The Cost of Tolerancing

Jessica DeGroote Nelson,[a] Richard N. Youngworth,[b] David M. Aikens[c]
[a]*Optimax Systems Inc., 6367 Dean Parkway, Ontario, NY 14519 USA*
[b]*Light Capture Inc., 1006 15th St., Riviera Beach, FL 33404, U.S.A.*
[c]*Savvy Optics Corp., 35 Gilbert Hill Rd. Chester, CT 06412 USA*
[a]*jnelson@optimaxsi.com,* [b]*ryoungworth@lightcaptureinc.com and* [c]*daikens@savvyoptics.com*

ABSTRACT

The design and development of an optical system includes completing detailed drawings that specify allowable error limits, commonly referred to as tolerances. The process of deriving tolerances is iterative, requires attention in the nominal design process, must take into account adjustments in production (compensators), and is highly dependent on designer skill. The performance of the resulting as-built systems will clearly be dependent upon the specified tolerances. Additionally, while frequently overlooked, the cost of the lenses is also strongly dependent on the difference between the specified tolerances and the limits of the optics manufacturer, the coater, and the metrologist. In spite of this relationship, many drawing tolerances are not reviewed at all, and default values are frequently used. In this paper, methodologies for assessing design robustness and tolerancing optical systems are covered. Typical "default" tolerances are evaluated for effectiveness and cost. Finally, the paper has a case study that explicitly shows a design with different sets of tolerances and relative costs, along with associated expected performance.

Keywords: Optical tolerancing, optical design, optical fabrication, specification

1. INTRODUCTION

The development of optical systems is a multi-stage process that requires significant designer skill and communication to obtain the best desired results.[1] There are a number of commercially available tools to facilitate the process, but in the end designer skill, experience, and working closely with manufacturers play the most vital role. Designing optical systems for lowest cost and ease of manufacture can be very challenging, regardless of the application and end user, and remains a manual process.

In current design methodology, tolerancing effectively has two stages that often intermingle. The first stage, which is part of the design process, is the effort to determine the best on paper (or nominal) design form for manufacture. Typically, this involves looking at multiple design forms as solutions and even looking back at the requirements to see if there is possible relief in the specifications. Fortunately, computing methods to help guide designs to desensitized forms are becoming more pervasive.[2-8]

The second stage is the assignment of tolerances to the system, and the corresponding analysis and verification that ensues. The primary optical analysis task in this key development step is to determine what errors are allowable in the optical system for production, regardless of volume. The design of parameters to tolerance and compensating adjustment rapidly becomes multidimensional, and the relationship of these parameters with cost can be difficult to obtain. Computing power, improved optimization methods, and design of experiments can all be used to lessen the impact of the challenges associated with a high number of dimensions. There are multiple analysis tools and methods[9-12] that have been used in this stage of the design. In spite of the recent improvements in computing, with the exception of more use of Monte Carlo simulations[13], the fundamental methodology many designers use has remained largely unchanged for the past few decades. In particular, optimization has been grossly underutilized in the assignment of tolerances. The challenge of determining relative cost versus parameter tolerances can be mitigated by designer or company experience (implicitly achieved currently), heritage with suppliers, and partnership with a supply base.

The goal of this paper is to show the importance of tolerancing; we specifically discuss how cost is intrinsic to an optimal tolerance assignment process. In Section 2 background material is given for tolerancing lenses including a review of specification and metrics used in tolerancing, a description of how tolerancing links the on-paper design to hardware (including high level descriptions of tolerance assignment methodology), and a discussion on how tolerances are a cost driver. In Section 3, we use an example lens to show the impact of different tolerances on both performance and cost, including a "traditional" tolerance assignment and some discrete cost-based tolerancing runs. Section 4 contains concluding remarks.

2. BACKGROUND FOR OPTICAL TOLERANCING

2.1 System specifications and metrics

Modern optical design is done almost exclusively using the capabilities of commercially available software (with user-modifications as needed). The majority of these programs have been built around the core concept of utilizing optimization with scalar figures of merit[14, 15] although there are noted exceptions.[16, 17] However, most systems have a number of different critical functional requirements that need to be satisfied. Examples of common metrics for performance of imaging systems include spot size or wave-front error (normally taken as a scalar field-averaged quantity[18, 19]), the effective focal length, back focal length (or flange focus), modulation transfer function, veiling glare and stray light, and packaging constraints. Some of these metrics can be assessed in sequential optical design codes and others require a rigorous approach to stray light, beam propagation or radiometry.

There are two primary ways that designers handle multiple requirements in tolerancing. The first is to create an array that takes the square root of the sum of the squares (rss) of the metrics of interest. For example, the rms spot size averaged over the field-of-view may be combined with the change in effective focal length from a target value in such a scalar quantity. The advantage of this approach is that the entire tolerancing job may be done in one set of analyses. The second method is to treat each key metric separately in tolerancing and analysis. The advantage of this approach is that this is a more rigorous means of ensuring requirements are met. However, this approach takes more time and requires extra diligence to correlate results and determine the best set of tolerances.

