Tolerancing Optical Systems

A guide detailing how to appropriately tolerance an optical system to achieve system performance while minimizing cost.

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Introduction

Tolerancing an optical system has traditionally fallen between an art and a science. Experience and intuition has driven optical engineers for decades in deciding the appropriate tolerances to place on optical components and the mechanics holding them. In an effort to systematically quantify this process, mathematical methods have been reported by Warren Smith, Ronald Willey, and others to develop an analytical approach. These efforts detail how to create a tolerance budget for an optical system.

The intent of this paper is to discuss the performance characteristics used in judging optical systems, identify the parameters frequently toleranced in optical systems, explain the sensitivity a parameter has on system performance, discuss the creation of a tolerance budget, and finally to detail the iterative process of tolerancing . This paper includes both how to create a system budget to achieve performance requirements but also investigates the costs associated with tightening tolerances. The concepts of the paper have been built upon the pillars established by Smith, Willey, Robert Ginsberg, and Simon Magarill. This paper serves to give a brief and concise overview and guide of the methods used in tolerancing optical systems.

Performance Characteristic

A tolerance analysis fundamentally analyzes the relationship that perturbations present in a system have on the performance of the system. A plethora of performance metrics exist for optical systems as seen in Table 1. In some cases the tolerances of an optical system may be physical parameters such as effective focal length or back focal length, and in other cases image quality metrics are the performance metrics used. Often the application of the system will determine which metric to employ. For instance, systems used with detectors may look at spot size with respect to pixel size. The Modulation Transfer Function (MTF), RMS Spot Size, Point Spread Function (PSF), and wavefront error are commonly used metrics.

Table 1- Performance characteristics used in tolerancing optical systems

Performance Characteristics
MTF
Resolution
Energy Distribution
Spot Size
Beam Divergence

Geometrical Aberrations
PSF
Boresight Shift
Effective Focal Length
Back Focal Length
Distortion
Image Plane Displacement

Warren Smith provides a method to relate MTF of a given frequency to the wavefront deformation (OPD) (Smith, 1985). This method enables for changes in aberrations to be found as a function of system perturbations. The following are the relations Smith provides between OPD and ray-traced aberrations; the OPD are in units of waves:

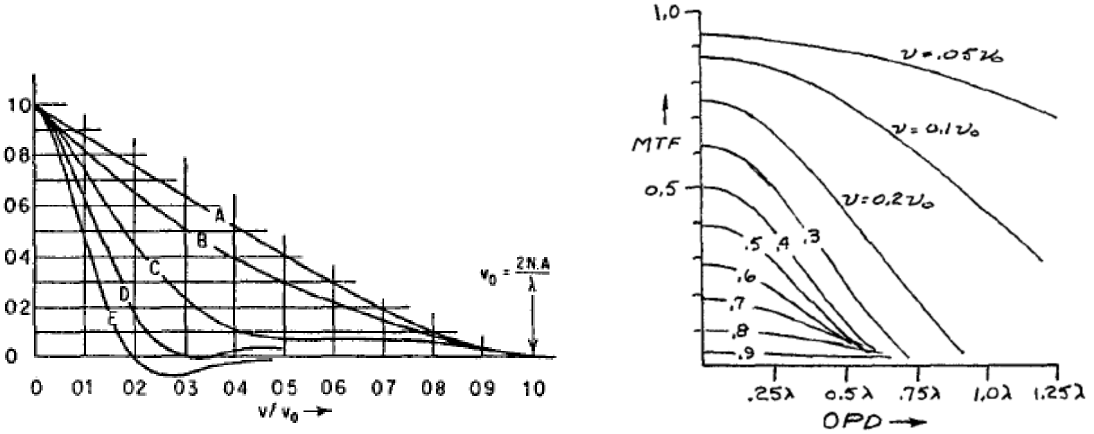
$$OPD = Transvers\ Spherical \cdot \frac{NA}{16\lambda} \tag{1}$$

$$OPD = Tangential\ Coma \cdot \frac{NA}{6\lambda} \tag{2}$$

$$OPD = Defocuse\ or\ Field\ Curvature \cdot \frac{NA^2}{2\lambda} \tag{3}$$

$$OPD = Longitudinal\ Chromatic \cdot \frac{NA^2}{8\lambda} \tag{4}$$

$$OPD = Lateral\ Color \cdot \frac{NA}{2\lambda} \tag{5}$$



(a) **(b)**

Figure 1 - The figure on the left is an MTF plot showing the effects of defocus. Curve A is in focus, Curve B has $\lambda/4$ of defocus, Curve C has a $\lambda/2$, and Curve D has $3\lambda/4$, and Curve E has 1λ of defocus. The figure on the left shows the relation between MTF at various spatial frequencies as a function of OPD present due to defocus. The MTF is scaled to the cutoff frequency where $\upsilon_o = 2NA/\lambda$. Figures from (Smith, 1985) (Burge, 2009)

