Fig. 9 show that the five cases for each maximum amplitude follow the same general curve, especially where there is significant flux (i.e., to the left of the respective shoulders). Additionally, as expected there is a sharp cutoff beyond the shoulder point. There are 3 important parameters that define the Harvey model: shoulder parameter, l ; slope parameter, s ; and BSDF at 0 degrees, b_0 . These three parameters have the following relationships:

1. Shoulder parameter, l : increases by 0.028 for every additional 0.01 mm of amplitude error,
2. Slope parameter, s : is constant at -13 for all frequency and amplitude values, and
3. BSDF, b : follows the plot shown in Fig. 10. Note that b is related to b_0 by $b_0 = b(100I)^m$. b is the BSDF at 0.01 radians when there is a shoulder.

These three parameters are then assigned to the optical surfaces with a functional form of the Harvey method.

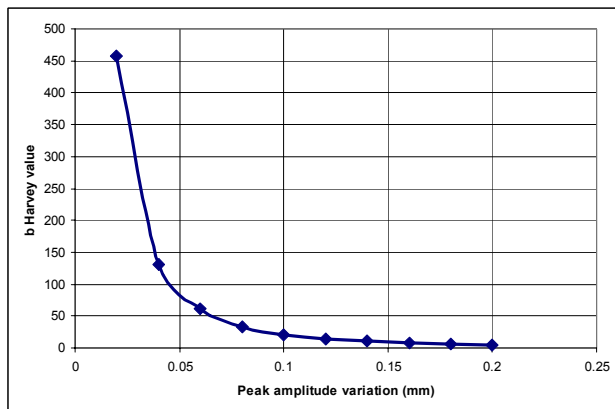
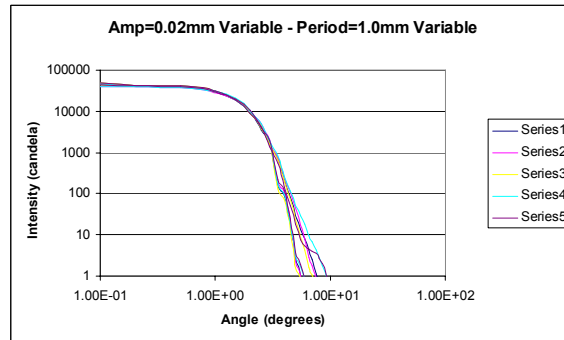
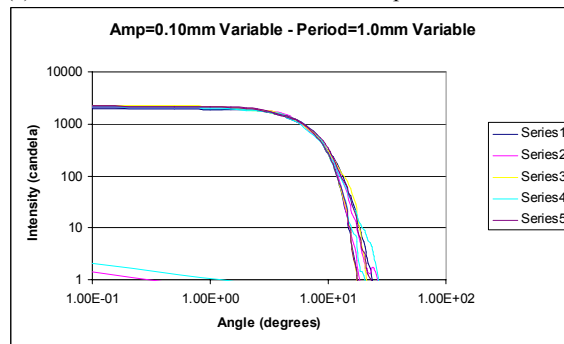


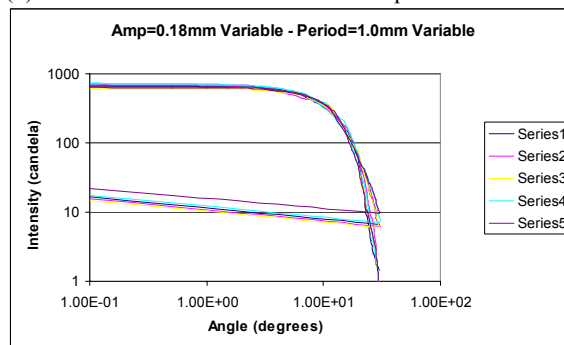
Figure 10. The BSDF at 0.01 radians parameter as a function of the maximum amplitude variation.



(a) Five runs for 0.02-mm maximum amplitude variation.



(b) Five runs for 0.10-mm maximum amplitude variation.



(c) Five runs for 0.18-mm maximum amplitude variation.

Figure 9. Scatter plots for three maximum amplitude variations, (a) 0.02 mm, (b) 0.10 mm, and (c) 0.18 mm. These curves are the results of five individual ray traces from a randomly built nominally flat surface.

Next the Harvey scatter method was compared to that of the randomly perturbed rebuilding method. Figure 11 shows the results for (a) a rebuilt surface and (b) a Harvey model approximation. In this case rays are incident on a reflective surface with peak amplitude variation of 0.06 mm and peak period variation of 1.0 mm. For the Harvey model: $s = -13$, $l = 0.168$, and $b = 60.93$. The intensity distributions are within a couple percent between the two cases (note that the axes are slightly different). This result indicates that the Harvey method can be used to approximate the deformations of an injection-molded surface. Ray tracing of Harvey surfaces rather than rebuilt surfaces saves nearly two orders of magnitude in time. In fact it only requires about 5% more time to calculate the Harvey surface perturbations rather than the nominal design surface reflections. This small increase in calculation time means that the designer can incorporate the deformations in all steps of the design process. Additionally, the designer can now allow the deformation amplitude parameter to vary in the tolerance modeling. The b and l parameters are then set dependent on the maximum amplitude value. With this method the designer can determine the tolerance of the illumination system to deformation.