In the example presented in Section 3, explicit analysis will be done for a diffraction-limited lens using field-averaged rms wave-front error as a metric. The analysis will be done with back focus as a compensation variable to mitigate the effect of errors. Using back focus as an adjustment in fabrication is very common and greatly helps to mitigate the effects of rotationally-symmetric errors in lenses. We have chosen not to include other types of metrics and adjustments for the sake of simplicity. Furthermore, we have not determined a specific optomechanical design for mounting the lenses, and have bypassed other types of optomechanical adjustments (usually determined by assessing what sensitive parameters can be adjusted most readily).

2.2 Tolerancing as the link from paper to hardware

In optical system design, the optical layout is usually developed first, after system requirements are specified. It is then common to consider multiple design forms and work closely with a mechanical engineering team while discussing fabrication issues with suppliers. The design team normally works concurrently to assess the best ways to mount elements, fabricate components, assemble the system, and perform required tests for elements and the system. There are a large variety of applications and have many variants depending on precision, application, and volume. Regardless, this type of iterative process can be quite challenging and is a true engineering exercise of balancing constraints in almost all cases. The goal is to determine the most robust design that also fits the budget or business case.

Tolerances ultimately are the bridge that ties idealized "perfect" values of the design parameters to a realistic as-built system (or set of systems) with errors. The general tolerance assignment problem is shown schematically in Figure 1. Construction parameters have random values that are bound by tolerances and they combine, depending on the parameters' functional relationship with the scalar figure of merit, to form an overall probability distribution for performance. In low volume systems this estimates the probability of success; for high volume systems, this relates to the yield.[20] Additionally, there is cost associated with holding the tolerances to given values. Tightening tolerances almost always increases expense and adds potential production difficulty. In addition to determining allowable errors, it is common in development to determine what measurements and adjustments can be made in production or by the user of the system. These adjustments need to be properly designed into the production build for the system, along with appropriate ranges and resolution. Such parameter design is an area where optical designers have often excelled by providing adjustment to relieve extremely tight tolerance requirements germane to the precision many optical systems require.

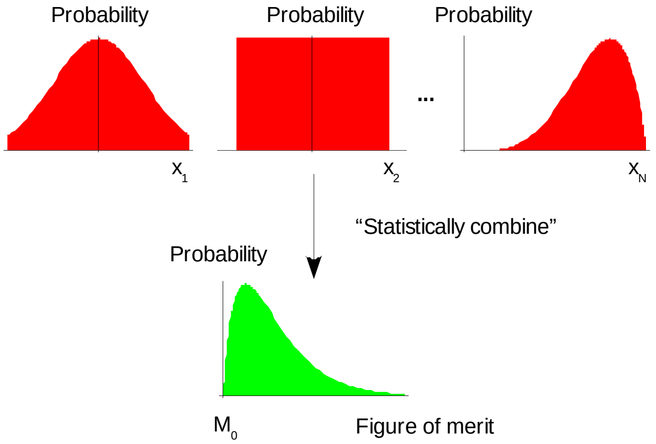

Figure 1: The scalar figure of merit for as-built systems is intrinsically statistical in nature. It depends on the toleranced parameters' (x_1, …, x_N) probability density functions, the magnitude of the tolerances, and the functional relationship between those variables and the figure of merit. M_0 is figure-of-merit value of the nominal design.

Since roughly the 1960's the traditional means for a first-pass at assigning tolerances in optical design is based on the assumption that the conditions of the Central Limit Theorem[21] are sufficiently satisfied to allow the root-sum-squaring (rss) of the effects of errors.[9] This is a reasonable approach for a first-order tolerance assignment, albeit on the pessimistic side. Nonetheless, without such an approximation most systems would be prohibitively expensive or have impossibly tight tolerances. Initial tolerances can be set using the rss approach with inverse sensitivity, experimentation, or experience. Refinement is achieved by looking at the sensitivity (and inverse sensitivity) of the design to errors and manually adjusting tolerances to limit the impact of sensitive parameters. The effects of multiple errors and statistics can be verified with Monte Carlo analyses. This entire process is typically repeated until the set of tolerances is suitable. Note that any incorporation of cost and manufacturing expertise is dependent entirely on the designer making the appropriate assessments and working very hard to ensure that assumptions being used in tolerance assignment match reality. In effect, the traditional means of assigning tolerances is highly skill- and experience-based, requiring iteration in analysis with some trial and error. The design community has effectively learned in many cases to engineer around the loose tie between design and manufacturing often with only an intuitive approach to cost.

As a final note, considering the importance of tolerances on both cost and performance, it is surprising to consider that the fundamental methods for assigning tolerances are only recently starting to take full advantage of available computing power. The reasons for the slow development likely lie in the fact that obtaining data to effectively assign tolerances by building cost explicitly into the assignment is challenging and can take significant work. Almost all data on cost is highly process- and supplier-dependent and obtaining reliable and current data on cost, beyond some rough guidelines relating such quantities that may not always apply,[22-28] requires building a database or forming a close relationship with manufacturers. Information on detailed costs is clearly very important to suppliers and most consider such information as trade secret. The difficulty in getting such information has made implementation of methods and tools, such as integrated design and cost-based tolerancing,[12, 29-31] develop more slowly than commercially available tools for other design tasks. We believe this problem is not as intractable as it first may appear when working closely with manufacturers, and we discuss a discrete optimization case in Section 3.6 to indicate the value utilizing computer-based methods help find solutions.