Figure 1a shows the MTF curves for varying amounts of defocus present. The change in MTF will be different for aberrations other than defocus. However, the affects seen from defocus are simple enough to provide a conceptual understanding of how MTF changes with respect to system perturbations. An optical system is generally designed (MTF_{design}) to perform better than its specification (MTF_{spec}). Using Fig. 1b, the OPD for an MTF value at a given spatial frequency can be extrapolated. The Root Sum Square (RSS) between the difference in OPD_{design} and OPD_{spec} is therefore the allowable tolerance OPD_{tol}.

It is easy to move from RMS wavefront aberrations (w) to the Strehl ratio (S) through the equation

$$S = (1 - 2\pi^2 w^2)^2 \, . \tag{6}$$

The choice of performance characteristic is of course up to the optical engineer.

Component Tolerance Parameters

With a performance characteristic chosen for tolerancing the optical system, the next step is to identify the variable tolerances within the system. Simon Magarill introduces the definition of primary parameters (Magarill, 1999). A primary parameter is one that is independent of other parameters. For instance airspace is dependent on the primary parameters of spacer thickness, contact diameter, sag, and radii.

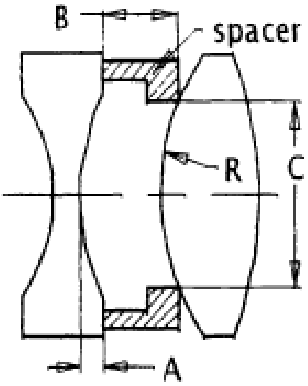


Figure 2 – Figure from (Magarill, 1999). Airspace is dependent on sag (A), spacer thickness (B), contact diameter (C), and radii (R).

The following parameters are what Magarill defines as primary and can be used to tolerance an optical system. There are twelve parameters in total and each represent a characteristic that will orthogonally affect image quality.

Table 2 – Primary parameters in lens assemblies (Magarill, 1999)

Parameter	Definition	Applicable to:
Center Thickness	Axial distance between two consecutive vertexes.	-Lenses -Spacers
Surface Sag	Axial distance from basis flat to vertex of optical surface.	-Lenses
Index of Refraction		-Lenses
Contact Diameter	Diameter of the seat in contact with non-plano optical surfaces.	-Barrel -Spacers
Axial Seat Position	Axial distance from mechanical assembly datum point to barrel seat.	-Barrel
Wedge	Edge thickness difference.	-Lenses -Spacers
Seat Tilt	Tilt or flat seat relative to common mechanical axis.	-Barrel

Contact Diameter Eccentricity	Displace of seat diameter axis from common mechanical axis	-Barrel -Spacers
Surface to Surface Displacement	Lateral displacement of optical surface of the lens	-Aspherical lenses
Base Diameter Eccentricity	Displacement of base diameter axis from common mechanical axis	-Barrel
Second Barrel Clearance	Clearance between main and secondary barrel	-Primary/Secondary Barrel Interface

All though these primary parameters are orthogonal, more explicit parameters may need to be defined. Explicit parameters such as radius are necessary to specify an optic to an optics manufacturer. The following is a list of typical parameters defined in a tolerance budget and values associated with them. The values given are intended to give an approximation of tolerances used in industry and are by no means reflect hard and cut capabilities of manufacturers. The loose tolerance values are referred as commercial grade and should be considered the base tolerance; moving to a looser tolerance does not decrease the cost of the manufacturing process.

Table 3 – Parameters associated with optics.

Parameters	Loose Tolerance	Tight Tolerance	Unit
Index of Refraction	0.001	0.0003	
Radius	5	1	fringes
Irregularity	2	1/8	fringes
Thickness	0.150	0.50	mm
Sag	0.05	0.025	mm
Diameter	0.10	0.025	mm
Wedge	0.05	0.01	mm
Surface Roughness	50	20	RMS

Table 4 – Parameters associated with assembly

Parameters	Loose Tolerance	Tight Tolerance	Unit
Airspace	0.50	0.050	mm
Decenter – Optial Axis	0.50	0.025	mm
Decenter – Lateral	5	0.5	arcmin
Tilt	0.3	2	mrad
Lens Roll	0.50	0.025	mm