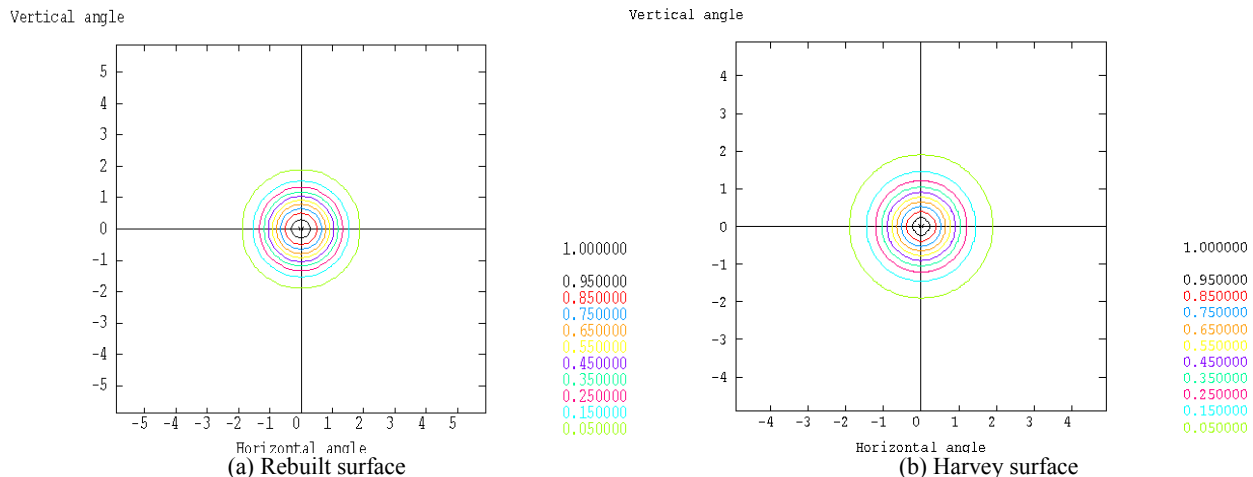


Figure 11. Intensity distributions for (a) rebuilt surface and (b) Harvey surface.

The results of Fig. 11 indicate that the Harvey method will work well for illumination systems; however, Fig. 11 only shows the results in the far field. Will it work in the near field? Collecting the light emitted from a transmissive surface for the rebuilt and Harvey surfaces investigated this uncertainty. Two million rays were traced for each case. Figure 12 shows the results for (a) a rebuilt surface and (b) a Harvey surface. Note that at 1.0 mm from the Harvey surface the irradiance distribution is uniform, while that of the rebuilt surface shows significant structure over the aperture. As the light is collected on a detector positioned further from the emission aperture, the two distributions tend to become more circular in nature, but the Harvey surface shows appreciable structure over a great distance. Only in the far field do the two distributions tend to the same profile. The reason behind this phenomenon is that the Harvey method randomly perturbs each ray when it is incident on the surface, thus two rays that strike the same exact position will see two different slopes. The rebuilt surface only perturbs the surface once thus two rays striking the same exact location on the surface will see the same slope. This result indicates the time-demanding rebuilding method must be used in the near field. An exception to this rule is for illumination structures that have several ray-surface interactions. For such systems (such as the lightpipe of Section 3), the multiple reflections will wash out the structure evidenced in the plots of Fig. 12. The more interactions the less dependence on localized surface deformation. Typically, in lightpipes one may use the approximate Harvey method (the example from Section 3 was within a couple percent of the rebuilding method).

5. CONCLUSIONS

We have explained the basics of how to tolerance an illumination system. Important parameters are determined during the design process. These important parameters are investigated with a parameter sensitivity analysis. A restricted list of important parameters is studied with a Monte Carlo analysis in order to determine the tolerance ranges for the important parameters. In order to include surface deformations, the designer should measure (i.e., laser scan) a witness sample from an injection-mold machine. One can now include the deformations by rebuilding the surface based upon the measurement or, better yet, if in the far field, apply a Harvey model that agrees with the scatter distribution.