2.3 Tolerances and the optical shop – design considerations

Placing an exact price tag on an optic is like trying to hit a moving target, or even like hitting multiple moving targets simultaneously. In addition to continually evolving optics fabrication practices and novel materials emerging into the market, each optical fabrication shop has its unique strengths and weaknesses and as mentioned earlier, its own cost model. In general, when a tighter tolerance is placed on an optic or when an optic is more difficult for an optician to fabricate, the price of the optic will increase. The relationship between tolerances and cost is typically not linear and is unique for each tolerance. Many specifications are dependent on each other and subjective to the individual optics shop, making a universal optical component cost model anything but an exact science. The following are a few basic guidelines to help minimize fabrication costs of custom spherical glass optics.

One way to reduce material cost is to choose an optical material with a high melt frequency or a material off your vendors preferred glass list. This choice helps keep the bulk material cost to a minimum. The quality and certification of the material also influences the cost (e.g. refractive index, striae, birefringence, etc.) and lead time. In addition, most optical shops include a "difficulty level" of a material to be fabricated into their cost model. This difficulty level can have a huge effect on cost and it is uniquely defined by each individual shop. It is usually based on the mechanical, chemical and thermal characteristics of the material as well as the shop's capabilities and experience. Having open communication with your vendor helps to reduce costs, especially if there is flexibility in your system design regarding material choice.

Once the material has been chosen, there are many other specifications to consider. From the fabricators' point of view, it is easier to fabricate the component if there is sufficient difference between the clear aperture and the diameter of the optic. This also applies to the coating process, where the coating vendor usually utilizes this area outside the clear aperture to hold onto the optic during the coating process. A good guideline to follow is allowing the clear aperture to be less than 90% of the full aperture (or minimum of 2mm).

The cost impact of center thickness tolerance is tied very closely with material type, irregularity and cosmetics. If a very soft material is chosen, a tight center thickness tolerance is more difficult to achieve because the potential to polish through the center thickness tolerance is much higher as material is removed quickly. Tight irregularity and cosmetic specifications (such as scratch-dig) play a role in the center thickness specification because an optician continues to polish an optic until these requirements have been satisfied. Such reworking of the optic clearly may cause the part to become too thin.

The radius tolerance can be specified as either a power tolerance relative to the nominal reference surface (test plate) or a linear radius tolerance (laser interferometry or spherometer). One thing to keep in mind when placing a power tolerance on a surface is that tighter power tolerances are more difficult for smaller f-number surfaces.[32]

Other items to be cognizant of during the design phase are aspect ratio, thin edges and bevels. High aspect ratio (diameter to center thickness ratio) optics are prone to distortion due to thermal and mechanical stress, which will make the optic more difficult to manufacture and increase the cost. Thin edges (<2 mm) should also be avoided when possible. If an optic has a very thin edge, it raises the risk of scratches from edge debris and a thin edge makes it difficult for the optician to place a bevel on the edge. Bevels are a great way to minimize risk for edge chips forming during handling.

Two parameters that do not usually affect system performance and yet can drive up element cost unnecessarily are surface quality and texture. Surface quality, such as scratch-dig specifications using the MIL-PRF-13830B standard, and surface texture specifications such as rms surface roughness for scale-lengths shorter than 80 microns, are again dependent on the material. Softer glasses are much more prone to scratches and digs compared to their harder counterparts. Optical shops currently suggest a 60-40 scratch-dig specification for precision visible optics, which is a good general guideline. When placing tolerances on scratch-dig, Plummer[22] reminds us that "optics are made to look through, not at". Surface quality can at times conflict with surface irregularity requirements depending on the material and fabrication method. When specifying surface roughness, you should also include the measurement method and spatial bandwidth to be measured, although increasingly optical shops use a default of an 80-micron high-pass filter setting if it is not specified.

When considering the wedge or tilt tolerance of the optical component, be sure to also consider how the optic is mounted in its final housing. Centering tolerances need to be considered on a lens-by-lens basis and lens elements with longer focal lengths need to be controlled more tightly. As indicated later in Table 1, the optomechanical tolerances (tilt, decenter and axial spacing) are typically greater than the optical component tolerances. Whenever possible for production systems, designing element and mechanical symmetry helps reduce manufacturing costs.

3. CASE STUDY: DIFFRACTION LIMITED DOUBLE GAUSS LENS

3.1 Design and description of lens

A specific lens was developed to use as a case study in order to demonstrate the principles of proper cost-based tolerancing and to see the performance and cost impact of using default tolerances. A schematic of this lens, based on a fairly traditional double Gauss form, is shown in Figure 2.

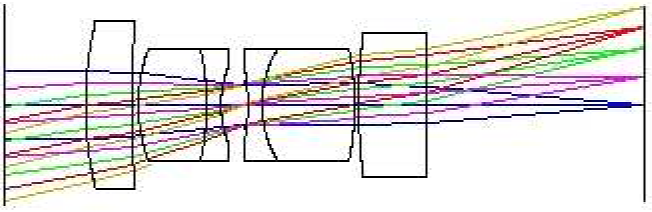

Figure 2: Schematic of the case study lens, an f/6 diffraction-limited double Gauss lens.