Determine Sensitivities

With the optical and mechanical parameters chosen, the sensitivity of each parameter can be found. These sensitivities can be approximated to be linear. A small perturbation should be applied (0.001 for index, 0.01 mm for thickness/diameter/etc.) to each parameter in order to find the resulting change in the performance specification. This can be done in a ray trace program. From here the sensitivity is simply equal to

$$sensitivity = \frac{\Delta performance}{\Delta parameter} \ , \tag{7}$$

which is recognized as the slope with the intercept set equal to zero (representing the part manufactured at the specification). It should be evident that certain parameters are more sensitive than other and therefore have a large affect on system performance. With this mind, tolerances can be assigned to each parameter (t_i). The resulting change in system performance (p_i) for each tolerance should subsequently be found or calculated using its respective sensitivities. To find the net effect of all the tolerances on the system, the RSS is used. This net value ($error_{syst}$) resulting from all system parameters needs to fall below the performance specification for the system.

$$error_{syst} = \sqrt{\sum {p_i}^2}. \tag{8}$$

Table 5 displays and example tolerance table for assembly errors for a simple doublet. Here the performance characteristic is wavefront error. With the exception of the airspace, the target value for all the parameters is 0. A tolerance is assigned and the respective sensitivity and resulting wavefront error is displayed. The RSS of all the assembly parameters is calculated and displayed at the bottom of the table. This is the value that must be less than the performance specification of the system.

Table 5 – Example of a tolerance budget displaying tolerance, sensitivity, and resulting wavefront error.

Error Type	**Units**	**Tolerance**	**Tolerance Value**	**Sensitivity**	**WF Error Φ *(λ)***
L1 Tilt	*deg*	+/- 0.10	0.1	0.132	0.011
L1 Decenter	*mm*	+/- 0.09	0.09	0.187	0.019
Airspace L1-L2	*mm*	+/- 0.10	1.1	0.016	0.003
L2 Tilt	*deg*	+/- 0.10	0.1	0.192	0.018
L2 Decenter	*mm*	+/- 0.09	0.09	0.186	0.019
RSS					***0.036***

Creating a Budget

Once a tolerance table has been established the iterative process of finalizing the tolerance table begins. The initial tolerances need to be refined to enlarge the tighter tolerances because generally a tighter tolerance leads to a higher cost is more difficult to achieve. The principle factor of adjusting tolerances is to recognize which parameters are the most sensitive. These parameters will ultimately control the tolerance budget. Among trying to reach performance requirements, cost requirements may need to be considered. Generally placing a tight tolerance on a component leads to increased cost. Ronald Willey has provided several in depth analyses looking at the relationship between tolerances and production costs. The following simple equation creates another element to be integrated into the tolerance budget when cost is a factor for an optical system.

$$C_i = \frac{A_i}{T_i} + B_i \tag{9}$$

This equation is reported by Willey (Willey R. R., 1984) where C_i is the cost of a tolerance, B_i is the base cost of a component, A_i is the constant relating to the cost of the tolerance, and T_i is reported as the reciprocal of the tolerance. Willey in his papers has compiled data in conjunction with Plummer and Lagger (Lagger, 1982) demonstrating the cost of tightening tolerances using Equation 9. Figure 3 demonstrates the percentage cost increase of tightening the radius of curvature. For further data on other parameters refer to Willey.

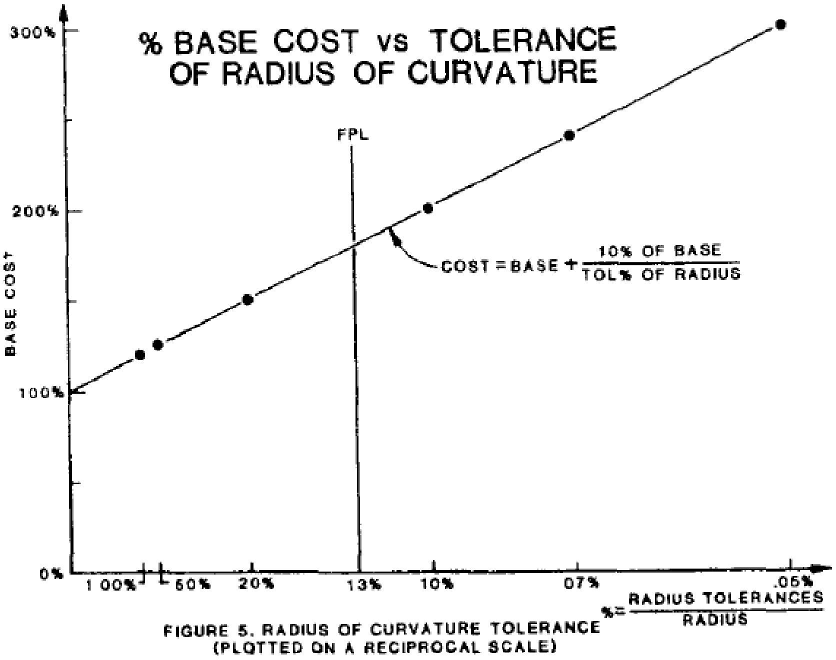


Figure 3 – Showing the relationship of cost to the tolerance of radius of curvature. Figure from (Willey R. R., 1984)

With the "cost sensitivity" of each parameter known, the cost of each tolerance now becomes part of the tolerance budget just as each parameter's effect on system performance. The engineer can now properly evaluate the cost of each tolerance in the optical system and subsequently optimize. This type of cost analysis is integral in optical systems that see mass production.