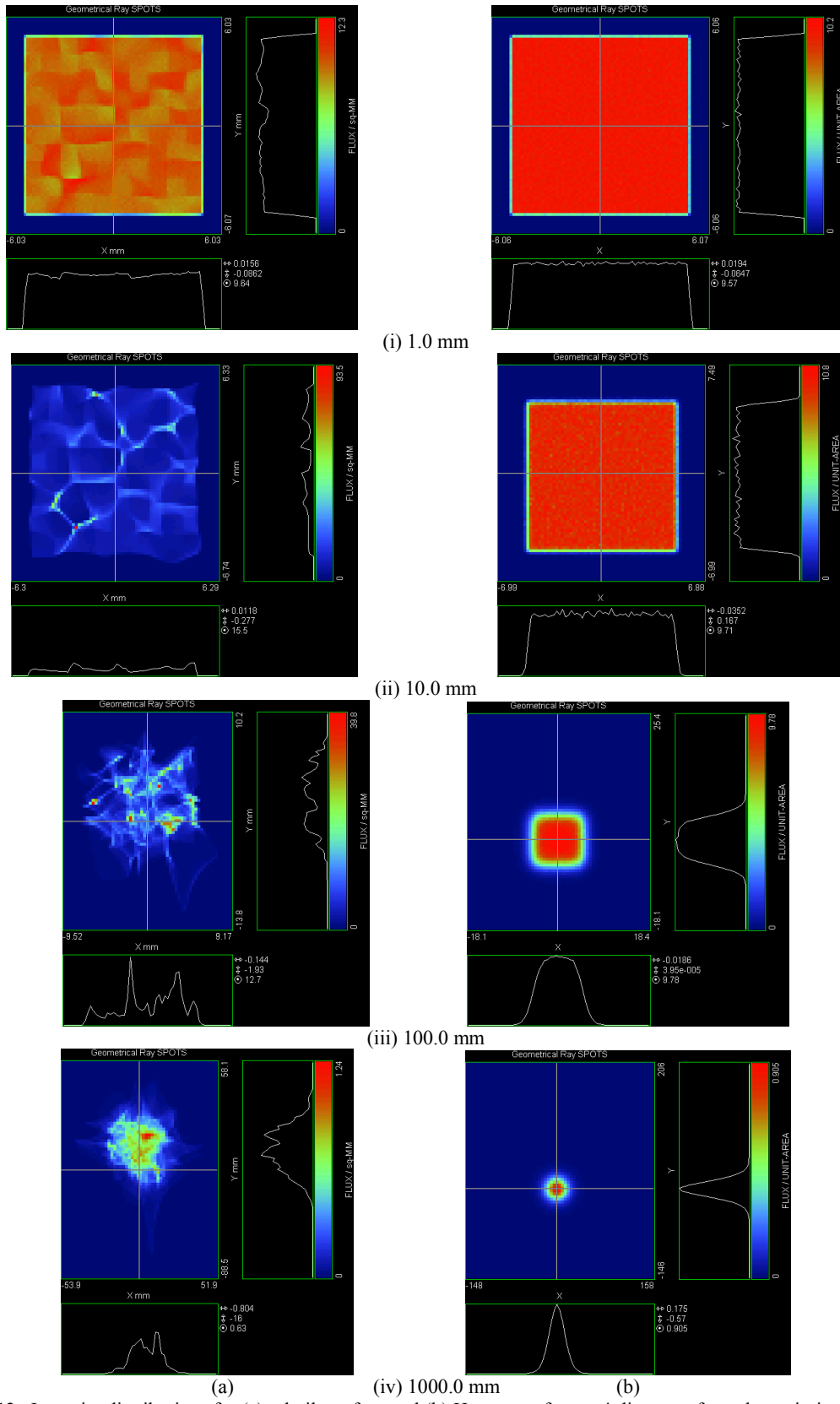


Figure 12. Intensity distributions for (a) rebuilt surface and (b) Harvey surface at 4 distances from the emission aperture.

This method provides an algorithm to include surface deformations arising from the injection-mold process (or, for that matter, any other fabrication technique). The possibility that a fabricated part does not meet performance metrics is greatly reduced; however, it does not reduce it completely to zero. There are still uncertainties due to the variation of the machinery from day to day and the fact that a witness sample was measured. Also, the geometry of the molding, especially during the annealing process, affects the shape of the ripples. This method does provide guidance and the building blocks in order to refine this tolerancing method. One can measure the deterministic ripple and then parameterize the Harvey terms or rebuilding terms within the design code such that its inclusion is automated. Additionally, the designer can determine the required quality of the injection-mold process before fabrication rather than an iterative investigation in the laboratory. All of these processes will save time in the time-consuming fabrication at the expense of a slight increase in design time.

Future refinements include the potential of including the physics of the rippling through analytic models based on finite element analysis, automated protocols between FEA and optical analysis codes, and a library of witness sample results for different machines, materials, and so forth. With these refinements, the designer will not have to be involved in the laborious task of setting up the deformation models since they can be controlled directly by software. It will allow the designer to spend all of his/her time doing the optical design rather than worrying about tolerance details.

REFERENCES

1. Advanced Systems Analysis Program (ASAP™) was used to generate the illumination distributions within this paper, Breault Research Organization, Inc., 6400 East Grant Road, Suite 350, Tucson, AZ, 85715; www.breault.com.
2. Laser Design, Inc. provided the laser scan discussed herein. They may be found at 9401 James Ave. S. – Suite 162, Minneapolis, MN USA 55431; www.laserdesign.com.
3. Harvey, J. E., *Light-scattering characteristics of optical surfaces*, Ph.D. Dissertation, Optical Sciences Center, University of Arizona (1976).
4. Stover, J. C., *Optical scattering measurement and analysis*, 2nd Ed., Society of Photo Optical 1995).