The design is a flat field, low distortion 100mm EFL f/6 lens with an unvignetted field of view of 27 degrees. The design residual aberrations, before tolerancing, are below the diffraction limit for the modest design spectrum of 540 nm to 680 nm over the entire field of view. The average polychromatic RMS wavefront error is 38 nm, or about 0.06 waves RMS at 610nm. This level of design residual performance might be typical for an as-built requirement of 0.1 waves RMS.

This lens design has not been optimized for any particular application; indeed it is not really even a completed optical design. Still it serves the purpose of a springboard to show the impact of various default tolerances on system performance.

3.2 Defining the tolerances for the case study

In this case study, the lens described above was toleranced in a series of five campaigns, based on fairly typical tolerance values. Specifically, tolerances for errors in surface power and irregularity, center thicknesses and wedge, mean material refractive index and dispersion (or V-number), airspace and axial spacing, element tilt, and element decenter. These are the primary manufacturing errors which are calculated using computer-based tolerancing in most lens designs. For simplicity, no error terms were generated for radius of curvature (aside from the power term), face-flat decenter, inhomogeneity, or for barrel tilts and group decenters, aside from the simple tilts and decenters of each element individually.

The subject cases are shown in Table 1 and described in more detail below. The as-toleranced lens performance was evaluated using a 100 system Monte Carlo simulation analysis assuming a uniform distribution of errors within the corresponding range of tolerances. For comparison, the mean expected value and standard deviation of the average RMS wavefront error over the field of view was calculated.

				Optimax Tolerancing Chart www.optimaxsi.com		
Tolerance	**Definition/Units**	**Representative Lens Design Defaults**	**ISO (30-100mm parts)**	**Commercial**	**Precision**	**Practical Limit**
Component – Surface						
Surface Power	sag in microns	**1.30**	**2.73**	**1.580**	**0.950**	**0.317**
Surface Form	sag in microns	**0.30**	**0.55**	**0.633**	**0.158**	**0.063**
Surface Texture, Rq	in nm, (80 micron highpass)	**0.00**	**0.00**	**5.000**	**2.000**	**0.200**
Scratch/Dig	per MIL-PRF-13830B	**0**	**5/5x0.4**	**80 - 50**	**60 - 40**	**10 - 5**
Component – Compound						
Center Thickness	mm	**0.20**	***0.40***	**0.150**	**0.050**	**0.025**
Wedge	ETD in mm	**0.21**	***0.44***	**0.050**	**0.010**	**0.002**
Material						
Mean Index	error in average index, %	**0.0008**	**0.0010**	**0.0010**	**0.0005**	**0.0002**
V-Number	error in abbe V number, %	**0.90%**	**0.90%**	**0.80%**	**0.50%**	**0.30%**

Table 1: Default tolerances run as a series of cases on the f/6 double Gauss (italicized values are estimated).

Modern optical design codes all offer tools for facilitation of both tolerancing and drawing generation. These tools provide default values for tolerances, when no value has been entered by the designer. These defaults vary by design code, but are for the most part very loose tolerances at best. Most lens designers over-write these values with default values which reflect their experience or the class of designs they tend to develop. Occasionally, however, the lens design code defaults will make it all the way to the production drawing.

The authors surveyed several of the optical design codes and created a representative set of design defaults. These are shown in Table 1, under the heading "Representative Lens Design Defaults", or "Defaults".

Another source of default tolerances is ISO 10110-11, the international drawing standard for optics. In that standard, specific values are given as defaults, in the event that nothing is specified on the drawing. These values are shown in Table 1 under the heading "ISO".

A third source of default tolerances is from optical design literature.[28] Over time, the estimations for default tolerances for commercial grade, precision grade, and "as good as it gets" have evolved as the industry has matured. In addition, these estimations have converged; all current references checked by the authors now refer to the Optimax Tolerancing Chart found on the internet, which is maintained by Optimax Systems Inc.[33] The final three cases were based on these commercial, precision and manufacturing limit tolerances.

In addition to the terms controlled with computer generated tolerancing, there are other key manufacturing errors which are frequently specified on optical drawings. The most prominent of these quantities are surface quality and surface roughness. Unless there is a compelling reason to the contrary, these errors should be toleranced as indicated in Table 1 under "commercial" tolerances, as they have little or no impact on the performance of most optical systems.

3.3 Case study runs

Each of the five cases were created in a commercial optical design code using a fairly typical tolerance table approach. Since there is no mechanical design, all element tilts were about the front vertex, and all outside surfaces were tilted for wedge. Care was taken to make certain the actual range of possible values show in Table 1 was properly reflected in the tolerance values. This is especially important in the case of element wedge, element tilt and element decenter, each of which were entered as Cartesian limits when in actuality they will be toleranced on the drawing in polar coordinates. In these cases, the values entered were de-rated by the square root of two.

The as-toleranced lens performance was evaluated using a 100 system Monte Carlo analysis assuming a uniform distribution of errors within the various range of tolerances, and the results summarized in table 2. Design residual indicates the ideal system RMS wavefront error. Mean of 100 systems shows the expected performance based on a randomly generated ensemble of 100 systems from the tolerance errors given. The standard deviation for these 100 systems indicates the system-to-system variability of performance. The probability values provided (i.e. cumulative probability) indicate the probability any random system will meet the RMS wavefront error indicated.