Table 6 - Relative costs of glass compared to BK7. Source: (Willey R. , 1992)

BK7	100%
SF56	120%
Pyrex	125%
Germanium	130%
Fused Silica	140%
Zerodur	150%
ZnS, ZnSe	160%
FK2, BaF2, Amtir	170%
LaKN9, LaFN21	200%
Electroless Ni	250%
CaF2, LiF	275%
MgF2, Si	300%
Electrolytic Ni	350%
Ruby	700%
Sapphire	800%

The choice of optimizing for cost therefore becomes a balance of engineer salary and the potential savings seen in large scale production. If either an initial tolerance reveals a component that is overly sensitive or too costly, the iterative process of either adjusting other tolerances or making adjustments to the optical design needs to be made. It may even be necessary to relax performance specifications in certain circumstances. Magarill provides a flow chart showing this iterative process in optical system tolerancing.

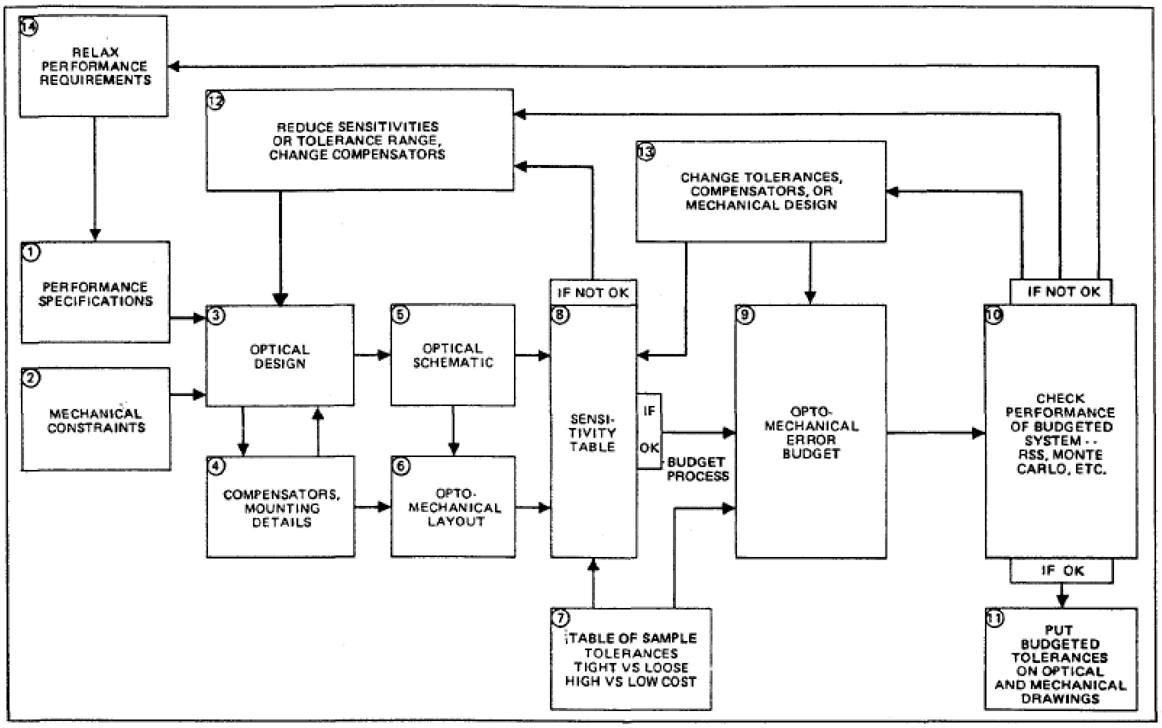


Figure 4 – The iterative process of tolerancing an optical system. Reproduced from (Magarill, 1999).

Conclusion

Despite the ability of being able to auto-tolerance an optical system in a ray trace program the process of tolerancing is involved. Experience aids in this systematic processes beginning with choosing a performance metric, identifying the variable parameters within the system, finding the sensitivity of each parameter, and creating a tolerance budget for system's parameters. This process of tolerancing an optical system is iterative to ensure system performance requirements are met and costs are minimized. The iterative process ranges from simply adjusting tolerances within the budget, reducing sensitivities by altering an optical design, or by fundamentally changing the initial performance requirements.

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