	Case 1 **Defaults**	Case 2 **ISO**	Case 3 **Commercial**	Case 4 **Precision**	Case 5 **"limit"**
Design residual	0.059	0.059	0.059	0.059	0.059
mean of 100 systems	0.418	1.064	0.354	0.116	0.064
standard deviation	0.183	0.495	0.156	0.043	0.004
90% probability	0.661	1.766	0.582	0.171	0.069
80% probability	0.564	1.471	0.468	0.143	0.067
50% probability	0.401	0.947	0.346	0.106	0.063

Table 2: Results of case study runs. All values are RMS wave-front error averaged over the field of view, in waves at 610nm.

Clearly it is not a good idea to use the design code defaults or the ISO defaults for a diffraction-limited lens design. The expected performance is 0.4 waves RMS and 1.1 waves RMS, respectively, in spite of only 0.06 waves RMS design residual. Indeed, for a six element, diffraction-limited design, the commercial case makes little sense as well. If the performance indicated were allowable, a less expensive lens could be designed using perhaps two doublets. Even the precision case, while the mean system performance of 0.116 waves may be acceptable, the standard deviation is large enough that wide performance variability could be expected. Only the “limit” case, with all its anticipated additional cost, yields results typical to a diffraction-limited lens design requirement. In this case, we can expect every lens to be significantly better than 0.1 waves RMS. Specifying lenses at the manufacturing limit, however, results in extremely high costs.

In summary, none of the cases based on conventional lens design defaults, drawing defaults or industry defaults, show a proper trade-off between cost and performance that is readily achievable in lens design today.

3.4 Traditional tolerance run

Presuming our objective is to achieve 0.1 wave RMS as-built performance with 90% certainty, a refining of the first-pass sensitivity analysis can be performed. Since the “precision” defaults are close, we start with this set of tolerances, refining it to loosen tolerances that are not influencing the performance while tightening the parameters that stand out as “tall poles” or “worst offenders”. In practice, this level of refinement would also come with a modification of the tolerance set to reflect the actual mechanical design and alignment methodology. We would also usually look for additional cost-saving adjustments or compensators that would be routinely performed in the factory but are not reflected in the tolerance budget. Since this is an exercise, we leave all that alone and focus only on the values as currently defined.

To conduct this analysis we consider the sensitivity of the average rms wave-front error to changes in each parameter, which is the result of our selected first-pass tolerance run. The worst offenders on the precision tolerancing case are the x and y element tilts of the front lens and the two doublets, each contributing (in an rss sense) changes on the order of the design residual. These parameters are clearly good candidates for tightening. Dropping these tolerances to the practical limit makes a significant impact on the performance statistics. Having tighter tolerances on these parameters requires more precise mechanical design and alignment that increases the cost of the assembly.

In order to offset these costs, we look through the sensitivity tables for tolerances that can be opened up to allow more manufacturing freedom. Here again consider the sensitivity tables, looking for tolerances with an rms wave-front change of less than 0.0001 for parameter changes greater or less than the design value. Since the rss addition responds to the square of these contributions, we can reasonably expect that loosening these parameters will not impact system performance. Such a review identifies 10 tolerances with more than an order of magnitude of headroom: power on surfaces 2, 4, 8, 10 and 11; irregularity on surfaces 4 and 8; the stop position: and the index and thickness of the last lens. These can all be brought up to commercial grade without a performance penalty. The results of this custom tolerance

Monte-Carlo are shown as Case 6 in Table 3. The system is extremely good, with the mean of systems having diffraction-limited performance and 90% of systems better than 0.08 waves RMS.

	Case 6 **Custom 1**	Case 7 **Custom 2**
Design residual	0.059	0.059
mean of 100 systems	0.071	0.075
standard deviation	0.007	0.009
90% probability	0.079	0.089
80% probability	0.076	0.084
50% probability	0.070	0.073

Table 3. Results of custom tolerance runs. All values are RMS wavefront error averaged over the field of view, in waves at 610nm. Case 6 is based on the Precision tolerance case, but with tilts tightened. Case 7 is based on tolerances shown in Table 4.

We could stop here; the as-toleranced performance will meet our design criteria better than 90% of the time. A second pass, however, will help to reduce costs even further. The next step is to tune in the individual tolerances to capitalize on the remaining performance headroom. We know that the tilts are sensitive and cannot be loosened significantly, but there are many other tolerances not driving system performance that can be loosened. Setting as a threshold a change contribution of 0.001 to the RMS wave-front error or less, there are 34 tolerances eligible to be loosened; all the remaining power and irregularity tolerances, wedge on the first and last elements, thicknesses and separations of all but the first doublet, the dispersion of the last two lenses and all the indices. Loosening these to a contribution of 0.002 to the RMS wave-front error (or the commercial limit, if it results in a lower contribution,) results in the tolerances shown in Table 4. The expected performance is shown as Case 7 in Table 3.

Tolerance	**Units**	**Custom Tolerance Results**
Component – Surface		
Surface Power	sag in microns	**1.580**
Surface Form, sfc 1, 3	sag in microns	**0.318**
Surface Form, all other sfcs	sag in microns	**0.633**
Component – Compound		
Center Thickness, lens 2,3	mm	**0.050**
Center Thickness, all other	mm	**0.130**
Wedge, lens 1, 6	TIR in mm	**0.020**
Wedge, all other	TIR in mm	**0.010**
Material		
Mean Index	absolute	**0.001**
V-Number, lens 5, 6	in%	**0.80%**
V-Number, all other	in%	**0.50%**
Optomechanical		
Axial Spacing, first doublet	mm	**0.100**
Axial Spacing, second doublet	mm	**0.050**
Axial Spacing, all other	mm	**0.130**
Element tilt, lens 6	degrees	**0.182**
Element tilt, all other	degrees	**0.037**
Element decenter	mm	**0.051**

Table 4. Custom tolerance values, used in Case 7.

In this last case, we have a mix of tolerances for the various lens parameters that are the subject of this paper. While the tilts of many of the elements are controlled extremely well, most of the other lens parameters are actually at the commercial grade. An analysis of a six element lens to this level of tolerance can be completed easily in an afternoon.

3.5 Cost functions for the lens example

For the purposes of this paper, the price of an optic is referred to as the relative cost. The relative cost is normalized to a base cost[26] of producing an optic (base cost associated with generating, grinding, polishing and centering a generic optical glass). These relative costs refer to spherical glass optics (f/1 or slower) 30-100mm in diameter, they do not take into account the material cost or individual shop dependent costs. The relative costs and guidelines given in this paper are not to be considered the rule, but rather suggestions to assist in producing the most cost effective solution.

The basis for these cost functions came from previous work on this topic,[22, 23, 26] but have been updated to be a more accurate indicator of today's optical manufacturing capabilities. Cost functions have been updated for power, irregularity, surface roughness, cosmetics (scratch-dig), center thickness, wedge and material index and Abbe number along with the optomechanical properties, axial spacing, element tilt and decenter. For this example the cost functions are calculated independent of each other and do not include the inter-dependent relationships mentioned in Section 2. Hence component costs are multiplied and all optomechanical costs are summed; the component and optomechanical costs are then added to compute the total relative cost. Table 5 lists the equations for the relative cost factors used for this paper.

Tolerance	Units	Relative Cost Factor
Component – Surface		
Power	um	1.2 x (Power)$^{-0.4}$
Irregularity	um	(Irregularity)$^{-0.2}$
Surface Roughness, Rq	nm (80 um highpass filter)	1.4 x (Surface Roughness)$^{-0.2}$
Scratch/Dig	per MIL-PRF-13830B	2 x [((Scratch)/10)+((Dig)/5)]$^{-0.2}$
Component – Lens		
Center Thickness	mm	0.6 x (Center Thickness)$^{-0.3}$
Wedge	ETD in mm	0.6 x (Wedge)$^{-0.2}$
Material		
Mean Index	error in average index, %	0.06 x (Index)$^{-0.4}$
Abbe Number	error in abbe number, %	0.04 x (Abbe Number)$^{-0.7}$
Opto-mechanical		
Axial Spacing	mm	0.6 x (Axial Spacing)$^{-0.3}$
Element tilt	degrees tilt with respect to axis	(Element Tilt)$^{-0.2}$
Element decenter	mm decenter from optical axis	0.6 x (Element Decenter)$^{-0.3}$

Table 5: Updated relative cost functions used in this paper for power, irregularity, surface roughness, scratch-dig, center thickness, wedge, material index and Abbe number along with the optomechanical specifications for axial spacing, element tilt and decenter.

3.6 The role of cost and actively balancing it with performance

At this juncture, we have a system with tolerances that have been assigned explicitly utilizing yield (hence performance) as a driving metric. Granted that a well-done job of tolerancing shown in Section 3.4 can lead to a successful production run, we really do not know if this is the optimal balance of tolerances for both performance and cost. In order to gain such knowledge, we can assess the traditional toleranced solution in light of cost as discussed in Section 3.5.

The cost of the traditional tolerance solution, Case 7 from Section 3.4, is 35.44. In order to fully grasp the value in tolerancing a system properly, consider the plot of mean performance for the different cases investigated thus far, as shown in Figure 3. Clearly, the system cost and performance have been indirectly balanced by the traditional tolerancing process. Even seeing the improvement in Case 7 provides for cost with good performance, we can now ask if this is the best possible solution by looking more deeply at the cost drivers and then consider a scenario to cut cost and preserve performance.

The cost drivers are the tightened tolerances (relative to commercial quality) in the following order of importance (with cost factors in parentheses): element tilt for singlet 1 and both doublets (1.94), V-Number for lenses 1-4 (1.632), wedge for elements in the doublets (1.507), the center thicknesses in doublet 1 (1.474), decenter of all elements (1.465), element tilt for the last singlet (1.406), and wedge for the singlets (1.312). The remaining costs are all less significant which comes as no surprise since these are less sensitive elements with loose tolerances, many at the commercial quality level. Noting these drivers is important when attempting to cut cost or improve performance without unacceptable expense.

We now consider an effort to cut over 8% of the cost of the lens Case 7 solution while losing no more than 1% in the statistical mean performance. While there are many variables that may be loosened to reduce cost, it makes the most sense to reduce parameters that incur the most cost – even though they are more sensitive than less expensive parameters (as discussed in Section 3.4). Two cases of tightening sets of parameters are investigated. The first is loosening the tilt tolerances by a factor of 2 on the first singlet and both doublets. This loosening reduces cost by 2.1% but degrades the mean performance by 1.7%. The second case is to make all of the V-number tolerances 0.8%, which reduces cost by 10.5% but degrades the performance by 3.3%. Clearly, the latter case is quite promising on cost, but it violates the 1% performance increase criterion. To mitigate the performance hit caused by loosening V-number, the wedge tolerances assigned to the singlets are both tightened by a factor of 2. Combining the V-number loosening with the singlet wedge tightening balances the cost and performance considerations, resulting in a 9% cost reduction with only a 1% increase in the mean performance. This last case is plotted as Case 8 in Figure 3, and provides superior cost advantages with only a small increase in mean performance.

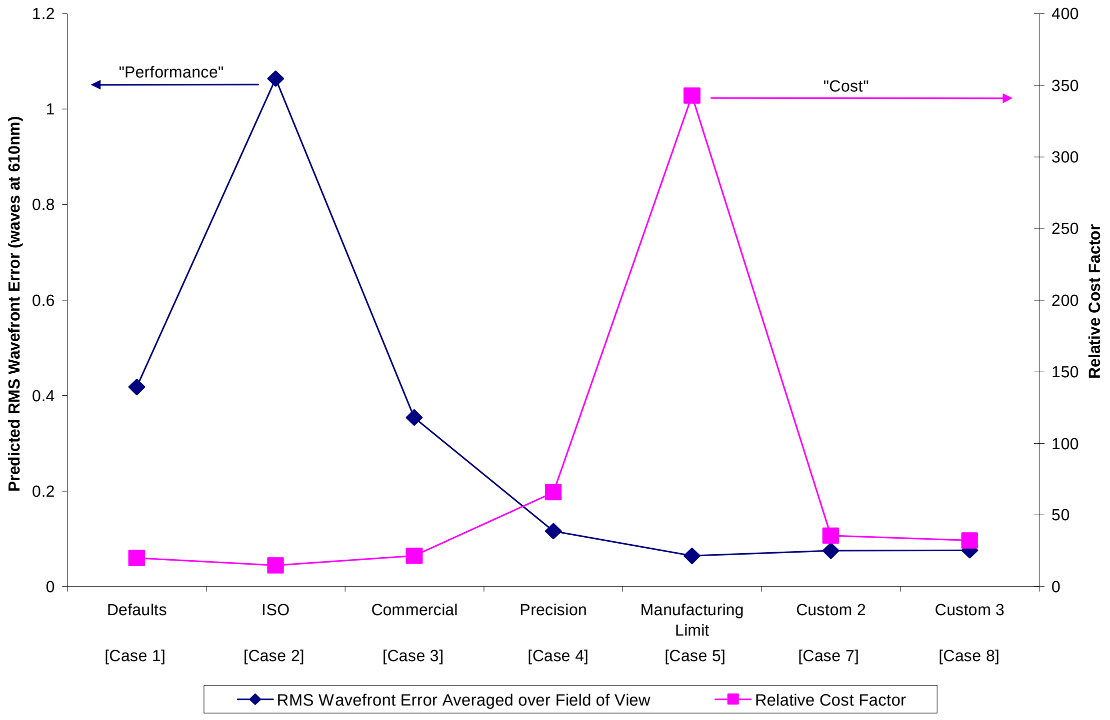

Figure 3: Plots of the mean performance and example cases described in the text.

One can envision a more formal assessment of sensitivity including cost or even utilizing computing power to do cost-based tolerancing, because we have the majority of key information required to employ such methods. Clearly in medium and high volume applications, such an optimized tolerance campaign would be warranted. Such efforts can also actively incorporate more detailed statistical distribution information as well. In this study we have assumed a uniform distribution of probability; but other distributions (e.g. Gaussian) may be more likely. The selection of this statistical property does impact the results, especially near the tail of the performance probability distribution curve. It is fair to say that finding the best solution for performance and cost with manual calculations is quite challenging, and proper incorporation of the cost of tolerancing can rapidly become quite difficult to manage. Developing methods that explicitly attempt to balance cost and yield (or performance) are a natural and very likely beneficial exercise for further consideration.

4. CONCLUSION

Optical tolerancing remains a crucial link between an on-paper design and production-build prints and systems. In this paper, we have shown that tolerancing significantly influences both performance and cost. Default and reference tolerances can serve as a reasonably good guideline to tolerance lenses in a practical manner, but must always be assessed based on the specific design, system requirements, and manufacturer processes. By working closely with suppliers, a design that fits both the requirements and manufacturing processes may be obtained. Corresponding analysis can include the effects of cost as well as performance in such a scenario. Moreover, the benefits of doing analysis and assessing cost can lead to many opportunities to cut cost with manual analyses or even cost-based tolerancing and optimization. Such opportunities that take full advantage of computing power lead directly to increased success and competitiveness for all parties involved.

REFERENCES

1. R. N. Youngworth, "The continual evolution of tolerance assignment in optics," (2009).
2. D. S. Grey, "Tolerance sensitivity and optimization," Applied Optics **9**, *3*, 523-526 (1970).
3. D. S. Grey, "The inclusion of tolerance sensitivities in the figure of merit for lens optimization," (SPIE, 1978), pp. 63-65.
4. M. Jeffs, "Reduced manufacturing sensitivity in multi-element lens systems," (SPIE, 2002), pp. 104-113.
5. M. Isshiki, L. Gardner, and G. G. Gregory, "Automated control of manufacturing sensitivity during optimization," (SPIE, 2004), pp. 343-352.
6. M. Isshiki, D. C. Sinclair, and S. Kaneko, "Lens design: Global optimization of both performance and tolerance sensitivity," (SPIE, 2006), p. 63420N.
7. J. Rogers, "Using Global Synthesis to find tolerance-insensitive design forms," (SPIE, 2006), p. 63420M.
8. J. P. McGuire Jr., "Designing easily manufactured lenses using the global method," (SPIE, 2006), p. 63420O.
9. W. J. Smith, "Fundamentals of the optical tolerance budget," (SPIE, 1990), pp. 474-481.
10. S. Magarill, "Optomechanical sensitivity and tolerancing," (SPIE, 1999), pp. 220-228.
11. G. Adams, "Selection of tolerances," (SPIE, 1988), pp. 173-185.
12. R. N. Youngworth, "21st Century optical tolerancing: a look at the past and improvements for the future," in *International Optical Design Conference*, G. G. Gregory, J. M. Howard, and R. J. Koshel, eds. (SPIE, 2006), pp. 6342031-6342015.
13. D. Heshmanty-Manesh, and G. Y. Haig, "Lens tolerancing by desk-top computer," Applied Optics **25**, 1268-1270 (1986).
14. C. G. Wynne, "Lens designing by electronic digital computer: I," Proceedings of the Physics Society London **73**, 777-787 (1959).
15. G. H. Spencer, "A flexible automatic lens correction procedure," Applied Optics **2**, 1257-1264 (1963).
16. R. Schuhmann, and G. Adams, "Enhancements to the optimization process in lens design (I)," (SPIE, 2001), pp. 30-36.
17. R. Schuhmann, and G. Adams, "Enhancements to the optimization process in lens design (II)," (SPIE, 2002), pp. 37-40.
18. G. W. Forbes, "Optical system assessment for design: numerical ray tracing in the Gaussian pupil," J. Opt. Soc. Am. A **5**, 1943-1956 (1989).
19. G. W. Forbes, "Errata: Optical system assessment for design: numerical ray tracing in the Gaussian pupil," J. Opt. Soc. Am. A **6**, 1123 (1989).
20. G. Cassar, E. Vigier-Blanc, and T. Lepine, "Improved tolerancing for production yield anticipation of optical micro-modules for camera phones," (SPIE, 2008), p. 71000F.
21. http://mathworld.wolfram.com/CentralLimitTheorem.html Mathworld is a mathematical reference database sponsored by Worlfram Research. Accessed April 22.

22. J. L. Plummer, "Tolerancing for economies in mass production optics," in *Contemporary Optical Systems and Components Specifications*, R. E. Fischer, ed. (SPIE, 1979), pp. 181-183.
23. R. R. Willey, "Economics in Optical Design, Analysis and Production," in *Optical System Design, Analysis and Production*, Rogers, and Fischer, eds. (SPIE, 1983), pp. 371-377.
24. R. R. Willey, "The impact of tight tolerances and other factors on the cost of optical components," (SPIE, 1984), pp. 106-111.
25. R. R. Willey, "Optical design for manufacture," (SPIE, 1989), pp. 96-102.
26. R. R. Willey, and M. E. Durham, "Maximizing production yield and performance in optical instruments through effective design and tolerancing," Critical Review **CR43**, *Optomechanical Design*, 76-108 (1992).
27. R. R. Willey, and R. E. Parks, eds., *Handbook of Optomechanical Engineering* (CRC Press, Boca Raton, FL, 1997).
28. R. E. Fischer, B. Tadic-Galeb, and P. R. Yoder, "Chapter 18: Optical Manufacturing Considerations," in *Optical System Design*, S. S. Chapman, ed. (McGraw-Hill Companies, Inc., 2008).
29. A. P. Grammatin, and N. E. Kundeleva, "Calculation of tolerances on the construction elements of optical systems taking technological limits into account," Sov. J. Opt. Technol. **48**, 61 (1981).
30. R. N. Youngworth, and B. D. Stone, "Cost-based tolerancing of optical systems," Applied Optics **39**, *25*, 4501-4512 (2000).
31. R. N. Youngworth, and B. D. Stone, "Elements of cost-based tolerancing," Optical Review **8**, *4*, 276-280 (2001).
32. B. Light, and R. Plympton, "21st Century Radius Tolerancing," in *Optifab*, (SPIE, Rochester NY, 2009), pp. TD06-24.
33. "Optimax Systems Inc., 6367 Dean Parkway, Ontario NY, 14519, (585) 265-1020, www.optimaxsi.com."